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TESIS DOCTORAL

EVALUACIÓN EXPERIMENTAL DEL
FENÓMENO DEL “CRACK SHIELDING”
INDUCIDO POR PLASTICIDAD EMPLEANDO
TÉCNICAS ÓPTICAS DE CAMPO COMPLETO
PARA LA MEDIDA DE TENSIONES Y
DEFORMACIONES

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Resumen

Un tema que ha interesado a gran cantidad de investigadores durante mucho tiempo ha sido la evaluación del daño producido por grietas originadas debido a procesos de fatiga. Recientemente, ha incrementado la popularidad de técnicas ópticas para el estudio de la integridad estructural en la mecánica experimental. De entre estas técnicas cabe destacar la fotoelasticidad por transmisión, correlación digital de imágenes (DIC) y electronic speckle pattern interferometry (ESPI), tratándose de técnicas ópticas experimentales de campo completo que se emplean para el análisis de tensiones y deformaciones en elementos mecánicos. Dichas técnicas muestran un gran potencial para la evaluación del efecto de ‘crack shielding’ por fatiga ya que mediante las mismas se pueden cuantificar los campos de tensiones y desplazamientos alrededor del vértice de la grieta.

De acuerdo con lo anteriormente indicado, el objetivo principal de esta tesis es la evaluación y cuantificación del efecto de ‘crack shielding’ inducido por plasticidad en la vida a fatiga de elementos mecánicos. Para ello, se ha desarrollado una metodología experimental basada en el cálculo de los factores de intensificación de tensiones (SIFs). Así, el efecto de ‘crack shielding’ se evalúa a partir del análisis de los SIFs. Este análisis se lleva a cabo mediante el estudio de cuatro modelos diferentes para la descripción de los campos de tensiones/desplazamientos en las inmediaciones del vértice de la grieta, siendo estos los modelos de Westergaard, Williams, Muskhelishvili y el CJP. Además de esto, también se evalúa cuál es el modelo más útil para la cuantificación del efecto de ‘crack shielding’ inducido por plasticidad.

La metodología se ha implementado satisfactoriamente mediante la realización de distintos ensayos a fatiga en probetas compact-tension (CT). Así, se emplearon tres materiales diferentes dependiendo de la técnica implementada. De esta forma, se emplearon probetas de policarbonato para fotoelasticidad por transmisión, aluminio 2024-T3 para DIC y titanio comercialmente puro para ESPI. Para la evaluación del efecto de ‘crack shielding’ por fatiga se han realizado varios ensayos a diferentes *R*-ratios. Además de esto, también se ha evaluado el efecto en el crecimiento de grieta debido a la aplicación de sobrecargas. Para ello, se han realizado distintos ensayos a fatiga a carga de amplitud constante interrumpidos por distintas sobrecargas individuales.

Por último, los resultados obtenidos con DIC se han comparado con los obtenidos mediante métodos basados en ‘compliance’, siendo estos los métodos del ‘strain offset’ y el ‘offset compliance’. Los resultados obtenidos mediante estos dos métodos basados en ‘compliance’ y los obtenidos mediante DIC han mostrado un gran nivel de acuerdo. Por lo tanto, esto pone de

manifiesto la capacidad de la metodología propuesta basada en el análisis de los SIFs para cuantificar el efecto de ‘crack shiedling’ y el potencial de las técnicas ópticas evaluadas para predecir de forma real la vida a fatiga de elementos mecánicos.

Abstract

An interesting topic for many researchers since long time has been the damage evaluation produced by a growing fatigue crack. Recently, the popularity of optical techniques to the structural integrity study in experimental mechanics has increased. Within these techniques include transmission photoelasticity, digital image correlation (DIC) and electronic speckle pattern interferometry (ESPI), being full-field experimental optical techniques which are employed for the analysis of stresses and strains in mechanical elements. These techniques seem to show an enormous potential in the evaluation of fatigue crack shielding since stress and displacement fields around the crack tip can be accurately quantified.

Based on this premise, the main objective of the current thesis is the evaluation and quantification of plasticity-induced crack shielding in fatigue life of mechanical elements. For this purpose, a methodology based in the calculation of the stress intensity factors (SIFs) is developed. Thus, the evaluation of crack shielding is performed from the analysis of the SIFs. This analysis is conducted by studying four different models to describe the stress/displacement fields around the crack tip, namely, Westergaard's, Williams's, Muskhelishvili's and CJP models. In addition, it is evaluated which is the most suitable to quantify the plasticity-induced fatigue crack shielding effect.

The methodology has been successfully implemented conducting several fatigue tests on compact-tension (CT) specimens. Three different materials for specimens were employed depending on the implemented technique. Thus, polycarbonate specimens were employed for transmission photoelasticity, 2024-T3 aluminium for DIC and commercially pure titanium for ESPI. Several fatigue tests at different R -ratios have been conducted for the evaluation of fatigue crack shielding. In addition, the effect due to the application of overloads on fatigue crack growth has been also evaluated. For this purpose, fatigue tests at constant amplitude loading have been interrupted by different single overload levels.

Finally, results obtained using DIC have been compared with those obtained using two compliance based methods, namely the strain offset and the offset compliance offset methods. Experimental results obtained from the two compliance methods have showed a good level of agreement with those obtained using DIC. It highlights the ability of the studied optical techniques to quantify fatigue crack shielding and to realistically predict fatigue life in mechanical elements.

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Nomenclature

A_{Ip}, A_{IIp} :	coefficients on Williams's expansion series for the crack tip stress fields
$A_k^j, B_k^j, C_k^j, D_k^j$:	coefficients on Muskhelishvili's model for the crack tip displacement fields
A_M, B_M :	series coefficients of stress field equations on Muskhelishvili's model
a :	crack length (m)
a_k, b_k, c_k :	complex coefficients for Fourier series representation
a_o :	amplitude of the object beam ($W \cdot m^{-2}$)
a_p, b_p :	coefficients on Williams's expansion series for the crack tip displacement fields
a_r :	amplitude of the reference beam ($W \cdot m^{-2}$)
C :	relative stress-optic coefficient (MPa^{-1})/compliance in presence of closure
C_0 :	compliance in absence of closure
$c_{1,2}$:	stress-optic coefficients (MPa^{-1})
$\vec{d}$:	displacement vector
E :	Young's modulus (MPa)
$F_{Ax,y}$:	reaction forces to the applied remote load
F_C :	contact force between crack faces
$F_{Px,y}$:	forces induced by the compatibility requirements on the elastic-plastic boundary
F_S :	shear force on the elastic-plastic boundary
F_T :	force due to the T-stress
F_σ :	material stress fringe value ($N \cdot mm^{-1} \cdot fringe^{-1}$)
G :	shear modulus (MPa)
I :	intensity of the point P in the interferogram in initial state ($W \cdot m^{-2}$)
I' :	intensity of the point P in the interferogram in deformed state ($W \cdot m^{-2}$)
I_s :	resulting intensity by subtracting I and I' ($W \cdot m^{-2}$)
i :	square root of -1
i_m :	intensity term that takes into account the incoming external light in polariscope
i_v :	light intensity observed when all optical axes are parallel in a polariscope
j :	selected data point
K_{cl} :	closure stress intensity factor ($MPa \cdot m^{1/2}$)
K_F :	opening mode stress intensity factor in the CJP model ($MPa \cdot m^{1/2}$)
K_I :	mode I stress intensity factor ($MPa \cdot m^{1/2}$)
K_{II} :	mode II stress intensity factor ($MPa \cdot m^{1/2}$)
K_{max} :	maximum stress intensity factor ($MPa \cdot m^{1/2}$)
K_{op} :	opening stress intensity factor ($MPa \cdot m^{1/2}$)
K_R :	retardation stress intensity factor ($MPa \cdot m^{1/2}$)

K_S :	shear stress intensity factor ($\text{MPa}\cdot\text{m}^{1/2}$)
$\vec{k}_1$:	illumination vector
$\vec{k}_2$:	observation vector
$\vec{k}_s$:	sensitivity vector
L :	length parameter in mapping function
M :	limit on the Fourier series
M' :	limit on the truncated Fourier series
m :	shape parameter in mapping function
N :	fringe order (fringe)
n :	refractive index in the unstressed state
$n_{1,2}$:	refractive indices associated with the principal directions
P_{cl} :	crack closure load (N)
P_{op} :	crack opening load (N)
p :	number of terms on Williams's expansion series
r, θ :	polar coordinates, r (m) and θ (radian)
t :	thickness of the model (m)
u, v :	horizontal and vertical displacements (m)
W :	specimen width (mm)
z :	complex coordinate in the physical plane
α_k, β_k :	real and imaginary parts of a_k respectively
γ :	isoclinic angle (radian)
Δ :	phase change between the initial and deformed states (rad)
ΔK_{eff} :	effective stress intensity factor range ($\text{MPa}\cdot\text{m}^{1/2}$)
ΔK_{nom} :	nominal stress intensity factor range ($\text{MPa}\cdot\text{m}^{1/2}$)
ΔP :	load range (N)
δ :	relative retardation (radian)
ε_U :	ultimate strain (%)
ε_Y :	yield strain (%)
κ :	function of Poisson's ratio
λ :	wavelength (m)
ν :	Poisson's ratio
ζ :	complex coordinate in the mapping plane
$\sigma_{1,2}$:	maximum and minimum principal stresses (MPa)
σ_U :	Ultimate stress (MPa)
$\sigma_{x,y}$:	normal stresses along x and y axes (MPa)
σ_Y :	Yield stress (MPa)

σ_{0x} :	T-stress (MPa)
τ_{xy} :	shear stress (MPa)
$\Phi(z), \Psi(z)$:	Muskhelishvili's analytical functions for the crack tip stress fields
$\phi(z), \psi(z)$:	Muskhelishvili's analytical functions for the crack tip displacement fields
ϕ_{or} :	phase random in initial state (rad)
ϕ'_{or} :	phase random in deformed state (rad)
ω :	mapping function
Θ_o :	phase of the object beam (rad)
Θ_r :	phase of the reference beam (rad)

Capítulo 1. Introducción

1.1. Motivaciones y objetivos del trabajo de investigación

1.1.1. Fotoelasticidad por transmisión, correlación digital de imágenes y electronic speckle pattern interferometry: posibles técnicas para la evaluación del efecto de ‘crack shielding’

Proporcionar respuestas de forma cuantitativa a problemas relacionados con grietas contenidas en elementos mecánicos o estructurales ha sido un tema de interés a gran número de investigadores desde hace tiempo. En particular, grietas originadas por fatiga han sido una de las principales fuentes de fallo sobre estructuras en servicio, en los que la Mecánica de la Fractura ha contribuido a un mejor entendimiento de los mecanismos de crecimiento de grietas por fatiga. Sin embargo, hay aún cuestiones que permanecen sin resolver o sin un claro entendimiento, siendo uno de estos aspectos el fenómeno de ‘crack shielding’ por fatiga. Esta falta de entendimiento proviene principalmente de problemas en su medida e interpretación [1].

Recientemente, las técnicas ópticas experimentales de campo completo han contribuido a un mejor entendimiento de los diferentes mecanismos de fatiga y en el efecto de retardo que puede ser inducido durante el crecimiento de grietas por fatiga. Así, el análisis de los campos de tensiones y/o deformaciones en las inmediaciones del vértice de una grieta juega un papel determinante. En este aspecto, fotoelasticidad por transmisión, correlación digital de imágenes (DIC) y electronic speckle pattern interferometry (ESPI) parecen ser técnicas útiles para cuantificar el fenómeno de ‘crack shielding’ ya que mediante su utilización se pueden cuantificar con gran exactitud los campos de tensiones y desplazamientos alrededor del vértice de una grieta.

El fenómeno de cierre de grieta (‘crack closure’) disminuye la velocidad de crecimiento de grieta a fatiga mediante la reducción del rango del factor de intensificación de tensiones efectivo debido al contacto entre las caras de la grieta cuando la grieta empieza a cerrarse prematuramente. En los últimos años, se han desarrollado diferentes metodologías basadas en la cuantificación del rango del factor de intensificación de tensiones efectivo [2, 3]. En particular, James et al. [2] desarrollaron un novedoso procedimiento para evaluar el cierre de grieta en probetas de policarbonato empleando fotoelasticidad por transmisión basado en los potenciales

complejos de Muskhelishvili. Ellos dedujeron un conjunto de valores del factor de intensificación de tensiones a diferentes niveles de carga durante el ciclo de carga a partir del análisis de imágenes fotoelásticas. Los resultados mostraron claramente efectos de ‘shielding’ debido al cierre inducido por plasticidad. Además, Díaz et al. [3] desarrollaron un procedimiento para evaluar el efecto de cierre de grieta a partir del análisis de imágenes termoelásticas cuantificando el rango del factor de intensificación de tensiones efectivo. Además de estas dos técnicas, el empleo de DIC para el análisis de problemas de integridad estructural se ha visto notablemente incrementado. Recientemente, se han desarrollado metodologías basadas en el cálculo de los factores de intensificación de tensiones [4 - 6] a partir del análisis de datos experimentales medidos en las inmediaciones del vértice de una grieta. Estas metodologías combinan datos experimentales con modelos matemáticos que describen los campos de desplazamientos en el vértice de una grieta para llevar a cabo un ajuste matemático. Un ejemplo es el trabajo realizado por López-Crespo et al. [5], quienes desarrollaron una metodología basada en el método Multi-Point Over-Deterministic (MPODM) desarrollado por Sanford y Dally [7] para determinar los factores de intensificación de tensiones mediante el análisis de los campos de desplazamientos medidos alrededor del vértice de una grieta. Por otra parte, DIC se ha empleado también para la evaluación del cierre de grieta durante el crecimiento de grieta por fatiga. Un ejemplo es el trabajo llevado a cabo por de Matos y Nowell [8], quienes estudiaron el efecto del espesor en el cierre de grieta inducido por plasticidad. Más trabajo fue también realizado por López-Crespo et al. [9], quienes presentaron una metodología basada en los potenciales complejos de Muskhelishvili [10] para la evaluación del cierre de grieta. Además de esto, fotoelasticidad por transmisión y DIC parecen ser técnicas muy útiles para cuantificar el efecto de la aplicación de sobrecargas [11, 12] en la vida a fatiga y su correspondiente efecto de ‘shielding’ en el crecimiento de grieta. Por otro lado, hoy en día sistemas compactos de ESPI han hecho posible extender el uso de esta técnica para el estudio de la integridad estructural de elementos mecánicos. Sin embargo, muy pocos trabajos de investigación empleando ESPI se pueden encontrar en la literatura para el análisis de problemas de mecánica de la fractura. Por lo tanto, una nueva línea de investigación se puede abrir, que implicaría un avance importante en el estudio del efecto de ‘crack shielding’ durante el crecimiento de grieta a fatiga.

Todas las ideas que se han indicado previamente en el párrafo anterior evidencian el enorme potencial de las técnicas para el análisis experimental de tensiones, destacando la fotoelasticidad por transmisión, DIC y ESPI para la evaluación del efecto de ‘crack shielding’. Por tanto, dicho efecto producido por la estela plástica generada en las inmediaciones del camino dejado por la grieta en su crecimiento puede ser evaluado mediante las tres técnicas ópticas experimentales indicadas anteriormente.

1.1.2. Motivación del trabajo de investigación

La principal motivación del presente trabajo de investigación está relacionada con el estudio de la integridad estructural en elementos mecánicos o estructurales. En este sentido, una de las principales fuentes de fallo en estructural reales es el crecimiento de grietas debido a procesos de fatiga. Hoy en día, es vital el diseño de componentes mecánicos más seguros, más ligeros y más duraderos para aplicaciones ingenieriles en distintos sectores industriales. Desde el punto de vista de la fatiga, un diseño más seguro implica un mejor entendimiento de los diferentes mecanismos a fatiga generados durante la vida en servicio de componentes ingenieriles. En este aspecto, la fotoelasticidad por transmisión, DIC y ESPI hacen posible obtener los campos de tensiones y desplazamientos en las inmediaciones de una grieta a fatiga, contribuyendo a un mejor entendimiento de los diferentes mecanismos de fatiga. Así, uno de los fenómenos más relevantes es el efecto de ‘crack shielding’ inducido por la plasticidad generada durante el crecimiento de una grieta por fatiga.

Además, algunos de los trabajos de investigación se han realizado como parte del proyecto de investigación ‘*Proyecto de Investigación de Excelencia TEP 2009-5177*’, financiado por la *Consejería de Economía, Innovación y Ciencia de la Junta de Andalucía* con fondos *FEDER*. Este proyecto tiene como objetivo principal el estudio de la integridad estructural de elementos mecánicos empleando técnicas ópticas experimentales para la medida de tensiones y deformaciones. En este sentido, la fotoelasticidad por transmisión, DIC y ESPI ofrecen la posibilidad de obtener la distribución de tensiones y deformaciones en elementos mecánicos y, por tanto, pueden ser aplicadas para el análisis de la integridad estructural durante procesos de fatiga. Esto añade una motivación adicional al presente trabajo ya que podría tener una importante repercusión en términos de seguridad y coste.

1.1.3. Objetivos del trabajo de investigación

El objetivo principal de esta tesis es el desarrollo de una metodología para la evaluación experimental del efecto de ‘crack shielding’ en elementos mecánicos empleando técnicas ópticas experimentales de campo completo. En este sentido, el efecto de ‘shielding’ durante el crecimiento de grieta por fatiga se evalúa a partir del análisis de los factores de intensificación de tensiones (SIFs) obtenidos empleando las técnicas de fotoelasticidad por transmisión, DIC y ESPI. Los SIFs son determinados a partir del análisis de los campos de tensiones en el vértice de la grieta, en el caso de fotoelasticidad por transmisión, y del análisis de los campos de desplazamientos en el vértice de grieta para DIC y ESPI.

Para la realización de la presente investigación, el trabajo se ha dividido en cuatro pasos. El primer paso es el desarrollo de un procedimiento experimental para cuantificar los factores de

intensificación de tensiones a partir del análisis de los campos de tensiones y desplazamientos alrededor del vértice de la grieta. El siguiente paso es la predicción de la vida a fatiga basada en el análisis del rango del factor de intensificación de tensiones. Una vez establecido la capacidad de las tres técnicas ópticas para la predicción de la vida a fatiga, el tercer paso es evaluar el potencial de dichas técnicas para la cuantificación del efecto de ‘crack shielding’ y su efecto en durante la vida a fatiga. Finalmente, el último paso es la evaluación del efecto de la aplicación de sobrecargas en la vida a fatiga.

1.2. Alcance de la tesis

El objetivo principal de la presente tesis es la investigación del efecto de ‘crack shielding’ durante el crecimiento de grieta a fatiga empleando técnicas ópticas experimentales de campo completo para la medida de tensiones y deformaciones. De acuerdo con esta premisa, la tesis se ha organizado en ocho capítulos:

En el capítulo 2 se describen los fundamentos y los conceptos básicos que serán empleados en los capítulos siguientes de la presente tesis. El capítulo comienza con una descripción de los fundamentos teóricos de las técnicas de fotoelasticidad por transmisión, correlación digital de imágenes y electronic speckle pattern interferometry. A continuación, se describen los cuatro modelos para la definición de los campos de tensiones y desplazamientos en las inmediaciones del vértice de la grieta adoptados para el cálculo de los factores de intensificación de tensiones. Por otra parte, se describen los fundamentos del fenómeno de cierre de grieta y una breve revisión de los distintos mecanismos de cierre recogidos en la literatura. Finalmente, se revisa una descripción del efecto de la influencia de sobrecargas en la vida a fatiga.

El capítulo 3 se trata de una revisión literaria dividida en dos áreas principales. La primera es una revisión histórica acerca del fenómeno de cierre de grieta por fatiga, exponiendo las técnicas y métodos presentados en la literatura para su evaluación y cuantificación. La segunda área es una revisión sobre cómo las técnicas de fotoelasticidad por transmisión, DIC y ESPI se han empleado dentro de la mecánica de la fractura. En particular, se revisan los diferentes procedimientos y metodologías para el cálculo de los factores de intensificación de tensiones así como los trabajos de investigación más relevantes desarrollados sobre la evaluación del efecto de ‘shielding’ y del efecto de la aplicación de sobrecargas en la vida a fatiga.

En el capítulo 4 se describe el procedimiento experimental. Se presentan los equipos y las probetas seleccionadas en el presente trabajo de investigación. También se describen los procesos de fabricación de las probetas empleadas, sus propiedades mecánicas y su preparación para los ensayos a fatiga. Finalmente, se describe el procedimiento experimental para llevar a cabo los ensayos a fatiga para cada una de las técnicas.

En el capítulo 5 se detalla la metodología experimental desarrollada para la determinación de los factores de intensificación de tensiones. Así, para la fotoelasticidad por transmisión, los SIFs se obtienen a partir del análisis de los datos isocromáticos obtenidos en las inmediaciones del vértice de la grieta mediante la resolución de un sistema no lineal de ecuaciones. Para DIC y ESPI, se emplean los campos de desplazamientos horizontales y verticales medidos alrededor del vértice de la grieta para el cálculo de los SIFs mediante la resolución de un sistema lineal de ecuaciones.

En el capítulo 6 se presentan y discuten los resultados experimentales sobre el efecto de ‘crack shielding’ obtenidos mediante el uso de las técnicas de fotoelasticidad en transmisión, DIC y ESPI. Los resultados se obtuvieron empleando probetas CT de distintos materiales dependiendo de la técnica implementada. Inicialmente, el efecto de ‘crack shielding’ se estudia sobre probetas de policarbonato usando la fotoelasticidad por transmisión, siendo un material suficientemente dúctil para permitir el crecimiento de grieta por fatiga y mostrar clara evidencia de efecto de ‘crack shielding’ inducido por plasticidad. Después de esto, el estudio del efecto de ‘shielding’ se extiende a materiales metálicos. Así, aluminio 2024-T3 fue empleado para las probetas ensayadas en DIC mientras que probetas de titanio comercialmente puro se emplearon para la técnica de ESPI. Los resultados obtenidos mediante DIC fueron comparados con los obtenidos mediante técnicas basadas en ‘compliance’. Además, al final del capítulo se propone una metodología para la estimación del tamaño de la zona plástica en el vértice de la grieta mediante ESPI.

En el capítulo 7, la metodología adoptada en el anterior capítulo para la evaluación del efecto de ‘shielding’ se extiende para el estudio del efecto causado por la aplicación de sobrecargas en la vida a fatiga. Así, diferentes niveles de sobrecargas se aplicaron sobre probetas CT ensayadas a ciclo de carga de amplitud constante para cada una de las técnicas. Al igual que en el capítulo 6, los resultados obtenidos mediante DIC fueron comparados con los obtenidos mediante un método basado en ‘compliance’. Finalmente, la metodología previamente propuesta para estimar el tamaño de la zona plástica empleado ESPI se extiende al estudio de la influencia de sobrecargas a través de variaciones observadas en el tamaño de la zona plástica.

Finalmente, el capítulo 8 recoge una discusión general del trabajo de investigación descrito en la presente tesis. Después, se enumeran las conclusiones más relevantes establecidas a partir del análisis de la discusión previa. Para concluir, se exponen diferentes líneas de investigación futuras derivadas de la presente investigación.

Chapter 1. Introduction

1.1. Motivations and aims of the research

1.1.1. Transmission Photoelasticity, Digital Image Correlation and Electronic Speckle Pattern Interferometry: potential techniques for evaluating fatigue crack shielding

Providing quantitative answers to crack problems in mechanical or structural elements has been an interesting topic of research since long time. In particular, fatigue cracks have been one of the main sources of structural failure in real service structures, where Fracture Mechanics has contributed to a better understanding of fatigue crack growth mechanisms. However there are still issues that remain unresolved or misunderstood, one of these aspects is the fatigue crack shielding phenomenon. This misunderstanding comes mainly from problems in its measurement and interpretation [1].

Recently, full field experimental optical techniques have contributed to a better understanding of the different fatigue mechanisms and the retardation effect that can be induced during fatigue crack growth. Thus, the analysis of the stress or strain fields at the vicinity of the crack tip plays a significant role. In this respect, transmission photoelasticity, digital image correlation (DIC) and electronic speckle pattern interferometry (ESPI) seem to be some very suitable techniques for quantifying the crack shielding phenomenon since stress and displacement fields around the crack tip can be quantified with high level of accuracy.

Crack closure phenomenon decreases the fatigue crack growth rate by reducing the effective stress intensity factor range due to the contact between crack faces as the crack starts closing in a premature way. In recent years, different methodologies based on the calculation of the effective stress intensity factor range have been developed [2, 3]. In particular, James et al. [2] developed a novel approach for evaluating crack closure in polycarbonate specimens using transmission photoelasticity based on Muskhelishvili's complex potentials. They were able to infer a set of stress intensity factor values at different load levels during a loading cycle from the direct analysis of photoelastic images. Results clearly illustrated a shielding effect due to plasticity-induced crack closure. In addition, Díaz et al. [3] developed an approach to assess crack closure effect from the analysis of thermoelastic images quantifying the effective stress intensity factor range. Besides these two techniques, the use of DIC has been significantly

increased in the analysis of structural integrity problems. Recently, new methodologies based on the calculation of the stress intensity factors [4 – 6] from the analysis of experimental data measured around the crack tip have been developed. These methodologies combine experimental data with mathematical models describing the crack tip displacement fields to perform a mathematical fitting. Such an example is the work conducted by López-Crespo et al. [5], who developed a methodology based on the Multi-Point Over-Deterministic Method (MPODM) developed by Sanford and Dally [7] to determine the stress intensity factor from the analysis of the displacement fields measured around the crack tip. Moreover, DIC has been also used for evaluating crack closure during fatigue crack growth. Such an example is the work conducted by de Matos and Nowell [8], who studied the thickness effect in plasticity-induced fatigue crack closure. Further work was also conducted by López-Crespo et al. [9], who presented a methodology based on Muskhelishvili's complex potentials [10] for the evaluation of crack closure. In addition, transmission photoelasticity and DIC seem to be very suitable techniques for quantifying the effect of the application of overloads [11, 12] in fatigue life and their shielding effect in fatigue crack growth. On the other hand, nowadays compact ESPI systems have made possible to extend the use of this technique to the study of structural integrity on mechanical elements. However, very few research works using ESPI for the analysis of fracture mechanics problems can be found in the literature. Therefore a new research line can be opened, which would imply a significant advance in the study of shielding effect during fatigue crack growth.

All the ideas previously indicated in the above paragraph evidence the enormous potential of experimental stress analysis techniques, namely transmission photoelasticity, DIC and ESPI for the evaluation of fatigue crack closure. Hence, the shielding effect produced by the plastic zone generated around the crack wake on the surrounding elastic material, can be potentially evaluated by these three experimental optical techniques.

1.1.2. Motivation for the research

The main motivation of this research is related to the study of the structural integrity in mechanical or structural elements. In this sense, one of the main sources of failure in real structures is the growth of cracks due to fatigue processes. Nowadays, it is vital the design of safer, lighter and more durable mechanical components for engineering applications in different industrial sector. From the fatigue point of view, safer design imply a better understanding of the different fatigue mechanisms generated during service life of the engineering components. In this aspect, transmission photoelasticity, DIC and ESPI make it possible to obtain the stress and displacement fields at the vicinity of the crack tip, contributing to a better understanding of

the different fatigue mechanisms. Thus, one of the most relevant phenomena is the crack shielding effect induced by plasticity generated during fatigue crack growth.

In addition, some of the work has been conducted as part of the research project '*Proyecto de Investigación de Excelencia TEP 2009-5177*', funded by *Consejería de Economía, Innovación y Ciencia* from *Junta de Andalucía* with FEDER funds. This project has as main objective the study of structural integrity in mechanical elements using experimental optical techniques for measuring stresses and strains. In this sense, transmission photoelasticity, DIC and ESPI offer the possibility to obtain the stress and strain distributions in mechanical elements and, hence they can be applied for analysing structural integrity during fatigue. This adds an additional motivation to the current work since it could have a significance repercussion in terms of safety and cost.

1.1.3. Aims of the research

The aim of this thesis is to develop a methodology for the experimental evaluation of fatigue crack shielding in mechanical elements using full field experimental optical techniques. In this sense, the shielding effect during fatigue crack growth is evaluated from the analysis of the stress intensity factors (SIFs) obtained using transmission photoelasticity, DIC and ESPI techniques. SIFs are inferred from the analysis of the crack tip stress fields, in the case of transmission photoelasticity, and the analysis of the crack tip displacement fields for DIC and ESPI.

To conduct the current investigation, the research work has been divided in four steps. The first step is the development of an experimental procedure for quantifying the stress intensity factors from the analysis of stress and displacement fields around the crack tip. The next step in the current work is a prediction the fatigue life based on the analysis of the SIF range. Once established the ability of the three optical techniques for the prediction of fatigue life, the third step is to evaluate the potential of these techniques for the quantification of fatigue crack shielding and its effect during fatigue life. Finally, the last step is the evaluation of overload effect in fatigue life.

1.2. Scope of the thesis

The main objective of the current thesis is the investigation of fatigue crack shielding during fatigue crack growth using full-field optical techniques for stress and strain measurement, namely transmission photoelasticity, digital image correlation and electronic speckle pattern interferometry. Based on this premise, the thesis has been organized into 8 chapters.

In chapter 2 the fundamentals and basic concepts that will be employed in subsequent chapters of the current thesis are described. The chapter starts with a description of the theoretical fundamentals of transmission photoelasticity, digital image correlation and electronic speckle pattern interferometry. Subsequently, the four models for the definition of crack tip stress and displacement fields adopted for the calculation of the stress intensity factors are described. Moreover, the fundamentals of fatigue crack closure phenomenon are described and a brief review of the different crack closure mechanisms reported in the literature. Finally, a description of the effect of the influence of overloads in fatigue life will be reviewed.

Chapter 3 is a literature review divided into two main areas. The first one is a historical review of the fatigue crack closure phenomenon, exhibiting the techniques and methods presented in the literature for its evaluation and quantification. The second area is a review about how transmission photoelasticity, DIC and ESPI techniques have been employed in fracture mechanics. In particular, different approaches and methodologies for the calculation of the stress intensity factors are reviewed as well as the most relevant research conducted on the evaluation of fatigue crack closure and the effect of overloads in fatigue life.

In chapter 4 the experimental procedure is described. The employed equipments and the selected specimens in the current investigation are presented. The manufacturing processes of the specimens, their mechanical properties and their preparation for fatigue tests are also described. Finally, the experimental procedure for performing the fatigue tests in each of the technique is described.

In chapter 5 the experimental methodology developed for the determination of the stress intensity factors is detailed. Thus, for transmission photoelasticity the SIFs are obtained from the analysis of isochromatic data at the vicinity of the crack tip solving a nonlinear system of equations. For the particular case of DIC and ESPI the horizontal and vertical displacement fields around the crack tip are employed for the determination of the SIFs by solving a linear equations system.

In chapter 6 the experimental results on fatigue crack shielding obtained from the use of transmission photoelasticity, DIC and ESPI are presented and discussed. Results were obtained using CT specimens manufactured in different materials depending on the implemented technique. Initially, the crack shielding effect is studied on polycarbonate specimens using transmission photoelasticity, being a material enough ductile to allow fatigue crack growth and to show clear evidence of plasticity-induced crack shielding. After that, the study of fatigue crack shielding is extended on metallic specimens. Thus, 2024-T3 aluminium specimens were used in DIC while commercially pure titanium specimens were used in ESPI. Results obtained by DIC are compared with those obtained from methods based on compliance. In addition, at

the end of the chapter a methodology to estimate plastic zone size at the crack tip using ESPI is proposed.

In chapter 7, the methodology adopted to evaluate fatigue crack shielding in the previous chapter is extended for studying the effect caused by the application of overloads. Thus, different overload levels were applied on CT specimens tested at constant amplitude loading cycle for each of the studied techniques. As was made in the previous chapter, results obtained from using DIC are compared with those obtained from the strain offset method. Finally, the methodology previously proposed to estimate plastic zone size at the crack tip using ESPI is extended to study the influence of the overloads through variations in plastic zone size.

Finally, chapter 8 reports an overall discussion of the research work described in this thesis. Then, the major conclusions established from the analysis of the previous discussion are numbered. To conclude, different future research lines derived from the current investigation are exposed.

Chapter 2. Fundamentals and theory

2.1. Introduction

In this chapter the theoretical fundamentals and the basic principles that will be employed during the current investigation will be described. The chapter starts with a brief description of the theoretical fundamentals of the three optical techniques employed in this work: Transmission Photoelasticity, Digital Image Correlation (DIC) and Electronic Speckle Pattern Interferometry (ESPI).

After that, a description of the four models describing the crack tip stress/displacement fields employed in this is done. In addition, a brief introduction in the calculation of stress intensity factor in linear elastic fracture mechanics (LEFM) is also made.

Finally, a brief description of the fundamentals of the fatigue crack closure phenomenon is presented with special attention to different closure mechanisms and the effect of overloads in fatigue life.

2.2. Fundamentals of the optical techniques

In the following epigraph, the theoretical fundamentals of the three optical techniques employed for the current investigation are described.

2.2.1. Fundamentals of transmission photoelasticity

Photoelasticity is a full field experimental optical technique that is employed for the analysis of the stresses in mechanical elements. Its implementation can be performed in two different ways, in transmission and in reflection. However, for the current investigation only transmission photoelasticity will be adopted.

2.2.1.1. Physical principle used in photoelasticity

Some non-crystalline transparent materials are optically isotropic under normal conditions but become doubly refractive or birefringent under load. This effect normally persists while the loads are maintained but vanishes, almost instantaneously or after a time interval depending on the material and loading conditions, when the loads are removed.

This phenomenon is called temporary or artificial birefringence and was first observed by Brewster [13] in 1816. This is the physical principle in which photoelasticity is based on. A

characteristic feature of birefringent materials is that the incident light is divided in two orthogonal polarised components, called ordinary and extraordinary components. The directions of polarisation are called principal directions, while the associated axes in the material are called principal axes of the refractive index.

2.2.1.2. Polarisation

The light vector propagation direction is completely random. However, if this vector is forced to follow a defined direction, it is said that the light is polarised. There are different ways to obtain polarised light, however the most common one is the plane polarised light (figure 2.1a) when the light vector is parallel to a given direction in the wave front; and circular polarised light (figure 2.1b) when the tip of the light-vector describes a circle, which can be created by combining two orthogonal plane polarised waves of equal amplitude that are out of phase by exactly one quarter of the wavelength, i.e. $\lambda/4$.

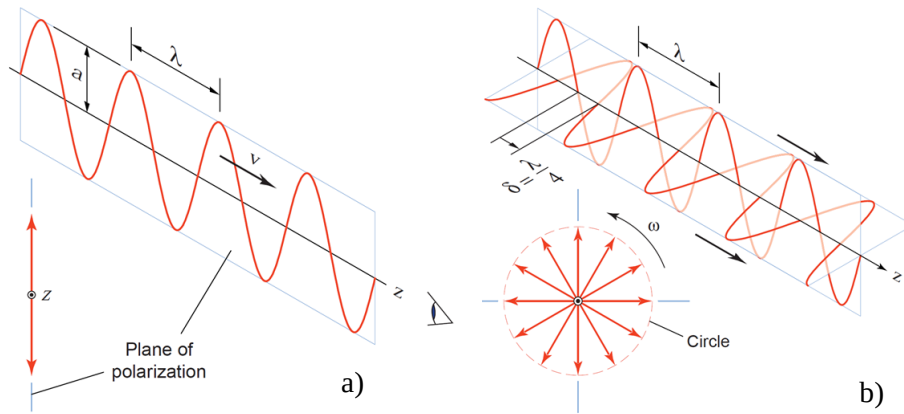


Figure 2.1. Plane (a) and circular (b) polarised light

2.2.1.3. Stress-optic law [14]

If a birefringent model subjected to a plane stress state is considered, the stress state at a point is characterised by the principal stresses σ_1 , σ_2 and their orientation. When the model is stressed becomes doubly refractive and the directions of the polarising axes at any point in the model plane coincide with the direction of the principal stresses at that point. Maxwell formulated the relations between stresses and the indices of refraction as:

$$\begin{aligned} n_1 - n &= c_1 \sigma_1 - c_2 \sigma_2 \\ n_2 - n &= c_1 \sigma_2 - c_2 \sigma_1 \end{aligned} \quad (2.1)$$

Where n_1 and n_2 are the refractive indexes associated with the principal directions, n is the refractive index in the unstressed state and c_1 and c_2 are the stress-optic coefficients.

If a plane polarised light passes through the model, then the relative retardation can be obtained as a function of refractive indexes as:

$$\delta = \frac{2\pi t}{\lambda} (n_1 - n_2) \quad (2.2)$$

Where t is the model thickness.

Substituting equation 2.1 into equation 2.2:

$$\delta = \frac{2\pi}{\lambda} (c_1 + c_2) (\sigma_1 - \sigma_2) \quad (2.3)$$

If in the previous expression $c_1 + c_2$ is replaced by C , the relative retardation is given as:

$$\delta = \frac{2\pi}{\lambda} C (\sigma_1 - \sigma_2) \quad (2.4)$$

This equation indicates that in a photoelastic model, the relative retardation changes from point to point depending on the stress level. The relative stress-optic coefficient C is usually assumed to be a material constant that is independent of the wavelength of the light being used. However, a study by Vandaele-Dossche and van Geen [15] has shown that this coefficient may depend on wavelength in some cases as the model material passes from the elastic to the plastic state. Thus, the dependence of the relative stress-optic coefficient C on the wavelength of the light being used is referred to as photoelastic dispersion or dispersion of birefringence.

The previous expression can be rewritten in terms of fringe order N as

$$N = \frac{\delta}{2\pi} = t \frac{C}{\lambda} (\sigma_1 - \sigma_2) \quad (2.5)$$

Finally, the principal stress difference can be expressed as:

$$\sigma_1 - \sigma_2 = \frac{NF_\sigma}{t} \quad (2.6)$$

Where $F_\sigma = \lambda/C$ is known as the material stress fringe value with the units N/(mm·fringe).

Equation 2.6 is famously known as stress-optic law and constitutes the fundamental equation in photoelasticity. This expression relates the stress state (in terms of the principal stress difference) with optical measurement (in terms of the fringe order N).

2.2.2. Fundamentals of digital image correlation (DIC)

Digital image correlation (DIC) is an optical full-field experimental technique employed for displacement and strain measurements in mechanical elements. DIC works analysing a sequence of images of a model from an initial state (undeformed) to a final state (deformed). The displacement and strain fields can be directly determined in 2D (in plane) and 3D (in and out-of-plane). In this thesis only in plane fields will be analysed, thus 2D DIC will be adopted.

The implementation of 2D DIC comprises the following steps [16]:

- 1) Specimen and experimental equipment preparations.
- 2) Capture a sequence of images.
- 3) Processing of captured images.

Figure 2.2 shows a schematic illustration of a typical 2D DIC experimental setup. The specimen surface must have a random gray intensity distribution (i.e. the random speckle pattern), which deforms together with the specimen surface. The speckle pattern can be the natural texture of the specimen surface or artificially made by spraying black paint over the specimen surface. The camera must be placed with its optical axis normal to the specimen surface to observe the planar specimen surface at different loading states.

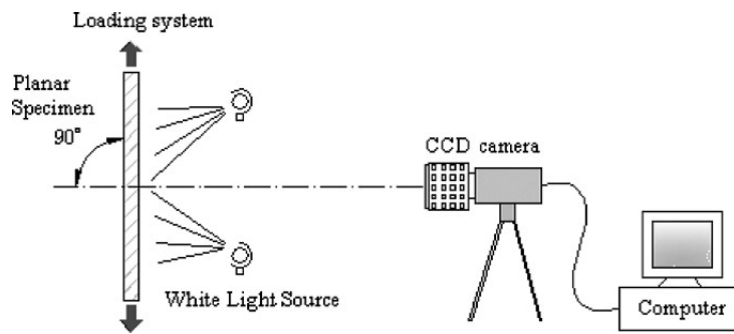


Figure 2.2. Typical optical image acquisition system for 2D DIC [16]

After preparing the specimen and assembling the setup, a sequence of images is captured at an initial or reference state (deformed state) until a final state (deformed state).

Once the sequence of images has been captured, the next step is its processing. The basic principle of 2D DIC consists on tracking of the displacement of points in two recorded images before and after deformation, as schematically illustrated in figure 2.3. To compute the displacements at point P , a square reference subset of $(2M + 1) \times (2M + 1)$ pixels centred at point $P(x_0, y_0)$ from the reference image is chosen and used to track its corresponding location in the deformed image.

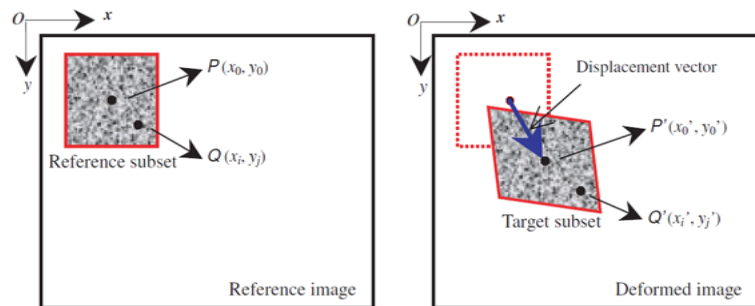


Figure 2.3. Scheme of the reference subset before and after deformation [16]

To implement 2D DIC, it is necessary to define the area of interest (AOI) in the reference image. This AOI is divided into evenly spaced squares called subset as shown in figure 2.4a. The displacements are computed at the centre of each subset to obtain the full-field deformation (figure 2.4b).

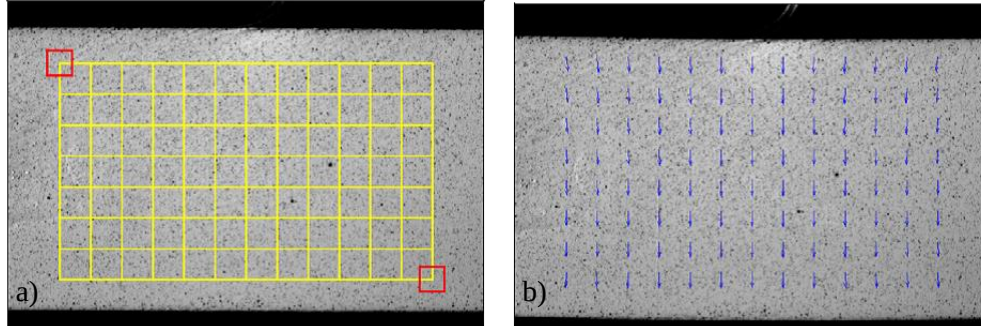


Figure 2.4. AOI in the reference image (a) and displacement vector of the deformed image (b) [16]

To evaluate the degree of similarity between the reference and the deformed subset, a correlation criterion must be defined. The most commonly employed correlation criteria are cross-correlation (CC) [16] and sum-squared difference correlation (SSD) [16]. The matching procedure is completed searching the peak position of the distribution of correlation coefficient. Once the correlation coefficient is detected, the position of the deformed subset is determined. The differences in the positions between centres at the reference subset and the target subset provides the in-plane displacement vector at point P , as illustrated in figure 2.4b.

2.2.3. Fundamentals of electronic speckle pattern interferometry (ESPI)

Electronic speckle pattern interferometry (ESPI) is inside the group known as speckle interferometry (SI) techniques. These techniques are based on the analysis of phase variation due to intensity changes occurring at the object surface. ESPI is an optical full-field experimental technique employed for displacement measurements and strain analysis in mechanical elements. This technique employs coherent laser illumination on the specimen and monitors the change of intensity pattern with a CCD camera. From the physical point of view, ESPI employs monochromatic laser light illumination, and it is based on the superposition of two coherent beams on the CCD camera plane and the change of the optical phase between the two beams due to specimen deformation. It provides full-field information of 3D-displacement vectors when the specimen is illuminated from different directions. Displacement fields are numerically differentiated in order to obtain strain maps.

2.2.3.1. Fundamentals of ESPI technique [17]

A schematic setup of a speckle interferometer is shown in figure 2.5. A reference beam and an object beam, which is scattered from the surface of the object, are superimposed to generate an interfered speckle pattern in the image plane, which is known as a speckle interferogram.

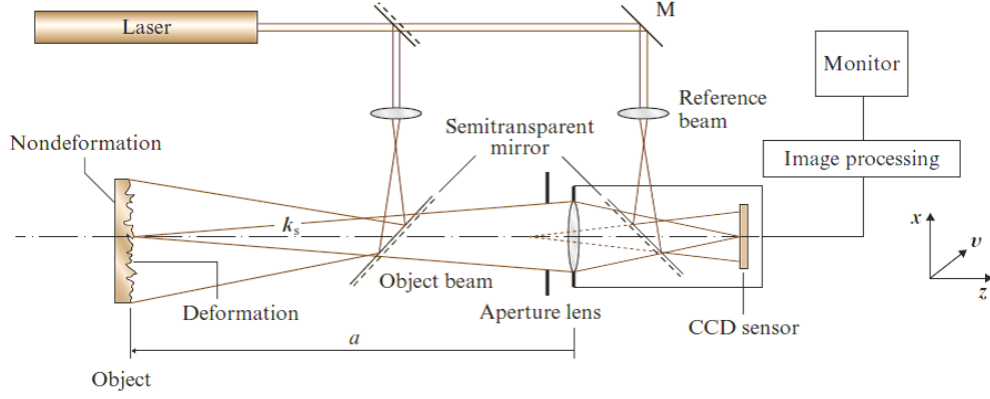


Figure 2.5. Speckle interferometer for measuring the displacements in the vertical direction to the object surface [17]

The intensity corresponding to the initial state of a point $P(x,y)$ in the speckle interferogram can be expressed as:

$$I = (a_o e^{i\theta_o} + a_r e^{i\theta_r}) (a_o e^{i\theta_o} + a_r e^{i\theta_r})^* = a_o^2 + a_r^2 + 2a_o a_r \cos(\theta_o - \theta_r) = a_o^2 + a_r^2 + 2a_o a_r \cos(\phi_{or}) \quad (2.7)$$

Where $\phi_{or} = \theta_o - \theta_r$ is the random phase; $a_o e^{i\theta_o}$ and $a_r e^{i\theta_r}$ are the object and reference beams respectively; a_o and a_r are the amplitudes of the object and reference beams respectively and θ_o and θ_r are the phases of the object and reference beams respectively.

When the object is deformed, the intensity I' at the point P in the interferogram after loading can be described as:

$$I' = a_o'^2 + a_r^2 + 2a_o' a_r \cos(\theta_o' - \theta_r) = a_o'^2 + a_r^2 + 2a_o' a_r \cos(\phi_{or} + \Delta) = a_o'^2 + a_r^2 + 2a_o' a_r \cos(\phi_{or}') \quad (2.8)$$

Where $\Delta = \phi_{or}' - \phi_{or}$ is the phase change between the two states. Since the change of the amplitude in the object wave can usually be neglected ($a_o \approx a_o'$), the difference between the intensities I and I' can be interpreted as:

$$I_s = |I - I'| = 2a_o a_r |\cos(\phi_{or}) - \cos(\phi_{or} + \Delta)| = 4a_o a_r \left| \sin\left(\phi_{or} + \frac{\Delta}{2}\right) \sin\left(\frac{\Delta}{2}\right) \right| \quad (2.9)$$

In ESPI, two speckle patterns corresponding to the object before and after deformation are recorded by a CCD chip separately and stored in a computer. Fringes can be generated by digital subtraction and they can be observed in quasi real time.

If each speckle covers one pixel, the pixels will be black ($I_s = 0$) when the intensity of both images are identical, namely $\Delta = 2\pi k$ ($k = 0, 1, 2, \dots$). Thus, pixels with the same brightness generate macroscopic lines (fringes) in the resulting image I_s .

2.2.3.2. Fringe interpretation [17]

The fringes of an interferogram describe the distribution of relative phase changes. Figure 2.6 shows the geometric relation between the illumination vector $\vec{k}_1$, the observation vector $\vec{k}_2$, and the displacement vector of a point P on the surface of an object $\vec{d}$. The relative phase difference can be determined as

$$\Delta = \vec{k}_2 \cdot \vec{d} - \vec{k}_1 \cdot \vec{d} = \vec{k}_s \cdot \vec{d} \quad (2.10)$$

Where $\vec{k}_s = \vec{k}_2 - \vec{k}_1$ is called the sensitivity vector.

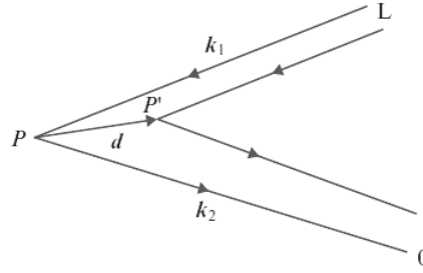


Figure 2.6. Geometric relation between the illumination vector, the observation vector and the displacement vector [17]

In x, y and z coordinates, the above equation can be expressed as

$$\Delta = \vec{k}_s \cdot (u\vec{e}_x + v\vec{e}_y + w\vec{e}_z) \quad (2.11)$$

Where u, v and w are the components of the displacement vector and $\vec{e}_x, \vec{e}_y$ and $\vec{e}_z$ are the units vectors in the x, y and z directions, respectively. The sensitivity vector is located in the bisector of the angle between the illumination and observation vectors and it is not the same for each point of the object surface due to the change in the illumination and observation directions (figure 2.7a). However, it can be assumed that the sensitivity vector at each point of the studied surface is the same when the dimensions of the object are small compared with the distances between the laser and the object or the camera and the object. In figure 2.7b it is shown how the centre point of the object is chosen to determine the sensitivity vector, where its magnitude can be expressed as

$$|\vec{k}_s| = \frac{4\pi}{\lambda} \cos\left(\frac{\theta_{xz}}{2}\right) \quad (2.12)$$

Where λ is the wavelength of the laser light and θ_{xz} is the angle between the illumination and observation vectors in the xz plane.

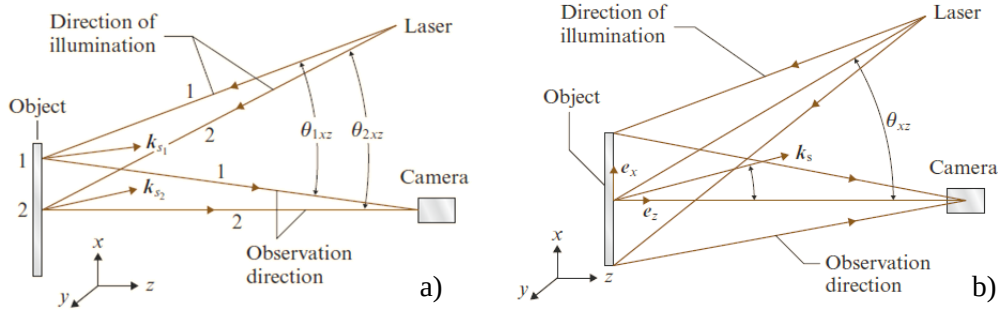


Figure 2.7. Sensitivity vector at different points on the object surface (a) and simplified sensitivity vector (b) [17]

If the illumination and observation vectors are perpendicular to the object surface ($\vec{k}_s \cdot \vec{e}_x = \vec{k}_s \cdot \vec{e}_y = 0$ and $\vec{k}_s \cdot \vec{e}_z = 1$), only the out-of-plane displacements are measured and therefore the relative phase change is

$$\Delta = \frac{4\pi}{\lambda} w \quad (2.13)$$

This kind of interferometer is known as an out-of-plane-sensitivity interferometer.

For measuring in-plane displacements (figure 2.8), two lasers are arranged symmetrically on each side of the object with identical incidence angles. When the surface of the object is illuminated by the two laser beams simultaneously, the relative phase change in the x direction can be determined as

$$\Delta_x = \frac{2\pi}{\lambda} \left[u(\sin \theta_{xz}^+ + \sin \theta_{xz}^-) + w(\cos \theta_{xz}^+ - \cos \theta_{xz}^-) \right] = \frac{4\pi}{\lambda} u \sin \theta \quad (2.14)$$

The relative phase change in the y direction can be measured in a similar way when both laser beams illuminate the surface of the object in the yz plane.

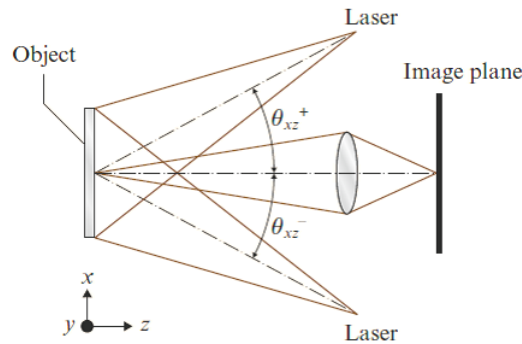


Figure 2.8. Optical ESPI arrangement for measuring in-plane displacements [17]

2.3. Description of the models for defining crack tip stress and displacement fields

In this epigraph it is presented a brief description of the mathematical models employed in the course of this investigation for the characterisation of the crack tip stress and displacement fields at the vicinity of the crack tip.

2.3.1. Introduction

Traditionally, it has been assumed that in Linear Elastic Fracture Mechanics (LEFM) the stress and/or displacement fields around the crack tip can be characterised by the Stress Intensity Factors (SIFs). In literature there are a large amount of models that describe the crack tip stress and displacement fields from the analysis of the SIFs. In the current work, four different models describing the crack tip stress and displacements field have been investigated. In the following points a brief description of these models is presented.

2.3.2. Model based on Westergaard's classic equations

The first model evaluated is based on Westergaard's classic equations [18]. According to this model, the stress fields around the crack tip can be described through the stress intensity factors K_I and K_{II} and the polar coordinates of a set of points at the region surrounding the crack tip. This mathematical description of the crack tip stress/displacement fields assumes that the origin of the adopted coordinate system is located at the crack tip. The stress fields around the crack tip are defined as:

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} = \frac{K_I}{\sqrt{2\pi r}} \cos \frac{\theta}{2} \begin{Bmatrix} 1 - \sin \frac{\theta}{2} \sin \frac{3\theta}{2} \\ 1 + \sin \frac{\theta}{2} \sin \frac{3\theta}{2} \\ \sin \frac{\theta}{2} \cos \frac{3\theta}{2} \end{Bmatrix} + \frac{K_{II}}{\sqrt{2\pi r}} \begin{Bmatrix} -\sin \frac{\theta}{2} \left(2 + \cos \frac{\theta}{2} \cos \frac{3\theta}{2} \right) \\ \sin \frac{\theta}{2} \cos \frac{\theta}{2} \sin \frac{3\theta}{2} \\ \cos \frac{\theta}{2} \left(1 - \sin \frac{\theta}{2} \sin \frac{3\theta}{2} \right) \end{Bmatrix} + \begin{Bmatrix} -\sigma_{0x} \\ 0 \\ 0 \end{Bmatrix} \quad (2.15)$$

In the above expression σ_{0x} is a constant stress term for the x normal stress known as T-stress.

The parameter of study in photoelasticity is the fringe order. Hence an expression has to be developed which relates the fringe order with the stress fields. According to the stress-optic law (equation 2.6), the fringe order is directly related to the principal stress difference:

$$\frac{NF_\sigma}{h} = \sigma_1 - \sigma_2 = \sqrt{(\sigma_y - \sigma_x)^2 + (2\tau_{xy})^2} \quad (2.16)$$

Consequently, if expression 2.15 is substituted into expression 2.16, a nonlinear is obtained (equation 2.17). This expression relates the fringe order with the stress intensity factors, the T-stress and the polar coordinates of the selected points around the crack tip.

$$\frac{NF_{\sigma}}{h} = g(K_I, K_{II}, \sigma_{0x}, r, \theta) \quad (2.17)$$

Finally, to determine the stress intensity factors and the T-stress an iterative calculation process must be adopted.

In a similar way, the displacement fields at the vicinity of the crack tip can be described as:

$$\begin{aligned} \begin{Bmatrix} u \\ v \end{Bmatrix} &= \frac{K_I}{2G} \sqrt{\frac{r}{2\pi}} \begin{Bmatrix} \cos \frac{\theta}{2} \left(\kappa - 1 + 2 \sin^2 \frac{\theta}{2} \right) \\ \sin \frac{\theta}{2} \left(\kappa + 1 - 2 \cos^2 \frac{\theta}{2} \right) \end{Bmatrix} + \frac{K_{II}}{2G} \sqrt{\frac{r}{2\pi}} \begin{Bmatrix} \sin \frac{\theta}{2} \left(\kappa + 1 + 2 \cos^2 \frac{\theta}{2} \right) \\ \cos \frac{\theta}{2} \left(\kappa - 1 - 2 \sin^2 \frac{\theta}{2} \right) \end{Bmatrix} \\ &+ \frac{\sigma_{0x}}{8G} r \begin{Bmatrix} (\kappa + 1) \cos \theta \\ (\kappa - 3) \sin \theta \end{Bmatrix} \end{aligned} \quad (2.18)$$

Where $G = \frac{E}{2(1+\nu)}$ is the shear modulus, E and ν are the Young's modulus and the Poisson's

ratio of the material respectively, and $\kappa = \frac{3-\nu}{1+\nu}$ for plane stress or $\kappa = 3-4\nu$ for plane strain.

If DIC is employed, the displacement fields can be directly obtained. Therefore, the stress intensity factors and the T-stress can be inferred by solving a linear system of equations.

2.3.3. Model based on Williams's expansion series

The second model evaluated is based on Williams's expansion series [6]. According to this model the crack tip stress fields can be expressed as a function of the number of adopted terms in the series, the series coefficients and the polar coordinates of a set of points at the region surrounding the crack tip:

$$\begin{aligned} \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} &= \sum_{p=1}^{\infty} \frac{p}{2} A_{Ip} r^{\frac{p-2}{2}} \begin{Bmatrix} \left[2 + (-1)^p + \frac{p}{2} \right] \cos\left(\frac{p-1}{2}\theta\right) - \left(\frac{p-1}{2}\right) \cos\left(\frac{p-3}{2}\theta\right) \\ \left[2 - (-1)^p - \frac{p}{2} \right] \cos\left(\frac{p-1}{2}\theta\right) + \left(\frac{p-1}{2}\right) \cos\left(\frac{p-3}{2}\theta\right) \\ - \left[(-1)^p + \frac{p}{2} \right] \sin\left(\frac{p-1}{2}\theta\right) + \left(\frac{p-1}{2}\right) \sin\left(\frac{p-3}{2}\theta\right) \end{Bmatrix} \\ &- \sum_{p=1}^{\infty} \frac{p}{2} A_{Iip} r^{\frac{p-2}{2}} \begin{Bmatrix} \left[2 - (-1)^p + \frac{p}{2} \right] \sin\left(\frac{p-1}{2}\theta\right) - \left(\frac{p-1}{2}\right) \sin\left(\frac{p-3}{2}\theta\right) \\ \left[2 + (-1)^p - \frac{p}{2} \right] \sin\left(\frac{p-1}{2}\theta\right) + \left(\frac{p-1}{2}\right) \sin\left(\frac{p-3}{2}\theta\right) \\ - \left[(-1)^p - \frac{p}{2} \right] \cos\left(\frac{p-1}{2}\theta\right) - \left(\frac{p-1}{2}\right) \cos\left(\frac{p-3}{2}\theta\right) \end{Bmatrix} \end{aligned} \quad (2.19)$$

Where $A_{I1} = \frac{K_I}{\sqrt{2\pi}}$, $A_{II1} = -\frac{K_{II}}{\sqrt{2\pi}}$, $4A_{I2} = -\sigma_{0x}$.

As in the case of Westergaard's model, the stress-optic law relates the fringe order with the stress fields around the crack tip, therefore, substituting expressions 2.19 into equation 2.16 the stress intensity factors and the T-stress can be determined by solving a nonlinear equation.

In a similar way, the displacement fields around the crack tip can be described as:

$$\begin{aligned} \begin{Bmatrix} u \\ v \end{Bmatrix} = \sum_{p=1}^{\infty} \frac{r^{p/2}}{2G} a_p \begin{Bmatrix} \left[\kappa + \frac{p}{2} + (-1)^p \right] \cos \frac{p\theta}{2} - \frac{p}{2} \cos \frac{(p-4)\theta}{2} \\ \left[\kappa - \frac{p}{2} - (-1)^p \right] \sin \frac{p\theta}{2} + \frac{p}{2} \sin \frac{(p-4)\theta}{2} \end{Bmatrix} \\ + \sum_{p=1}^{\infty} \frac{r^{p/2}}{2G} b_p \begin{Bmatrix} - \left[\kappa + \frac{p}{2} - (-1)^p \right] \sin \frac{p\theta}{2} - \frac{p}{2} \sin \frac{(p-4)\theta}{2} \\ \left[\kappa - \frac{p}{2} + (-1)^p \right] \cos \frac{p\theta}{2} + \frac{p}{2} \cos \frac{(p-4)\theta}{2} \end{Bmatrix} \end{aligned} \quad (2.20)$$

Where $a_1 = \frac{K_I}{\sqrt{2\pi}}$, $b_1 = -\frac{K_{II}}{\sqrt{2\pi}}$, $a_2 = \frac{\sigma_{0x}}{4}$

2.3.4. Model based on Muskhelishvili's complex potentials

The third model evaluated in the current work is based on Muskhelishvili's complex potentials [10]. In the following sections the stress and displacement fields around the crack tip are described.

2.3.4.1. Description of the crack tip stress fields [19]

For the mathematical description of the crack tip stress field based on Muskhelishvili's complex potentials [10], the formulation developed by Nurse and Patterson [19] has been adopted. According to this formulation, the stress field around the crack tip is represented by two analytical functions, $\Phi(z)$ and $\Psi(z)$ of the complex variable $z = x + iy$:

$$\sigma_y - \sigma_x + 2i\tau_{xy} = 2[\bar{z}\Phi'(z) + \Psi'(z)] \quad (2.21)$$

Where x and y are Cartesian coordinates, the prime denotes differentiation and the overbar denotes complex conjugate.

The boundary conditions of a crack can be taken into account by using a conformal function [20]. Thus, the problem of a crack in an infinite plate can be conveniently addressed by solving it as the equivalent problem corresponding to a hole in a plate. Then, the boundary conditions for the crack surfaces are satisfied through the use of a conformal mapping function in which a circle in the mapping plane is mapped onto an elliptical shape in the physical plane (figure 2.10):

$$z = \omega(\zeta) = L \left(\zeta + \frac{m}{\zeta} \right) \quad (0 \leq m \leq 1) \quad (2.22)$$

Where $\omega(\zeta)$ is the conformal mapping function, ζ is the complex coordinate in the mapping plane, L represents a length parameter and m describes the shape of the mapped circle. The extreme values of m are used to map the circle onto either a crack ($m = 1$) or a hole ($m = 0$). A schematic illustration showing the adopted approach is presented in figure 2.10.

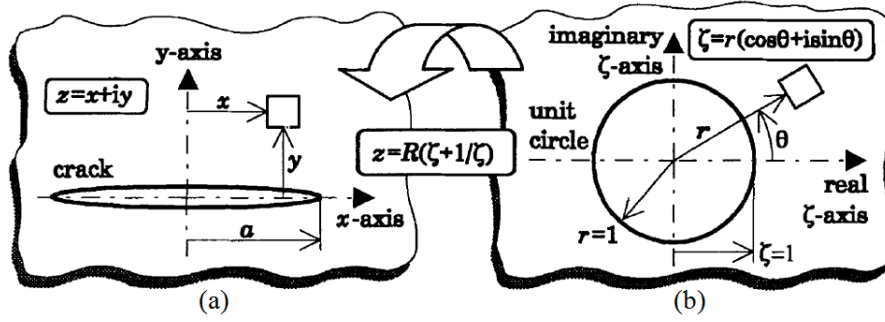


Figure 2.10. Crack coordinates system in (a) physical and (b) mapping planes [19] for Muskhelishvili's complex potential model

The complex variable ζ is calculated from a system of polar coordinates in the mapping plane using:

$$\zeta = r(\cos \theta + i \sin \theta) \quad (2.23)$$

However, the solution procedure requires that data collected in Cartesian coordinates in the physical plane have to be converted into polar coordinates in the mapping plane though the following expression:

$$\zeta = \frac{z \pm \sqrt{z^2 - 4L^2 m}}{2L} \quad (2.24)$$

In the mapping plane the complex stress functions $\Phi(\zeta)$ and $\Psi(\zeta)$ are given as complex Fourier series form [10]:

$$\begin{aligned} \Phi(\zeta) &= \sum_{M=0}^{\infty} A_M \zeta^{2M} + \sum_{m=1}^{\infty} \frac{a_m}{\zeta^{2m}} \\ \Psi(\zeta) &= \sum_{M=0}^{\infty} B_M \zeta^{2M} + \sum_{n=1}^{\infty} \frac{b_n}{\zeta^{2n}} \end{aligned} \quad (2.25)$$

Assuming the stress field is symmetrical about the imaginary axis ($\theta = \pm \pi/2$). The series parameters A_M , B_M , a_m and b_n are generally complex and they are used to describe different states of stress. Expression 2.24 can be inserted into expression 2.21 to provide the stresses in

the mapping plane; however, boundary conditions for traction-free crack surfaces have not been satisfied. In the physical plane the boundary conditions on the crack are:

$$\sigma_y + i\tau_{xy} = 0 \quad (-a \leq x \leq a, y = 0) \quad (2.26)$$

In the mapping plane this is written more conveniently as:

$$\sigma_y + i\tau_{xy} = 0 \quad (r = 1) \quad (2.27)$$

It can be observed [19] after a long differentiation process that the complex functions are determined through the following expressions:

$$\begin{aligned} \Phi(\zeta) &= A_0 + \frac{A_0 + \bar{A}_0 + \bar{B}_0}{\zeta^2 - 1} + \sum_{M=1}^{\infty} \left[\left(\frac{2M}{\zeta^{2M}} \right) \left(\frac{\zeta^2 + 1}{\zeta^2 - 1} \right) \bar{A}_M - \frac{\bar{A}_M}{\zeta^{2M}} - \frac{\bar{B}_M}{\zeta^{2M}} + A_M \zeta^{2M} \right] \\ \psi(\zeta) &= B_0 + \frac{B_0 - \bar{B}_0}{\zeta^2 - 1} + 2(A_0 + \bar{A}_0 + \bar{B}_0) \frac{\zeta^2 (\zeta^2 + 1)}{(\zeta^2 - 1)^3} \\ &\quad + \sum_{N=1}^{\infty} \left[\left(\frac{4M^2}{\zeta^{2M}} \right) \frac{(\zeta^4 - 1)(\zeta^2 + 1)}{(\zeta^2 - 1)^3} \bar{A}_M + \frac{8M}{\zeta^{2M}} \frac{\zeta^2 (\zeta^2 + 1)}{(\zeta^2 - 1)^3} \bar{A}_M \right. \\ &\quad \left. - \frac{4M}{\zeta^{2M}} \left(\frac{\zeta^2 + 1}{\zeta^2 - 1} \right) \bar{A}_M - \frac{2M}{\zeta^{2M}} \left(\frac{\zeta^2 + 1}{\zeta^2 - 1} \right) \bar{B}_M + \frac{\bar{B}_M}{\zeta^{2M}} + B_M \zeta^{2M} \right] \end{aligned} \quad (2.28)$$

General expressions for stress σ_x , σ_y and τ_{xy} can be written for the physical plane, using the coordinate system in the mapping plane, by substituting expression 2.28 into expression 2.21. The singularity at the crack tip, which occurs at $\zeta = \pm 1$ in the mapping plane, is apparent in expression (2.28). The unknown series parameter A_M and B_M are used to describe the generalised state of stress around the crack and it must be determined to solve problem in question. The real parts of A_M and B_M describe the mode I stress field and the imaginary parts describe the mode II stress field. The complex stress intensity factor $K_I + iK_{II}$ is calculated using the limiting value of $\Phi(z)$ as $\zeta \rightarrow \pm 1$, i.e.:

$$K_I + iK_{II} = A_0 + \bar{A}_0 + B_0 + 2 \sum_{M=1}^{\infty} (A_M + \bar{A}_M) \quad (2.29)$$

2.3.4.2. Description of the crack tip displacement fields [5]

For the mathematical description of the displacement fields around the crack tip based on Muskhelishvili's complex potentials [10], the formulation employed by Lopez-Crespo et al. [5] has been adopted. According to this formulation, the displacement fields at the vicinity of the crack tip is represented by two analytical functions, $\phi(z)$ and $\psi(z)$, with $z = x + iy$:

$$2G(u + iv) = \kappa \phi(z) - z \overline{\phi'(z)} - \overline{\psi(z)} \quad (2.30)$$

As in the case of the stress fields, using the conformal mapping functions in the expression 2.22, the above equation in the mapping plane will take the following form:

$$2G(u + iv) = \kappa \phi(\zeta) - \frac{\omega(\zeta)}{\omega'(\zeta)} \overline{\phi'(\zeta)} - \overline{\psi(\zeta)} \quad (2.31)$$

In the mapping plane the analytic functions $\phi(\zeta)$ and $\psi(\zeta)$ can be represented as infinite Fourier series [10]:

$$\phi(\zeta) = \sum_{k=-\infty}^{+\infty} a_k \zeta^k, \quad \psi(\zeta) = \sum_{k=-\infty}^{+\infty} b_k \zeta^k \quad (2.32)$$

Where a_k and b_k are complex coefficients.

It can be observed [5] after a long differentiation process that the displacement fields around the crack tip can be described through the following linear system of equations:

$$\begin{aligned} 2Gu^j &= \sum_{k=-M}^M A_k^j \alpha_k + \sum_{k=-M}^M B_k^j \beta_k \\ 2Gv^j &= \sum_{k=-M}^M C_k^j \alpha_k + \sum_{k=-M}^M D_k^j \beta_k \end{aligned} \quad (2.33)$$

Where j indicates the selected data point from the crack tip displacement fields, $\pm M$ is the limits on the Fourier series, A_k^j, B_k^j, C_k^j and D_k^j are coefficients calculated at the same point j , and $\alpha_k = \text{Re}(\alpha_k)$ and $\beta_k = \text{Im}(\alpha_k)$ are the system unknowns. The expressions to calculate the coefficients in equation (2.33) are the following:

$$\begin{aligned} A_k &= \kappa \text{Re}(\zeta^k) - k \text{Re}(\Omega) \text{Re}(\zeta^{k-1}) - k \text{Im}(\Omega) \text{Im}(\zeta^{k-1}) + \text{Re}(\zeta^{-k}) + k \sum_{l=-k}^{M'} \text{Re}(c_{l+k-1}) \text{Re}(\zeta^{-l}) \\ B_k &= -\kappa \text{Im}(\zeta^k) + k \text{Re}(\Omega) \text{Im}(\zeta^{k-1}) - k \text{Im}(\Omega) \text{Re}(\zeta^{k-1}) + \text{Im}(\zeta^{-k}) - k \sum_{l=-k}^{M'} \text{Re}(c_{l+k-1}) \text{Im}(\zeta^{-l}) \\ C_k &= B_k + 2\kappa \text{Im}(\zeta^k) - 2 \text{Im}(\zeta^{-k}) \\ D_k &= \kappa \text{Re}(\zeta^k) + k \text{Re}(\Omega) \text{Re}(\zeta^{k-1}) + k \text{Im}(\Omega) \text{Re}(\zeta^{k-1}) + \text{Re}(\zeta^{-k}) - k \sum_{l=-k}^{M'} \text{Re}(c_{l+k-1}) \text{Re}(\zeta^{-l}) \end{aligned} \quad (2.34)$$

Where M' is the limit of the truncated Fourier series, $\Omega = \omega(\zeta)/\overline{\omega'(\zeta)}$ and c_k is a complex coefficient which is determined as follows:

$$c_k = \begin{cases} m & k = -1 \\ (m^2 + 1)m^{\frac{k-1}{2}} & k = 2n+1 \quad n = 0, 1, 2, \dots \\ 0 & \text{all other } k \end{cases} \quad (2.35)$$

Finally, the SIFs are defined from the following expression:

$$K_I - iK_{II} = 2\sqrt{\frac{\pi}{a}} \sum_{k=-M}^M ka_k \quad (2.36)$$

In the above expression a is the half of the crack length and $a_k = \alpha_k + i\beta_k$. Thus, the real part of the complex stress intensity factor corresponds to K_I , while the imaginary part corresponds to K_{II} .

2.3.5. CJP model (Christopher-James-Patterson)

CJP model is a novel mathematical model developed by Christopher, James and Patterson [21 - 23] based on Muskhelishvili's complex potentials [10]. The authors postulated that the plastic enclave that exists around a fatigue crack tip and along the crack flanks will shield the crack from the full influence of the applied elastic stress field. Crack tip shielding includes the effect of crack flank contact forces (so-called crack closure) and a compatibility-induced interfacial shear stress at the elastic-plastic boundary. Figure 2.11 illustrates schematically the forces acting at the interface of the plastic zone and the surrounding elastic material; and for clarity forces on the elastic field and their reactions on the plastic field are illustrated. Thus, F_{Ax} and F_{Ay} are the reaction forces to the remote load that generates the crack tip stress fields. The remote load also generates a T-stress and a corresponding force, F_T whose sense is dependent on the specimen geometry. The previous forces cause a plastic zone ahead of the crack tip such that the material will become permanently deformed inducing forces F_{Px} and F_{Py} during unloading. These forces arise from the interaction between the permanent and the elastic deformed material at either side of the interface. For tensile applied loading the permanent deformation in the plastic zone will be expansive in the direction perpendicular to the crack and contractive along the crack as a consequence of Poisson's ratio effects. F_s is the induced force by the interfacial shear at the elastic-plastic boundary of the crack wake. F_C is the contact force generated when the plastic wakes contact during unloading, so the crack closes under the action of the elastic field. This can be considered as a classical closure effect. Therefore, F_C and F_P induce a shielding effect on the crack tip.

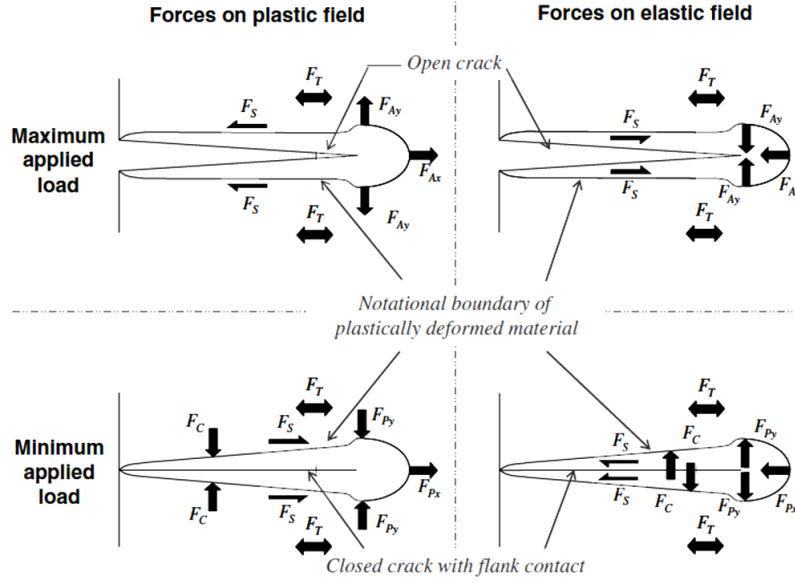


Figure 2.11. Schematic idealization of the forces acting at the interface of the plastic enclave and the surrounding elastic material [21] in the CJP model

According to the expression 2.21, using Muskhelishvili's potential functions [10], the stress field around the crack tip is defined through the following expression:

$$|\sigma_y - \sigma_x + 2i\tau_{xy}| = |Az^{-1/2} + Bz^{-3/2}\bar{z} + Cz^0 + Dz^{-1/2}\ln z + Ez^{-3/2}\bar{z}\ln z| \quad (2.37)$$

Where z is the complex coordinate and A , B , C , D and E are unknown coefficients that need to be determined.

As it was indicated in equation 2.30, the displacement field at the vicinity of the crack tip can be solved from Muskhelishvili's complex functions [10]. Thus, according to this model the displacements around the crack tip area can be defined as:

$$\begin{aligned} 2G(u + iv) = \kappa & \left[-2(B + 2E)z^{\frac{1}{2}} + 4z^{\frac{1}{2}} - 2Ez^{\frac{1}{2}}\ln z - \frac{C - F}{4}z \right] \\ & - z \left[-(B + 2E)\bar{z}^{\frac{1}{2}} - E\bar{z}^{\frac{1}{2}}\ln \bar{z} - \frac{C - F}{4} \right] \\ & - \left(A\bar{z}^{\frac{1}{2}} + D\bar{z}^{\frac{1}{2}}\ln \bar{z} - 2D\bar{z}^{\frac{1}{2}} + \frac{C + F}{4}\bar{z} \right) \end{aligned} \quad (2.38)$$

As it was previously indicated, z is the complex coordinate and A , B , C , D , E and F are unknown coefficients that need to be determined.

Thus, this new model employs four parameters to characterise the stress and displacement fields around the crack tip generated by the forces indicated in figure 2.11: the opening mode stress intensity factor K_I , the retardation stress intensity factor K_{II} , the shear stress intensity factor K_{III} and the T-stress σ_{0x} .

The opening stress intensity factor K_F is characterised by the driving crack growth force F_A generated by the remote load that generates the crack tip stress fields traditionally characterised by K_I :

$$K_F = \sqrt{\frac{\pi}{2}}(A - 3B - 8E) \quad (2.39)$$

The retardation stress intensity factor K_R is characterised by F_C and F_P that induce a shielding effect on the crack tip and therefore a retardation effect on the fatigue crack growth:

$$K_R = \frac{\pi^{3/2}}{\sqrt{2}}(D - 3E) \quad (2.40)$$

The shear intensity factor K_S is characterised by F_S that acts in the interfacial boundary between the generated plastic zone and the surrounding elastic field:

$$K_S = \sqrt{\frac{\pi}{2}}(A + B) \quad (2.41)$$

T-stress is characterised by F_T generated by the remote load, which is expressed by the components T_x in the x-direction and T_y in the y-direction:

$$\begin{aligned} T_x &= -C \\ T_y &= -F \end{aligned} \quad (2.42)$$

2.4. Fundamentals of fatigue crack closure

The phenomenon of fatigue crack closure explains that a fatigue crack can close prematurely even under a fully tension cycle load [24]. The possibility that a fatigue crack can close even at far-field tensile load was first experimentally reported by Elber [25, 26]. He noticed an anomaly in the elastic compliance of several fatigue specimens (figure 2.12a). At high loads the compliance agreed with standard expressions for fracture mechanics specimens, but at low loads the compliance was close to that for an uncracked specimen. Elber believed that this change in compliance was due to the contact between crack surfaces (i.e., crack closure) at low load levels greater than zero. On this way, Elber argued that a zone of residual tensile plastic deformation is left in the wake of a fatigue crack tip. The reduction in crack opening displacement gives rise to premature contact between the faces of the crack and causes a reduction in the apparent driving force for fatigue advance.

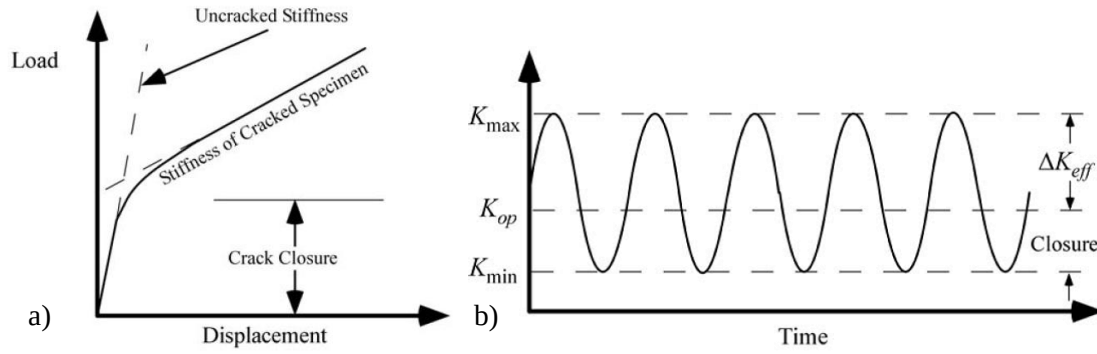


Figure 2.12. Crack closure during fatigue crack growth. The crack faces contact at a positive load (a), resulting in a reduced driving force for fatigue, ΔK_{eff} (b): a) load-displacement behaviour and b) definition of effective stress intensity factor range [27]

Elber postulated that crack closure decreased the fatigue crack growth rate by reducing the effective stress intensity factor range. Figure 2.12b illustrates the closure concept. When a specimen is cyclically loaded between K_{max} and K_{min} , the crack faces are in contact below the stress intensity factor at which the crack opens K_{op} . Elber assumed that the portion of the cycle that is below K_{op} did not contribute to fatigue crack growth. This type of closure is known as *plasticity-induced crack closure*. Other authors established that Elber's mechanism was not the unique cause of closure, but that other types of closure phenomena also influence the rate of fatigue crack advance. These types of closure are *oxide-induced crack closure*, *roughness-induced crack closure*, *fluid viscous-induced crack closure* or *phase transformation-induced crack closure* (figure 2.13).

2.4.1. Plasticity-induced crack closure

Plasticity-induced crack closure phenomenon (figure 2.13a) was discovered by Elber [25, 26], who established for the first time that crack growth rates are not only influenced by the conditions ahead of the crack tip, but also by the nature of crack flank contact behind the crack tip.

An atomically sharp notch or a saw-cut closes only at zero or compressive loads. However, under tensile cyclic loading, the propagation of a fatigue crack creates a wake of material that has previously deformed plastically. As a fatigue crack is propagating under constant amplitude of cyclic tensile, residual tensile strains are left in the material behind the advancing crack front, as only elastic recovery occurs after the creation of the fracture surfaces (figure 2.14). Thus, the deformed material within the plastic zone now forms an envelope of plastic zones in the wake of the crack front, with an increase in the stress intensity factor and the size of the plastic zone due to crack advance. The result is that the load at which the crack closes is therefore tensile rather than zero or compressive. As the crack cannot propagate while it is closed at the crack tip, a

knowledge of the crack opening load is essential to refine the prediction of the crack propagation rate.

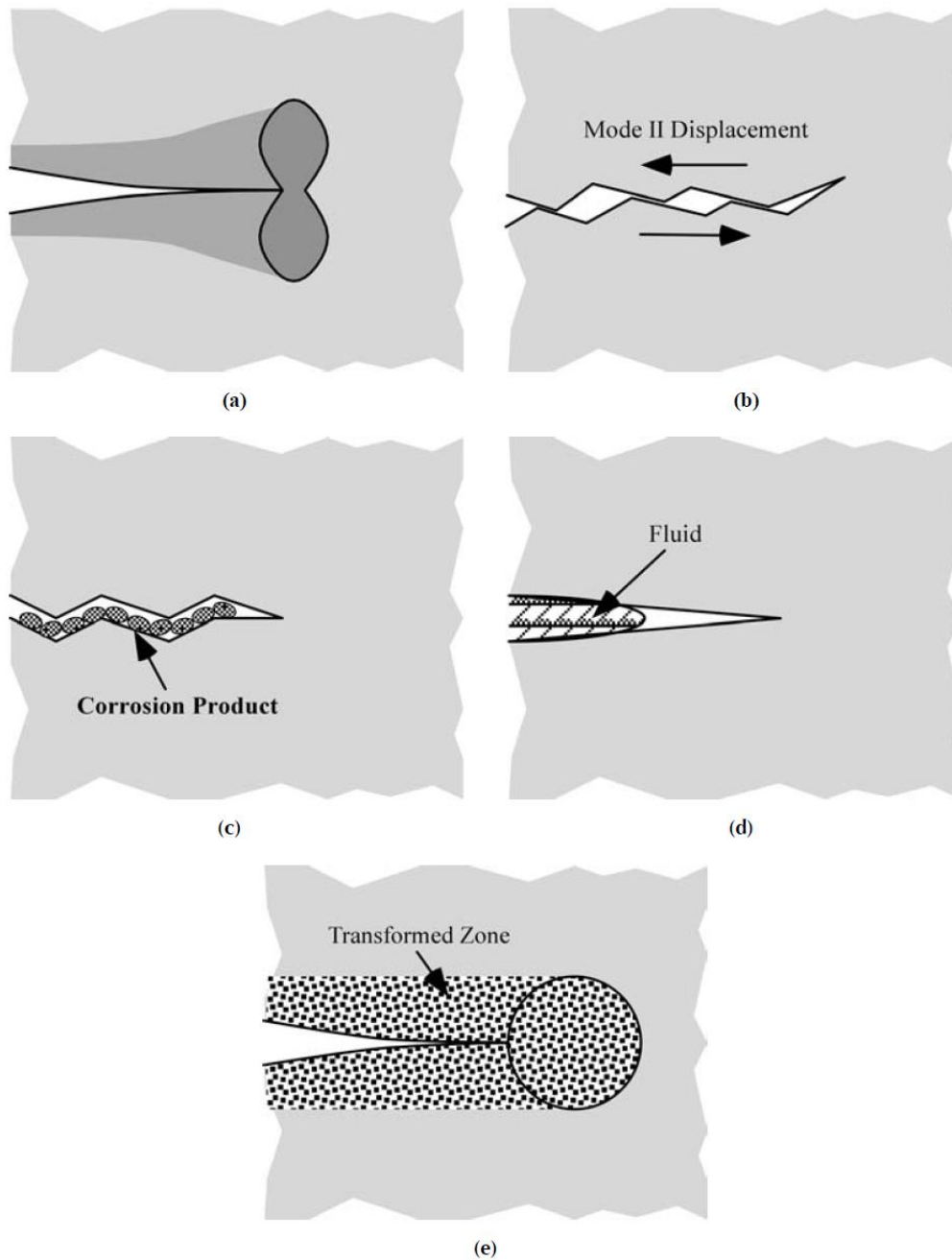


Figure 2.13. A schematic illustration of the different fatigue crack closure mechanisms. a) Plasticity-induced crack closure, b) oxide-induced crack closure, c) roughness-induced crack closure, d) viscous fluid-induced crack closure and e) phase transformation-induced crack closure [27]

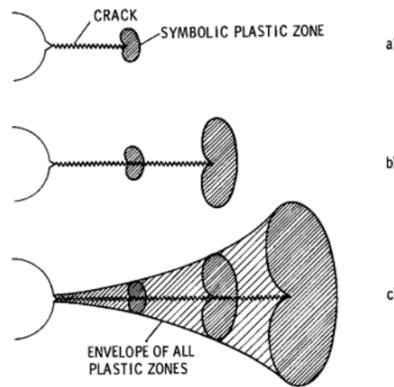


Figure 2.14. Development of a plastic zone envelope around a fatigue crack [26]

The phenomenon of plasticity-induced crack closure can be visualized if the stress versus the crack tip displacement is plotted over one cycle (figure 2.15). Figure 2.15a shows the crack configuration and gage location for a typical test. Figure 2.15b shows the relation between the applied stress and the displacement measured by the gage. In the regions between point A and B the stress-displacement relation is linear and the measured stiffness $d\sigma/d\delta$ is equal to the stiffness of the uncracked sheet. The stress-displacement (σ - δ) plot for the uncracked sheet is shown for comparison. Between points C and D the relation σ - δ also is linear and the measured stiffness is equal to the measured stiffness of an identical sheet containing a saw-cut of the same length as the fatigue crack. Between points B and C the curvature $d^2\sigma/d^2\delta$ is negative. Because plastic behaviour of the material would produce a positive curvature on unloading, the only possible cause for a negative curvature is a change in configuration which increases the stiffness for decreasing loads. This change of configuration can be explained by crack closure only. From these considerations, it can be concluded that the crack is fully open between D and C during unloading. The crack closes gradually between points C and B and is fully closed between points B and A.

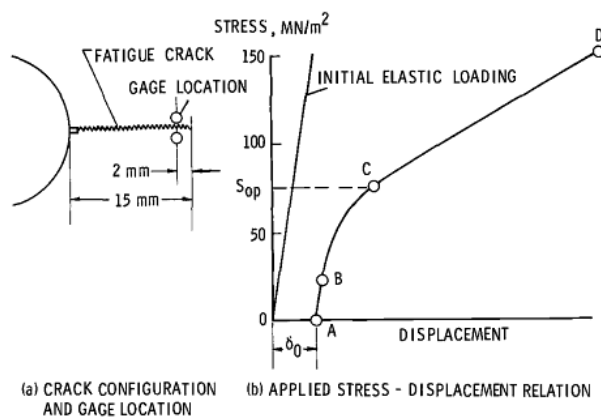


Figure 2.15. a) Crack configuration and gage location and b) applied stress versus crack tip displacement measured by the gage illustrating the plasticity-induced crack closure phenomenon

[26]

2.4.2. Oxide-induced crack closure

Oxide-induced crack closure is usually associated with an aggressive environment. Thus, during the propagation of a fatigue crack, the presence of a moist atmosphere can produce oxidation of the freshly formed fracture surfaces (figure 2.13b). Oxide debris or other corrosion products become wedged between the crack faces. In this respect, at low amplitudes of cyclic crack tip opening displacement, i.e. at near-threshold ΔK levels and low R -ratios, the possibility of repeated contact between the crack faces during tensile fatigue can be increased as a consequence of local mixed-mode crack opening, microscopic roughness of the surface and some plasticity-induced crack closure. Consequently, a continual breaking and reforming of the oxide scale behind the crack tip occurs. As a result, oxide layers are formed between the crack faces and consequently premature contact between the faces occurs as the applied load decreases [28].

