# INVESTIGATION OF CRACK CLOSURE BY USING THERMOELASTIC STRESS ANALYSIS

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## ABSTRACT

A comparison is presented between the effective stress intensity factors obtained using the replicas method and those determined by thermoelastic stress analysis (TSA). The investigation was performed on mixed-mode propagating cracks in a biaxial fatigue testing machine using cruciform specimens with 45° cracks. A successive load cycle was used to grow the cracks in order to prevent crack branching during propagation. Thermoelastic data was recorded for a crack half length of 9 mm with an applied mixed-mode ratio $\Delta K_I/\Delta K_{II} = 0.45$, and the stress intensity factor and closure ratio determined for a range of R ratios. The thermoelastic measurements were performed at lower applied cyclic loads than those used to propagate the crack in order to prevent the crack growth and branching during the data acquisition. Surface replicas were used to measure the opening displacements, but not the sliding displacements due to the very small amount of sliding displacement produced by the predominantly mode I applied loads. Three R ratios of R = 0, 0.2 and 0.5 were considered. The measured maximum and minimum opening displacements from the replicas were found to be higher than the theoretical ones. This can be explained by the plastic deformation left by the successive loading cycle used for crack propagation.

The comparison between the theoretical, the experimental (obtained by thermoelasticity) and the effective values (obtained from replicas method) of the stress intensity factor $\Delta K_I$ highlights that the experimental results obtained by thermoelasticity represents the driving force for crack propagation. However, the experimental values of the stress intensity factors obtained by thermoelasticity are below the theoretical ones but above the effective values obtained taking into account the closure using the replicas.

## Introduction

In the last 30 years several different methods have been used to measure the crack closure (mode I) or crack locking (mode II). These methods could be classified in the following categories:

- methods based on compliance change that use strain/clip gauges [1], [2];
- the surface replica technique that measures the displacement field around the crack tip [3];
- experimental stress analysis methods based on direct assessment of $\Delta K_{eff}$ from the stress field, e.g. using the photoelasticity [4] or thermoelasticity [5], [6].

For mixed mode propagated cracks Wong [3], studying the crack closure effect on rail steel obtained a compliance change for mode I, and no obvious slope change for mode II loading. He concluded that the strain gauge technique could detect mode I closure but cannot measure the mode II crack locking. He used the surface replica technique in order to measure the mode II crack locking

Tomlinson [5], Diaz[6] and Dulieu – Barton et al. [7] have all investigated the use of thermoelasticity for the determination of the effective stress intensity factor and the use of this experimental stress analysis method to identify the extent of closure. Tomlinson [5] investigated crack closure by measuring the effects on the stress intensity factor of cutting out the wake of a fatigue crack, and Diaz [6] made a comparison of the effective crack closure measured by thermoelasticity and a compliance method for mode I cracks in welded structures. However, no direct measure of mixed mode effective stress intensity factors, has been presented. Therefore this paper presents the results obtained when measuring the crack closure for mixed mode cracks using the surface replica technique and thermoelastic investigation.

## Methods for determining the effective stress intensity factors

### *Surface replicas technique*

The surface replicas compare the real range of opening and sliding displacement ranges with the theoretical one. The effective range of stress intensities can be expressed as:

$$\Delta K_{Ieff} = \frac{v_{\exp\_\max} - v_{\exp\_\min}}{v_{th\_\max} - v_{th\_\min}} \Delta K_I \qquad (1)$$

$$\Delta K_{IIeff} = \frac{u_{\exp\_\max} - u_{\exp\_\min}}{u_{th\_\max} - u_{th\_\min}} \Delta K_{II} \qquad (2)$$

where v represents the opening displacement and u the sliding displacement, and subscripts *th* and *exp* are the theoretical value and experimental measured displacement respectively. The relations used to calculate the theoretical values for opening and sliding displacements, on the crack face under plane strain conditions are respectively, [8]:

$$v_{th} = \frac{2K_I}{E}\left(1-\nu^2\right)\sqrt{\frac{2r}{\pi}}\sqrt{1-\frac{r}{2a}} \qquad (3)$$

$$u_{th} = \frac{K