Oxide-induced crack closure is promoted by moisture-containing environments, elevated temperatures, low load ratios, low ΔK levels, high cyclic frequencies, and lower strength and coarser-grained microstructures where fretting and rubbing along fracture surface asperities become favourable.

2.4.3. Roughness-induced crack closure

Experimental investigations on many ductile materials reveal that crack growth in the near-threshold fatigue regime occurs by means of a single slip mechanism. This mechanism is produced when the crack and the zone of plastic deformation around the crack tip are confined to within a few grain diameters. Crack propagation occurs predominantly by single shear in the direction of the primary slip system (figure 2.13c). This mechanism leading to a zig-zag crack path has been termed stage I crack growth by Forsyth [29]. This stage I growth mechanism leads to a highly serrated fracture morphology and an increase in the crack closure stress. It is also known that permanent plastic deformation ahead of the crack tip and the possibility of slip irreversibility during unloading from the stress peak, causes mismatch between the fracture surface asperities [30].

2.4.4. Viscous fluid-induced crack closure

This crack closure mechanism occurs when a viscous fluid penetrates a growing fatigue crack (figure 2.13d). Endo et al. [31] argued that the hydrodynamic pressure generated when the fluid penetrated the crack produced a reduction in the effective stress range and consequently, it caused a deceleration in fatigue crack growth.

2.4.5. Phase transformation-induced crack closure

This crack closure mechanism is characterised by phase changes at the crack tip generating an increase in the volume of the transforming region (figure 2.13e). Similar to at plasticity-induced crack closure, compressive residual stresses are induced within the permanent deformed zone during cyclic tension. In addition, this permanent deformed zone left in the crack wake tends to close the crack prematurely at a far-field tensile stress. Pineau and Pelloux [32] studied fatigue crack growth in metastable austenitic stainless steels and showed that strain-induced martensitic transformation generally resulted in a reduction in crack growth rates at low to mid- ΔK levels.

2.5. The effect of the application of overloads

During the growth of a fatigue crack, the application of an overload can result in the retardation of crack propagation or even in the complete arrest of the crack. A constant fatigue loading is interrupted by a single overload (figure 2.16a), after which the K amplitude resumes its previous value. Prior to the overload, the plastic zone would have reached a steady-state, but the overload produces a significantly larger plastic zone. When the load drops to the original K_{min} and K_{max} , the residual stresses that result from the plastic zone generated by the overload are likely to influence subsequent fatigue behaviour.

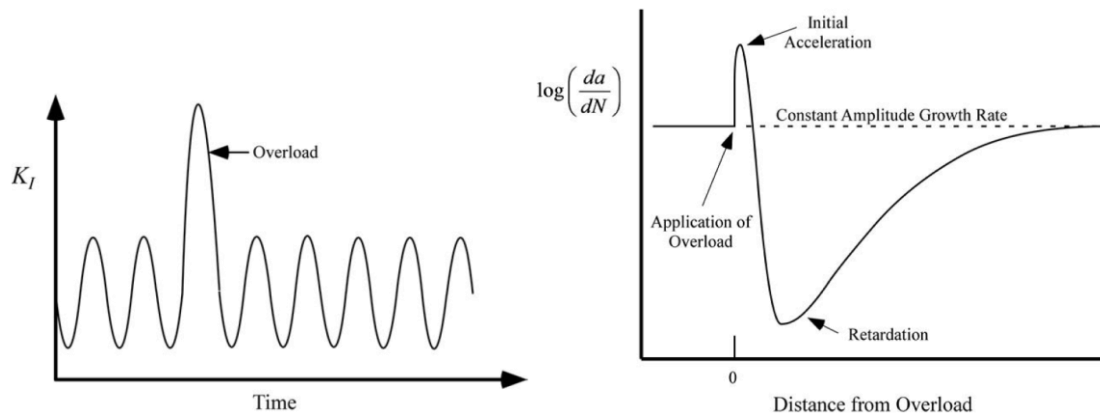


Figure 2.16. Application of a single overload during cycling loading (a) and typical crack growth behaviour following the application of an overload [27]

Figure 2.16b shows the typical behaviour in the fatigue crack growth following the application of an overload. The burst of accelerated crack advance is generally followed by a prolonged period of decelerated crack growth, when the post-overload fatigue crack is subject to the same baseline stress intensity factor range as the pre-overload regime. This progressive reduction in crack rate continues over a determined crack distance, reaching a minimum and after that the crack growth rate begins to increase and eventually catch up with the pre-overload value.

Three possible mechanisms have been proposed to explain retardation following an overload:

- a) As the crack grows into the overload zone, residual stresses behind the crack tip result in plasticity-induced crack closure.
- b) The crack blunts following an overload, and crack growth is delayed while the crack tip resharpenes.
- c) The residual compressive stresses in front of the crack tip delay the crack growth rate.

2.5.1. Plasticity-induced crack closure as retardation mechanism in the study of overloads

Elber [25, 26] argued that such plasticity-induced crack closure can also account for the transient retardation phenomena due to overloads. The application of an overload produces a larger plastic stretch in the wake of the crack tip (as compared to the baseline ΔK) as the fatigue crack propagates through the overload plastic zone. The contact of the fracture surface causes an enhancement in the level of plasticity-induced crack closure in the post-overload regime which promotes a retardation of the crack growth rate.

2.5.2. Crack tip blunting as retardation mechanism in the study of overloads

Rice [33] argued that the blunting of the crack tip by an overload cycle can lead to crack growth retardation. The underlying mechanism for retardation is that the blunted crack tip behaves like a notch with a less severe stress concentration than the originally sharp crack tip. Although crack tip blunting does influence the rate of post-overload crack growth, it cannot account for the existence of delayed retardation and cannot quantitatively rationalize the experimentally observed reductions in post-overload crack growth.

2.5.3. Residual compressive stresses as retardation mechanism in the study of overloads

It has been suggested [34] that the residual compressive stresses can retard post-overload crack growth. However, difficulties are encountered on rationalising that retardation effect could be induced solely by residual compressive stresses: i) the largest residual compressive stresses exist in the vicinity of the crack tip. Hence, instantaneous retardation or crack arrest, rather than delayed retardation, is predicted contrary to experimental observations. ii) Experiments show [35] that the retardation can persist even when the post-overload crack has traversed through the zone of residual compressive stresses.

Chapter 3. Literature review

3.1. Introduction

This chapter is a literature review divided into two main areas. The first one is an historical review of the fatigue crack closure phenomenon, describing the techniques and methods reported in the literature for its evaluation and quantification. The second area is a review about how transmission photoelasticity, DIC and ESPI techniques have been employed in fracture mechanics. In particular, different approaches and methodologies for the calculation of the stress intensity factors are reviewed as well as the most relevant research conducted on the evaluation of fatigue crack shielding and the effect of overloads in fatigue crack growth rate.

3.2. Fatigue crack shielding

3.2.1. Introduction

Many research works on fatigue crack propagation have highlighted a dominant role of crack closure phenomenon in influencing growth rate behaviour. It is shown that many of the commonly observed effects of mechanical factors, such as load ratio, microstructural factors, (strength and grain size), and certain environmental conditions can be traced to the extrinsic influence of closure in modifying the effective driving force for crack propagation. Nonetheless, nowadays there are some unresolved or misunderstood issues on fatigue crack closure. These misunderstandings or controversies proceed mainly from problems in its measurement and interpretation [1].

Many authors disagree about the existence of crack closure phenomenon or about if this phenomenon is the only effect that can shield the crack during its fatigue growth. Thus, some authors [21] postulate that not only the crack closure effect can shield the crack during fatigue growth, but also a compatibility-induced interfacial shear stress at the elastic-plastic boundary is generated which will shield the crack from the influence of the surrounding elastic field originated by the applied load. For this reason, in the current thesis the term fatigue crack shielding has been adopted to explain the retardation effect in the crack growth rate instead of fatigue crack closure.

This chapter is divided into two sections: the first is a historical review of the fatigue crack closure phenomenon, including the crack closure concept, a review of the different mechanisms

reported in the literature and the different theories and approaches employed for its explanation. The second section is a review of the different methods and techniques conventionally employed for the quantification of the crack closure effect.

3.2.2. Historical review

The concept of interaction between crack faces producing a decrease in stress intensity at the crack tip was initially stated by Christensen [36] in 1963. His results demonstrated that an increase in fatigue life occurred due to the presence of trapped oxide particles between the fracture surfaces of centre-cracked plates manufactured in 2024-T3 aluminium alloy, but this increase was greater when part of the cycle was compressive. Similar results were also found by Endo et al. [37], who observed lower crack growth rates for a low strength steel in water compared to air. They suggested that this observed difference in crack growth rates could be attributed to corrosion deposits formed between crack surfaces which prematurely closed the crack. Nevertheless, at that time it was thought that in the study of fatigue crack propagation, crack closure only occurred under compressive loads [33].

The first mechanical justification for crack closure in terms of linear elastic fracture mechanics concepts was presented by Elber [25] in 1970. He concluded from his experiments that the crack closure phenomenon is a direct consequence of the permanent tensile plastic deformations left in the wake of the propagating crack. In addition, he also concluded that a fatigue crack is fully open for only a part of the load cycle, even when the loading cycle is fully in tension. Elber observed the crack closure phenomenon when a partially cracked sheet specimen was cut open in order to allow fractographic investigations of the fracture surfaces. Thus, Elber conducted a set of tests to show that a fatigue crack growing under zero-to-tension loading was fully closed at zero load due to internal forces existing in the specimen. His experiments were based in the two following principles: the first one was that the net internal force acting across a section in a statically indeterminate structure can be obtained by cutting the section and measuring the force system required to reverse the displacements system produced by the cut. Moreover, the second principle was that a crack in a structural member is closed when the stiffness of the member is the same as the stiffness of an identical uncracked element under the same load conditions. Finally, Elber concluded that the determination of the crack opening load (load at which contact between the crack surfaces is broken during loading) and the crack closure load (load at which contact between the crack flanks is established during unloading) were aspects that had to be required to establish the influence of crack closure on fatigue crack growth. Thus, in further work, Elber [26] determined the crack opening load and the crack closing load by recording the stress and displacement at the crack tip on a sheet of 2024-T3 aluminium alloy (figure 3.1a). Figure 3.1b shows a relationship between the stress and displacement at the crack tip. It can be

observed that one main characteristic of this relationship is that it is nonlinear. The relation between points A and B is linear, highlighting that the crack is closed and the stiffness is equal to the stiffness of the uncracked sheet; between points B and C the curvature is negative, attributed to the change in the stiffness resulting from the lost of contact between the crack flanks, indicating that the crack is opening; between points C and D the relation is linear; and between D and E the curve again has a negative curvature due to plasticity. A similar behaviour was also observed during the unloading part of the cycle. Elber went further in his investigation trying to develop an approach to determine the crack opening load. This approach was based on the premise that during the first stage of the unloading part, elastic behaviour of the material at the crack tip was expected. Moreover, the stiffness of the specimen in this stage should be identical to the situation when the crack was fully open, provided that the material was behaving elastically. Hence, by drawing a tangent line to the loading branch of the load-displacement curve using the slope corresponding to the initial part of the unloading branch, Elber was able to estimate a value for the opening load (figure 3.1b). The estimated crack opening load was employed to obtain the effective stress intensity factor range, ΔK_{eff} :

$$\Delta K_{eff} = K_{max} - K_{op} \quad (3.1)$$

Where K_{max} and K_{op} are the stress intensity factors at the maximum and opening loads respectively. This effective stress intensity factor range was adopted as reference level since crack propagation occurred only during the portion of the cycle at which the crack was fully open at the crack tip. Therefore, the effective range was the range that truly contributed to crack propagation.

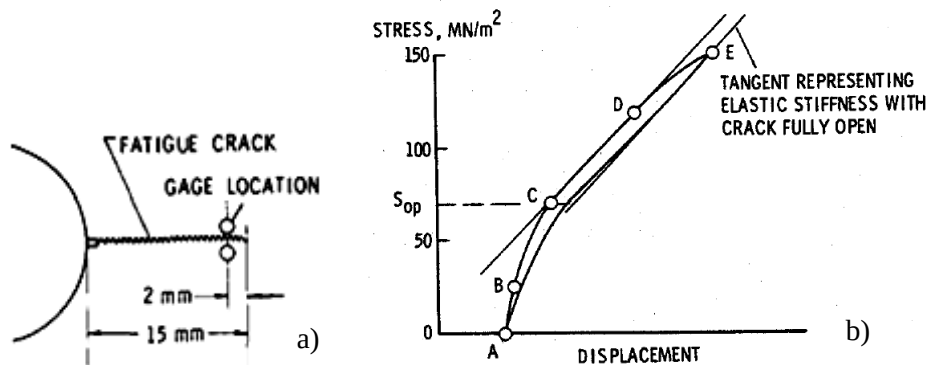


Figure 3.1. a) Crack configuration and gage location and b) applied stress versus crack tip displacement measured by the gage illustrating the plasticity-induced crack closure phenomenon

[26]

Elber also performed a set of constant amplitude tests to establish the crack opening load under various conditions of stress intensity range, load ratio and crack length. Thus, he was able to

establish a relation between the effective stress intensity factor range, the applied stress intensity factor range and the load ratio:

$$U = \frac{\Delta K_{eff}}{\Delta K} = 0.5 + 0.4R \quad (3.2)$$

This correlation described results from fatigue experiments better than other solutions previously proposed by Forman et al. [38] and Erdogan [39].

Further experiments were also conducted using variable amplitude loading. Thus, it was concluded that the crack closure phenomenon under variable amplitude loading accounted for acceleration and retardation effects in crack propagation.

This kind of closure reported by Elber is normally referred to as plasticity-induced crack closure. It normally occurs at stress intensities much greater than the threshold stress intensity [30], since the mechanism governing the phenomenon results from the constraint of the elastic material surrounding the plastic zone at the crack tip. This fact makes this type of closure likely to appear even in relatively long cracks. Nevertheless, at very high stress intensity levels once the material becomes fully plastic, plasticity-induced crack closure becomes insignificant.

Experimental investigations published in the later 1970s and early 1980s established that Elber's mechanism was not the only cause of closure, but other types of closure phenomena also influence the rate of fatigue crack propagation. Another common source of closure is that known as oxide-induced crack closure. Suresh et al. [28] suggested the possibility of crack closure due to corrosion debris influencing near-threshold growth crack rates and threshold ΔK_0 values. They reported the first experimental attempts to quantify the effects of corrosion deposits on fatigue crack propagation rates, especially in the near-threshold regime where the extent of oxide formation within the crack was found to be comparable to the scale of crack tip opening displacements. The concept of oxide-induced crack closure [28] is based on the phenomenon that at low load ratios, near-threshold growth rates are significantly reduced in moist environment (such as air or water), compared to dry environments (such as hydrogen or helium gas), due to the formation of excess corrosion deposits on crack faces which enhances crack closure. Moist atmospheres lead to the formation of oxide layers within the crack. These layers are thickened at low load ratios by a continual breaking and reforming of the oxide scale behind the crack tip as a results of the repeated contact between the fracture surfaces arising from mode II displacements and plasticity-induced crack closure ("fretting oxidation").

A third source crack closure occurs at near-threshold stress intensities due to the rough nature of the fracture surface. This mechanism is known as roughness-induced crack closure [30] and it occurs when crack tip opening displacements become comparable to the size-scale of fracture surface asperities. Ritchie and Suresh [30] noted that at near-threshold levels, in addition to the

role of plasticity- and oxide-induced crack closure, fracture surface roughness may promote significant closure effects in plane strain. This was attributed to the fact that when the maximum plastic zone sizes is small compared to the grain size, fatigue crack growth occurs by a single shear decohesion mechanism associated to mode I+II displacements. Thus, the resulting serrated fracture surfaces together with mode II displacements induce high closure loads by wedging the crack open at discrete contact points.

Another additional source of closure can arise from the presence of a viscous fluid penetrated within a growing crack. This mechanism of closure is known as viscous fluid-induced crack closure and takes place when the presence of the fluid can give rise to hydrodynamic wedging action counteracting the closing of the crack. Endo et al. [31] experimentally demonstrated that this mechanism of viscous fluid-induced crack closure becomes relevant for fatigue crack propagation in oil environment, where the crack growth rate has been found to be sensitive to the kinematic viscosity of oil.

The last source of closure reported in literature is known as phase transformation-induced crack closure. Pineau and Pelloux [32] studied fatigue crack growth in metastable austenitic stainless steels and showed that strain-induced martensitic transformation generally resulted in reduced crack growth rates at low to mid- ΔK levels. With reference to fatigue crack closure, crack tip phase transformation is analogous to crack tip plasticity in the sense that compressive residual stresses are induced within the nonlinear zone during cyclic tension. Furthermore, in both cases, the residual displacements left in the wake of the growing fatigue crack close the crack prematurely at a far-field tensile stress. Therefore, as in the case of plasticity-induced crack closure, the constraint at the surrounding elastic material is necessary to promote transformation-induced closure since transformation of the entire specimen would not result in appreciable crack face contact. Thus, transformation-induced crack closure is strongly influenced by the size and geometry of the test specimen and of the fatigue crack.

Although in most of the cases fatigue crack closure effect has been observed to be more pronounced at low load ratios with long cracks, there are different variables that may affect the closure levels especially in near-threshold fatigue crack growth. These variables can be mechanical, such as the load ratio or the cyclic frequency [40]; microstructural, such as the strength level or the grain size [40]; and environmental, such as gaseous environmental, aqueous environmental, viscous environmental or temperature [40].

However, despite of many efforts to explain and clarify the fatigue crack closure phenomenon, there are still some unresolved issues. The whole topic of closure has been a vexed issue since Elber papers were published. Plain strain versus plane stress controversy was only one point of discussion. However, others features have been questioned as relevant factors taking part in

crack closure, such as at which applied ΔK and R -ratio crack closure is more dominant, characteristic size scales associated with each closure process (the height of the residual plastic wake for plasticity-induced crack closure, the thickness of the fracture surface oxide layer for oxide-induced crack closure, the height of the fracture surface asperities for crack closure due to roughness and the height of the transformation zone for closure arising from phase changes) or that closure is produced by mechanisms occurred both at the tip of the fatigue crack, such as plastic deformation or phase transformations, as well as phenomena which occur in the crack wake, such as fracture surface oxidation. These facts have motivated different approaches and theories to explain the different closure sources that in some cases lead to contradictory positions within the scientific community. Such a case is the work published by Vasudevan et al. [41], where they established from their analysis that plasticity cannot contribute to crack closure in the near-threshold regime. In addition, they reported that the crack closure contribution can be significant only if the crack is fully closed, which is reflected as an infinite slope in the load-displacement curve. Moreover, they reported that formation of asperities from a fretting action is a random process that cannot explain the deterministic behaviour of the load ratio effect at the threshold regime. Other conclusion that they established was that the closure contribution from the asperities resulting from oxides or corrosion products, or surface roughness, it is less than 20% of what it is conventionally calculated from the change in the slope of the load-displacement curves. Finally, they concluded that the crack closure effect can exist, but its magnitude is either small or negligible. To support their observations, they proposed a new model based on the dislocation theory, where two critical stress intensity parameters, K_{max} and ΔK_{th} , must be satisfied simultaneously as the crack tip driving forces for the fatigue advance increase. Some other mathematical models based on different mechanical concepts have been also developed over the last thirty years. Budianski and Hutchinson [42] applied the Dugdale-Barenblatt strip-yield model to study fatigue crack growth under steady cyclic loading and showed that residual stretch in the plastic wake causes the crack faces to close at a positive remote stress. Moreover, several researchers have developed models based on dislocation emission from the crack tip [43] or blockage of slip bands by grain boundaries [44].

Finite element analysis is perhaps the most commonly used numerical method to model different crack closure mechanisms. Newman [45] simulated plasticity-induced crack closure using a model based on Dugdale-Barenblatt strip-yield model at different stress ratios. Wei and James [46] built plane strain and plane stress finite element models to simulate fatigue crack closure in polycarbonate. Solanki et al. [47] presented an overview about the use of finite element analysis to study plasticity-induced fatigue crack closure. Thus, they summarized different issues that must be addressed during the fatigue crack growth simulation, such as the mesh refinement level, stabilization of crack opening load, the crack contact surface, the crack

advance scheme, the crack opening assessment location, variable amplitude loading, plane-stress and plane-strain conditions, geometry effects and the R ratio effects. In addition, finite element analysis has been also employed for the analysis of others crack closure mechanisms. Such an example is the work reported by Llorca [48], who developed a model to examine roughness-induced crack closure using the finite difference method. Recently, it has been observed that numerical studies play a major role in the understanding and prediction of plasticity-induced crack closure. However, it is also well known that the numerical models simplify the reality by considering discrete crack propagations, relatively high fatigue crack growth rates, sharp cracks and that propagation occurs at a well-defined load. In this sense, Antunes and Rodrigues [49] reported a discussion about the numerical study of plasticity-induced crack closure. Thus, they identified the parameters affecting the accuracy of the numerical simulations and the dependent parameters used to characterise the plastic wake and the closure level. In addition, they also analysed the influence of the radial size of crack front elements and crack propagation. They performed the numerical simulations using a three-dimensional elasto-plastic finite element program (DD3IMP), employing for their analysis a MT specimen subjected to plane stress mode I loading. Further work [50] was performed to study the effect of cracks shape on plasticity-induced crack closure since in the most of the previous 3D numerical studies ideal shapes were assumed for the cracks. Thus, a 3D numerical model was developed to predict plasticity-induced crack closure in MT specimens with different thickness and crack shapes. In addition, they studied the radial size of crack tip elements and the stabilisation of closure level to ensure the quality of numerical predictions. Related to these two previous works, Antunes et al. [51] have reported a work to find if the numerical predictions of plasticity-induced crack closure were close to experimental results. Thus, experimental work consisted of to obtain crack opening values in 1-mm-thick MT specimens of AA6016-T4 aluminium alloy. The opening level was determined from remote compliance data captured by a pin microgauge placed at the centre of the specimen. On the other hand, they developed and optimised a numerical model replicating the experimental test in terms of sample geometry, loading parameters, material behaviour and crack opening measurement technique. They found a good level of agreement between experimental and numerical results. Zapatero et al. [52] developed 2D plane stress and plane strain numerical models to study plasticity induced crack closure. They analysed the effect of three principal factors, the maximum load, the crack lengths and the stress ratio. They found that the results were independent of maximum load and the crack length, and there existed a direct influence of the stress ratio. Authors also observed that differences between opening and closing points and between the different criteria employed to compute crack closure. Further work was performed by González-Herrera and Zapatero [53], where 12-mm-thick CT aluminium specimens were modelled tri-dimensionally. The plastic zone was visualised and quantified, observing an abrupt transition in a thin external slice of the

specimen: only captured with a fine meshing of the thickness. They computed crack opening/closure load along the thickness. Additionally, results showed that closure was only relevant in this small external area and its size was not affected by the thickness. Moreover, de Matos and Nowell [54] focused their work on the crack growth scheme adopted for modelling fatigue crack growth in crack closure problems. Thus, the number of load cycles between node releases usually reported in the literature has been, in general, one or two. According to this, they showed that increasing the number of load cycles between node releases had a strong effect on the opening stresses, particularly, under plane strain conditions and 3D fatigue cracks. In contrast, plane stress showed little variation with increasing number of load cycles.

3.2.3. Fatigue crack closure quantification using experimental methods

Different techniques and methods have been developed for the experimental evaluation of fatigue crack closure since Elber introduced its bases. Most of them are based on the measurement of the change in stiffness of cracked specimens as the premature contact between the crack faces occurs. However, alternative techniques based on different principles have been also employed. Thus, the methods for crack closure measurement can be classified in three main categories [55]:

- Methods based on the direct observations of the distance between the crack faces. These techniques include optical microscopy, scanning electron microscopy, photography, optical and laser interferometry, replica, surface strain, X-ray tomography and caustics.
- Methods based on compliance measurements. Such as clip gauges, surface strain gauges and back face strain gauges.
- Methods based on the measurement of the fatigue crack growth. Such as crack growth rate observations or striation spacing measurements.

Many researchers have used several of these methods or combinations of them. Davidson [56] tried to measure the opening load in cracked specimens by taking photographs of the same region at minimum load. Then, he compared them in a stereoscope with photographs of the same region at progressively higher loads. Using this technique, he directly measured the open portion of the crack using a ruler. Moreover, as the open portion of the crack was approaching the crack tip, higher magnification photographs were captured making it potentially possible to calculate very accurately the load at which the crack was actually opening. Nevertheless, it was observed that if opening loads were measured repeatedly for a growing crack at constant stress intensity factor range, there was variation in the opening load that was greater than the uncertainty in the measurements. Thus, it was shown that the accuracy with which opening load could be determined was reduced. Evans and Spence [57] investigated the possibility to measure crack closure in quarter circular and elliptical cracks. For this purpose they used three

different techniques: potential drop, strain gauges and the replica monitoring technique. The results obtained by the last technique were found to be consistent with the stereo-imaging work made by Davidson [56]. Jones et al. [58] measured the displacement-load curves at three different regions on a specimen using three different techniques: in the front of the crack tip using optical interferometry, behind the crack tip using an interferometric displacement gauge and at the notch mouth of the specimen using a displacement gauge. They observed that the results were dependent on the region where the measurement was made. Bowman et al. [59] developed measurement of crack closure using back faces strain gauges and clip gauges, trying to validate them using laser interferometry. Again, results showed dependence on the measurement location.

More recently, optical techniques, such as thermoelastic stress analysis (TSA), transmission photoelasticity or DIC have been implemented to quantify crack closure. Díaz et al. [3, 60] developed an approach to evaluate crack closure effect from the analysis of thermoelastic images from the quantification of the effective stress intensity factor range. In addition, thermoelastic results were compared with those obtained using compliance methods [60], showing a very good level of agreement and illustrating the ability of TSA to infer successfully the effective ΔK . Moreover, transmission photoelasticity has been also employed to evaluate plasticity-induced crack closure because it offers the opportunity for direct visualisation of crack tip and crack flanks stresses, and the interaction between these. Polycarbonate has been the most extensively material employed because it is enough ductile to grow fatigue cracks, exhibiting plasticity-induced closure (figure 3.2) [2]. Further work was performed by Pacey et al. [61], who modified the current photoelastic stress analysis methods to include an assessment of crack tip shielding mechanisms. Thus, authors developed a simplistic model which demonstrated that analysis of the global photoelastic stress field could capture highly localised stress effects from plasticity-induced shielding. More recently, Christopher et al. [21] have introduced a novel mathematical model of crack tip stress fields which considers the effects of plasticity through an analysis of their shielding effects on the applied elastic field. They employed transmission photoelasticity to evaluate the ability of the model to characterise the plasticity-induced crack shielding effects on the elastic stress fields. Moreover, besides thermoelasticity and photoelasticity, DIC has been also employed to quantify crack closure. Such a case is the work conducted by Sutton et al. [62], where they tried to measure crack closure through the obtained load versus crack tip opening displacements curves (figure 3.3). Further work was also conducted by de Matos and Nowell [8], who studied the thickness effect in plasticity-induced fatigue crack closure. López-Crespo et al. [9] presented a methodology based on Muskhelishvili's complex potentials [10] for the evaluation of crack closure. In

addition, transmission photoelasticity and DIC seem to be very suitable techniques for quantifying the effect of the application of overloads [11, 12] on fatigue crack growth.

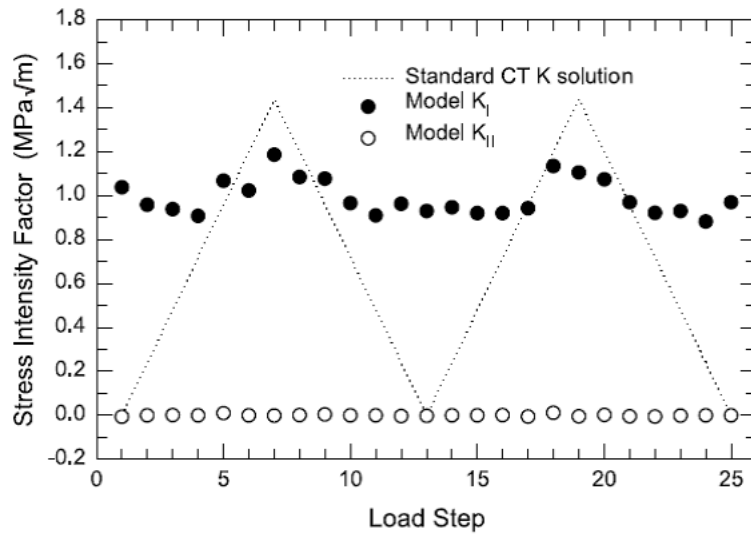


Figure 3.2. Crack tip stress intensity factors obtained by fitting the mathematical model based on Muskhelishvili's complex potentials to full field photoelastic fringe patterns [1]

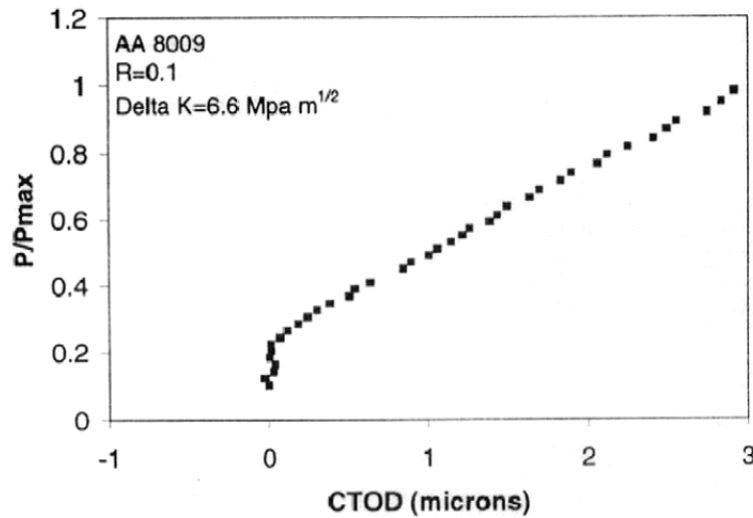


Figure 3.3. Curve load versus crack tip opening displacement obtained with digital image correlation for crack closure measurement [62]

However, despite the many alternative techniques for the experimental measurement of the opening and closing loads, compliance methods have been the most extensively used for quantifying crack closure. James and Knott [63] measured crack closure in steel using a back face strain gauge together with an offset elastic displacement circuit. Another example is the work conducted by Garz and James [64] used a clip gauge and a back face strain gauge to measure crack closure in a plain carbon steel and aluminium compact tension samples. Chen et al. [65] measured crack closure using strain gauges placed in bending fatigue tests, and Huang

et al. [66] also reported some crack closure measurements using a clip gauge, surface strain gauges and the potential drop technique. Nevertheless, there exists a big controversy between published results. Although it has been recognized by different researchers that the technique and the measurement location are important factors when estimating closure, reported results are different and in some cases contradictory. This fact has made it necessary to review the methods, techniques and the different sources of uncertainty when crack closure is measured. In a review, James [1] identified as possible reasons of uncertainty the following:

- Variation in crack closure measurements obtained using different techniques. This encompasses differences arising from compliance-based and other techniques, surface versus bulk measurements, and position/sensitivity of the measurement system.
- Interpretation of compliance traces and the methodology adopted for characterising the closure values.
- Values of closure are sensitive to material, environmental parameter and also to test techniques.
- Disagreement on the importance and magnitude of plasticity-induced closure between analytical and numerical models.

In addition to the above controversies, the plane strain versus the plane stress controversy is still one of the most reasons of uncertainty. Thus, it has been shown that data measured using clip gauges were normally lower than those obtained from near crack tip strain gauges on the specimen surface. This is usually explained as being due to the difference in the material response to plastic deformation at the surface (plane stress) and the bulk of the specimen (plane strain). It has been also observed that the ability of different techniques to give absolute values rather than indicative trends will depend also on the resolution of the technique [63, 64] and the position in the crack wake where the major contribution to closure occurs. This fact has been studied by Pippan [67], and Gan and Weertman [68], who investigated the sensitivity of a surface strain gauge for different orientations and locations at the crack tip.

Another issue that has also been observed is that the sensitivity of direct compliance is much less than the offset compliance techniques [1]. It has been also reported that compliance curves obtained from either notch mouth clip gauge or a back face strain gauge are not sensitive enough to characterise pure plasticity-induced crack closure, and so, data should be measured close to the crack tip [1]. On the other hand, Vasudevan et al. [41] suggested that displacements should be measured at the loading line of the specimen, using for example a notch mouth clip gauge.

Another major issue in the measurement of crack closure has been the interpretation of the compliance traces. Different methods have been developed to obtain the opening load:

- Intersection of two tangent lines [69]. In this method, two tangent lines are drawn for the upper part and the low part of the P-COD curve respectively. The opening load is determined as the intersection of the two lines. This crack opening load determined is a kind of median load between the crack fully open and the crack fully close (figure 3.4a).
- Variation of the slope [69]. In this case, the upper part of the P-COD curve is obtained by regression analysis. Subsequently, going down in the P-COD curve, the local averaged slopes are obtained for each point by considering a number of neighbouring points on both sides of the data point. The criterion to determine the opening load is a difference of 5 % with the slope of the upper part in the P-COD curve.
- Tangent point method [70]. In this method, the upper part of the P-COD curve is represented by a linear function, while the lower part is approximated by a second order polynomial. The coefficients for both approximations are determined by regression. A condition for the tangent point is that the coordinates and the slopes of the linear part and the second order part should be the same at the tangency point. The tangency point is selected as the point with minimum error in the regression (sum of the square deviation of both parts) (figure 3.4b).

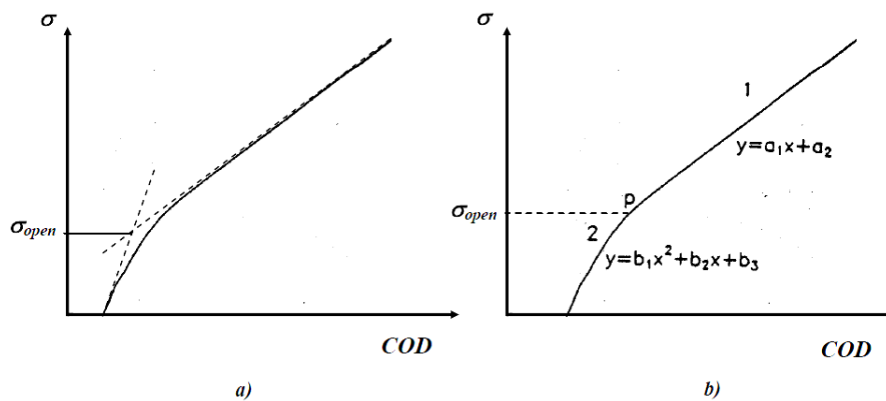


Figure 3.4. Schematic illustration of two of the methods employed for the determination of the opening stress from compliance traces: a) Intersection method, b) Tangent point method [69]

3.2.4. Conclusions

Since the concept of fatigue crack closure was introduced by Elber through his investigations about plasticity-induced crack closure, other sources of closure have been observed. These mechanisms seem to have a major influence in the near-threshold regime, such as oxide-induced crack closure and roughness-induced crack closure; or in particular environments or specific materials, such as viscous fluid-induced crack closure and phase transformation- induced crack closure. On the other hand, plasticity-induced crack closure appears to be the predominant effect

in long cracks; however, a contribution of the surface roughness and oxide particles is always expected, especially in aggressive environments.

Different mathematical, analytic and numerical models have been developed in an attempt to explain and understand the principles of crack closure. However, in some cases they showed contradictory results, which created controversies and some unresolved issues about the measurement, mechanism and interpretation of fatigue crack closure.

Different techniques and methods have been developed and employed for the experimental measurement of fatigue crack closure. The techniques more extensively used and reported in literature have been those based on compliance. The measurement location and the sensitivity of the technique have been shown as crucial issues for quantifying the crack opening and closing loads. Several researchers have reviewed all the possible points of controversy and the sources of uncertainty during the experimental evaluation of fatigue crack closure. All these aspects have made that the scientific community made a call for a collaborative effort between researchers in order to make a better understanding of the fatigue crack closure phenomenon. Despite this, there still are many issues on crack closure that remain to be solved.

3.3. Transmission photoelasticity

3.3.1. Introduction

Transmission photoelasticity has been employed since the middle of 1950s as an experimental technique for the analysis of fracture problems. However, its fundamentals and principals date from 1852, when the phenomenon of temporary or artificial birefringence was first observed. The following section provides an overview of the most of the material published on transmission photoelasticity since its birth. Attention has been extensively focused in the application of this technique to fatigue and fracture mechanics. In particular, the attention has been focused on methods for the calculation of stress intensity factors from isochromatic data, fatigue crack shielding and the effect of overloads using transmission photoelasticity. Finally, some conclusions are drawn according to the different aspects reviewed.

3.3.2. Historical review

The history of photoelasticity reaches back at least 160 years, when Maxwell established the photoelastic laws in 1852. However this time span includes long periods of relative inactivity, from its initial discovery until polymers became readily available in the 1940s and after the development of the finite element method [71] in the late 1950s.

An early description of the method of photoelasticity was provided by Coker and Filon [72] in 1931. Then, in 1937, Oppel [73] introduced the concept of frozen stress photoelasticity, which facilitated the analysis of three-dimensional problems with the use of two-dimensional concepts. This was achieved by the initially stress freezing the model and then mechanically slicing it. The mechanical slicing was replaced by optical slicing with the use of scattered light by Weller [74] in 1939. A new branch of photoelasticity was then developed, the scattered light photoelasticity [75]. Analysis of three-dimensional model as a whole was proposed by Aben [76] and the technique is known as integrated photoelasticity, but it was considered too complex for general use.

In a photoelastic test, two fringe contours are obtained: isochromatics (contours of constant principal stress difference) and isoclinics (loci of points along which the principal stress orientation with respect to a reference axis is a constant). Thus, for stress analysis at any point, the photoelastic data required are the isochromatic fringe order and the isoclinic parameter at the point. Generally, the fringes do not appear as thin lines, but they appear as broad bands. So, first step in fringe processing is to identify the actual fringe in this dark band.

Early methods for measurement the fringe data were manual. Magnification of the photographs of the fringe pattern was performed to increase the accuracy when identifying fringes; then, midpoints between edges were joined to produce fringe lines. Efforts were also made to reduce the width of fringe bands [77]. With the advent of the electronic revolution, photoelectric devices [78] were used to measure the darkest points (positions with minimum intensity) those form the actual fringe contour. Brown and Hickson [79] and Frocht et al. [80] fitted a photoelectric photometer to their polariscopes to facilitate the location of the skeleton of isochromatic and isoclinic fringes. In early methods, data was collected only at fringe locations. Thus, if only a few fringes were observed, the amount of data that could be collected was limited. Hence, efforts were made to obtain fringe multiplication [81 - 84].

One of the earliest approaches that used intensity information to calculate the fringe order was proposed by Voloshin and Burger [85]. In their investigation, the hardware feature of the black and white image processing system was used to directly find the fractional fringe orders between 0 to 0.5. By interactive ordering of full fringe orders, the technique could be made full field [86].

Regarding to algorithms based on considering the fringe patterns as a binary image, one of the most elegant methods for fringe thinning in this was reported by Chen and Taylor [87]. In this method, the binary image obtained after thresholding was scanned left to right, right to left, top to bottom and bottom to top sequentially to eliminate border pixels forming the fringe bands.

Later, intensity based methods were developed [88 - 92]. These methods were classified into mask-based methods and global methods.

In the early stages of automatic acquisition of photoelastic data, several point-by-point methods were proposed which also employed intensity information. In these approaches, either the analyzer/polarizer or the compensator was continuously rotated to produce a modulated signal at the point of interest. It was required to record a sequence of images with different optical arrangements for a given experimental situation (commonly known as phase-shifting or phase-stepping methods).

The phase shifting concept for photoelasticity was first introduced by Hecker and Morche [93] in 1986. However, Patterson and Wang [94] reported in 1991 a fully automated procedure for photoelastic analysis. They used a circular polariscope to implement the method and defined different steps of optical rotation of the elements to produce a higher modulation over the field. Several researchers have also proposed techniques based on a circular polariscope [95 - 100]. Special attempts have also been reported to improve isochromatic considering low-modulation areas [98], influence of isoclinic interactions [99], and influence of the quarter-wave plates [100]. Determination of continuous isoclinic contours has also received attention in the literature [101 - 103]. In 1992, Sarma et al. [104] reported a methodology using a plane polariscope. Later in 1993, Asundi [105] reported a new methodology which extended the compensation Tardy method to evaluate the fractional fringe order at all the points lying on the isoclinic line. Other approaches have also reported where, based on a plane polariscope, the exit light from the model was analysed by a quarter-wave plate and an analyzer [106, 107]. Brown and Sullivan [108] introduced polarisation stepping for photoelastic analysis in 1990. In addition, the use of Fourier Transform for photoelastic analysis was introduced by Quan et al. [109]. Later, Morimoto et al. [110] used polarisation stepped images to separate isoclinics and isochromatics by Fourier transform. On the other hand, Ng [111] proposed the use of Fourier transforms in conjunction with load stepping.

Phase stepping technique readily provides the magnitude of the phase difference or relative retardation, which is proportional to the principal stress difference, but its sign is usually ambiguous or undertermined. This ambiguity arises from the definition of the isoclinic angle that is related to the directions of the one of the principal stresses although it is usually unclear which one. A number of algorithms have been developed to perform the correction and generate an unambiguous distribution of relative retardation but most of them are limited to samples with simple stress distribution. In 1995, Buckberry and Tower [112] proposed an automatic full-field technique that required six images for each of three different wavelengths. In the same year, Wang and Patterson [99] developed an alternative automatic method that used only six images combined with a fuzzy set classification. This latter technique [99] and its derivatives [113],

[114] are fast and almost completely automatic with practically no intervention from the user but failed when the fringe distribution becomes complex. Three automatic and robust techniques have been presented by Ramji and Ramesh [115], Quiroga and González-Cano [116], and Villa et al. [117]. In the most recent work [115], ten phase-shifted images were used to obtain an angle that corresponded to the same principal stress direction everywhere, i.e., a map of demodulated isoclinic angle from which the unambiguous isochromatic phase could be obtained. The demodulation process used by Ramji and Ramesh [115] followed a quality map to demodulate the isoclinic angle was proposed by Siegmann et al. [114], but it was performed pixel by pixel, increasing the robustness of the algorithm but decreasing the processing speed. The method proposed by Quiroga and González-Cano [116] performed a regularized phase-tracking (RPT) process using five phase-shifted images that were proposed by Servin et al. [118]. This method also follows quality maps for both the isoclinic angle as well as the isochromatic value and, at each pixel the minimization of a cost function was performed to obtain the demodulated isoclinics and the unwrapped and unambiguous isochromatic map. The work conducted by Villa et al [117] also used a RPT process to obtain the map of demodulated isoclinic angle. In this RPT process, minimization of the cost function at each pixel was performed with an inversion of a simple 2×2 matrix, increasing the processing speed considerably with respect to other previous methods [116]. Moreover, Siegmann et al. [119] developed a new technique that allowed to obtain directly the relative retardation from the isochromatic map without first demodulating the isoclinic angle. This technique includes a RPT process that chooses between two possible solutions at each point in the image for the wrapped relative retardation. The main advantage of the proposed algorithm was that regularization was achieved without the minimization of a cost function, thus reducing the computational complexity and allowing a much shorter processing time.

3.3.3. Experimental methods for the calculation of SIFs from isochromatic fringe patterns

The experimental analysis of stress fields around a fatigue crack tip together with the experimental determination of stress intensity factors have constituted a major area of research for many years. Traditionally, LEFM [18] assumes that stress fields at the vicinity of the crack tip can be characterised by stress intensity factors (SIFs), K_I and K_{II} respectively.

The first reported research work that applied the photoelasticity stress analysis to fracture mechanics problems was conducted by Post and Wells [120, 121]. Nevertheless, Irwin [122] was the first to propose a methodology for the determination of the opening mode stress intensity factor K_I in the presence of the T-stress. Irwin's method was only applicable if the shearing mode stress intensity factor K_{II} was zero. The method was based on selecting a point

(with polar coordinates from the crack tip $r = r_m$ and $\theta = \theta_m$) (figure 3.5) on a given fringe loop (locus of constant τ_m). Thus, K_I and σ_{0x} could be determined from the following expressions:

$$K_I = \frac{NF_\sigma \sqrt{2\pi r_m}}{t \sin \theta_m} \left[1 + \frac{2 \tan\left(\frac{3\theta_m}{2}\right)}{3 \tan \theta_m} \right] \left[1 + \left(\frac{2}{3 \tan \theta_m} \right)^2 \right]^{-0.5} \quad (3.1)$$

$$\sigma_{0x} = - \frac{2 \frac{NF_\sigma}{t} \cos \theta_m}{\cos\left(\frac{3\theta_m}{2}\right) \left[\cos^2 \theta_m + \frac{9}{4} \sin^2 \theta_m \right]^{0.5}} \quad (3.2)$$

Where N is the fringe order, F_σ is the material fringe value and t is the specimen thickness. This method was found to be very sensitive to the fringe order and the coordinates of the selected data points.

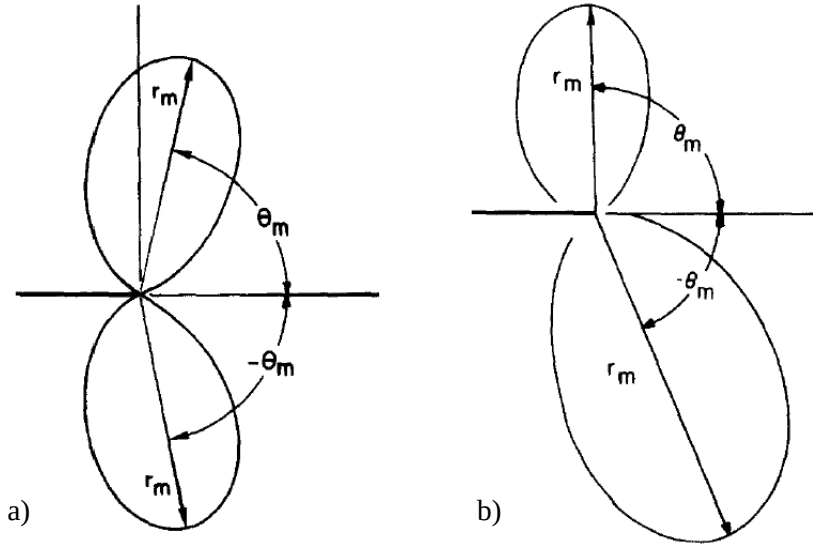


Figure 3.5. Isochromatic fringe loops at the tip of a crack corresponding to the opening mode (a) and the mixed mode (b) [7]

Bradley and Kobayashi [123] modified the Irwin's approach and employed two points along a line intersecting two different fringe orders. Schroedl and Smith [124] employed a differencing approach identical to that used by Bradley and Kobayashi except that θ was set equal to 90 degrees, simplifying the expression to obtain K_I . In general terms, both differencing approaches provided a more accurate method of analysis than Irwin's approach [125]. However, these methods were based on a two-parameter (K_I , σ_{0x}) analysis.

Etheridge and Dally [126] developed a method based on the analysis of three parameters by modifying Westergaard's stress function [18] to more closely account for stress field variations near the crack tip. However, methods including the shearing stress intensity factor in their analysis were much more limited. Chisholm and Jones [127] studied the case for pure mode II

and Smith and Smith [128] and Gdoutos and Theocaris [129] developed a procedure for the analysis of fringe loops under mixed mode conditions but in this case T-stress was not included.

Bradley and Kobayashi [130] introduced a multiple-point method of analysis to determine the coefficients in Williams's expansion series. They employed from 7 to 19 data points to determine 2 to 10 coefficients. Unfortunately, the convergence of the method was found sensitive to errors in the data and the initial estimates of the coefficients.

A significant step forwards in the calculation of SIFs from the analysis of isochromatic data was established by Sanford and Dally [7] through their Multi-Point Over-Deterministic Method (MPODM). This was a generalised method to determine mixed mode stress intensity factors together with T-stress from isochromatic data. In this way, they developed a nonlinear function based on Westergaard's classic equations [18] that related fringe order with stress intensity factors, T-stress and the polar coordinates of the data points selected around the crack tip (equation 3.3).

$$f(K_I, K_{II}, \sigma_{0x}) = \frac{1}{2\pi} \left[(K_I \sin \theta + 2K_{II} \cos \theta)^2 + (K_{II} \sin \theta)^2 \right] + \frac{2\sigma_{0x}}{\sqrt{2\pi}} \sin \frac{\theta}{2} \left[K_I \sin \theta (1 + 2 \cos \theta) + K_{II} (1 + 2 \cos^2 \theta + \cos \theta) \right] + \sigma_{0x}^2 - \left(\frac{NF_\sigma}{f} \right)^2 = 0 \quad (3.3)$$

The method was based on Newton-Raphson method combined with a least-squares analysis to provide an iterative solution based on collected data points over the isochromatic fringe patterns. Thus, Taylor series expansion of function f were written to give an over-deterministic set of equations in terms of the corrections factors ΔK_I , ΔK_{II} and $\Delta \sigma_{0x}$ according to the following expression:

$$[f] = [A][\Delta K] \quad (3.4)$$

Where the matrices were defined as

$$[f] = \begin{bmatrix} f_1 \\ \dots \\ f_m \end{bmatrix}_i; \quad [A] = - \begin{bmatrix} \frac{\partial f_1}{\partial K_I} & \frac{\partial f_1}{\partial K_{II}} & \frac{\partial f_1}{\partial \sigma_{0x}} \\ \dots & \dots & \dots \\ \frac{\partial f_m}{\partial K_I} & \frac{\partial f_m}{\partial K_{II}} & \frac{\partial f_m}{\partial \sigma_{0x}} \end{bmatrix}_i; \quad [\Delta K] = \begin{bmatrix} \Delta K_I \\ \Delta K_{II} \\ \Delta \sigma_{0x} \end{bmatrix}_i \quad (3.5)$$

Where i denotes the selected data point and m is the set of selected data points.

The least-squares minimisation process was accomplished by multiplying from the left both sides of equation 3.4 by the transpose of matrix $[A]$, to give

$$[A]^T [f] = [A]^T [A][\Delta K] \rightarrow [d] = [c][\Delta K] \quad (3.6)$$

$$[d] = [A]^T [f], \quad [c] = [A]^T [A]$$

Finally, the correction terms were given by:

$$[\Delta K] = [c]^{-1}[d] \quad (3.7)$$

The solution provided ΔK_I , ΔK_{II} and $\Delta \sigma_{0x}$ values that were used to correct initial estimates for K_I , K_{II} and σ_{0x} . The convergence was achieved in a very fast way with only a few iterations to obtain precise estimates of K_I , K_{II} and σ_{0x} .

Sanford and Dally employed a specimen machined from Homalite 100 (figure 3.6). The model was loaded with off-axis tensile forces to produce a mixed-mode stress field with distortion present due to the non-singular T-stress. Twenty data points were processed using the MPODM, assessing the accuracy of these estimated values by comparing the experimental fringe patterns with a theoretical fringe patterns (figure 3.7) plotted [134] using the computed values of K_I , K_{II} and σ_{0x} . However, difficulties in locating the crack tip produced serious errors in measuring θ . These errors depended on the radius of the fringe loops being considered with the largest error occurring with the high order fringes very close to the crack tip. Thus, $\pm 3^\circ$ errors in θ were observed for fringe loops with $r = 2.5$ mm and $\pm 8^\circ$ errors with $r = 0.9$ mm.

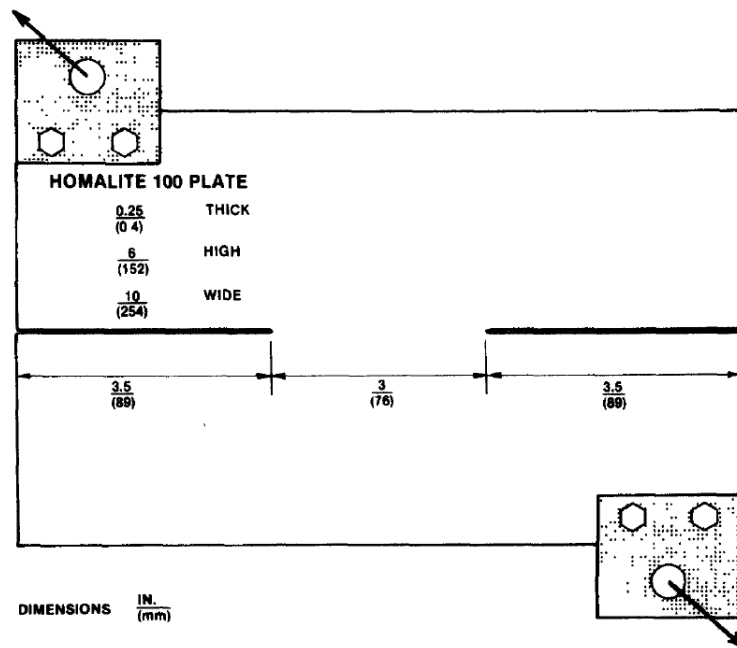


Figure 3.6. Homalite 100 specimen tested by Sanford and Dally in their experiments using transmission photoelasticity [7]

Since the MPODM was introduced, this approach has been extensively used by many different authors to report stress intensity factor results for several fracture mechanics problems [131 - 133].

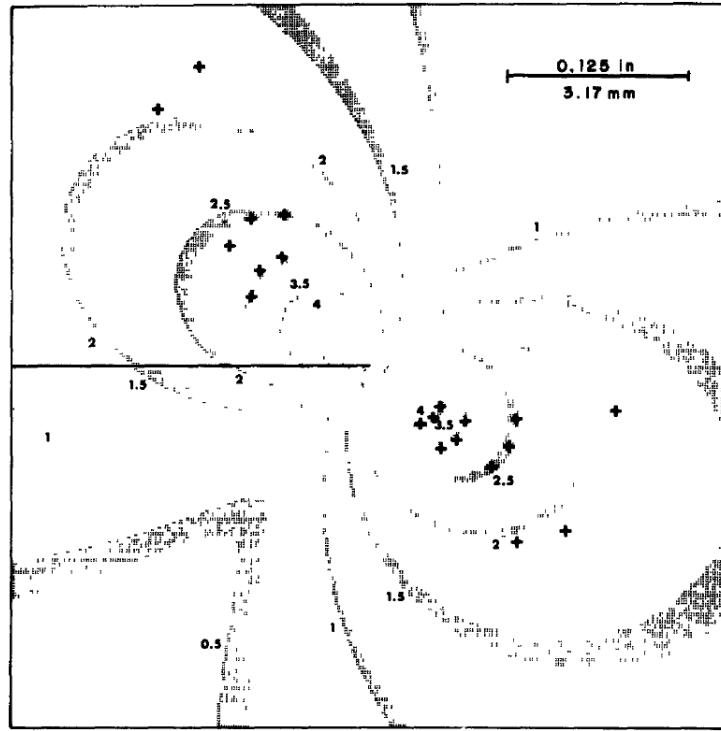


Figure 3.7. Illustration showing data points selected on isochromatic fringe pattern around the crack tip to implement the MPODM [7]

Another significant advance in determining stress intensity factors using transmission photoelasticity was made by Nurse and Patterson [19], who developed a methodology based on Muskhelishvili's complex potentials [10]. According to this approach, the in-plane stresses were represented by two analytical functions $\Phi(z)$ and $\Psi(z)$ of the complex variable $z = x + iy$. The stress equations were generated from Fourier series in complex form where the coefficients of each term were variables that allowed different stress states to be described. According to this model, the stress fields in a loaded body could be written as follows:

$$\begin{aligned}\sigma_x + \sigma_y &= 2[\Phi(z) + \overline{\Phi(z)}] \\ \sigma_y - \sigma_x + 2i\tau_{xy} &= 2[\bar{z}\Phi'(z) + \Psi(z)]\end{aligned}\quad (3.8)$$

The requirements of internal equilibrium and compatibility were automatically satisfied and only the boundary conditions remained to be satisfied. The boundary conditions for the crack surface were satisfied by using a conformal mapping function in which the crack geometry in the physical plane was mapped onto a circle in the mapping plane (figure 2.10). Subsequently, the stress equations were generated from Fourier series in complex form (equation 2.25). As a result, substituting 2.25 into 3.8, the complex stress functions were determined depending exclusively on the coefficients of the Fourier series and the coordinates of points surrounding the crack tip (equation 2.28). Thus, the unknown series parameter A_M and B_M were used to

describe the generalised state of stress around the crack. Finally, the complex stress intensity factor could be determined through the equation 2.29.

However, it has been established in the literature that the region for data collection to determine SIFs using isochromatic data is restricted to an annular mesh centred on the crack tip, which could be defined by an inner and outer radius. The inner radius was chosen to prevent nonlinear and three-dimensional effects that exist very close to the crack tip. The adopted value for the inner radius is 5 times the notch root radius [135]. The outer radius is less easy to define and usually it is adopted a distance from the crack tip where the crack tip stress equations no longer describe the state of stress. Thus, Nurse and Patterson addressed this problem and defined the outer radius according to the furthest isochromatic fringe that formed a closed loop surrounding the crack tip within the field of view (figure 3.8).

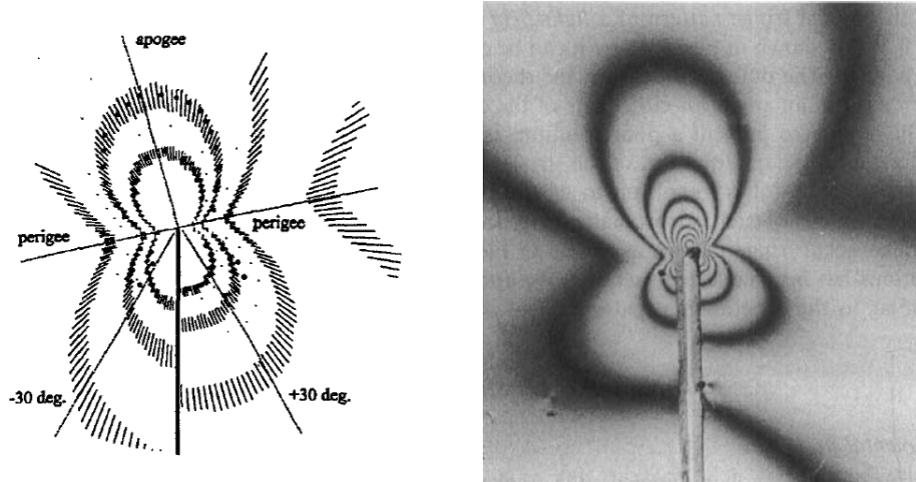


Figure 3.8. Isochromatic fringe patterns for a normalized crack length of $a/w = 0.315$ in a four-point-bend specimen. Results obtained from stress field equations (left) and results obtained experimentally (right) [19]

To determine SIFs a best-fit solution of the unknown series parameters using isochromatic data was adopted. Thus, authors adapted the procedure proposed by Sanford and Dally [7] to solve the stress field equations. In addition, to evaluate the quality of the solution, they performed statistical calculations based on the mean and the variance of the least-squares fit, defining the a confidence interval corresponding to a 95% probability that the true SIF will be contained within the intervals. As a result of this work, the authors looked for advancements towards a more accurate and versatile method for SIF determination using transmission photoelasticity. These improvements were focused on the formulation of crack tip stress equations and the method of solution. However, there is still some doubt with regard to the limit of the data collection zone.

Ramesh et al. [136] proposed an alternative over-deterministic least squares technique using Alturi and Kobayashi's equations [137] (equation 2.19) to evaluate the mixed-mode stress field parameters [138]. The authors showed that the use of Alturi and Kobayashi's equations led to a very simple analysis increasing the number of terms in mode I or mode II series depending on the problem requirements until the experimental fringes were correctly modelled.

Recently, several authors [2, 21, 61] have contributed to the development of different models of crack tip stress fields from which the effects of crack tip plasticity can be evaluated. James et al. [2] were the first authors that showed that polycarbonate is a material ductile enough to study fatigue crack growth and showed that this material exhibited plasticity-induced closure. Further work was reported by Pacey et al. [61], who developed a simplistic model with demonstrated that analysis of the global elastic stress field surrounding the crack wake could capture highly localised stress effects from plasticity-induced shielding. They modelled mathematically the crack tip stress fields using the Muskhelishvili's complex potentials [10]. This model was fitted to full-field experimental stress data obtained using photoelasticity for a fatigue crack that was grown in a compact tension specimen made of polycarbonate. A combination of a simple genetic algorithm and the downhill simplex method [139] was used to perform the mathematical fitting. The stress intensity factors during two load cycles fitted well with the applied load cycle and clearly displayed evidence of crack closure. The technique offered a significant advance in the ability to characterise the behaviour of fatigue cracks with plasticity-induced closure, and hence gain new insights into associated mechanisms.

Recently, Christopher et al. [21] have developed a new mathematical model that represents a major advance on work previously reported by Pacey et al. [61]. This model is called CJP (Christopher, James and Patterson) and it is based on Muskhelishvili's complex potentials [10]. Thus, the model considers the effects of shielding via a more accurate multi-parameter representation and presents them in a unique stress intensity-based description which, for the first time, allows a coherent interpretation of plasticity-induced shielding on the elastic stress field. In particular, this model characterises the shielding effect of the plastic enclave surrounding the crack through two parameters; a 'crack retardation intensity' associated with the crack wake and near-tip plastic zone and an 'interfacial shear stress intensity' at the elastic-plastic boundary induced by compatibility requirements. According to this model, the authors postulated that the plastic enclave around a propagating fatigue crack exerts a set of forces on the surrounding elastic material which are illustrated in figure 2.11. Thus, the stress fields generated by the previous forces can be characterised by four parameters: an opening mode stress intensity factor K_F (similar to classical K_I originated by the applied load on the specimen), the retardation stress intensity factor K_R (which characterises the direct stresses acting parallel to the crack growth direction), the shear stress intensity factor K_S (which characterises the shear

stress on the elastic-plastic boundary) and the T-stress. Several works [22, 23] have been made by using this model, but they were mainly focused on highlighting the potential of CJP model for the evaluation of the effect of plasticity on the global elastic stress field. These works will be for evaluating plasticity-induced shielding in a growing fatigue crack. However, these works will be reviewed in the following section related to fatigue crack shielding using photoelasticity.

In 2009, Díaz et al. [140] have developed a new method for the calculation of the stress intensity factors from the analysis of isochromatic data. The method was based on the analysis of the retardation map obtained by combining two photoelastic images corresponding to light- and dark-field of a crack from a circular polariscope. This experimental retardation was compared with the theoretical solution predicted by Westergaard's model [18]. In this way, the necessity of unwrapping and calibrating the isochromatic fringe order distribution was avoided and potential sources of error were eliminated. Subsequently, K_I , K_{II} and σ_{0x} were inferred by minimizing an error function. The potential and efficiency of this method was showed from photoelastic images (figure 3.9) captured during fatigue tests conducted in a polycarbonate Centre-Cracked-Tension (CCT) specimen. Results showed an excellent level of agreement with those predicted from theory (figure 3.10), highlighting the potential of the proposed methodology.

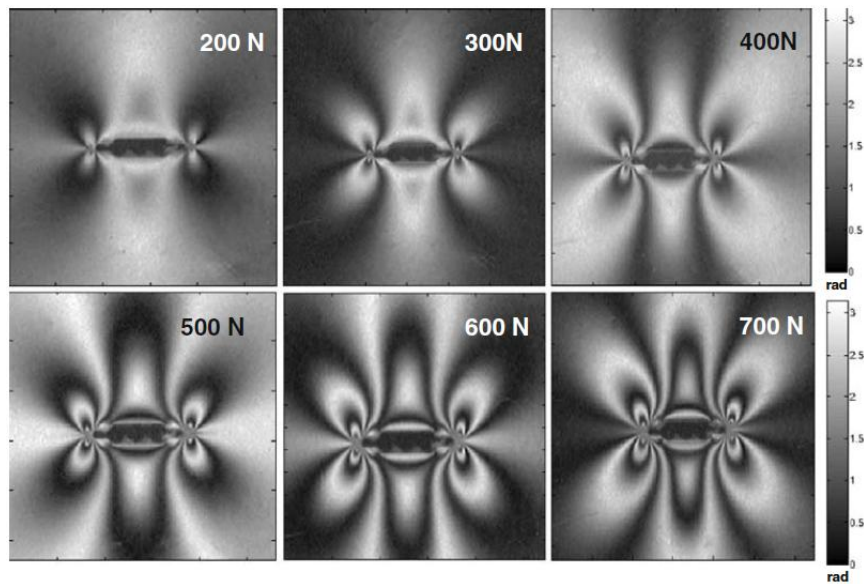


Figure 3.9. Dark field fringe patterns captured on a polycarbonate CCT specimen for different load levels corresponding to a 10.92 mm crack length [140]

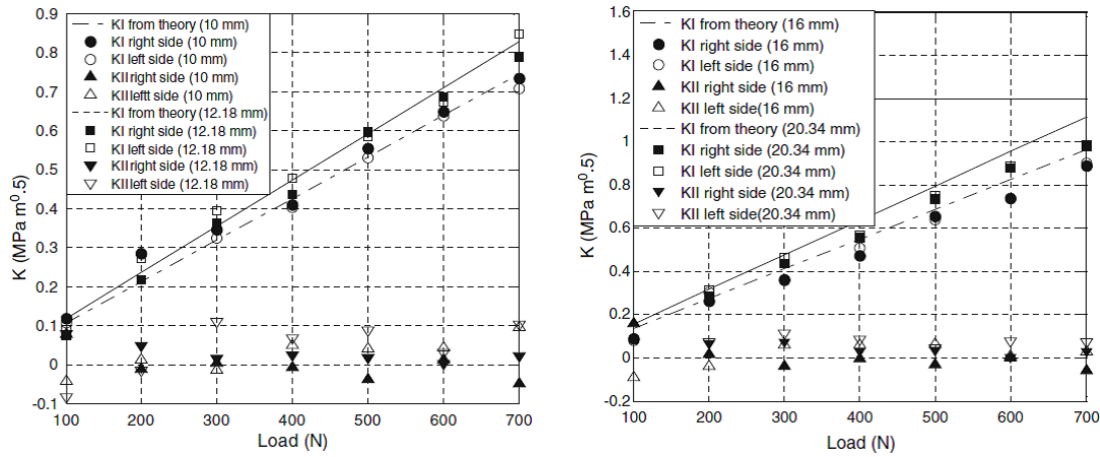


Figure 3.10. K_I and K_{II} values obtained experimentally using an approach based on combining two photoelastic images for different load levels corresponding to four different crack lengths [140]

3.3.4. Investigation of fatigue crack shielding using transmission photoelasticity

Since Elber [25, 26] introduced the principles of crack closure in 1970, many research works have been published for the measurement and interpretation of this phenomenon using different methods and techniques (direct observation methods, methods based on compliance and indirect observation methods) [55]. A fundamental issue in the experimental evaluation of fatigue crack growth is identifying how a growing crack influences the plastic zone size and shape. In this sense, transmission photoelasticity plays a significant role since this technique allows the direct observation of crack tip and crack flanks stresses and the interaction between them. Another important issue in fatigue crack growth is the effective evaluation that plasticity originated around the crack can produce during fatigue growth rates. These effects include the shielding that the plastic enclave generates on the surrounding elastic material and therefore, the retardation associated to fatigue crack growth.

It is believed that the first study on closure effects using photoelasticity was made by Christensen [36], who used a rubber manufactured on polyurethane to make a specimen that consisted on a cracked plate and introduced a cylindrical plug into the notch to simulate a crack. His results demonstrated that an asperity reduced the fringe order and the stress in the boundary by up to 67%.

Until 1990s, most experimental photoelastic work was performed using sharp notches in brittle epoxy resins to simulate cracks. Such resins were not amenable for growing real fatigue cracks, and therefore they could not be employed to evaluate phenomena related to fatigue crack growth, like crack closure or crack shielding. However, polycarbonate is a birefringent material

that is enough ductile to allow the study of fatigue crack growth and to show clear evidence of plasticity-induced crack closure [2]. James et al. [2] employed transmission photoelasticity to study plasticity-induced fatigue crack closure in CT polycarbonate specimens with real fatigue cracks. They observed that the plastic zone surrounding the crack was clearly visible, and its width corresponded well with that expected from the formation of the plastic zone by Dugdale, although the mechanism of plastic deformation and crack growth was via crazing. They also observed that fringe patterns were considerably influenced by the contact between the fracture surfaces. It was observed that fringe loops at the crack tip did not disappear when the load was removed, showing that residual stresses remained in the specimen. In this work, the authors developed an elastic stress solution based on Muskhelishvili's complex potentials [10] for a model of a closed crack in an infinite plane. This model could be fitted to experimental fringe patterns by optimising the applied stresses, stress direction and contact pressure. This model used a memetic algorithm, which was a combination of a genetic algorithm and a local search technique. Mixed mode stress intensity factors were also calculated from the fitted theoretical stress field and the crack wake contact pressure was inferred. From the analysis of K_I , it was obtained that K_{min} during the cycle remained around $0.9 \text{ MPa}\cdot\text{m}^{1/2}$ (figure 3.2), rather than dropped off to zero. Therefore, this observation was consistent with the presence of crack closure. Thus, an opening and closing loads of about 80 N were obtained, which corresponded with a ratio $P_{op}/P_{max} = 0.65$. These results correlated well with the changes in the gradient of the compliance trace (figure 3.11), which showed a point of inflexion at 72 N during loading ($P_{op}/P_{max} = 0.58$), and changes in the gradient at 80 ($P_{op}/P_{max} = 0.65$) and 61 N ($P_{op}/P_{max} = 0.49$) as the load was removed. They concluded from these observations that the model was capable of describing both the correct trends for variation of stress intensity factor during fatigue cycling, and of producing values of K_{min} and K_{max} that were justifiable and in agreement with the compliance traces. In addition, they made a numerical study by finite element modelling using ANSYS 5.4. FE results showed a stable level opening load ratio (P_{op}/P_{max}) around 0.55 within 20 loading cycles (figure 3.12). This value agreed well with the mean value obtained from compliance traces of 0.58 (shown with a dashed line in figure 3.12), and is reasonable close to the value of 0.65 derived from the photoelastic analysis. Finally, authors concluded that plasticity-induced crack closure was more accurately described as shielding of the crack tip from the applied tensile stress field. Therefore, they proposed that the plastic enclave around a crack tip will shielded the crack from the full influence of the applied stress field.

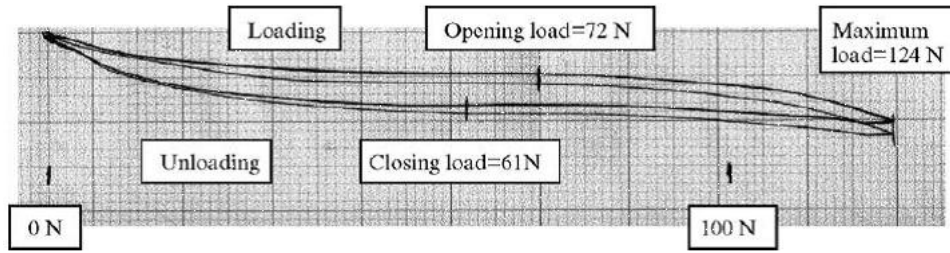


Figure 3.11. Compliance traces recorded simultaneously with the photoelastic images showing the strain recorded by a strain gauge aligned with the principal strain, as a function of applied load [2]

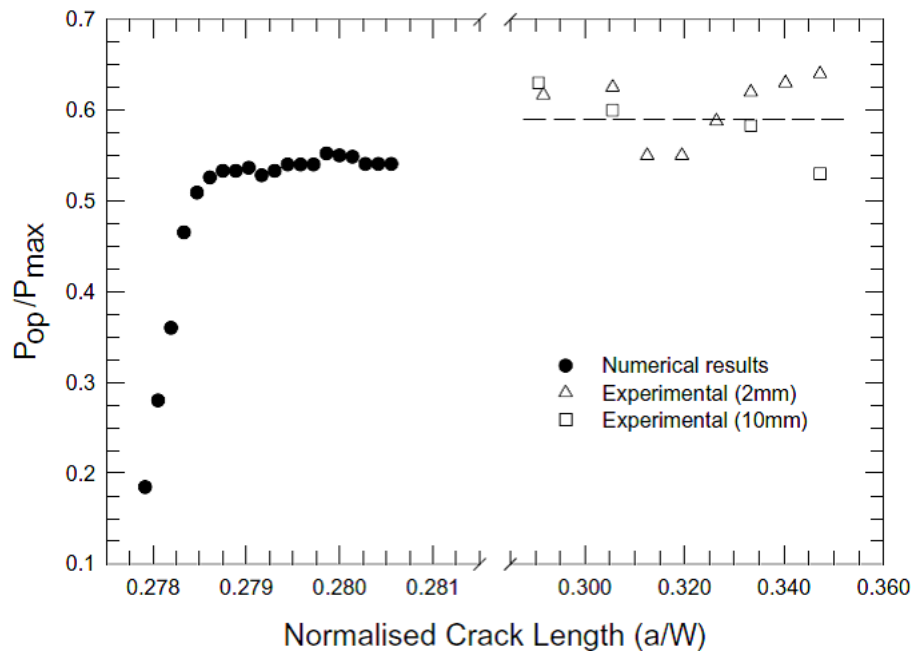


Figure 3.12. Comparison between results for the crack opening load obtained numerically and experimentally from the compliance traces [2]

Further work was conducted by Pacey et al. [61], who developed a mathematical model based on Muskhelishvili's complex potentials [10] to describe the stresses near the crack tip experiencing fracture surface contact. The model was fitted to full-field experimental stress data obtained using transmission photoelasticity for a fatigue crack that was grown in a compact tension specimen made of polycarbonate. For the mathematical fitting, they employed a combination of a simple genetic algorithm and the downhill simplex method [139]. The stress intensity factors during two load cycles were calculated and they clearly displayed evidences of crack closure. It was possible to measure the crack opening and closing loads and stress intensity factors and these results were compared with those results obtained from using compliance methods.

A major advance on previous work reported by Pacey et al. [61] was made by Christopher et al [21]. In this first work they introduced a novel mathematical model describing the stresses around the tip of a fatigue crack. The model accounted the effect of plasticity considering an analysis of the shielding effects over the applied elastic field. This model was called CJP (Christopher, James and Patterson) and was previously described in section 2.3.5 of the current thesis. They focused this first study on determining the shielding stress components (induced by compatibility requirements at the elastic-plastic interface along the crack flank and via the crack tip plastic zone) and how they influenced the crack tip elastic stress fields during a load cycle. Authors validated their model evaluating different stress cases by comparing experimental fringe patterns and those fringe patterns obtained from the application of their model. Thus, they compared a pure elastic case without T-stress (figure 3.13), a pure elastic case with T-stress (figure 3.14) and a stress case with shielding and interfacial shear stress (figure 3.15). From these observations, authors concluded that the model could be used to evaluate the effective stress intensity factor under pure mode I loading conditions and the new intensity factors K_S and K_R to characterise the interfacial shear and retarding stresses, by fitting the model to the observed photoelastic fringe patterns.

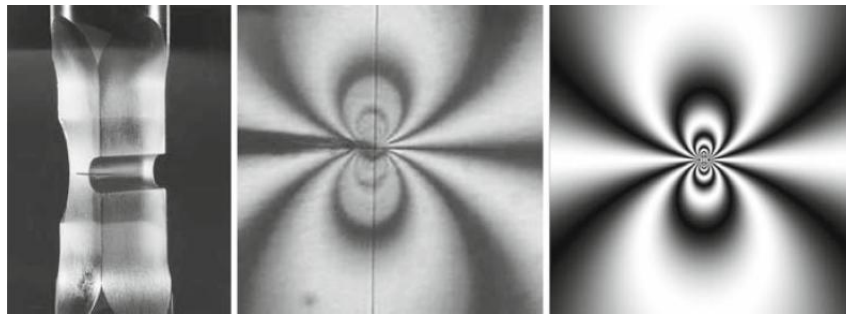


Figure 3.13. Experimental validation for a purely elastic field in the absence of T-stress using a grooved tensile specimen with a semi-elliptical corner crack (left) from which slices were cut following stress freezing (middle) and the corresponding results using CJP model (right) [21]

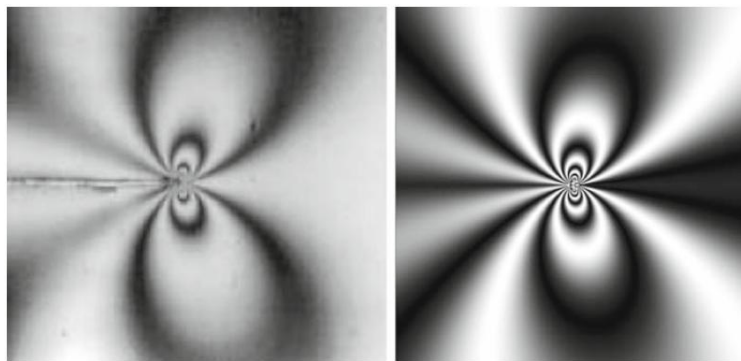


Figure 3.14. Photoelastic fringe patterns from a machined, crack-like notch exhibiting the effects of negative T-stress (left) and the corresponding result using CJP model [21]

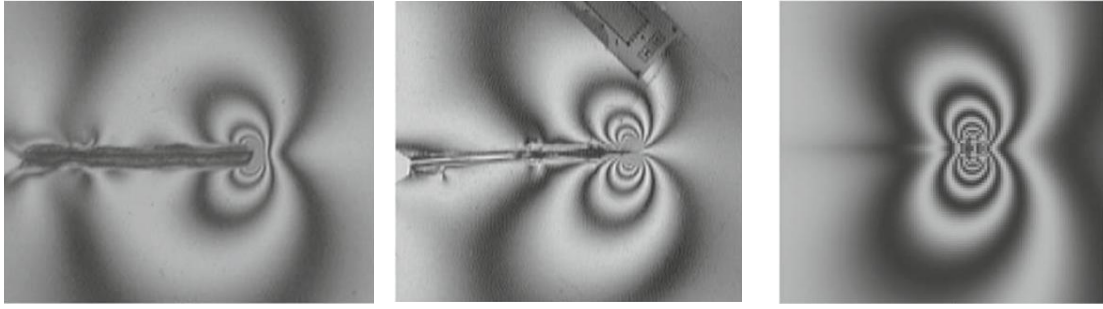


Figure 3.15. Fringe patterns in CT specimens generated by cutting a notch in a polycarbonate specimen (left); by applying the maximum load in a fatigue cycle to a propagating crack (middle); and by modeling with CJP model (right) [21]

Further work was conducted by Christopher et al. [22]. In this additional work, authors made a quantitative evaluation of plasticity-induced shielding CJP model from real cracks isochromatic data. They employed polycarbonate CT specimens containing a real propagating crack from which full-field data was obtained using the phase-stepping method developed by Patterson and Wang [94]. Thus, values for the opening stress intensity factor and T-stress were calculated for three crack lengths (figure 3.16). In addition, the two new stress intensity factors introduced by CJP model were calculated (figure 3.17), namely an interfacial shear stress intensity factor and a retardation stress intensity factor, from the same data. The fundamental purpose of this work was to identify and quantify the real influence or effect on the applied elastic stresses arising from the plastic deformation associated with crack growth. Results showed that an interfacial shear existed at the elastic-plastic boundary along the crack faces which reversed its direction during opening and closing of the crack. Moreover, it was observed that this effect was much stronger when the crack was open, which implied that retarding forces in the direction parallel to the crack resisted the propagation of the crack. Finally, authors concluded that these insights into the origins of plasticity-induced crack tip shielding appeared to assist in reconciling conflicting observations of the classic plasticity-induced crack closure obtained over the last 30 years.

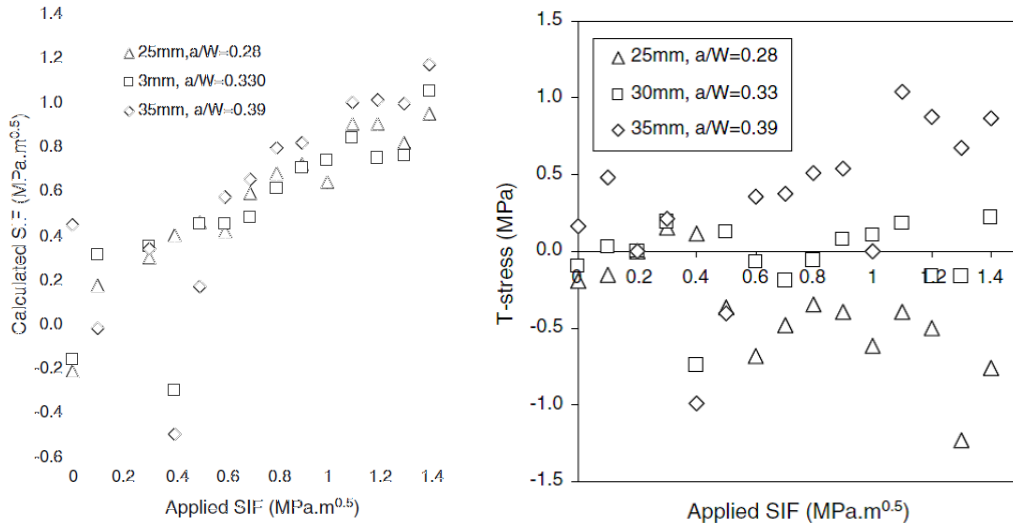


Figure 3.16. K_I and T-stress values calculated on a polycarbonate CT specimen as a function of the nominal stress intensity factor for three different crack lengths [22]

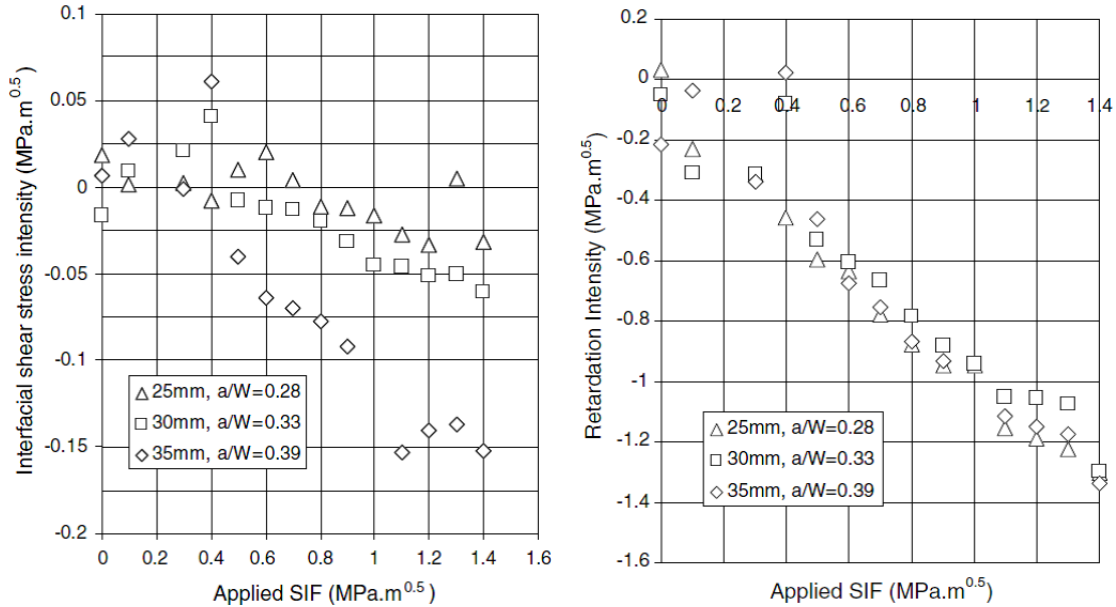


Figure 3.17. K_S (left) and K_R (right) values calculated on a polycarbonate CT specimen as a function of the nominal stress intensity factor for three different crack lengths [22]

More recently, James et al. [23] have extended the use of CJP model for the evaluation of plasticity-induced crack shielding in growing fatigue cracks. They explored issues such as the repeatability of data between duplicate tests or determine whether the observed trends were sensitive to the crack length and the stress ratio. In addition, in this work it was also evaluated differences in the quality of the mathematical fitting between the experimental and theoretical data. Thus, they made an exploration of the influence of several aspects in the fringe patterns over the data fit. Figure 3.18 shows the complete rectangle of data which could be acquired from a specimen, and gives the results of the fitting process in different regions in the

unwrapped isochromatic data inside the rectangle. It provides values of the normalised residual, the normalised mean error and the standard deviation. Results demonstrated that the quality of the fit for region *I* with fringe order $N \geq 2.5$ is the best, and the corresponding standard deviation is 0.0413; the fitting quality for the regions *II*, *III* and *IV* (outside region *I*) is poor, with standard deviations larger than 0.2; and a poor fit was mainly caused by collecting data points from region *III* in front of the crack tip. They also defined the inner limit, adopting a rectangle with the width and the distance from the short edge to the crack tip twice the Dugdale plastic zone size to remove the zone of plastic deformation around the crack. Moreover, values for K_F , K_R and K_S as a function of the crack length (figure 3.19) and as a function of stress ratio (figure 3.20) were calculated for a half loading cycle. They observed that K_F showed an increase but with very stable values at low K values compared with standard value K_I . There was also an evident trend for K_F to become steadily lower than K_I as the crack length increased. These results were interpreted as an indication that crack wake contact was causing shielding at the crack tip at K values smaller than $0.4\text{--}0.5 \text{ MPa}\cdot\text{m}^{1/2}$. About K_R , they observed an increase with the crack length. This demonstrated that the plastic inclusion effects increased with the crack length at a constant applied peak load which decreased the forward driving force on the crack and increased the crack retardation force. Moreover, K_S values appeared to remain constant over this range of crack sizes. It appeared that the CJP model could provide a clear demonstration of the plastic zone effects as the crack length and hence the plastic zone size got bigger. According to these results, authors concluded that the insight view that the model offered into plasticity-induced shielding and its potential to explicitly include shielding influences in its output parameters of K_F , K_R and K_S made it a very powerful tool for fatigue life prediction.

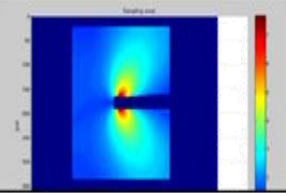
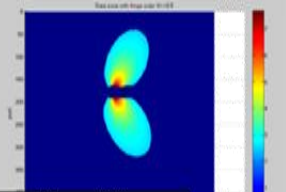
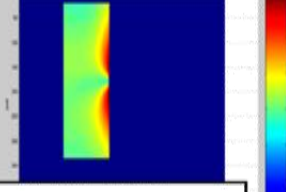
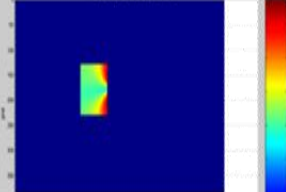
Region	Number of data points	Q ,	μ ,	S
 Data zone: $R_{outer} = 0.6a$	94198	0.0019,	0.0445,	0.1885
 I: $N \geq 2.5$	28573	0.0007,	-0.0024,	0.0413
 II: $N < 2.5$	65625	0.0048,	0.0648,	0.2211
 III: $0.5a \times 1.2a$	42500	0.0385,	0.1363,	0.2406
 IV: $0.3a \times 0.4a$	7853	0.0023,	0.0588,	0.2078

Figure 3.18. Results of the fitting process in different regions in the unwrapped isochromatic data. Values for the normalised residual, normalised mean error and standard deviation are shown [23]

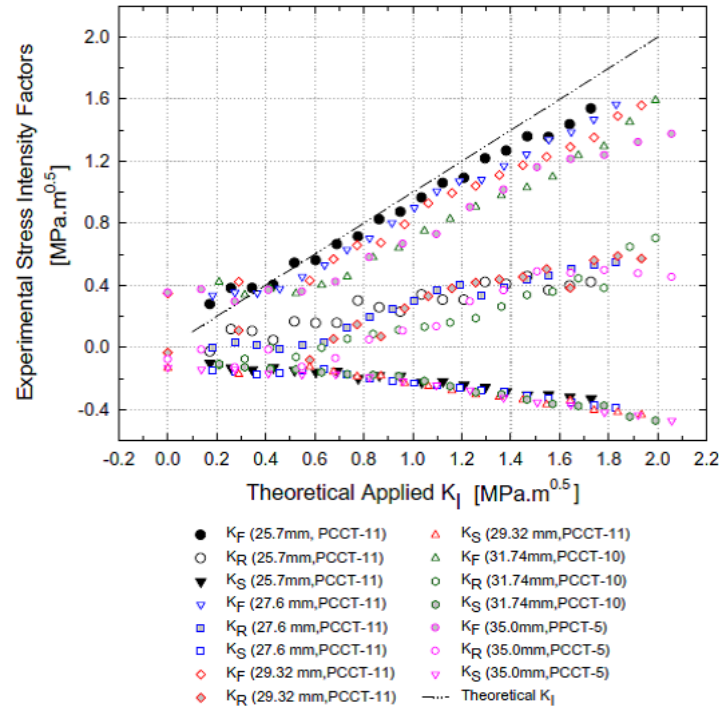


Figure 3.19. Results for K_F , K_R and K_S for a half loading cycle at different crack lengths ($P_{max} = 120 \text{ N}$ and $R = 0.1$) [23]

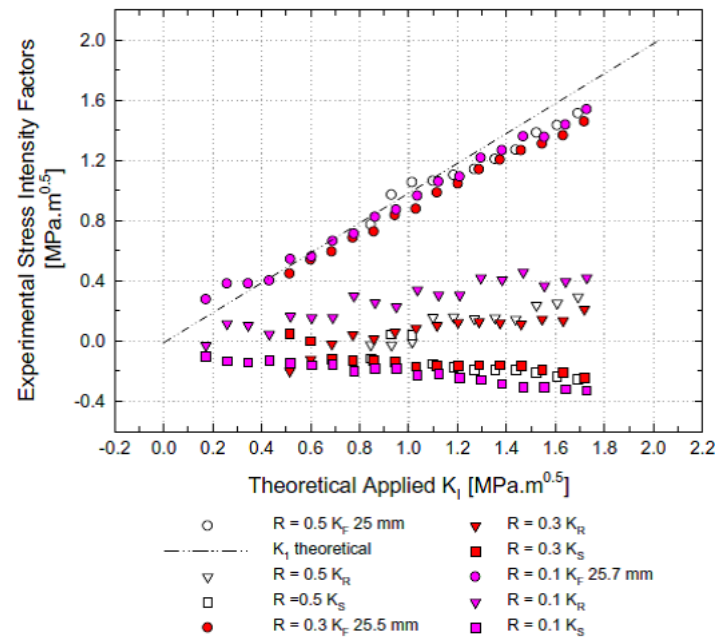


Figure 3.20. Results for K_F , K_R and K_S at different crack lengths and different R ratios [23]

3.3.5. Overload effect investigation using transmission photoelasticity

Besides the investigation of plasticity-induced shielding in growing fatigue cracks, another interesting research issue is the study of the effect of the application of overloads in fatigue life.

Little research work has been made about the evaluation of the effect of overloads in fatigue crack growth using transmission photoelasticity. Colombo et al. [11] did an extension of the research conducted by Pacey et al. [61] and Christopher et al. [22]. Colombo considered variable amplitude loading and evaluated the impact of an overload on the extent of the plastic zone around the crack tip and its effect on the crack propagation rate followed the overload. The aim of their research was to quantify the effect of crack shielding and the change that occurred during and immediately after the overload. They intended to gain a deeper understanding of the mechanisms controlling fatigue crack growth. Authors employed CJP model with phase-stepped photoelastic images of a polycarbonate compact tension specimen. In this study, photoelastic images at zero load illustrated the extent of the plastic zone around the crack tip and along its faces and showed a substantial increase in the crack tip plastic zone after the overload. Results for K_F , K_R and K_S supported this mechanism with an increase in the interfacial shear stress occurring during the overload (130% increase in the retardation intensity K_R), but with a very low increase (only 1/3) in K_F , which implied a net decrease in the crack growth driving force (figure 3.21). Finally, this study demonstrated that plasticity-induced shielding, sometimes referred to as plasticity-induced closure, had a substantial effect on fatigue crack growth rates as a consequence of (a) the stress field ahead of the crack generated by crack tip plastic zone and acting to opposite to crack extension; and (b) an interfacial shear stress at the elastic-plastic boundary between the plastic zone in the crack wake and the surrounding elastic material.

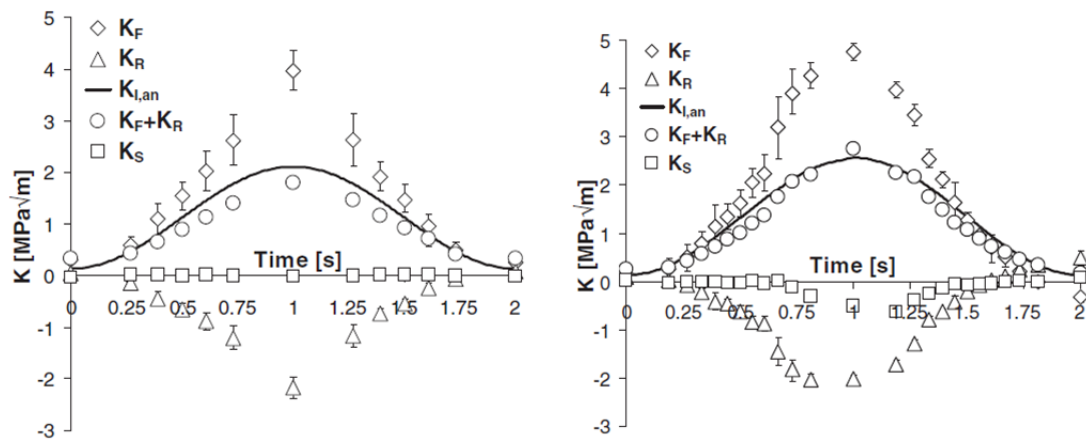


Figure 3.21. Stress intensity factors calculated as a function of time during a loading cycle for a crack under constant amplitude loading at $a = 28.1$ mm (left) and after a 118% overload at $a = 27.9$ mm (right) [11]

Further work [141] was developed by Colombo and Vergani from the experimental results obtained previously [11] to compare them with those obtained by a numerical simulation. A good correspondence was found and the authors concluded that the CJP model could be

satisfactory applied not only to experimental photoelastic data, but also to numerical simulations.

Recently, James et al. [142] presented a revised characterisation of the elastic stresses ahead of a crack tip in polycarbonate which takes into account the elastic-plastic boundary stresses induced by the presence of the crazed region that surrounding a crack. Confocal laser scanning microscopy and scanning electron microscopy were employed to identify the crazed region and the location of the crack tip position. This work presented crack growth rate data obtained at several stress ratio values, as a function of the modified stress intensity factors obtained from the CJP model. In addition, some information about the influence of a 15% overload on crack growth and on the value of stress intensity factor was also provided. The crack increment in the overload cycle was approximately 0.7 mm. Thus, the application of this overload had a significant effect on K_F and K_R and very small effect on K_S (figure 3.22).

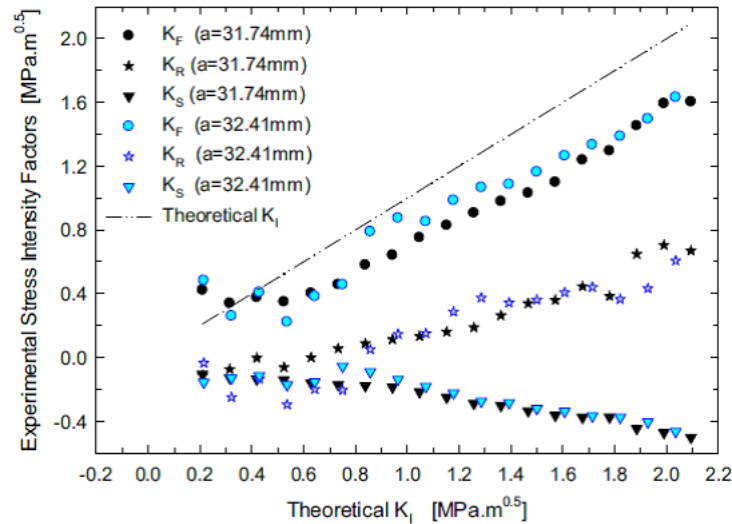


Figure 3.22. Stress intensity factors calculated through a loading half-cycle immediately before and immediately after the application of a single 15% overload (from 120 N peak load to 140 N peak overload) [142]

3.3.6. Conclusions

Since Maxwell established the photoelastic laws in 1852, many researchers have demonstrated that transmission photoelasticity is a powerful technique for the structural integrity analysis of mechanical elements. However, during this time long periods of relative inactivity occurred, the first following its initial discovery. However, there are two main issues that have contributed to the growth of this technique: the development of stereolithography and fringe automation analysis.

Different methodologies have been developed for the experimental determination of stress intensity factors from the analysis of isochromatic data. These methods are based on a combination of isochromatic data with mathematical models describing the stress fields at the vicinity of the crack tip. The most widely reported mathematical models employed in the literature are those based on Westergaard's classic equations, Williams's expansion series, Muskhelishvili's complex potentials, and recently the mathematical model called CJP. Results obtained from these methods describe quite well the theoretical predictions for simple loading cases and geometries such as, pure mode I loading, notches or artificially generated data. However, for more complicated cases like mixed-mode or predominantly mode II cracks, results exhibit some errors, more or less significant depending on the analysed problem. Moreover, all the reported methods require knowledge of the location of the crack tip. However, it cannot be found in the literature any rational criterion that could be followed for determining the crack tip location from isochromatic fringe patterns. This fact could have a major influence in the accuracy of the calculated parameters.

Moreover, in most of the techniques for the calculation of the stress intensity factors, isochromatic data must be collected from a region surrounding the crack tip. It has been recognised by several authors that data must be selected close to the crack tip but not extremely close in order to avoid the influence of plasticity since the adopted mathematical models are based on linear elastic fracture mechanics. For this reason, there are still some controversies about what is the most effective region, both in dimensions and shape of the data points collection.

Although the great potential of transmission photoelasticity for the analysis of fatigue and fracture problems is globally accepted, relatively little work has been done in the study of parameters affecting the fatigue and fracture behaviour of different materials and, in particular, crack closure or crack shielding and effect due to overloads. Several researchers have reported some indications of crack shielding from the evaluation of stress intensity factors obtained from isochromatic data, but in none of them there was a comparison between the most important methods to determine SIFs in order to establish what is the most efficient to evaluate crack shielding and at the same time can assist in reconciling conflicting observations about the classical fatigue crack closure. Special interest is found about the use of CJP model for evaluating fatigue crack shielding since it seems to show great potential to evaluate crack shielding in growing fatigue cracks, however this potential remains to be explored.

Finally, another issue related to the evaluation of fatigue crack shielding is the study of the effect of overloads in fatigue life of mechanical elements. Little work has been done in the study of overload effects and their possible influences in fatigue crack growth rates, and therefore it is a field to be explored.

3.4. Digital image correlation

3.4.1. Introduction

The term digital image correlation (DIC) refers to the class non-contacting methods that acquire images of an object, store images in digital form and perform image analysis to extract full-field shape, deformation and/or motion measurement. Therefore, DIC has been developed as an experimental technique that is employed for the measurement of displacements and strains in mechanical components. This technique can be implemented for both in-plane (2D-DIC) and out-of-plane (3D-DIC) measurement. Thus, in relation to the current thesis, where the different studies were performed in 2D, the literature review will be focused on 2D-DIC. In the following section, it is presented a review research work published on digital image correlation since its birth until today. Special attention has been paid on the application of this technique to fatigue and fracture mechanics problems. In particular, methodologies for the determination of stress intensity factors from crack tip displacement or strain fields obtained with DIC have been reviewed. Another reviewed issue has been the evaluation of crack shielding on growing fatigue cracks. In addition, the effect of overloads has been another phenomenon reviewed. Finally, this section closes with the main conclusions established from the different aspects reviewed above.

3.4.2. Historical review

Some of the first work about image correlation was performed by Hobrough [143] in the early 1950s, who compared analog representations of photographs to register features from various views. In 1961, Hobrough designed and built an instrument to “correlate high-resolution reconnaissance photography with high precision survey photography in order to enable more precise measurement of changeable ground conditions”. In this way, he was one of the first researchers to attempt a form of digital image correlation to extract positional information from the image correlation/matching process.

One of the earliest works to propose the use of computer-based image acquisition and deformation measurements in material systems was published by Peters and Ranson [144] in 1982. They performed the original application based on developing and digitally recording a full-field pattern by subjecting an object to ultrasonic waves before loading (the reference image) and during the loading process (the deformed image). The method suggested by the authors was based on a comparison of the digital images for various small regions (known as subsets) throughout the images before and after deformation, locating the positions of each of these subsets after deformation through digital image analysis.

Using this method, in 1983 Sutton et al. [145] developed numerical algorithms and performed preliminary experiments using optically recorded images to show that the approach, known today as 2D Digital Image Correlation (2D-DIC), was feasible when using optically recorded images. Anderson et al. [146] performed rigid body motion measurements using the previous algorithms, demonstrating that both planar translations and rotations could be reliably estimated through 2D-DIC. In 1985, Chu et al. [147] performed a set of experiments to demonstrate that the method could be applied to measure rotations and deformations in solids. To improve the speed of the analysis process, in 1986 Sutton et al. [148] demonstrated that the use of gradient search methods (subset-matching) could be performed with sub-pixel accuracy throughout the image to obtain a dense set of full-field two-dimensional displacement measurements. Over 1990s these procedures were validated, modified and refined [149, 150]. In 1988, Sutton et al. [151] performed one-dimensional numerical simulations to provide initial estimates for the accuracy of deformation measurements in image correlation. In an effort to quantify internal deformations in a composite sheet, in 1989 Russell et al. [152] performed X-ray radiography before and after deformation.

The application of 2D-DIC to fracture mechanics began in the early 1980s and continues until today. Early work by McNeill et al. [153] demonstrated that stress intensity factor could be determined by 2D-DIC measurements. Sutton et al. [154] employed measurements of the plastic zone around the crack tip to estimate the area affected by three-dimensional effects. Another work related to the use of 2D-DIC on applications of fracture mechanics was developed by Dawicke and Sutton [155], who measured crack opening displacement. Amstutz et al. [156], [157] measured tensile and shear deformations in Arcan specimens undergoing mixed mode I/II loading. Han et al. developed a high magnification optical system to measure deformations around stationary [158] and growing [159] crack tips under nominally Mode I loading.

In addition to the work in fracture mechanics, researchers used 2D-DIC to understand deformation behaviour on different materials, including metals [160 - 162] and plastics [163], [164]. On the other hand, damage in composite materials applying 2D-DIC has been another topic studied by researchers in the late 1990s and 2000 [165, 167].

Prior to recent emphasis on nano-science and nanotechnology, efforts of researchers such as Davidson and Lankford [168, 169] in the 1980s extended 2D-DIC concepts to the microscale for large deformation measurements near fatigue flaws. Additional high magnification studies [170, 171] were performed using 2D-DIC. Of particular note is the effort to extend the work of Davidson and Lankford, as described in the work of Sutton et al. [171]. The authors developed a fully automated image acquisition and analysis system using a Questar far-field microscope to image a 700 x 700 μm crack tip region. Ridell et al. [170] employed the system to measure crack tip deformations as part of a study focused on crack closure assessment.

Fracture studies in recent years have included measurements in composites [172, 173], metals [174] and polymers [175] among others.

3.4.3. Calculation methods for the evaluation of SIFs from displacement fields obtained using DIC

Since 1980s, the use of digital image correlation (DIC) has become very popular for the analysis of structural integrity problems [147, 176]. Traditionally, in linear elastic fracture mechanics (LEFM) [18] it has been known that displacement fields at the vicinity of the crack tip can be described by stress intensity factors (SIFs). The first authors that used 2D-DIC for estimating stress intensity factor were McNeill et al. [153]. They determined K_I from the analysis of the displacement data obtained by digital image correlation. Experimental results for a C-specimen and a 3-point bending specimen were presented and compared with accepted analytical results. Thus, the authors employed a least-square method to combine Westergaard solution [18] with experimental displacements to estimate the stress intensity factor. The comparison between the ASTM K and the fitted values for the C-specimen was consistently in range of 10 to 20% for most the cases. However, for the 3-point bending specimen there was better agreement between the ASTM standard and the fitted K_I with differences from 0 to 10%.

The results obtained by McNeill et al. [153] were usually scattered because of the inaccuracy in the location of the crack tip in the data. Yoneyama et al. [4] developed a method for determining mixed-mode intensity factors from displacement fields obtained by DIC. In their study, they used the Williams's expansion series to describe crack tip displacement fields. In addition to SIFs, the location of the crack tip, the higher-order terms in the expansion series and the rigid-body motion (horizontal and vertical translations and rotation) were also determined simultaneously using nonlinear least squares fitting based on the Newton-Raphson method. An specimen manufactured on PMMA (figure 3.23) was employed for experiments. Moreover, the effect of the higher-order terms is shown in figure 3.24. The authors concluded that as mixed-mode stress intensity factors can be evaluated easily, simply and automatically by this methodology, it was expected that the proposed method could be applied to solve multiple fracture problems.

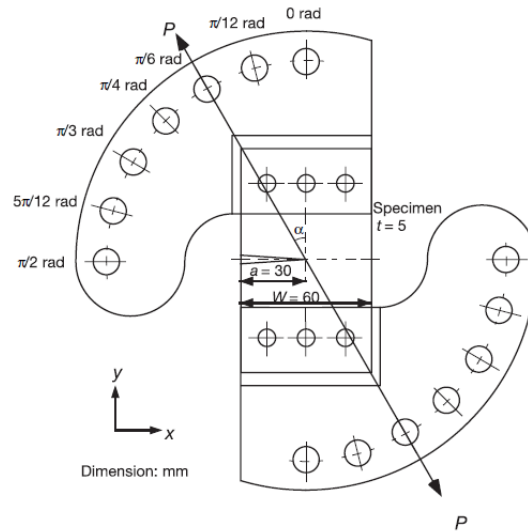


Figure 3.23. PMMA specimen and grips used to conduct different mixed-mode loading [4]

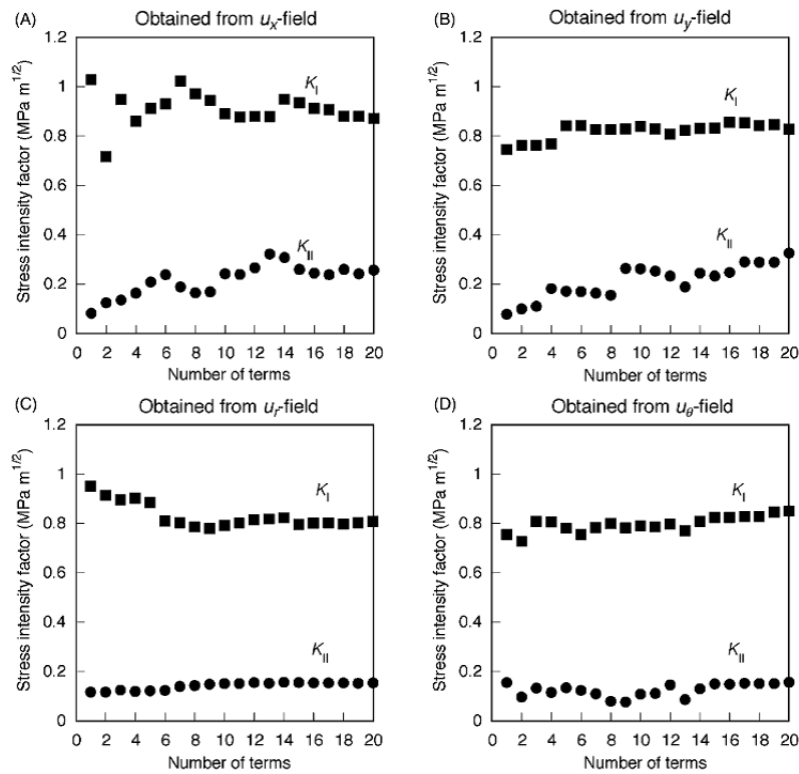


Figure 3.24. Effect of higher-order terms on the determination of the stress intensity factors ($P = 294 \text{ N}$, $\alpha = \pi/12 \text{ rad}$) [4]

López-Crespo et al. [177] determined the mixed-mode stress intensity factors for a crack emanating from a fastener hole. For this purpose, a fatigue crack was grown in pure mode I from a 50 mm diameter hole in a Al 7010-T7651 alloy plate test-piece (figure 3.25). The crack was then loaded elastically under several combinations of mixed-mode (I+II) displacements. The authors employed the Muskhelishvili's complex potentials [10] to describe the

displacement fields (figure 3.26) around the crack tip and to calculate the mixed mode stress intensity factors. The authors used a Sobel edge-finding algorithm implemented in Matlab[®] to locate the crack tip. The Multi-Point Over-Deterministic Method (MPODM) developed by Sanford and Dally [7] was employed to determine the SIFs, using a rectangular array approximately 1100 data-points (figure 3.26) in the immediate vicinity of the crack. In figure 3.27 it is shown the experimental results together with the nominal applied SIFs calculated from the solution for an inclined crack with a length of 5.25 mm emanating from an elliptical hole under tension. According to these results, the authors concluded that the approach showed a great potential for in-service monitoring of cracks in structures.

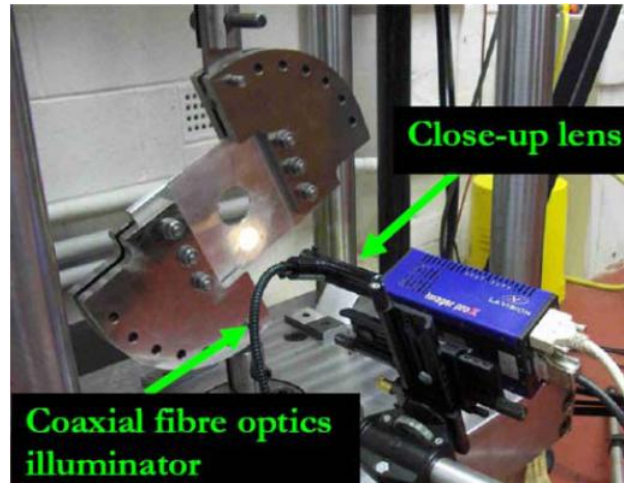


Figure 3.25. Specimen and experimental setup showing the loading adopted for experiments [177]

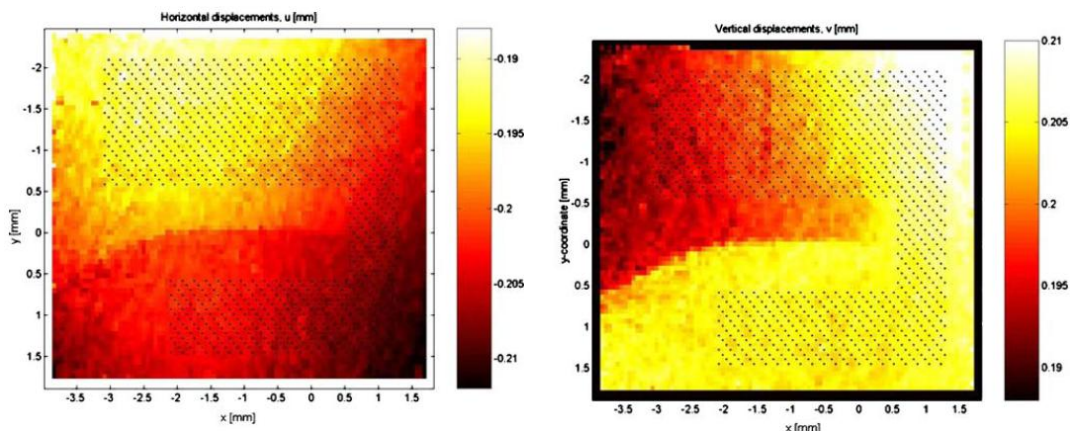


Figure 3.26. Horizontal (left) and vertical (right) displacement fields for a crack loaded at $\theta = 34.5^\circ$. Illustration showing the collected data points used to calculate the SIFs using the MPODM [177]

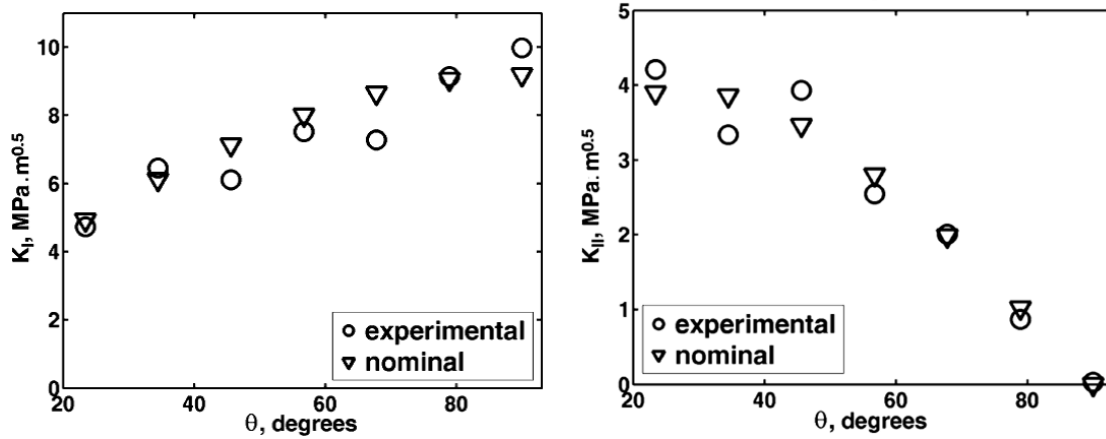


Figure 3.27. Experimental and SIFs results for a 5.25 mm crack emanating from a hole in a plate loaded over a range of mode mixities using the apparatus shown in figure 3.25, where $\theta = 90^\circ$ represents pure mode I [177]

In addition to the previous work, López-Crespo et al. [5] published similar additional work. The authors employed the methodology developed in the previous work for the determination of the stress intensity factors K_I and K_{II} for different modes of mixity directly from displacement fields obtained by digital image correlation. They employed a cracked aluminium plate (figure 3.28) as an example problem. No speckle pattern was generated on to the metal surface and instead a fine network of random scratches produced by polishing was used for correlation. The authors believed to be the first successful determination of SIFs from image correlation using the bare metal surface around a fatigue crack. Discrepancies of around 1 MPa.m^{1/2} were typically observed between the nominally applied SIFs and those determined on the basis on the crack tip displacements over the complete range of mixed mode loading from pure mode I to pure mode II.

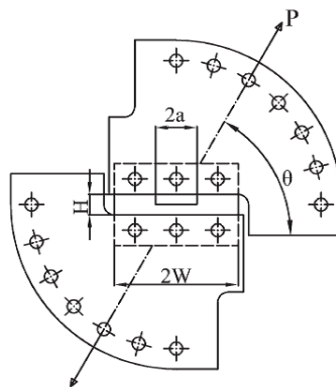


Figure 3.28. Schematic illustration of a centre cracked plate, showing the direction (θ) of the applied load (P), relative to the crack. The seven holes enabled seven loading cases ranging from pure mode I ($\theta = 90^\circ$) to pure mode II ($\theta = 0^\circ$). Geometrical details are $2a = 40$ mm, $H = 20$ mm and $2W = 120$ mm [5]

Du et al. [178] performed the characterisation of the stress field around a crack propagating in a large (4.8 m x 1.4 m) commercial aircraft wing-skin test panel (figure 3.29) using digital image correlation combined with the multi-point over-deterministic method [7] to obtain the mixed mode stress intensity factors. In their study, the MPODM was combined with the methodology developed by López-Crespo et al. [5] based on the Muskhelishvili's complex potentials [10] to evaluate SIFs during the propagation of the crack along the panel. More than 800 images were taken during 10 minutes as the fracture of the panel occurred under monotonic loading. In figure 3.30 the vertical displacement fields at different time periods are shown, with the crack propagation from left to right. Among their results, they obtained a value of the mode I stress intensity factor that initially increased linearly to around $50 \text{ MPa}\cdot\text{m}^{1/2}$ ($K_{IC} = 37 \text{ MPa}\cdot\text{m}^{1/2}$) and afterwards non-linearly reaching 300 to $400 \text{ MPa}\cdot\text{m}^{1/2}$ for crack extensions of the order of 100 mm (figure 3.31). Authors proposed that these high values of stress intensity factor did not represent an unrealistically high material fracture toughness but rather were indicative of the high resistance to crack growth of the structural assemblage of ribs, stringers and hole reinforcements in the panel which allowed the skin to sustain a strain level that would otherwise cause unstable crack growth. Finally, the results demonstrated that DIC was particularly powerful in evaluating this structural behaviour.

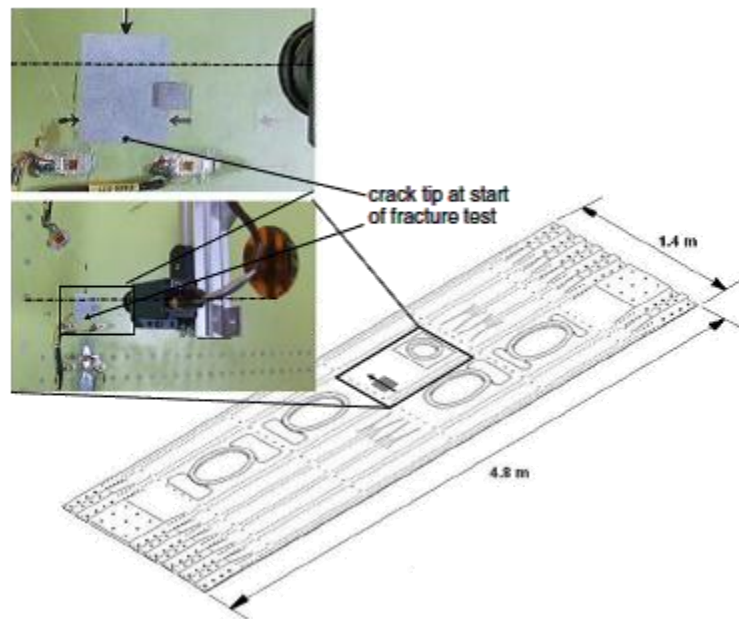


Figure 3.29. Schematic diagram showing the specimen area painted with speckled [178]

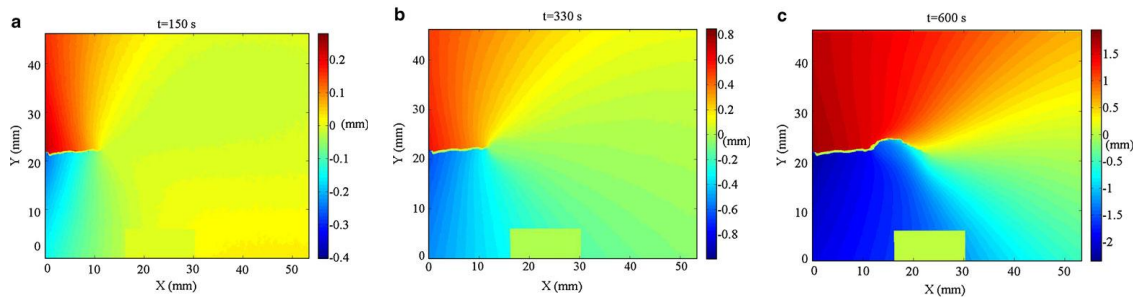


Figure 3.30. Displacement fields in y-direction at $t = 150$ s (a), $t = 330$ s (b), and $t = 600$ s (c) with crack propagation from left to right, i.e. images were rotated 90° clockwise relative to figure 3.29 [178]

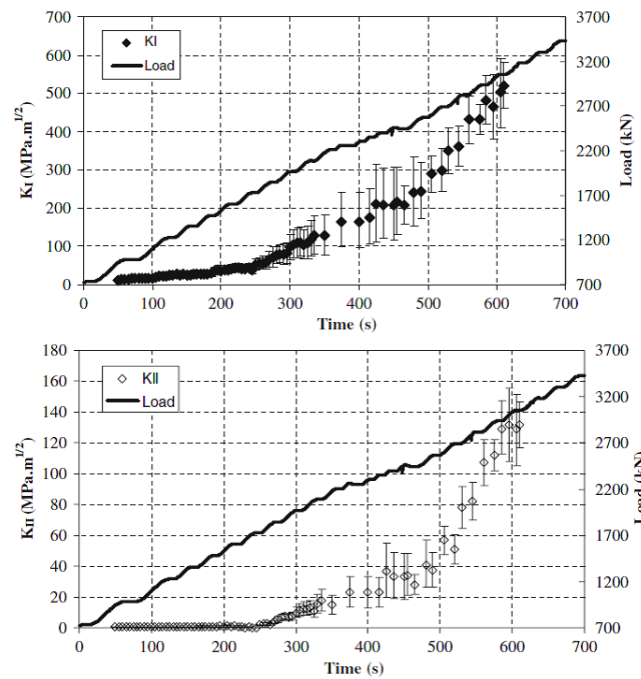


Figure 3.31. Values of stress intensity factors, K_I (top) and K_{II} (bottom) as function of time from the start of monotonic loading with error bars showing the 95% confidence limits, together with the applied load [178]

Yates et al. [6] presented an overview of some possible applications of DIC for crack tip characterisation. This included the evaluation of SIFs and T-stress for fatigue cracks in a double cantilever beam (DCB) specimens, crack closure effects on measured K_I using CT specimens, CTOA characterisation from displacement field data as well as 3D full field displacement data for tearing cracks in an anisotropic material. Thus, for the evaluation of stress intensity factor and T-stress, authors employed Williams' approach [138] to describe the displacement fields around the crack tip. During fatigue tests, pure mode I loading conditions were created ahead of 4 mm notch in a 5 mm thick DCB specimen (figure 3.32) manufactured on 7010-T7651 aluminium alloy. In figure 3.36 a comparison of stress intensity factors and T-stress determined

by ABAQUS, 3 terms Williams and 15 terms Williams for 0.5-1.5 kN load range is shown. According to these results, authors concluded that the proposed methodology provided a reliable and robust technique for the determination of the elastic constraint in fatigue and fracture testing.

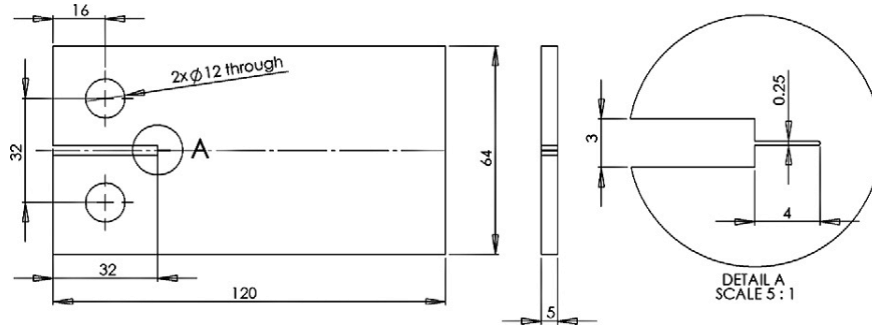


Figure 3.32. Dimensions (mm) of 7010-T751 aluminium alloy DCB specimen tested to evaluate SIFs and T-stress for fatigue cracks [6]

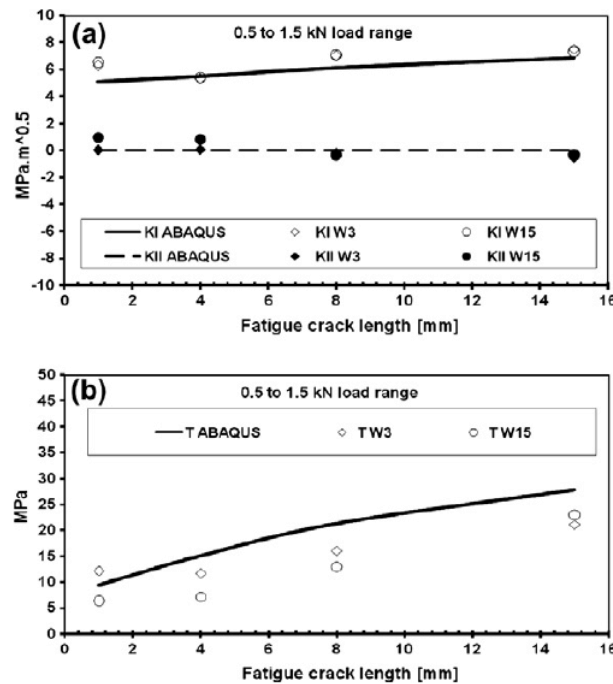


Figure 3.33. Comparison of stress intensity factors (a) and T-stress (b) obtained on DCB specimen, results were determined using ABAQUS, 3 terms Williams (3W) and 15 terms Williams (15W) for 0.5-1.5 kN load range [6]

Recently, James et al. [23] developed their CJP model to evaluate stress intensity factors from displacement fields measured at the vicinity of the crack tip. However, little work has been done by authors about using the CJP to infer SIFs from the analysis of the displacements by DIC. Thus, in figure 3.34 the values of stress intensity factors (K_F , K_R and K_S) for a 2024-T3 aluminium specimen containing a 25.6 mm crack with a maximum applied load of 1.2 kN are

shown. K_F was consistently about 14% lower than the nominal calculated value, K_R had a value > 0 at K_{min} in the cycle and began to progressively increase above an applied stress intensity factor value of $0.4 K_{max}$, while K_S was initially slightly greater than zero and decreased to values < 0 at applied stress intensity values above about $0.4 K_{max}$. Further work using DIC and CJP model to study fracture mechanics problems was developed by Vasco-Olmo et al. [179]. This work will be reviewed in the following section since it was focused on the evaluation of fatigue crack shielding from the analysis of the SIFs obtained from DIC measurements.

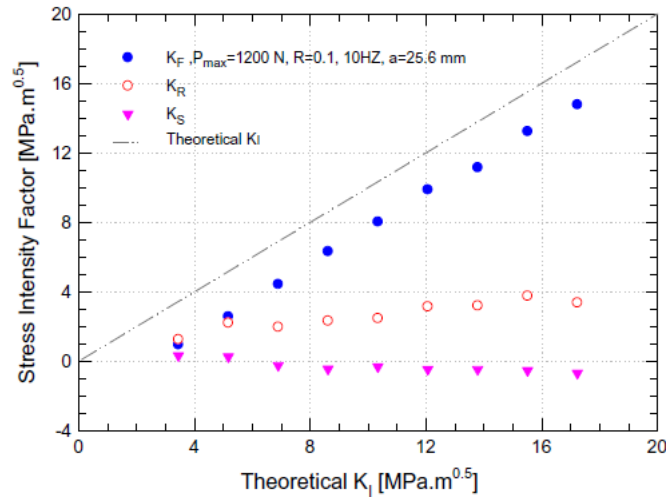


Figure 3.34. K_F , K_R and K_S results for a tensile half cycle obtained using DIC on a 2024-T3 aluminium CT specimen with a 25.6 mm crack tested at $R = 0.1$ [23]

3.4.4. Investigation of fatigue crack shielding using DIC

The use of digital image correlation for studying problems related to fracture mechanics started in 1980s, therefore most of the research work developed on the evaluation of fatigue crack shielding is quite recent. Thus, the first application of DIC to the measurement of fatigue crack closure was published by Sutton et al. [62] in 1999. They developed a methodology for the estimation of crack closing loads measuring the crack opening displacements behind the crack tip (figure 3.35) during the entire fatigue crack growth process. The regions were selected near the crack tip, and images were acquired automatically during a loading/unloading cycle. From the analysis of the images, authors obtained the crack opening displacement as a function of load. They employed this information to estimate the crack closing load (figure 3.3).

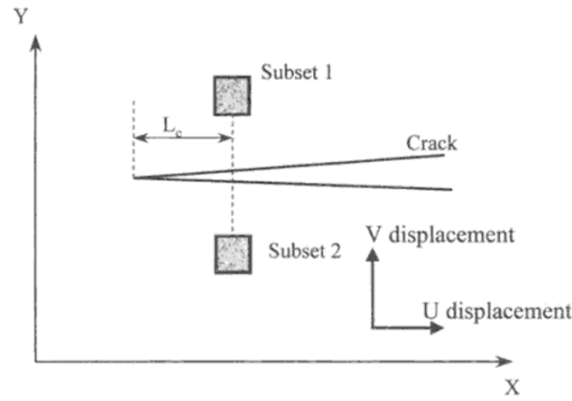


Figure 3.35. Illustration showing a pair of points behind crack tip employed for the measurement of crack closure [62]

More recently, de Matos and Nowell [8] evaluated the effect of the specimen thickness during closure using 6082-T6 aluminium alloy CT specimens. Crack closure was assessed using a back face strain gauge (BF), a crack mouth gauge (CMOD) and digital image correlation (figure 3.36). The procedure described to measure crack closure using DIC was efficient and seemed to be a good alternative to conventional surface gauges. The use of DIC allowed the selection of several points (figure 3.37) for the analysis of relative displacements between the pairs of points selected behind the crack tip after the experiments (figure 3.38). Their results reported that fatigue cracks propagated faster in thick specimens than in thinner specimens. Authors believed that this effect seemed to be related to the development of different level of crack closure. When the state of stress along the crack front was closer to plane stress, both measurements from BF gauge and DIC were in good agreement. As the thickness increased, the size of the plastically deformed region became small in comparison to the thickness of the specimen. Under these conditions a considerable difference was found between bulk measurement and surface measurements. When the closure measurements results were used to calculate effective stress intensity factors, it was shown that results from the BF gauge lead to better correlation of crack growth rate. Finally, authors concluded that the back face strain gauge was the most suitable technique for the measurement of effective crack closure when predicting the crack growth rate.

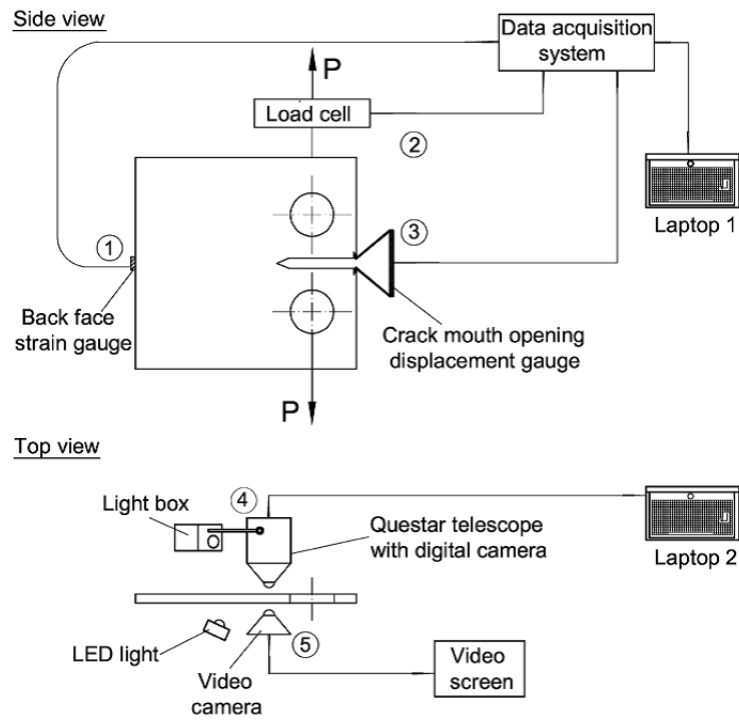


Figure 3.36. Schematic representation of the adopted experimental configuration to evaluate crack closure using a back face strain gauge, a crack mouth gauge and DIC [8]

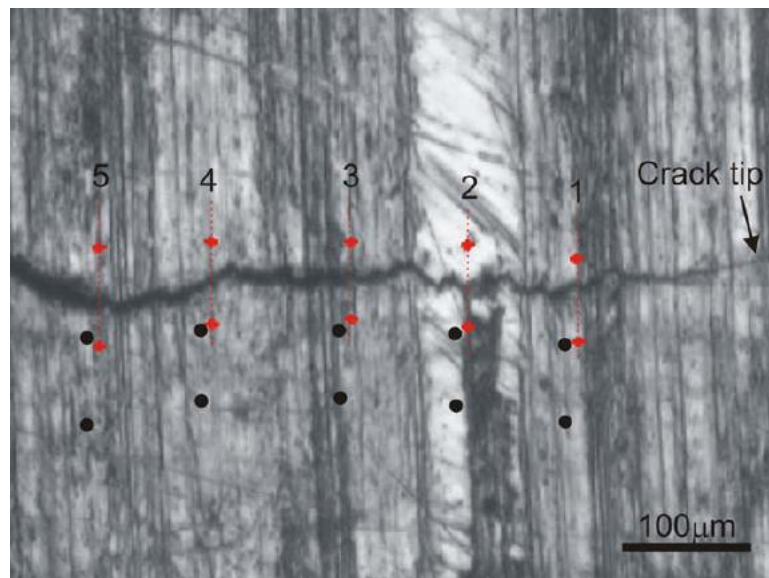


Figure 3.37. Typical image used in DIC, showing pairs of points in their original (black points) and deformed (red points) positions [8]

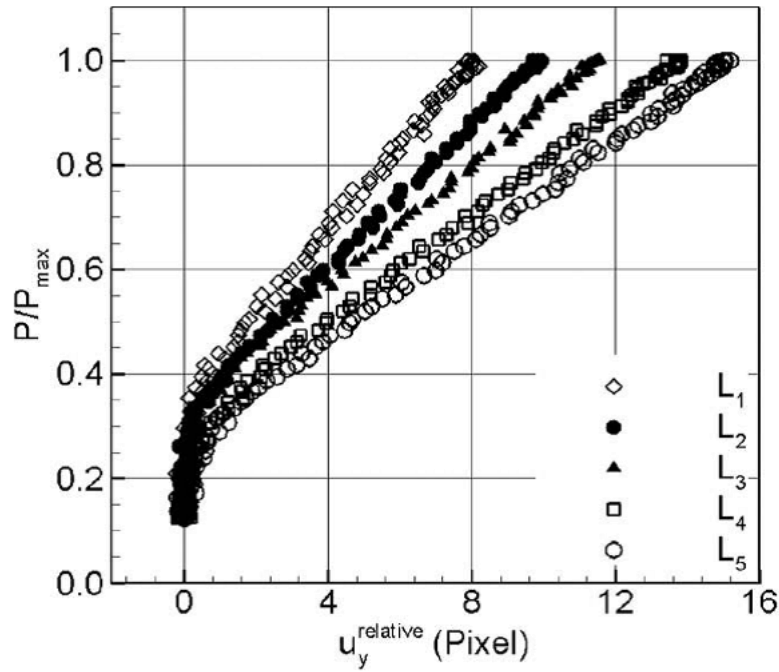


Figure 3.38. Variation of relative displacements with load in CTF6 specimen at 29500 cycles. L_1 to L_5 correspond to different locations along the crack according to the pairs of points shown in figure 3.37 [8]

López-Crespo et al. [9] developed an approach to evaluate fatigue crack closure and incorporate the effect of crack-tip plasticity on $K_{I,eff}$ and $K_{II,eff}$ from experimental observations using digital image correlation. Two types of geometries were employed to investigate closure and plasticity effects. Closure tests were conducted on centre-cracked plate (CCP) specimens manufactured in Al7010-T7651 subjected to different mixed-mode (I+II) loads. In addition, investigations on crack-tip plasticity were done on Al2024-T351 wedge-opening loaded (WOL) specimens. The geometry was similar to the common CT specimen employed in fracture toughness testing. For the determination of the stress intensity factors, authors employed a method based on the Muskhelishvili's complex potentials [10]. Thus, the evaluation of the effective mixed-mode stress intensity factor allowed them to quantify the contact effect as a consequence of the interlocking of fracture surface asperities and plastic deformation of the asperities. Therefore, when low load ranges were applied, that is under conditions where crack closure usually has an important effect (figure 3.39), the technique could be used to estimate the opening stress intensity factor. Furthermore, when the load was increased to values close to fracture toughness, the approach generated enhanced values $K_{I,eff}$, incorporating the effect of crack-tip plasticity.

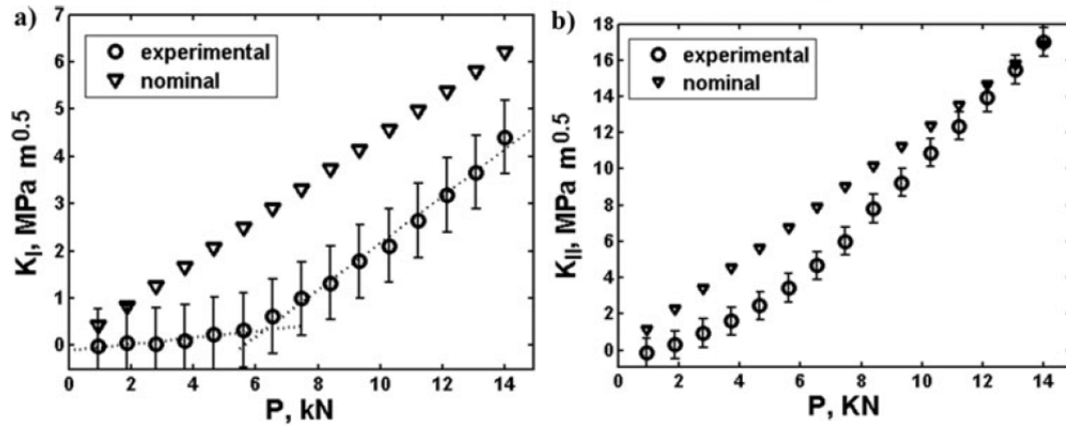


Figure 3.39. Opening (a) and shearing (b) mode stress intensity factors measured during the loading portion of a fatigue cycle ($R = 0$) with $\theta = 30^\circ$ on a 7010-T7651 aluminium alloy centre-cracked plate. The nominal values were calculated neglecting closure effects. The experimental values were determined relative to an image captured at zero load [9]

More recently, Vasco-Olmo et al. [179] proposed a methodology for the evaluation of fatigue crack shielding using 2D-DIC. This methodology was based on the analysis of the stress intensity factors calculated from the displacement fields measured around the crack tip. Thus, in their work, they performed a comparison between four different mathematical models describing crack tip displacement fields (namely Westergaard, Williams, Muskhelishvili and CJP models). For the purpose of the work, they conducted a set of fatigue tests on Al2024-T3 CT specimens at different R ratios. In addition, results obtained from DIC technique were compared with those obtained using compliance-based methods from the analysis of the data recorded with an extensometer. In their study, authors established that CJP model was the most suitable for evaluating fatigue crack shielding from the analysis of the opening mode stress intensity factor, K_F , and the retardation stress intensity factor, K_R (figure 3.40). Thus, from the change observed in the trend for the values of K_F , authors calculated the opening and closing stress intensity factors and, therefore from these the opening and closing crack loads were obtained (figure 3.41). These experimental results obtained by DIC in combination with CJP model showed a very good level of agreement with those obtained from the use of the compliance techniques. Finally, as main conclusion, authors established that opening and closing loads were in a load range between 75 and 125 N, but the determination of a single value for P_{op} and P_{cl} was difficult to perform since crack shielding phenomenon is a gradual process.

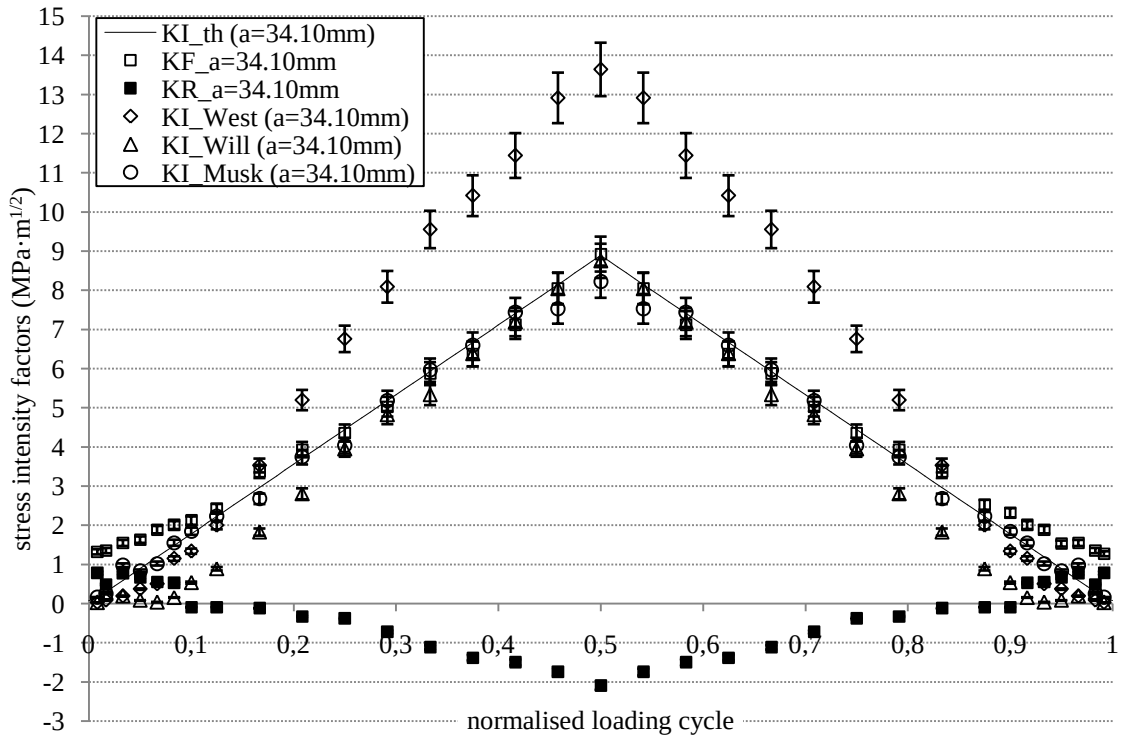


Figure 3.40. Experimental stress intensity factors obtained using four different models (Westergaard's, Williams's, Muskhelishvili's and CJP models) to describe crack tip displacement fields at a crack length of 34.10 mm [179]

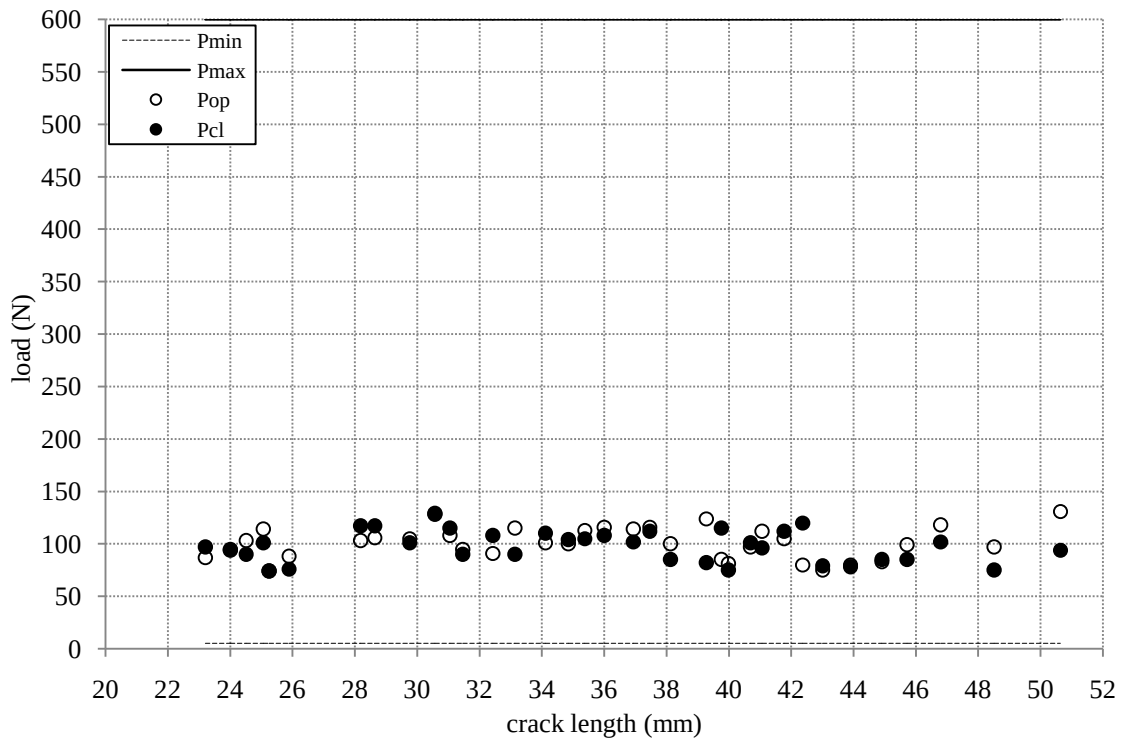


Figure 3.41. Crack opening and closure loads obtained at different crack lengths using CJP model [179]

3.4.5. Investigation of the effect of overloads using DIC

Another topic related to the evaluation of fatigue crack shielding that has focused the attention of many researchers has been the evaluation of the effects produced by the application of overloads during fatigue life. As in the case of transmission photoelasticity, little work has been conducted on this topic.

Nowell and de Matos [180] presented results of crack growth rate and crack opening loads before and after a single overload that was applied during constant amplitude fatigue experiments. Fatigue tests were performed on Al6082-T3 CT specimens with three different thicknesses. Authors employed digital image correlation together with conventional strain gauges (back face gauge and crack mouth gauge). Thin specimens (3 mm) showed high level of closure (figure 3.42), as measured by conventional strain gauge compliance methods. These were in good agreement with surface measurements obtained by digital image correlation. Crack opening loads increased rapidly following the overload, and they did not recover to pre-overload levels until the crack had grown to about 150% of its pre-overload length. Nevertheless, thick (25 mm) (figure 3.43), and medium thickness (10 mm) specimens showed reduced levels of closure, when assessed by strain gauge compliance. However, DIC measurements provided similar results to those obtained for thin specimen. This suggested that plasticity-induced crack closure is primarily a surface effect, as it was predicted by three-dimensional FE models.

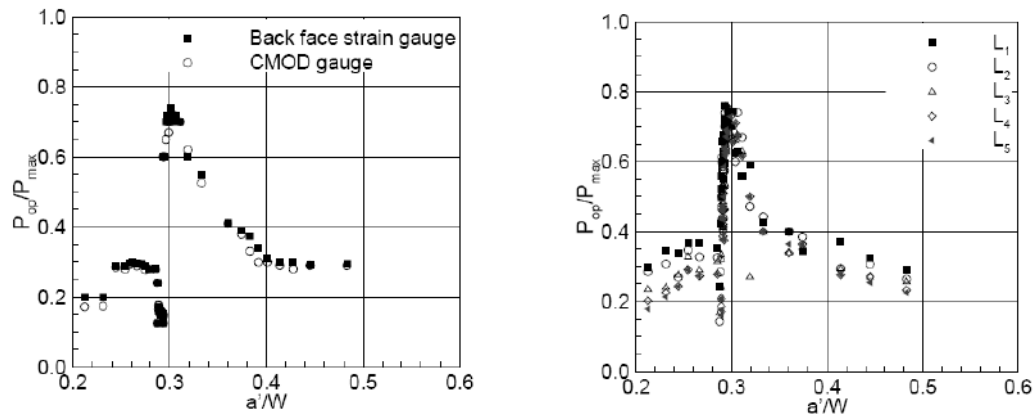


Figure 3.42. Variation of crack opening load for an Al6082-T3 CT specimen of 3 mm thick: a) conventional measurements using a back face strain and a crack mouth gauges; b) DIC measurements [180]

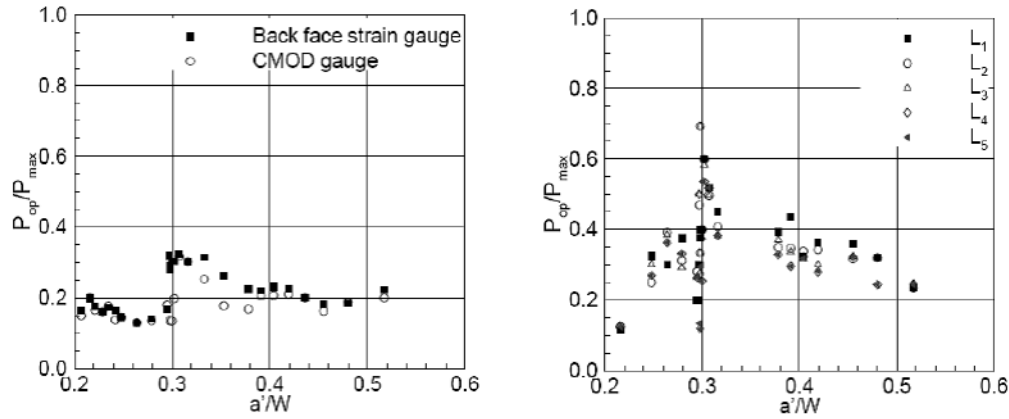


Figure 3.43. Variation of crack opening load for an Al6082-T3 CT specimen of 25 mm thick: a) conventional measurements using a back face strain and a crack mouth gauges; b) DIC measurements [180]

Recently, López-Crespo et al. [12] performed a study to evaluate the effect of an overload on fatigue crack tip fields by surface and bulk analysis. Their study was performed on three 316L stainless steel CT specimens of 3 mm thick. The first specimen was employed to obtain fatigue crack growth data (figure 3.44), the second specimen was employed to study the surface behaviour by DIC and the third one was employed to study the bulk behaviour by X-ray diffraction. Digital image correlation was employed to obtain COD data at several locations behind the crack tip by subtracting the vertical displacements of the upper and the lower flanks of the crack. Figure 3.45 shows the variation of COD versus the applied load for different fatigue stages at different distances behind the crack tip. From this figure, authors obtained opening and closing loads.

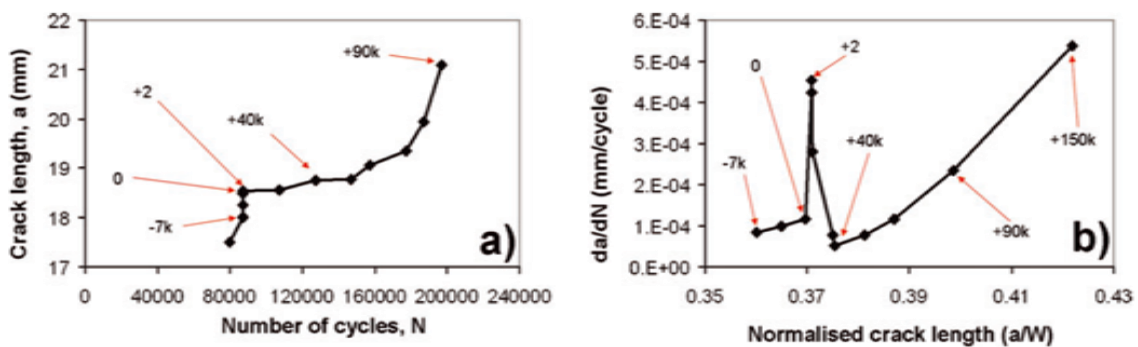


Figure 3.44. Crack length evolution as a function of the number of applied cycles (a) and crack growth rate (da/dN) as a function of normalised crack length (b) for a 316L stainless steel CT specimen of 3 mm thick [12]

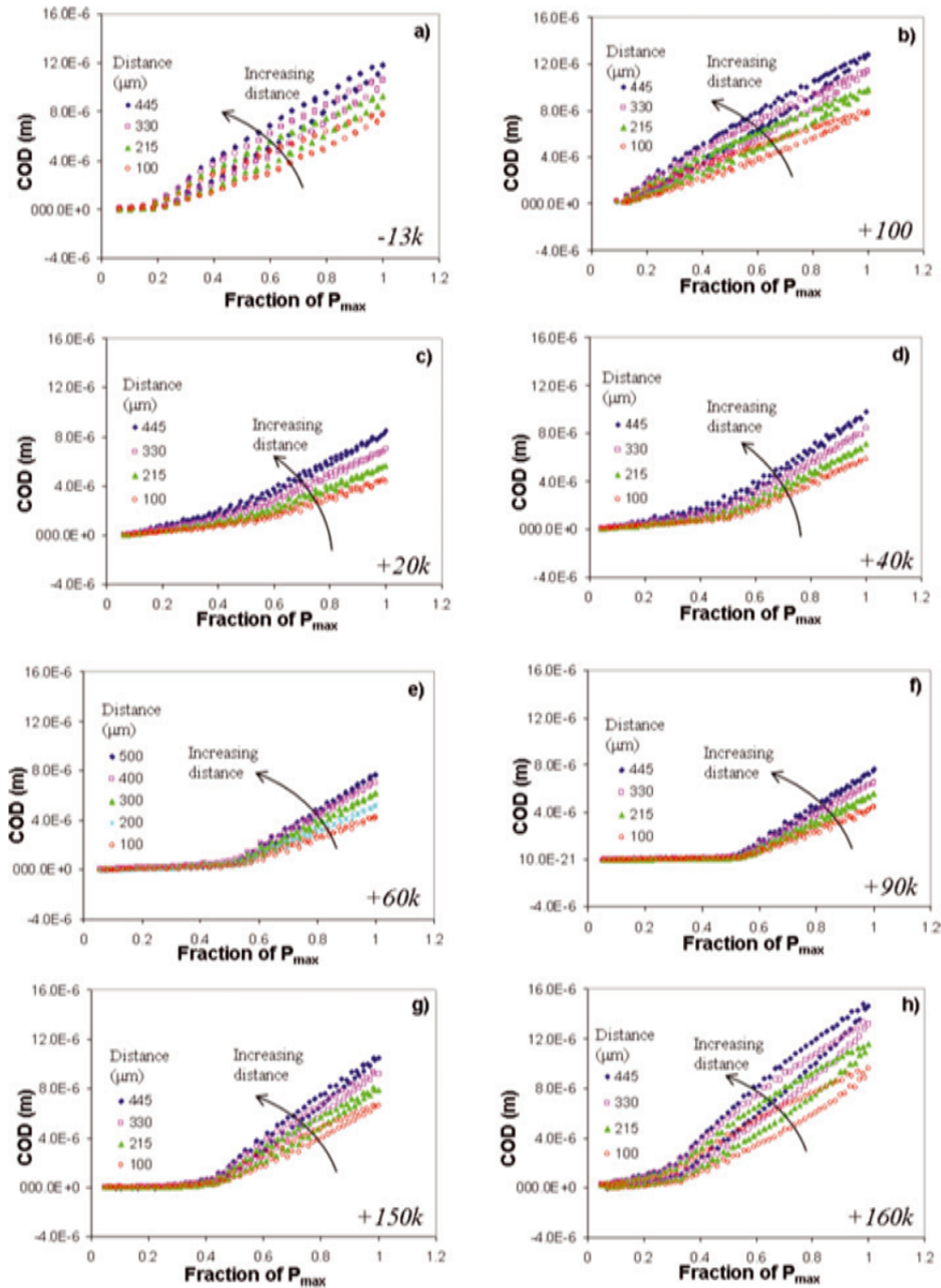


Figure 3.45. Evolution of COD versus load for different fatigue stages and different measurement distances behind the crack tip for the following crack lengths: a) -0.98 mm, b) +0.07 mm, c) +0.27 mm, d) +0.29 mm, e) +0.58 mm, f) +1.45 mm, g) +5.61 mm and h) +7.35 mm beyond of the point of overload [12]

3.4.6. Conclusions

Since Peter and Ranson [144] published the first paper about the use of digital image correlation on experimental mechanics, the popularity of DIC has been notably increased. One major reason for this is that the technique is a non-contacting and it is easy to implement. This reason

has strongly contributed to the development of DIC for the analysis of fracture mechanics problems.

Different methodologies have been developed for the determination of stress intensity factors experimentally from the analysis of the displacement fields measured around the crack tip. These experimental methodologies employ displacements data in combination with analytical models describing the crack tip displacement fields. The most extensively used mathematical models are those based on the Westergaard's equations, Williams' expansion series, Muskhelishvili's complex potentials, and recently the mathematical model called CJP. In these models, stress intensity factors are linearly related with the coordinates of the data points selected around the crack tip. However, these methods require knowledge of the crack tip location.

Moreover, all the reviewed methods for the calculation of stress intensity factors, the displacement data must be collected from a region surrounding the crack tip. However, since the mathematical models used are based on linear elastic fracture mechanics, it is recognised that data must be selected near to the crack tip but not extremely close to avoid the influence of crack tip plasticity.

Although digital image correlation is globally accepted as a powerful technique for the analysis of fatigue and fracture problems, relatively little work has been done on the evaluation of crack closure and crack shielding in growing fatigue cracks. Many researchers have reported some indications of crack shielding from the evaluation of stress intensity factors, but in none of them there was a quantitative comparison between methods. Special interest has been focused on CJP model since it seems to show enormous potential for the evaluation of crack shielding in growing fatigue cracks.

Finally, another issue related to the evaluation of fatigue crack shielding is the effect of overloads in fatigue. Little work has been found on this topic. Therefore it is a field to be explored.

3.5. Electronic speckle pattern interferometry

3.5.1. Introduction

Electronic speckle pattern interferometry (ESPI) is a full-field non-contacting optical technique for displacement measurement. It is based on the optical physics of surface-generated laser speckle. Since 1970s ESPI has gradually evolved into different optical designs and has been applied to a range of engineering and non-engineering applications. The development of ESPI continued during 1990s with the introduction of new laser and optical technology into the

interferometers, allowing further optimisation and extending the potential applicability of the technique. In the following section it is presented a review of the most notable developments for in-plane ESPI design and applications published until today. Special attention has been paid on the application of this technique to fracture mechanics problems, in particular to methodologies developed for stress intensity factor determination from crack tip displacement or strain fields obtained with ESPI. Unlike to what it was previously reviewed for transmission photoelasticity and DIC, it is believed that there is not any work on the application of ESPI for evaluating fatigue crack shielding and the effect of overload during fatigue crack growth rate. Therefore it becomes an innovation research field that needs to be approached. Finally, this section closes with the main conclusions established from the different aspects reviewed above.

3.5.2. Historical review

The development of the ESPI technique can be attributed to Leendertz [181] in 1970. Simultaneously, Macovski et al. [182] and Butters and Leendertz [183] demonstrating the use of vidicon-based TV cameras as recording devices, producing ‘real-time’ (25 Hz) results. This work continued at Loughborough University during the 1970s with the optimisation of the optical configurations and to ensure their applicability to different engineering applications.

The development of fringe pattern analysis and continuous improvements, achieved in computer science during 1980, added new emphasis to the development of ESPI as a potentially useful engineering tool. Up to this point in time, its analysis was generally qualitative, with quotable numerical results being obtained by counting fringes and observing the spatial characteristics of the fringe patterns. Application of computing techniques allowed calculating the optical phase change, calibrating and generating quantitative data. The 1990s took place resurgence renaissance of interferometer design and optimisation, with the implementation of features such as fibre optics, laser diode modulation, compact designs, multiple sensitivity and integrated phase-stepping devices.

The development and application of in-plane ESPI to study solid mechanics problems was addressed by different research groups. Sirohi and Krishna Mohan [184] optimised the optical design reporting an optical configuration with a twofold increase in sensitivity, although it required whole-field filtering of a photographic recording made at the image plane. Sohmer and Joenathan [185] improved upon the work of Sirohi with a similar configuration which operated with a CCD-TV camera, also producing a twofold increase sensitivity and halving the fringe function.

In an engineering context it is questionable whether a twofold increase sensitivity is useful, since engineering strains and consequently in-plane displacements are large, often achieving hundreds of micrometers or more. Floureaux [186] considered this problem and developed a

method of incremental adding in-plane data to vastly extend the range of the analysis. This led to a series of publications describing the use of this form of in-plane ESPI for highly localised displacement/strain fields [187] and examination of subsurface damage in fibre-reinforced composites [188, 189].

All of the work reviewed so far had one common aspect, the use of just one in-plane interferometer, measuring the u and v component of in-plane displacement, but not both simultaneously. In the case of ESPI for measuring in-plane displacements, it is required the simultaneous operation of the two interferometers. This problem was considered and solved by Moore and Tyrer [190]. They presented an integration of two in-plane ESPI interferometers using different polarisation vectors for each interferometer to preserve the integrity of the data for the horizontal in-plane analysis and the vertical in-plane analysis respectively. Figure 3.46 provides an example of this approach showing the analysis of a human mandible. This integrated interferometer approach was further optimised by Moore and Tyrer with the introduction of quantitative data around a crack tip, leading to the generation of strain components [191], stress intensity factors and J contour integrals [192, 193]. The use of integrated interferometers has been taken up by other researchers in experimental mechanics.

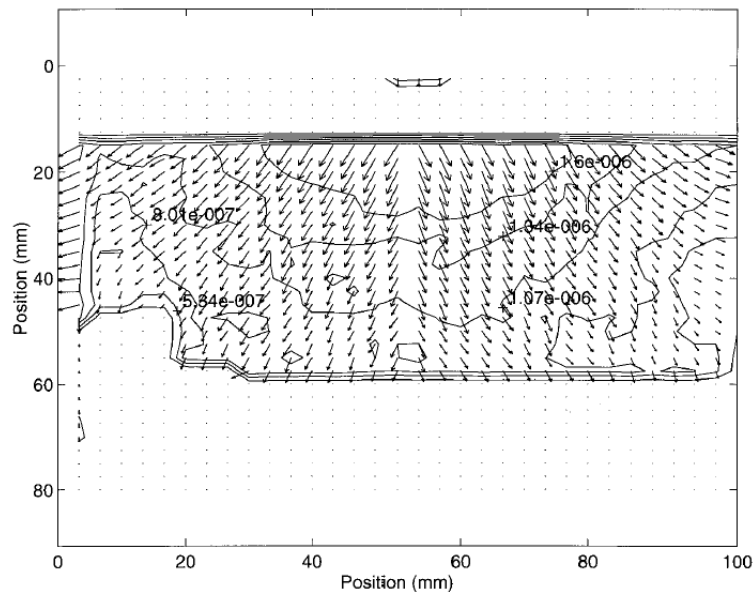


Figure 3.46. In-plane displacement (m) map obtained from dual in-plane analysis of a human mandible under load [190]

Perhaps the most ambitious extension of the development of the integrated in-plane ESPI interferometers is the work developed by Wang et al. [194]. Authors not only built an interferometer that measured simultaneously the two in-plane displacement components but the system also incorporated an out-of-plane interferometer. Whereas the interferometer of Wang et al. generated 16 speckle patterns which were then processed, Takatsuji et al. [195] simplified

the process by using carrier fringes to encode the surface displacement. One camera recorded contributions from four laser waves and the three displacement components were extracted using Fourier methods.

It is evident that in-plane variants of ESPI were regarded with importance within the experimental mechanics community for the examination of solid mechanics problems. Thus, several European manufactures are now offering in-plane ESPI interferometers with associated fringe pattern analysis software [196].

3.5.3. SIF calculation from the analysis of displacement fields using ESPI

Since its birth, little work has been developed with ESPI in the field of fracture mechanics. Of particular interest is the determination of stress intensity factors from the analysis of the displacement fields measured around a fatigue growing crack. Thus, in this section different methods for the calculation of the stress intensity factor from crack tip displacement fields measured by ESPI are reviewed. Moore and Tyrer [193] were the first to propose a methodology to infer K_I and J integral from the in-plane displacements measured around the crack tip using ESPI. Three HS30TF aluminium CT specimens were tested (figure 3.47). Specimens were statically loaded in a rigid hydraulic tensiometer. To exclude all plasticity effects, notches approximately 4 mm of width were manufactured by electro-discharge machining (EDM). A phase-stepping method was employed to obtain phase-maps and determine in-plane displacements. Typical results for ESPI fringe patterns and phase maps are shown in figure 3.48. The evaluation of K_I was carried out by a least squares solution originally proposed by Barker et al. [197]. This method was based on a multi-parameter description of the displacement field surrounding the crack tip proposed by Sanford [198]. K_I was calculated from data sets collected around the crack tip from the unwrapped phase-maps. Figure 3.49 shows the results obtained for K_I for the three specimens studied. Thus, measurements were shown to be accurate within 10% range.

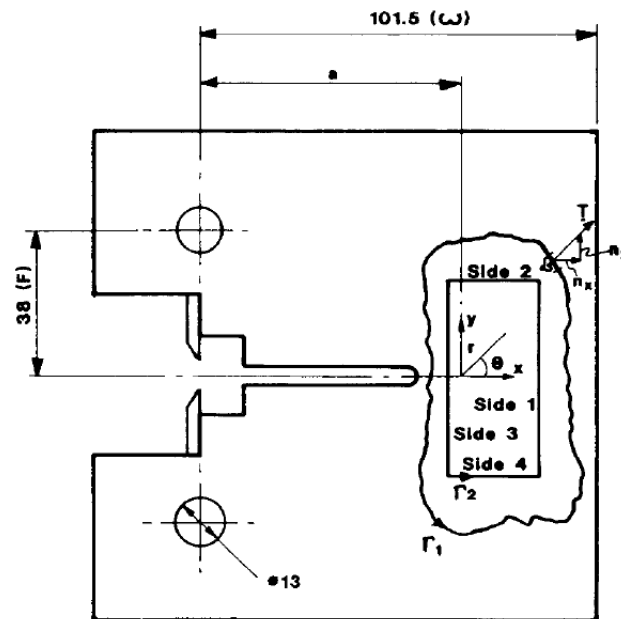


Figure 3.47. Compact tension specimen tested under static conditions to infer SIFs using ESPI [193]

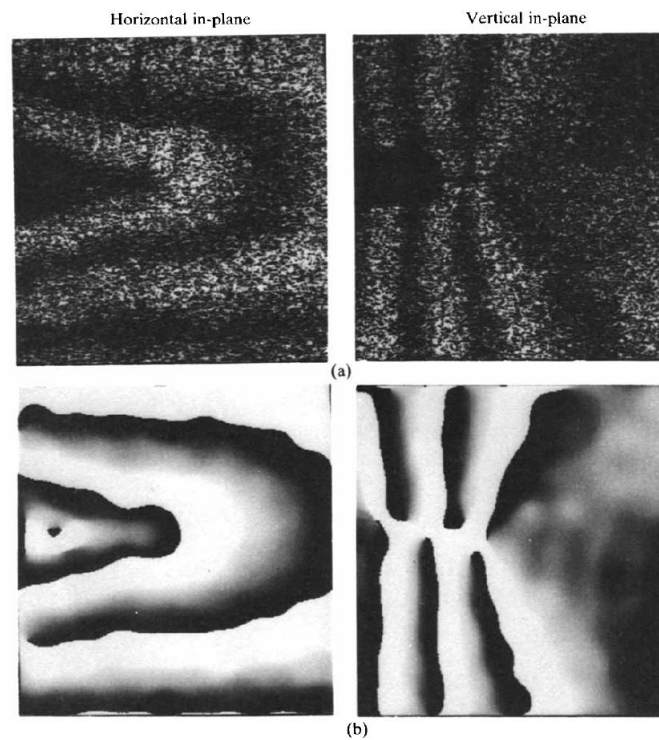


Figure 3.48. Typical ESPI results obtained on a compact tension specimen subject to 99 N: a) ESPI fringe patterns and b) phase maps [193]

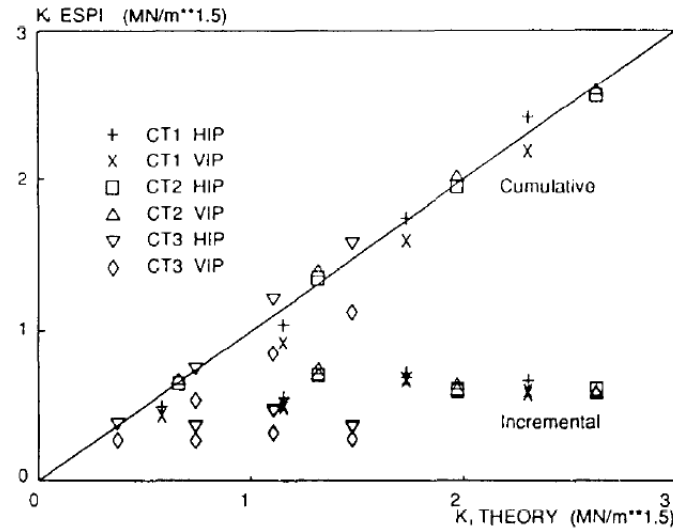


Figure 3.49. Values for K_I obtained for three compact tension specimens from the displacement fields measured with ESPI [193]

Further work was conducted by Moore and Tyrer [191]. They employed the same specimens and the same methodology as previously to obtain the displacement fields at the vicinity of the crack tip. In addition, to determine the first spatial derivative of displacements, a linear least-squares fit of a plane surface to the phase values at the neighbourhood of each pixel was employed. In figure 3.50 shows both experimental strain fields (left-hand side) obtained by ESPI and theoretical strain fields (right-hand side) from the strain distribution described by Sanford's polynomial expansion [198]. The displacement and strain measurements accuracy were shown to be $\pm 0.03 \mu\text{m}$ and $\pm 6 \mu\text{strain}$, respectively.

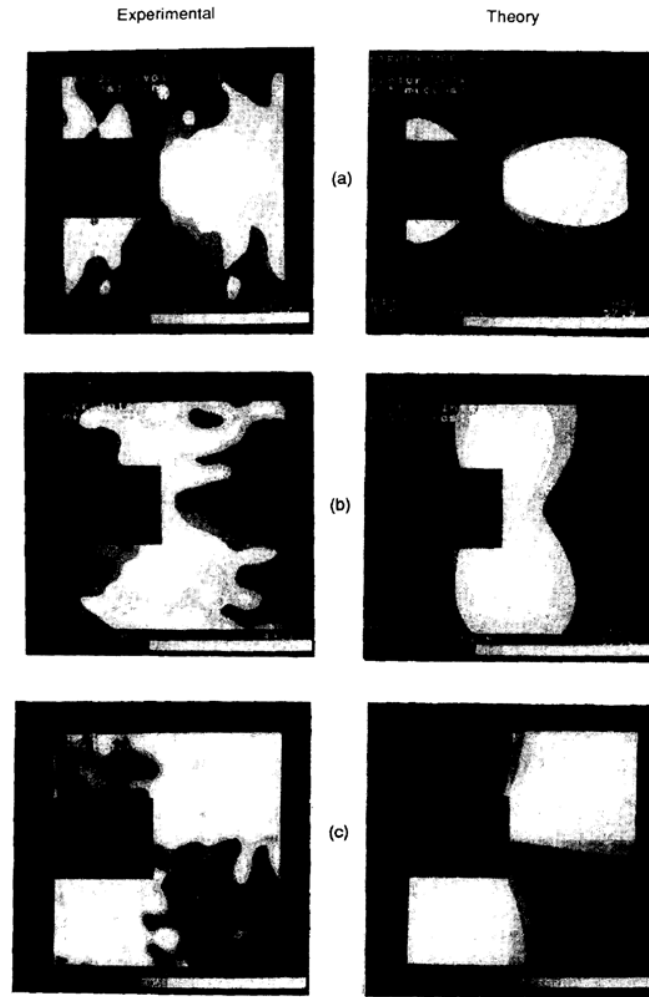


Figure 3.50. Experimental and theoretical strain fields for a CT specimen at 99 N; a) ε_{xx} , b) ε_{yy} , c) γ_{xy} [191]. Experimental results were obtained by differentiating the displacements measured with ESPI and theoretical results were obtained from the strain distribution described by Sanford's polynomial expansion [198]

Recently, Yoneyama et al. [199] proposed a method to evaluate mode I, mode II and mixed-mode stress intensity factors from in-plane displacement fields using a nonlinear least-squares fit [4]. Together with the stress intensity factors, the crack tip location and rigid body displacement components were determined from both displacement components. The method was validated by comparing mixed-mode displacement fields obtained with digital image correlation, elasto-plastic finite element method, and displacement fields around a fatigue crack obtained by ESPI. In the case of ESPI, authors used a 50.8 mm width and 10 mm thick chromium-molybdenum steel of 2.25Cr-1Mo CT specimen. A fatigue test was conducted at a frequency of 20 Hz using a 10 kN servo-hydraulic testing machine. A nominal stress intensity factor range of $\Delta K_I = 15 \text{ MPa}\cdot\text{m}^{1/2}$ was applied. The displacement fields around the crack tip obtained by ESPI are shown in figure 3.51, while the stress intensity factor ranges ΔK_{Id} and

ΔK_{ld} and the crack tip positions Δa and Δl are shown in figure 3.52. It can be observed that there is a good level of agreement from 3 terms.

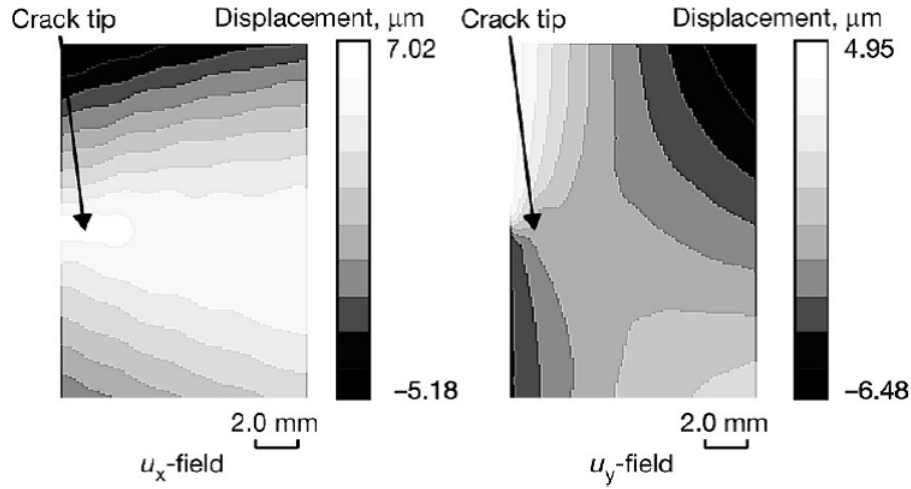


Figure 3.51. Displacement fields obtained by ESPI around a fatigue crack tip using a CT specimen [199]

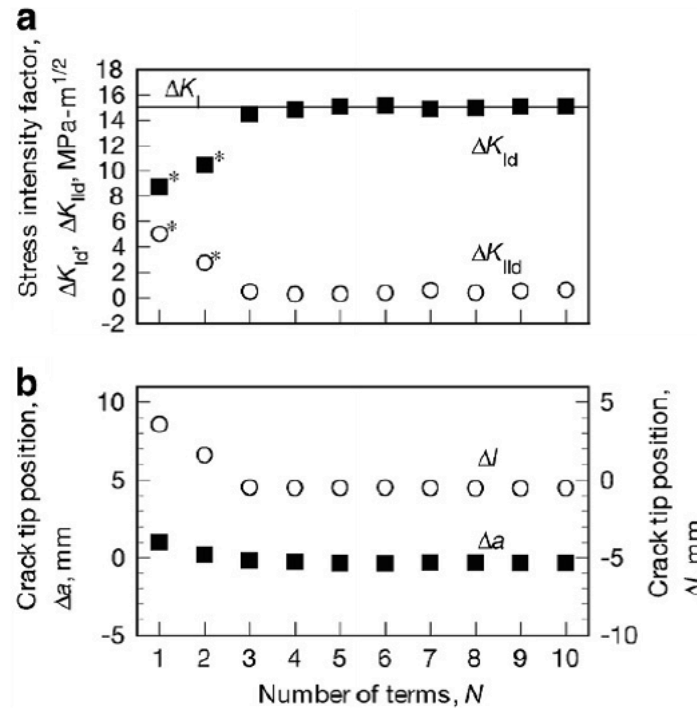


Figure 3.52. Effect of higher-order terms on the determination of (a) the stress intensity factors and (b) the crack tip position from the displacement fields measured in a fatigue crack tip [199]

Finally, unlike for transmission photoelasticity and DIC, it is believed that there is not any contribution in the literature about the evaluation of the shielding effect and the evaluation of the effect of the applications of overloads in fatigue crack growth. These topics become great innovation issues that must be explored.

3.5.4. Conclusions

Since Leendertz [181], a vast amount of research work has been conducted with ESPI, especially in its application on vibration problems. However, very little work has been done so far about the use of ESPI in the analysis of fracture problems.

As in the case of DIC, the displacement fields around a fatigue crack tip can be measured by ESPI. Therefore similar methodologies could be used to determine the stress intensity factors. In this sense, some works have been published about the calculation of the SIFs using a method based on Williams's expansion series to describe displacement fields around the crack tip. However, other methods developed for DIC could be employed to check the potential of ESPI for studying problems related to fracture mechanics. Among these different models to describe the displacement fields around the crack tip, special interest is found about the use of CJP model for evaluating fatigue crack shielding since it seems to show an enormous potential to evaluate crack shielding effect in growing fatigue cracks. However this potential remains to be explored.

Finally, another issue related to the evaluation of fatigue crack shielding is the study of the effect of overloads in fatigue life. It is believed that no work has been done with ESPI, and therefore it is another field to be explored.

3.6. Concluding remarks

Despite of the development of different analytical, mathematical and numerical models attempting to explain and understand the principles of crack shielding, there is an evidence in the existence of the crack shielding phenomenon. In fact, many researchers believe that not only crack closure can shield the crack tip but also other factors can produce this shielding effect. For this reason, in this research work, it has been decided to use the term crack shielding rather the term crack closure. Thus, the shielding effect influences the crack growth rate in propagating fatigue cracks, especially at low stress ratios. This influence is characterised by a decrease in the nominal stress intensity factor range, defining an effective stress intensity factor range that truly contributes to crack growth, increasing therefore fatigue life in mechanical components. Different experimental techniques based on the measurement of compliance change due to the premature contact between the crack flanks have been reported. However, in most of the cases they are sensitive to different aspects that make difficult to obtain an accurate and independent value for the effective stress range.

Experimental techniques seem to show a great potential to study problems related to fracture mechanics. Especial interest exists about the application of transmission photoelasticity, digital image correlation (DIC) and electronic speckle pattern interferometry (ESPI). In this sense, the

determination of stress intensity factors plays an important part in the evaluation of growing fatigue cracks. The validity of these three techniques to calculate the stress intensity factors in cracked components has been demonstrated. Thus, stress fields around the crack tip can be characterised through stress intensity factors from transmission photoelasticity, while from DIC and ESPI, stress intensity factors can be determined from the analysis of the displacement fields surrounding the crack tip.

According to the above paragraph, different mathematical models describing stress and displacement fields at the vicinity of the crack tip have been developed. Thus, the stress intensity factors will be determined by fitting a set of experimental data points around the crack tip to different equations that define the mathematical models. In this sense, an important issue is the development of a methodology for the collection of data points around the crack tip. Since the models reviewed are based on linear elastic fracture mechanics, this methodology must be able to ensure that the experimental data will not be affected by any plasticity generated at the crack tip and/or at the crack wake. Another significant aspect that must be taken into account is that depending on the applied technique, a linear or nonlinear system of equations must be fitted to calculate the stress intensity factors. Thus, for transmission photoelasticity, as the relation between stress intensity factors and isochromatic data is nonlinear, a nonlinear system of equations must be fitted. On contrary, with DIC and ESPI, the stress intensity factors are determined by solving a linear system of equations since the relation between the displacement fields and stress intensity factors is linear.

As it was indicated above, another important topic that has interested many researchers since a long time ago is the evaluation of fatigue crack shielding. In this sense, this phenomenon can be evaluated from the analysis of the stress intensity factors. Therefore, putting in common experimental results obtained from transmission photoelasticity, DIC and ESPI could assist to a greater understanding and interpretation of crack shielding. In addition, another issue very interesting related to the crack shielding effect is the evaluation of the application of overloads in fatigue crack growth. In this sense, the study of the effect of overloads with transmission photoelasticity, DIC and ESPI could assist to a greater understanding of the mechanisms controlling fatigue crack growth.

Besides the comparison between the different experimental results obtained from the studied techniques in the current work, standard techniques based on compliance measurements (although they have been strongly criticised) can provide a good comparison with experimental results from optical techniques.

Chapter 4. Apparatus and methods

4.1. Introduction

As stated in chapters 2 and 3, experimental techniques for strain/stress measurements seem to have an enormous potential in the field of experimental mechanics. These techniques include transmission photoelasticity, digital image correlation (DIC) and electronic speckle pattern interferometry (ESPI). In recent years, these techniques have been used for the study of problems related to fracture mechanics such as the determination of stress intensity factors, the evaluation of fatigue crack shielding or the evaluation of the overload effects in fatigue life.

In this chapter all the relevant aspects related to the adopted experimental procedure regarding to the apparatus, specimens and tests are reviewed. In a first section, the equipment employed for transmission photoelasticity, including the optical elements, the calibration procedure and the image acquisition setup are described. In a second section, the equipment employed for DIC is presented and described. Subsequently, ESPI technique is reviewed, focusing the attention on the apparatus and the operational features of the software employed for image processing. Finally, in the last section a description of the materials, specimens and the experimental procedure for the fatigue experiments employing the three described techniques is made.

4.2. Transmission photoelasticity

4.2.1. Introduction

In transmission photoelasticity, the stress field is evaluated through the use of polarised light. The basic equipment employed in transmission photoelasticity is the polariscope. Thus, in this section, the optical elements and the different polariscope configurations employed in transmission photoelasticity will be described. In addition, adopted calibration methodology and the image acquisition setup will be presented.

4.2.2. Apparatus

4.2.2.1. Optical elements

The practical implementation of transmission photoelasticity requires two main optical elements: the polariser and the wave plate.

4.2.2.1.1. Polariser

A polariser (figure 4.1) is an optical device that converts randomly polarised light into plane polarised light. In figure 4.1, a single light wave with randomly oriented wave amplitude approaches the polariser from the left. As this wave encounters the polariser, it is divided into two orthogonal components, one parallel to the polarising direction of the polariser, and another one perpendicular to it. The parallel component passes through the device, while the perpendicular one is rejected. Light emanating from the polariser is therefore plane polarised in the polarisation direction of the polariser.

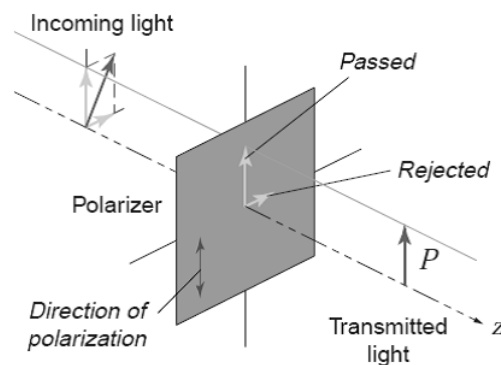


Figure 4.1. Principles of a polariser

4.2.2.1.2. Wave plate

A wave plate (figure 4.2a) divides incident light into two components, but instead of rejecting one of the components, it induces a relative retardation to the other component. In figure 4.2a, the 'fast' axis has an angle α respect to an arbitrarily chosen reference direction. The component f of the incident light is retarded as it passes through the wave plate. However, the perpendicular component s is retarded even more, resulting in a relative retardation δ between 'slow' and the 'fast' components. The term *double refraction* is often used to describe this behaviour.

Wave plates can be either permanent or temporary. Permanent wave plates (the most commonly employed in photoelasticity) have a fixed fast-axis orientation α and a fixed relative retardation δ . On contrary, temporary wave plates have the ability to produce a double refraction response under mechanical solicitations. Thus, photoelastic specimens can be considered as temporary wave plates.

One special type of wave plate is the quarter-wave plate (figure 4.2b). It is a permanent wave plate that induces a relative retardation δ equal to $\lambda/4$. Where λ is the wavelength of the light being used. In figure 4.2b, the incident light is assumed to have its amplitude vector in a vertical plane, and the fast axis of the quarter-wave plate has been oriented at 45° with respect to the horizontal axis.

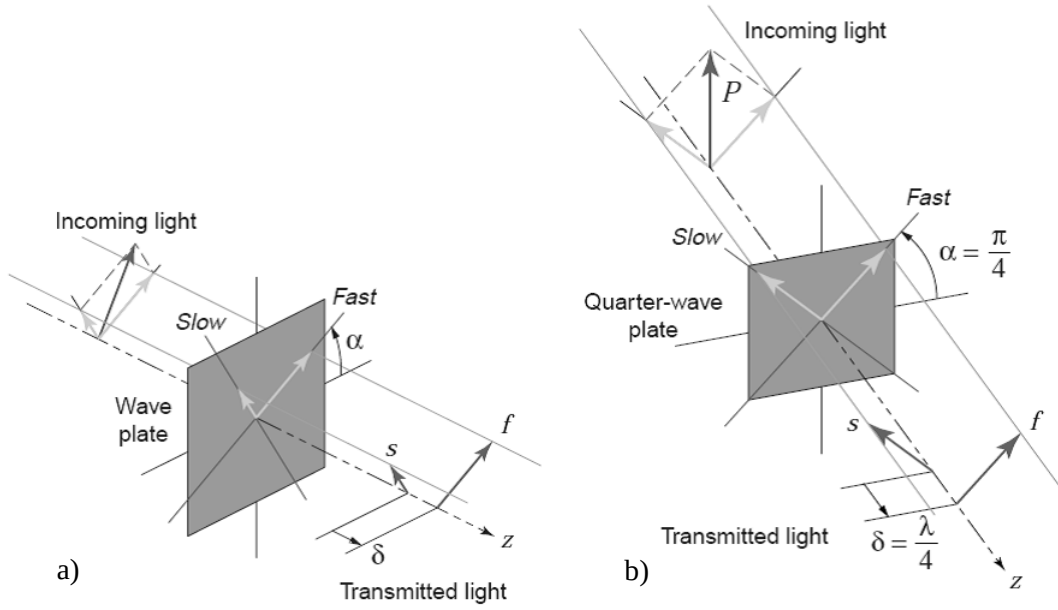


Figure 4.2. Principles of a wave plate (a) and a quarter-wave plate (b)

4.2.2.2. The polariscope

The polariscope is the basic equipment adopted for transmission photoelasticity. A model made of birefringent material is placed in the polariscope so that the fringe patterns related to the principal stress difference and the directions of principal stresses can be captured using a digital camera and subsequently processed. Two types of polariscope are commonly employed, the plane polariscope and the circular polariscope.

4.2.2.2.1. Plane polariscope

A plane polariscope (figure 4.3) consists of a light source, a polariser, the specimen and an analyser (polariser that helps to analyse the emergent light) that is crossed respect to the polariser. Thus, the most common arrangement for a plane polariscope is to place the polariser with its polarisation axis oriented to 90° with respect to the horizontal direction, while the analyser will be arranged with its polarisation axis at 0° with respect to the horizontal direction. If the light emerging from the two optical elements is analysed, the observed light intensity is described by the following expression:

$$I_p = I_a \sin^2 2\theta \sin^2 \frac{\delta}{2} \quad (4.1)$$

Where I_a is the amplitude of the incident light, θ is the principal stress direction in the specimen and δ is the relative retardation. According to equation 4.1, the intensity of light emerging from the analyser is zero when (a) $\theta = 0$ or $\pi/2$ or (b) $\delta = 2m\pi$ ($m = 0, 1, 2, \dots$).

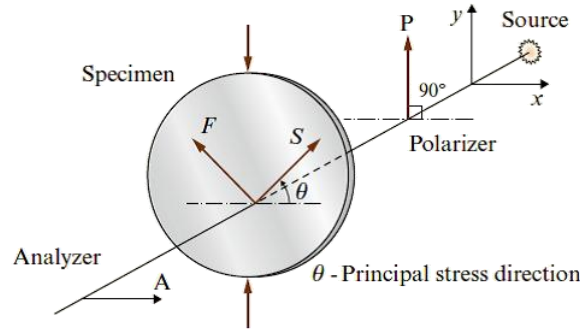


Figure 4.3. Arrangement of optical elements in a plane polariscope [17]

From the first condition, since θ is the angle between the principal stress direction and the polarisation direction of the analyser, the emerging intensity will be zero at those regions of the specimen where the principal stress directions are aligned with the polarisation direction of the polariser and the analyser. These contours are called isoclinics and represent the fringe patterns observed in the model where the orientation of the principal stress direction is constant.

The second condition happens when the principal stress difference causes a relative phase difference of $2m\pi$. Therefore, isochromatics represent the fringe pattern observed in the model where the relative retardation is constant.

4.2.2.2.2. Circular polariscope

Figure 4.4 shows a general arrangement for a circular polariscope. In this case, circular polarised light is employed to reveal the stress information in the model. A circular polariscope consists of a light source, a polariser, a quarter-wave plate oriented at 45° with respect to the polariser, the specimen, a second quarter-wave plate, and an analyser. The arrangement shown in figure 4.4 cuts the light beyond the model boundary and the background appears dark and hence the arrangement is known as a dark-field arrangement. If the intensity of light transmitted in dark-field is denoted as I_d , this is given as follows:

$$I_d = I_a \sin^2 \frac{\delta}{2} \quad (4.2)$$

By rotating the analyser and keeping it along the vertical, a bright background is observed. The intensity of light as I_l is given by the following expression:

$$I_l = I_a \cos^2 \frac{\delta}{2} \quad (4.3)$$

It must be noted that in both dark and bright-field, the intensity equations are independent of θ and hence the extinction condition is only a function of δ and thus only isochromatics will be observed. This is a significant achievement in separating isoclinics and isochromatics fringes.

Although several combinations of the optical elements can provide either dark or bright-field, the most common combinations are given in table 4.1.

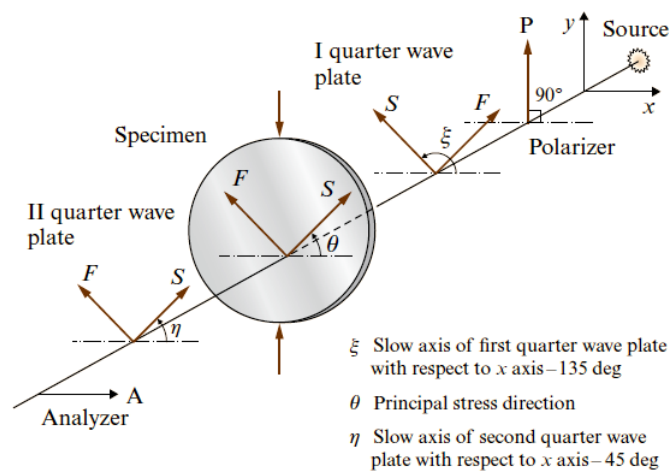


Figure 4.4. Arrangement of optical elements in a circular polariscope [17]

Table 4.1. Polariscope arrangements and background field observed

Arrangement	Polariser and analyser	Quarter-wave plates	Background field
Plane polariscope	Crossed	None	Dark
Circular polariscope	Crossed	Crossed	Dark
	Parallel	Parallel	Dark
	Crossed	Crossed	Bright
	Parallel	Crossed	Bright

In figure 4.5 only isochromatics are shown for dark and bright-field arrangements over a compression disc using a circular polariscope. It can be also observed the fringe shift between the dark and bright-field images.

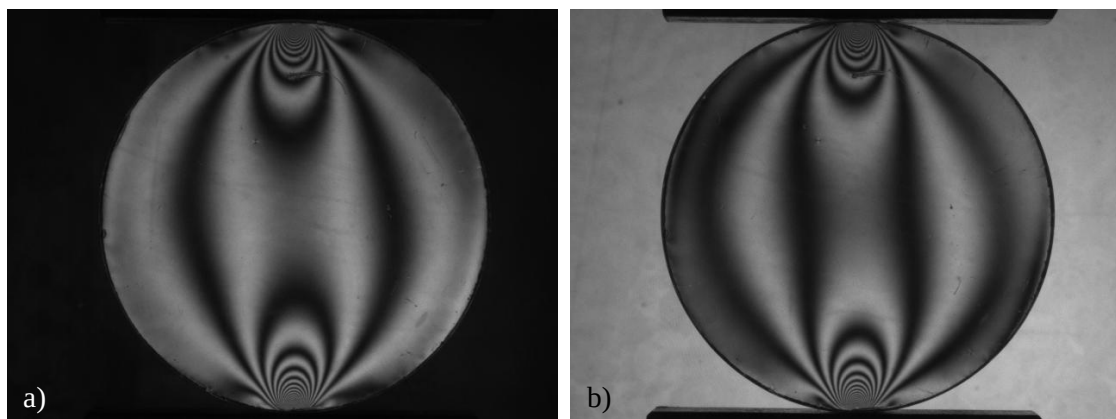


Figure 4.5. Isochromatics in dark-field (a) and bright-field (b) arrangements observed over a disc under diametral compression in a circular polariscope

4.2.2.2.3. Calibration of the polariscope

A problem to be faced after assembling the different optical elements in a polariscope is how to establish the orientations of the axes of polarisers and quarter-wave plates. This process is called calibration of the polariscope. The adopted calibration procedure was the following:

1. Fabricate or obtain a calibration specimen. The purpose is to use a model that will show a well-defined and well-known isoclinic fringe pattern sensitive to misalignment of the polarisers. This goal can be achieved by generating the zero-degree isoclinic in a model having an axis of symmetry for both geometry and loading. Normally, a disc made of birefringent transparent material is employed as a specimen for the calibration of the polariscope elements.
2. Set the empty holders to zero rotation angle in their mountings.
3. Establish approximately the polarisation axis of the polariser. An easy way to do this is to treat it as a sunglass. Look through it at light and rotate the polariser to produce minimum intensity of the reflected light. The polarising axis will then be close to vertical. Mark it with a piece of tape and mount it loosely in its holder with its axis maintained as close to vertical as you can manage.
4. Repeat previous step with the analyser, but mount it so its polarisation axis is horizontal.
5. Tweak the polarisers in their holders so as to produce minimum intensity of the transmitted light. This step assures that the polarisation axes are crossed, but their axes are probably not absolutely vertical and horizontal with respect to global coordinates.
6. Mount the calibration specimen in the load frame of the polariscope and apply sufficient load to produce the desired isoclinic fringe. Arrange the disc so it is loaded in exact diametral compression.
7. Establish the directions of the transmission axes of the polariser and analyser with respect to earth. Rotate the polariser and analyser together, keeping their axes crossed, until the isoclinic appears along the appropriate axes of the model. For a disc, it will look something like a Celtic cross (figure 4.6). The transmission axes of the crossed polariser and analyser are thus known to be lined up parallel and perpendicular to the principal axes on the horizontal and vertical model axes. Symmetry requires that the principal stresses on these axes be parallel and perpendicular to these axes, so this procedure aligns the transmission axes of the polariser and analyser with respect to the specimen. Because the specimen load axis was set to vertical, the polarisation axes now match global horizontal and vertical. At this point, it is had a properly calibrated linear polariscope.
8. Locate the directions of the transmission axes in the first quarter-wave plate by placing it between the polariser and the model. Rotate it within its holder until maximum extinction is observed and the zero-degree isoclinic is restored in the model. In this position, the

principal axes of the quarter-wave plate are lined up with the transmission axes of the polariser and analyser. The procedure does not tell us which is the fast principal axis of the quarter-wave plate. This will be solved then.

9. Remove the first quarter-wave plate from the system and place the second quarter-wave plate between the model and the analyser and repeat the step 8.
10. Now put the first quarter-wave plate back into the polariscope and check to see that the symmetrical isoclinic in the calibration specimen is reproduced. If the background intensity is minimum and the isoclinic is correct, then the calibration is finished and the fast axes of the quarter-wave plates are properly crossed. If the background is bright, then the fast axes are parallel. To correct, simply rotate one of the quarter-wave plates by 90° .
11. At this stage, the device is properly calibrated and aligned to operate as a linear dark-field polariscope. The quarter-wave plates are within the polariscope, but, since their axes are aligned with the axes of polariser and analyser, they are not serving any function except to reduce overall light intensity and diminish contrast.
12. To convert to the linear bright-field arrangement, simply rotate the polariser or the analyser by 90° .
13. Now, to convert the linear dark-field polariscope to the circular dark-field configuration, the transmission axes of the quarter-wave plates must be arranged so that they are at 45° to the axes of the polariser and analyser but with their fast axes still crossed.
14. If it is wished to change from circular dark-field circular to circular bright-field, rotate either the polariser or the analyser through 90° . This procedure places the polarisers parallel, with the two quarter-wave plates still being crossed.

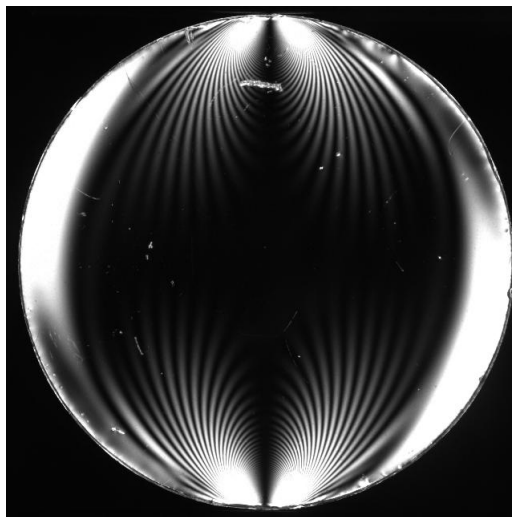


Figure 4.6. Celtic cross observed over a disc under diametral compression in the calibration of the polariscope

After the calibration procedure, two models were employed in order to check if this procedure was performed correctly.

Disc under compression

The first model to check the calibration procedure consisted of a 60 mm diameter polycarbonate disc 10 mm thick under compression. In figure 4.7 the six images of the disc under a compression load of 200 N corresponding to the phase-stepping method developed by Patterson and Wang [94] are shown. These images were processed [114] to obtain the unwrapped isochromatic fringe map (figure 4.8). Profiles along horizontal and vertical axes are also shown. In addition, to validate the results, they were compared with those simulated with a virtual polariscope implemented in Matlab[®] (figure 4.8). Experimental and theoretical results show the excellent level of agreement highlighting that the calibration procedure for the circular polariscope was correctly performed.

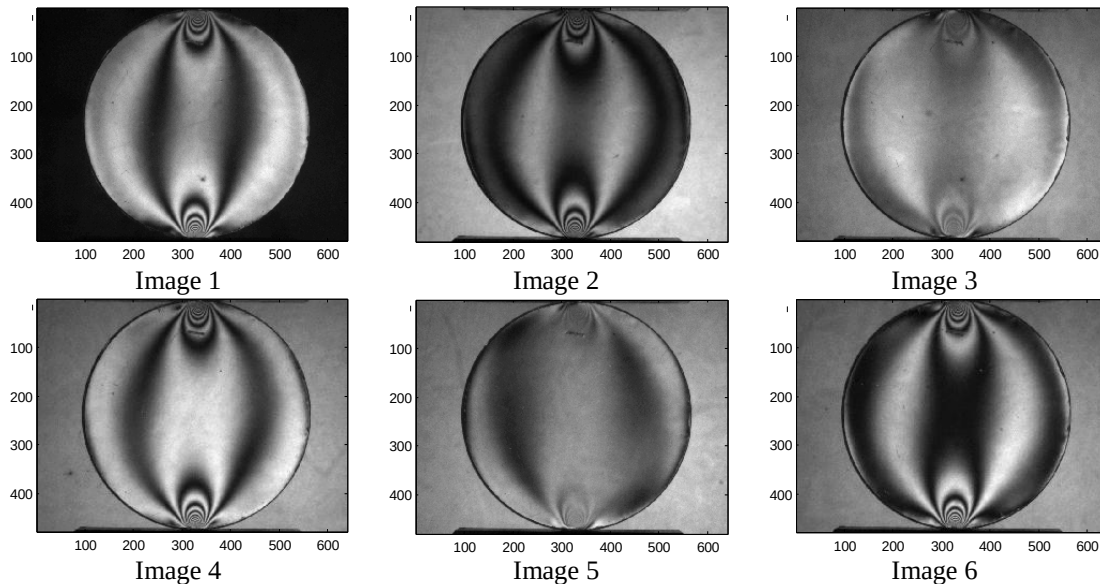


Figure 4.7. Phase-stepping images for a disc under diametral (200 N)

Ring under compression

An additional model was used in order to double check the calibration procedure previously described. Thus, a ring (6 mm thick with 80 mm and 40 mm external and internal diameters respectively) made of polycarbonate under diametral compression was employed. The six images of the ring at a compression load of 150 N were processed using the phase-stepping method developed by Patterson and Wang [94] as shown in figure 4.9. The unwrapping isochromatic fringe map together with the profiles along horizontal and vertical axes are shown in figure 4.10. The experimental results show a fringe order distribution similar to that observed from theory [14].

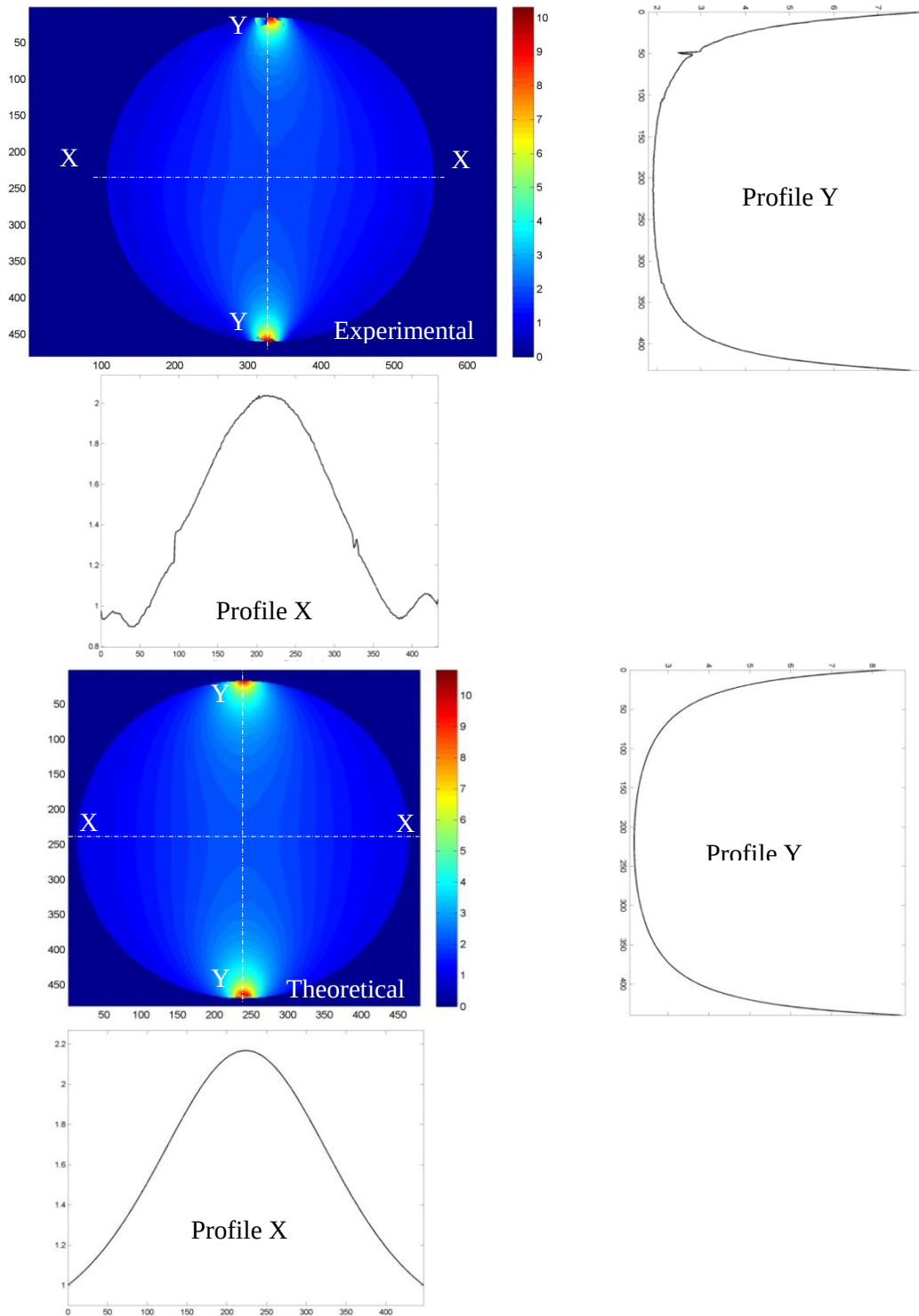


Figure 4.8. Experimental (top) and theoretical (bottom) isochromatic fringe map for a disc under compression (200 N). Profiles along horizontal and vertical axes have been plotted

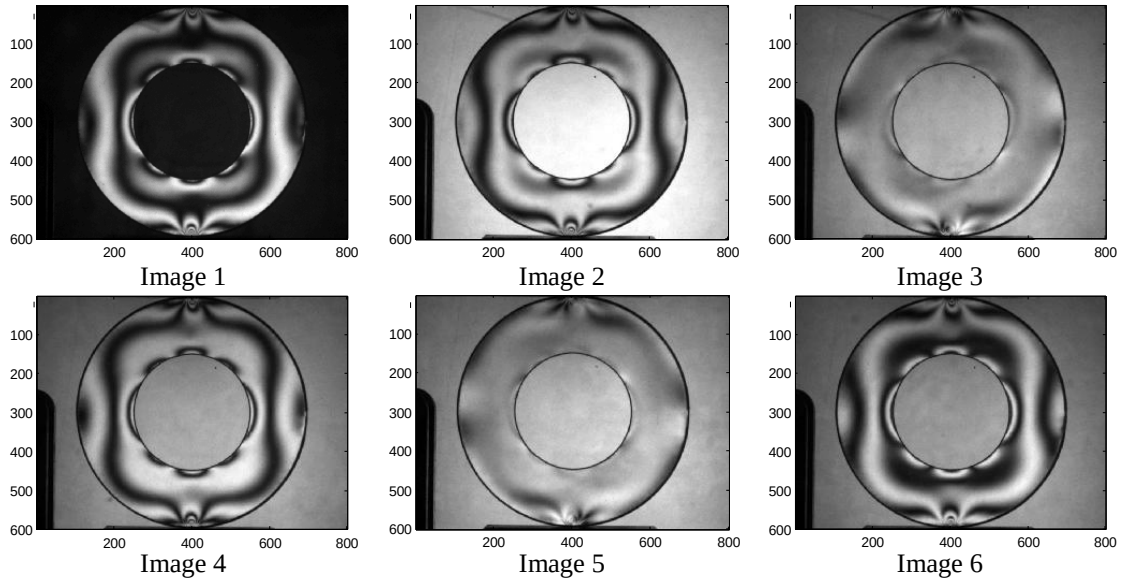


Figure 4.9. Phase-stepping images for a ring under diametral compression (150 N)

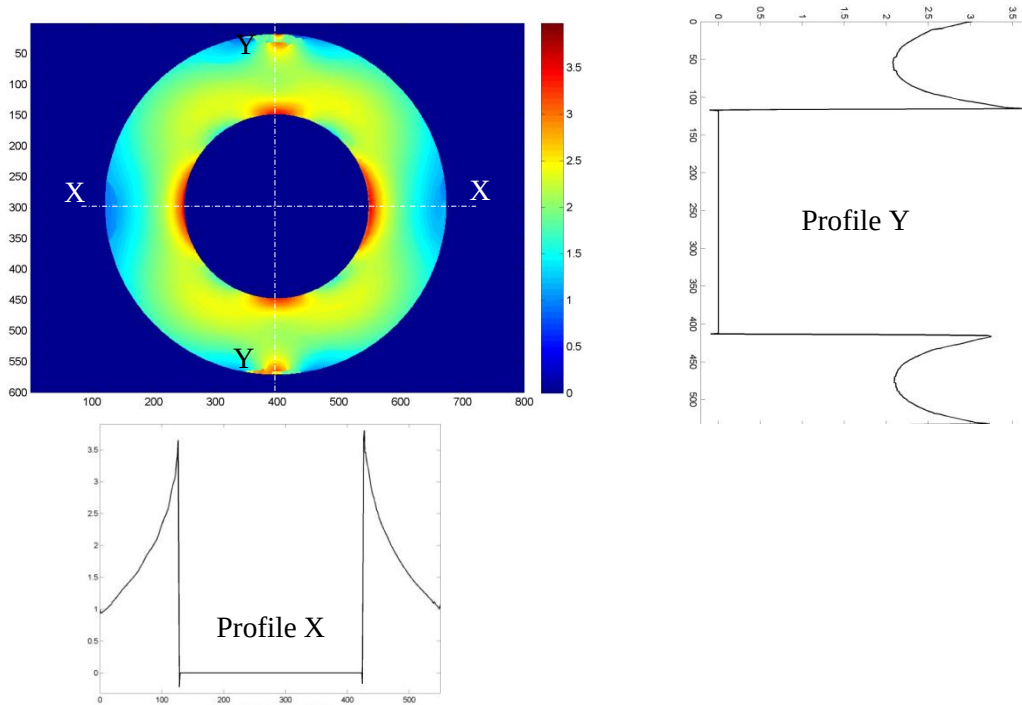


Figure 4.10. Experimental isochromatic fringe map for a ring under diametral compression (150 N) and profiles along horizontal and vertical axes

4.2.2.3. Image acquisition system

Images were captured using a monochromatic CCD camera (Allied Vision Technology, model Marlin F-146B/C; specifications in table A.1 in appendix A) with a macro zoom lens (EO, model MLH-10X; specifications in table A.2 in appendix A) to increase the spatial resolution at the region surrounding the crack tip. The CCD camera was controlled by a 3500 Intel Core i3

Dell-Vostro laptop through a FWB-EC3402 video card (specifications in the table A.3 in appendix A).

4.3. Digital Image Correlation (DIC)

4.3.1. Introduction

Two-dimensional digital image correlation (2D DIC) is a widely accepted and commonly used optical technique for quantitative in-plane deformation measurement of a planar surface. This technique provides full-field displacements with sub-pixel accuracy and full-field strains by comparing digital images of a test object surface acquired before and after deformation. In general, the implementation of the 2D DIC technique comprises the following three steps: 1) specimen and setup preparations; 2) recording images of the planar specimen surface before and after loading; 3) processing the acquired images to obtain the desired displacement and strain information. In this section the system adopted for capturing the images and the operational features of the equipment employed for DIC-2D are described.

4.3.2. Apparatus

The sequence of images necessary for implementing DIC was captured using a monochromatic CCD camera (Allied Vision Technologies, model Stirling F-504B/C; specifications in table B.1 in appendix B) with a 75 mm lens controlled by an E6510 Intel Core i5 Dell-Latitude laptop through a FWB-EC3402 video card.

In addition, an extra camera (Allied Vision Technologies, model Pike F-032B/C; specifications in table B.2 in appendix B) was employed to track the crack tip and monitor the crack growth during the fatigue experiments.

4.3.3. Operational features of the equipment for DIC

A commercial software package was employed for implementing the DIC technique, namely Vic-2DTM system [202] was used to process the captured images to obtain in-plane displacements. Thus, this commercial software package employs optimised correlation algorithms to provide full-field displacement and strain data for mechanical testing on planar specimens. In-plane movement can be determined for a deforming object at every point within the measurement area, as well as the Lagrangian strain tensor.

Vic-2DTM can measure in-plane displacements and strains from 50 μ strain to 2000% strain and above, for specimen sizes ranging from < 1 mm to > 10 m. the adopted experimental setup is

simple, and the specimen preparation only requires the application of a random speckle pattern. No special illumination or lasers are required.

4.4. Electronic Speckle Pattern Interferometry

4.4.1. Introduction

ESPI is an optical full field experimental technique employed for displacement measurement and strain analysis in mechanical components. From the physical point of view, ESPI employs monochromatic laser light illumination, and it is based on the superposition of two coherent beams on a CCD camera and the change of the optical phase between the two beams due to specimen deformation. Thus, in this section the apparatus employed for the implementation of ESPI and the operational features of the ESPI system used are described.

4.4.2. Apparatus

ESPI technique was implemented by employing the Q-300 ESPI-3D system (figure 4.11; specifications in table 4.7) developed by Dantec Dynamics GmbH [203]. This system (figure 4.11) is composed by a sensor (specifications in table C.1 in appendix C) for deformation measurement, a PC with the software used for processing images and a VGA monitor with a resolution of 1600 x 1200 pixels for visualising the captured images and the processed data. All the ESPI system was managed and controlled by the commercial software ISTRa (version 3.4, Dantec Dynamics GmbH).

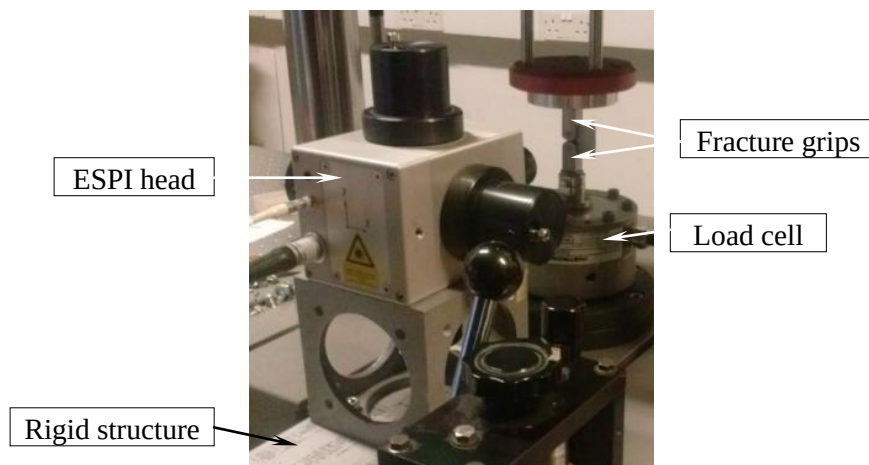


Figure 4.11. Illustration showing the experimental setup employed during fatigue tests using ESPI

The ESPI sensor (traditionally known as ESPI head) is a high-quality measuring device for full field high precision, non-contact deformation measurements on the surface of test objects and

components. Thus, the very compact size and high optical quality of the sensor confer a wide range of applications and its low weight allows easy mounting on different objects. As it was indicated in previous sections, ESPI was implemented for studies on little CT specimens and hence in-place measurements were made, however out-of-plane measurements can be also made with this system.

4.4.3. Operational features of the ESPI system

All the ESPI system indicated in the previous section was managed and controlled by the ISTR software (version 3.4, Danted Dynamics GmbH). Thus, the ISTR was employed to control the ESPI sensor and to evaluate speckle interferograms and other interference patterns using a phase-shifting method. Some of main capabilities and function of ISTR software are the following:

- Demodulation of interference images recorded through a phase-shifting method.
- Free definable file formats of the pictures.
- Free definable evaluation zones for demodulation, where several zones may be used within the same picture.
- Scaling of the object coordinates axes.
- Special phase filter for evaluation.
- Easy transfer of graphics into word processors through the Windows clipboard.
- Storage of the results as TIFF, ASCII or ISTR files.
- Free definition of the dimensions of the results.
- Real-time subtraction of speckle interference patterns.
- Recording of interference patterns using the phase-shifting method.
- Various filter options.
- Loading and saving of images.
- Adjustable phase-shifting method.
- Automatic calibration of the phase-shifting unit.
- Selection of the illumination direction of the ESPI sensor.
- Analysis of the test results.
- Data smoothing with part section interpolation.
- Differentiation of the data sets.
- Automatic series measurement.
- Integration of the data sets.
- Strain and stress calculation (the stress calculation is based on the thin layer method).

4.5. Materials, specimens and the experimental setup for fatigue testing

4.5.1. Introduction

An important aspect to achieve the objective of the current thesis is the appropriate selection of the materials, the specimens and the experimental setup for fatigue experiments employing the different techniques previously described. Thus, in the first epigraph of this section the mechanical properties of the materials selected for each technique are detailed. After that, the selected specimen geometries as well as their preparation are reviewed. Finally, the adopted experimental procedure for fatigue experiments is described.

4.5.2. Mechanical properties of the materials

In this section the mechanical properties of the selected materials for each technique are detailed. For transmission photoelasticity the selected material was polycarbonate, for DIC the selected material was aluminium 2024-T3, while titanium commercially pure was selected for ESPI technique.

4.5.2.1. Polycarbonate mechanical properties

Polycarbonate is a material ductile enough to allow fatigue crack growth and to show clear evidence of plasticity-induced crack shielding. Specimens were manufactured from 2 mm thick Makrolon[®] UV sheets (provided by the Bayer MaterialScience Company). The mechanical properties obtained from tensile tests according to the ISO 527-1 standard [200] are shown in table 4.2.

Table 4.2. Mechanical properties for Makrolon[®] UV obtained from tensile tests according to the ISO 527-1 standard [200]

Mechanical property	Unit	Value
Young's modulus, E	MPa	2350
Yield stress, σ_Y	MPa	>60
Yield strain, ε_Y	%	6
Nominal strain at break, ε_U	%	>50
Poisson's ratio, ν	-	0.38

4.5.2.2. Aluminium 2024-T3 mechanical properties

Specimens for DIC fatigue experiments were made of 2 mm thick 2024-T3 aluminium alloy sheets. Table 4.3 shows the mechanical properties of the adopted aluminium material, according to the ASTM E 8M-00 standard [201].

Table 4.3. Mechanical properties for Al2024-T3 obtained from tensile tests according to the ASTM E 8M-00 standard [201]

Mechanical property	Unit	Value
Young's modulus, E	MPa	73100
Yield stress, σ_Y	MPa	345
Ultimate stress, σ_U	MPa	483
Ultimate strain, ε_U	%	18
Poisson's ratio, ν	-	0.33

4.5.2.3. Titanium mechanical properties

The specimens tested using ESPI were manufactured from sheets of commercially pure titanium (TiCP) grade 2 UNS R50400 (chemical composition in table 4.4 according to ASTM F67 [204]) with a thickness of 0.7 mm. The mechanical properties obtained from tensile tests according to the ASTM E 8M-00 standard [201] are detailed in table 4.5.

Table 4.4. Chemical composition for commercially pure titanium grade 2 UNS R50400 [204]

Element	Nitrogen	Carbon	Hydrogen	Iron	Oxygen	Titanium
Composition % (mass/mass)	0.03	0.08	0.015	0.30	0.25	balance

Table 4.5. Mechanical properties for commercially pure titanium obtained from tensile tests according to the ASTM E 8M-00 standard [201]

Mechanical property	Unit	Value
Young's modulus, E	MPa	107000
Yield stress, σ_Y	MPa	360
Ultimate stress, σ_U	MPa	448
Ultimate strain, ε_U	%	18
Poisson's ratio, ν	-	0.33

4.5.3. Specimen geometry

The adopted specimen geometry for fatigue experiments was compact tension (CT) specimen. This geometry was adopted since it is a standard specimen extensively used in fracture mechanics applications and hence results obtained could be contrasted with those previously by other authors. For transmission photoelasticity and DIC the dimensions of the specimens were the same (figure 4.12a) while for ESPI the specimen dimensions were smaller (figure 4.12b). The dimensions of ESPI specimens were smaller since the expected displacements during experiments are in the order of several μm , while for the case of DIC are in the order of mm. In addition, as a part of future work, ESPI specimens were intended to be studied after fatigue experiments using scanning electronic microscopy (SEM). Hence this is another reason whereby a little geometry for the titanium specimens was selected.

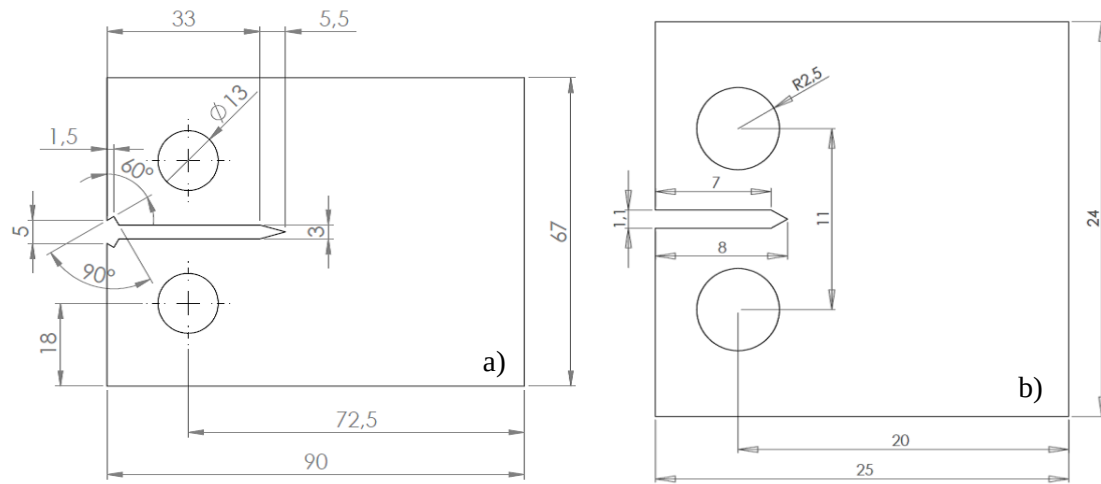


Figure 4.12. Geometry and dimensions of the CT specimen used with transmission photoelasticity and DIC (a) and with ESPI (b)

4.5.4. Specimen preparation

In this section, specimen manufacturing process and their preparation for fatigue experiments using the previously described optical techniques are described.

4.5.4.1. Preparation of the polycarbonate specimens for transmission photoelasticity

As it was previously indicated, the specimens employed with transmission photoelasticity were made of polycarbonate. Different samples were cut by waterjet to avoid the generation of residual stress in the material due to the cutting process. In addition, to generate an initial crack from the notch of the CT specimen, a razor blade was employed. Thus, by hitting the razor blade against the CT specimen at the notch location it was possible to precrack the specimen. This process was carefully conducted to avoid sinking the blade and consequently the generation of plasticity at the crack tip before starting fatigue experiments.

4.5.4.2. Preparation of the aluminium 2024-T3 specimens for DIC

The specimens tested by DIC were manufactured using aluminium 2024-T3 alloy. As in the case of transmission photoelasticity, the specimen was cut by waterjet technique, however, in this case the notch was spark eroded. In addition, to implement DIC technique, the specimen surface was prepared to obtain a gray intensity distribution (i.e. a random speckle pattern). The speckle pattern was generated by spraying black paint over the specimen surface with a previously painted white background (figure 4.13).

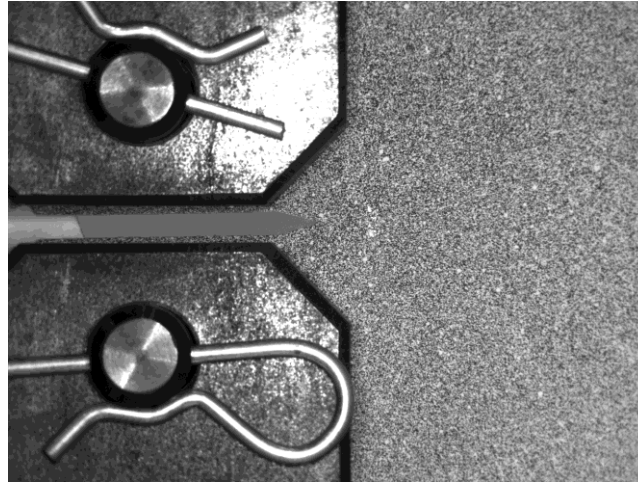


Figure 4.13. Illustration showing the speckle pattern applied to CT specimen using DIC technique

4.5.4.3. Preparation of the titanium specimens for ESPI

Specimens for ESPI technique were made of commercially pure titanium grade 2 UNS R50400 (see table 4.4 for chemical composition) [204], and they were manufactured by wire erosion process. ESPI specimens did not need any special previous preparation before fatigue testing. Specimen surfaces were rough enough to produce the required speckle when illuminated by a coherent light source. Thus, it was not necessary to previously spray the specimen surface with any paint as in the case of DIC. Nevertheless, sometimes depending on the homogeneity or the cleaning of the specimen surface, it is required the application of white paint over the surface to assist to the correct observation of the electronic speckle. Moreover, several specimen surfaces were polished until a mirror finish was achieved to their study by SEM as was previously indicated.

4.5.5. Procedure for fatigue testing

In this section, the experimental procedure for performing the fatigue testing is described. The experimental procedure fatigue analysis had some small differences on particularities depending on adopted optical technique.

4.5.5.1. Experimental procedure for transmission photoelasticity

Fatigue experiments with transmission photoelasticity were conducted using a MTS 370.02 servohydraulic machine with a maximum load capacity of 25 kN at a cycling frequency of 2 Hz (figure 4.14). A set of fracture grips was manufactured to transmit the load from the machine to the specimen (figure 4.14). In addition, two adapters were employed to connect the grips to the hydraulic cylinder and to the load cell (figure 4.14) and the fracture grips were screwed fixing

them with a nut. Finally, the connection between the specimens and the grips was performed using two pins.

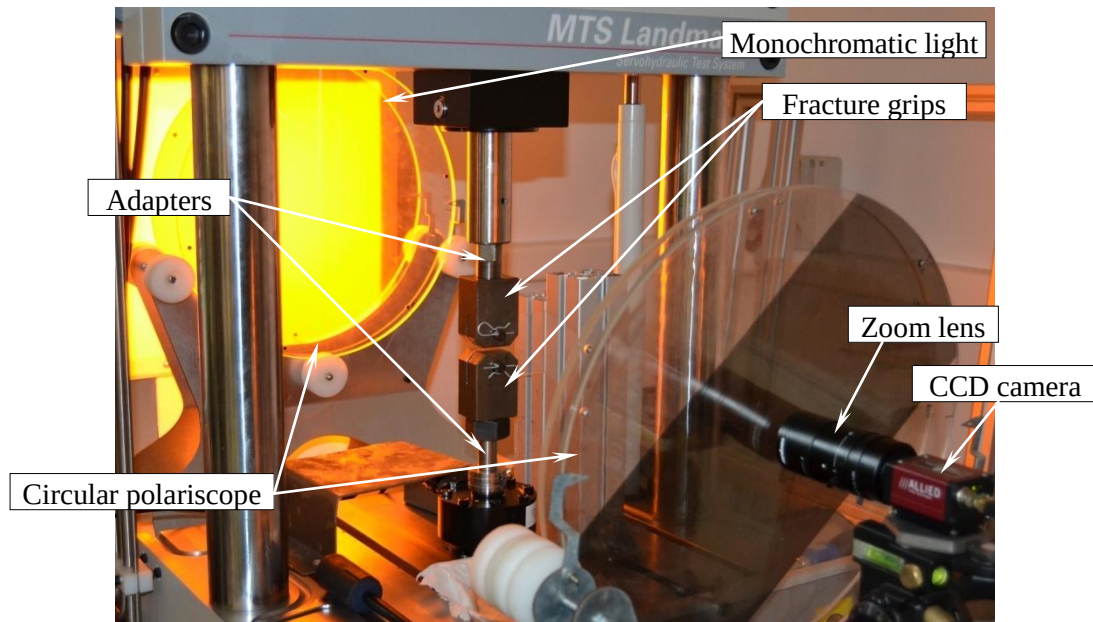


Figure 4.14. Illustration showing the experimental setup employed during fatigue experiments using transmission photoelasticity

A circular polariscope for transmission photoelasticity with a monochromatic light source (figure 4.14) was employed to visualise the fringe patterns. Images were captured using a Marlin camera (perpendicular to the specimen surface) with a macro zoom lens (MLH-10X EO) to increase the spatial resolution at the region surrounding the crack tip (figure 4.14). CCD camera was controlled by a laptop (Dell, model Vostro) and a video card (FWB-EC3402).

During the fatigue tests, after a certain number of cycles, the loading cycle was momentarily stopped to capture photoelastic images at different load levels. During the image acquisition process a phase-stepping method was required for a subsequent fringe analysis. Moreover, for each number of cycles, the crack length was measured by tracking of the crack tip from the direct observation of the fringe pattern.

4.5.5.2. Experimental procedure for DIC

As previously indicated, DIC specimens were manufactured with Al2024-T3. The equipment adopted for fatigue testing consisted on a MTS 370.10 servohydraulic machine with a maximum load capacity of 100 kN at a cycling frequency of 10 Hz (figure 4.15). The same fracture grips previously indicated for transmission photoelasticity were employed to connect the specimen to the loading system. In this case, the machine has two hydraulic grips with round wedges and

two special adapters to connect the fracture grips to the hydraulic grips were employed (figure 4.15). Finally, two pins were employed to connect the CT specimen to the fracture grips.

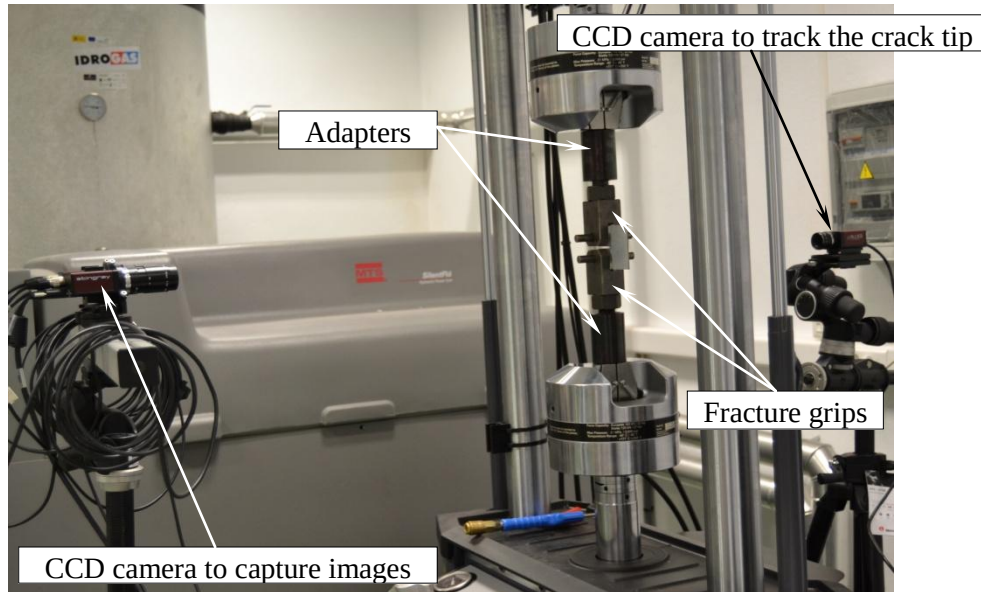


Figure 4.15. Illustration showing the experimental setup employed during fatigue experiments using DIC

The sequence of images required for DIC was captured using a CCD camera (Allied Vision Technology, model Stirling) placed perpendicularly to the specimen surface with a 75 mm lens controlled by an E6510 Intel Core i5 Dell-Latitude laptop through a FWB-EC3402 video card. In addition, the specimen surface was illuminated by a 150 W halogen light source. Captured images were processed using the commercial software package Vic-2D [202].

As in the case of photoelasticity, the test was stopped after a certain number of cycles and images were captured from the reference state to a deformed state at different load levels. To monitor the crack growth, an additional CCD camera (Allied Vision Technology, model Pike) with a 25 mm lens was located at the back of the specimen (see figure 4.15).

4.5.5.3. Equipment and experimental procedure for ESPI

Fatigue experiments using ESPI equipment were conducted using an ElectroPuls E3000 electromechanic machine with a dynamic load capacity of 3000 N at a cycling frequency of 10 Hz, with its frame fixed to an optical table (figure 4.11). To transmit the load from the machine to the specimen, a set of fracture grips was manufactured (figure 4.11). As in previous cases, the load was transmitted from the machine to the specimen with two pins.

The ESPI technique was implemented using the Q-300 ESPI-3D system. The ESPI head was mounted on a rigid structure (figure 4.11) attached to the optical table to isolate the head from the influence of the external vibrations. A sequence of images was captured by a CCD sensor

incorporated inside the ESPI head with a 25 mm lens. The ESPI sensor was connected to its control console composed by the PC and the VGA monitor. All the ESPI system was managed and controlled by the ISTR software.

During fatigue experiments, again after a certain number of cycles, the loading cycle was momentarily stopped to record a sequence of images at different load levels from a reference state. To obtain the displacement fields, the software performed an image process implementing a phase-shifting method. At each analysed state, the crack length was measured by directly tracking the crack tip over the captured images.

Chapter 5. Experimental methodology for SIF calculation

5.1. Introduction

In previous chapters it has been described how optical techniques such as transmission photoelasticity, DIC or ESPI seem to show a great potential to calculate the stress intensity factors from the analysis of the stress and displacement fields around the crack tip in growing fatigue cracks. In the case of transmission photoelasticity, the fringe order is directly related to the principal stress difference according to the stress-optic law (equation 2.6), while for the case of DIC and ESPI, the SIFs can be directly determined from the displacement fields observed at the vicinity of the crack tip. According to this, in order to accurately infer the stress intensity factors a methodology must be adopted.

In this chapter a description of the proposed methodology for the calculation of the stress intensity factors for each one of the studied techniques is presented. The chapter starts with a description of the adopted methodology for the calculation of the SIFs from the analysis of isochromatic data. Subsequently, the experimental methodology is extended to the case of DIC technique. Finally, the SIF methodology employed for DIC is extended to the case of ESPI technique. As previously indicated in chapter 2, these proposed methodologies are employed for the calculation of SIFs using four different models of crack tip stress/displacement fields, namely Westergaard's equations, Williams' expansion series, Muskhelishvili's complex potentials and the CJP model.

5.2. SIF calculation

In this section the experimental methodology for SIF calculation is described. Figure 5.1 schematically shows the different steps to implement the proposed methodology. Thus, the particularities depending on the adopted technique will be detailed in each one of the described steps.

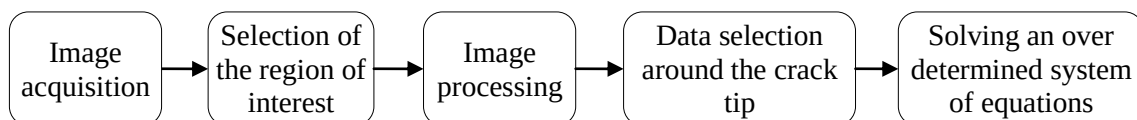


Figure 5.1. Experimental methodology for the calculation of stress intensity factors

5.2.1. Image acquisition

The first step in the experimental methodology for the calculation of the SIFs is capturing the images during fatigue experiments. In the case of transmission photoelasticity, the phase-stepping method by Patterson and Wang [94] has been adopted for the analysis of isochromatic data. Thus, for a particular state of loading, six images with different angular orientations of the output quarter-wave plate and the analyser in the circular polariscope were captured. Table 5.1 shows the different orientations for the output quarter-wave plate and the analyser together with the resultant light intensity for each image; where i_m is an intensity term that takes into account the incoming external light in polariscope, i_v is the light intensity observed when all optical axes are parallel, δ is the relative retardation and γ is the isoclinic angle.

Table 5.1. Output quarter-wave plate and the analyser angular orientations, and resultant light intensities for each image

Image	Angle of output quarter-wave plate (rad)	Angle of analyser (rad)	Light intensity
1	0	$\pi/4$	$i_1 = i_m - i_v \cos \delta$
2	0	$-\pi/4$	$i_2 = i_m + i_v \cos \delta$
3	0	0	$i_3 = i_m - i_v \sin \delta \sin 2\gamma$
4	$\pi/4$	$\pi/4$	$i_4 = i_m + i_v \sin \delta \cos 2\gamma$
5	$\pi/2$	$\pi/2$	$i_5 = i_m + i_v \sin \delta \sin 2\gamma$
6	$3\pi/4$	$3\pi/4$	$i_6 = i_m - i_v \sin \delta \cos 2\gamma$

Figure 5.2 shows an example of the observed fringe patterns for a 25.93 mm crack with a 20 N applied load for different quarter-wave plate and analyser orientations. As indicated in chapter 4, a circular polariscope configuration with a monochromatic light source was employed (figure 4.14).

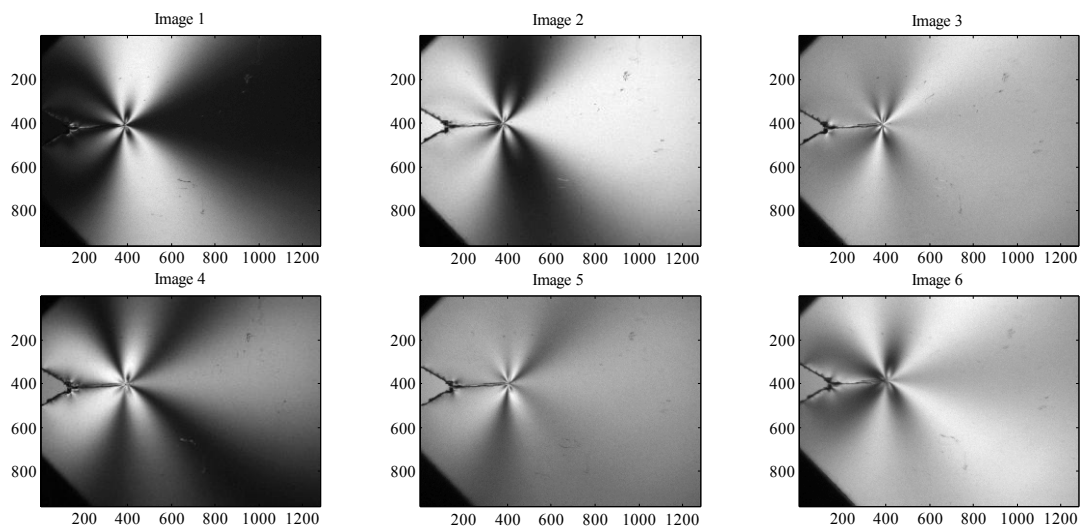


Figure 5.2. Fringe patterns observed for the six phase-stepping images ($a = 25.93$ mm, $P = 20$ N) required to implement transmission photoelasticity

Moreover, for the case of DIC and ESPI, a sequence of images was captured between a reference state (undeformed) and a deformed state at different loading steps. However, in ESPI, for each loading step four images were captured according to a four-step phase-shifting method [17] to determine the experimental value of the phase distribution $\phi(x,y)$. Thus, four intensity images with a known optical phase change ($\phi_i = \pi/2, \pi, 3\pi/2, 2\pi$) were acquired using a piezoelectric transducer located inside the ESPI head. Thus, the phase shift corresponding to the reference state was determined by the following expression:

$$\phi(x,y) = \tan^{-1} \frac{I_4(x,y) - I_2(x,y)}{I_3(x,y) - I_1(x,y)} \quad (5.1)$$

The same procedure was repeated at the different loading steps to obtain the phase distribution $\phi'(x,y)$ for the different deformed states. Finally, the phase difference was determined by subtracting the two phase distributions previously determined, $\Delta = \phi - \phi'$. The procedure is illustrated in figure 5.3. An example of wrapped phase map is shown in figure 5.4 at a 6.78 mm crack and a load of 600 N.

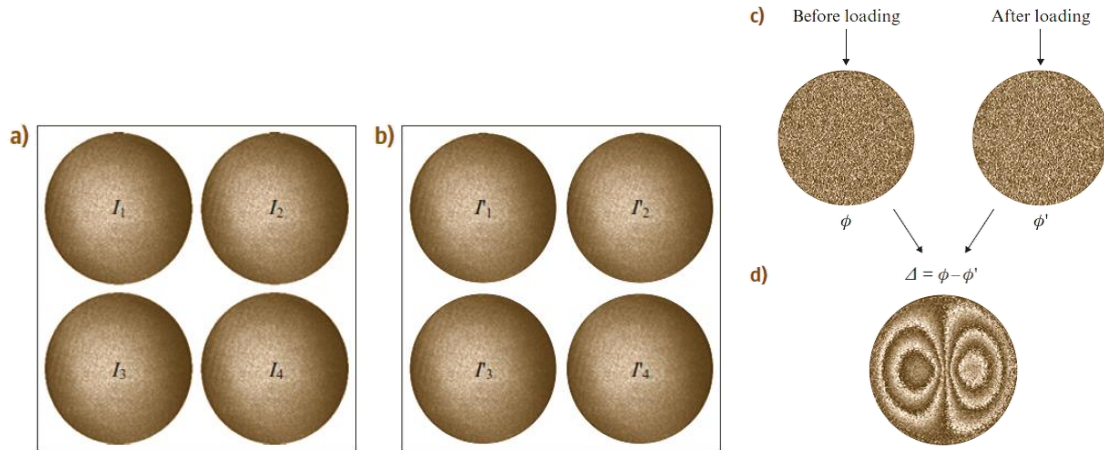


Figure 5.3. Four-step phase-shifting method employed in ESPI: a) Four stored intensity distributions I_1 to I_4 for the undeformed or preloaded state. b) Four stored intensity distributions I'_1 to I'_4 for the deformed or second loaded state. c) Phase distributions ϕ and ϕ' as a result of the measured intensities. d) Relative phase change Δ obtained by digital subtraction of ϕ' from ϕ

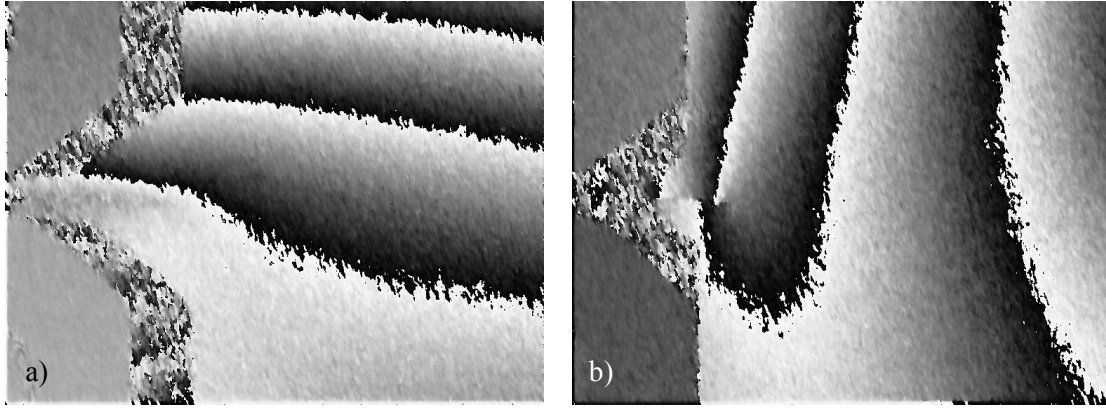


Figure 5.4. Wrapped phase maps in x-direction (a) and y-direction (b) obtained by ESPI at a crack length of 6.78 mm and a load level of 600 N

5.2.2. Selection of the region of interest

The adopted models describing crack tip stress/displacement fields are based on linear elastic fracture mechanics. According to this, in the case of transmission photoelasticity, a mask must be applied at the near-tip region and along the crack flanks (figure 5.5). The purpose of this mask is to remove from the analysis the generated plastic zone and the areas where the optical system does not have enough spatial resolution.

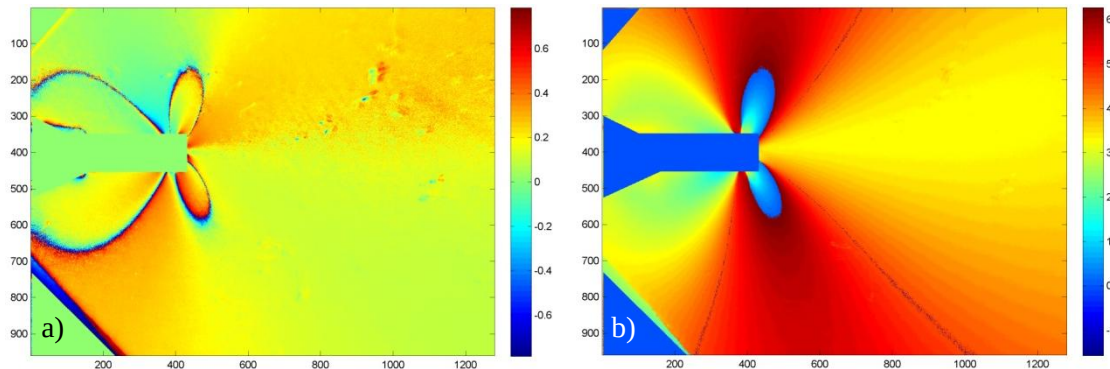


Figure 5.5. a) Isoclinic map and b) wrapped isochromatic map ($a = 25.93$ mm; $P = 20$ N) obtained by transmission photoelasticity

Moreover, for the case of DIC and ESPI, the areas corresponding to the notch and the grips were avoided in the SIF calculation since these areas do not have any relevant information for the measurement of the displacement fields experienced by the specimen.

5.2.3. Image processing

After to select the region of interest avoiding the generated plasticity and the areas with no relevant information, the next step in the proposed methodology for calculating the SIFs consists on the image processing. For transmission photoelasticity, the six images previously

captured using the phase-stepping method are modulated and they must be processed to obtain a continuous fringe map. The image processing is composed by the following steps: first, the isoclinic map (equation 5.2) is obtained from the images from 3 to 6 images. This map represents the angle between the directions of principal stresses and a reference direction. After that, the wrapped isochromatic map (equation 5.3) is obtained from the isoclinic map. It represents the relative retardation at each point of the specimen. Figure 5.5 shows the isoclinic and the wrapped isochromatic map for a 25.93 mm with a 20 N applied load. Finally, an unwrapping process must be performed to obtain a continuous fringe order map (figure 5.6).

Isoclinic map:
$$\gamma = \frac{1}{2} \tan^{-1} \frac{i_5 - i_3}{i_4 - i_6} \quad (5.2)$$

Wrapped isochromatic map:
$$\delta = \tan^{-1} \frac{(i_5 - i_3) \sin 2\gamma + (i_4 - i_6) \cos 2\gamma}{i_1 - i_2} \quad (5.3)$$

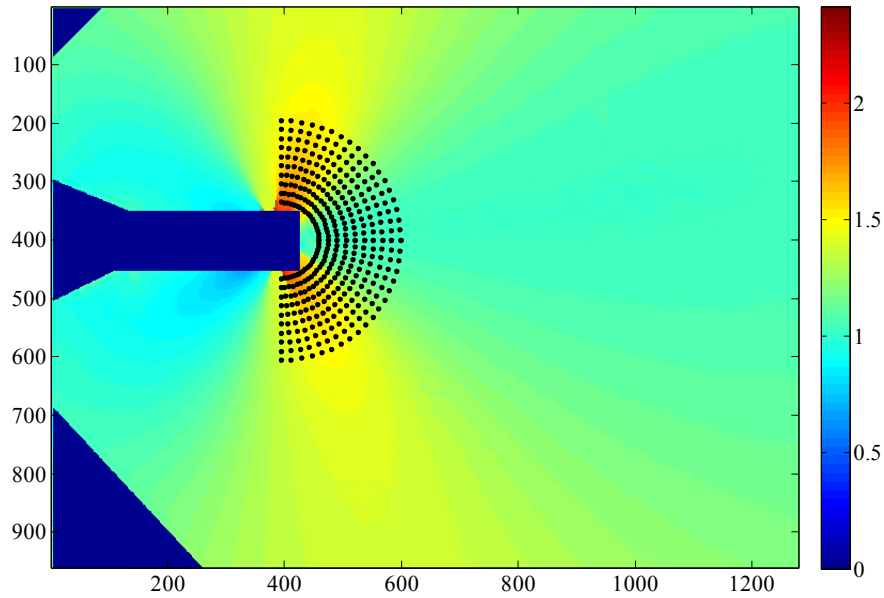


Figure 5.6. Illustration showing an unwrapped isochromatic map or fringe order map and the selection of points around the crack tip ($a = 25.93$ mm; $P = 20$ N)

The isochromatic image analysis has been conducted using a set of algorithms developed by Siegmund et al. [114] that are based on processing areas to demodulate the isoclinic map and using a quality map to guide the unwrapping process.

In the case of DIC, the sequence of captured images were processing using a cross-correlation algorithm [176]. For this task, the commercial software package Vic-2D [202] was employed. As a result, both horizontal and vertical displacements fields around the crack tip were inferred at the different loading steps between the minimum and maximum applied loads. Figure 5.7 shows the displacement fields measured for a 34.10 mm crack at a load level of 600 N. In this figure it can be clearly observed in dark blue the regions corresponding to the notch and the

grips where no relevant information is available and they must be avoided during image processing.

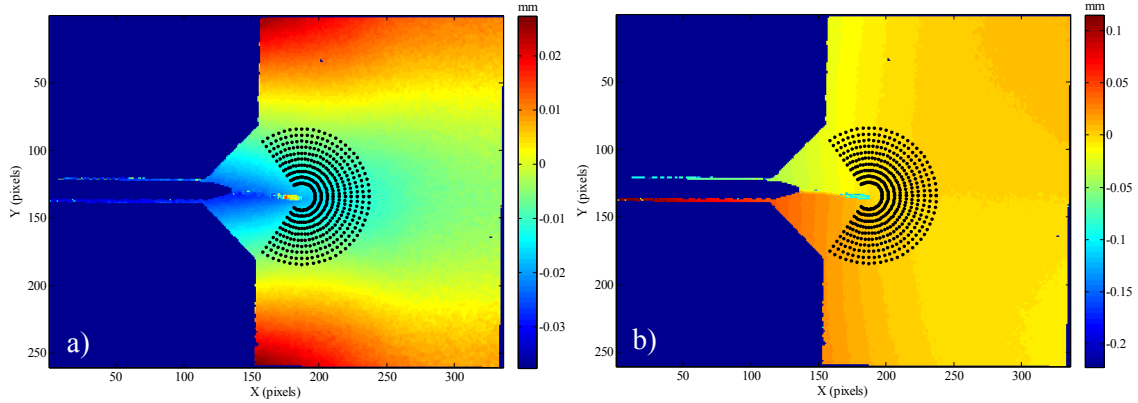


Figure 5.7. Illustration showing the horizontal (a) and vertical (b) displacement fields measured by DIC and the selection of points around the crack tip ($a = 34.10$ mm; $P = 600$ N)

Moreover, for ESPI, the sequence of images was processed by the ISTR software. However, the inferred relative phase difference is noisy, and exhibiting 2π phase jumps (modulo 2π). Thus, a filter algorithm is initially employed to reduce the signal-to-noise ratio. Moreover, optional median or average filtering algorithms can be also implemented in speckle interferometry. After that, a demodulation procedure in the observed fringe patterns (phase unwrapping) is performed. This consists of integrating or adding the phase values along a line or path. Each time the phase value jumps from zero to 2π , the actual phase value is increased by 2π . Similarly, 2π is subtracted from the actual phase value when the phase value jumps from 2π to zero. Finally, after the unwrapping process, the displacement fields are obtained. Figure 5.8 shows the horizontal and vertical displacement fields for a 6.78 mm crack length with an applied load of 600 N.

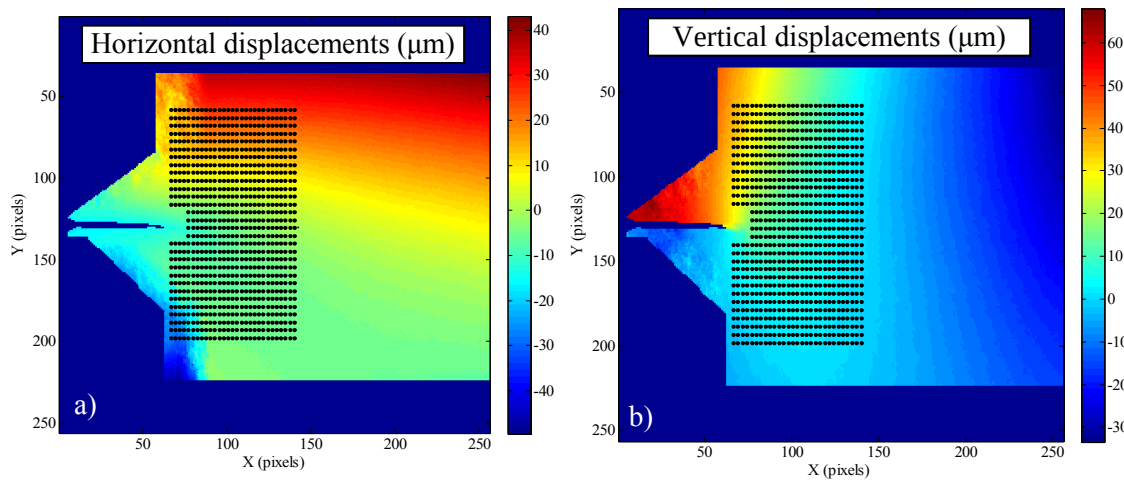


Figure 5.8. Horizontal (a) and vertical (b) displacement fields measured by ESPI for a crack length of 6.78 mm and a load level of 600 N; and the data points selected around the crack tip

5.2.4. Data selection around the crack tip

In the proposed methodology, SIFs are derived from the multi-point over-deterministic method developed by Sanford and Dally [7]. Thus, a set of data points at the region surrounding the crack tip must be selected from the fringe order map (for transmission photoelasticity) or the displacement fields (for DIC and ESPI) previously obtained. An important aspect is the way to define the region around the crack tip. Thus, for transmission photoelasticity and DIC an annular region has been adopted, while for ESPI the adopted region has been rectangular. According to this, two main parameters are selected to define these regions, namely an inner limit and another outer. In this way, the inner limit must be defined to prevent data being collected too close to the crack tip where plasticity effects exist. According to the above paragraph, the adopted inner limit was defined as the Dugdale plastic zone size to guarantee the removal of any plastic deformation around the crack. In addition, in the case of transmission photoelasticity, this inner limit will be restricted by the mask applied around the crack.

Moreover, the outer limit is less easy to define and usually it is adopted a distance from the crack tip where the crack tip stress/displacement equations no longer describe the state of stresses or displacements. According to this, in the case of transmission photoelasticity, this outer radius was defined from the loops generated surrounding the crack tip as can be clearly observed in figure 5.6. In addition, these loops can be also observed from the observation of the isoclinic and wrapped isochromatic maps (figure 5.5) that establish the influence area due to the stress concentration generated at the crack tip. Moreover, for DIC and ESPI, the outer limit was defined from the influence zone of the crack tip. This information can be extracted from the vertical displacement field where it is observed a change in the displacement orientation due to the interaction between the influence zone of the crack tip and the influence zone of the free edge of the specimen. In addition, in the case of ESPI, this information can be observed from the wrapped phase map as can be observed in figure 5.9.

Besides the two main parameters defined in the above paragraph, other secondary parameters are required to define the data collection around the crack tip. Thus, in the case of the annular mask, the data collection angle, the angle between lines and the number of points per line must be selected to define the data density. In addition, in the case of the rectangular mask, the data density is defined from the number of data points collected in the horizontal and vertical directions. According to this, Figures 5.6, 5.7 and 5.8 show the data collection from the defined parameters for transmission photoelasticity, DIC and ESPI respectively.

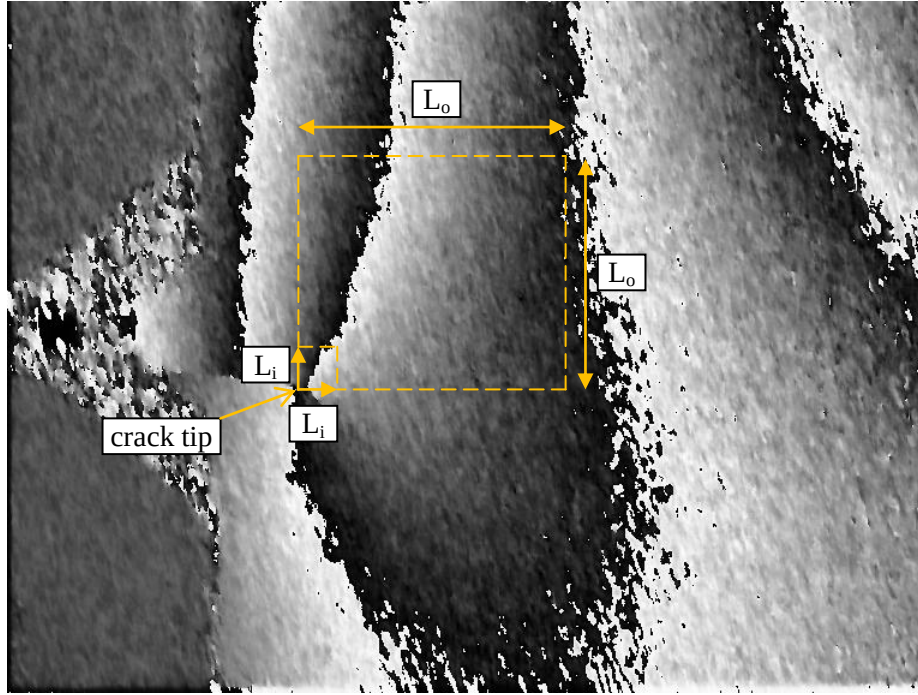


Figure 5.9. Definition of the region for data point collection from the direct observation of the phase map obtained by ESPI

Another important aspect is crack tip location. Thus, for transmission photoelasticity, it is defined from its direct selection over the second image corresponding to the phase-stepping method where the crack path can be clearly observed. In addition, in the case of DIC and ESPI, the crack tip is defined from its direct selection over the measured displacement fields.

In a subsequent section, a sensitivity analysis will be performed to evaluate how the parameters for the definition of the data collection can influence in the correct determination of the stress intensity factors.

5.2.5. Solving the over deterministic system of equations

In chapter 2, the four models describing crack tip stress/displacement fields were presented and discussed. However, depending on the adopted model, the mathematical description of the stress fields (equations 2.15, 2.19, 2.21 and 2.37) and the displacement fields (2.18, 2.20, 2.30 and 2.38) around the crack tip will be different. In addition, for transmission photoelasticity, according to the stress-optic law (equation 2.6), the observed stress fields are related to the fringe order. A nonlinear system of equations is obtained since the unknown coefficients are nonlinear. Moreover, for DIC and ESPI, the displacement fields are directly related to a set of unknown coefficients, but in this case the resultant system of equations is linear. Thus, an error function must be defined to relate the experimental fringe order or the measured displacement fields experimentally with a mathematical expression that varies depending on the adopted mathematical model:

Transmission photoelasticity	
Westergaard:	$g_i = f_i(K_I, K_{II}, \sigma_{0x}, r, \theta) - \frac{NF_\sigma}{t} = 0 \quad (5.4)$
Williams:	$g_i = f_i(A_{In}, A_{IIIn}, r, \theta) - \frac{NF_\sigma}{t} = 0 \quad (5.5)$
Muskhelishvili:	$g_i = f_i(A_0, B_0, A_M, B_M, z) - \frac{NF_\sigma}{t} = 0 \quad (5.6)$
CJP:	$g_i = f_i(A, B, C, D, E, z) - \frac{NF_\sigma}{t} = 0 \quad (5.7)$
DIC/ESPI	
Westergaard:	$\begin{Bmatrix} g_{u,i} \\ g_{v,i} \end{Bmatrix} = \begin{Bmatrix} f_{u,i}(K_I, K_{II}, \sigma_{0x}, r, \theta, E, \nu, a_0, c_0 r \cos \theta) \\ f_{v,i}(K_I, K_{II}, \sigma_{0x}, r, \theta, E, \nu, b_0, -c_0 r \sin \theta) \end{Bmatrix} - \begin{Bmatrix} u_i \\ v_i \end{Bmatrix} = 0 \quad (5.8)$
Williams:	$\begin{Bmatrix} g_{u,i} \\ g_{v,i} \end{Bmatrix} = \begin{Bmatrix} f_{u,i}(a_p, b_p, r, \theta, E, \nu, a_0, c_0 r \cos \theta) \\ f_{v,i}(a_p, b_p, r, \theta, E, \nu, b_0, -c_0 r \sin \theta) \end{Bmatrix} - \begin{Bmatrix} u_i \\ v_i \end{Bmatrix} = 0 \quad (5.9)$
Muskhelishvili:	$\begin{Bmatrix} g_{u,i} \\ g_{v,i} \end{Bmatrix} = \begin{Bmatrix} f_{u,i}(A_k^i, B_k^i, \alpha_k, \beta_k, z, E, \nu, a_0, c_0 r \cos \theta) \\ f_{v,i}(C_k^i, D_k^i, \alpha_k, \beta_k, z, E, \nu, b_0, -c_0 r \sin \theta) \end{Bmatrix} - \begin{Bmatrix} u_i \\ v_i \end{Bmatrix} = 0 \quad (5.10)$
CJP:	$\begin{Bmatrix} g_{u,i} \\ g_{v,i} \end{Bmatrix} = \begin{Bmatrix} f_{u,i}(A, B, C, D, E, F, z, G, \nu, a_0, c_0 r \cos \theta) \\ f_{v,i}(A, B, C, D, E, F, z, G, \nu, b_0, -c_0 r \sin \theta) \end{Bmatrix} - \begin{Bmatrix} u_i \\ v_i \end{Bmatrix} = 0 \quad (5.11)$

Where the sub-index i indicates the value of the error function evaluated at the i^{th} data point of with polar (r, θ) or Cartesian coordinates (x, y) .

It is important to indicate that for DIC and ESPI, in all the above mathematical expressions, rigid body motion terms have been considered. Therefore, three additional terms were included in the formulation (a_0 : horizontal translation, b_0 : vertical translation and c_0 : rotation). If rigid body motion is not considered, DIC algorithm will consider it as a virtual displacement induced by the applied load, affecting to the accuracy of the calculated SIF.

The error function is indicative of the error between experimental data and the mathematical model evaluated at the same coordinates referred to the crack tip at which isochromatic or displacement data were obtained. Consequently, the right values for the coefficients will be achieved when the error function is zero for all those data points at which the function is evaluated.

As indicated above, in the case of transmission photoelasticity, a nonlinear system of equations was obtained for each studied model. Therefore, an iterative calculation approach was necessary to solve the resultant system of equations. In the current research work, the nonlinear least-squares method was adopted. This method was implemented in Matlab[®] through the function called *lsqnonlin*. This function solves nonlinear least-squares curve fitting problems with the following mathematical formulation:

$$\min_x \|f(x)\|_2^2 = \min_x (f_1(x)^2 + f_2(x)^2 + \dots + f_n(x)^2) \quad (5.12)$$

Rather than computing the value $\min_x \|f(x)\|_2^2$ (the sum of squares), *lsqnonlin* requires an user-defined function to compute the vector-valued function

$$f(x) = \begin{bmatrix} f_1(x) \\ f_2(x) \\ \vdots \\ f_n(x) \end{bmatrix} \quad (5.13)$$

Then, problem can be formulated in vector terms and the optimisation problem can be restated as:

$$\min_x \|f(x)\|_2^2 = \min_x \left(\sum_{i=1}^n f_i(x)^2 \right) = \min_x (f_1(x)^2 + f_2(x)^2 + \dots + f_n(x)^2) \quad (5.14)$$

Where x is a vector and $f(x)$ is a function that returns a vector value. According to this, the different functions correspond to the function for each one of the evaluated data points.

In addition, the quality of the mathematical fitting has been assessed by two statistical parameters, such as the mean and the variance:

$$\mu = \frac{\sum_{i=1}^p h_i}{p}, \quad s^2 = \sum_{i=1}^p (h_i - \mu)^2 \quad (5.15)$$

Where:

Transmission photoelasticity	DIC/ESPI
$h_i = \frac{g_i}{N_i F_{\sigma/t}}$	$h_i = \frac{\begin{pmatrix} g_{u,i} \\ g_{v,i} \end{pmatrix}}{\begin{pmatrix} u_i \\ v_i \end{pmatrix}}$

(5.16)

Where i is the selected data point and p is the total number of collected data points.

Finally, the stress intensity factors are calculated from the solution of the unknown coefficients.

5.2.6. Graphical interface for the calculation of the SIFs

To aid in the calculation process of the stress intensity factors, a graphical computer interface has been built for transmission photoelasticity (figure 5.10) and DIC (figure 5.11) using Matlab[®]. The operational features of these computer programs are described in the following paragraphs:

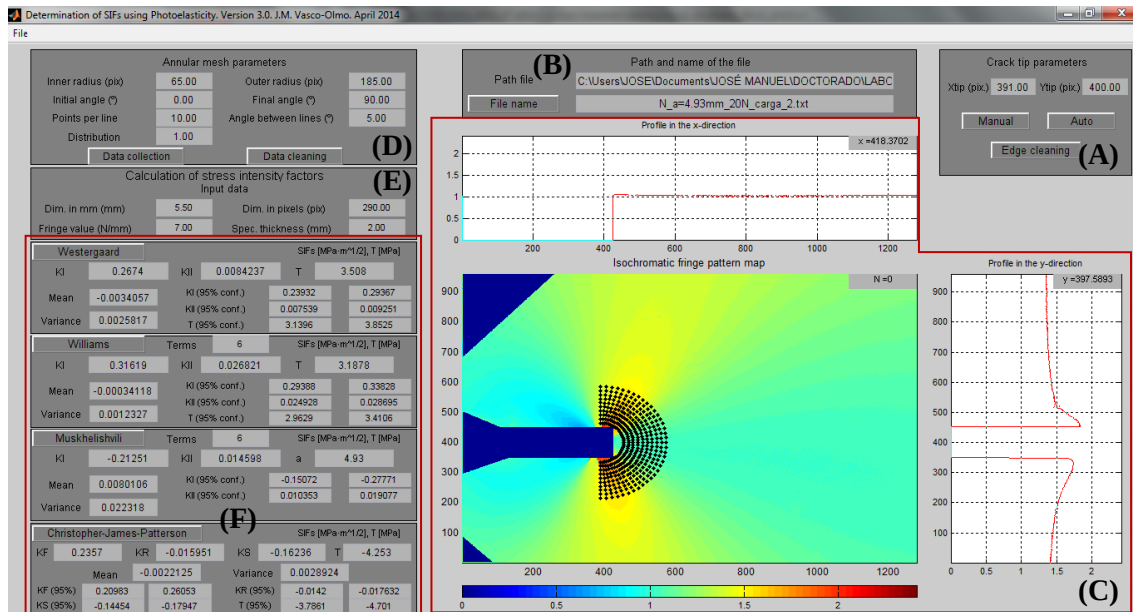


Figure 5.10. Graphical interface employed in the calculation of the SIFs from isochromatic data

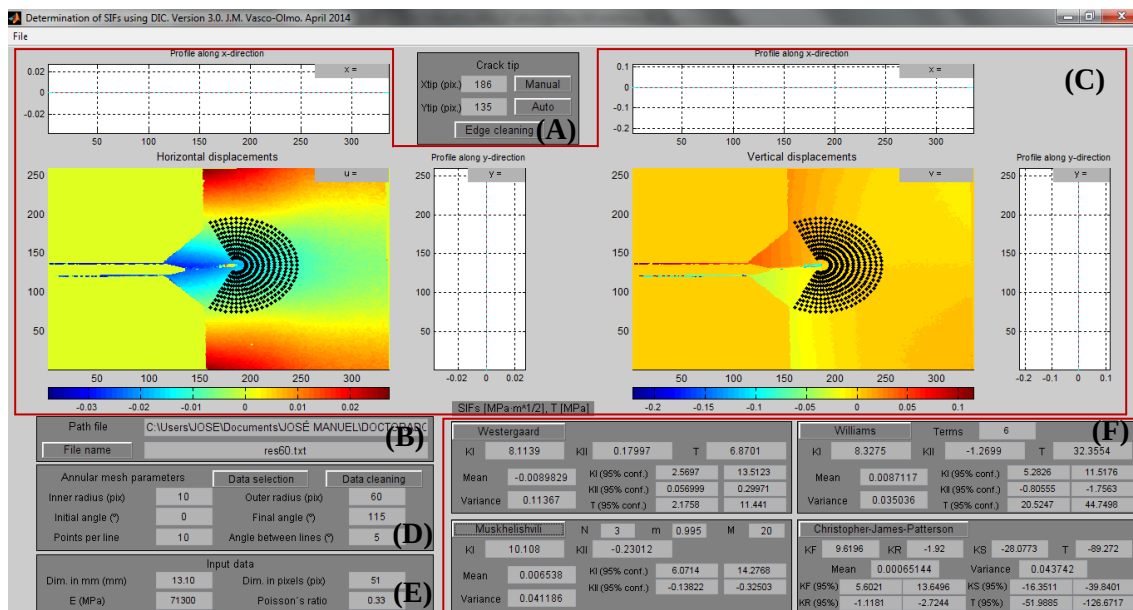


Figure 5.11. Graphical interface employed in the calculation of the SIFs from DIC data

In section A in figures 5.10 and 5.11 it is entered the crack tip location, that defined through its coordinates along the x and y axes in the analysed image. These crack tip coordinates can be manually introduced or by clicking over the image.

In section B in figures 5.10 and 5.11 the analysed image can be selected (isochromatic fringe pattern map or displacement fields). Thus, this image is introduced as a text file that contains the fringe order or the horizontal and vertical displacements in matrix form. Then, once image of study has been selected, it is shown in the window marked as C in figures 5.10 and 5.11. In

addition, profiles in the x and y -directions corresponding to the pointer position can be also visualised by clicking over the mouse.

Section D in figures 5.10 and 5.11 contains all the parameters required to define the annular region around the crack tip for the data collection. The coordinates of the collected data points must be referred to a reference system centred at the crack tip location, with its abscissa axis o parallel to the crack. Thus, the angular extension of the data collection area will be defined by two angles, namely the initial and final angles. These two angles are referred counterclockwise with respect to the x axis. Therefore, the data collection process consists on selecting a set of data points radially distributed with respect to the crack tip position. For this purpose, it is also required to define the angle between radial lines and the number of data points per radial line. In addition, for the graphical interface employed in transmission photoelasticity (figure 5.10), another parameter called in the interface as ‘Distribution’ has been created to define the way in which the collected data points are distributed along the radial lines. Thus, data points are distributed according to a power law from which as the exponent of the power law increases, the number of data points collected from the region close to the crack tip is also increased. According to this, a value for the parameter ‘Distribution’ equal to 1 will indicate that the data points will be equally spaced along radial lines. It seems that the use of this parameter has more sense for transmission photoelasticity since more data points could be collected at the near crack tip region where the stresses increase rapidly as a result of the stress concentration.

Another important issue that must be considered is that in fatigue cracks some plasticity is generated both at the flanks and at the crack tip. Thus, an annular region must be defined with an inner radius that excludes the data points immediately ahead of the crack tip. According to this, the radially distributed data points previously described are collected between two concentric circles, centred at the crack tip. In this way, by adjusting the inner radius, data points affected by plasticity can be avoided. Moreover, the outer radius allows defining the data collection over the region influenced by the crack tip stress fields.

Additional input data are also required to calculate the stress intensity factors. In section E in figures 5.10 and 5.11, four parameters have to be defined to estimate the SIFs. The conversion factor between pixels and mm (in the interfaces there are two parameters to define a known dimension in pixels and the same dimension in mm), the material fringe constant and the specimen thickness in the case of transmission photoelasticity (figure 5.10). Moreover, for DIC, besides the conversion factor, the Young’s modulus and the Poisson’s ratio of the analysed material must be entered (figure 5.11).

Finally, in the last section (section F in figure 5.10 and 5.11), stress intensity factors and the T-stress for each one of the adopted mathematical models can be determined. There is a section

for each model, the mean (μ) and the variance (s^2) of the mathematical fitting. The criterion adopted for a good data set is that which produces values of $\mu \pm 2s$ which are less than 5 % of the SIF solution. Therefore, there is a 95% probability that the true SIF K_T drawn from the distribution (μ, s) will be contained in the interval $(1 + \mu - 2s)K_S \leq K_T \leq (1 + \mu + 2s)K_S$, where K_S is the solution of the least-squares fit. In this way, these confidence intervals for the SIFs are calculated for each one of the models (section F in figures 5.10 and 5.11).

Moreover, to calculate the SIFs using ESPI, section D in figure 5.11 was adapted to define a rectangular region around the crack tip for the data collection.

5.2.7. Sensitivity analysis of the data collection

The main objective of the current thesis is the evaluation of fatigue crack shielding from the analysis of the SIFs. Mathematical models such as Westergaard's, [7, 153], Williams's [4, 6, 136] and Muskhelishvili's [5, 9, 19, 178] models have been extensively employed to study the crack tip stress/displacement fields. However, CJP model is the only mathematical model considering the shielding effect due to plasticity ahead of the crack tip. In this section a sensitivity analysis of the parameters required for data collection is performed. For this purpose, a photoelastic image (fringe order map) and the horizontal and vertical displacement fields for a pure mode I crack have been artificially generated using the Westergaard's crack tip stress field equations [18]. Thus, a value of the stress intensity factor is first defined to create the artificial images. Subsequently, a selection of data points are collected at the crack tip position and the SIF calculated. The difference between the initial SIF and the calculated SIF will provide a clear indication about how the different data collection parameters would influence the mathematical fitting during the SIF calculation. Thus, the fringe order map and the horizontal and vertical displacement fields (figure 5.14) were created for $K_I = 10 \text{ MPa}\cdot\text{m}^{1/2}$ and $\sigma_{0x} = 50 \text{ MPa}$. The image size was 320 by 240 pixels, the crack length was 10 mm and the crack tip coordinates were (100, 120) pixels.

The first parameter evaluated was the final angle of the annular mask of data collection. Angles between 80 and 120° were analysed (tables 5.2 and 5.3), using an initial angle of 0° with 10 data points per line, an angle between radial lines of 5° and equally spaced data points along the radial lines. In addition, an inner radius of 10 pixels and an outer radius of 60 pixels were adopted to create the annular mask around the crack tip. Figures 5.14 and 5.15 show the data collection area for an annular angle of 100° for the isochromatic fringe map and the displacement fields respectively.

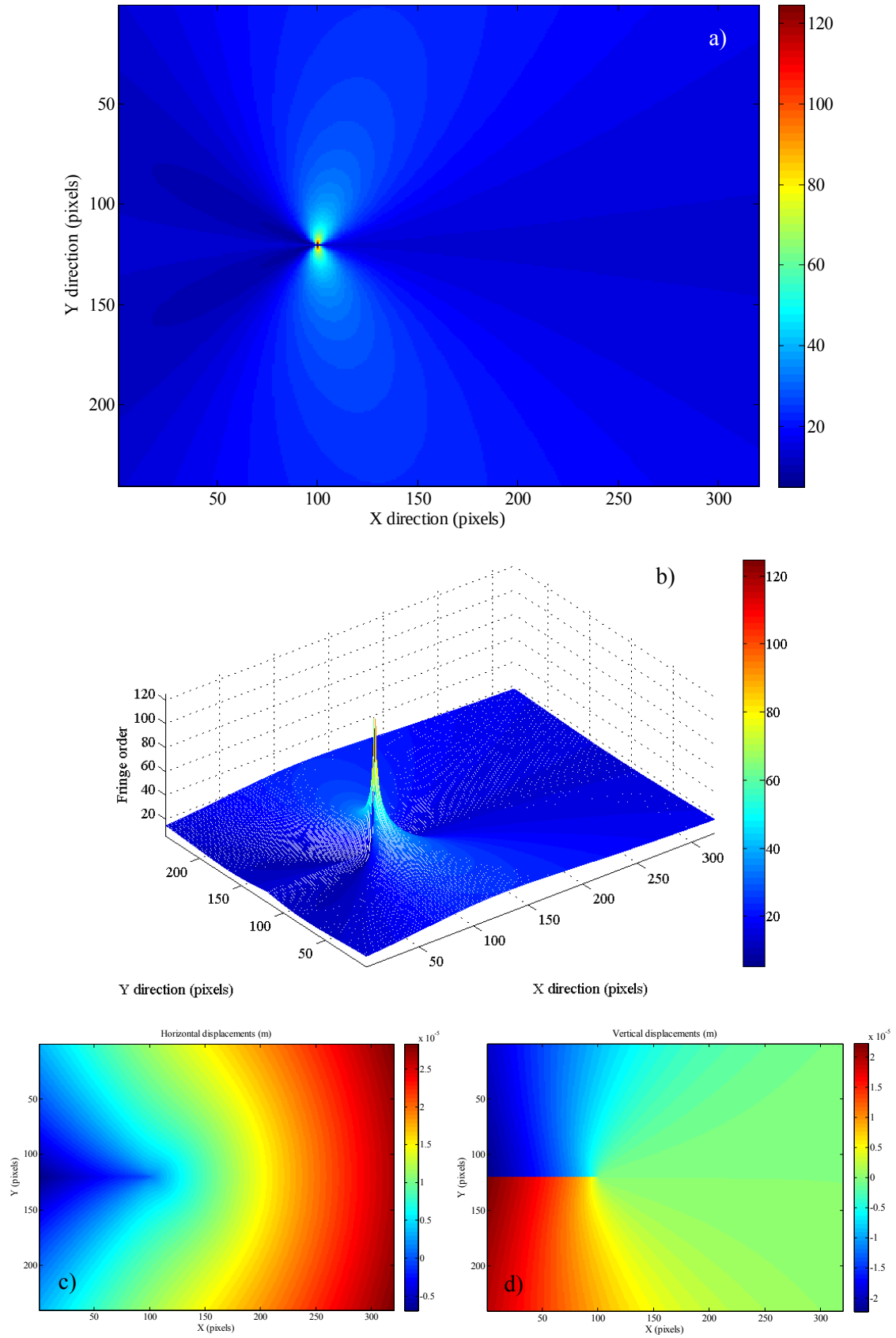


Figure 5.13. 2D (a) and 3D (b) artificial isochromatic fringe maps and artificial horizontal (c) and vertical (d) displacement fields for sensitivity analysis ($K_I = 10 \text{ MPa} \cdot \text{M}^{1/2}$, $\sigma_{0x} = 50 \text{ MPa}$, $a = 10 \text{ mm}$, image size 320 by 240 pixels, CTIP = (100, 120) pixels)

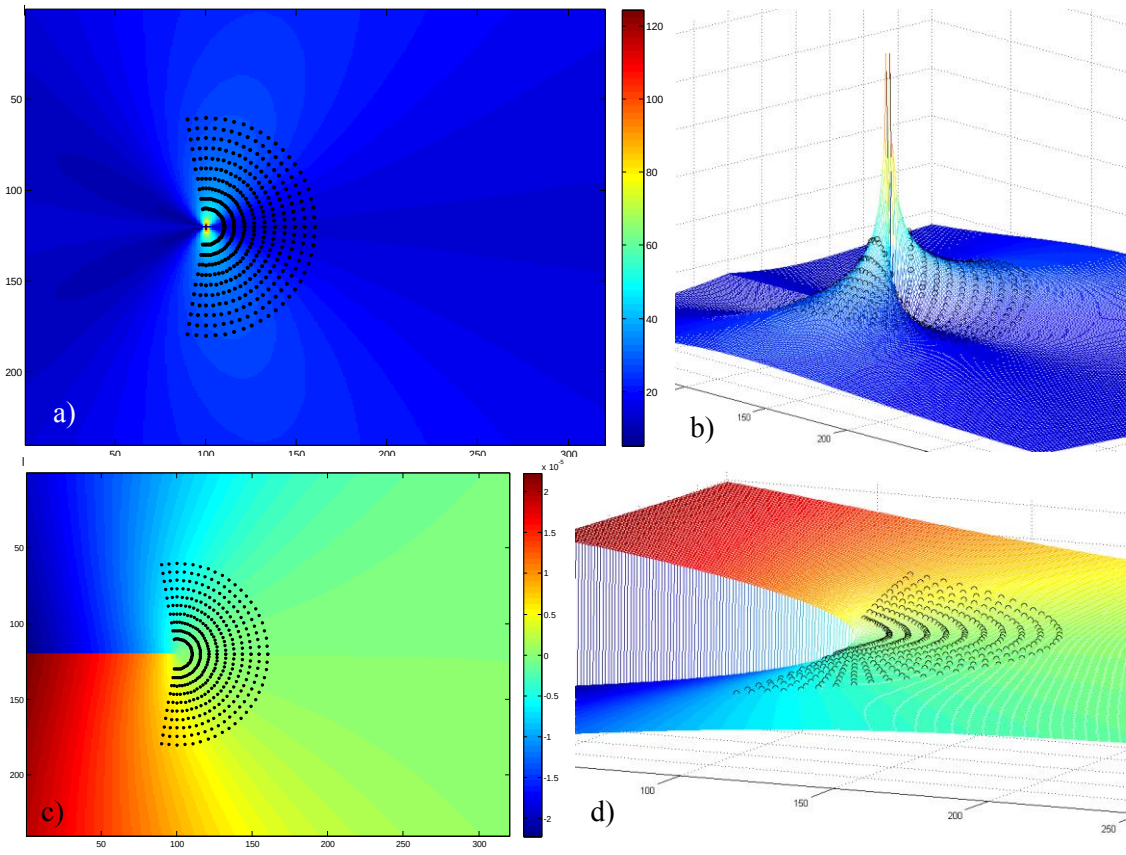


Figure 5.14. Detail of the data collection area around the crack tip (inner radius = 10 pixels, outer radius = 60 pixels, initial angle = 0° , final angle = 100° , points per line = 10, angle between lines = 5° and distribution of data points equally spaced). a) 2D and b) 3D fringe order map and c) 2D and d) 3D vertical displacement field

Table 5.2. Results showing the final angle influence of the annular mask in SIF calculation.

Results for a 10 mm pure mode I crack ($K_I = 10 \text{ MPa}\cdot\text{m}^{1/2}$ and $\sigma_{0x} = 50 \text{ MPa}$)

Final angle (degrees)	K_F ($\text{MPa}\cdot\text{m}^{1/2}$)	K_R ($\text{MPa}\cdot\text{m}^{1/2}$)	K_S ($\text{MPa}\cdot\text{m}^{1/2}$)	σ_{0x} (MPa)	Mean	Variance
From isochromatic data						
80	10	$-1.4907\cdot 10^{-7}$	$-2.1073\cdot 10^{-7}$	-50	$-6.8121\cdot 10^{-10}$	$1.4384\cdot 10^{-16}$
85	10	$-1.4301\cdot 10^{-7}$	$-4.2402\cdot 10^{-7}$	-50	$-3.9775\cdot 10^{-10}$	$1.3694\cdot 10^{-16}$
90	10	$-1.3073\cdot 10^{-7}$	$-6.0144\cdot 10^{-7}$	-50	$-1.5082\cdot 10^{-10}$	$1.3479\cdot 10^{-16}$
95	10	$-1.5648\cdot 10^{-7}$	$-6.5986\cdot 10^{-7}$	-50	$-1.2378\cdot 10^{-10}$	$1.3183\cdot 10^{-16}$
100	10	$-1.5804\cdot 10^{-7}$	$-7.2327\cdot 10^{-7}$	-50	$-8.0663\cdot 10^{-11}$	$1.2923\cdot 10^{-16}$
105	10	$-1.1642\cdot 10^{-7}$	$-3.4757\cdot 10^{-7}$	-50	$-1.6697\cdot 10^{-10}$	$1.2666\cdot 10^{-16}$
110	10	$-3.8012\cdot 10^{-8}$	$8.5748\cdot 10^{-8}$	-50	$-3.0826\cdot 10^{-10}$	$1.252\cdot 10^{-16}$
115	10	$3.1566\cdot 10^{-9}$	$1.6433\cdot 10^{-7}$	-50	$-3.0428\cdot 10^{-10}$	$1.2657\cdot 10^{-16}$
120	10	$2.2832\cdot 10^{-8}$	$1.5759\cdot 10^{-7}$	-50	$-2.691\cdot 10^{-10}$	$1.308\cdot 10^{-16}$
From displacement data						
80	10	$5.0073\cdot 10^{-7}$	$9.9082\cdot 10^{-7}$	50	$4.9\cdot 10^{-10}$	$1.1491\cdot 10^{-16}$
85	10	$4.3484\cdot 10^{-7}$	$8.5276\cdot 10^{-7}$	50	$4.1202\cdot 10^{-10}$	$1.0939\cdot 10^{-16}$
90	10	$3.1423\cdot 10^{-7}$	$5.4003\cdot 10^{-7}$	50	$1.7596\cdot 10^{-10}$	$1.0375\cdot 10^{-16}$
95	10	$3.2331\cdot 10^{-7}$	$5.3063\cdot 10^{-7}$	50	$2.8633\cdot 10^{-10}$	$1.0052\cdot 10^{-16}$
100	10	$3.3777\cdot 10^{-7}$	$6.857\cdot 10^{-7}$	50	$5.1993\cdot 10^{-10}$	$9.8464\cdot 10^{-17}$
105	10	$1.7939\cdot 10^{-7}$	$5.1817\cdot 10^{-7}$	50	$2.4848\cdot 10^{-10}$	$9.7165\cdot 10^{-17}$
110	10	$1.1139\cdot 10^{-7}$	$4.8133\cdot 10^{-7}$	50	$1.8498\cdot 10^{-10}$	$9.4502\cdot 10^{-17}$

115	10	$2.1892 \cdot 10^{-7}$	$5.6812 \cdot 10^{-7}$	50	$4.3726 \cdot 10^{-10}$	$9.1209 \cdot 10^{-17}$
120	10	$-1.4535 \cdot 10^{-7}$	$2.9776 \cdot 10^{-7}$	50	$-5.1623 \cdot 10^{-10}$	$1.1178 \cdot 10^{-16}$

As a way to validate the previous results, the fringe order map generated from the Westergaard's model (figure 5.15a) was compared with that generated from the CJP model coefficients (figure 5.15b) inferred after processing the artificial image. The vertical profiles at the crack tip for both images and the difference between them has been also shown in figure 5.15c and 5.15d respectively. In addition, the displacement fields generated from Westergaard's model (figure 5.13c and 5.13d) were compared with those generated from the CJP model coefficients (figure 5.16a and 5.16b) inferred after processing the captured image. In addition, the difference between the displacement fields generated artificially from Westergaard's equations and those obtained from the CJP model coefficients are shown in figure 5.16c and 5.16d.

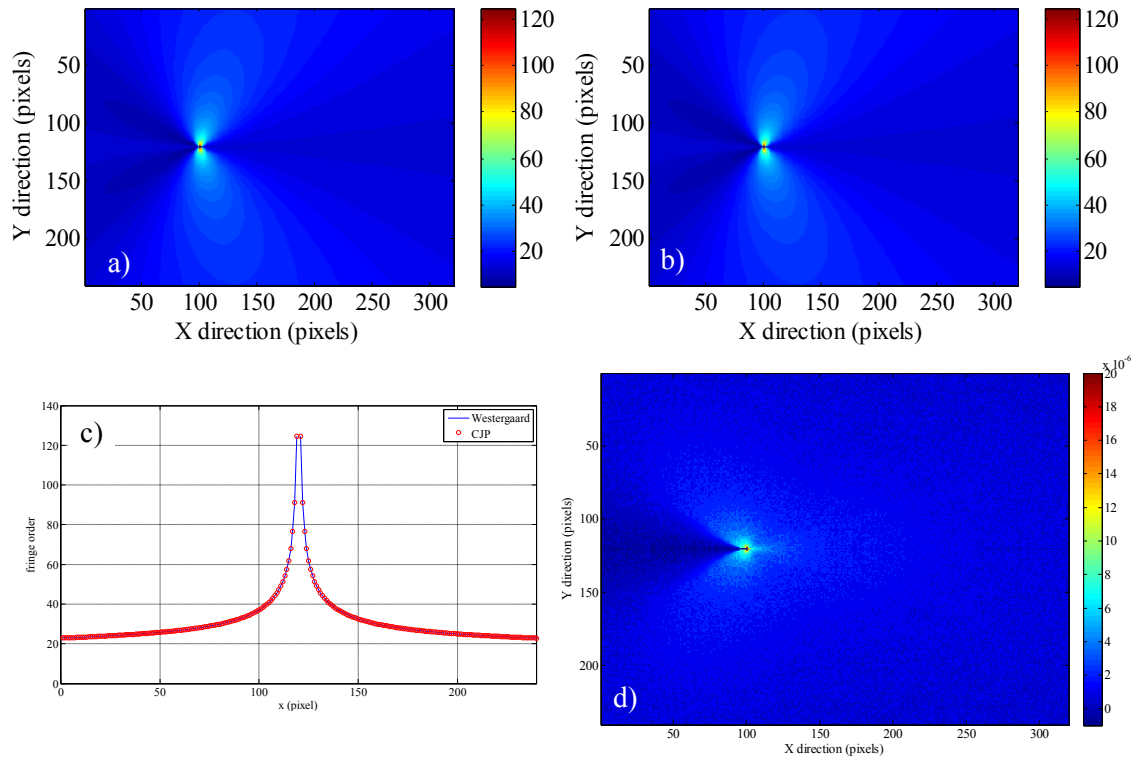


Figure 5.15. Illustration showing the error introduced after fitting the CJP model for a 10 mm pure mode I ($K_I = 10 \text{ MPa} \cdot \text{m}^{1/2}$, $\sigma_{0x} = 50 \text{ MPa}$). a) Initial fringe order map generated using the Westergaard's model, b) fringe order generated using the CJP model coefficients, c) vertical profile at the crack tip for both previous images, d) difference between both previous images

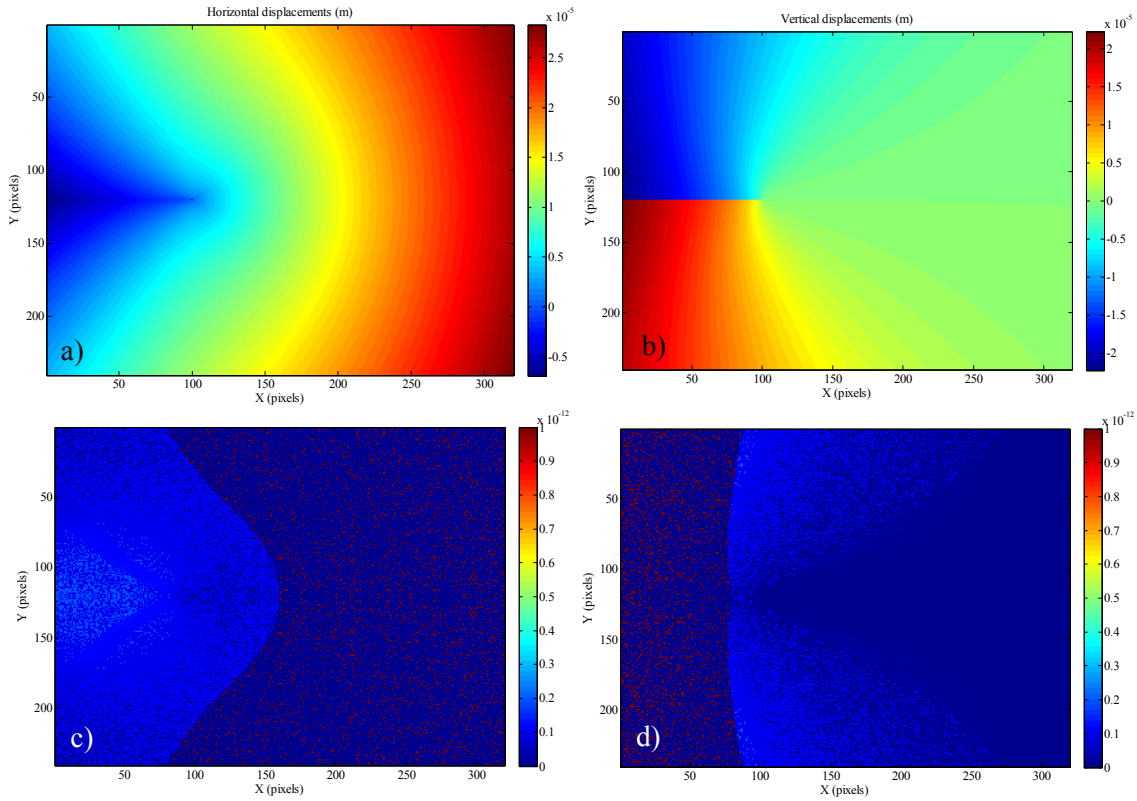


Figure 5.16. Illustration showing the induced error after performing the mathematical fitting using CJP model for a 10 mm pure mode I crack ($K_I = 10 \text{ MPa}\cdot\text{m}^{1/2}$, $\sigma_{0x} = 50 \text{ MPa}$). Horizontal (a) and vertical (b) displacement fields generated using the CJP model coefficients, c) difference between artificial and CJP horizontal displacement fields and d) difference between artificial and CJP vertical displacement fields

The number of data points per radial line was also evaluated. Thus, the influence in the SIF calculation for a number of data points between 8 and 20 was also analysed. The inner and the outer radius were of 10 and 60 pixels respectively, the initial angle was set to 0° , the final angle was 100° with an angle between lines of 5° and a distribution of data points equally spaced along the radial lines. Results are shown in table 5.3.

Table 5.3. Results showing the influence of the number of data points collected along the radial lines. Results for a 10 mm pure mode I crack ($K_I = 10 \text{ MPa}\cdot\text{m}^{1/2}$ and $\sigma_{0x} = 50 \text{ MPa}$)

Data points per line	K_F ($\text{MPa}\cdot\text{m}^{1/2}$)	K_R ($\text{MPa}\cdot\text{m}^{1/2}$)	K_S ($\text{MPa}\cdot\text{m}^{1/2}$)	σ_{0x} (MPa)	Mean	Variance
From isochromatic data						
8	10	$-7.6094\cdot 10^{-8}$	$-7.7409\cdot 10^{-7}$	-50	$5.8539\cdot 10^{-11}$	$1.4604\cdot 10^{-16}$
10	10	$-1.5804\cdot 10^{-7}$	$-7.2327\cdot 10^{-7}$	-50	$-8.0663\cdot 10^{-11}$	$1.2923\cdot 10^{-16}$
12	10	$1.6846\cdot 10^{-8}$	$-3.5681\cdot 10^{-7}$	-50	$3.7269\cdot 10^{-10}$	$1.5232\cdot 10^{-16}$
14	10	$-3.414\cdot 10^{-8}$	$-8.6307\cdot 10^{-7}$	-50	$2.5774\cdot 10^{-11}$	$1.5365\cdot 10^{-16}$
16	10	$-8.5065\cdot 10^{-8}$	$-1.0287\cdot 10^{-7}$	-50	$7.3637\cdot 10^{-11}$	$1.6194\cdot 10^{-16}$
18	10	$-3.7224\cdot 10^{-8}$	$-8.0359\cdot 10^{-7}$	-50	$2.3178\cdot 10^{-10}$	$1.5641\cdot 10^{-16}$
20	10	$-1.0382\cdot 10^{-7}$	$-9.3567\cdot 10^{-7}$	-50	$4.1916\cdot 10^{-11}$	$1.542\cdot 10^{-16}$
From displacement data						
8	10	$1.5171\cdot 10^{-7}$	$3.3986\cdot 10^{-7}$	50	$5.4928\cdot 10^{-10}$	$1.193\cdot 10^{-16}$

10	10	$3.3777 \cdot 10^{-7}$	$6.857 \cdot 10^{-7}$	50	$5.1993 \cdot 10^{-10}$	$9.8464 \cdot 10^{-17}$
12	10	$5.1914 \cdot 10^{-8}$	$9.6883 \cdot 10^{-8}$	50	$4.7504 \cdot 10^{-10}$	$1.0559 \cdot 10^{-16}$
14	10	$2.432 \cdot 10^{-7}$	$4.8285 \cdot 10^{-7}$	50	$5.2656 \cdot 10^{-10}$	$9.4154 \cdot 10^{-17}$
16	10	$1.2054 \cdot 10^{-7}$	$1.3767 \cdot 10^{-7}$	50	$5.8045 \cdot 10^{-11}$	$1.0259 \cdot 10^{-16}$
18	10	$1.8004 \cdot 10^{-7}$	$3.8754 \cdot 10^{-7}$	50	$2.757 \cdot 10^{-10}$	$9.4146 \cdot 10^{-17}$
20	10	$1.4948 \cdot 10^{-7}$	$3.0877 \cdot 10^{-7}$	50	$3.1838 \cdot 10^{-10}$	$9.899 \cdot 10^{-17}$

Another analysed parameter was the angle between the radial lines. A range of angles between 1 and 10° was analysed. The rest of required parameters were the same that those used in the previous analysis, with a number of data points per line of 10. This analysis is shown in table 5.4.

Table 5.4. Results showing the influence of the angle between radial lines. Results for a 10 mm pure mode I crack ($K_I = 10 \text{ MPa} \cdot \text{m}^{1/2}$ and $\sigma_{0x} = 50 \text{ MPa}$)

Angle between lines (degrees)	K_F ($\text{MPa} \cdot \text{m}^{1/2}$)	K_R ($\text{MPa} \cdot \text{m}^{1/2}$)	K_S ($\text{MPa} \cdot \text{m}^{1/2}$)	σ_{0x} (MPa)	Mean	Variance
From isochromatic data						
1	10	$-3.572 \cdot 10^{-8}$	$-3.5927 \cdot 10^{-7}$	-50	$9.2366 \cdot 10^{-11}$	$1.4042 \cdot 10^{-16}$
2	10	$-1.1151 \cdot 10^{-7}$	$-6.4001 \cdot 10^{-7}$	-50	$4.1188 \cdot 10^{-11}$	$1.4763 \cdot 10^{-16}$
3	10	$-4.7632 \cdot 10^{-8}$	$-4.3806 \cdot 10^{-7}$	-50	$8.0595 \cdot 10^{-11}$	$1.4155 \cdot 10^{-16}$
4	10	$-6.9485 \cdot 10^{-8}$	$-6.0936 \cdot 10^{-7}$	-50	$-2.0175 \cdot 10^{-10}$	$1.5626 \cdot 10^{-16}$
5	10	$-1.5804 \cdot 10^{-7}$	$-7.2327 \cdot 10^{-7}$	-50	$-8.0663 \cdot 10^{-11}$	$1.2923 \cdot 10^{-16}$
6	10	$-1.5755 \cdot 10^{-7}$	$-6.6547 \cdot 10^{-7}$	-50	$9.9099 \cdot 10^{-12}$	$1.395 \cdot 10^{-16}$
7	10	$-1.2056 \cdot 10^{-7}$	$-5.1009 \cdot 10^{-7}$	-50	$1.3411 \cdot 10^{-10}$	$1.3318 \cdot 10^{-16}$
8	10	$-6.9486 \cdot 10^{-8}$	$-6.0936 \cdot 10^{-7}$	-50	$-2.0256 \cdot 10^{-10}$	$1.5687 \cdot 10^{-16}$
9	10	$-1.3295 \cdot 10^{-8}$	$-5.5963 \cdot 10^{-7}$	-50	$-1.1768 \cdot 10^{-10}$	$1.5791 \cdot 10^{-16}$
10	10	$-1.5038 \cdot 10^{-7}$	$-3.9172 \cdot 10^{-7}$	-50	$-2.9578 \cdot 10^{-10}$	$1.3302 \cdot 10^{-16}$
From displacement data						
1	10	$1.0056 \cdot 10^{-7}$	$1.2495 \cdot 10^{-7}$	50	$1.7404 \cdot 10^{-10}$	$1.0679 \cdot 10^{-16}$
2	10	$6.355 \cdot 10^{-8}$	$1.2676 \cdot 10^{-7}$	50	$2.8876 \cdot 10^{-10}$	$1.1239 \cdot 10^{-16}$
3	10	$8.7173 \cdot 10^{-8}$	$1.23 \cdot 10^{-7}$	50	$3.1808 \cdot 10^{-10}$	$1.1346 \cdot 10^{-16}$
4	10	$1.6123 \cdot 10^{-7}$	$5.6554 \cdot 10^{-7}$	50	$7.5037 \cdot 10^{-10}$	$1.073 \cdot 10^{-16}$
5	10	$3.3777 \cdot 10^{-7}$	$6.857 \cdot 10^{-7}$	50	$5.1993 \cdot 10^{-10}$	$9.8464 \cdot 10^{-17}$
6	10	$1.0198 \cdot 10^{-7}$	$2.771 \cdot 10^{-7}$	50	$5.7401 \cdot 10^{-10}$	$1.2112 \cdot 10^{-16}$
7	10	$1.3019 \cdot 10^{-7}$	$3.5648 \cdot 10^{-7}$	50	$9.4756 \cdot 10^{-10}$	$1.0677 \cdot 10^{-16}$
8	10	$1.6217 \cdot 10^{-7}$	$5.6531 \cdot 10^{-7}$	50	$4.6991 \cdot 10^{-10}$	$1.2045 \cdot 10^{-16}$
9	10	$1.7421 \cdot 10^{-7}$	$4.5731 \cdot 10^{-7}$	50	$6.2924 \cdot 10^{-10}$	$1.0827 \cdot 10^{-16}$
10	10	$2.8174 \cdot 10^{-7}$	$6.1311 \cdot 10^{-7}$	50	$8.9407 \cdot 10^{-10}$	$8.9706 \cdot 10^{-17}$

The last parameter evaluated was the point distribution along the radial lines. Thus, as it was previously indicated a power law was employed define the distribution of the data points along the radial lines. Thus, as the exponent of the power law increases, data points will be more concentrated close to the crack tip. Therefore, a value of 1 for the exponent of the power law will indicate that the data points will be equally spaced along the radial lines. As previously indicated, it has more sense to use this parameter in the case of transmission photoelasticity where the stresses increase in the region near to the crack tip due to the stress concentration. The rest of the parameters used for the definition of the annular mask were the same as those employed in previous analyses (inner radius of 10 pixels, outer radius of 60 pixels, initial and

final angles of 0 and 100°, 10 data points per line and angle between lines of 5°). Results are represented in table 5.5.

Table 5.5. Results showing the influence of the distribution of the data points along radial lines from the analysis of isochromatic data. Results for a 10 mm pure mode I crack ($K_I = 10 \text{ MPa}\cdot\text{m}^{1/2}$ and $\sigma_{0x} = 50 \text{ MPa}$)

Distribution	K_F ($\text{MPa}\cdot\text{m}^{1/2}$)	K_R ($\text{MPa}\cdot\text{m}^{1/2}$)	K_S ($\text{MPa}\cdot\text{m}^{1/2}$)	σ_{0x} (MPa)	Mean	Variance
1	10	$-1.5804\cdot 10^{-7}$	$-7.2327\cdot 10^{-7}$	-50	$-8.0663\cdot 10^{-11}$	$1.2923\cdot 10^{-16}$
2	10	$-1.7953\cdot 10^{-7}$	$-1.3165\cdot 10^{-7}$	-50	$2.3351\cdot 10^{-10}$	$1.5981\cdot 10^{-16}$
3	10	$1.6959\cdot 10^{-8}$	$-6.4996\cdot 10^{-7}$	-50	$-2.3745\cdot 10^{-10}$	$1.2632\cdot 10^{-16}$
4	10	$-7.6654\cdot 10^{-8}$	$-5.7235\cdot 10^{-7}$	-50	$7.7067\cdot 10^{-11}$	$1.5801\cdot 10^{-16}$
5	10	$-9.8086\cdot 10^{-8}$	$-1.0125\cdot 10^{-6}$	-50	$-3.4111\cdot 10^{-10}$	$1.3101\cdot 10^{-16}$
6	10	$1.3384\cdot 10^{-9}$	$-2.6836\cdot 10^{-7}$	-50	$-2.1459\cdot 10^{-10}$	$1.3946\cdot 10^{-16}$
7	10	$-1.4898\cdot 10^{-8}$	$-4.7166\cdot 10^{-7}$	-50	$-2.3385\cdot 10^{-10}$	$1.4661\cdot 10^{-16}$
8	10	$-1.5039\cdot 10^{-7}$	$-1.1345\cdot 10^{-6}$	-50	$-1.8903\cdot 10^{-10}$	$1.3776\cdot 10^{-16}$
9	10	$-1.1673\cdot 10^{-7}$	$-7.0943\cdot 10^{-7}$	-50	$-1.3771\cdot 10^{-11}$	$1.3718\cdot 10^{-16}$
10	10	$-5.7037\cdot 10^{-8}$	$-4.8687\cdot 10^{-7}$	-50	$-3.9905\cdot 10^{-10}$	$1.3066\cdot 10^{-16}$

Another significant parameter in the calculation of the SIFs is the selection of the position of the crack tip. Thus, an error of a few of pixels in the crack tip location has been intentionally introduced to investigate how it affects to the SIF calculation and the quality of the fitting. The parameters adopted for this analysis were the same as in previous analyses with data points equally spaced along radial lines. Employed to define the annular mesh around the crack tip have been the following: an inner radius of 10 pixels, an outer radius of 60 pixels, an initial angle of the mesh of 0°, a final angle of 100°, a number of data points per line of 10, using an angle between lines of 5° and being them equally spaced along these lines. Results are shown in table 5.6.

Table 5.6. Results showing the influence of the crack tip location in the SIF calculation. Results for a 10 mm pure mode I crack ($K_I = 10 \text{ MPa}\cdot\text{m}^{1/2}$ and $\sigma_{0x} = 50 \text{ MPa}$)

Crack tip (X_{tip} , Y_{tip}) (pixels)	K_F ($\text{Mpa}\cdot\text{m}^{1/2}$)	K_R ($\text{Mpa}\cdot\text{m}^{1/2}$)	K_S ($\text{Mpa}\cdot\text{m}^{1/2}$)	σ_{0x} (Mpa)	Mean	Variance
From isochromatic data						
(100, 120)	10	$-1.5804\cdot 10^{-7}$	$-7.2327\cdot 10^{-7}$	-50	$-8.0663\cdot 10^{-11}$	$1.2923\cdot 10^{-16}$
(101,120)	15.7786	1.9473	-1.7098	-48.3034	0.0079067	0.00089359
(102,120)	21.4356	4.0577	-1.5493	-42.2674	0.013237	0.0025355
(99,120)	4.1628	-1.8121	3.2417	-48.0118	-0.0070883	0.0013243
(98,120)	7.6621	2.8459	40.5789	45.2028	0.01695	0.014456
(100,121)	10.2322	0.039098	-0.57324	-51.2466	-0.00099652	0.00107
(100,122)	10.9483	0.17133	-2.183	-54.6741	-0.0036819	0.0044795
(100,119)	10.2322	0.039098	-0.57324	-51.2466	-0.00099652	0.00107
(100,118)	10.9483	0.17133	-2.183	-54.6741	-0.0036819	0.0044795
(101,121)	16.0358	1.9996	-2.2191	-49.3509	0.0072809	0.0020462
(102,122)	22.5484	4.329	-3.2136	-45.4104	0.011479	0.0071756
(99,119)	4.366	-1.7937	2.5019	-49.7408	-0.0088346	0.0022258
(98,118)	-0.95605	-3.4463	4.93	-49.5818	-0.019593	0.009079
From displacement data						
(100, 120)	10	$3.3777\cdot 10^{-7}$	$6.857\cdot 10^{-7}$	50	$5.1993\cdot 10^{-10}$	$9.8464\cdot 10^{-17}$

(101,120)	14.7382	2.0992	2.3377	50.8867	0.00084776	$2.2517 \cdot 10^{-5}$
(102,120)	18.8786	3.9438	4.2106	51.1565	0.0016999	$7.3219 \cdot 10^{-5}$
(99,120)	4.6741	-2.3505	-2.8278	48.4084	-0.00079637	$3.3884 \cdot 10^{-5}$
(98,120)	-1.2133	-4.9424	-6.1623	46.0289	-0.0014927	0.00016584
(100,121)	10.0982	0.035609	-0.06787	49.6919	-0.0063633	0.0035231
(100,122)	10.3923	0.14221	-0.27121	48.7691	-0.0058307	0.0071779
(100,119)	10.0982	0.035609	-0.06787	49.6919	-0.0063633	0.0035231
(100,118)	10.3923	0.14221	-0.27121	48.7691	-0.0058307	0.0071779
(101,121)	14.8359	2.1348	2.2726	50.5868	-0.0050819	0.0032381
(102,122)	19.2499	4.0791	3.9522	49.9853	-0.0033357	0.0062705
(99,119)	4.7691	-2.3165	-2.9008	48.0898	-0.0076307	0.0040465
(98,118)	-0.85905	-4.8177	-6.4827	44.7045	-0.0082156	0.0097785

5.2.7.1. Discussion of the results

As a general observation, the adopted data collection methodology has been found to provide SIF results with a very good level of agreement respect to those SIF values employed to generate artificial photoelastic and displacement images. Different parameters affecting the definition of the data collection area, such as, the final angle of data collection (results presented in table 5.2), the number of data points per radial line (results shown in table 5.3), the angle between lines (results in table 5.4) and the distribution of data points along radial lines (results presented in table 5.5) have been investigated. Thus, in all of the cases the mean and the variance were taking extremely low values indicating a good quality fitting. Moreover, it has been also observed that from the analysis of isochromatic data, T-stress values obtained with CJP model were the same as those initially defined to generate the artificial images, but with sign inverted.

Another important aspect investigated was the effect of introducing a possible error in locating the crack tip in the photoelastic image when experimental data were collected around the crack tip. This analysis has been presented in table 5.6. From the analysis of these results it can be established that CJP model was very sensitive to the location of the crack tip along the x-direction. A 2 pixels error in the crack tip provided K_F values higher than twice the K_I employed to generate the artificial images. However, a 2 pixels error in y-direction provided differences in K_F close to 10% respect to K_I . Therefore, it can be concluded that especial care must be taken to define the crack tip location in the direction along the crack growth. However, for real fatigue cracks, as it will be explained in next the next chapter, the correct crack tip location will be defined according to the minimum mean and variance values after performing the mathematical fitting.

5.2.7.2. Conclusions

From the sensitivity analysis of the data collection, the following conclusions have been established:

- 1- Similar results were obtained from the analysis of the angular extension of collected data (results presented in table 5.2). Thus, the area of data collection does not seem to be sensitive to the angular extension of the annular mask. This can be visualised by very low values of the mean and the variance of the mathematical fitting.
- 2- Data density has been investigated through the number of data points per radial line and the angle between these radial lines. It has not been observed significant differences as the number of data points increases from 210 to 2010 (tables 5.3 and 5.4). Therefore, the SIF calculation has been insensitive to the number of collected data points, as indicated by extremely low values of the mean and the variance.
- 3- Data concentration has been evaluated through the distribution of data points along the radial lines. From the analysis of the exponent of the power law used for defining the distribution of data points along the radial lines (table 5.5), it has been observed that the SIF values were insensitive to the exponent of the power law for data point distribution.
- 4- T-stress values obtained for the analysis of isochromatic data using the CJP model were the same as those initially defined to generate the artificial images, but with sign inverted. Therefore, it seems that the CJP model, in the case of transmission photoelasticity, establishes a T-stress value with the sign inverted respect to Westergaard's equations.
- 5- CJP model has been shown quite sensitive to variations in the crack tip location. This sensitivity has been especially high for the case of the x crack tip coordinate. However, variations of the crack tip location in y -direction does not seem to be so critical.

5.3. Concluding remarks

According to previous work presented in this chapter, the following remarks can be extracted:

- 1- Four models describing the stress/displacement field around the crack tip have been adopted to calculate the stress intensity factors. These models are based on the Westergaard's stress field equations, Williams' expansion series, Muskhelishvili's complex potentials and CJP model. Thus, isochromatic data obtained in the region surrounding the crack tip are analysed to determine the SIFs using transmission photoelasticity, while for DIC and ESPI the horizontal and vertical displacement fields measured around the crack tip are employed for SIF calculation. The experimental methodology adopted for each of the adopted optical techniques is based on the MPOD method. Therefore, a set of data points must be collected around the crack tip. For the case of transmission photoelasticity and DIC an annular region around the crack tip with its origin in the crack tip has been defined; while for ESPI, a rectangular mask has been adopted. The MPOD method has been employed to calculate the SIFs from the analysis of

experimental data. As a result, an over determined system of equations must be solved to determine the SIFs. In the case of transmission photoelasticity the fringe order is not linearly related with the models coefficients and a nonlinear system of equations must be solved. For this purpose, the nonlinear least squares algorithm has been adopted to solve the system of equations. On contrary, in the case of DIC and ESPI, the displacements are linearly related with the unknown coefficients and a linear system of equations is obtained.

- 2- The scope of the current thesis is the experimental evaluation of the shielding effects in a growing fatigue crack from the analysis of the stress intensity factors. Therefore, among the four employed models, especial interest seems to show the use of the CJP model since in its formulation it is considered the effect of plasticity induced shielding.
- 3- The proposed methodology has been evaluated using artificially generated images from Wetergaard's model. The methodology in the case of CJP model has been shown to be insensitive to the data point collection parameters. Nevertheless, the calculation of the SIFs has been shown quite sensitive to errors in the definition of the crack tip position.
- 4- For mode I cracks, K_F values from CJP model show a total level of agreement with K_I values employed in the generation of artificial images. In the case of T-stress, values obtained from CJP model using isochromatic data had their sign inverted respect to those employed in artificial images. However, in the case of displacement fields, T-stress values show a total agreement with those employed in artificial images.

Chapter 6. Experimental results: crack shielding evaluation

6.1. Introduction

This section is concerned with the practical application of transmission photoelasticity, DIC and ESPI for the analysis of real growing fatigue cracks in CT specimens. In the previous chapter an experimental methodology for SIF determination from the analysis of isochromatic data (in the case of transmission photoelasticity) and displacement fields (in the case of DIC and ESPI) around a fatigue crack tip was described. This methodology has been demonstrated to work very well for pure mode I artificial images generated from Westergaard's equations. In this chapter, the adopted methodology has been extended to the case of real mode I cracks. Initially, the crack shielding effect has been studied on polycarbonate specimens since it is a material sufficiently ductile to allow fatigue crack growth and to show clear evidence of plasticity-induced fatigue crack shielding [2]. Since the polycarbonate is a transparent and birefringent material, transmission photoelasticity has been employed to evaluate shielding. Thus, an approach to estimate the opening (K_{op}) and closing (K_{cl}) stress intensity factors has been proposed. A comparative study between the four analytical models evaluated has been conducted to establish which is the most suitable for the evaluation of plasticity-induced crack shielding. Thus, the crack opening (P_{op}) and closing (P_{cl}) loads can be calculated from K_{op} and K_{cl} . Subsequently, the study of fatigue crack shielding has been extended to 2024-T3 aluminium using DIC. In addition, the adopted methodology to estimate P_{op} and P_{cl} has been verified by compliance based technique. Finally, ESPI technique has been employed to analyse fatigue crack shielding. This technique makes it possible to measure smaller displacements than DIC. Before this study, a calibration procedure for the ESPI system has been conducted using a calibration specimen and a calibration protocol. In addition, a methodology to estimate plastic zone size at the crack tip has been proposed. Thus, this methodology is based on the direct measurement of the plastic strain fields around the crack tip.

6.2. Experimental results

In this section it is reported crack shielding experimental results for growing fatigue cracks employing the three optical techniques evaluated in the current thesis. For this purpose, different fatigue tests on polycarbonate CT specimens (transmission photoelasticity), 2024-T3 aluminium

(DIC) and commercially pure titanium (ESPI) were conducted. It must be indicated that the polycarbonate specimens are referenced as ‘PC’, those manufactured in 2024-T3 aluminium as ‘Al’ and ‘Ti’ is used to reference titanium specimens. Thus, the same specimen dimensions (figure 4.12a) were employed in transmission photoelasticity and DIC, while a 3.6 smaller specimen was adopted for ESPI experiments (figure 4.12b).

6.2.1. Experimental results obtained by transmission photoelasticity

In this section the crack shielding results for growing fatigue cracks using transmission photoelasticity are presented. For this purpose, two fatigue tests at different R -ratios were conducted on polycarbonate CT specimens (figure 4.12a). The first test was performed at low R -ratio ($R = 0$) and the second one at high R -ratio ($R = 0.47$). Test conditions with the specimen references are shown in table 6.1.

Table 6.1. Loading conditions for fatigue tests conducted using transmission photoelasticity

Test reference	Specimen reference	P_{min} (N)	P_{max} (N)	R -ratio
PE_R=0	PC_CT3	0	50	0
PE_R=0.47	PC_CT4	35	75	0.47

During fatigue tests, the six images corresponding to the adopted phase-stepping method [94] were captured at different load states between the minimum and maximum at different crack lengths. Figure 6.1 shows the evolution of the crack length as a function of the number of cycles for the two specimens tested. The crack length was measured using the second image of the phase-stepping method for the crack tip tracking. In addition, to establish the relationship between pixels and millimetres, a 5.5 mm diameter circular piece of paper was stuck over the specimen surface.

Figure 6.2 shows the second phase-stepping image corresponding to PC_CT3 specimen at minimum load for different crack lengths. Figure 6.3 shows the second phase-stepping image for different load steps during loading for a 31.05 mm crack.

Figures 6.4 and 6.5 show the experimental SIFs as a function of the loading cycle for the specimen tested at low R -ratio at crack lengths of 31.05 and 35.01 mm respectively. Thus, mode I SIF (K_I) from Westergaard’s, Williams’s and Muskhelishvili’s models and the opening (K_F) and retarding (K_R) SIFs from CJP model have been plotted. In addition, K_I values calculated according to equation 6.1 [206] have been also represented.

$$\Delta K_{nom} = \frac{\Delta P}{t\sqrt{W}} \frac{2 + \frac{a}{W}}{\left(1 - \frac{a}{W}\right)^{3/2}} \left[0.886 + 4.64 \frac{a}{W} - 13.32 \left(\frac{a}{W}\right)^2 + 14.72 \left(\frac{a}{W}\right)^3 - 5.6 \left(\frac{a}{W}\right)^4 \right] \quad (6.1)$$

Where ΔP is the applied load range, t and W are the specimen thickness and width respectively and a is the crack length.

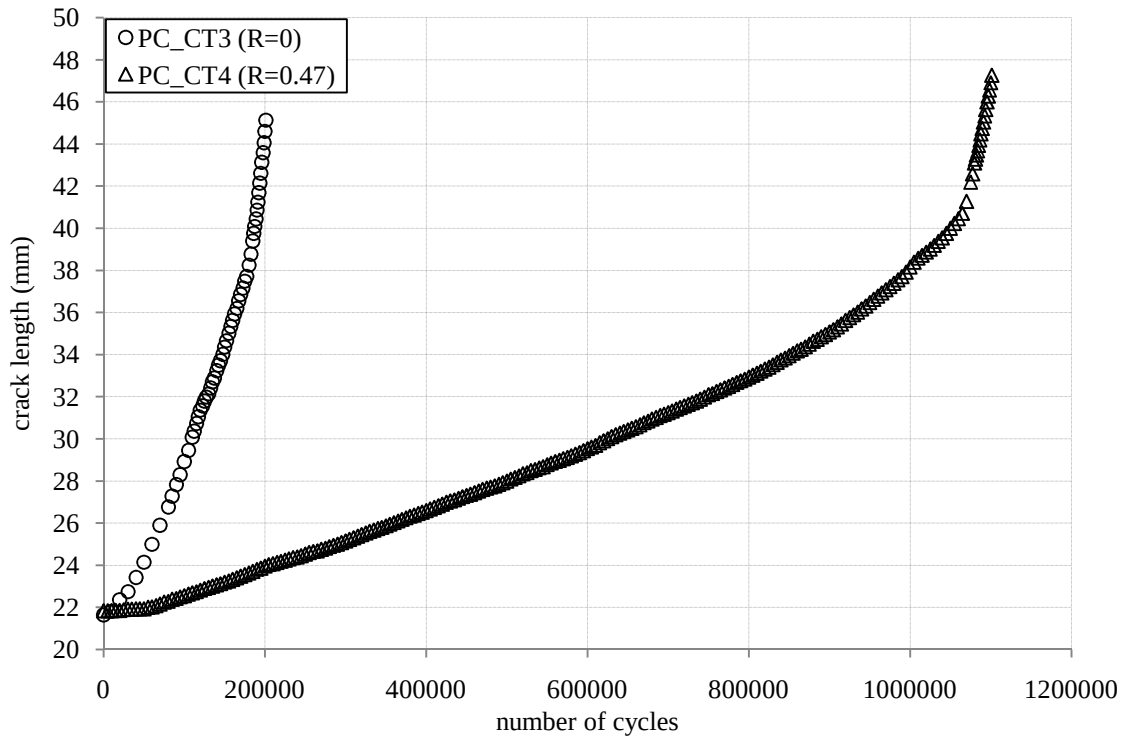
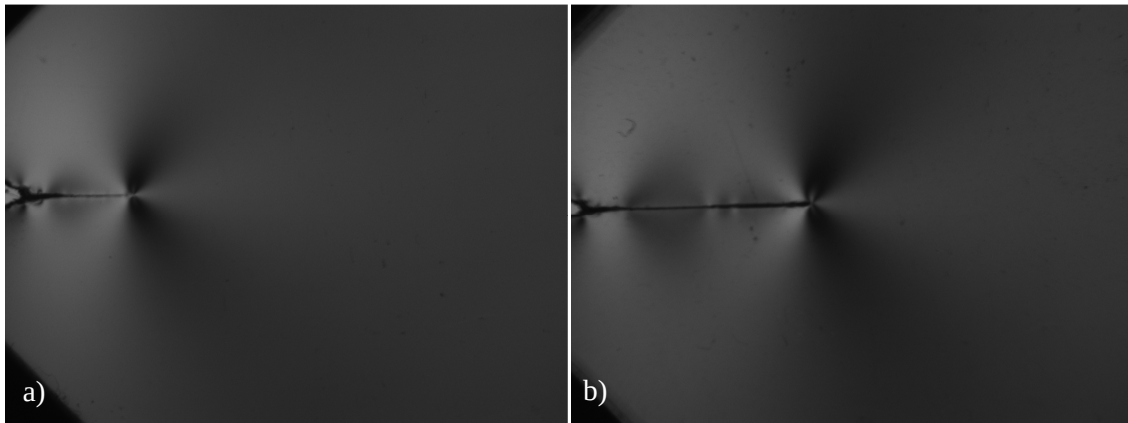


Figure 6.1. Crack length versus number of cycles for the specimens tested for the evaluation of fatigue crack shielding using transmission photoelasticity



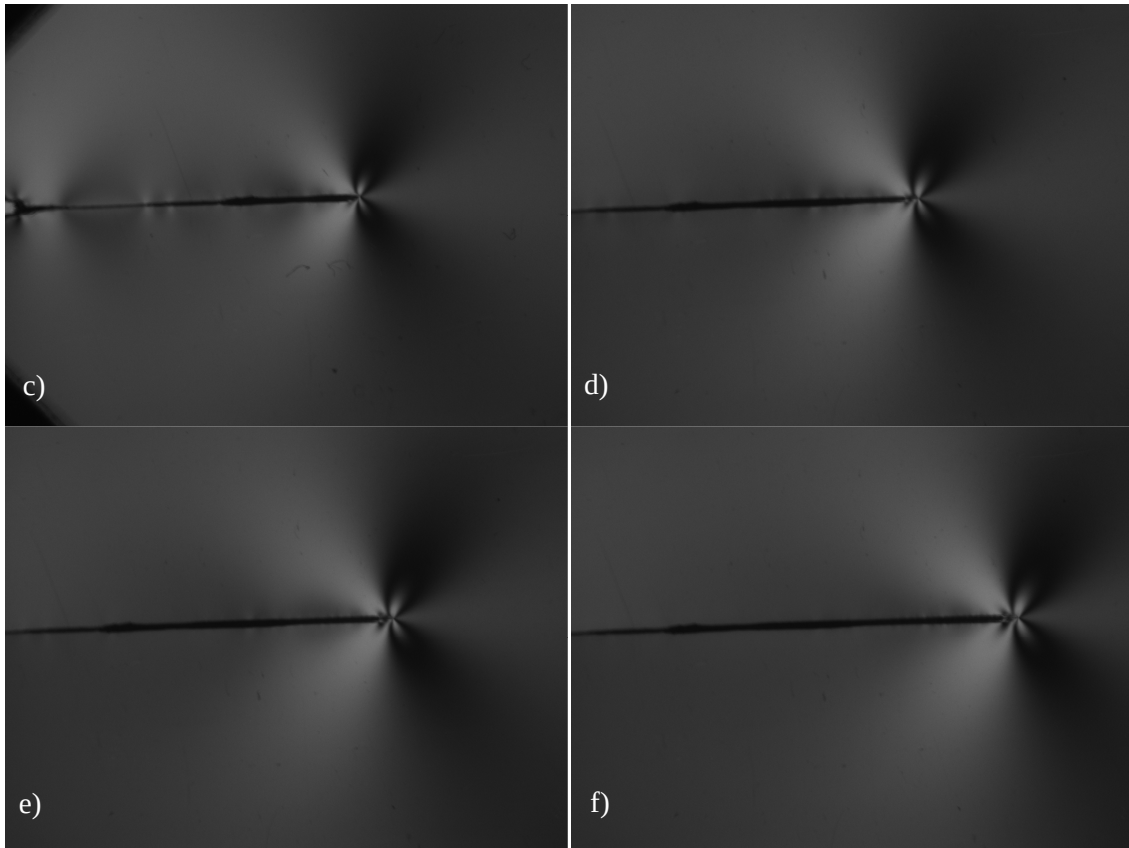
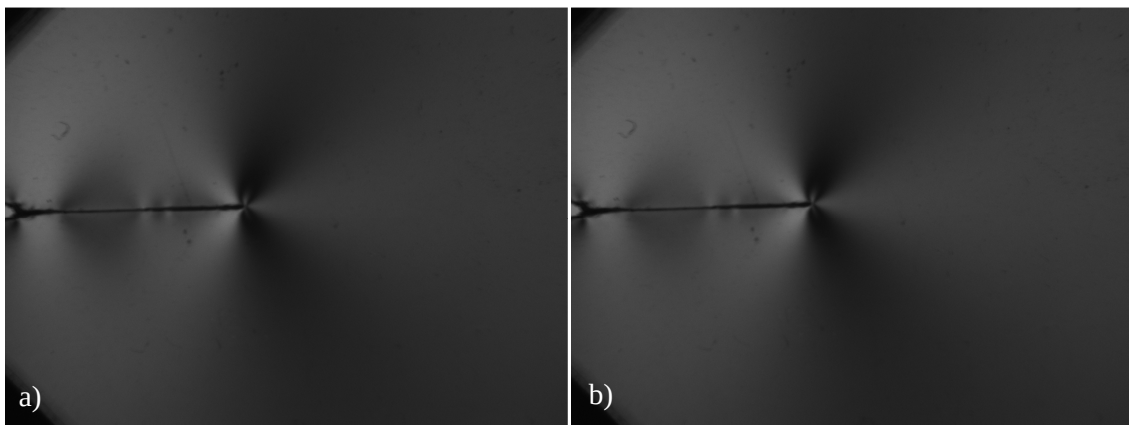


Figure 6.2. Second phase-stepping image corresponding to PC_CT3 specimen at the minimum applied load for different crack lengths. a) 70000 cycles ($a = 25.90$ mm), b) 117500 cycles ($a = 31.05$ mm), c) 162500 cycles ($a = 35.93$ mm), d) 190000 cycles ($a = 40.87$ mm), e) 195000 cycles ($a = 42.62$ mm), f) 201250 cycles ($a = 45.14$ mm)



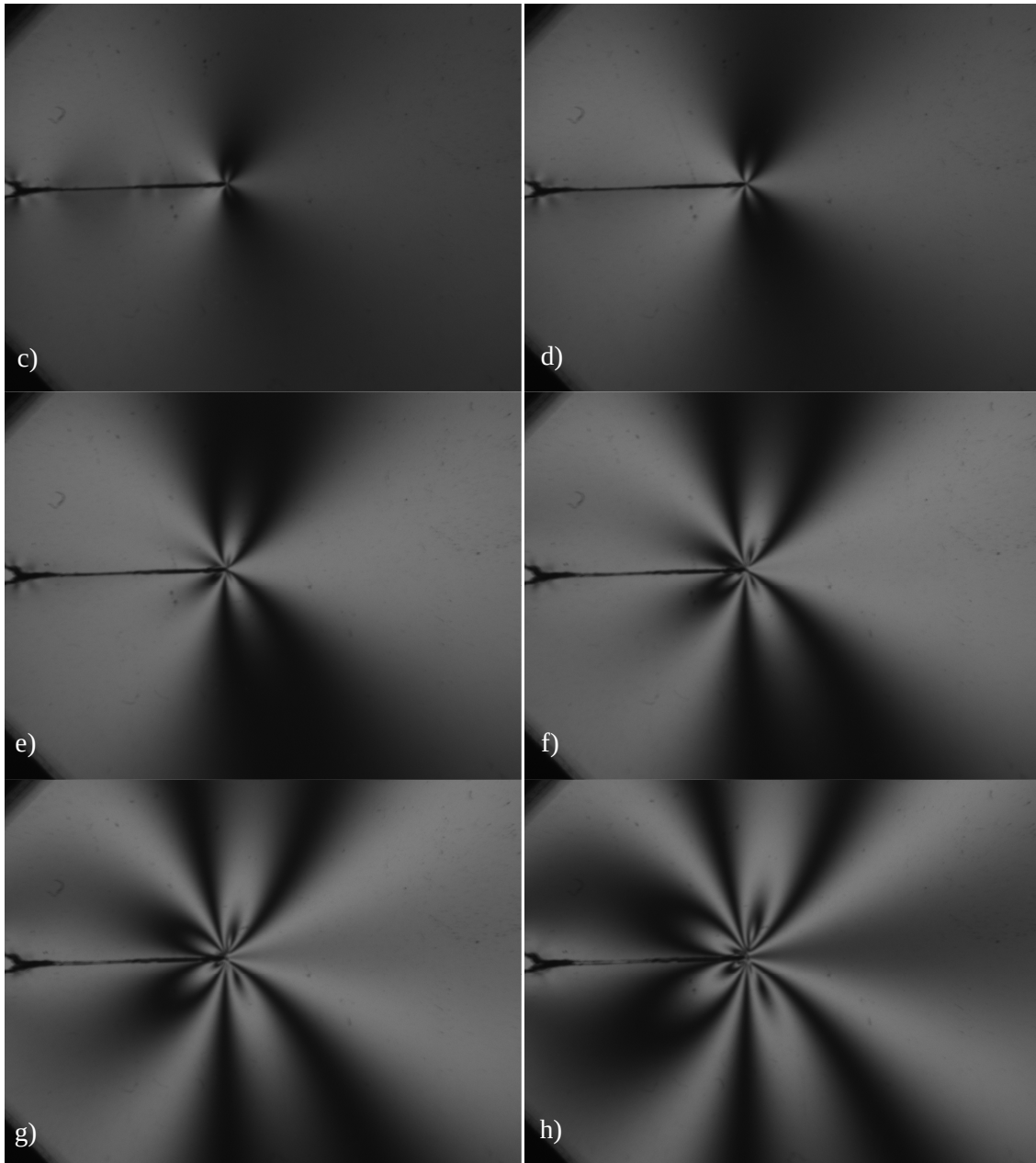


Figure 6.3. Second phase-stepping image corresponding to PC_CT3 specimen at different load states for a 31.05 mm crack: a) 0N, b) 2.5N, c) 5N, d) 10N, e) 20N, f) 30N, g) 40N, h) 50N

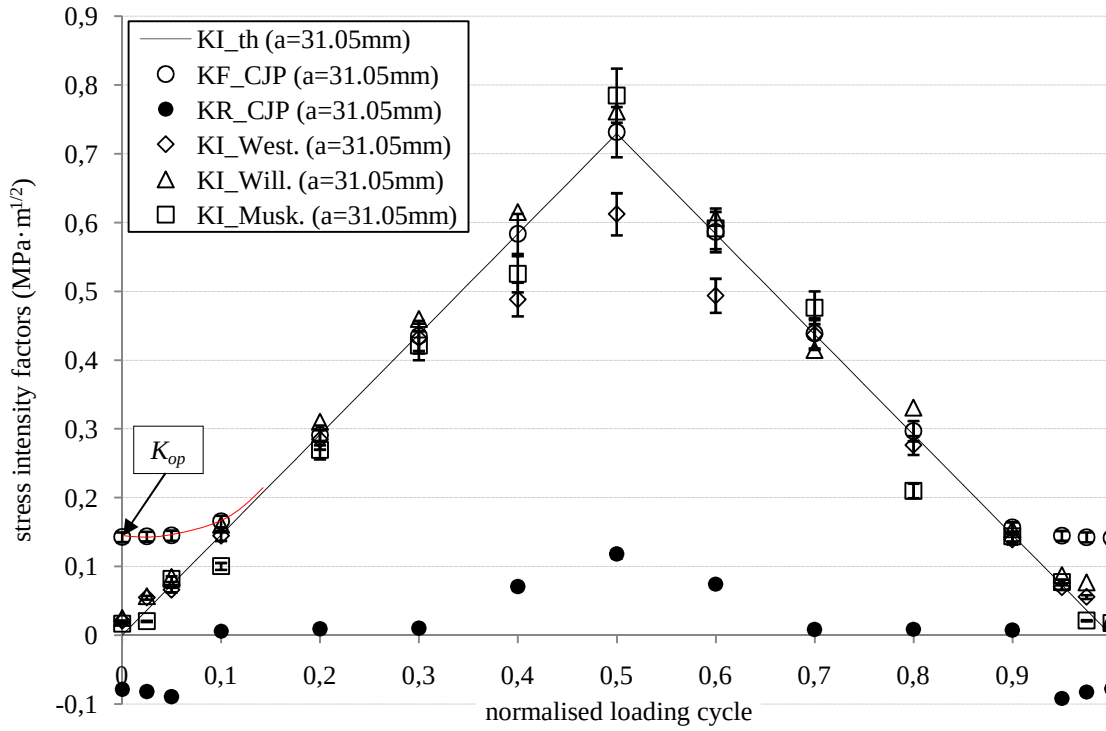


Figure 6.4. Experimental stress intensity factors obtained from the four models evaluated using PC_CT3 specimen for a crack length of 31.05 mm

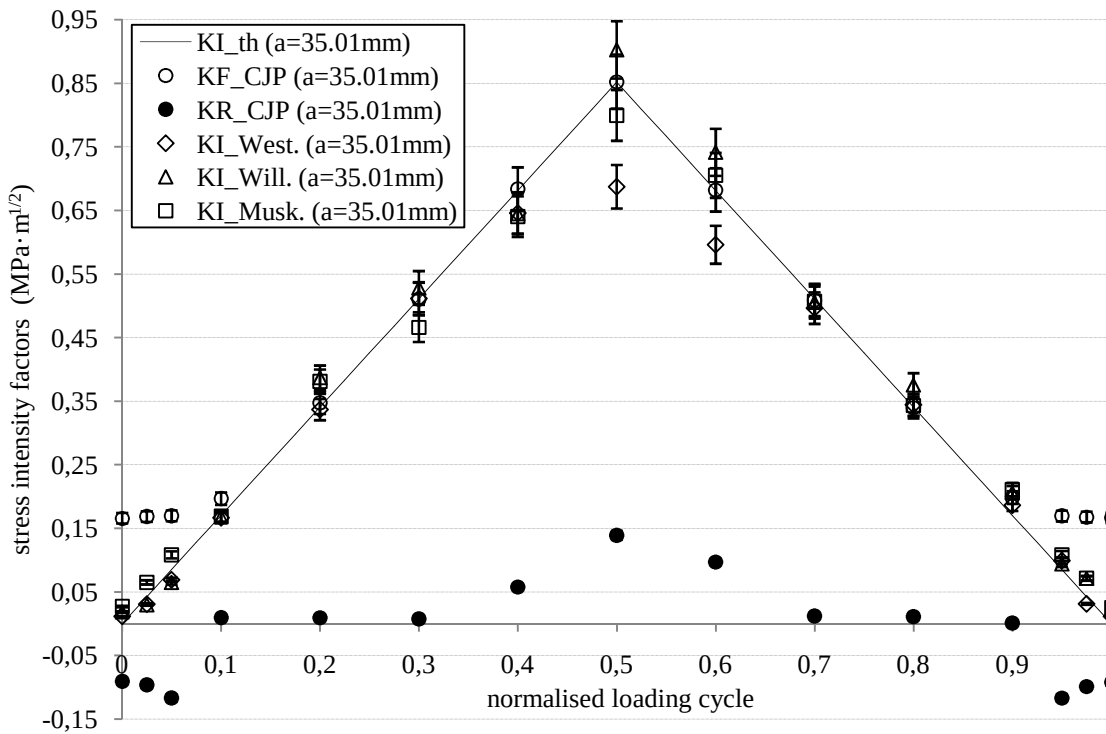


Figure 6.5. Experimental stress intensity factors obtained from the four models studied using PC_CT3 specimen for a crack length of 35.01 mm

From the analysis of K_F values, the opening stress intensity factor K_{op} can be determined. Thus, in figure 6.6 the estimated K_{op} for PC_CT3 specimen as function of the crack length has been plotted. In addition, the minimum and the maximum SIFs corresponding to the applied loading cycle have been also plotted. The crack opening load (P_{op}) can be calculated from K_{op} previously estimated using equation 6.1. P_{op} values for PC_CT3 specimen at the different crack lengths are presented in figure 6.7.

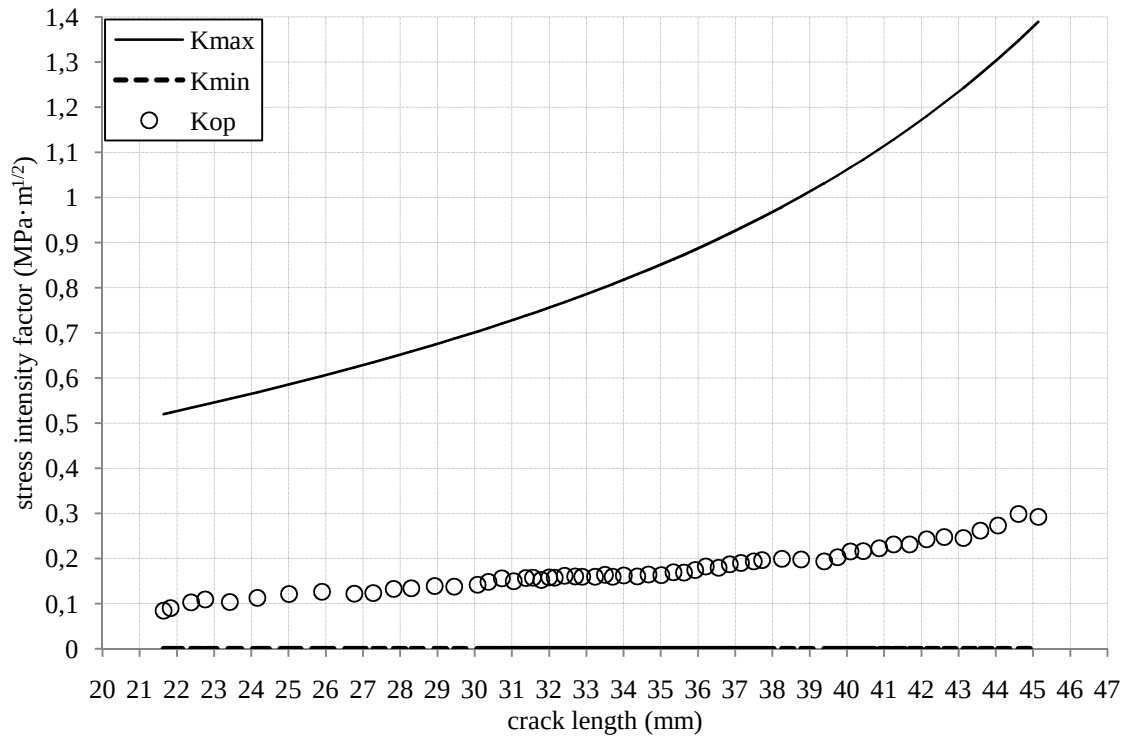


Figure 6.6. Estimated K_{op} as a function of the crack length for PC_CT3 specimen

K_{op} values can be used to obtain the effective stress intensity factor range (ΔK_{eff}). Thus, Paris law (equation 6.2) can be employed to relate the crack growth rate with the nominal and effective ΔK values (figure 6.8). In addition, Paris law coefficients for both curves have been calculated. These coefficients are presented in table 6.2.

$$\frac{da}{dN} = c \Delta K^m \quad (6.2)$$

Table 6.2. Paris law coefficients for PC_CT3 and PC_CT4 specimens using ΔK_{nom} and ΔK_{eff}

Specimen reference	R-ratio	ΔK_{nom}		ΔK_{eff}	
		c	m	c	m
PC_CT3	0	$2 \cdot 10^{-7}$	2.011	$3 \cdot 10^{-7}$	1.958
PC_CT4	0.47	$1 \cdot 10^{-10}$	3.097	$1 \cdot 10^{-10}$	3.080

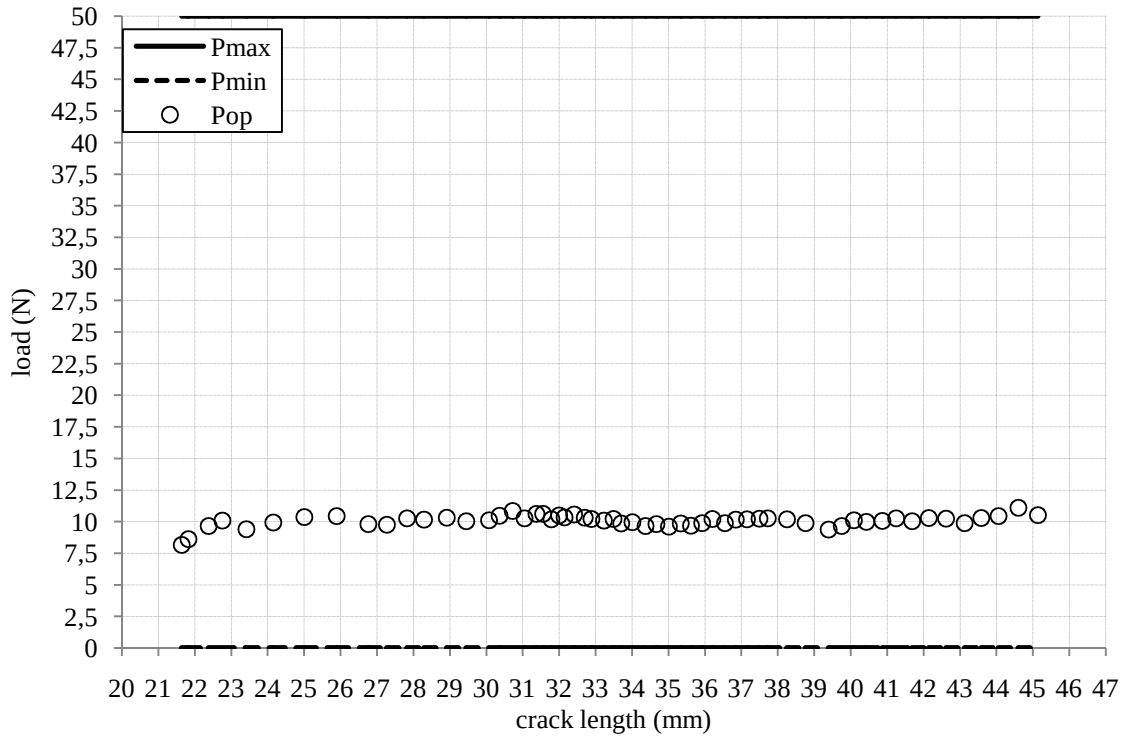


Figure 6.7. Crack opening load calculated from K_{op} as a function of the crack length for PC_CT3 specimen

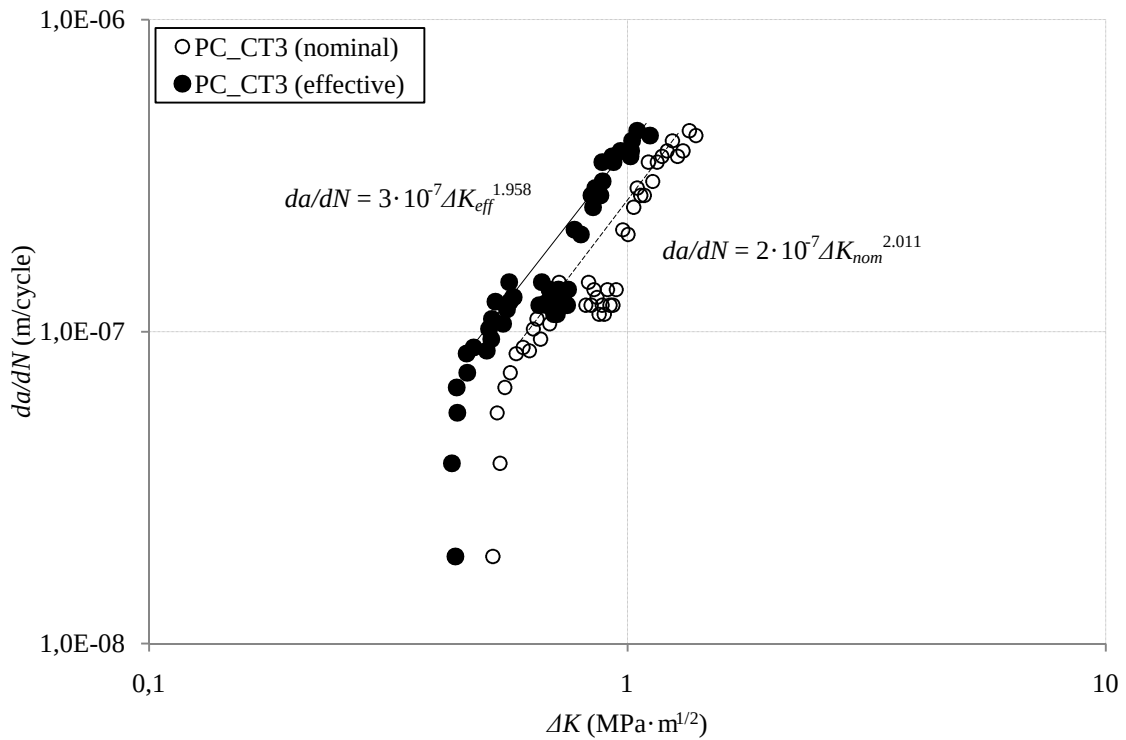


Figure 6.8. Paris law curves for PC_CT3 specimen obtained using ΔK_{nom} and using ΔK_{eff}

In a similar way, results are presented for the specimen tested at low R -ratio. Figure 6.9 shows normalised K_F and K_R values corresponding to PC_CT4 specimen (tested at $R = 0,47$) for three

different crack lengths (25.00, 31.01 and 34.64 mm) as a function of the loading cycle. In addition, K_I calculated from equation 6.1 has been also represented.

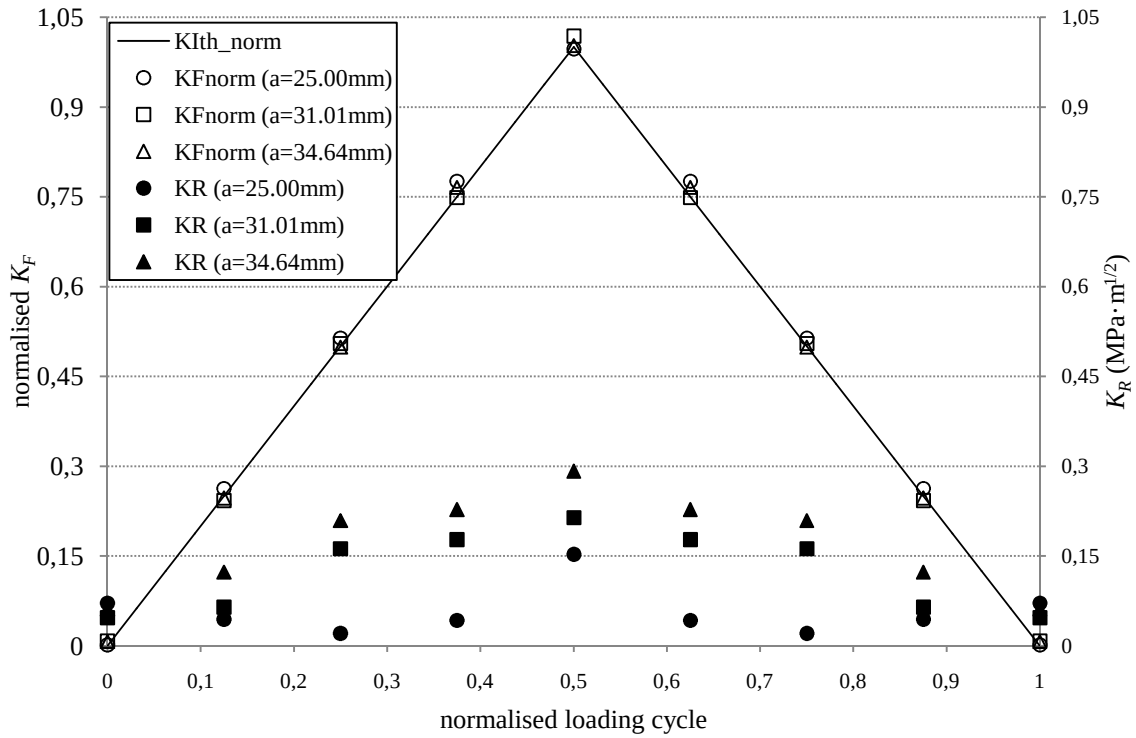


Figure 6.9. Normalised K_F and K_R values at three different crack lengths for PC_CT4 specimen ($R = 0.47$)

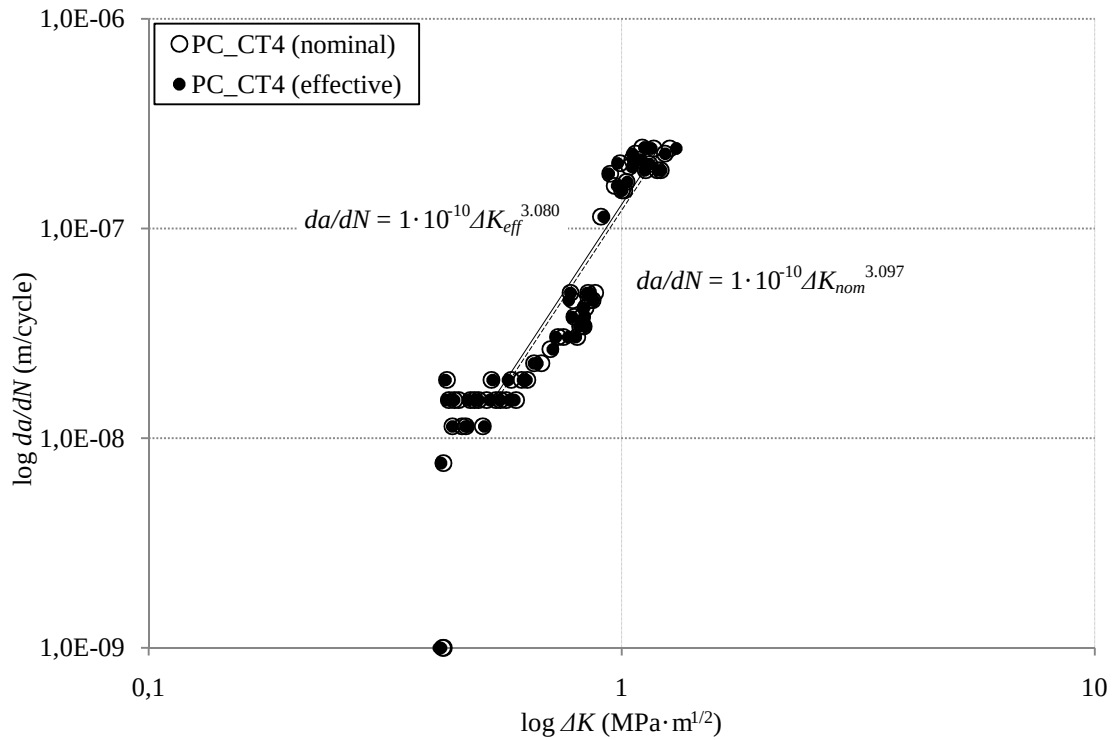


Figure 6.10. Paris law curves for PC_CT4 specimen using ΔK_{nom} and ΔK_{eff}

Finally, Paris law for PC_CT4 specimen using ΔK_{nom} and ΔK_{eff} are shown in figure 6.10. Paris law coefficients obtained for both curves are presented in table 6.2.

6.2.2. Experimental results obtained by DIC

Experimental results obtained using DIC for the evaluation of fatigue crack shielding are presented in this section. A set of fatigue tests at different R -ratios were conducted using CT 2024-T3 aluminium specimens (figure 4.12a). Thus, two tests were performed at low R -ratio ($R = 0$) and at high R -ratio ($R = 0.5$). The test conditions and the specimen references are shown in table 6.3. In addition, the influence of the plate rolling direction from which the specimens were cut out was studied. Thus, several specimens were cut out from normal directions, one parallel (named as horizontal orientation) and the another perpendicular to the crack direction (named as vertical orientation).

Table 6.3. Loading conditions for fatigue tests conducted using DIC

Test reference	Specimen reference	Orientation	P_{min} (N)	P_{max} (N)	R -ratio
DIC_R=0	Al_CT3	Horizontal	5	600	0
	Al_CT4	Vertical			
DIC_R=0.5	Al_CT5	Vertical	600	1200	0.5
	Al_CT7	Horizontal			

Figure 6.11 shows the evolution of the crack length versus the number of cycles for the different tests indicated in table 6.3. The crack length was measured using a CCD camera (AVT model Pike) placed at the back of the specimen (see figure 4.15) to track the crack tip position during the tests. Moreover, the notch width of the specimen was employed to calculate the relation pixels/millimetre (figure 6.12). In addition, the specimen surface was scratched to facilitate the observation of the crack tip.

To investigate the influence of the plate rolling direction, Paris law using nominal ΔK for specimens tested at low R -ratio (Al_CT3 and Al_CT4) are represented in figure 6.13.

During fatigue tests, a sequence of images was captured between an undeformed and deformed state for each one of the crack lengths analysed. Figure 6.14 shows the observed horizontal and vertical displacement fields corresponding to Al_CT3 specimen measured at different crack lengths for a loading state of 600 N.

In figures 6.15 and 6.16 the experimental SIFs corresponding to Al_CT3 specimen (tested at $R = 0$) at two crack lengths (34.10 and 41.07 mm respectively) are presented. Thus, K_I from Westergaard's, Williams's and Muskhelishvili's models and K_F and K_R from CJP model have been plotted. K_I values calculated from equation 6.1 have been also presented. In addition, figure 6.17 shows K_F and K_R values corresponding to Al_CT5 specimen (tested at $R = 0.5$) for

two different crack lengths (34.64 and 41.09 mm). Again, K_I calculated from equation 6.1 has been also presented.

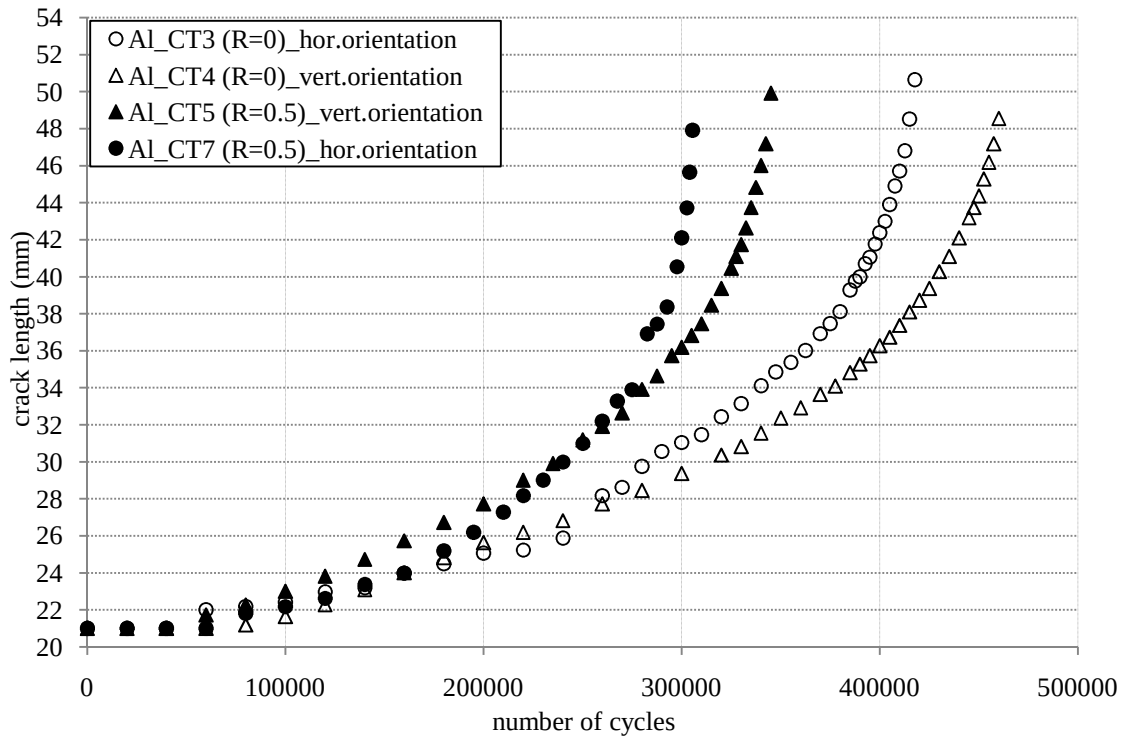


Figure 6.11. Crack length versus number of cycles corresponding to CT specimens tested using DIC

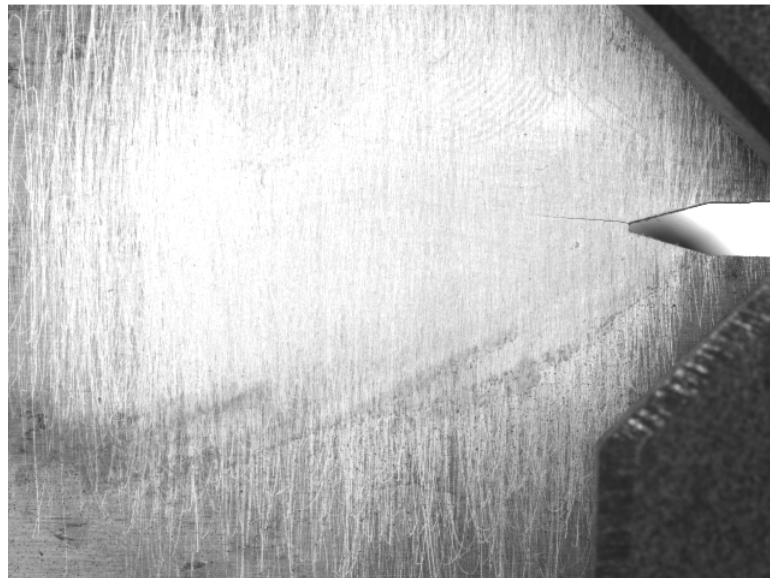


Figure 6.12. Image captured using a camera placed at the back of the specimen for crack tip tracking

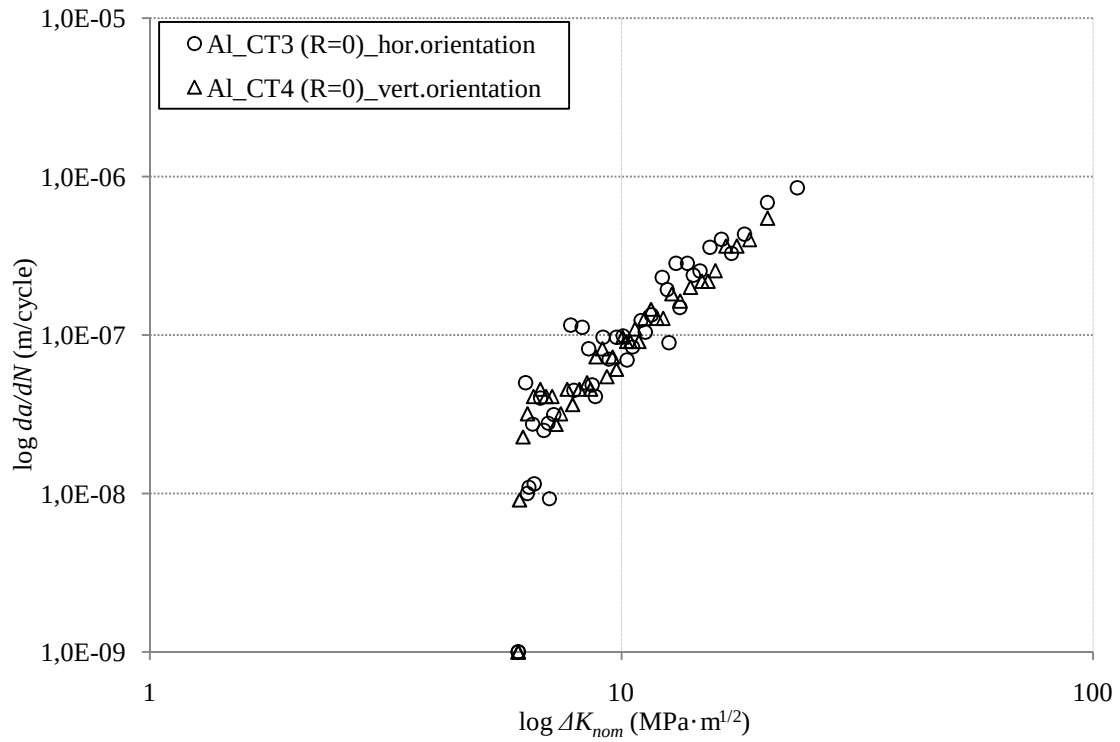
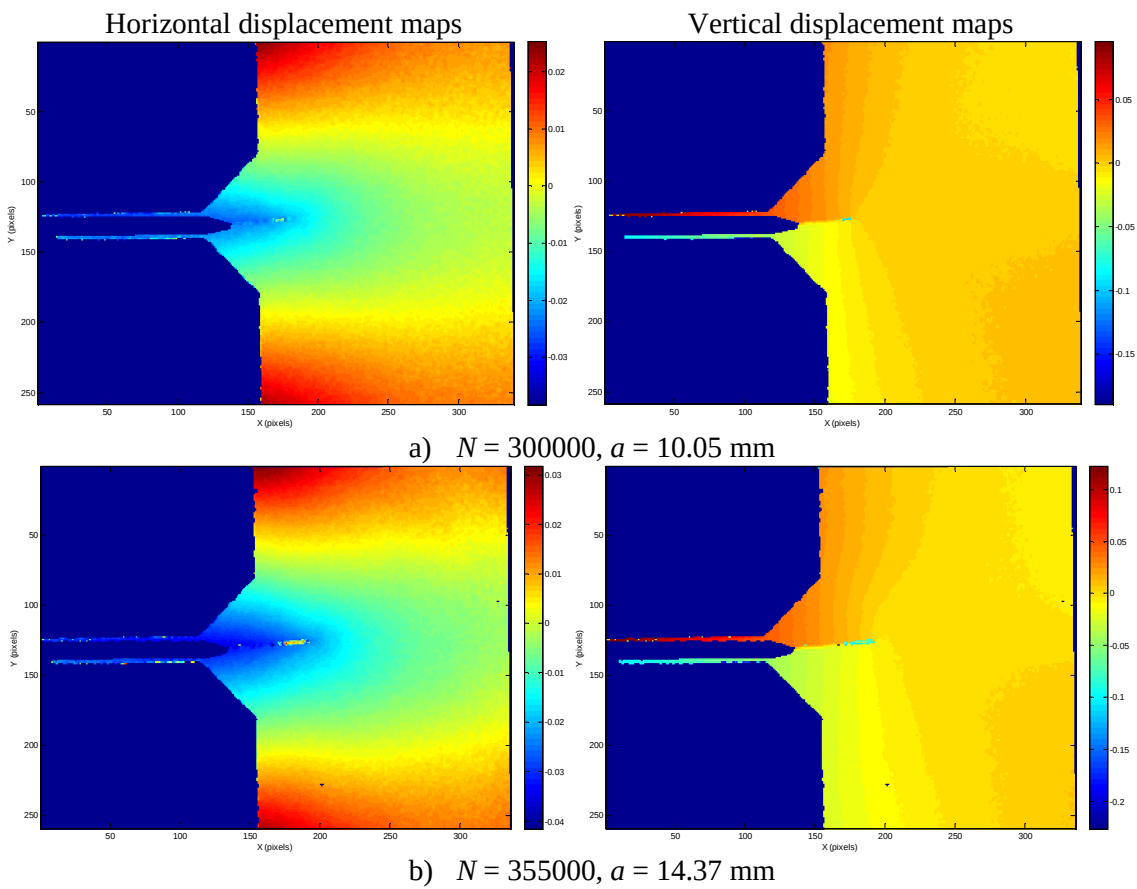


Figure 6.13. Fatigue crack growth rate against nominal SIF range for aluminium CT specimens tested at low R -ratio



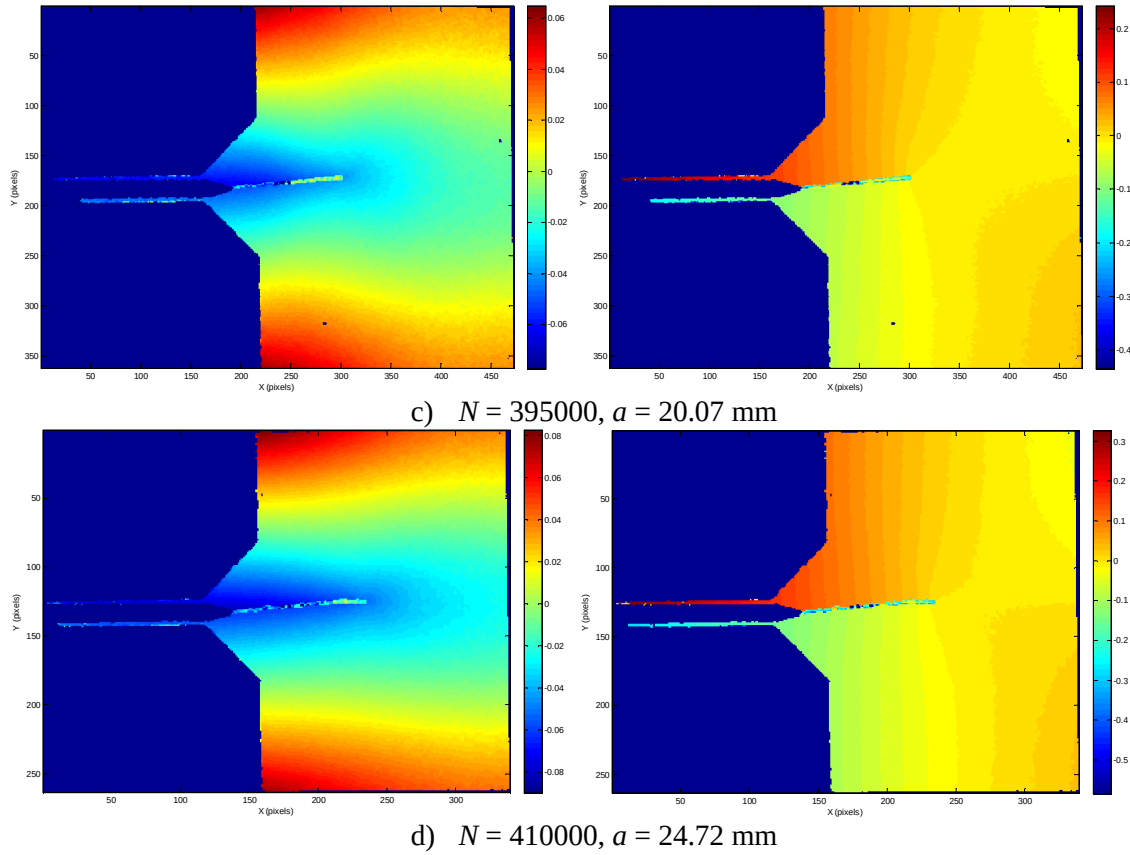


Figure 6.14. Horizontal and vertical displacement maps for Al_CT3 specimen measured at different crack lengths at the maximum applied load: a) 300000 cycles ($a = 10.05 \text{ mm}$), 355000 cycles ($a = 14.37 \text{ mm}$), c) 395000 cycles ($a = 20.07 \text{ mm}$) and d) 410000 cycles ($a = 24.72 \text{ mm}$)

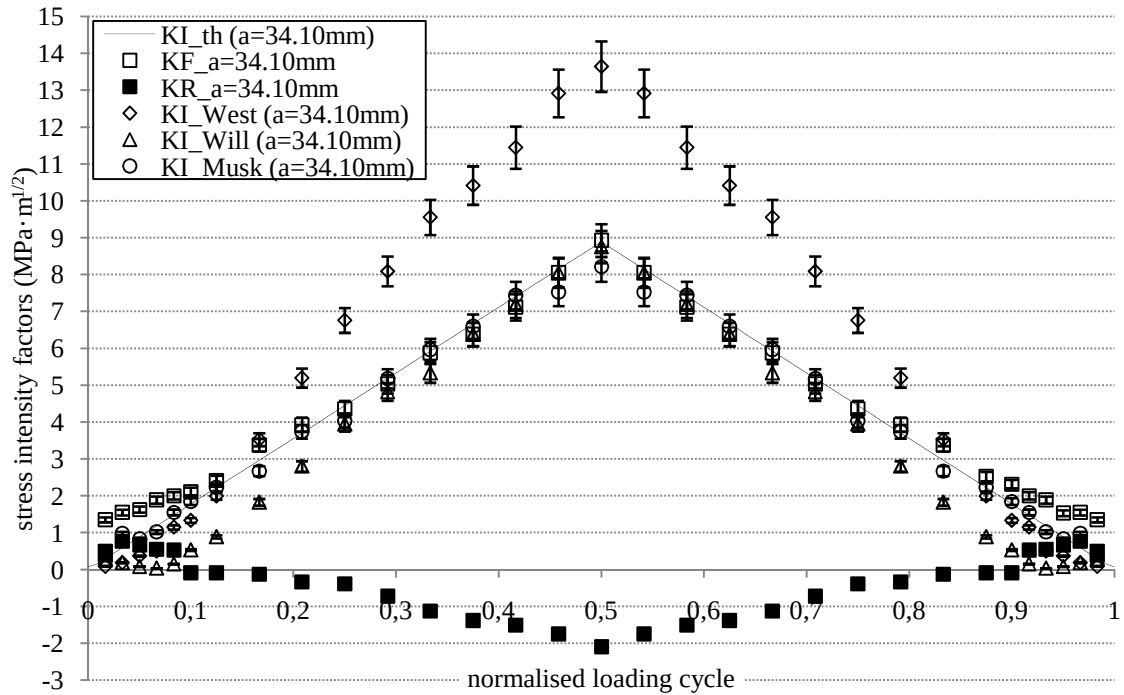


Figure 6.15. Experimental stress intensity factors obtained from the four models studied using Al_CT3 specimen for a crack length of 34.10 mm

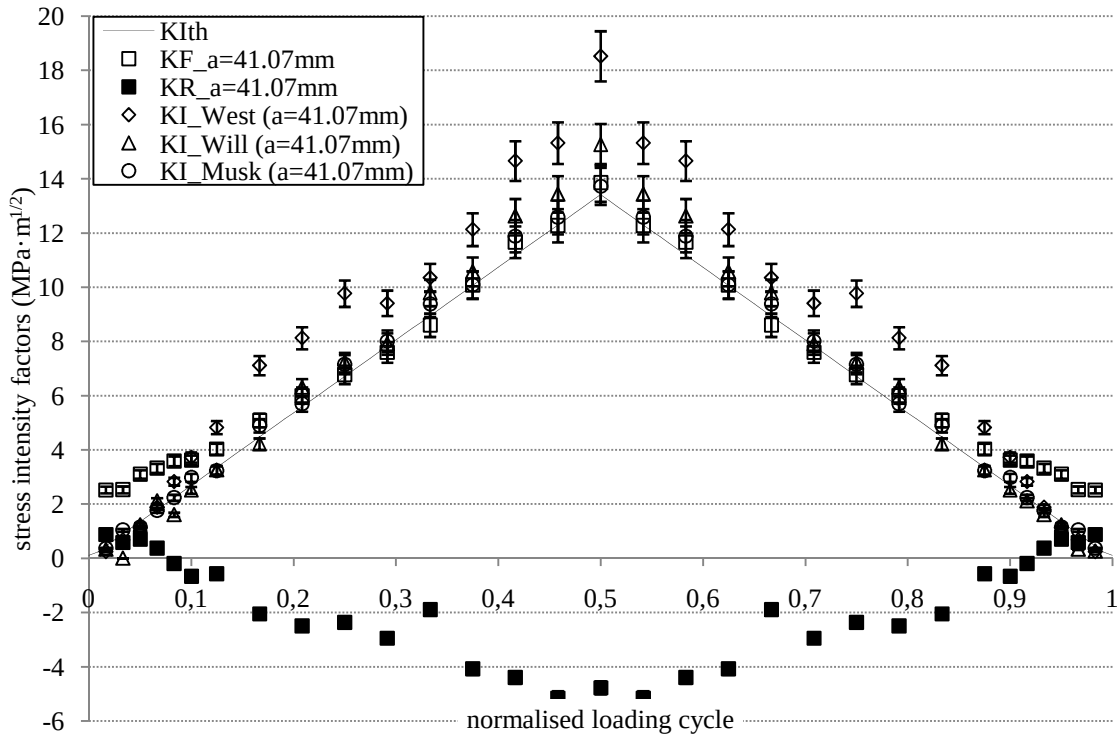


Figure 6.16. Experimental stress intensity factors obtained from the four models studied for Al_CT3 specimen for a crack length of 41.07 mm

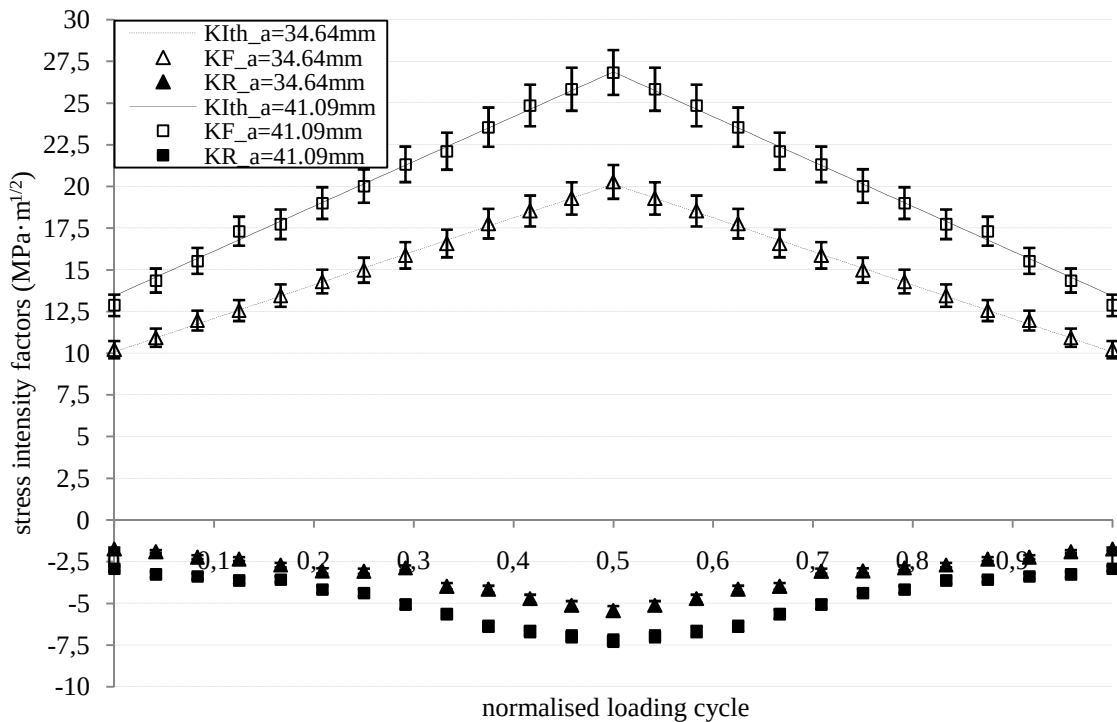


Figure 6.17. Experimental K_F and K_R corresponding to Al_CT5 specimen for two different crack lengths using CJP model

K_{op} and K_{cl} values obtained from the analysis of K_F for Al_CT3 specimen have been plotted in figure 6.18. In addition, P_{op} and P_{cl} values calculated from K_{op} and K_{cl} using equation 6.1 are shown in figure 6.19.

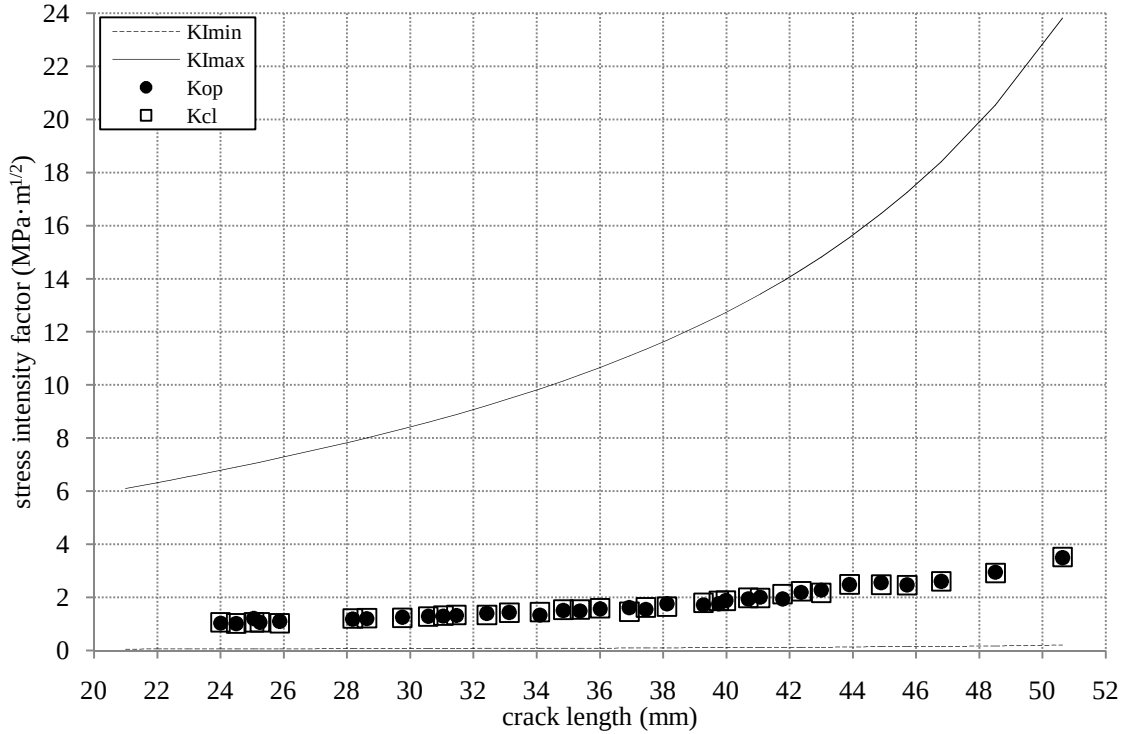


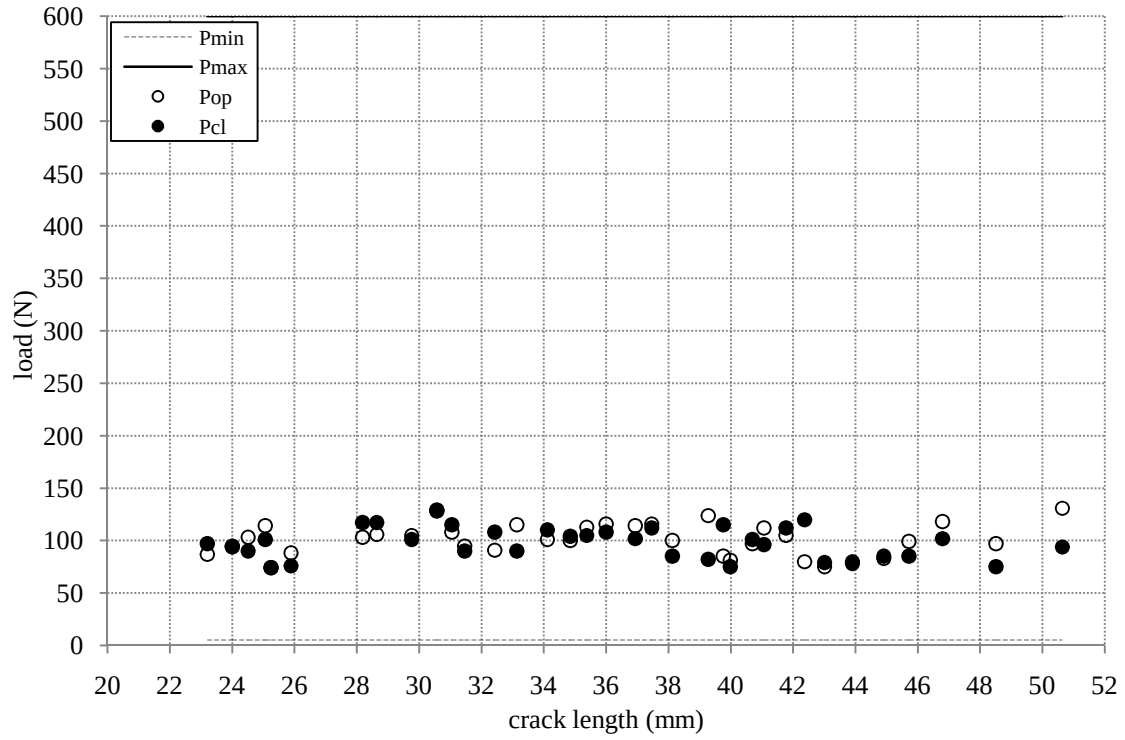
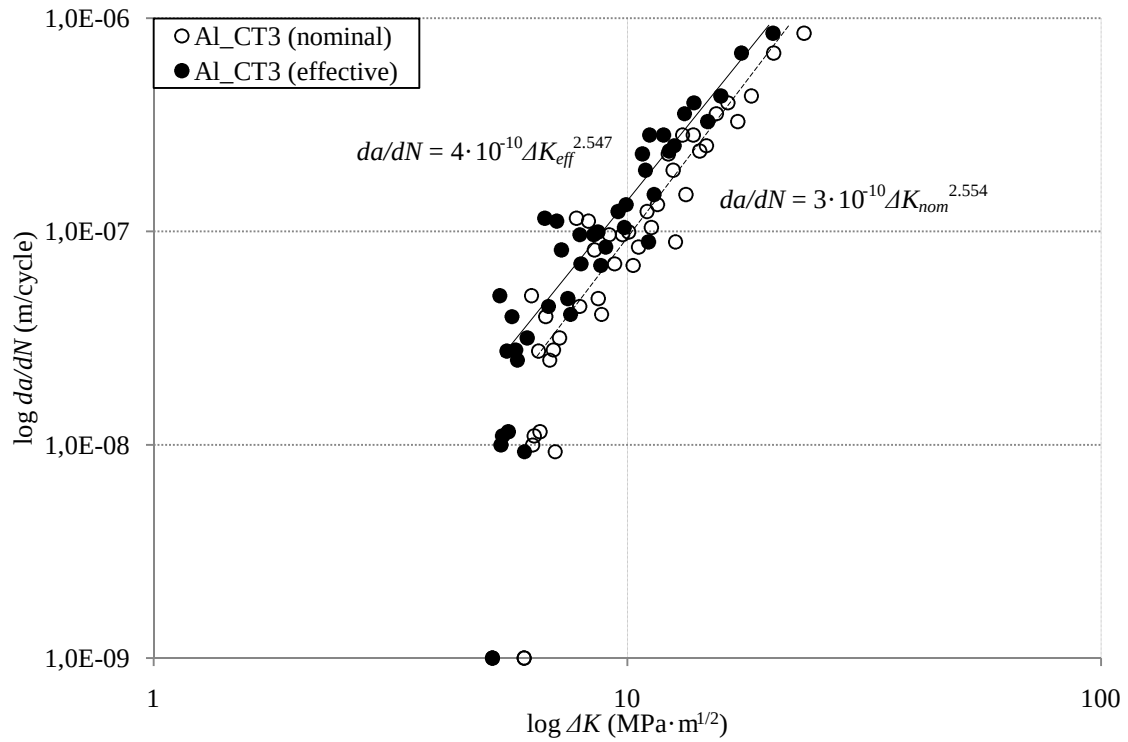
Figure 6.18. Estimated K_{op} and K_{cl} as a function of crack length for Al_CT3 specimen

Finally, the effective SIF range (ΔK_{eff}) can be determined using the K_{op} values previously estimated. Thus, Paris law curve previously plotted for the nominal SIF range can be compared with that obtained using the effective SIF range derived from DIC data analysis. Thus, in figures 6.20 and 6.21 the nominal and effective curves corresponding to Paris law obtained for Al_CT3 and Al_CT5 specimens are illustrated. In addition, c and m coefficients (equation 6.2) for the different curves have been estimated and they are detailed in table 6.4.

Table 6.4. Paris law coefficients for Al_CT3 and Al_CT5 specimens using ΔK_{nom} and ΔK_{eff}

Specimen reference	R-ratio	ΔK_{nom}		ΔK_{eff}	
		c	m	c	m
Al_CT3	0	$3 \cdot 10^{-10}$	2.554	$4 \cdot 10^{-10}$	2.547
Al_CT5	0.5	$2 \cdot 10^{-10}$	2.705	$2 \cdot 10^{-10}$	2.715

To compare the results obtained from transmission photoelasticity and DIC, figure 6.22 shows the normalised opening load as a function of the crack length for specimens tested at low R -ratio (PC_CT3 and Al_CT3).


 Figure 6.19. P_{op} and P_{cl} at different crack lengths for Al_CT3 specimen

 Figure 6.20. Nominal and effective Paris law curves for Al_CT3 specimen obtained from ΔK_{nom} and ΔK_{eff}

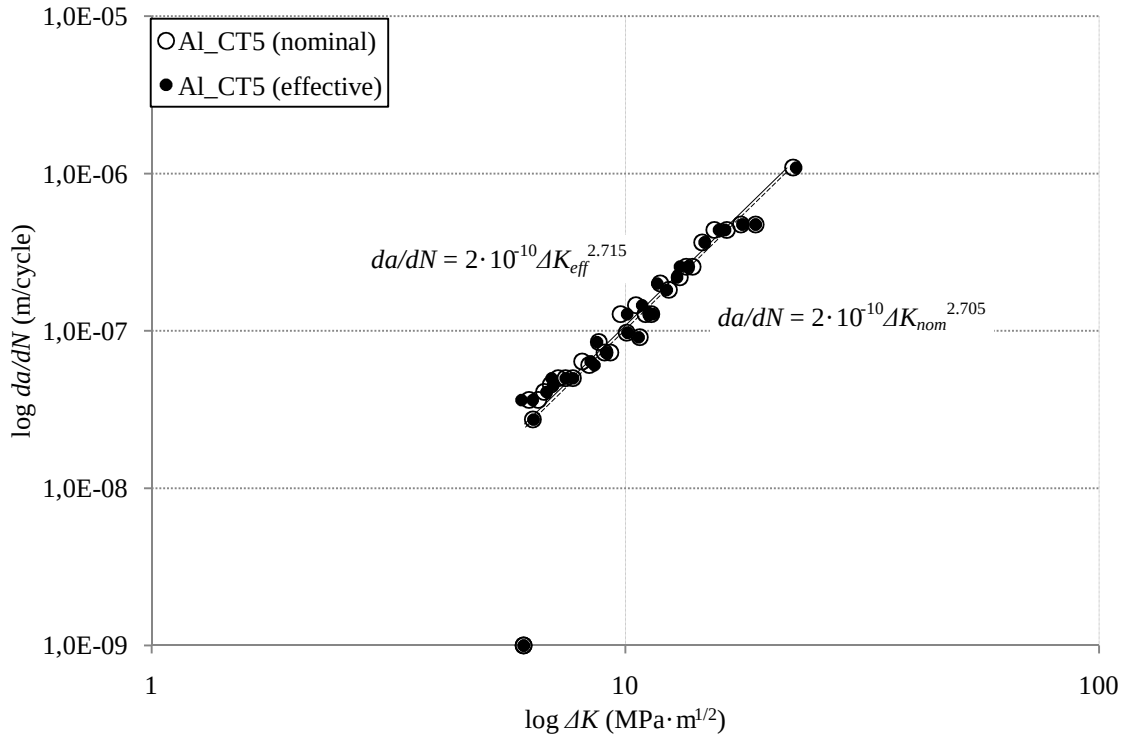


Figure 6.21. Nominal and effective Paris law curves for Al_CT5 specimen obtained from ΔK_{nom} and ΔK_{eff}

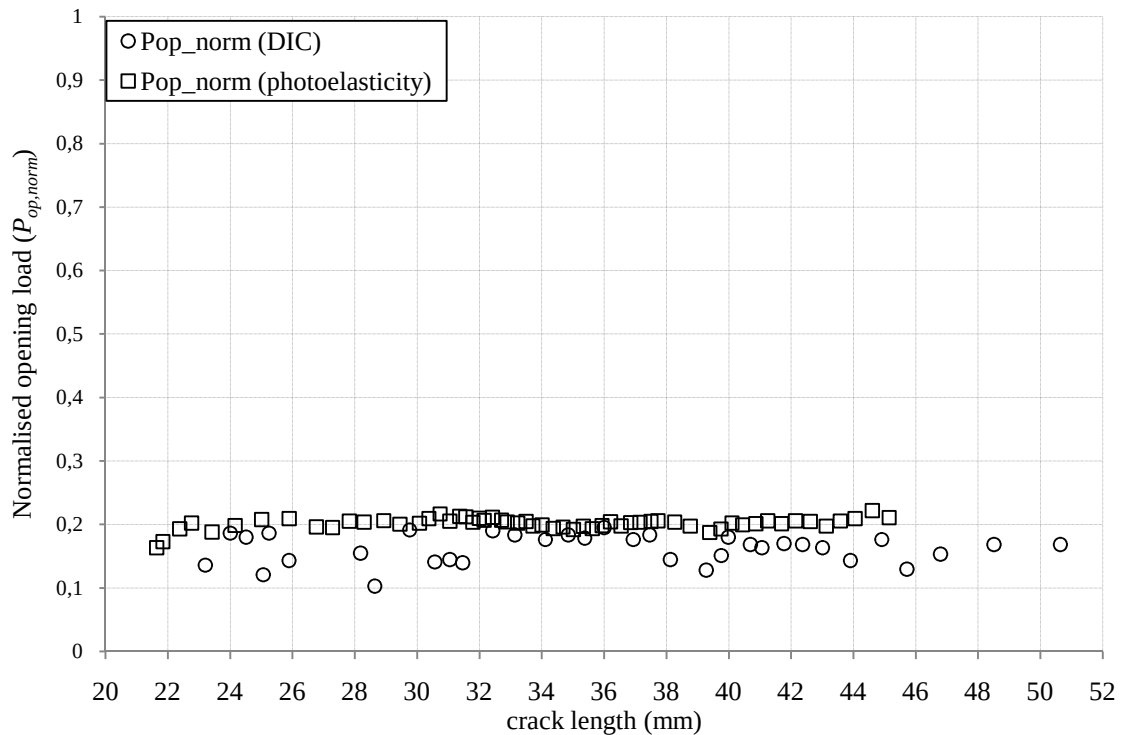


Figure 6.22. Normalised opening load obtained from DIC and transmission photoelasticity as a function of the crack length for specimens tested at low R -ratio

6.2.3. Verification of the results using the compliance technique

Crack opening and closing loads have been obtained from the analysis of K_F , which has been calculated from the displacement fields measured at the vicinity of the crack tip using DIC. However, DIC is a modern technique that has not been established yet as standard method for the evaluation of crack shielding. Therefore, to support the idea that DIC can provide information about real prediction of fatigue crack growth rates, in this section opening and closing loads obtained using DIC are compared with those calculated from compliance based methods, namely strain offset and offset compliance methods.

6.2.3.1. The compliance concept

Compliance based techniques have been one of the most extensively reported techniques for the measurement of crack opening/closing loads when crack closure or shielding is present. The compliance concept is derived from the crack closure phenomenon, according to which the fracture surfaces of a fatigue crack come into contact during the unloading portion of a loading cycle and load is transferred across the crack. Contact between crack faces result in a change of the specimen stiffness and consequently in the specimen compliance. Thus, the compliance is defined as the inverse of the stiffness:

$$C = \frac{v}{P} \quad (6.3)$$

Where v is the displacement between measurement points and P is the applied load.

Thus, compliance based techniques estimate crack opening/closing loads by analysing the change in the specimen stiffness as the crack starts opening or closing. According to this, the compliance in a notched or cracked specimen can be measured by recording the crack opening displacement (COD) as a function of the applied load. In absence of crack closure, the relationship between load and displacement is linear (figure 2.15). In real fatigue cracks where crack closure is likely to occur, when the crack is fully open the relationship between load and COD is also linear. But as the crack starts closing prematurely, the behaviour is not linear and the observed curvature is due to a change in specimen configuration which increases the stiffness as decreasing the load, and consequently a decrease in its compliance (figure 2.15). Thus, the point at which the crack closes prematurely can be identified as the point where deviation from linearity occurs in the load versus COD curve. Nevertheless, in practice the identification of such point is not always an easy task, and it has lead to the development of different procedures and methods for the correct interpretation of the load at which the crack is opening or closing [69].

6.2.3.2. Compliance based techniques

Different strain methods to quantify crack closure can be found in the literature. However, strain gauges are one of the most extended methods for the quantification of such a phenomenon. This technique employs strain gauges or extensometers [207] located at different places of the specimen to determine the near crack tip strains or the COD. The two methods adopted in this thesis have been the strain offset method [208] and the offset compliance method [206].

One of the most important problems during the data acquisition process is the presence of high frequency noise in the collected data. This fact constitutes an important limitation when using this technique, since the interpretation of the compliance traces can be difficult and lead to uncertainty. To avoid this problem, different noise reduction techniques and processing algorithms have been developed by several authors [69, 206, 208 - 210]. Some of these methods employ various curve-fitting techniques applied directly on the $P-\varepsilon$ or $P-COD$ signal [69, 206] to minimise the noise influence in the measured data. Another alternative is to smooth the load signal and/or the strain or COD signal as function of time independently, and then combine them into a $P-\varepsilon$ or $P-COD$ plot. Such noise reduction can be done either in an analogue way by operating on the electrical signals using an appropriate electric circuit or through numerical filtering of the digitised $P-t$ and $\varepsilon-t$ or $COD-t$ data. An example of numerical smoothing is the work performed by Dougherty [209], who employed a quadratic polynomial fit using a least squares regression to smooth each variable versus time plot. Daniewicz [210] applied a dynamic programming filter for which an optimal smoothing parameter was found via generalised cross-validation. After that, Blandford et al. [211] assessed the quality of this filtering method for the calculation of opening load from the compliance traces. Other additional noise reduction techniques have been also employed in the calculation of opening load from the compliance traces, namely moving averages, the Butterworth low-pass filter and cubic smoothing splines [208].

In the strain offset method, the signal collected from a strain gauge or an extensometer is divided into two data sets corresponding to the loading and unloading branches of the applied loading cycle. The two branches are represented on a load versus strain or COD plot, and a least squares straight line is fit to experimental data at the part of the loading cycle at which the crack is fully open. For this purpose, a segment that spans a range of approximately 25 % of the cycle load range is selected to represent the fully open crack configuration. Then, a linear fit corresponding to the load range to fully open crack is employed to calculate the theoretical strain or COD for a particular load value. The difference between theoretical and experimental strain or COD values is calculated to obtain the strain offset. Finally, the strain offset is presented as a function of the applied load, and the crack opening load (P_{op}) from the loading

branch and the crack closing load (P_c) from the unloading branch are obtained as the load value at which the strain offset reaches the zero value.

The offset compliance method is recommended by ASTM E647-00 [206]. The step-by-step procedure to determine opening/closing loads from strains or displacements data is as follows. The first step is similar to that previously described in the strain offset method. Thus, collected data are divided into two groups corresponding to the loading and unloading branches of the loading cycle. Subsequently, for each branch, a least squares straight line is fitted to a segment that spans a range of approximately 25 % of the load range starting just below the maximum load (not less than 0.90 of the maximum load). The slope of this line is assumed to be the compliance value C_0 , which correspond to the fully open crack configuration. After that, and starting just below the maximum load (not less than 0.95 of the maximum load), least squares straight lines are fitted to data segments that span a range of approximately 10 % of the load range with a loading overlap of 5 % (figure 6.23). For each segment, the slope C and the corresponding mean load are calculated to obtain the compliance offset as follows:

$$\text{compliance offset} = \frac{C_0 - C}{C_0} \cdot 100 \quad (6.4)$$

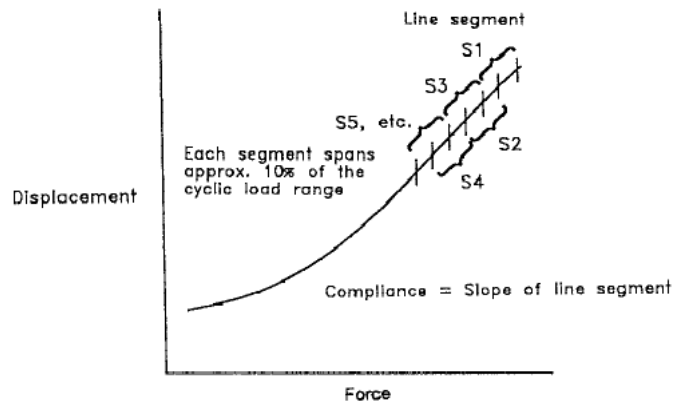


Figure 6.23. Evaluation of the variation of compliance with load for the determination of opening load [206]

Then, the points (compliance offset, mean load) from the segments are plotted and connected with straight lines (figure 6.24). Finally, the opening (loading branch) and closing (unloading branch) loads are determined according to the selected offset criterion as the lowest load at which a line connecting points has the value of compliance offset equal to the offset criterion (0, 2 or 4 %) [206].

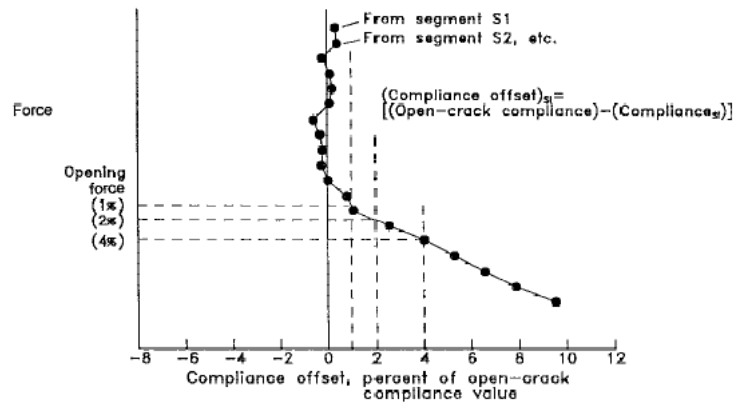


Figure 6.24. Determination of opening load using the offset compliance method [206]

6.2.3.3. Results obtained from compliance based techniques

Experimental shielding results obtained from the analysis of the displacement fields measured with DIC have been compared with those from the interpretation of the compliance traces. Thus, in the current thesis, the compliance evaluation has been performed from the COD measurements using an extensometer (model MTS 632.03F-30) located at the mouth of aluminium CT specimens (figure 6.25) with a data sampling frequency of 5 Hz. To minimise the influence of noise, the collected data were filtered. For this purpose, an incremental polynomial method similar to that described by ASTM E647-00 [206] was adopted. This method operated directly with load and COD data collected, grouping them into segments according to a specified load increment. In addition, an overlap between segments was adopted. Subsequently, for each segment, a first order polynomial was fitted using a least squares method. Finally, the results used for each segment were the load and the corresponding COD at its middle point.

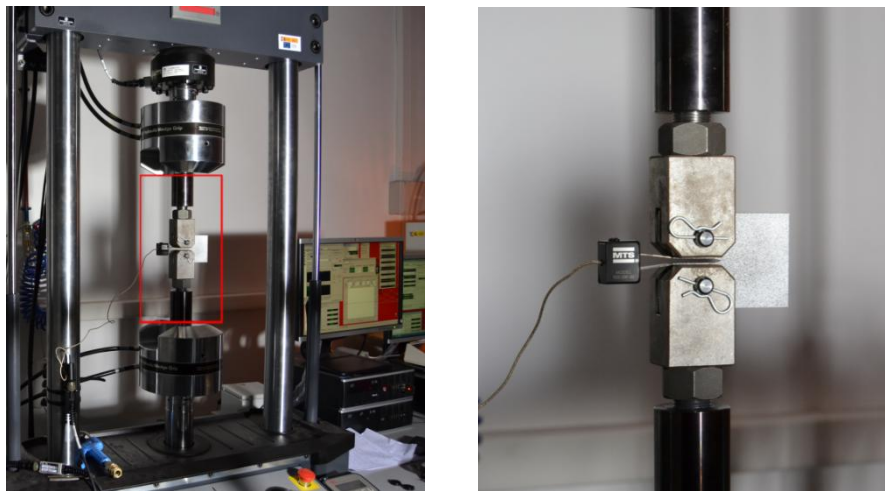


Figure 6.25. Extensometer located at the mouth of the notch in aluminium CT specimen

First, results corresponding to one of the tests conducted at low R -ratio are presented. Figure 6.26 shows the results obtained from strain offset and offset compliance methods for a 35.47 mm crack corresponding to Al_CT3 specimen. Plots located on the left correspond to results for the loading branch, while those located on the right correspond to the unloading branch. Top plots show the applied load versus the measured COD for loading (left) and unloading (right) branches. In both plots, it can be observed raw data, filtered data and a fitted line corresponding to no closure. This line has been obtained considering data results above 150 N (corresponding to a 25 % of the cycle load range) and performing a least squares fitting. The two middle plots show the applied load versus the strain offset for loading (left) and unloading (right) branches. Bottom plots show the applied load versus the offset compliance for loading (left) and unloading (right) branches.

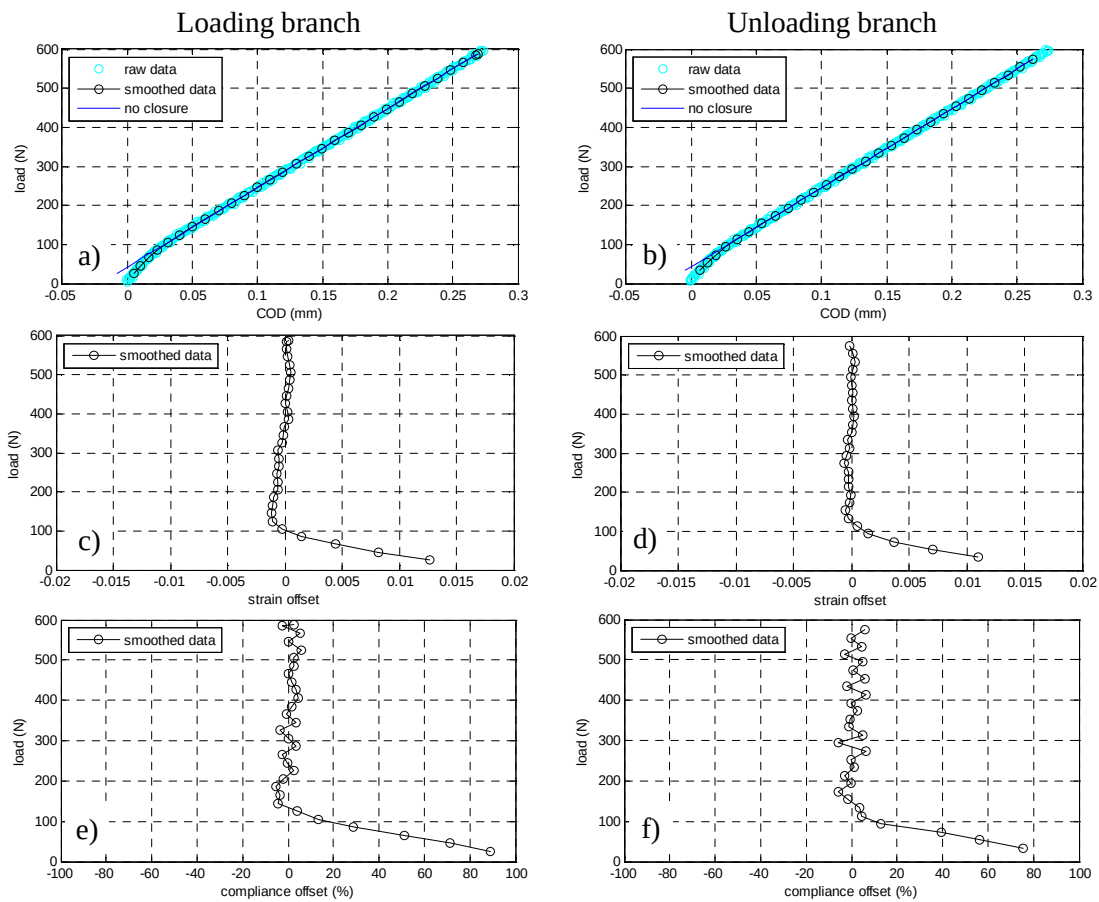


Figure 6.26. Results obtained from strain offset and offset compliance methods for a crack length of 35.47 mm corresponding to Al_CT3 specimen ($R = 0$). a) Applied load versus COD for loading branch, b) applied load versus COD for unloading branch, c) applied load versus strain offset for loading branch, d) applied load versus strain offset for unloading branch, e) applied load versus compliance offset for loading branch, f) applied load versus compliance offset for unloading branch

From the previous graphs, opening (from loading branch) and closing (from unloading branch) loads can be determined according to the approach indicated in the previous section. In this way, the same procedure is conducted for the rest of the crack lengths analysed. In figure 6.27 opening and closing loads obtained at different crack length for Al_CT3 specimen are presented. It can be observed that the 2% offset criterion has been selected for the offset compliance method.

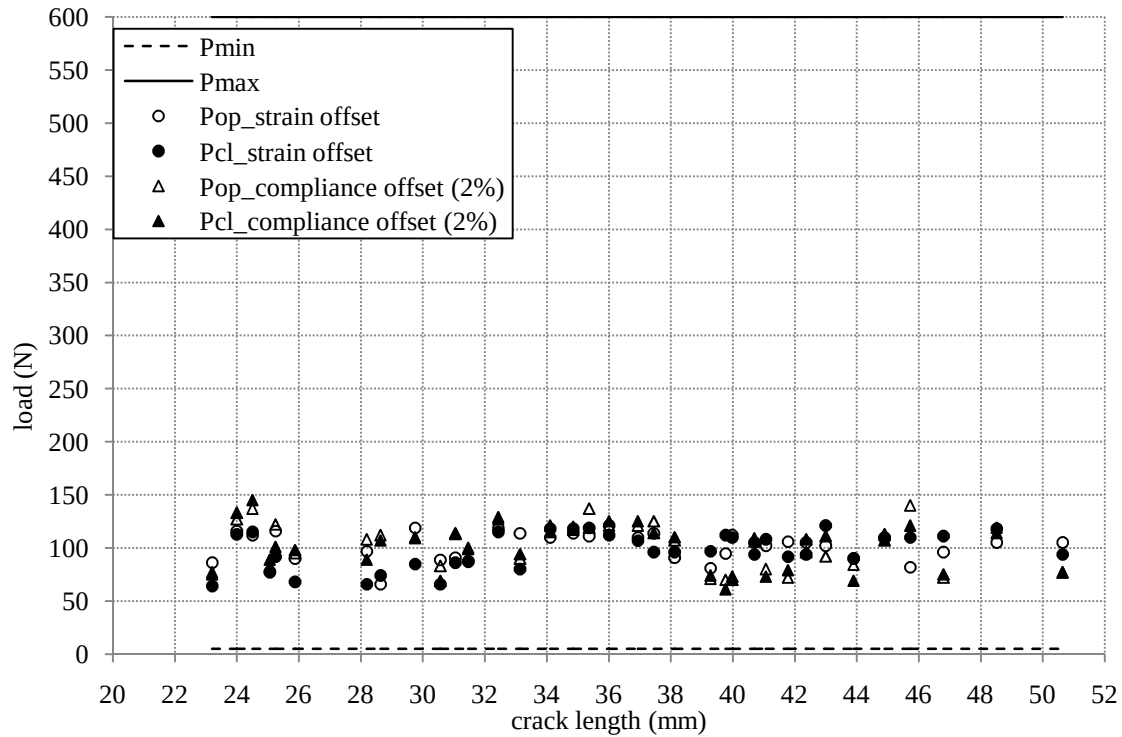


Figure 6.27. Opening and closing loads obtained at different crack lengths for Al_CT3 specimen using strain offset and offset compliance methods

Figure 6.28 shows strain offset and offset compliance results for a crack length of 35.73 mm corresponding to Al_CT5 specimen. As previously represented in the case of tests at low R -ratio, the applied load versus COD for loading (a) and unloading (b) branches, the applied load versus strain offset for loading (c) and unloading (d) branches, and the applied load versus compliance offset for loading (e) and unloading (f) branches have been presented.

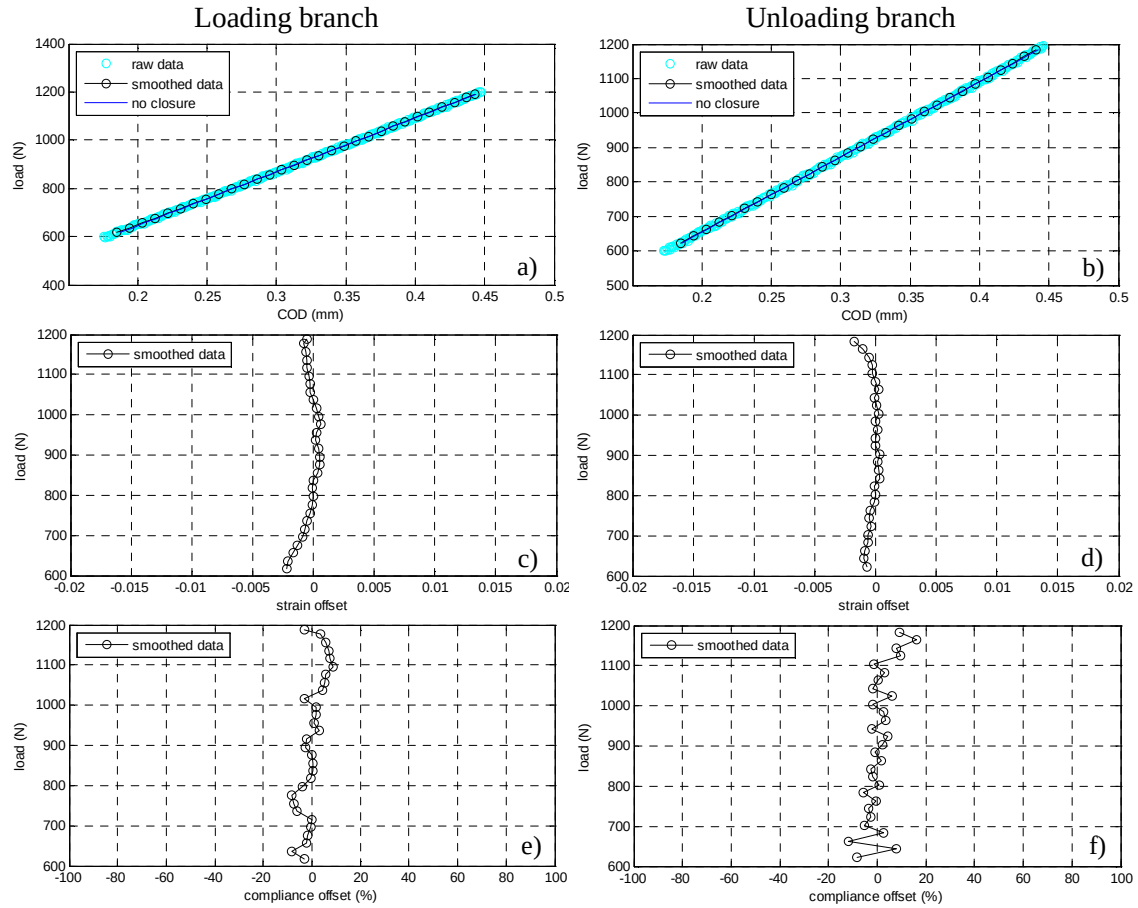


Figure 6.28. Results obtained from strain offset and offset compliance methods for a crack length of 35.73 mm corresponding to Al_CT5 specimen ($R = 0.5$). a) Applied load versus COD for loading branch, b) applied load versus COD for unloading branch, c) applied load versus strain offset for loading branch, d) applied load versus strain offset for unloading branch, e) applied load versus compliance offset for loading branch, f) applied load versus compliance offset for unloading branch

6.2.4. Experimental results obtained by ESPI

In this section the ability of ESPI technique for the evaluation of crack shielding induced by plasticity at the crack tip. Initially, a calibration test for the ESPI system is exposed. Subsequently, crack shielding results are presented. Finally, the ability of ESPI to estimate the plastic zone size is also explored.

6.2.4.1. Calibration of the ESPI system

The 3D ESPI system Q-300 developed by Dantec Dynamics [203] was adopted for the implementation of ESPI technique. Before using this system during fatigue tests, a calibration was performed using a specially prepared specimen according to the protocol defined by the

Standardisation Project for Optical Techniques of Strain measurement (SPOTS) standard [212]. Thus, the calibration procedure developed by Whelan et al. [213] was employed as reference.

6.2.4.1.1. Calibration specimen

The specimen employed for calibration was a particular embodiment of a four-point bending test and was based on a monolithic design concept (figure 6.29). The design eliminates the knife-edges or rollers typically used for load application in four-point bending rigs, replacing them with solid joints. Details A, B and C in figure 6.29 indicate the ligament-whiffletree joint, the set of reference surfaces for facilitating applied displacement measurement using transducers, and the interlock feature to protect from overloading, respectively. Another important feature of the SPOTS design is the fact that it is almost completely parametric, with every dimension scaled with the beam width, w . In this calibration test a specimen with a width of 15 mm and a thickness of 7.5 mm (i.e. $w/2$) was employed.

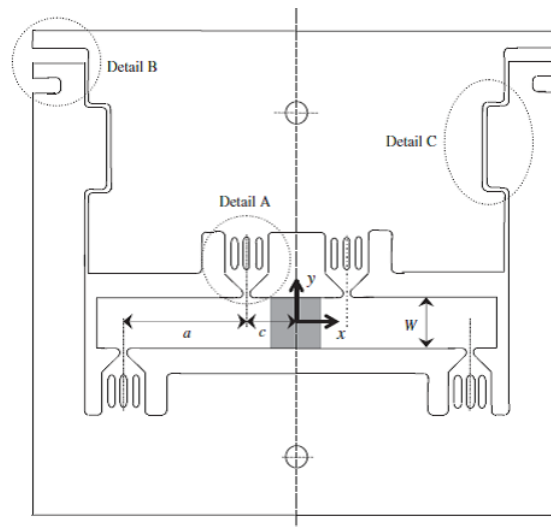


Figure 6.29. Schematic illustration showing the monolithic specimen used for calibration of the ESPI system [213]

The calibration specimen was manufactured by a numerically controlled (NC) spark-erosion process from a plate of aluminium (EN AW-5754/ISO: AlMg₃), which had been milled to the correct thickness. In this work the specimen was loaded in compression but a tensile load could have been applied if desired by inserting loading pins through the two holes located along the centreline of the frame.

The region of the reference material intended for use in a calibration procedure (gauge section) is located in the central section of the beam, between the two inner loading points (grey zone in figure 6.29). Simple beam theory can be used to derive expressions for the strain components and their gradients in this region, in terms of both applied load and displacement, as follows:

$$\varepsilon_{xx} = -\frac{\bar{v}}{6w^2}(\kappa y + \eta) \quad (6.5)$$

Where $\bar{v}$ is the displacement load applied to the inner loading points, w is the width of the beam, y is the distance from the neutral axis, as indicated by coordinate system shown in figure 6.29, and κ and η are the factors correcting for any rotational constraint and displacement constraint in the x direction, respectively because of the monolithic design of the calibration specimen and the presence of the whiffletrees. In this work, the κ and η values obtained in the study developed by Whelan et al. [213] were used because of the lack of equipment in the laboratory. Thus, these correction factors can be determined from the following expressions:

$$\kappa = 6w \frac{\sum_{j=1}^N (\varepsilon_{xx}^{y_{\max}} - \varepsilon_{xx}^{y_{\min}})_j \bar{v}_j}{\sum_{j=1}^N \bar{v}_j^2}, \quad \eta = 3w^2 \frac{\sum_{j=1}^N (\varepsilon_{xx}^{y_{\max}} + \varepsilon_{xx}^{y_{\min}})_j \bar{v}_j}{\sum_{j=1}^N \bar{v}_j^2} \quad (6.6)$$

Where $\varepsilon_{xx}^{y_{\max}}$ and $\varepsilon_{xx}^{y_{\min}}$ are the strain measurements from a strain gauge bonded to the outer face of the beam within the gauge section (i.e. $y_{\max} = w/2$ and $y_{\min} = -w/2$), $x = 0$). In addition, the applied displacement applied was measured using two LVDTs attached to the sides of the specimen. So, the mean of the two LVDT readings was considered as the actual displacement applied to the beam. The experiment itself [213] consisted of applying a monotonically increasing load at constant crosshead displacement of 0.5 mm/min, while recording the LVDT readings, strains, applied force and crosshead displacement. The correction factors were determined by plotting differences and sums of $\varepsilon_{xx}^{y_{\max}}$ and $\varepsilon_{xx}^{y_{\min}}$ as function of $\bar{v}$ and making straight-lines fits (figure 6.30).

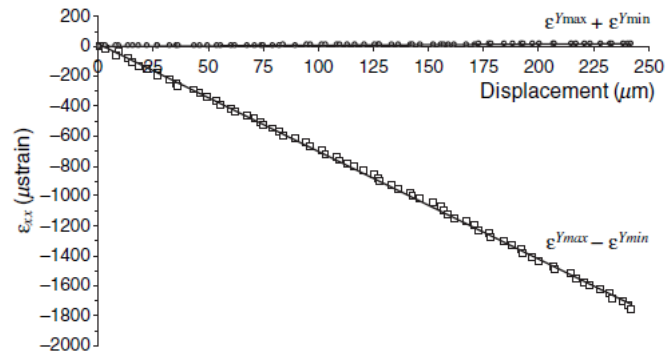


Figure 6.30. Plots of $\varepsilon_{xx}^{y_{\max}} - \varepsilon_{xx}^{y_{\min}}$ and $\varepsilon_{xx}^{y_{\max}} + \varepsilon_{xx}^{y_{\min}}$ versus applied displacement $\bar{v}$ [213]

From the analysis of the results obtained in figure 6.30, the values obtained for the correction factors were $\kappa = 0.864$ and $\eta = -0.089$ mm [213]. These values were used to calculate the predicted values for ε_{xx} using equation 6.5.

6.2.4.1.2. Experimental procedure

The setup adopted in the current calibration test is shown in figure 6.31. The calibration specimen was mounted in an Instron electromechanic machine (model ElectroPuls E3000), which had a dynamic load capacity of 3000 N and was located over an optical table. At the same time, the ESPI head was attached to a rigid system that was attached to the optical table to guarantee that the system was rigid enough to implement ESPI technique without any problem. Two dial gauges were placed at each side of the specimen to check the specimen alignment when the load was applied and to measure the applied displacements to the specimen. As it can be observed in figure 6.31, the gauge section was painted in white for the correct implementation of the technique.

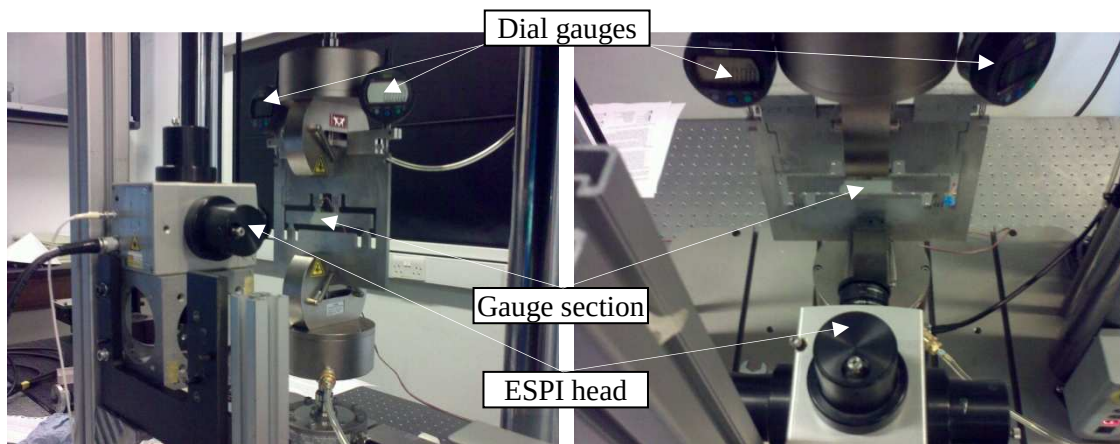


Figure 6.31. Setup employed for calibration of the ESPI system

A lens with a focal length of 16 mm was mounted on the ESPI head, with a working distance of 155 mm (distance between the specimen surface and the camera CCD). The ESPI head was connected to a PC control console and the whole system was managed by ISTR software (version 3.4, Dantec Dynamics).

For the definition of the test loading, SPOTS standard was adopted. It specifies that three measurements should be taken at equal displacement increments distributed between 10 and 90 % of the maximum allowable load range. SPOTS standard defines this maximum load range as the load that will cause the onset of yielding in the gauge section of the beam. However, it was presumed that yielding may occur at other locations in the specimen (e.g. loading joints) before this load was reached. Therefore, it was decided to define the maximum allowable load to be equal to half the load that would cause yielding in the gauge section of the beam. Thus, three displacement increments [213] were adopted, namely 25, 125 and 225 μm .

The calibration test was performed as follows. A very small preload was applied to minimise rigid body displacements. This loading state was assumed as the reference position. A speckle reference image was captured and the test started with a crosshead speed of 0.5 mm/min.

Images were captured in step increments of 25 μm until 225 μm . For each step, ISTRA software recorded a sequence of wrapped-phase maps. The four-step algorithm adopted, thus four phase-shifted speckle reference images and four phase-shifted speckle measurement images were employed to calculate a phase map. ISTRA software generated automatically displacement maps in x , y and z directions. In addition, from the differentiation of these displacement maps, the strain maps were obtained.

6.2.4.1.3. SPOTS standard protocol

The first step defined in SPOTS protocol is the comparison between measured and the predicted values for ε_{xx} . Therefore, the difference between these two values was determined (equation 6.7).

$$d_k(i, j) = \varepsilon_{xx, predicted}^k(i, j) - \varepsilon_{xx, measured}^k(i, j) \quad (6.7)$$

Where k represents the displacement level.

The next protocol step was to determine the variance of the previous difference. Thus, two fit parameters must be calculated:

$$\alpha_k = \frac{1}{N} \sum_{i,j} d_k(i, j), \quad \beta_k = \frac{\sum_{i,j} y_j d_k(i, j)}{\sum_{i,j} y_j^2} \quad (6.8)$$

The variance or mean squared residual deviations $d_k(i, j)$ was also evaluated from a linear fit using the next expression:

$$u^2(d_k) = \frac{1}{N} \sum_{i,j} [d_k(i, j)]^2 - \alpha_k^2 - \beta_k^2 \frac{1}{N} \sum_{i,j} y_j^2 \quad (6.9)$$

The standard uncertainty for each fit parameter was then calculated from the following equations:

$$u(\alpha_k) = \sqrt{\frac{u^2(d_k)}{N}}, \quad u(\beta_k) = \sqrt{\frac{u^2(d_k)}{\sum_{i,j} y_j^2}} \quad (6.10)$$

An expanded uncertainty can be defined as $2u$, where $\pm 2u$ corresponds to an interval for the fit parameter within its actual value can be asserted to lie with 95 % confidence.

Once the fit parameters and their uncertainties had been calculated for each loading step, it was necessary to estimate the combined standard uncertainty of the strains generated by the calibration specimen. This uncertainty was determined from the following expression:

$$u_{CS}(\varepsilon_{xx})_k \approx \sqrt{\varepsilon_{xx}^2 \left[\frac{u^2(\bar{v}_k)}{\bar{v}_k^2} + \frac{16u^2(w) + u^2(a) + u^2(c)}{4w^2} + u^2(\kappa) \right] + \left(\frac{\bar{v}_k}{6w^2} \right)^2 u^2(\eta)} \quad (6.11)$$

The length terms a and c correspond to the distance between the inner and outer loading points and the distance between the inner loading points and the centre of the beam, respectively. The values of uncertainty values in the dimensions w , a and c were estimated from the machining tolerances associated with the production of the specimen. In table 6.5 the uncertainty values for w , a , c , $\bar{v}_k$, κ and η employed to estimate the combined standard uncertainty for strains produced by the calibration specimen in the gauge section are summarised.

Table 6.5. Uncertainty values for the parameters employed to estimate the combined standard uncertainty for strains

Parameter	Units	Nominal value	Uncertainty
w	mm	15	0.017
a	mm	45	0.017
c	mm	15	0.017
$\bar{v}_k$	μm	25, 125, 225	0.1, 0.53, 0.95
κ	-	0.864	0.013
η	mm	-0.089	0.135

Subsequently, the overall calibration uncertainty (u_{CAL}) was calculated by combining the uncertainties associated with both the calibration specimen and the measurement, that is,

$$u_{CAL}(\varepsilon_{xx})_k = \sqrt{u_{CS}^2(\varepsilon_{xx})_k + u^2(d_k)} \quad (6.12)$$

This calibration uncertainty was the minimum uncertainty with which measurement could be performed on any specimen using the ESPI system, for the strain range defined by the loading step used in the calibration procedure.

Finally, a relative uncertainty was estimated as a function of strain range measured within each loading level:

$$u_{rel}(k) = \frac{u_{CAL}}{\varepsilon_{\max} - \varepsilon_{\min}} \quad (6.13)$$

In the following section, results obtained using SPOT protocol are exposed.

6.2.4.1.4. Results and discussion

According to the protocol previously described, the procedure performed is composed by the following steps:

- Measurement of the displacement fields using ESPI

The first step in the calculation procedure is measuring the displacement fields using ESPI. The horizontal and vertical displacements for the displacement previously indicated (25, 125 and 225 μm) are represented in figure 6.32. It can be observed that the displacement distribution is the same for the different steps, changing only the values and the sharpness of the maps. In addition, it can be observed that the displacement fields improve as the applied displacement increases.

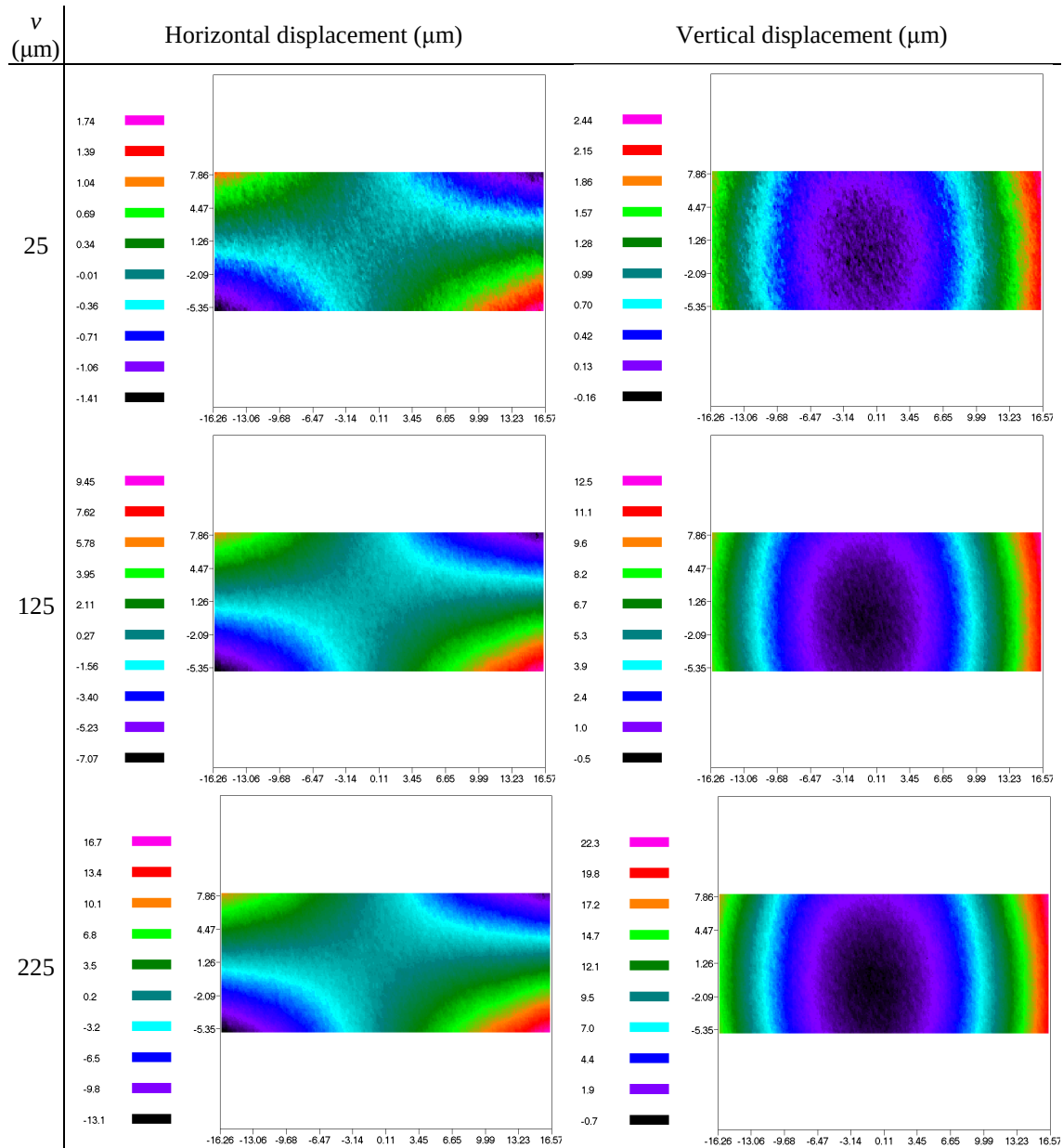


Figure 6.32. Horizontal and vertical displacement fields obtained at different displacement steps according to SPOTS calibration procedure for ESPI

- b) Determination of the experimental horizontal strains by differentiation of the horizontal displacements

Strain fields were obtained by differentiation of previous displacement fields. In the current work, the calibration of strains in the x -direction was conducted. However the same procedure can be employed to calibrate strains in the y -direction. Figure 6.33 shows horizontal strains for the applied displacement evaluated.

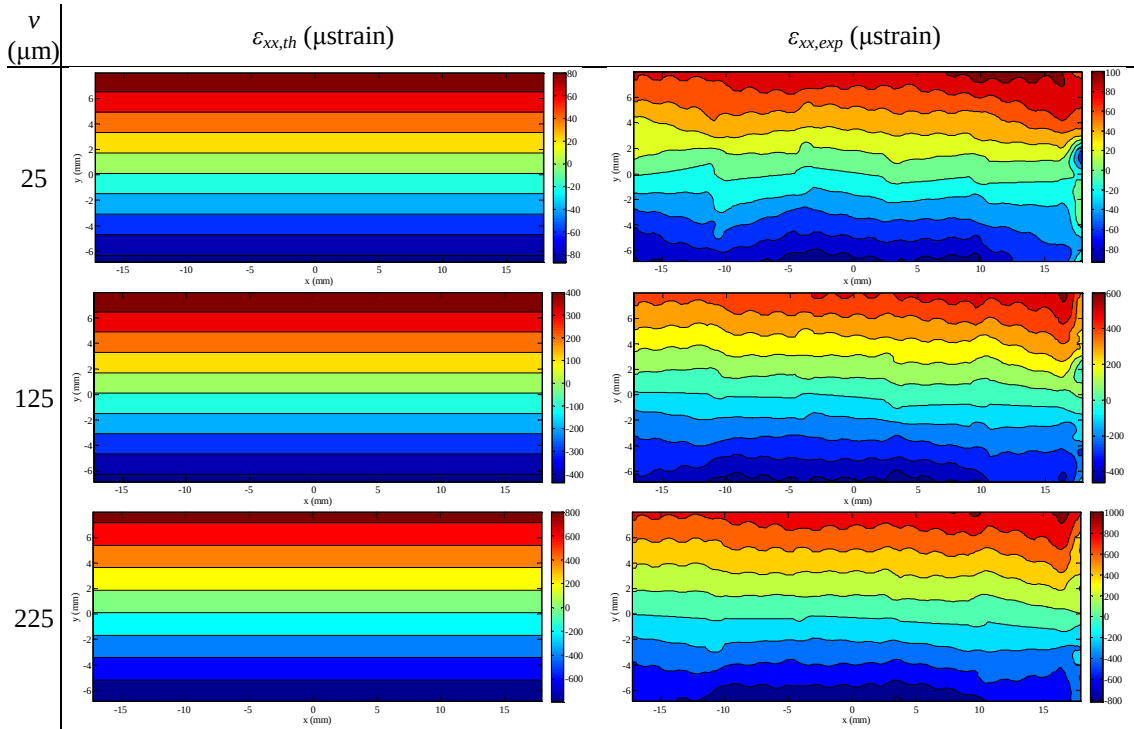


Figure 6.33. Theoretical and experimental horizontal strains determined for different the displacement steps during ESPI calibration

c) Calculation of the theoretical horizontal strains from beam theory

The next step was to calculate the theoretical horizontal strain field from theory. These maps for the three different applied displacement steps analysed are shown in figure 6.33. It can be observed a good level of agreement between theoretical and experimental results, with very similar distribution of the maps. A three-dimensional representation of the theoretical and experimental strain maps for a 225 μm displacement is shown in figure 6.34. A good agreement between the two strain fields is observed, however experimental results seem to be a little wavy. Nevertheless, the similarity between both maps will be established by determining the difference between them.

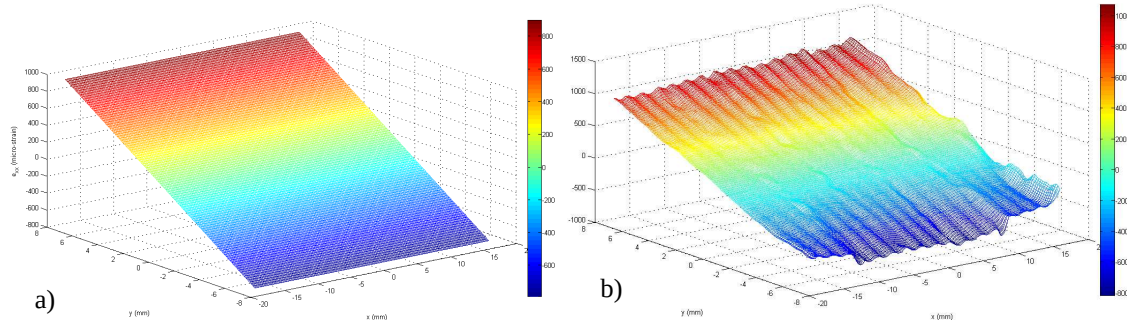
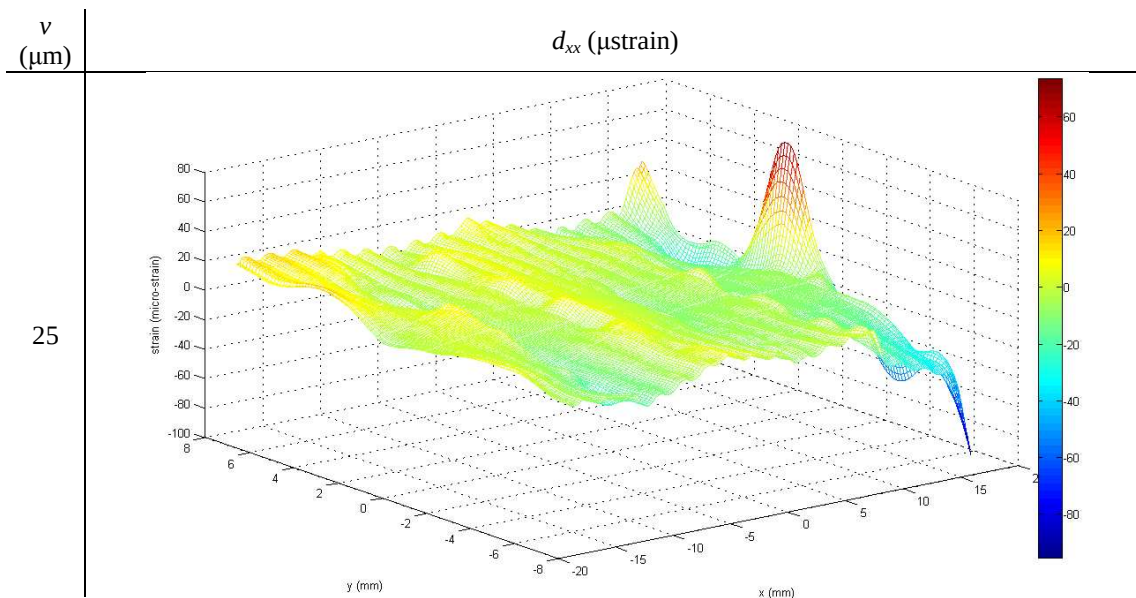


Figure 6.34. Three-dimensional representation of theoretical (a) and experimental (b) horizontal strain maps corresponding to a displacement step of 225 μm during ESPI calibration

d) Calculation of the difference between theoretical and experimental results

Once the theoretical and experimental horizontal strain maps were obtained, the next step was to calculate the difference between these maps. In figure 6.35 this difference is shown for each one of the displacement steps analysed. It can be observed that bigger differences occur in the right side of the matrices. This is understandable since the noise influence in the extremes can be more important than in the rest of the image. For this reason, a line-profile along the central vertical axis of the beam is plotted for theoretical and experimental strain fields and the difference between them. These plots can be observed in figure 6.36, showing a great level of agreement the difference plot.



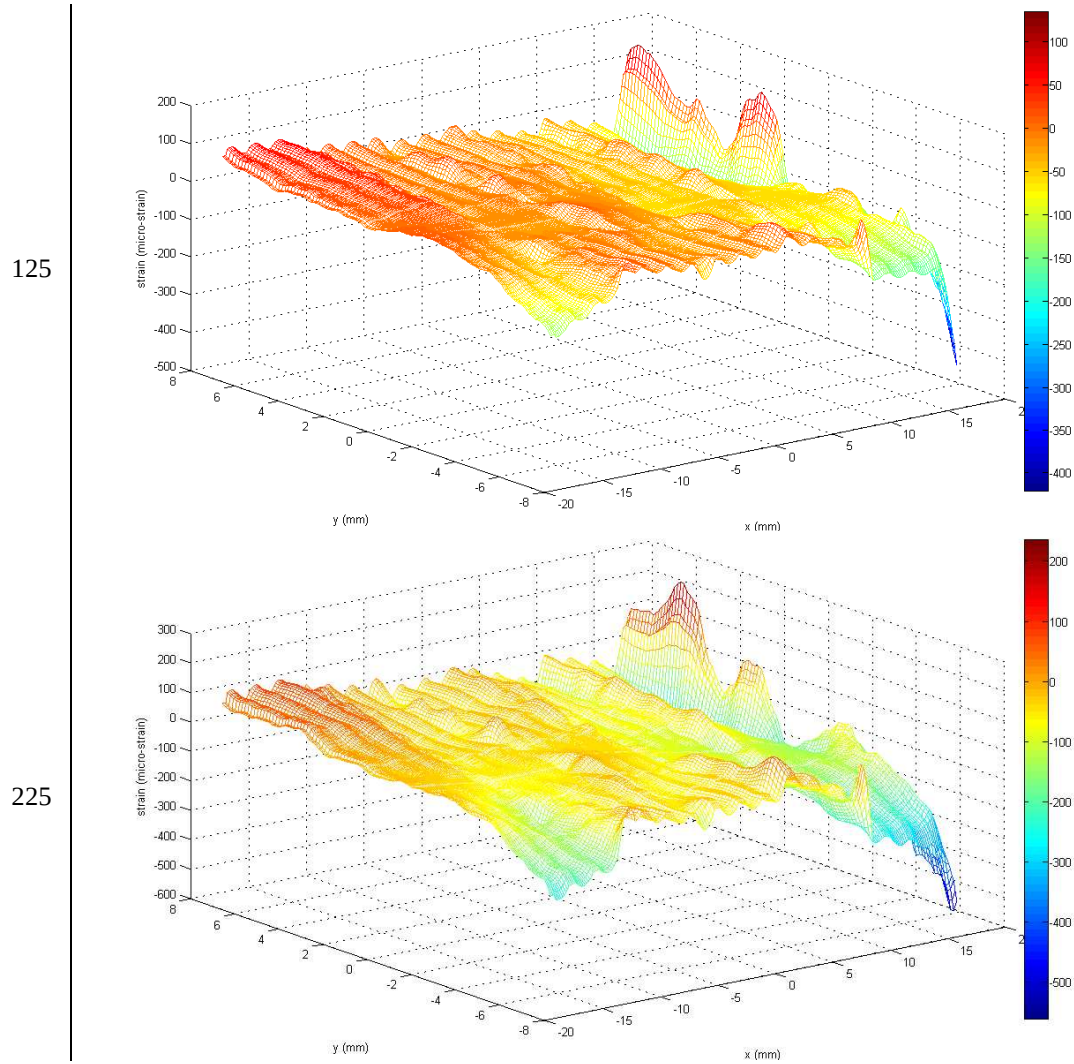
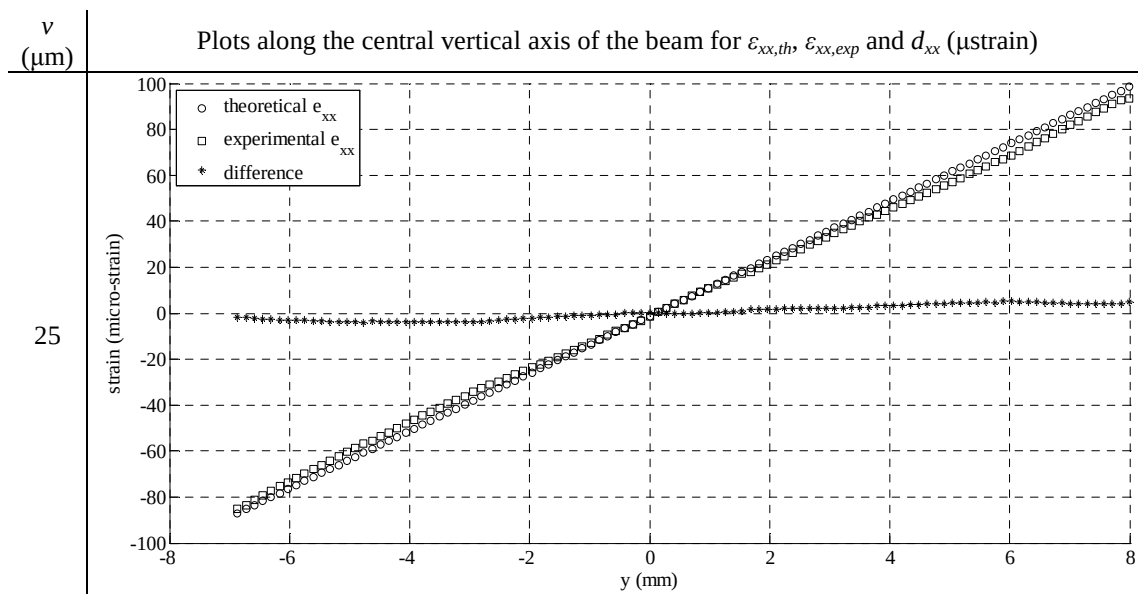


Figure 6.35. Difference between theoretical and experimental horizontal strain fields for each displacement step



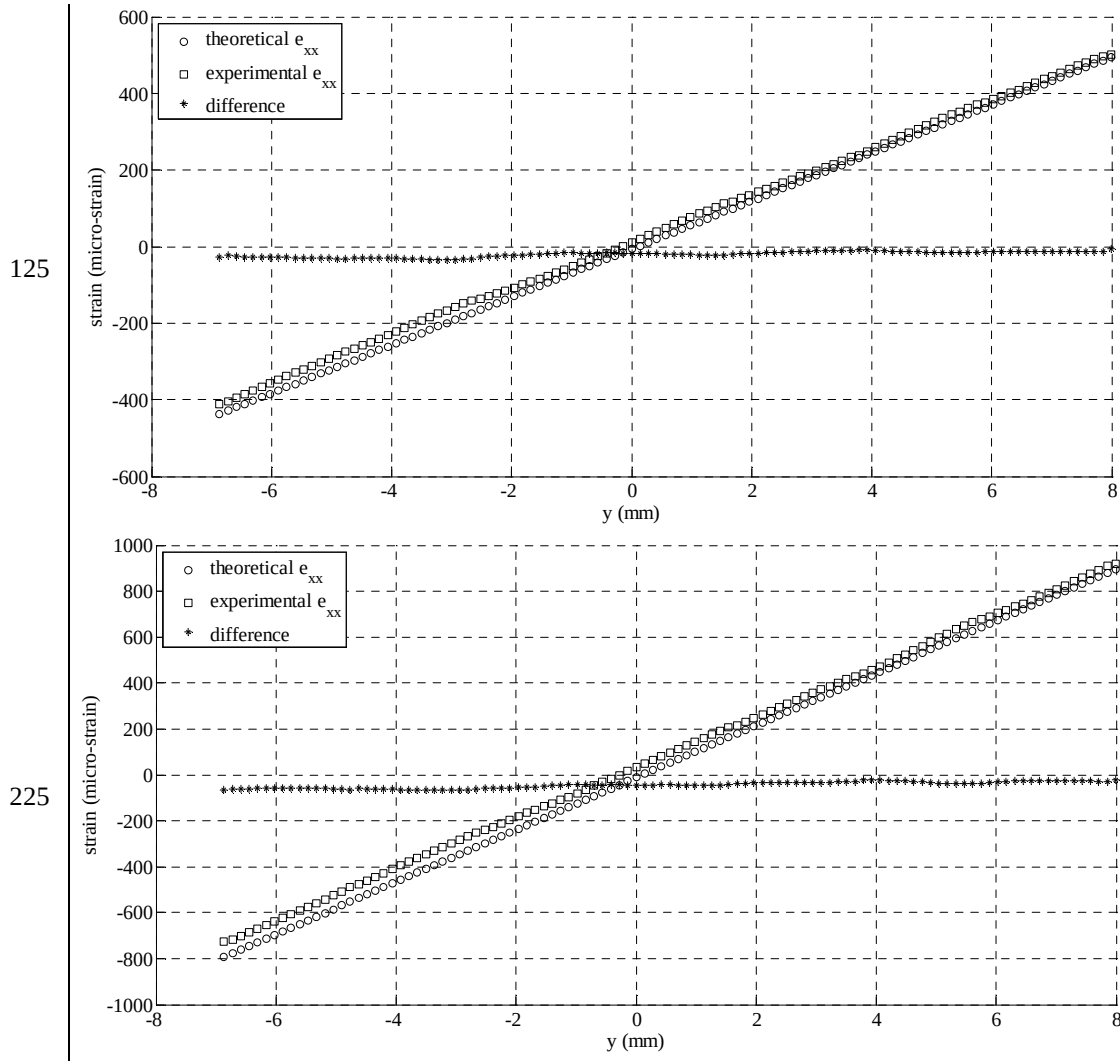


Figure 6.36. Plots along the central vertical axis of the beam for theoretical, experimental and difference values of ϵ_{xx} during ESPI calibration

e) Calculation of the fitting parameters (α, β) and their uncertainties

After determining the difference between the theoretical and experimental values in the horizontal strain maps, it was required to calculate the two fitting parameters and their associated uncertainties to obtain the discrepancy between theoretical and experimental values. These results are shown in table 6.6.

f) Calculation of the uncertainties

The last step in the procedure was the uncertainties calculation to evaluate if an acceptable calibration for the different displacement steps evaluated was achieved and no further adjustment of the ESPI system was required. These uncertainties were the strain uncertainty of the calibration specimen (u_{CS}), the overall calibration uncertainty (u_{CAL}) and the relative uncertainty (u_{rel}). These uncertainties obtained are shown in table 6.7.

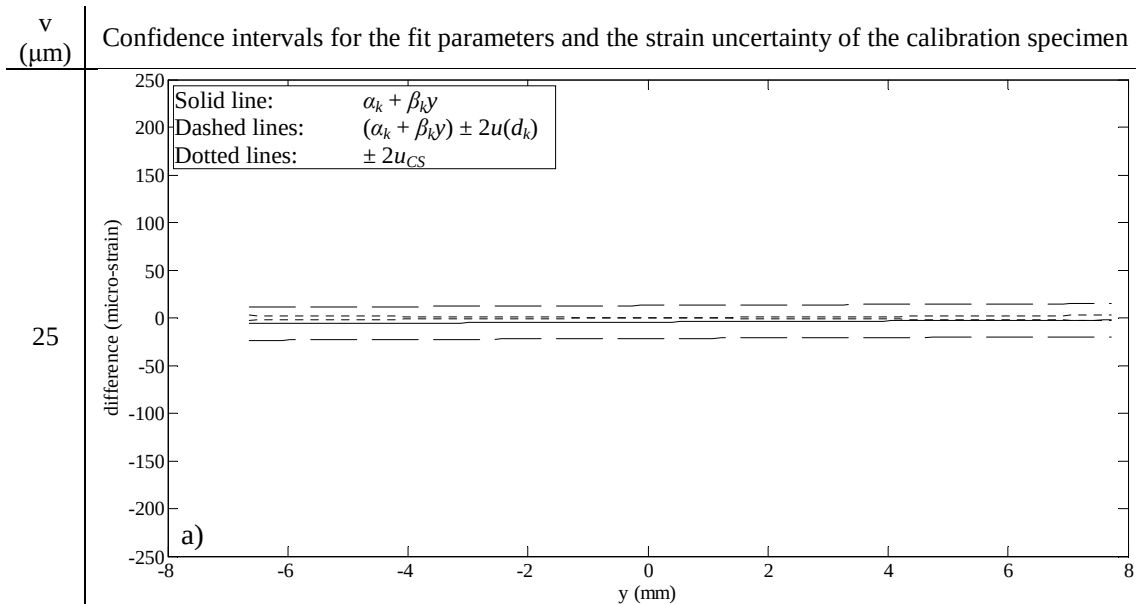
Table 6.6. Fitting parameters and their uncertainties for each of the three displacement steps

Fit parameter	Units	Applied displacement-load (μm)		
		25	125	225
α	μstrain	-4.17	-33.19	-68.72
$u(\alpha)$	μstrain	0.05	0.24	0.37
95 % CI (α)	μstrain	± 0.11	± 0.47	± 0.74
β	$\mu\text{strain} \cdot \text{mm}^{-1}$	0.67	1.47	3.96
$u(\beta)$	$\mu\text{strain} \cdot \text{mm}^{-1}$	0.01	0.05	0.08
95 % CI (β)	$\mu\text{strain} \cdot \text{mm}^{-1}$	± 0.02	± 0.11	± 0.17

Table 6.7. Uncertainties u_{CS} , u_{CAL} and u_{rel}

v (μm)	$u(d)$ (μstrain)	u_{CS} (μstrain)	u_{CAL} (μstrain)	u_{rel} (%)
25	9	2	8.9	4.2
125	39	9	40.0	3.7
225	61	15	62.8	3.3

The expanded uncertainty for the calibration specimen was then equal to $2u_{CS}$, where $\pm 2u_{CS}$ defines a 95 % confidence interval around the predicted ε_{xx} strains. In order to judge the significance of the fitting parameters with respect to the uncertainty inherent to the calibration specimen, the SPOTS standard advises plotting $\pm 2u_{CS}$ as a function of y , together with $(\alpha_k + \beta_k y) \pm 2u(d_k)$, for each displacement level, as presented in figure 6.37. In the case where the scatter band $(\alpha_k + \beta_k y) \pm 2u(d_k)$ overlaps the area described by $2u_{CS}$ for each displacement step value, the SPOTS standard concludes that an acceptable calibration for that displacement level has been achieved and no adjustment of the ESPI measurement system is required. According to this and from the confidence intervals obtained in figure 6.37, the overlap condition was satisfied for each displacement level.



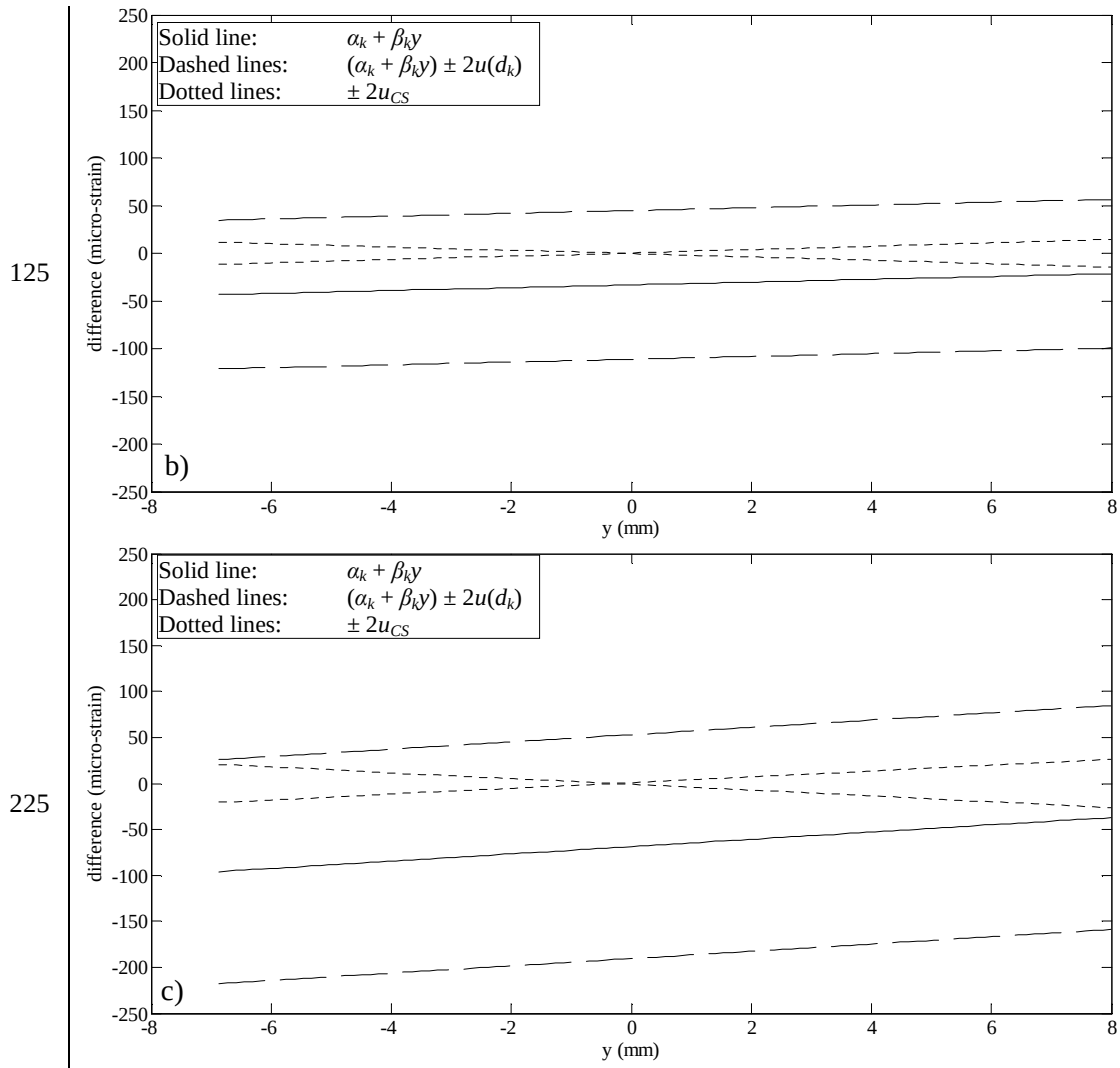


Figure 6.37. Plots of the expanded combined uncertainty for the calibration specimen ($\pm 2u_{CS}$) as a function of y , together with $(\alpha_k + \beta_k y) \pm 2u(d_k)$, for each displacement level of 25 μm (a), 125 μm (b) and 225 μm (c)

6.2.4.1.5. Conclusions

From the previous results, the following conclusions related to the calibration test for the ESPI system can be established:

1. ESPI has shown to be a powerful tool for measuring very small displacement fields (μm) in mechanical elements.
2. Satisfactory results have been obtained for the strain fields by differentiation of the displacement fields.
3. A good level of agreement has been obtained between theoretical and experimental strain fields.
4. Good results have been obtained for the fitting parameters and the different uncertainties.

5. Results have highlighted that an acceptable calibration of the ESPI system has been achieved and therefore, it is not necessary any additional adjustment of the system.
6. According to the obtained results, the ESPI system is perfectly suitable for conducting fatigue tests.

6.2.4.2. Experimental results on fatigue crack shielding

Once the potential of the ESPI system to measure displacements has been verified through the calibration test, a set of fatigue tests were conducted to study its ability to evaluate fatigue crack shielding. Thus, two fatigue tests at different R -ratios were conducted on titanium CT specimens (figure 4.12b). The two tests were defined in order to apply on the specimens the same load range. The first specimen was tested at low R -ratio ($R = 0.17$) and the second one at high R -ratio ($R = 0.58$). Test conditions and the specimen references are shown in table 6.8.

Table 6.8. Test conditions for experiments conducted for the evaluation of fatigue crack shielding using ESPI

Test reference	Specimen reference	P_{min} (N)	P_{max} (N)	R -ratio
ESPI_R=0.17	Ti_CT2	50	300	0.17
ESPI_R=0.58	Ti_CT4	350	600	0.58

In figure 6.38 it is shown the evolution of the crack length as function of the number of cycles for the two specimens tested.

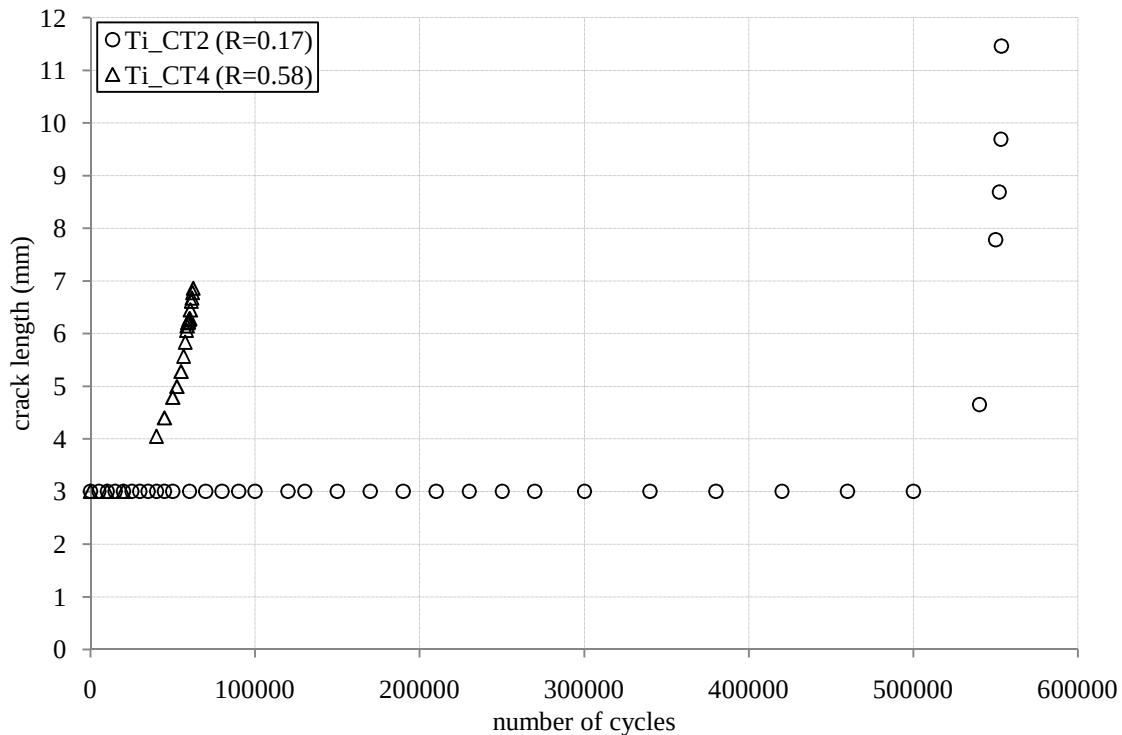
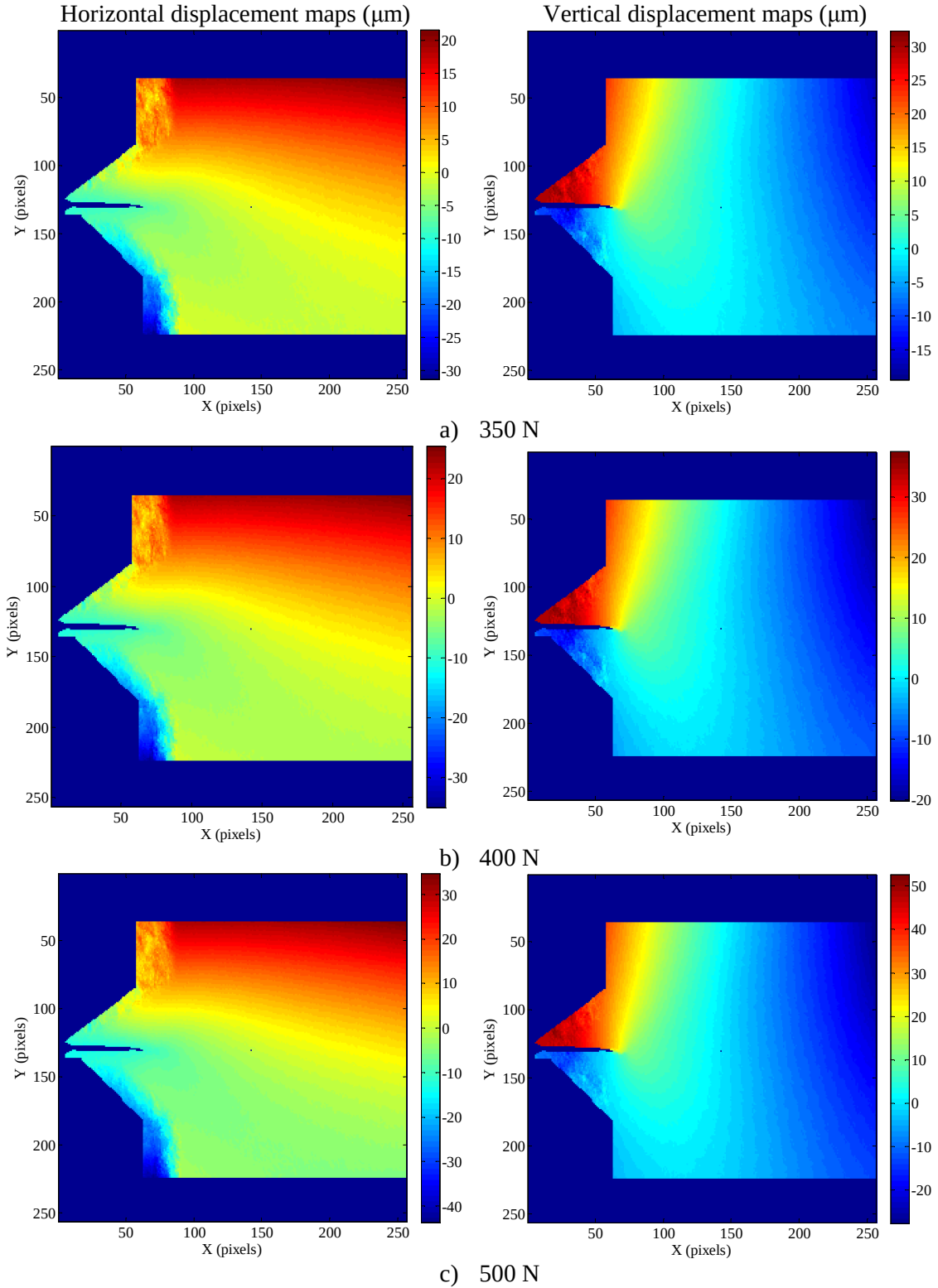


Figure 6.38. Crack length versus number of cycles for specimens tested using ESPI

During fatigue tests, a sequence of images between an undeformed state and the maximum applied load state was captured for the different crack lengths analysed. As example, in figure 6.39 the horizontal and vertical displacement fields obtained at different load states corresponding to a crack length of 6.78 mm for Ti_CT4 specimen are shown.



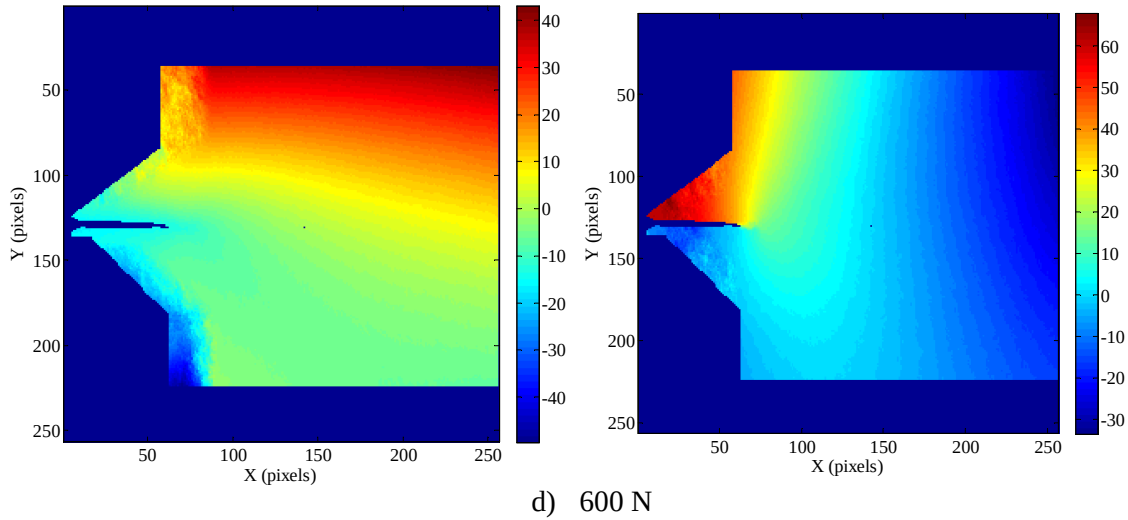


Figure 6.39. Horizontal (left) and vertical (right) displacement fields obtained by ESPI at different load steps for a crack length of 6.78 mm in Ti_CT4 specimen. a) 350 N, b) 400 N, c) 500 N, d) 600 N

The same methodology previously proposed for DIC was employed for the determination of opening/closing loads. Figure 6.40 shows K_F and K_R values for a crack length of 8.68 mm corresponding to Ti_CT2 specimen (tested at $R = 0.17$) as a function of the loading cycle. K_I values have been also plotted in this figure.

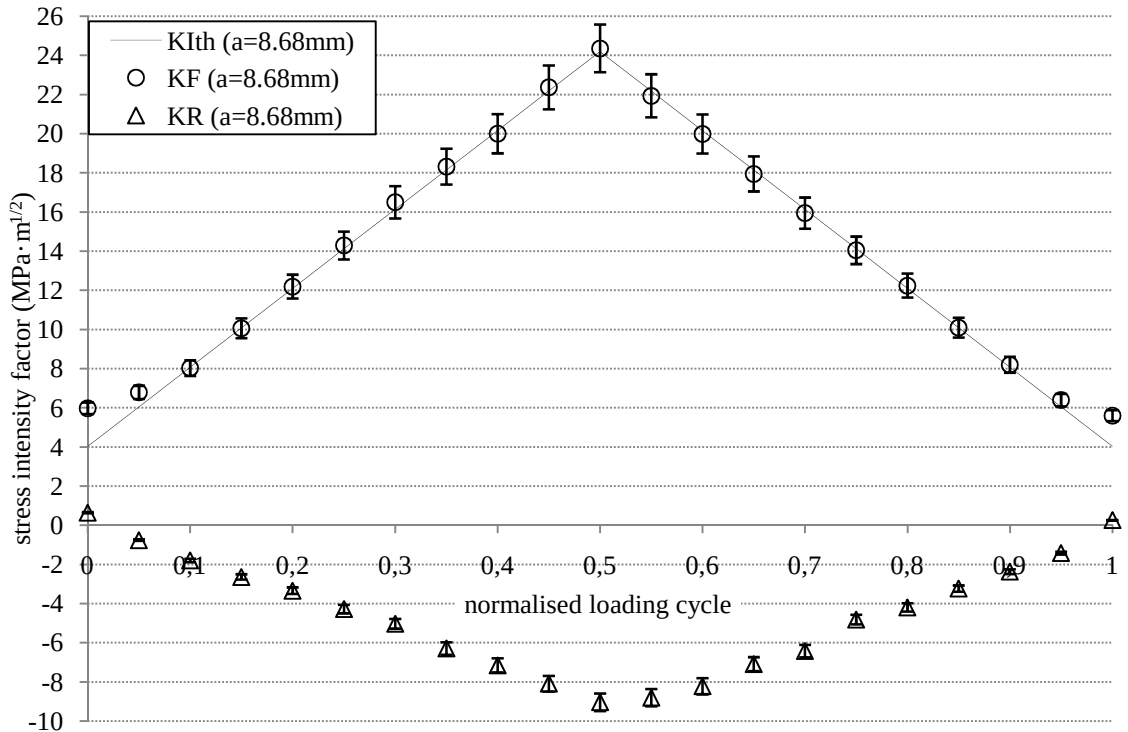


Figure 6.40. K_F and K_R obtained as a function of the loading cycle for a crack length of 8.68 mm in Ti_CT2 specimen

According to the methodology previously proposed, K_{op} and K_{cl} can be determined from the analysis of the K_F along the loading and unloading branches respectively. Thus, in figure 6.41 these values obtained for Ti_CT2 specimen for the different crack lengths evaluated are presented. In addition, P_{op} and P_{cl} were calculated from the K_{op} and K_{cl} values using equation 6.1. These results are shown in figure 6.42. In addition, the minimum and maximum loads corresponding to the applied loading cycle have been also presented.

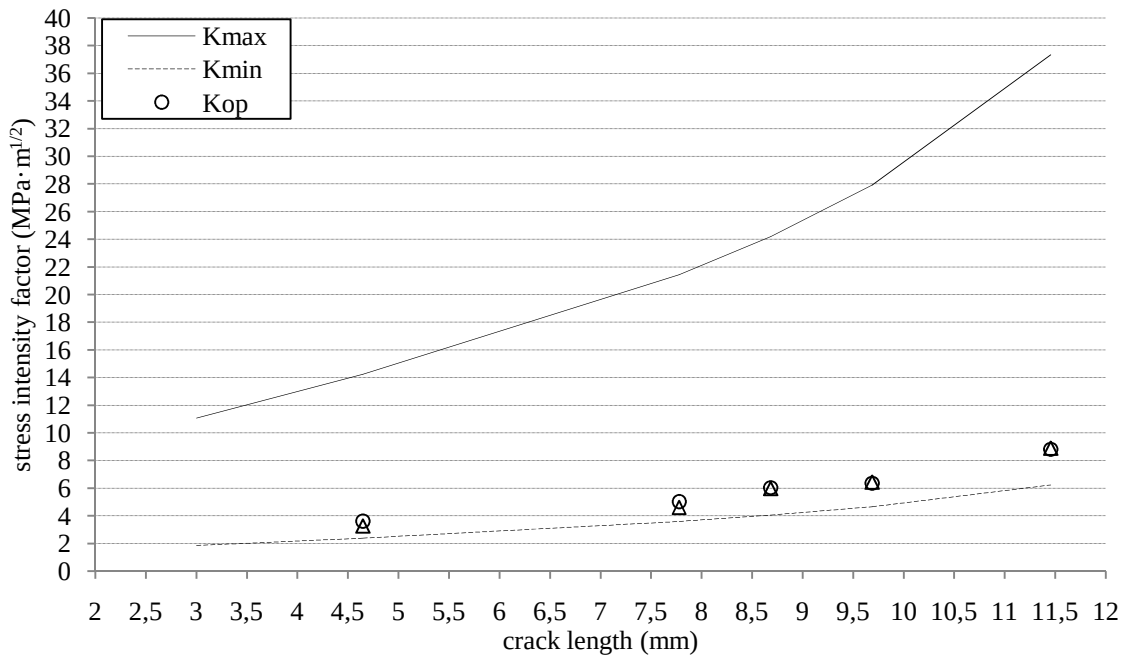


Figure 6.41. Estimated K_{op} and K_{cl} as a function of crack length for Ti_CT2 specimen

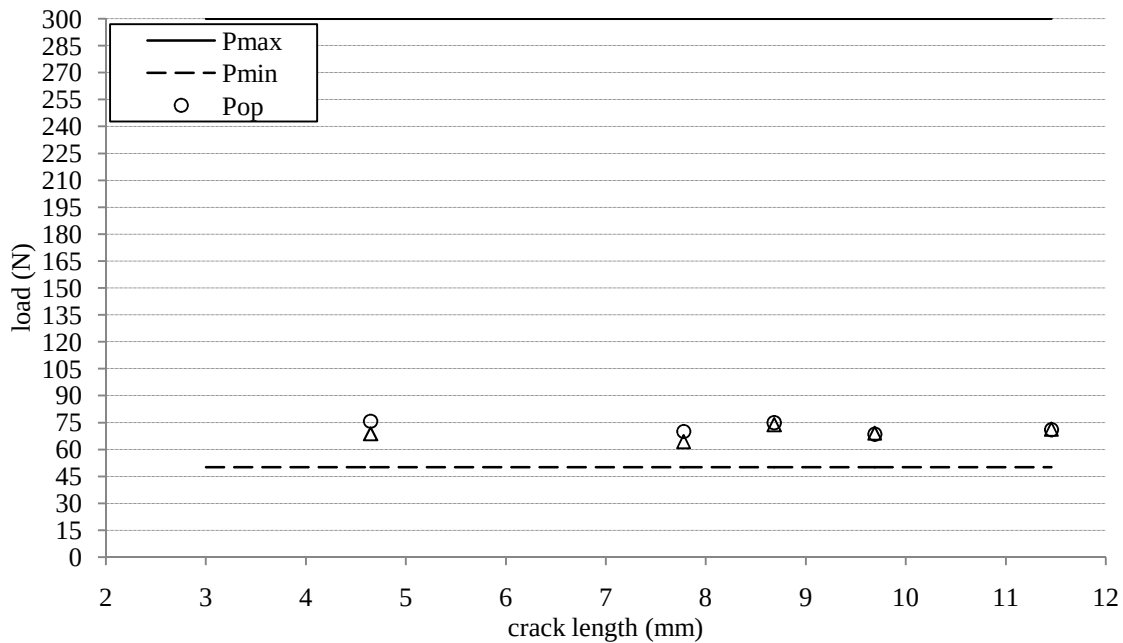


Figure 6.42. Crack opening and closing loads as a function of the crack length for Ti_CT2 specimen

In a similar way, figure 6.43 shows K_F and K_R values obtained as a function of the applied loading cycle for Ti_CT4 specimen at a crack length of 6.68 mm.

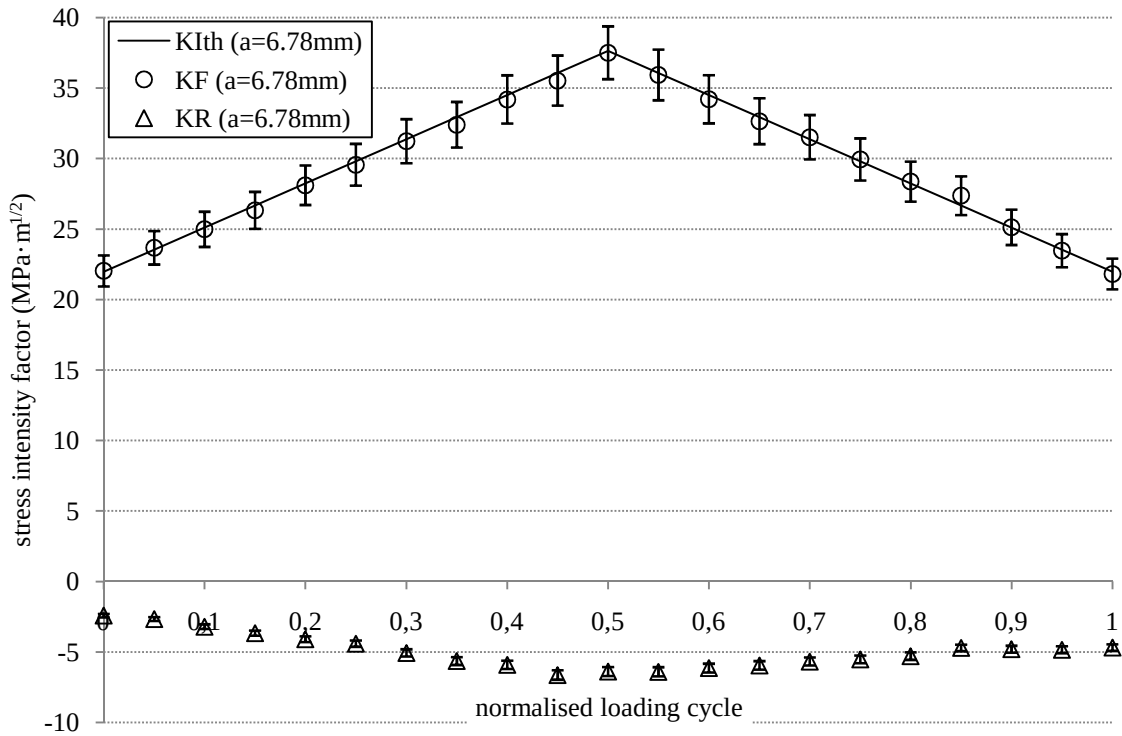


Figure 6.43. K_F and K_R obtained for a crack length of 6.78 mm for Ti_CT4 specimen

6.2.4.3. Estimation of the plastic zone size

ESPI allows to measure very small displacements compared with DIC. Therefore, the spatial resolution at the crack tip area can be substantially increased. Thus, one aspect investigated in the current thesis is the ability of ESPI to estimate the plastic zone size. This aspect can be especially useful in the study of overload effect since the retardation effect induced on crack growth could be related to the subsequent increase of plastic zone at the crack tip due to the overload application. Thus, in this section it will be investigated whether ESPI can be sensitive enough to estimate the plastic zone size at the crack tip.

6.2.4.3.1. Crack tip plasticity

Linear elastic stress analysis of sharp cracks predicts infinite stresses at the crack tip. However, in real materials, stresses at the crack tip are not infinite since the crack tip radius must be finite. Inelastic material deformation, such as plasticity in metals and crazing in polymers, leads to further relaxation of the crack tip stresses.

In the literature it is well known that the size of the plastic zone can be estimated by two methods [27]: Irwin approach and Dugdale approach. Both approaches lead to simple corrections for crack tip yielding.

According to Irwin approach, a first-order estimation of plastic zone size is given by the following equation:

$$r_y = \frac{1}{2\pi} \left(\frac{K_I}{\sigma_{ys}} \right)^2 \quad (6.14)$$

Where σ_{ys} is the yield stress of the material.

However, if the second-order estimation of plastic zone size by Irwin is adopted, this is twice the size of the first-order estimate:

$$r_p = \frac{1}{\pi} \left(\frac{K_I}{\sigma_{ys}} \right)^2 \quad (6.15)$$

If Dugdale approach is adopted, the plastic zone size can be estimated by the following expression:

$$\rho = \frac{\pi}{8} \left(\frac{K_I}{\sigma_{ys}} \right)^2 \quad (6.16)$$

These three approaches will be used to compare the plastic zone size obtained from experiments.

6.2.4.3.2. Methodology for the experimental estimation of the plastic zone size

An experimental methodology has been proposed to estimate plastic zone size at the crack tip. This methodology is based on the direct measurement of the crack tip plastic strain fields together with Von Mises yield criterion. Thus, the methodology is composed by the following steps:

The first step in the methodology consists on measuring the horizontal and vertical displacement fields around the crack tip. As previously indicated, a sequence of images must be captured between an undeformed state and a deformed state. In figure 6.39 the horizontal and vertical displacement fields corresponding to Ti_CT4 specimen for different load levels for a crack length of 6.78 mm are shown.

The second step is the calculation of the strain fields at the crack tip by differentiation of the displacement fields. For this purpose, the Green-Lagrange strain tensor [214] was employed, which is given by the following expression:

$$\begin{pmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{pmatrix} = \begin{pmatrix} \frac{\partial u}{\partial x} \\ \frac{\partial v}{\partial y} \\ \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \end{pmatrix} + \frac{1}{2} \begin{pmatrix} \frac{\partial u}{\partial x} & 0 & \frac{\partial v}{\partial x} & 0 \\ 0 & \frac{\partial u}{\partial y} & 0 & \frac{\partial v}{\partial y} \\ \frac{\partial u}{\partial y} & \frac{\partial u}{\partial x} & \frac{\partial v}{\partial y} & \frac{\partial v}{\partial x} \end{pmatrix} \begin{pmatrix} \frac{\partial u}{\partial x} \\ \frac{\partial u}{\partial y} \\ \frac{\partial v}{\partial x} \\ \frac{\partial v}{\partial y} \end{pmatrix} \quad (6.17)$$

Figure 6.44 shows the strain fields in Ti_CT4 specimen for a crack length of 6.78 mm at a load level of 600 N.

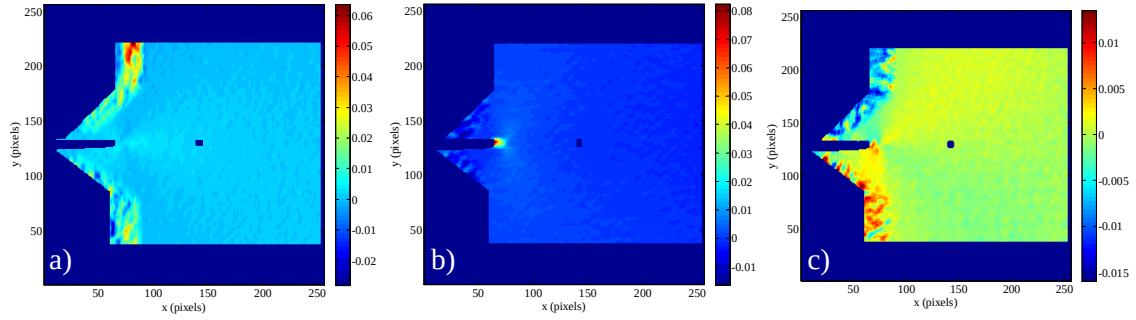


Figure 6.44. Strain fields obtained for Ti_CT4 specimen at a crack length of 6.78 mm for a load level of 600 N. a) Horizontal ε_x , b) vertical ε_y and c) shear γ_{xy} strains (strains)

Once the strain fields have been calculated, the next step is to calculate the stress fields using Hooke's law (equation 6.18).

$$\left. \begin{aligned} \varepsilon_x &= \frac{1}{E} (\sigma_x - \nu \sigma_y) \\ \varepsilon_y &= \frac{1}{E} (\sigma_y - \nu \sigma_x) \\ \gamma_{xy} &= \frac{1}{G} \tau_{xy} \end{aligned} \right\} \quad (6.18)$$

Then, the principal stresses are calculated from the normal and shear stresses using the equations corresponding to the Mohr's circle (equation 6.19).

$$\sigma_{1,2} = \frac{\sigma_x + \sigma_y}{2} \pm \sqrt{\left(\frac{\sigma_y - \sigma_x}{2} \right)^2 + \tau_{xy}^2} \quad (6.19)$$

From the stress fields, the Von Mises equivalent stress is given for the following expression:

$$\sigma_{VM} = \sqrt{\sigma_1^2 + \sigma_2^2 - \sigma_1 \sigma_2} \quad (6.20)$$

According to the Von Mises yield criterion, yielding is produced when the Von Mises stress reaches the yield stress of the material. Therefore, the plastic zone at the crack tip is defined by using the stress yield as a threshold value. Figure 6.45a shows the Von Mises stress map above

the yield stress corresponding to Ti_CT4 specimen for a crack length of 6.78 mm at a load level of 600 N. In addition, figure 6.45b shows the procedure for the estimation of the plastic zone size both in the x-direction and y-direction.

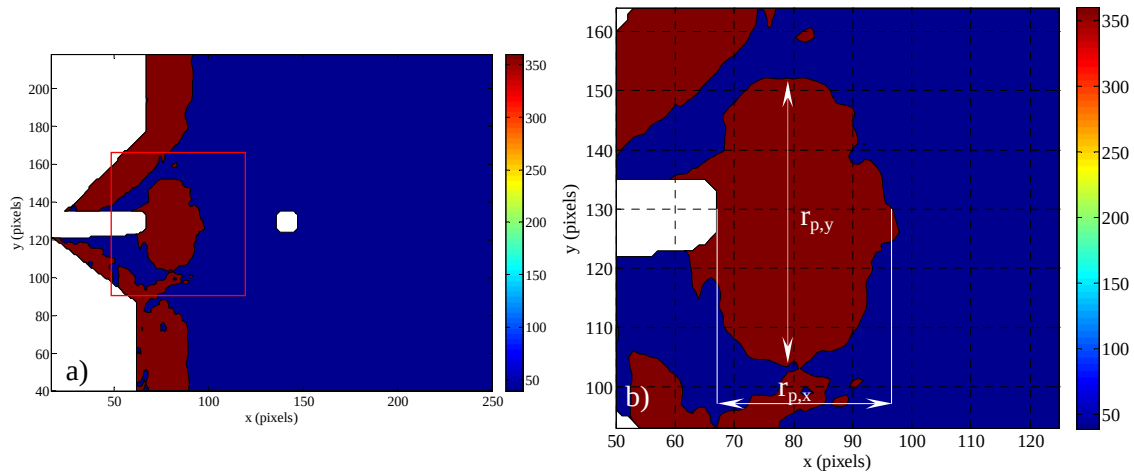


Figure 6.45. Von Mises stress map above the yield stress corresponding to Ti_CT4 specimen for a crack length of 6.78 mm at a load level of 600 N. a) Whole map and b) map centred at the crack tip

6.2.4.3.3. Results

The ability of ESPI to estimate the plastic zone size has been investigated using Ti_CT4 specimen. Thus, a validation of the proposed methodology has been performed. As it can be observed in table 6.8, high loading conditions were defined to generate enough plasticity at the crack tip.

Figure 6.46 shows the plastic zone sizes estimated in x and y directions as a function of the applied loading cycle for Ti_CT4 specimen at a crack length of 6.78 mm. In addition, the plastic zone size predicted by the three approaches previously described (first-order and second-order estimates by Irwin and Dugdale's estimate) have been also presented.

Besides studying the evolution of plastic zone with the applied load, its behaviour along the crack length has been also investigated. Thus, in figure 6.47 shows the horizontal and vertical plastic zone sizes estimated as a function of the crack length for Ti_CT4 specimen at the maximum applied load. Again, the estimates predicted by theory have been also represented.

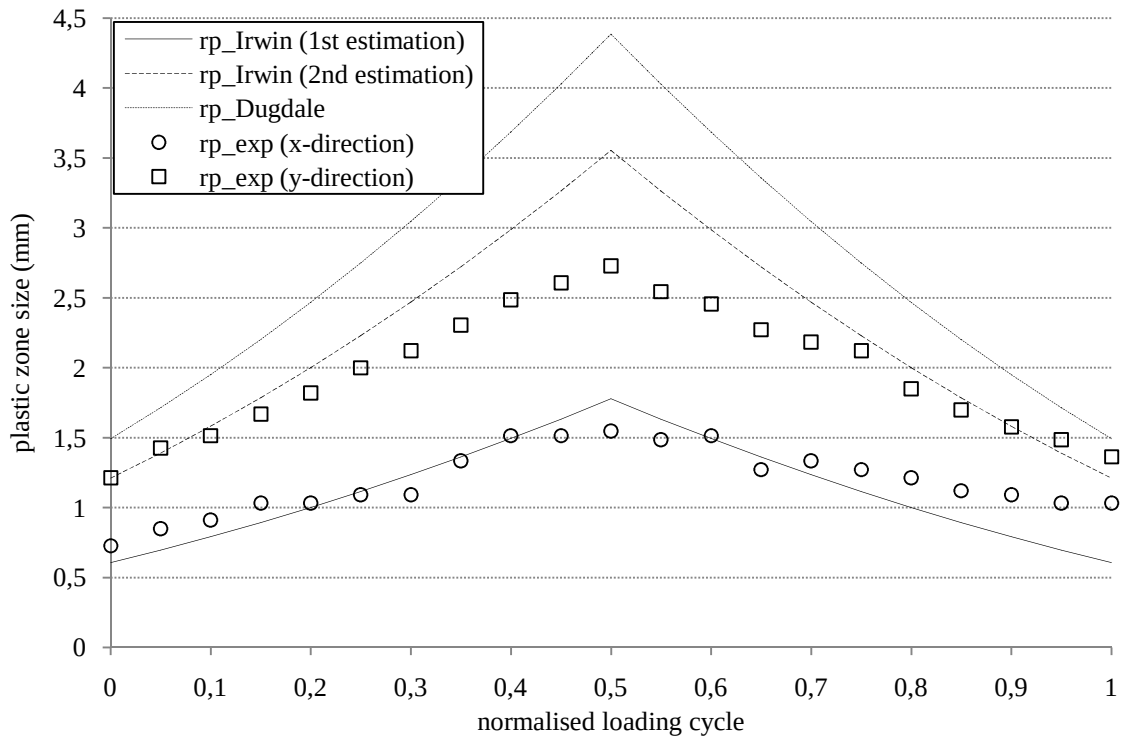


Figure 6.46. Experimental plastic zone size in x and y directions as a function of the loading cycle measured from the direct observation of the plastic strain fields at the crack tip. Results correspond to Ti_CT4 specimen for a crack length of 6.78 mm

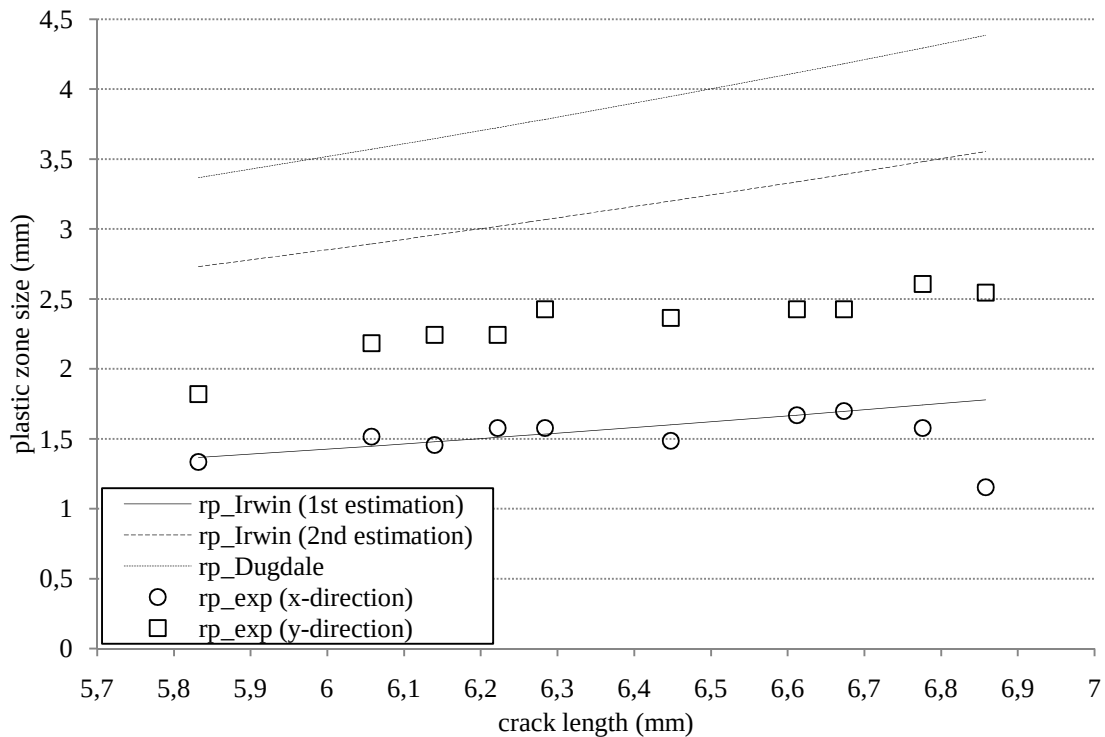


Figure 6.47. Experimental plastic zone size in x and y directions as a function of the crack length measured from the direct observation of the plastic strain fields at the crack tip. Results correspond to Ti_CT4 specimen for a load level of 600 N

6.3. Discussion of the results

The evolution of the different fatigue tests conducted is shown in figures 6.1, 6.11 and 6.38. It can be observed that fatigue life of the aluminium and titanium specimens tested at low R -ratio is longer than those tested at high R -ratio (figures 6.11 and 6.38). This is due to the fact that the effective load range applied was higher in the case of specimens tested at high R -ratio although the applied load range was the same for all the specimens manufactured with the same material. This behaviour is not observed on polycarbonate specimens (figure 6.1), where fatigue life of the specimen tested at high R -ratio was much longer than that observed for the specimen at low R -ratio. This difference in fatigue crack growth rates was due to the fact that the nominal SIF range applied to PC_CT4 specimen was equal to $40 \text{ MPa} \cdot \text{m}^{1/2}$, while for PC_CT3 specimen was $50 \text{ MPa} \cdot \text{m}^{1/2}$. In addition, the influence of the rolling direction in fatigue life for the aluminium specimens was investigated. Thus, in figure 6.11 it can be observed that fatigue life of the cut specimens with the rolling direction parallel to crack growth direction (Al_CT3 and Al_CT7) was a little shorter than that corresponding to the specimens with crack growth direction perpendicular to the rolling direction (Al_CT4 and Al_CT5). Nevertheless, the real fatigue behaviour is established through Paris law. According to this, figure 6.13 shows curves corresponding to Paris law for specimens tested at low R -ratio (Al_CT3 and Al_CT4), where it can be observed that there are not practically differences between both curves and therefore, fatigue crack growth rate was not affected by the specimen cutting direction.

An important aspect investigated was to establish which is the most suitable model to evaluate the influence of plasticity-induced crack shielding effect in fatigue life. For this purpose, a comparative study among the four models previously described was performed. Thus, the evolution of the SIFs during a loading cycle was analysed. Figures 6.4, 6.5, 6.15 and 6.16 show the experimental SIFs obtained for the four models for specimens tested at low R -ratio. Figures 6.4 and 6.5 correspond to transmission photoelasticity (PC_CT3 specimen) at two different crack lengths (31.05 and 35.01 mm respectively); while figures 6.15 and 6.16 correspond to those results obtained using DIC for specimen Al_CT3 at crack lengths of 34.10 and 41.07 mm respectively. If K_I value is evaluated, it is observed that results from Westergaard's model show worse fitting than those obtained from Williams's and Muskhelishvili's models when they are compared with nominal K_I value inferred from equation 6.1. These differences are more relevant for load levels close to the maximum load of the loading cycle. However, results obtained from Williams's and Muskhelishvili's models show a good correspondence with those calculated from equation 6.1. It has to be emphasised that the difference observed between results obtained from Westergaard's and Williams's models is due to the number of terms adopted (in the case of Williams's equations, 6 terms were employed to determine the SIFs).

Special interest shows the analysis of SIFs from the CJP model. Thus, it is observed that from 10 N in the case of transmission photoelasticity (figures 6.4 and 6.5) and approximately from 150 N in the case of DIC (figures 6.15 and 6.16), K_F values show a total level of agreement with those calculated from equation 6.1. Nevertheless, K_F values below this load are higher than those K_I values predicted from equation 6.1. It is observed a gradual change in the slope of the tendency followed by K_F as the load decreases. This behaviour agrees with the observation reported by Elber [25, 26] when he defined the plasticity-induced crack closure phenomenon. Thus, opening SIF (K_{op}) can be estimated from K_F trend as that value corresponding to the minimum applied load (see red line in figure 6.4). In a similar way, K_{cl} can be also estimated from the unloading branch. It can be observed that there is practically no difference between the loading and the unloading branches. Moreover, from the analysis of K_R , a sign change can be observed as load reaches 10 N for transmission photoelasticity (figures 6.4 and 6.5) and 100 N for DIC (figures 6.15 and 6.16). Below this load K_R takes negative values (in the case of photoelasticity) and positive values (in the case of DIC), while above this load K_R changes its sign. Therefore, K_R values divide the loading cycle in two portions, so the first one corresponds to the loading interval at which the crack is closed, while another portion corresponds to the interval at which the crack is open. According to this, a correspondence between the change in the K_F trend and the sign change in K_R can be observed. The same behaviour can be observed in figure 6.40, where K_F and K_R obtained from ESPI for Ti_CT2 specimen at a crack length of 8.68 mm have been plotted. It can be observed a change in the trend of K_F and a sign change in K_R values from 75 N in a similar way to that was previously observed by transmission photoelasticity and DIC. It must be indicated that K_R behaviour is similar to that observed in DIC since both technique are based on a displacement analysis. Thus, the loading cycle portion of the cycle with positive K_R values corresponds to that at which the crack is closed, remaining open when K_R values are negative.

According to the adopted methodology previously described, K_{op} and K_{cl} can be estimated from the analysis of the loading and unloading branches. In figure 6.6 K_{op} values estimated by transmission photoelasticity for PC_CT3 specimen at the different crack lengths analysed are plotted. In the same way, K_{op} and K_{cl} values estimated from DIC and ESPI as function of the crack length are represented in figures 6.18 and 6.41 respectively. In addition, the minimum and maximum SIFs corresponding to the applied loading cycle have been also plotted. In the three figures it can be observed a gradual increase of K_{op} and K_{cl} values along the crack length. These values are always above K_{min} and hence, it highlights that crack opens or closes at a load higher than the minimum applied load. In addition, it can be observed that there are not practically differences between K_{op} and K_{cl} values in the cases of DIC and ESPI. Crack opening (P_{op}) and closing (P_{cl}) loads can be calculated from K_{op} and K_{cl} values previously estimated using

equation 6.1. Thus, P_{op} values obtained using transmission photoelasticity for PC_CT3 specimen are plotted in figure 6.7, while P_{op} and P_{cl} results for DIC and ESPI are represented in figures 6.19 and 6.42 respectively. In addition, the minimum and maximum loads have been also presented. In the three graphs, it can be observed that as the crack grows, P_{op} and P_{cl} values are within a load interval, which is different depending on the adopted technique. Thus, for transmission photoelasticity this load range is between 8 and 12 N, for DIC is between 75 and 125 N and for ESPI is between 65 and 75 N. Some scatter is observed, which is attributed to the fact that crack opens or closes in a gradual way, and consequently, it is difficult to establish a single value for P_{op} or P_{cl} . Thus, there will be an interval at which the crack changes from fully closed to fully open. Nevertheless, results can be referenced with respect to the maximum applied load in order to establish a comparative between them. Thus, the percentage obtained for each of the techniques has been the following: transmission photoelasticity (16 to 24 %), DIC (12.5 to 21%) and ESPI (22 to 25 %). The ranges obtained for transmission photoelasticity and DIC are very similar, however, in the case of ESPI the range was narrower. This is due to the number of data analysed in the case of ESPI it was much smaller than in the case of transmission photoelasticity and DIC. However, it can be considered that a good correspondence is achieved for the different techniques although three different materials were employed. In addition, to support these results, in figure 6.22 the normalised opening load has been plotted for transmission photoelasticity and DIC, which highlights the similarity obtained with both techniques.

These techniques are modern and have not been yet established as standard methods for the evaluation of fatigue crack shielding. For this reason, an important aspect that must be considered is the verification of the adopted methodology using standard methods. In the current work, two methods based on compliance were employed to verify the results obtained by DIC from the analysis of the COD data collected with an extensometer located at the mouth of the aluminium CT specimens. The possibility of using the extensometer in polycarbonate CT specimens tested in transmission photoelasticity was investigated. However, the force applied at the mouth of the specimen by the extensometer originated the opening of the crack due to the low specimen stiffness making non-viable its use. Figure 6.26 shows the results obtained for Al_CT3 specimen at a crack length of 35.47 mm. The top plots show the applied load versus COD for the loading (top left) and unloading branches (top right). It can be observed a change in the slope of experimental data for load values between 100 and 110N, which indicates that the crack starts opening. The two middle plots show the applied load versus the strain offset for the loading (middle left) and unloading (middle right) branches. In this case, it is observed that for load values higher than 100 N (for loading branch) and 115 N (for unloading branch) the strain offset is almost 0, which indicates that the crack is completely open. Bottom plots show

the applied load versus compliance offset for the loading (bottom left) and unloading (bottom right) branches. A similar behaviour is also observed for loads between 110 and 120 N when the 2 % offset criterion is adopted. In addition, the presence of noise is more evident in the offset compliance method. In this way, this methodology has been used to estimate the opening and closing loads at different crack lengths. Figure 6.27 shows P_{op} and P_{cl} values for Al_CT3 specimen at different crack lengths using the strain offset and the offset compliance methods. In both methods, results are very similar, with opening and closing values between 75 and 125 N. Moreover, as in figure 6.19 it is not observed a significant difference between P_{op} and P_{cl} for the different crack lengths analysed. Finally, if figures 6.19 and 6.26 are compared, it can be observed that most of the results are between 75 and 125 N, with no apparent differences between P_{op} and P_{cl} obtained from the CJP model and from the two methods based on compliance adopted. As previously discussed, the variation in the estimated opening and closing loads is attributed to the fact that fatigue crack shielding phenomenon is a gradual process. It is also remarkable that no significant increase and decrease in the opening and closing loads are observed along the crack length.

According to the previously obtained results, from K_{op} values the effective stress intensity factor range (ΔK_{eff}) can be calculated. This highlights that the evaluated optical techniques are powerful alternative to predict fatigue life in mechanical components. Thus, in figures 6.8 and 6.20 the curves obtained from nominal load conditions and from effective values corresponding to PC_CT3 and Al_CT3 are presented. An important difference between nominal and effective curves can be observed at the beginning of the crack growth. According to this, ΔK_{eff} is smaller than ΔK_{nom} predicted from equation 6.1. This implies that the portion of the loading cycle below K_{op} does not contribute to fatigue crack growth since the crack is closed, inducing a retardation effect on the crack growth rate. This is verified from Paris law coefficients (equation 6.2) detailed in tables 6.2 and 6.4, where it is observed that c and m coefficients are smaller than those obtained from nominal results. An smaller slope in the effective curve indicates that both curves would join if they were prolonged and therefore, this indicates that the retardation effect goes slightly decreasing with the crack growth.

In a similar way, results obtained from the specimens tested at high R -ratio have been also analysed. K_F and K_R values obtained by transmission photoelasticity, DIC and ESPI as a function of the loading cycle at different crack lengths are plotted in figures 6.9, 6.17 and 6.43 respectively. Again, K_I calculated from equation 6.1 has been also presented. Results from Westergaard's, Williams's and Muskhelishvili's models have not been shown since as it was previously justified, CJP model was the most appropriate to study fatigue crack growth retardation due to the plasticity-induced shielding. It is observed that K_F values show a total level of agreement throughout the whole loading cycle with those calculated from equation 6.1.

Therefore, there is no change in the slope of K_F as in the case of specimens tested at low R -ratio, which indicates the absence of the shielding effect and consequently, the crack remains fully open during the loading cycle. In addition, this behaviour is also observed from the analysis of K_R , where there is no change in its sign during the loading cycle, which is interpreted as no variation in crack configuration and therefore, the crack keeps fully open throughout loading cycle.

Moreover, the behaviour previously observed for the specimens tested at high R -ratio is also observed from Paris law. Thus, in figures 6.10 and 6.21 the nominal and effective Paris law curves obtained by transmission photoelasticity and DIC are presented. It can be observed that there is no significant difference between the effective and nominal SIF ranges as in the case of the specimens tested at low R -ratio. This highlights, as indicated in the previous paragraph, that no retardation effect on fatigue crack growth in the specimens tested at high R -ratio occurred. This is also highlighted through the m Paris law coefficient (tables 6.2 and 6.4), that is the same for PC_CT4 and Al_CT5 specimens.

As it was done in specimens tested at low R -ratio, Al_CT5 specimen was verified using the methods based on compliance. Results are shown in figure 6.28. It can be observed that there is no change in the slope of the COD data throughout the loading cycle (top plots in figure 6.28). At the same time, it is not observed any offset in each of the analysed methods (middle and bottom plots in figure 6.28).

Finally, the last aspect investigated was the ability of ESPI to estimate the plastic zone size at the crack tip from the direct measurement of the plastic strain fields. For this purpose, fatigue experiments conducted on Ti_CT4 specimen tested at high R -ratio were conducted with an applied load level high enough to generate necessary plasticity. Figure 6.46 shows the estimated plastic zone size in x and y directions as a function of the applied loading cycle. In addition, results have been compared with those predicted from theory. It can be observed that plastic zone size estimated in x -direction shows a good correspondence with the first-order Irwin estimation. However, plastic zone size estimated in y -direction was compared with the second-order Irwin estimation. Good correspondence it is observed for low load levels, however the difference between theoretical and experimental results increases with the load. Besides the analysis of the plastic zone size as a function of the applied loading load, it has been also investigated the influence of the crack length. Thus, in figure 6.47 the plastic zone size as a function of the crack length for the maximum applied load is plotted. It can be observed that the plastic zone size estimated in x -direction shows a good agreement with the first-order Irwin estimation, while that estimated in y -direction shows values between the first and the second-order Irwin estimations. The reason of this behaviour can be due to fact that Irwin estimations consider a circular shape of the crack tip plastic zone. However, the shape obtained from

experiments it is more similar to an ellipse or a kidney as it can be observed in figure 6.45. Nevertheless, results can be considered as quite promising if it is assumed that the first-order Irwin estimation is not strictly correct since it is based on a pure elastic analysis. Moreover, the second-order estimation accounts for the stress redistribution by means of an effective crack length, which is also simplistic and not totally correct.

6.4. Conclusions

The previous work presented in this chapter leads to the following conclusions:

1. Real fatigue cracks have been successfully studied using transmission photoelasticity, DIC and ESPI. Thus, several fatigue tests were conducted on CT specimens manufactured using different materials depending on the implemented optical technique, namely polycarbonate for transmission photoelasticity, 2024-T3 aluminium for DIC and commercially pure titanium for ESPI.
2. The potential of these techniques has been studied from their ability to calculate the stress intensity factors at the crack tip adopting the methodology described in chapter 5.
3. Plasticity-induced fatigue crack shielding has been investigated from the analysis of the SIFs. Four different models to describe the crack tip stress/displacement fields have been evaluated. It can be concluded that CJP model was the most suitable to quantify the shielding effect on growing fatigue cracks.
4. A methodology to quantify the shielding effect on growing fatigue cracks has been proposed by estimating the opening (K_{op}) and closing (K_{cl}) stress intensity factors from the analysis of K_F obtained at loading and unloading branches.
5. Crack opening (P_{op}) and closing (P_{cl}) loads have been also calculated from K_{op} and K_{cl} . A range for crack opening/closing loads respect to the maximum applied load has been obtained for each technique: Transmission photoelasticity (16 – 24 %), DIC (12.5 – 21 %) and ESPI (22 – 25 %). A good correspondence has been achieved for the three different materials employed.
6. The ability of the techniques studied to realistically predict fatigue crack growth has been analysed by calculating the effective stress intensity factor range from the estimated K_{op} values. According to this, a retardation effect on fatigue crack growth has been quantified for the specimens tested at low R -ratio. Moreover, no retardation effect has been observed for specimens tested at high R -ratio.
7. The adopted methodology to calculate P_{op} and P_{cl} has been verified using the compliance based techniques using an extensometer located at the mouth of the notch in aluminium specimens.

8. Two different compliance methods have been studied for the calculation of the opening and closing loads, strain offset and offset compliance methods. The offset compliance method has been observed to be more sensitive to scatter data than the strain offset method.
9. P_{op} and P_{cl} obtained from the compliance showed a high level of agreement with those previously obtained using DIC. A loading range for opening and closing loads between 75 and 125 N was inferred from compliance methods and DIC. No apparent differences between P_{op} and P_{cl} were observed.
10. The ability of ESPI to estimate the crack tip plastic zone size has been studied. For this purpose, a novel methodology has been proposed. This methodology is based on the direct measurement of the plastic strain fields by differentiation of the displacement fields measured around the crack tip.
11. Good correspondence has been obtained between experimental results and theoretical estimations.

Chapter 7. Experimental results: overload evaluation

7.1. Introduction

In the previous chapter it has been illustrated the ability of transmission photoelasticity, DIC and ESPI for the study of shielding on growing fatigue cracks. Thus, a novel experimental methodology has been developed to estimate K_{op} from the analysis of K_F defined by CJP model. In addition, it has been also shown how this methodology can be employed as a powerful tool to characterise the effective SIF range, and thus to realistically predict fatigue crack growth. This issue has been highlighted from results obtained for several fatigue tests conducted at different R -ratios. In addition, the adopted methodology has been verified by two methods based on compliance using the recorded data with an extensometer. Moreover, it has been shown that ESPI is sensitive enough to estimate the plastic zone size at the crack tip. Thus, a methodology based on the direct measurement of the plastic strain field at the crack tip has been proposed.

In this chapter, the ability of the methodology previously adopted to estimate K_{op} is extended to the analysis of the effect on fatigue crack growth rate caused by the application of different overloads. In addition, this issue is also investigated by using the proposed methodology to estimate the plastic zone size using ESPI. Thus, several fatigue tests at constant amplitude loading cycle on CT specimens have been conducted. These tests were interrupted by different single overload levels at different crack lengths.

The chapter starts exposing results obtained using the three techniques studied. The overload influence is studied from the analysis of the changes observed in the trends followed by the different parameters (K_{op} , ΔK_{eff} and P_{op}). Additionally, as it was done in the previous chapter, a technique based on the compliance measurement is employed to verify the results obtained by DIC using an extensometer. At the same time, the effect of the overload application is also studied by plotting the fatigue crack growth rate corresponding to the effective SIF range. Finally, in an attempt to relate the variations experienced by the effective SIF range with an increase in the crack tip plastic zone size due to the overloads, the methodology previously proposed to estimate the plastic zone size is adopted to check whether there is any relationship between them.

7.2. Overload results

This part of the chapter reports the experimental results about the evaluation of the effect originated by the application of overloads. For this purpose, several fatigue tests at constant amplitude loading were conducted on CT specimens. The same loading conditions as in previous tests were applied for the evaluation of crack shielding. Thus, tests at low R -ratio ($R = 0$) were conducted in the case of transmission photoelasticity and DIC, while for ESPI tests at high R -ratio ($R = 0.58$) were defined. ESPI results were also employed to evaluate the plastic zone size. Tests were interrupted by single overload levels applied at different crack lengths. Test conditions are detailed in table 7.1. In the case of overloads, it is detailed the overload percentage respect to the maximum applied load, the overload value and the crack length and the number of cycles at which the overload was applied.

Table 7.1. Test conditions for overload effect evaluation

Optical technique	Specimen reference	Load conditions		Ratio R	Overload			
		P_{min} (N)	P_{max} (N)		%	P_{OL} (N)	a_{OL} (mm)	N_{OL}
Transmission photoelasticity	PC_CT5	0	50	0	50	75	26.68	120000
					100	100	28.94	145000
					200	150	31.11	167500
DIC	Al_CT8	5	600	0	100	1200	26.12	280000
	Al_CT10				125	1350	26.72	200000
ESPI	Ti_CT7	350	600	0.58	10	660	6.51	70000
	Ti_CT8				25	750	6.76	66500
	Ti_CT10				50	900	6.48	70500

The variation of the crack length with the number of cycles for the tests showed in table 7.1 is represented in figures 7.1, 7.2 and 7.3. Figures 7.1 and 7.2 show the results for specimens tested at low R -ratio using transmission photoelasticity and DIC. Figure 7.3 shows ESPI results from 65000 cycles to magnify the region at which the overloads were applied.

Once the overload influence has been analysed from the variation of the crack length with the number of cycles, the retardation effect due to the application of the overloads is evaluated from K_{op} and ΔK_{eff} values. Figures 7.4, 7.5 and 7.6 show these results as a function of the crack length for transmission photoelasticity, DIC and ESPI respectively. In addition, K_{min} corresponding to the minimum applied load and ΔK obtained from the nominal loading range have been also presented.

After K_{op} was obtained, the crack opening load was calculated from equation 6.1. Results obtained for each of the applied overloads have been plotted as a function of crack length in figures 7.7, 7.8 and 7.9 for transmission photoelasticity, DIC and ESPI respectively. In addition, the zones affected by the different overloads have been also marked.

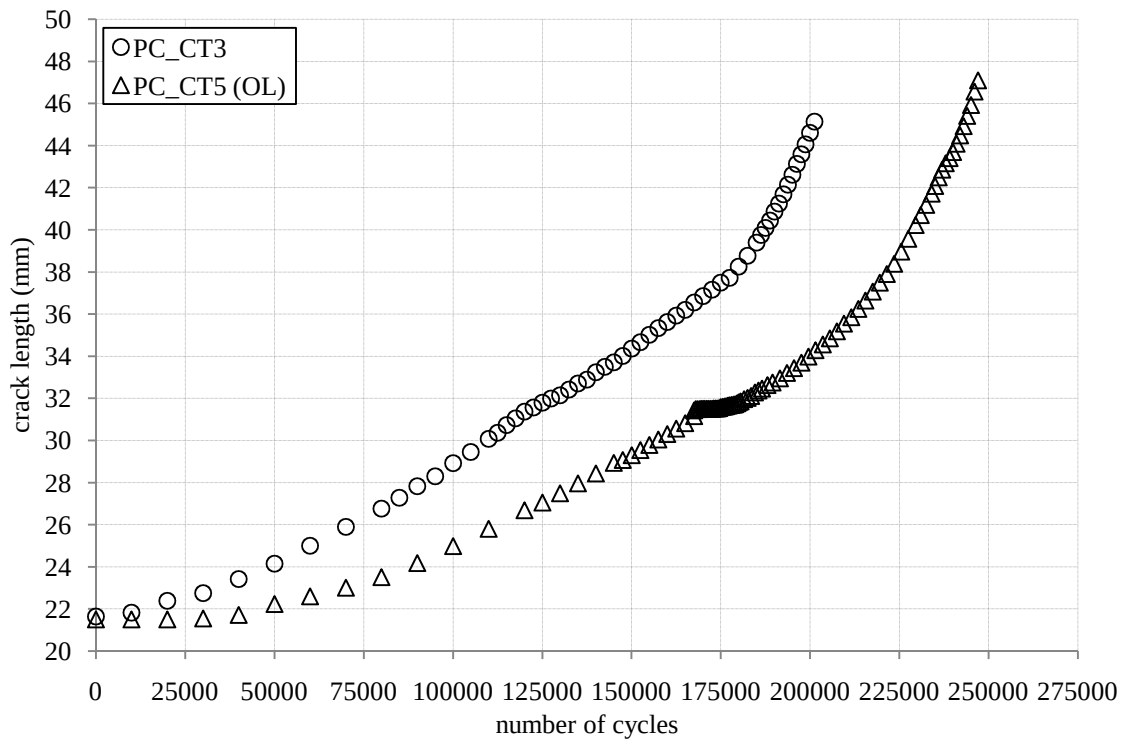


Figure 7.1. Variation of the crack length with the number of cycles for specimen with applied overloads (PC_CT5) and without overloads (PC_CT3) using transmission photoelasticity

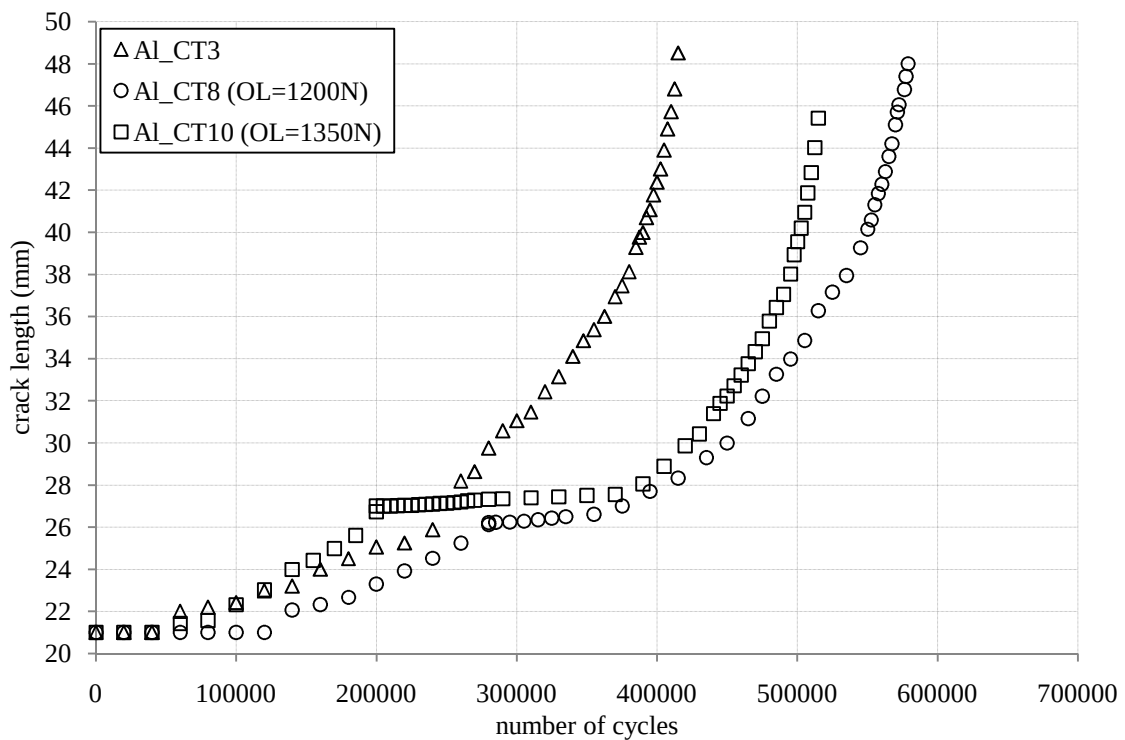


Figure 7.2. Evolution of the crack length with the number of cycles for specimens with an applied overload (Al_CT8 and Al_CT10) and without overload (Al_CT3) using DIC

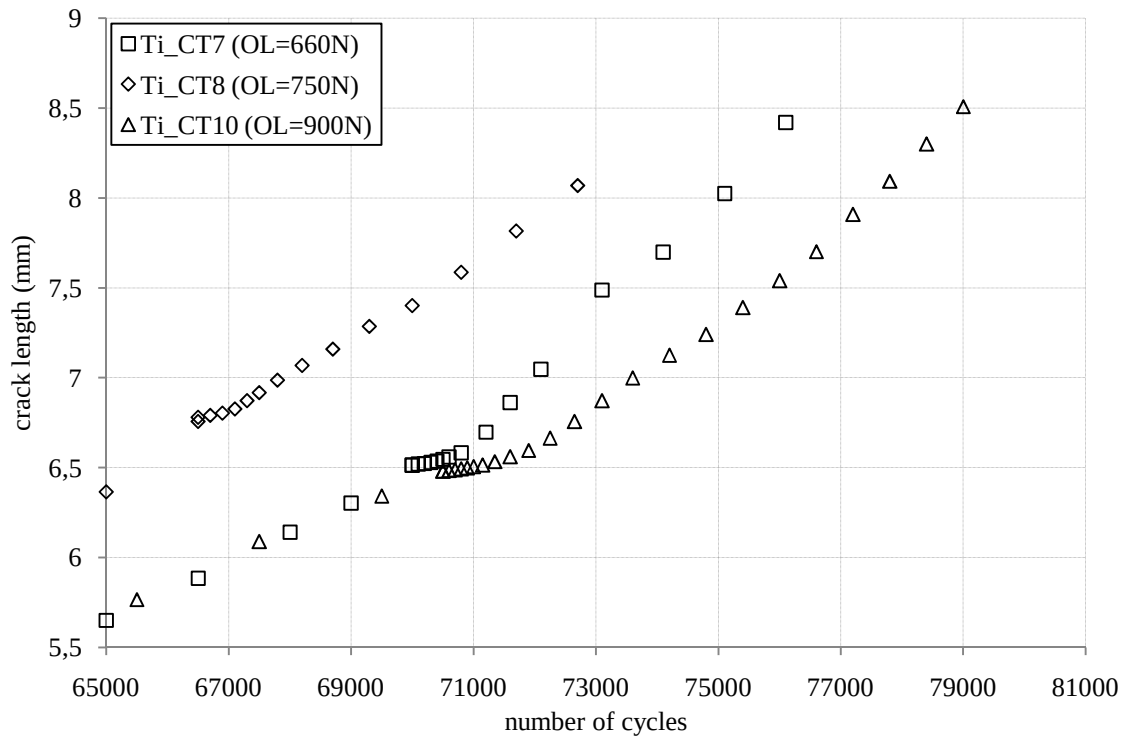


Figure 7.3. Evolution of the crack length with the number of cycles for specimens with an applied overload (Ti_CT7, Ti_CT8 and Ti_CT10) using ESPI

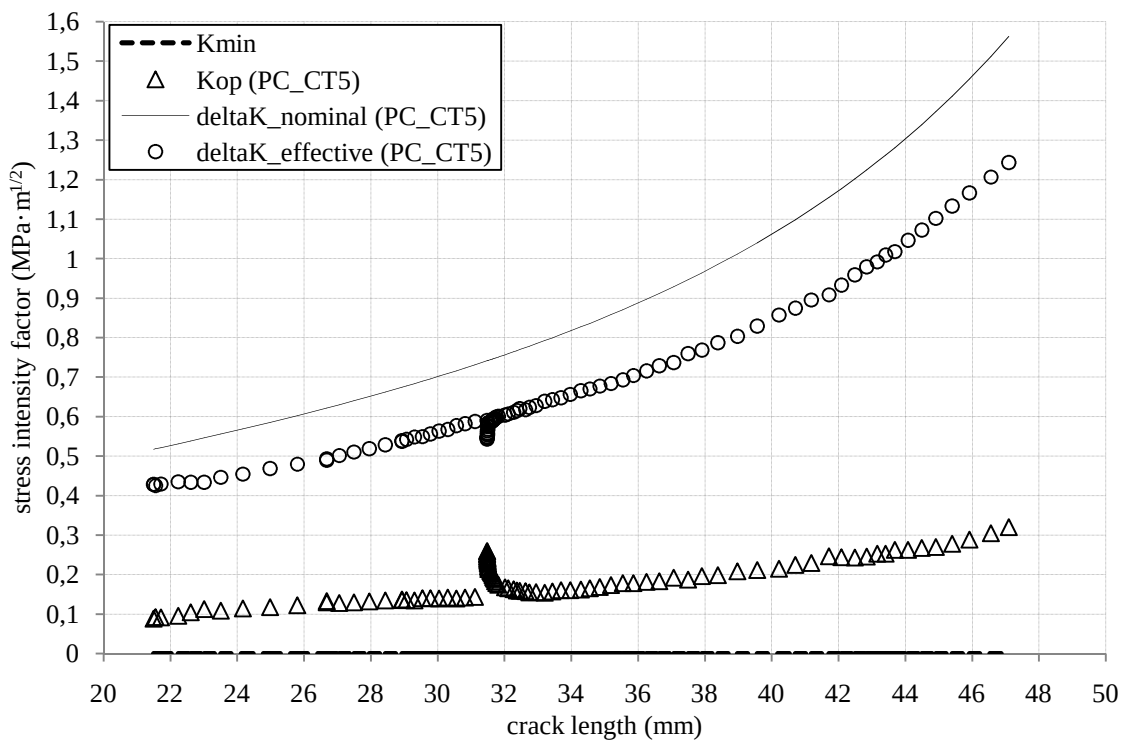
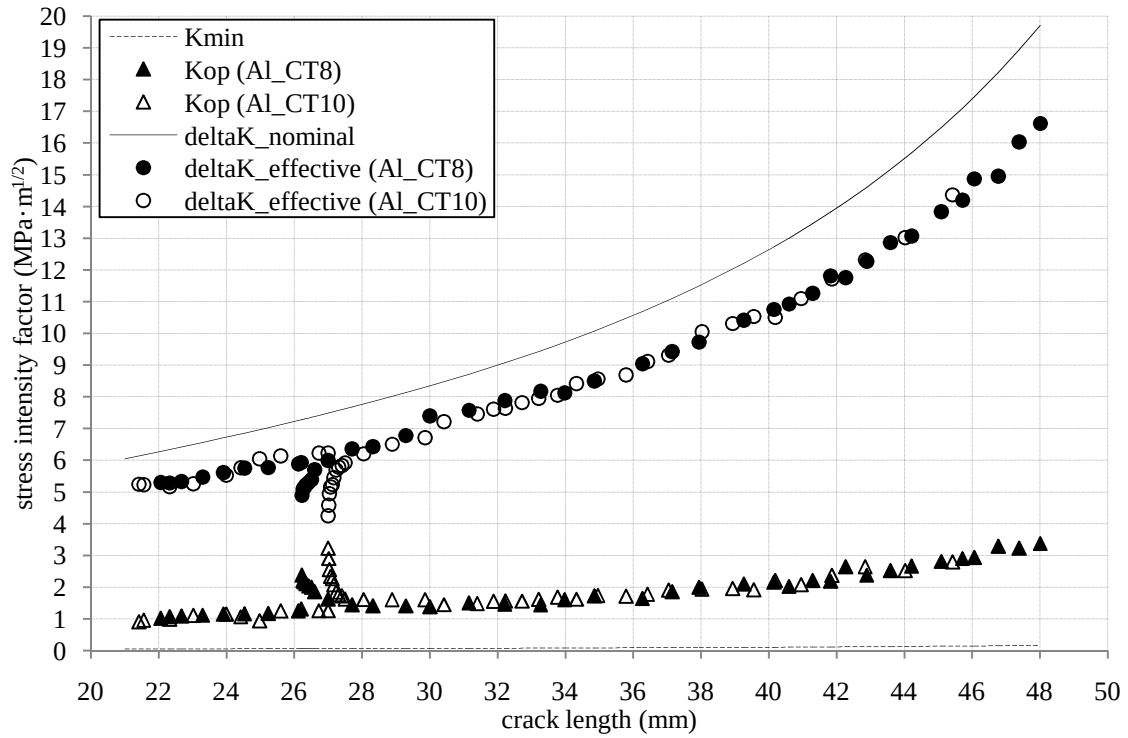
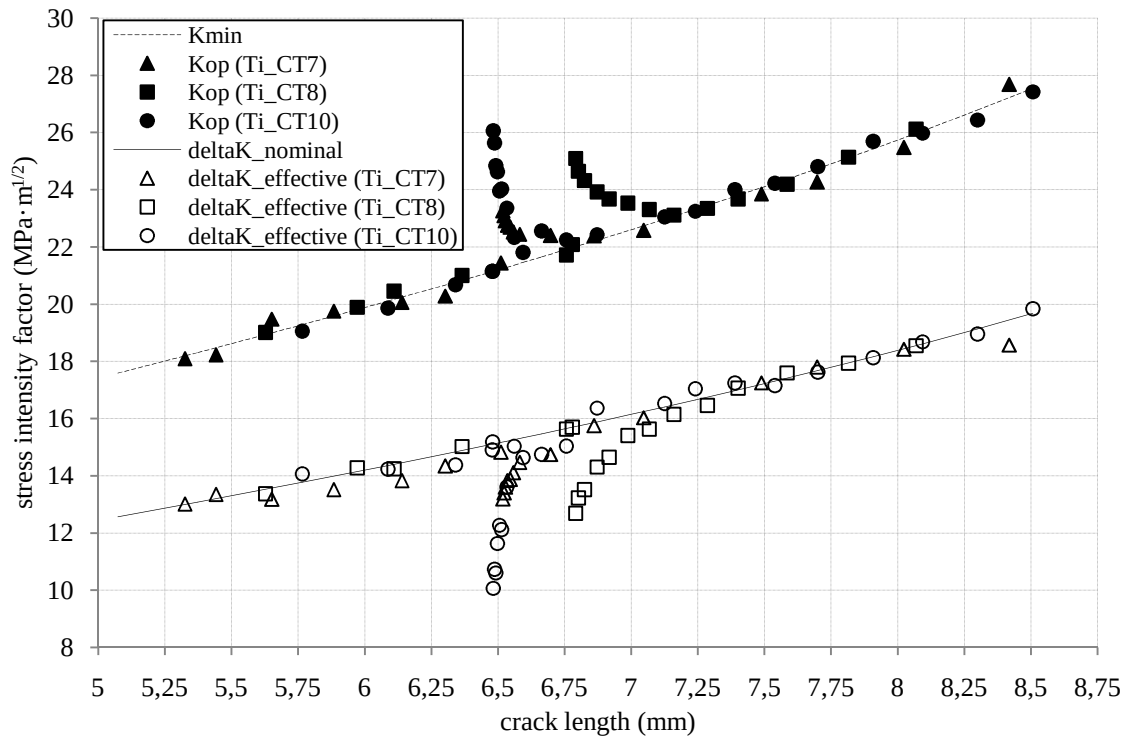


Figure 7.4. Variation of K_{op} and ΔK_{eff} with the crack length for an overload test using transmission photoelasticity

Figure 7.5. Variation of K_{op} and ΔK_{eff} with the crack length for two overload tests using DICFigure 7.6. Variation of K_{op} and ΔK_{eff} with the crack length for three overload tests using ESPI

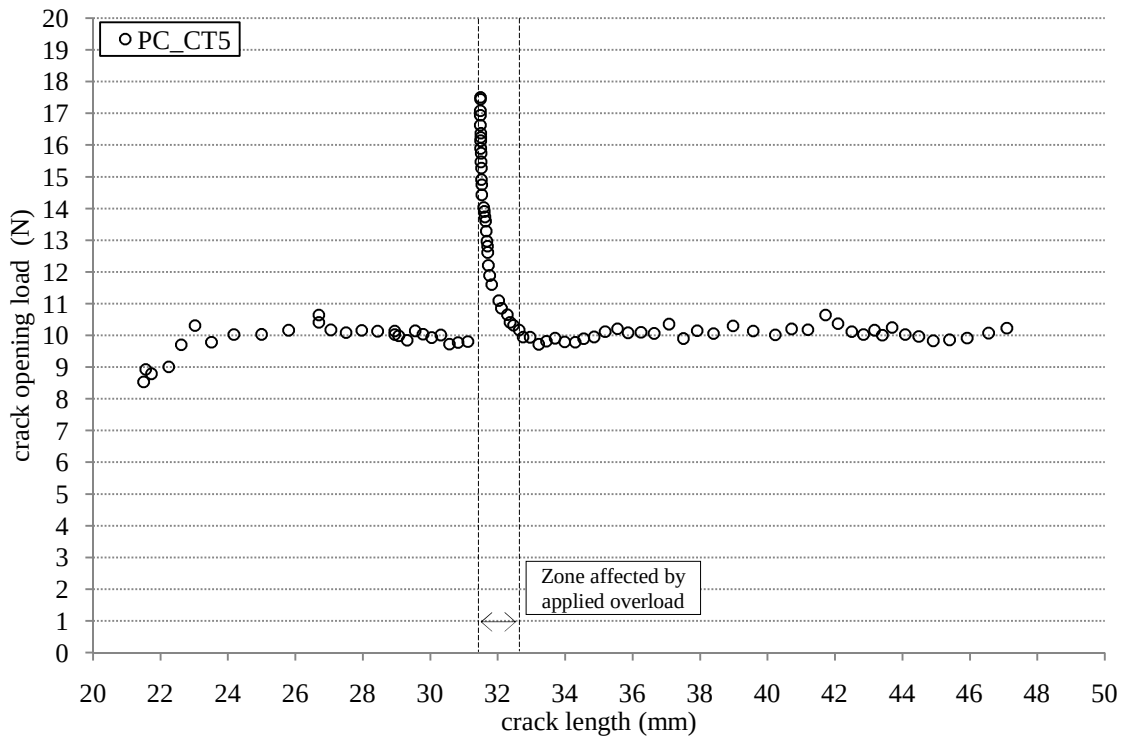


Figure 7.7. Variation of crack opening load with the crack length due to the application of an overload using transmission photoelasticity

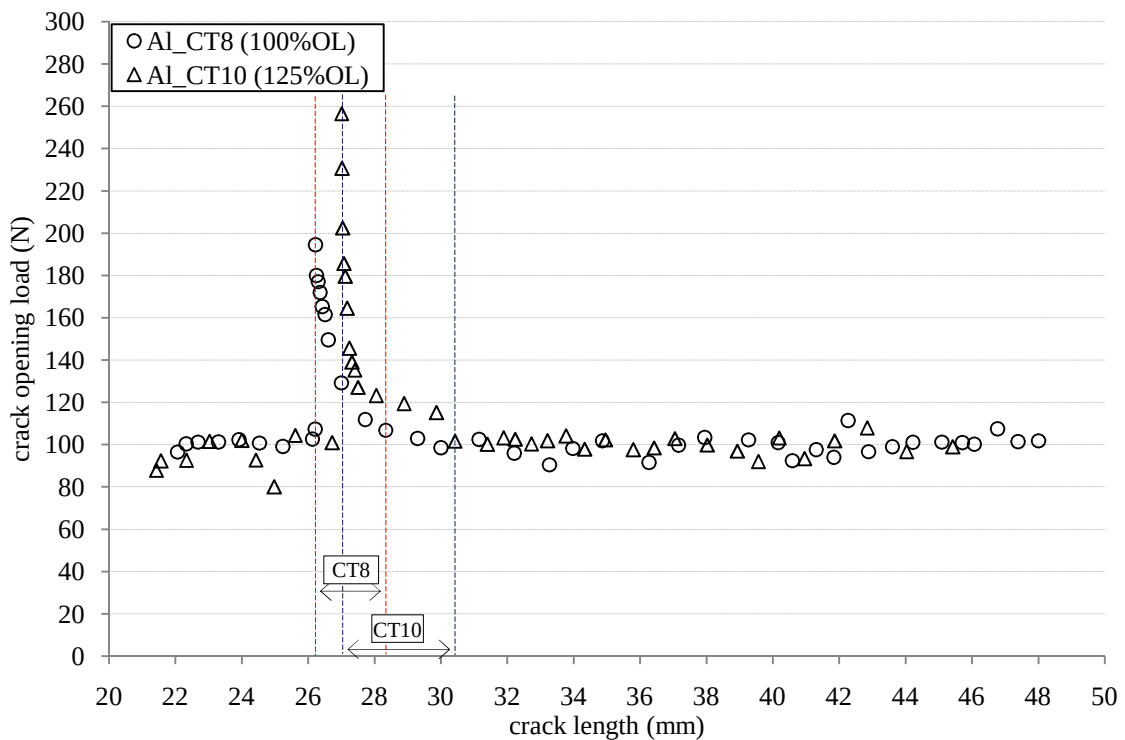


Figure 7.8. Plots showing P_{op} variation with the crack length for two different overloads applied on the aluminium specimens tested by DIC

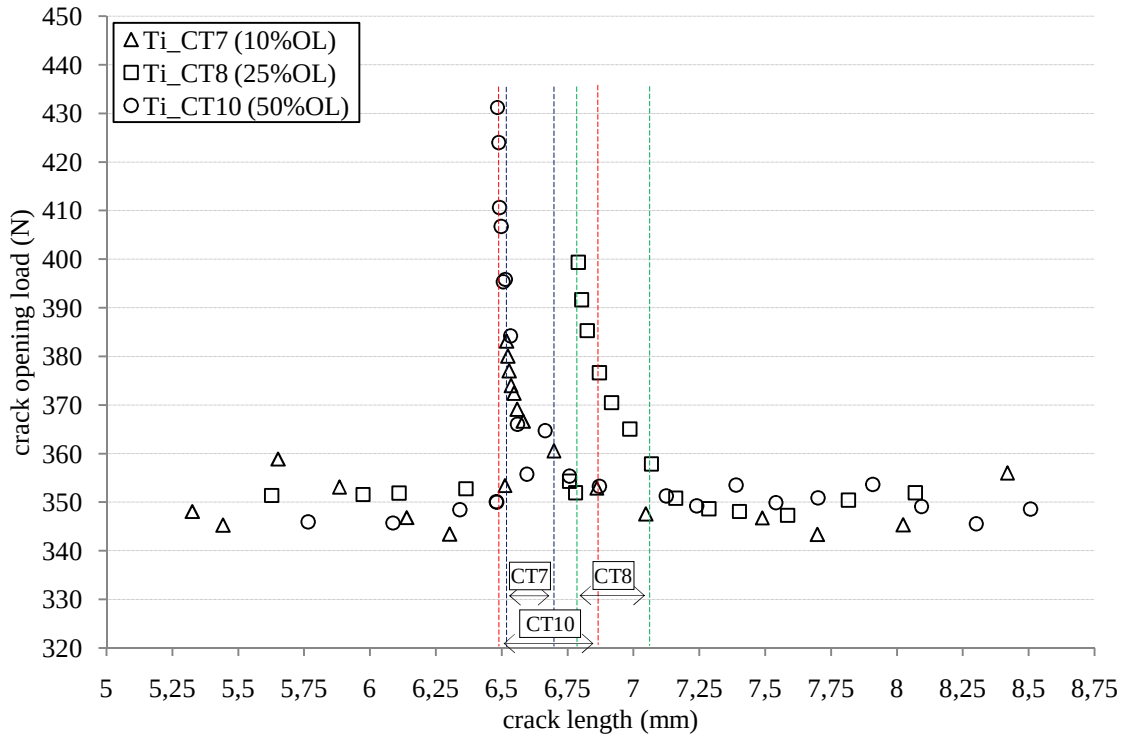


Figure 7.9. Plots showing the evolution of Pop with the crack length for three different overload levels on the titanium specimens tested by ESPI

P_{op} values obtained by DIC have been verified using a compliance based technique. In this case, it has been employed the strain offset method using an extensometer. Figure 7.10 shows P_{op} values obtained by DIC and by the strain offset method along the crack length for the two different specimens.

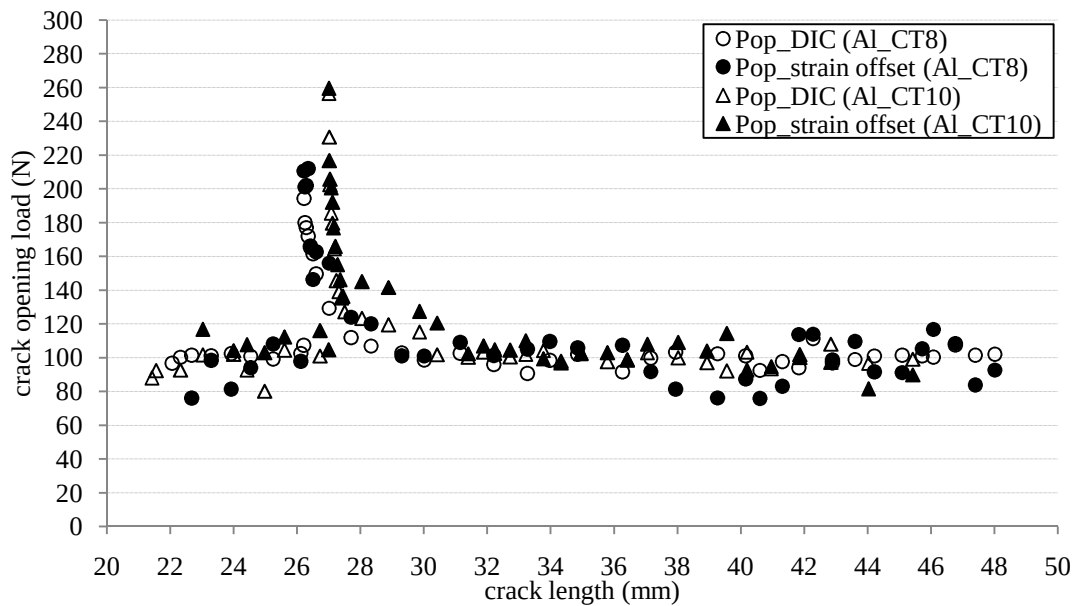


Figure 7.10. Variation of P_{op} with the crack length for aluminium specimens using DIC and the strain offset method

After results have been verified, fatigue crack growth can be evaluated from Paris law. Thus, in figure 7.11 the effective SIF range has been employed to plot Paris law using polycarbonate PC_CT5 specimen. In addition, the crack growth evolution has been marked using a red line to facilitate its later discussion.

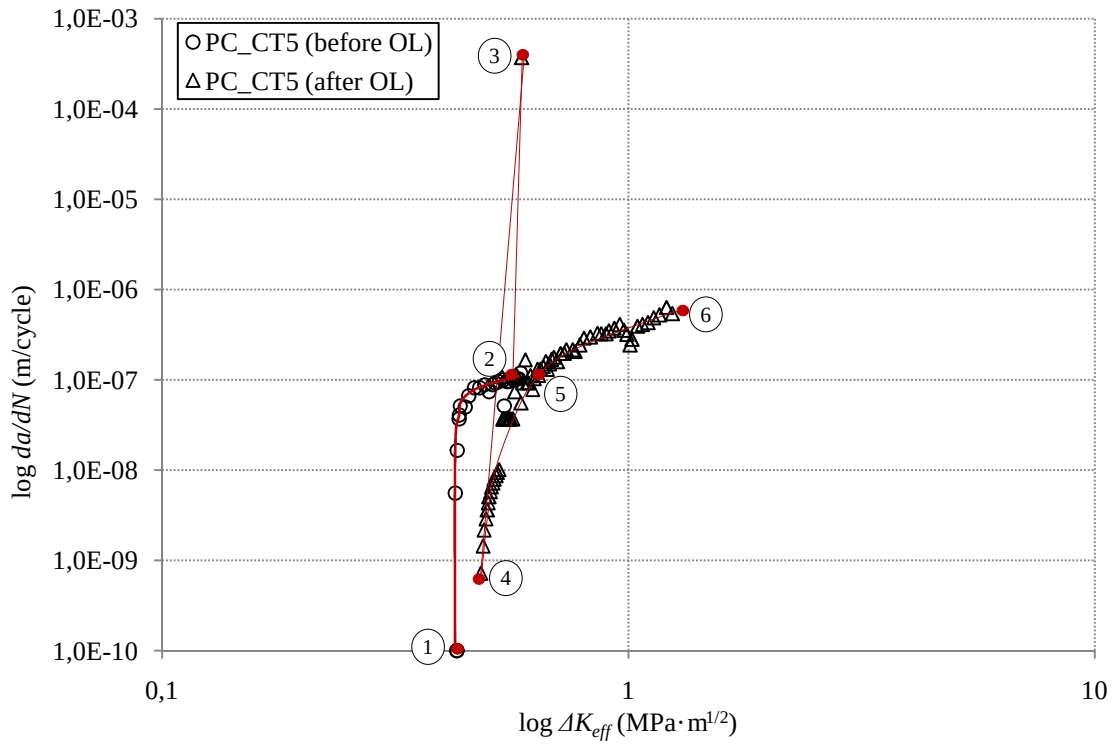


Figure 7.11. Paris law obtained from the effective SIF range in polycarbonate PC_CT5 specimen

In order to focus the overload problem, special interest has been paid to the analysis of crack growth behaviour after the overload. Thus, figures 7.12, 7.13 and 7.14 show Paris law curves using the nominal and effective SIF range.

Finally, the last aspect investigated was the ability of ESPI to estimate the plasticity increase generated at the crack tip due to an overload application. Thus, the plastic zone size at the crack tip was estimated during fatigue tests using the methodology proposed in the previous chapter. Figure 7.15 shows the variation of the plastic zone size with the crack length for the different titanium specimens. An example showing the change in the plastic zone size prior to and after the overload is shown in figure 7.16. Images correspond to a load level of 600 N with a 50 % overload. Finally, figure 7.17 illustrates the relationship between the effective stress intensity factor range and the plastic zone size as a function of the crack length for a specimen tested with the most severe overload (50 % overload).

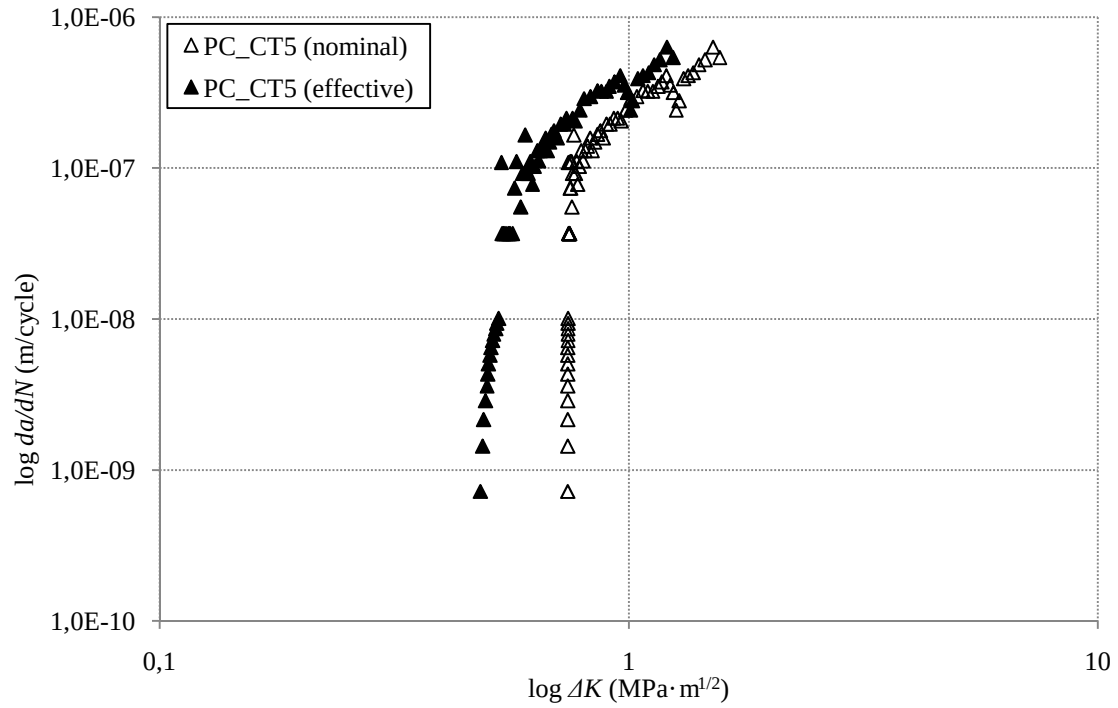


Figure 7.12. Nominal and effective Paris law curves obtained after overload for specimen tested using transmission photoelasticity

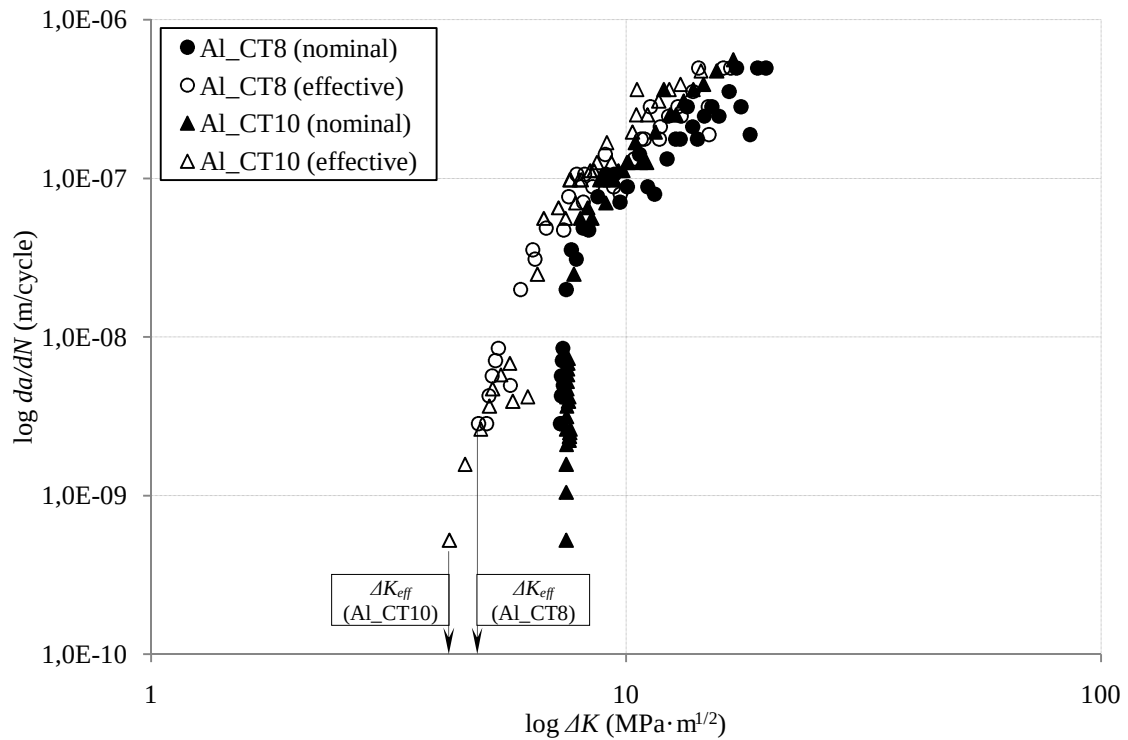


Figure 7.13. Nominal and effective Paris law curves obtained after overload for aluminium specimens tested using DIC

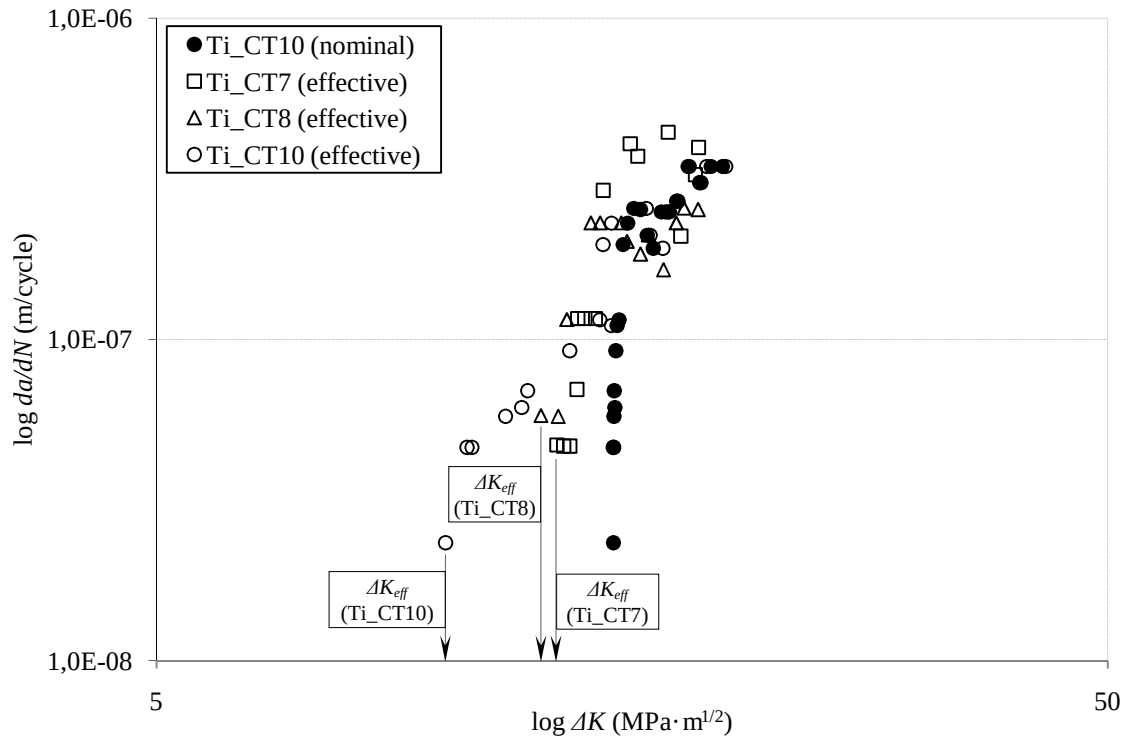


Figure 7.14. Nominal and effective Paris law curves plotted after overload for titanium specimens tested using ESPI

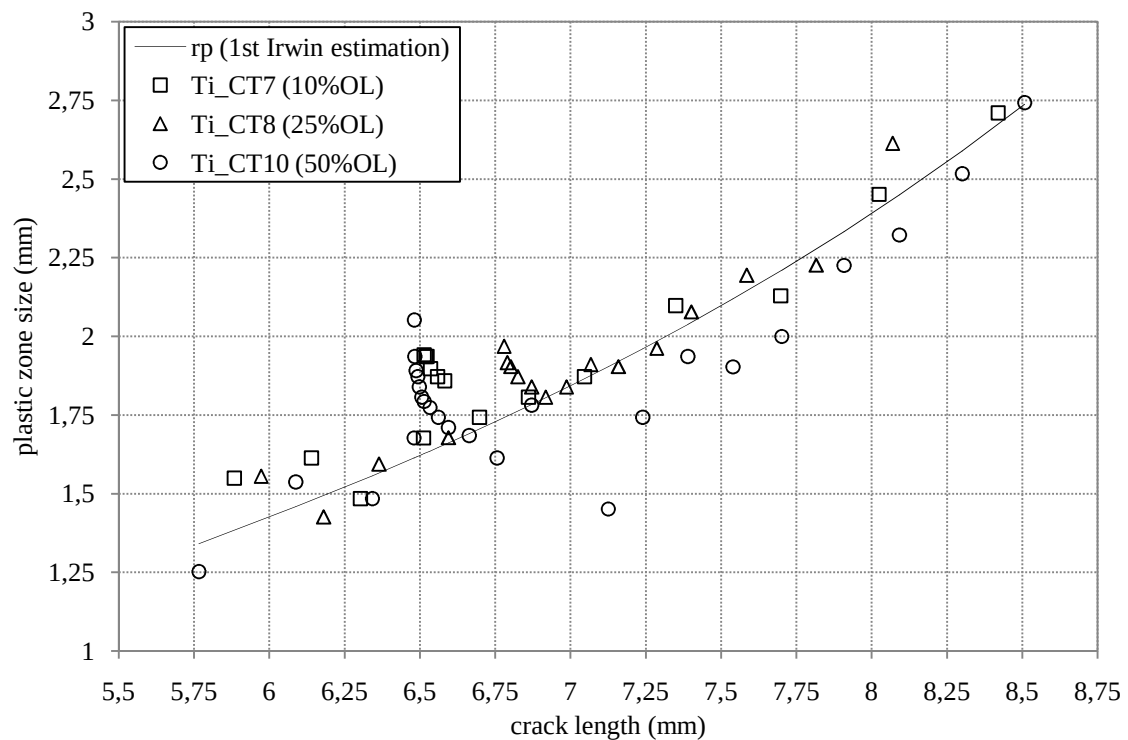


Figure 7.15. Variation of the plastic zone size with the crack length during the application of an overload in titanium specimens

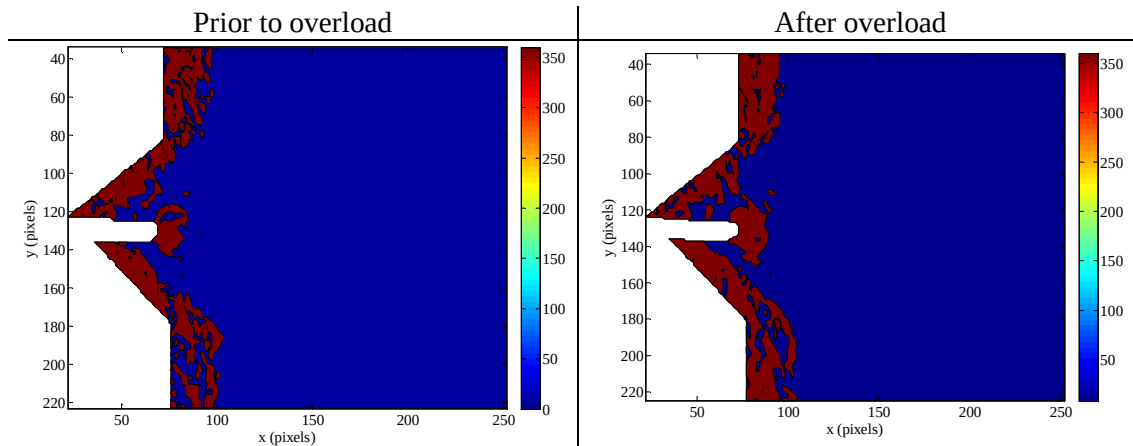


Figure 7.16. Von Mises stress maps obtained prior and after the application of a 50 % overload in a titanium specimen

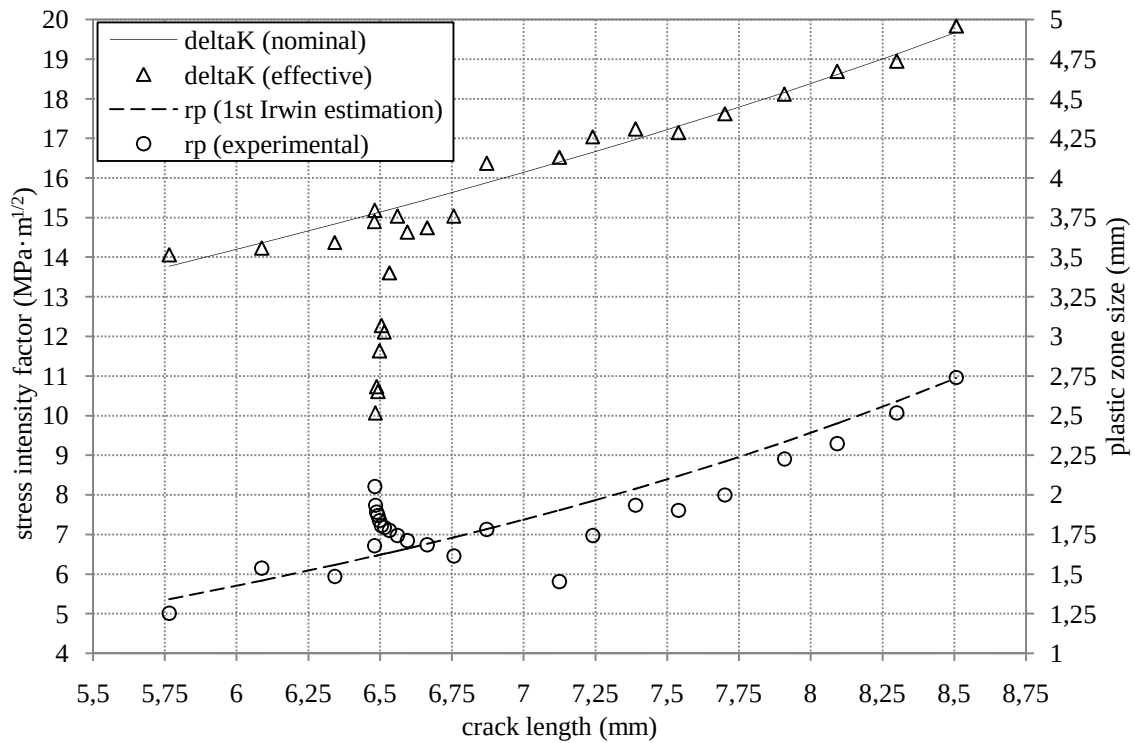


Figure 7.17. Plot showing the relation between the effective stress intensity factor range and the plastic zone size with the crack length for a specimen with a 50 % overload

7.3. Discussion of the results

The overload effect has been investigated during different fatigue tests at constant amplitude loading interrupted by single overload application at different crack lengths.

The first way to study the influence originated by the application of overloads has been from the analysis of the variation of the crack length with the number of cycles. Thus, in figures 7.1, 7.2 and 7.3 it can be clearly observed the retardation effect on crack growth rate induced by the

application of different overloads. It can be observed in figure 7.1 that only the third applied overload applied (200 % of the maximum load) generated a retardation effect on the polycarbonate specimen. The influence of the overload remained approximately until 189500 cycles, which supposes a period of 22000 cycles, which corresponds to a crack growth of 1.28 mm. However, this effect was not observed for overloads corresponding to a 50 and 100 % of the maximum applied load. In the case of aluminium specimens, as it can be observed in figure 7.2, the retardation effect induced by the overload remained during 415000 cycles ($\Delta a \approx 2.11$ mm) for the case of 100 % overload. Nevertheless, this retardation effect was about 420000 cycles ($\Delta a \approx 2.86$ mm) for the case of a 125 % overload. Finally, the influence of different overloads was also evaluated on titanium specimens (3.6 times smaller). In figure 7.3 it can be observed that the crack growth rate for a 10 % overload induced a retardation of 1200 cycles ($\Delta a \approx 0.19$ mm). In addition, that specimen subjected to a 25 % overload experienced a retardation effect of 1700 cycles ($\Delta a \approx 0.29$ mm), while the retardation experienced by Ti_CT10 specimen (subjected to a 50 % overload) was of 2600 cycles ($\Delta a \approx 0.39$ mm).

After the study of overload influence with the number of cycles, an important aspect investigated was the ability to evaluate the retardation effect on fatigue crack growth. This retardation effect was evaluated from the calculation of K_{op} and ΔK_{eff} . K_{op} was estimated using the methodology proposed in the previous chapter based on the analysis of K_F values obtained from CJP model. Moreover, ΔK_{eff} was calculated from the difference between K_F corresponding to the maximum applied load and K_{op} . In figures 7.4 and 7.5, it can be observed that K_{op} shows a gradual increase with the crack length, with values always above K_{min} . As it was previously observed in the evolution of the crack length with the number of cycles, from figure 7.4 it can be deduced that only the third overload generated an increase in K_{op} , while the two previous overloads did not produce any change in the K_{op} trend. In addition, it is also observed a gradual increase in ΔK_{eff} , but with values always below ΔK_{nom} . This behaviour is not new, it was observed during the quantification of the plasticity-induced shielding effect when the specimens were tested at a low R -ratio. In addition, it is also observed an increase in K_{op} immediately after the application of the overloads, decreasing gradually until it approaches again the trend prior to the overload. An opposite behaviour is observed for ΔK_{eff} , decreasing just after the overloads to subsequently increase until it approaches the trend prior to the overload. Therefore, a higher retardation effect was observed at each of the points where the overload was applied. This behaviour was a direct consequence of the plasticity increase at the crack tip as a result of the overload. In figure 7.5 it is observed that the retardation effect observed for a 125 % overload was higher than that corresponding to an overload of 100 %. All previously indicated results can be extrapolated to the case of ESPI, with the only difference that tests were conducted at high R -ratio. According to this, it can be observed that K_{op} and ΔK_{eff} agree with K_{min} and ΔK_{nom}

respectively except in the zones affected by overloads. In these zones a similar behaviour was observed to that previously described for the case of transmission photoelasticity and DIC. It can also be observed how after the influence of the overloads, K_{op} and ΔK_{eff} values agree with the nominal values. Again, as in the case of DIC, a higher overload implies a higher retardation effect.

Another important aspect investigated was how different overloads could affect in the shielding degree. For this purpose, P_{op} was calculated from K_{op} using equation 6.1. The variation of P_{op} with the crack length for each of the techniques has been plotted in figures 7.7, 7.8 and 7.9. It is observed that K_{op} and P_{op} values are always above the minimum applied load for polycarbonate (figure 7.7) and aluminium (figure 7.8) specimens. Thus, P_{op} takes a value around 10 N in the case of transmission photoelasticity and 100 N in the case of DIC before and after the zone affected by the applied overload. This behaviour was previously observed for K_{op} , which highlights that a shielding effect due to plasticity is induced during crack growth. In addition, P_{op} experienced an increase immediately after the application of the overload, decreasing later in a progressive way until it reaches trend prior to the overload application. The increase experienced by P_{op} was different depending on the overload level and the evaluated material. Thus, the applied overload on the polycarbonate specimen produced an increase in P_{op} until 17.51 N (figure 7.7), which supposes a 35 % with respect to the applied load range. For the case of aluminium specimens with DIC (figure 7.8) with a 100 %, P_{op} experienced an increase until 194.41 N, which corresponds to a 31.83 % of the applied load range. In the case of a 125 % overload, P_{op} increased until 256.42 N, which supposed a 42.25 % with respect to the applied load range. All the discussed results indicate that the crack opens at load levels above the minimum applied load throughout the crack length, while for overload affected zones the crack opens at loads higher loads than those corresponding to the zones not affected by overloads. Moreover, a plasticity-induced crack shielding effect and the consequent retardation effect can be observed at the influence overload affected zone in titanium specimens used in ESPI (figure 7.9). Thus, P_{op} reached a value of 383.15 N for the specimen with minimum overload; while for the specimens subject to 25 and 50 % overloads, P_{op} reached a value of 399.34 and 431.24 N respectively. These values corresponded to percentages of the applied load range of 13.26 % (Ti_CT7), 19.74 % (Ti_CT8) and 32.50 % (Ti_CT10). However, at not overload affected zones, P_{op} agreed with the minimum applied load, highlighting the absence of any shielding effect at $R = 0.58$. According to this, the crack is fully open in those zones not affected by overloads; while in zones affected by overloads the crack remains closed at loads below P_{op} due to the shielding effect induced in the crack growth. In addition, zones affected by applied overloads have been marked. A similar behaviour is evident from the data related to the crack length versus the number of cycles showing in figures 7.1, 7.2 and 7.3. However, in the case of P_{op} versus crack

length, overload affected zones are better defined than in those above indicated. Thus, a zone affected by the overload with a length of 1.15 mm can be observed in the case of polycarbonate specimen, 2.11 and 3.42 mm in the case of aluminium specimens with 100 and 125 % overloads, and 0.18, 0.28 and 0.39 mm for specimens Ti_CT7, Ti_CT8 and Ti_CT10 respectively. Finally, in an attempt to compare results obtained by the three techniques, P_{op} values have been referenced to the effective opening load. Thus, this load value corresponds to 10 N in transmission photoelasticity and 100 N in the case of DIC. For ESPI, this value corresponds to the minimum applied load since no shielding effect was observed in the zones not affected by overloads. These results are detailed in table 7.2.

Table 7.2. Opening load percentage respect to the effective opening load corresponding to the zones not affected by overloads

Technique	Specimen	Overload			
		%	P_{op}^{eff} (N) (prior to overload)	P_{op}^{ol} (N) (after overload)	$\frac{P_{op}^{ol} - P_{op}^{eff}}{P_{op}^{eff}}$ (%)
Photoelasticity	PC_CT5	200	10	17.51	75.1
DIC	Al_CT8	100	100	194.40	94.4
	Al_CT10	125	100	256.42	156.42
ESPI	Ti_CT7	10	350	383.15	9.47
	Ti_CT8	25	350	399.34	14.10
	Ti_CT10	50	350	431.24	23.21

It can be observed that the highest P_{op} values were obtained from aluminium specimens although the overload percentage that was applied to polycarbonate specimen was higher. It is believed that it can be attributed to the fact that the behaviour of polymer materials is totally different from metallic materials. In addition, phenomena that control crack growth in polymer materials are also different that those corresponding to metallic materials [27] and therefore, to obtain the same opening load originated by an overload, the overload level must be higher.

Results obtained by DIC have been verified with those obtained from the strain offset method based on compliance using an extensometer. Thus, P_{op} values obtained by both techniques as a function of the crack length for aluminium specimens have been plotted in figure 7.10. It can be observed the good level of agreement achieved. Therefore, this comparative study highlights that the proposed methodology to estimate K_{op} from the analysis of K_F constitutes a real alternative to evaluate the effect originated by overload application.

The effect of overloads has been also studied through Paris law. In figure 7.11 it is plotted the curve corresponding to Paris law for polycarbonate specimen obtained from the effective stress intensity factor range. Red lines and numbered points have been used to mark the crack propagation order and to facilitate its discussion. It can be observed a normal crack growth until the application of overload (line 1-2). Then, a brief acceleration in the crack growth rate is

observed immediately after the overload was applied (line 2-3), followed by a retardation effect that spans during 22000 cycles approximately (line 4-5). Finally, as the crack grows, the crack growth rate approaches that observed for constant amplitude loading cycle prior to the overload application. In addition, it can be clearly observed as point 4 moves to the left of point 3 due to the decrease experienced by ΔK_{eff} , which was originated by the plasticity increase at the crack tip due to the applied overload.

The previous plot was employed to explain the behaviour of fatigue crack growth due to the application of an overload. However, it is of particular interest to focus the overload problem. For this purpose, Paris law from the overload application has been plotted. Thus, both the nominal and effective Paris law curves obtained after the overload have been presented in figures 7.12, 7.13 and 7.14 for specimens employed in transmission photoelasticity, DIC and ESPI respectively. Similar behaviour can be observed in three plots and between points 4 and 6 in figure 7.11. Immediately after the overload, the effective curve is located to the left of the nominal one which highlights the induced retardation effect on the crack growth rate, followed by a progressive increase in ΔK_{eff} as the crack approaches the crack growth rate observed prior to the overload. In addition, in figures 7.13 and 7.14 it can be observed that ΔK_{eff} is smaller when the applied overload level is higher, which highlights that a longer and bigger retardation effect is induced at higher overload levels.

Finally, the last of the aspects investigated was whether ESPI could be employed to study the influence of overloads by estimating the plastic zone size at the crack tip. For this purpose, the plastic zone size was estimated along the crack length in order to investigate the behaviour originated on crack growth due to the overload application. In figure 7.15 it can be observed an increase in the plastic zone size immediately after the application of overloads for the three titanium specimens. After that, a progressive decrease in the plastic zone size is experienced as the crack tip goes through the permanently deformed material. In addition, a plastic zone size bigger was observed as the overload levels increase (figure 7.15). Moreover, not affected overload zones show a similar behaviour to that corresponding to the first-order Irwin estimation (equation 6.14). An example of the variation of plastic zone size due to the application of an overload is shown in figure 7.16. These images correspond to Von Mises stress maps above the yield stress at a load value of 600 N prior and after the 50 % overload was applied. It can be observed the plasticity increase at the crack tip due to the overload application. A last significant aspect was investigated in figure 7.17, where the effective SIF range was related to the plastic zone size as a function of crack length for the specimen subject to the most severe overload level. It can be observed that the increase in the plastic zone size intensified the effect of plasticity-induced shielding at the crack tip, which caused a reduction in the effective stress intensity factor.

7.4. Conclusions

The previous analysis leads to the following conclusions:

1. The overload effect during fatigue crack growth has been successfully studied by transmission photoelasticity, DIC and ESPI. To achieve that, several fatigue tests at constant amplitude loading with different overload levels were conducted on CT specimens made in different materials, namely polycarbonate, 2024-T3 aluminium and commercially pure titanium.
2. Evidences of retardation on fatigue crack growth were observed when the variation of the crack length with the number of cycles was analysed. Longer retardation was observed as the overload levels got higher.
3. K_{op} was estimated from the methodology adopted in the previous chapter and ΔK_{eff} was calculated from K_{op} values. A retardation effect in the fatigue crack growth rate for each one of the applied overloads has been identified through changes observed in K_{op} and ΔK_{eff} trends.
4. The retardation effect has been quantified by calculating the crack opening load. The influence zones of the applied overloads have been identified by observing the changes experienced in the trend followed by the P_{op} values. These zones affected by the applied overload agree with those observed in the plots corresponding to the crack length versus the number of cycles and those corresponding to K_{op} and ΔK_{eff} as a function of the crack length. In addition, P_{op} values obtained by DIC have been verified from those obtained by the strain offset method.
5. The ability of the three studied techniques to realistically predict fatigue crack growth has been analysed from Paris law obtained using ΔK_{eff} . According to this, a retardation effect on fatigue crack growth for each one of the applied overloads has been identified from the analysis of ΔK_{eff} with respect to the nominal Paris law curve.
6. ESPI has been used to study the influence of overloads by estimating the plastic zone size at the crack tip. An increase in the plastic zone size has been observed as consequence of the application of the different overloads. The zones affected by the applied overloads have been also identified by observing the change in the trend of r_p values along the crack length. Therefore, the increase in the plastic zone size was related to the decrease in ΔK_{eff} .
7. The retardation effect induced on the fatigue crack growth rate due to the application of an overload it is originated by an increase in the crack tip plastic zone size, which intensifies the plasticity-induced crack shielding effect and causes a reduction in the effective stress intensity factor range.

Capítulo 8. Discusión y conclusiones

8.1. Introducción

Este último capítulo proporciona una discusión general sobre el trabajo de investigación desarrollado y resume las conclusiones más relevantes establecidas. Además, en base a estas conclusiones, también se proponen algunas propuestas de trabajo futuro.

8.2. Discusión

8.2.1. Fotoelasticidad por transmisión, DIC y ESPI: herramientas alternativas para la cuantificación del efecto de ‘crack shielding’

Desde que Elber [25, 26] introdujera el concepto de cierre de grieta a través de sus investigaciones sobre cierre de grieta inducido por plasticidad, otras fuentes de cierre se han observado [24]. Estos mecanismos parecen tener una mayor influencia en el régimen cercano al umbral, tales como cierre de grieta inducido por oxidación y el cierre de grieta inducido por rugosidad; o en ambientes particulares o materiales específicos, tales como el cierre de grieta inducido por fluido viscoso y el cierre de grieta inducido por transformación de fase. Sin embargo, el cierre de grieta inducido por plasticidad parece ser el efecto predominante en grietas largas; por otra parte, siempre se espera una contribución de la rugosidad de la superficie y partículas de óxido, especialmente en ambientes agresivos. Además, el efecto de ‘shielding’ parece que es más pronunciado a bajo R -ratios y bajo condiciones de tensión plana.

Diferentes modelos matemáticos, analíticos y numéricos se han desarrollado en un intento de explicar y entender los principios del efecto de ‘crack shielding’. Sin embargo, in algunos casos estos modelos mostraron resultados contradictorios, que crearon controversia y algunas cuestiones sin resolver acerca de su medición, mecanismo e interpretación.

Diferentes técnicas y métodos se han desarrollado y empleado para la medición experimental del cierre de grieta por fatiga. Dentro de la literatura, las técnicas basadas en ‘compliance’ son las más empleadas y recogidas. La localización para la medida y la sensibilidad de la técnica se han mostrado como cuestiones cruciales para la cuantificación de las cargas de apertura y cierre de grieta. Varios investigadores han revisado todos los posibles puntos de controversia y las fuentes de incertidumbre durante la evaluación experimental del efecto de ‘crack shielding’. A pesar de esto, algunas cuestiones continúan aún sin resolver sobre el efecto de ‘crack shielding’.

La evaluación de los SIFs tiene un papel importante en el análisis de problemas observados en la mecánica de la fractura. En este aspecto, técnicas ópticas como la fotoelasticidad por transmisión, DIC o ESPI ofrecen la posibilidad de abordar la tema de la cuantificación del efecto de ‘crack shielding’ desde una perspectiva distinta. Así, fotoelasticidad por transmisión permite analizar los campos de tensiones alrededor del vértice de una grieta creciendo a fatiga, mientras que los campos de desplazamientos en las inmediaciones del vértice de una grieta pueden ser medidos mediante DIC o ESPI. En este sentido, estas tres técnicas ópticas permiten determinar los SIFs a partir del análisis de los campos de tensiones/desplazamientos alrededor del vértice de una grieta. Por lo tanto, se ha desarrollado un procedimiento basado en el cálculo de los SIFs para evaluar el efecto de ‘crack shielding’. De esta forma, este efecto puede ser abordado a partir del análisis de las variaciones observadas en las tendencias seguidas por los SIFs calculados de forma experimental. Sin embargo, a pesar de la importancia que el uso de estas tres técnicas ópticas en la investigación del efecto de ‘crack shielding’ podría tener en la evaluación del daño y la fatiga de estructuras reales, más trabajo de investigación debe de realizarse. Además, aunque hay un aparente enorme potencial de estas técnicas en la evaluación del efecto de ‘crack shielding’, hay también algunos aspectos de estas técnicas que se pueden criticar. Uno de estos aspectos radica en el hecho de que estas técnicas proporcionan información de la superficie de la probeta. Por lo tanto, parece que el efecto de ‘shielding’ a partir de estas técnicas correspondería principalmente al efecto de ‘shielding’ observado en la superficie de la probeta, donde se presentan condiciones de tensión plana. Un aspecto que puede criticarse acerca de la fotoelasticidad por transmisión es que el tiempo necesario para calcular los SIFs es normalmente mayor que para el caso de DIC y ESPI. Esto es porque en fotoelasticidad por transmisión, se deben capturan y procesar seis imágenes para cada nivel de carga analizado para obtener el mapa del orden de franja. Esto implica un coste computacional mayor que en el caso de DIC o ESPI. Además de esto, la fotoelasticidad por transmisión sólo se puede implementar en materiales transparentes. Respecto de DIC y ESPI, un aspecto que puede criticarse es el coste de los equipos. Su implementación requiere de un software comercial de procesamiento de imágenes que normalmente es caro. Sin embargo, una forma de resolver este inconveniente es desarrollar un algoritmo propio para implementarlas, pero esto requiere un conocimiento profundo de los algoritmos de correlación y procesamiento de imágenes. Por otra parte, ESPI se ha mostrado extremadamente sensible a condiciones externas, tales como vibraciones, que normalmente están presentes en ensayos de fatiga. Por lo tanto, se requiere un sistema suficientemente rígido para fijar el sensor de ESPI. No obstante, ESPI se ha mostrado también más sensible que DIC. Por tanto, se pueden abordar problemas como la estimación experimental del tamaño de la zona plástica en el vértice de la grieta. Esto constituye una importante línea de trabajo futura ya que se puede relacionar con el efecto de ‘crack shielding’, haciendo posible un mejor entendimiento del fenómeno. Finalmente, una ventaja importante que

presenta DIC comparada con fotoelasticidad por transmisión y ESPI es que se pueden estudiar problemas dinámicos ya que las imágenes capturadas se emplean directamente para el análisis de los desplazamientos evitando cualquier método de phase-shifting como en el caso de fotoelasticidad por transmisión o ESPI. Sin embargo, se requiere un equipo de adquisición de imágenes suficientemente rápido como para capturar imágenes durante la realización de los ensayo.

8.2.2. Cálculo de los factores de intensificación de tensiones

Para calcular los factores de intensificación de tensiones, se han empleado datos isocromáticos y desplazamientos medidos alrededor del vértice de la grieta. En este respecto, varios métodos están disponibles en la literatura para describir los campos de tensiones/desplazamientos en las inmediaciones del vértice de la grieta. Así, se han estudiado cuatro modelos, siendo éstos el modelo de Westergaard [18], Williams [6, 136], Muskhelishvili [5, 19] y CJP [21 - 23].

Se ha adoptado una metodología basada en el método multi-point over-deterministic desarrollado por Sanford y Dally [7] para determinar los SIFs. Así, en el caso de fotoelasticidad por transmisión, los SIFs no muestran una relación lineal con el campo de tensiones alrededor del vértice de la grieta. Por tanto, un sistema no lineal se ha resuelto para el cálculo de los SIFs. Sin embargo, en DIC o ESPI un sistema lineal se ha resuelto para la determinación de los SIFs ya que es lineal la relación con los campos de desplazamientos alrededor del vértice de la grieta. Además, la calidad del ajuste matemático para el cálculo de los SIFs se ha evaluado a través de la media y la varianza.

Un aspecto importante para determinar los SIFs es la definición de la región para la colección de datos alrededor del vértice de la grieta. Así, se ha adoptado una región anular tanto para fotoelasticidad por transmisión como para DIC, mientras que una región rectangular se ha definido en el caso de ESPI. De acuerdo con esto, dos parámetros principales se han seleccionado para definir estas dos regiones, un límite interior y otro exterior. De esta forma, el límite interior se ha definido como el tamaño de la zona plástica según Dugdale [27] para evitar los efectos de plasticidad que se generan en el vértice de la grieta cuando ésta se propaga. Sin embargo, el límite exterior se ha definido a través de la zona de influencia de los campos de tensiones/desplazamientos en las inmediaciones del vértice de la grieta. En el caso de fotoelasticidad por transmisión, este límite puede ser definido a partir de los lóbulos generados en el vértice de la grieta debido a la concentración de tensiones. Sin embargo, para DIC o ESPI, esta información se puede extraer a partir del campo de desplazamientos vertical donde se observa una variación en la orientación de los desplazamientos debido a la interacción entre la zona de influencia del vértice de la grieta y la zona de influencia del borde libre de la probeta. Además de esto, otros aspectos como la densidad de los datos seleccionados y la localización

del vértice de la grieta se han evaluado empleando imágenes artificiales generadas a partir de las ecuaciones de Westergaard. Así, respecto del primer aspecto, no se han obtenido diferencias relevantes respecto del número de puntos seleccionados. Por lo tanto, los SIFs se han mostrado insensibles a la densidad de los datos seleccionados, obteniendo valores muy bajos para la media y la varianza después del ajuste matemático. A partir del análisis de la localización del vértice de la grieta, se concluyó que debe tenerse especial cuidado en la definición de la localización del vértice de la grieta en la dirección a lo largo del crecimiento de la grieta. En este sentido, para la fotoelasticidad por transmisión la segunda imagen correspondiente al método de phase-stepping puede ser empleado para localizar con exactitud la posición del vértice de la grieta. En el caso de DIC y ESPI, el vértice de la grieta se ha localizado a partir de la observación del campo de desplazamientos vertical.

8.2.3. Ensayos a fatiga en probetas CT para evaluar el efecto de ‘crack shielding’

La metodología adoptada para determinar los factores de intensificación de tensiones se ha empleado para el estudio del efecto de ‘crack shielding’ en el crecimiento de grietas a fatiga. Para este propósito, se realizaron varios ensayos de fatiga a diferentes R -ratios en probetas CT. Las probetas se fabricaron en distintos materiales dependiendo de la técnica implementada. Así, policarbonato se empleó en fotoelasticidad por transmisión, aluminio 2024-T3 para DIC y titanio comercialmente puro para ESPI. Además, probetas con las mismas dimensiones se emplearon en fotoelasticidad por transmisión y DIC (figura 4.12a), mientras que en ESPI las probetas fueron 3.6 veces más pequeñas (figura 4.12b).

Para evaluar la presencia de ‘shielding’ durante los ensayos, la evaluación de los SIFs a lo largo de un ciclo de carga completo se ha analizado. Así, para los cuatro modelos estudiados, CJP ha mostrado ser el más apropiado para evaluar el efecto de ‘crack shielding’. En este aspecto, se ha observado un cambio en la tendencia de K_F por debajo de un determinado nivel de carga para las probetas ensayadas a bajo R -ratio. Este comportamiento es similar al que Elber [25], [26] observó cuando definió el concepto de cierre de grieta inducido por plasticidad: mientras que por encima de este valor de carga, los valores de K_F coinciden con los valores de K_I calculados según la norma ASTM E647-00 [206]. De acuerdo con esto, se ha adoptado una metodología para estimar K_{op} y K_{cl} a partir de las ramas de carga y descarga respectivamente. Así, los valores de K_{op} y K_{cl} se han estimado como aquel valor de K_F correspondiente a la carga mínima aplicada. Los resultados obtenidos a partir de DIC han puesto de manifiesto que no existen diferencias entre K_{op} y K_{cl} . Por otra parte, se ha observado un cambio de signo en los valores de K_R para un valor de carga similar que el previamente detectado del análisis de la tendencia de K_F . Por tanto, la parte del ciclo de carga por debajo de este valor corresponde con aquel para el

cual la grieta está cerrada; mientras que por encima de este valor corresponde a la parte del ciclo de carga para el cual la grieta está abierta.

Sin embargo, se observaron diferentes comportamientos en K_F y K_R para las probetas ensayadas a alto R -ratio. Así, no se observó ningún cambio en la tendencia de K_F , lo que implica que los valores de K_F coinciden con los valores de K_I a lo largo del ciclo de carga. Además, los valores de K_R no mostraron ningún cambio en su signo. Esto indica la ausencia de efecto de ‘shielding’ y, consecuentemente, que la grieta permanece abierta durante todo el ciclo de carga.

Otro aspecto investigado ha sido el cálculo de Pop y Pcl a partir de los valores de Kop y Kcl . Así, se ha obtenido un rango para estos valores que indica que el efecto de ‘crack shielding’ inducido por plasticidad es un proceso gradual y, por tanto hay un intervalo para el cual la grieta pasa de estar cerrada a estar abierta. Además, es remarcable también que no se han observado incrementos ni decrementos importantes en las cargas de apertura y cierre con la longitud de grieta. Por otro lado, los resultados obtenidos mediante DIC se han verificado empleando técnicas basadas en ‘compliance’. Buen nivel de concordancia se ha obtenido entre los resultados de DIC y los de ‘compliance’. Además, no se han observado variaciones en el ‘compliance’ para las probetas ensayadas a alto R -ratio, lo que indica la ausencia de efecto de ‘shielding’.

También se ha analizado la capacidad de las técnicas para predecir de forma real la velocidad de crecimiento de grieta a fatiga a través de la ley de Paris empleando el rango del factor de intensificación de tensiones efectivo calculado a partir de los valores de K_{op} . Así, se ha observado una clara diferencia entre las curvas obtenidas a partir de los valores efectivos y los nominales para las probetas ensayadas a bajo R -ratio. Se ha observado que ΔK_{eff} es más pequeño que ΔK_{nom} , lo que pone de manifiesto un efecto de retardo en el crecimiento de grieta debido al efecto de ‘crack shielding’ inducido por plasticidad.

Finalmente, otro aspecto investigado ha sido si ESPI es suficientemente sensible para estimar el tamaño de la zona plástica en el vértice de la grieta. Se ha propuesto una metodología basada en la medida directa del campo de deformación plástica en el vértice de grieta. Así, los campos de deformaciones se han calculado por diferenciación de los campos de desplazamientos medidos alrededor del vértice de la grieta. Se ha observado que el tamaño experimental de la zona plástica empleando la metodología propuesta puede compararse con las estimaciones predichas por Irwin o Dugdale [27].

8.2.4. Ensayos a fatiga en probetas CT para evaluar el efecto de sobrecargas

El efecto causado por la aplicación de sobrecargas en el crecimiento de grieta también ha sido estudiado. De forma similar a como se ha realizado para el caso del efecto de ‘crack shielding’, se realizaron varios ensayos a fatiga a carga de amplitud constante sobre probetas CT. Así, las probetas se sometieron a diferentes niveles de sobrecargas a distintas longitudes de grieta.

La metodología anteriormente adoptada para la estimación de K_{op} a partir del análisis de K_F se ha empleado para evaluar el efecto de ‘shielding’ durante la aplicación de sobrecargas. Así, se ha observado un efecto de retardo en la velocidad de crecimiento de grieta a fatiga en cada una de las sobrecargas aplicadas. Este efecto de retardo se ha identificado a partir de un incremento en los valores de K_{op} seguido de un descenso progresivo hasta que los valores de K_{op} alcanzan aquellos valores antes de la aplicación de la sobrecarga. De esta forma, las zonas afectadas por las sobrecargas se han identificado a partir de las observaciones de las tendencias seguidas por K_{op} y del ΔK_{eff} . Además, los valores de ΔK_{eff} se han empleado para trazar la ley de Paris, donde de nuevo se ha observado un efecto de retardo en el crecimiento de grieta por fatiga. Se ha observado una reducción en ΔK_{eff} respecto de ΔK_{nom} después de la sobrecarga, seguido de un incremento gradual hasta alcanzar aquellos valores antes de la aplicación de la sobrecarga.

El comportamiento que se observó previamente a partir del análisis de los SIFs también ha sido observado a partir de los valores de P_{op} . Así, después de la aplicación de la sobrecarga, P_{op} ha experimentado un incremento seguido de un descenso gradual hasta alcanzar los valores antes de la sobrecarga. De nuevo se han identificado las zonas afectadas por las sobrecargas, coincidiendo con las zonas previamente identificadas a partir del análisis de los SIFs.

Finalmente, también se ha estudiado el efecto de las sobrecargas a partir del análisis de la zona plástica estimada en el vértice de la grieta empleando los datos de ESPI. Así, se ha observado un incremento de la zona plástica como consecuencia de la aplicación de las sobrecargas. De esta forma, a la sobrecarga más severa le correspondió el mayor incremento en la zona plástica. Además, se ha relacionado el incremento de la zona plástica con la reducción en los valores de ΔK_{eff} .

8.3. Conclusiones

El trabajo de investigación llevado a cabo en esta tesis se centró en la investigación del potencial de las técnicas de fotoelasticidad por transmisión, DIC y ESPI para cuantificar el efecto de ‘crack shielding’ inducido por plasticidad. Además, esta cuestión se extendió al

estudio del efecto de sobrecargas en el crecimiento de grieta a fatiga. De acuerdo con el presente trabajo, las siguientes conclusiones generales pueden ser establecidas:

1. Existe aún un considerable desacuerdo y confusión acerca del fenómeno de ‘crack shielding’ por fatiga, especialmente respecto a aquellos aspectos relacionados con su naturaleza, magnitud, medición e interpretación. Parte del problema surge de la sensibilidad del equipo empleado para su medición o de la interpretación de los resultados obtenidos.
2. La fotoelasticidad por transmisión, DIC y ESPI permiten cuantificar el efecto de ‘shielding’ desde una perspectiva distinta con respecto a otros métodos empleados en el pasado, como por ejemplo los métodos basados en ‘compliance’. Así, se ha empleado un procedimiento basado en el cálculo de los SIFs para evaluar el efecto de ‘crack shielding’. Los SIFs se determinan a partir del análisis de datos isocromáticos (en fotoelasticidad por transmisión) o de campos de desplazamientos (en DIC y ESPI) alrededor del vértice de la grieta. Además, se han implementado cuatro modelos que describen los campos de tensiones/desplazamientos en el vértice de grieta para estudiar cuál es el mejor modelo para evaluar el efecto de ‘crack shielding’ inducido por plasticidad, estos son los modelos de Westergaard, Williams, Muskhelishvili y CJP.
3. Se ha adoptado una metodología basada en el método multi-point over-deterministic desarrollado por Sanford y Dally para el cálculo de los SIFs. En este sentido, un aspecto importante es la definición de la región para la colección de datos en las inmediaciones del vértice de la grieta. Así, se ha adoptado una región anular para fotoelasticidad por transmisión y DIC, mientras para ESPI se ha definido una región rectangular.
4. El modelo CJP ha mostrado ser el más idóneo para la evaluación del efecto de ‘crack shielding’. Así, a partir del análisis de K_F y K_R es posible establecer el rango del ciclo de carga para el cual la grieta se encuentra cerrada. Además, se ha adoptado una metodología para estimar los valores de K_{op} y K_{cl} a partir del análisis del cambio en la tendencia seguida por los valores de K_F correspondientes a las ramas de carga y descarga respectivamente.
5. Se han calculado las cargas P_{op} y P_{cl} a partir de los valores de K_{op} y K_{cl} . Se ha obtenido un rango para P_{op} y P_{cl} debido a que el fenómeno de ‘crack shielding’ inducido por plasticidad es un proceso gradual y, por tanto hay un intervalo para el cual la grieta cambia de estar completamente cerrada a estar completamente abierta.
6. La velocidad de crecimiento de grieta a fatiga se ha predicho de forma real a través del cálculo de ΔK_{eff} a partir de los valores de K_{op} estimados. De acuerdo con esto, se ha cuantificado un efecto de retardo en el crecimiento de grieta a fatiga para las probetas

ensayadas a bajo R -ratio. Por otro lado, no se ha observado ningún efecto de retardo para las probetas ensayadas a alto R -ratio.

7. Las cargas de apertura y cierre obtenidas mediante DIC se han comparado con las obtenidas empleando dos métodos basado en ‘compliance’, los métodos del ‘strain offset’ y del ‘offset compliance’. En ambos casos, los resultados muestran un alto nivel de concordancia con los obtenidos a partir del análisis de los campos de desplazamientos empleando la técnica de DIC.
8. El efecto de sobrecargas en el crecimiento de grieta a fatiga se ha estudiado satisfactoriamente mediante fotoelasticidad por transmisión, DIC y ESPI. Así, se ha cuantificado un efecto de retardo en el crecimiento de grieta a fatiga para cada una de las sobrecargas aplicadas a través de las variaciones observadas en las tendencias de K_{op} y ΔK_{eff} . Este efecto de retardo también se ha identificado a partir del trazado de la ley de Paris empleando ΔK_{eff} . Por otra parte, K_{op} se ha empleado para cuantificar la carga de apertura durante el crecimiento de grieta. Además, se han identificado las zonas afectadas por el efecto de las sobrecargas a través de la observación de los cambios experimentados en los valores de P_{op} . De nuevo, los valores de P_{op} obtenidos a partir de DIC se han verificado con los obtenidos mediante el método de ‘strain offset’.
9. ESPI ha mostrado ser lo suficientemente sensible para estimar el tamaño de la zona plástica en el vértice de la grieta. Por tanto, se ha propuesto una metodología basada en la medición directa del campo de deformaciones plástico en el vértice de la grieta. Esta metodología se ha empleado para estudiar la influencia de las sobrecargas mediante la estimación del tamaño de la zona plástica en el vértice de la grieta. De esta forma, se ha observado un incremento en el tamaño de la zona plástica como consecuencia de la aplicación de diferentes sobrecargas.
10. El incremento del tamaño de la zona plástica se ha relacionado con la reducción en el rango del factor de intensificación de tensiones efectivo. Así, el efecto de retardo inducido en la velocidad de crecimiento de grieta a fatiga originado por el incremento en la zona plástica, la que intensifica el efecto de ‘crack shielding’ y reduce el valor de ΔK_{eff} .

8.4. Trabajo futuro

Los resultados expuestos en la presente tesis ponen de manifiesto el potencial de las técnicas de fotoelasticidad por transmisión, DIC y ESPI para la evaluación del efecto de ‘crack shielding’. Sin embargo, hay aún algunas cuestiones que podrían ser consideradas como parte de un trabajo de investigación futuro:

1. Como se describió en la metodología para calcular los SIFs, el vértice de la grieta se debe seleccionar de forma manual. Por lo tanto, una posible mejora podría ser la introducción de las coordenadas del vértice de la grieta como variables en el proceso de cálculo. Sin embargo, el cálculo de los SIFs a partir del análisis de los campos de desplazamientos (es decir en DIC o ESPI) debería realizarse por la resolución de un sistema no lineal de ecuaciones, por lo que sería necesario un proceso de cálculo iterativo.
2. Se han empleado probetas de tipo CT para el estudio de la capacidad de las técnicas ópticas de estudio para cuantificar el efecto de ‘crack shielding’. Sin embargo, otras geometrías, por ejemplo ‘middle-tension’ (MT) o ‘single-edge-notched’ (SEN), podrían emplearse para analizar la exactitud y robustez de la metodología adoptada para estimar el K_{op} . El estudio de probetas tipo MT muestra especial interés ya que tiene una geometría simétrica y la rigidez de la probeta es mayor que en el caso de las probetas tipo CT o SEN.
3. El estudio de grietas a fatiga en modo mixto no era uno de los objetivos marcados en la tesis. Sin embargo, en recientes publicaciones, los autores han desarrollado una extensión del modelo CJP para grietas en modo mixto. Por consiguiente, una nueva posibilidad es extender el actual análisis al estudio de grietas inclinadas en policarbonato y materiales metálicos.
4. Otra área de trabajo futuro es el estudio del efecto de la interacción entre diferentes grietas en la vida a fatiga. De esta forma, se pueden estudiar probetas tipo ‘double-edge-notched’ (DEN) con diferentes separaciones entre las entallas para evaluar cómo la interacción entre las grietas podría afectar en la vida a fatiga de los componentes analizados.
5. Más trabajo de investigación se puede llevar a cabo en relación con la determinación del tamaño de la zona plástica en el vértice de grieta empleando ESPI. Así, la forma de la zona plástica se podría estimar empleando los modelos estudiados para obtener una expresión para la zona plástica en función de los factores de intensificación de tensiones, los coeficientes de los modelos y el ángulo de los puntos alrededor del vértice de la grieta. De esta forma, la forma de la zona plástica podría compararse con la estimada empleando la metodología basada en el análisis del campo de deformaciones plástico.
6. Relacionado con la anterior línea de trabajo futuro, microscopía electrónica de barrido (SEM) se puede emplear para comparar la distribución de deformaciones plásticas observadas con el tamaño de la zona plástica estimada a partir del campo de deformaciones plástico medido con ESPI.
7. De forma similar, DIC podría ser explorada para estimar el tamaño de la zona plástica empleando la metodología propuesta para ESPI.

8. Finalmente, un área adicional de investigación podría ser extender la metodología adoptada para la evaluación de la integridad estructural de componentes reales en servicio.

Chapter 8. Discussion and conclusions

8.1. Introduction

This last chapter provides an overall discussion on the research work performed and summarises the most significant conclusions established. In addition, on the basis of these findings, some proposals of future work are also exposed.

8.2. Discussion

8.2.1. Transmission photoelasticity, DIC and ESPI: alternative tools for fatigue crack shielding quantification

Since Elber [25, 26] introduced the concept of crack closure through his investigations on plasticity-induced crack closure, other sources of closure have been observed [24]. These mechanisms seem to have a major influence in the near-threshold regime, such as oxide-induced crack closure and roughness-induced crack closure; or in particular environments or specific materials, such as viscous fluid-induced crack closure and phase transformation-induced crack closure. However, plasticity-induced crack closure appears to be the predominant effect in long cracks; moreover, a contribution of the surface roughness and oxide particles is always expected, especially in aggressive environments. In addition, the shielding effect seems to be more pronounced at low R -ratios and under plane stress conditions.

Different mathematical, analytic and numerical models have been developed in an attempt to explain and understand the principles of crack shielding. However, in some cases they showed contradictory results, which created controversies and some unresolved issues about its measurement, its mechanism and its interpretation.

Different techniques and methods have been developed and employed for the experimental measurement of fatigue crack closure. In the literature, the techniques based on compliance have been the most extensively used and reported. The measurement location and the sensitivity of the technique have been shown as crucial issues when quantifying the crack opening and closing loads. Several researchers have reviewed all the possible points of controversy and the sources of uncertainty during the experimental evaluation of fatigue crack shielding. Despite this, there still are some issues on crack shielding that remain to be solved.

The evaluation of the SIFs has an important role in analysing problems observed in fracture mechanics. In this respect, optical techniques such as transmission photoelasticity, DIC or ESPI offer the possibility of approaching the issue about the quantification of crack shielding effect from a different perspective. Thus, transmission photoelasticity allows to analyse the stress fields around the tip of a growing fatigue crack, while the displacement fields at the vicinity of the crack tip can be measured by DIC or ESPI. In this sense, these three optical techniques allow to determine the SIFs from the analysis of crack tip stress/displacement fields around the crack tip. Therefore, an approach based on the calculation of the SIFs has been developed to evaluate the fatigue crack shielding effect. Thus, it can be approached from the analysis of the observed variations in the trends followed by the SIFs experimentally calculated. However, despite of the significance that using these three optical techniques in the investigation of crack shielding could have in the fatigue and damage assessment of real structures, further research work must be done. In addition, although there is an enormous apparent potential for these optical techniques in the evaluation of crack shielding, there are also some aspects from these techniques that can be criticised. One of these aspects is the fact that techniques provide information from the specimen surface. Therefore, it seems that the shielding effect from the analysis of these techniques would correspond mainly to shielding observed at the specimen surface, where plane stress conditions are present. An aspect that can be criticised about transmission photoelasticity is that the time spent to calculate the SIFs is normally higher than for the case of DIC and ESPI. This is because in transmission photoelasticity, six images must be captured and processed for each load level to obtain the fringe order map. This implies a computational cost higher than in the case of DIC and ESPI. Besides this, transmission photoelasticity can be only implemented on transparent materials. Regarding to DIC and ESPI, an aspect that can be criticised is the cost of the equipment. Their implementation requires from image processing commercial software, which is normally expensive. However, a way to solve this inconvenient is to develop an own algorithm for implementing them, but it requires a deep knowledge of the correlation or processing algorithms. Moreover, ESPI has been shown extremely sensitive to external conditions, such as vibrations, which are usually presents during fatigue tests. Thus, a system rigid enough is required to fix the ESPI sensor. Nevertheless, ESPI has been also shown more sensitive than DIC. Hence, problems as the experimental estimation of the crack tip plastic zone size can be approached. This constitutes an important future work line since it can be related with the crack shielding effect, making it possible a better understanding of the phenomenon. Finally, an important advantage that DIC presents compared to transmission photoelasticity and ESPI is that dynamic problems can be studied since captured images are directly employed for displacement analysis avoiding any phase-shifting method as in the case of transmission photoelasticity and ESPI. However, an image acquisition equipment fast enough is required to capture images during the tests.

8.2.2. Calculation of stress intensity factors

Isochromatic data and measured displacements around the crack tip have been employed to calculate the stress intensity factors. In this respect, several methods are available in the literature to describe the stress/displacement fields at the vicinity of the crack tip. Thus, four models have been studied in the current thesis, namely Westergaard's [18], Williams's [6, 136], Muskhelishvili's [5, 19] and CJP [21 - 23] models.

A methodology based on the multi-point over-deterministic method developed by Sanford and Dally [7] has been adopted to determine the SIFs. Thus, in the case of transmission photoelasticity, the SIFs do not show a linear relation with crack tip stress field. Therefore, a nonlinear system of equations has been solved for SIF calculation. However, in DIC or ESPI a linear system of equations has been solved to determine the SIFs since they are linearly related with the crack tip displacement fields. In addition, the quality of the mathematical fitting in the SIF calculation has been assessed by the mean and the variance.

An important aspect to determine the SIFs is defining the region for data collection around the crack tip. Thus, an annular region has been adopted for both transmission photoelasticity and DIC, while a rectangular region has been defined in ESPI. According to this, two main parameters have been selected to define these two regions, namely an inner and outer limit. Thus, the inner limit has been defined as the Dugdale's plastic zone size [27] in order to avoid the plasticity effects that are generated at the crack tip when a crack propagates. However, the outer limit has been defined from the influence zone of the crack tip on the stress/displacement fields. In the case of transmission photoelasticity, this limit can be defined from the generated lobe at the crack tip due to the stress concentration. However, for DIC or ESPI, this information can be extracted from the vertical displacement field where it is observed a variation in the displacement orientation due to the interaction between the influence zone of the crack tip and the influence zone of the free edge of the specimen. In addition, other aspects as the data point density and the location of the crack tip have been evaluated using artificial images generated from Westergaard's equations. Thus, regarding the first aspect, no significant differences have been obtained with the number of collected data points. Therefore, the SIFs have been shown insensitive to collected data density, obtaining very low values of the mean and the variance after the mathematical fitting. From the analysis of the location of the crack tip, it was concluded that especial care must be taken to define the crack tip location in the direction along the crack growth. In this sense, in transmission photoelasticity the second image corresponding to the phase-stepping method can be employed to locate with accuracy the crack tip position. In the case of DIC and ESPI, the crack tip has been located from the observation of vertical displacement field.

8.2.3. Fatigue tests on CT specimens to evaluate crack shielding

The adopted methodology to determine the stress intensity factors has been employed for the study of the crack shielding effect in growing fatigue cracks. For this purpose, several fatigue tests at different R -ratios in CT specimens were conducted. Specimens were manufactured in different materials depending on the technique implemented. Thus, polycarbonate was employed in transmission photoelasticity, 2024-T3 aluminium for DIC and commercially pure titanium for ESPI. In addition, specimens with same dimensions were used in transmission photoelasticity and DIC (figure 4.12a), while in ESPI specimens were 3.6 times smaller (figure 4.12b).

To evaluate the presence of shielding during the tests, the evolution of the SIFs along a whole loading cycle has been analysed. Thus, for four models studied, CJP has been shown as the most powerful to evaluate the fatigue crack shielding effect. In this respect, a change in the K_F trend has been observed below a determined load level for specimens tested at low R -ratio. This behaviour is similar to that previously observed by Elber [25, 26] when he defined the plasticity-induced crack closure concept; while above this load level, K_F values agree with those K_I calculated from the ASTM E647-00 standard [206]. According to this, a methodology to estimate K_{op} and K_{cl} from the loading and unloading branches has been adopted. Thus, K_{op} and K_{cl} values have been estimated as that K_F value corresponding to the minimum applied load. Results obtained from DIC have highlighted that there exist no differences between K_{op} and K_{cl} . Moreover, a sign change has been observed in K_R values for a similar load value to that previously detected analysing K_F trend. Therefore, the portion of the loading cycle below this value corresponds to that at which the crack is closed; while above this value corresponds to that portion of the loading cycle at which the crack is open.

However, different behaviour in K_F and K_R were observed for specimens tested at high R -ratio. Thus, no change in the K_F trend has been observed, which implies that K_F values agree with those K_I along the whole loading cycle. In addition, K_R values have not shown change in their sign. This indicates the absence of shielding and, consequently, the crack remains open during the whole loading cycle.

Another aspect investigated has been the P_{op} and P_{cl} calculation from K_{op} and K_{cl} values. Thus, a range for these values has been obtained which indicates that plasticity-induced crack shielding effect is a gradual process and, therefore there is an interval at which the crack changes from closed to open. In addition, it is also remarkable that no significant increases or decreases in the opening and closing loads have been observed along the crack length. Moreover, DIC results have been verified using compliance based techniques. Good level of agreement between DIC

and compliance results has been obtained. In addition, no compliance variation has been observed for specimens tested at high R -ratio, which indicates the absence of shielding.

It has been also analysed the ability of the techniques to realistically predict the fatigue crack growth rate from Paris law using the effective stress intensity factor range calculated from K_{op} . Thus, it has been observed a clear difference between curves obtained from the effective values and those obtained from nominal SIFs for specimens tested at low R -ratio. It has been observed that ΔK_{eff} is smaller than ΔK_{nom} , which highlights a retardation effect on fatigue crack growth due to the plasticity-induced crack shielding effect. Nevertheless, in the case of the specimens tested at high R -ratio this difference between the effective and nominal curves has not been observed, this indicates that a retardation effect has not been induced on fatigue crack growth due to the absence of shielding.

Finally, another aspect investigated has been whether ESPI is sensitive enough to estimate the crack tip plastic zone size. A methodology based on the direct measurement of the crack tip plastic strain field has been proposed. Thus, strain fields have been calculated by differentiating the displacement fields measured around the crack tip. It has been observed that the experimental plastic zone size obtained using the proposed methodology can be compared with those predicted estimations by Irwin or Dugdale [27].

8.2.4. Fatigue tests on CT specimens to evaluate the overload effect

The effect caused by the application of overloads on the crack growth has been also studied. In a similar way that it has been made for the case of crack shielding, several fatigue tests at constant amplitude loading on CT specimens were conducted. Specimens were subjected to different overload levels at different crack lengths.

The methodology previously adopted for estimating K_{op} from the analysis of K_F has been employed to evaluate the shielding effect during the overload application. Thus, a retardation effect on the fatigue crack growth rate has been observed in each of the applied overloads. This retardation effect has been identified from an increase in K_{op} followed by a progressive decrease until K_{op} values approach those values prior to the overload application. An opposite behaviour has been observed in ΔK_{eff} for the same zones affected by the overloads. In this way, the zones affected by overloads have been identified from the observations of K_{op} and ΔK_{eff} trends. In addition, ΔK_{eff} values have been used to plot Paris law, where again a retardation in the crack growth rate has been observed. A reduction in ΔK_{eff} respect to ΔK_{nom} has been observed after the overload, followed by a gradual increase until approaching those values before the overload application.

The behaviour previously observed from the analysis of the SIFs has been also observed from P_{op} . Thus, after the overload application, P_{op} has experienced an increase followed by a gradual decrease until approaching to that value prior to the overload. Again, the zones affected by the overloads have been identified, which agree with those previously identified from the analysis of the SIFs.

Finally, the overload effect has been also studied from the analysis of the plastic zone size estimated using ESPI data. Thus, an increase in the crack tip plastic zone size has been observed as consequence of the overload application. In this way, the highest increase was observed for the most severe overload. In addition, the increase in the plastic zone size has been related with the reduction in ΔK_{eff} .

8.3. Conclusions

The research work conducted in this thesis was focused on the investigation of the potential of transmission photoelasticity, digital image correlation and electronic speckle pattern interferometry to quantify the plasticity-induced fatigue crack shielding effect. In addition, this issue was extended to the study of the overload effect on fatigue crack growth. According to the presented work, the following general conclusions can be established:

1. There is still a considerable disagreement and confusion about fatigue crack shielding phenomenon, especially in aspects related to its nature, magnitude, measurement and interpretation. Part of the problem arises because of the sensitivity of the equipment employed for its measurement or the interpretation of the obtained results.
2. Transmission photoelasticity, DIC and ESPI allow the quantification of crack shielding effect from a different perspective respect to other methods employed in the past, as for instance compliance based methods. Thus, an approach based on the calculation of the SIFs has been employed to evaluate the crack shielding effect. SIFs are determined from the analysis of isochromatic data (in transmission photoelasticity) or displacement fields (in DIC and ESPI) around the crack tip. In addition, four models to describe crack tip stress/displacement fields have been implemented to study which model is the best to evaluate plasticity-induced crack shielding, namely Westergaard's, Williams's, Muskhelishvili's and CJP models.
3. A methodology based on the multi-point over-deterministic method developed by Sanford and Dally has been adopted to calculate SIFs. In this sense, an important aspect is the definition of the region for data collection around the crack tip. Thus, an annular region has been adopted in transmission photoelasticity and DIC, while a rectangular region has been defined in ESPI.

4. CJP model has been shown the most powerful model for the evaluation of crack shielding effect. Thus, from the analysis of K_F and K_R , it has been possible to establish the portion of the loading cycle at which the crack is closed. In addition, it has been adopted a methodology to estimate K_{op} and K_{cl} from the analysis of the change in the trend followed by K_F values corresponding to the loading and unloading branches, respectively.
5. P_{op} and P_{cl} loads have been calculated from K_{op} and K_{cl} . A range for P_{op} and P_{cl} has been obtained due to the fact that plasticity-induced crack shielding phenomenon is a gradual process and, therefore there is an interval at which the crack changes from fully closed to fully open.
6. Fatigue crack growth rate has been realistically predicted by calculating ΔK_{eff} from the estimated K_{op} values. According to this, a retardation effect on fatigue crack growth has been quantified for specimens tested at low R -ratio. Moreover, no retardation effect has been observed for specimens tested at high R -ratio.
7. Opening and closing loads obtained from DIC have been compared with those obtained using two compliance based methods, namely the strain offset method and the offset compliance method. In both cases, results show a high level of agreement with those obtained from the analysis of displacement fields using CJP model.
8. The overload effect on fatigue crack growth has been successfully studied by transmission photoelasticity, DIC and ESPI. Thus, a retardation effect on fatigue crack growth for each of the applied overloads has been quantified through variations observed in the K_{op} and ΔK_{eff} trends. This retardation effect has been also identified from Paris law plotted using ΔK_{eff} . Moreover, K_{op} has been employed to quantify the opening load values during on fatigue crack growth. In addition, the zones affected by the overload effect have been identified from the observation of changes occurring in P_{op} values. Again, P_{op} values obtained from DIC have been verified with those obtained by the strain offset method.
9. ESPI has shown to be sensitive enough to estimate the plastic zone size at the crack tip. Hence, a methodology based on the direct measurement of plastic strain fields at the crack tip has been proposed. This methodology has been employed to study the influence of overloads by estimating the plastic zone size at the crack tip. An increase in the plastic zone size has been observed as consequence of the application of different overloads.
10. The increase in the plastic zone size has been related to a reduction in the effective stress intensity factor range. Thus, the retardation effect induced on the fatigue crack growth rate originated by the increase in the plastic zone size, which intensifies the plasticity-induced crack shielding effect and reduces ΔK_{eff} .

8.4. Future work

The results exposed in the current thesis highlight the potential of transmission photoelasticity, DIC and ESPI for evaluating the plasticity-induced fatigue crack shielding effect. However, there are still some issues that could be addressed as part of future investigations:

1. As it was described in the methodology to calculate SIFs, the crack tip must be selected manually. Therefore, a possible improvement could be the introduction of the coordinates of the crack tip as variables in the calculation process. However, the calculation of SIFs from the analysis of the displacement fields (i.e. in DIC and ESPI) should be performed by solving a nonlinear system of equations, so an iterative calculation process would be necessary.
2. CT specimens have been employed to study the ability of full-field optical techniques to quantify the crack shielding effect. However, other geometries, e.g. middle-tension (MT) or single-edge-notched (SEN) could be employed to analyse the accuracy of the methodology adopted to estimate K_{op} . Special interest shows the study of MT specimens since it has a symmetric geometry and the specimen stiffness is higher than for the case of CT or SEN specimens.
3. The study of mixed-mode fatigue cracks was not an aim of the current thesis. However, in recent publications, authors have developed an extension of CJP model to mixed mode I and mode II. Therefore, a new possibility is to extend the current analysis to the study of inclined cracks in polycarbonate and metallic materials.
4. Another area of future work is the study of the effect of the interaction between different cracks in fatigue life. In this way, double-edge notched (DEN) specimens with different separations between notches can be studied to evaluate how the crack interaction affects fatigue life.
5. Further research work can be conducted related to the determination of the crack tip plastic zone size using ESPI. Thus, the plastic zone shape at the crack tip could be estimated using the studied models to obtain an expression for the plastic zone as a function of the stress intensity factors, the model coefficients and the angle of the points around the crack tip. Thus, the plastic zone shape could be compared with that estimated using the methodology based on the analysis of plastic strain fields.
6. Related to the previous future work line, scanning electronic microscopy (SEM) can be employed to compare the observed plastic strain distribution with the plastic zone size estimated from the plastic strain field measured with ESPI.
7. In a similar way, DIC could be explored to estimate the plastic zone size using the proposed methodology for ESPI.

8. Finally, an additional area of research could be to extend the adopted methodology for structural integrity evaluation for real in service structures.

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APPENDIX A: SPECIFICATIONS OF THE EQUIPMENT EMPLOYED FOR TRANSMISSION PHOTOELASTICITY

Table A.1. Specifications of the AVT Marlin F-146B/C camera

AVT Marlin F-146B/C camera	
Interface	IEEE 1394a – 400 Mb/s, 1 port
Resolution (pixel)	1392 x 1040
Sensor	Sony ICX267
Sensor type	CCD progressive
Sensor size	Type 1/2
Cell size (μm)	4.65
Lens mount	C
Maximum frame rate at full resolution (fps)	17
A/D (bit)	12
On-board FIFO (MB)	8
Bit depth (bit)	8–10
Mono modes	Mono8, Mono16
Colour modes YUV	YUV411, YUV422
Colour modes RGB	RGB8
Raw modes	Raw8
Power requirements (DC in V)	8 – 36
Power consumption, 12 V (W)	<3
Weight (g)	<120
Body dimensions (L x W x H in mm)	72 x 44 x 29

Table A.2. Specifications of the macro zoom lens (Edmund Optics, model MLH-10X)

EO MLH-10X macro zoom lens	
Magnification	10X
Maximum camera sensor format	1/2"
Focal length FL (mm)	13-130
Field of view, 1/2" sensor (mm)	7.8-280
Working distance (mm)	152-457
Primary magnification PMAG	Minimum: 0.82X – 0.085X Maximum: 0.23X – 0.023 X
Aperture (f/#)	F5.6 – 32 closed
Filter thread	M46 x 0.75 mm
Diameter (mm)	48
Length (mm)	98.5
Mount	C
Weight (g)	233

Table A.3. Specifications of the FWB-EC3402 express card

FWB-EC3402 express card	
Adapter type	IEEE1394b ↔ ExpressCard/34
1304 chipset	LSI FW643
Interface	1x bilingual port, screw lock, supplying up to 1300 mA bus power when externally powered
Speed	100, 200, 400, 800 Mb/s transfer rate
Bandwidth	100/80/64 MB/s at 800 Mb/s (gross/net/video)
DMA	8x isochronous transmit/receive channels
Compliance	FCC, CE

Dimensions	34 x 122 mm
Weight	40 g
External power in	Walkman-type 1.3 mm DC Jack
Operational temperature	5°-50°C
Compatibility	AVT software packages

APPENDIX B: SPECIFICATIONS OF THE EQUIPMENT EMPLOYED FOR DIGITAL IMAGE CORRELATION

Table B.1. Specifications of the AVT Stirling F-504B/C camera

AVT Stingray F-504B/C camera	
Interface	IEEE 1394a – 800 Mb/s, 2 ports
Resolution (pixel)	2452 x 2056
Sensor	Sony ICX655
Sensor type	CCD progressive
Sensor size	Type 2/3
Cell size (µm)	3.45
Lens mount	C
Maximum frame rate at full resolution (fps)	9
A/D (bit)	14
On-board FIFO (MB)	64
Bit depth (bit)	8–14
Mono modes	Mono8, Mono 12, Mono16
Colour modes YUV	YUV411, YUV422
Colour modes RBG	RGB8
Raw modes	Raw8, Raw12, Raw16
Power requirements (DC in V)	8 – 36
Power consumption, 12 V (W)	<4
Weight (g)	92
Body dimensions (L x W x H in mm)	72.9 x 44 x 29

Table B.2. Specifications of the AVT Pike F-032B/C camera

AVT Pike F-032B/C camera	
Interface	IEEE 1394a – 800 Mb/s, 2 ports
Resolution (pixel)	640 x 480
Sensor	Truesense KAI-0340
Sensor type	CCD progressive
Sensor size	Type 1/3
Cell size (µm)	7.4
Lens mount	C
Maximum frame rate at full resolution (fps)	208
A/D (bit)	14
On-board FIFO (MB)	64
Bit depth (bit)	8–14
Mono modes	Mono8, Mono 12, Mono16
Colour modes YUV	YUV411, YUV422
Colour modes RBG	RGB8
Raw modes	Raw8, Raw12, Raw16
Power requirements (DC in V)	8 – 36
Power consumption, 12 V (W)	4
Weight (g)	250
Body dimensions (L x W x H in mm)	96.8 x 44 x 44

APPENDIX C: SPECIFICATIONS OF THE EQUIPMENT EMPLOYED FOR ELECTRONIC SPECKLE PATTERN INTERFEROMETRY

Table C.1. ESPI sensor specifications

Sensor of the Q-300 ESPI-3D system	
Operating voltage	12 V DC
Typical power consumption	4 W
Dimensions (H x W x D) without illuminations arms	80 x 80 x 120 mm ³
Length of illumination arms	55 mm
Weight	2.5 kg
Ambient operating temperature range	15 – 35°C
Storage temperature range	-10 – 50°C
Pressure	600 – 1300 mbar
Piezoelectric input voltage	-20 – +180 V DC
Piezoelectric input current	Max. 140 mA
Supply input current	Typ. 300 mA
Shutter input voltage	Typ. 7 – 12 V
Shutter input current	Typ. 13 mA
LD1/2 input current	Max. 130 mA
Lens mount	C-mount
CCD image area	752 (H) x 582 (V) pixels, 1/3"
Object distance, image size	Depending on the lens
Measuring sensitivity	Depending on illumination arm, distance and wavelength: 0.05 – 1 μm

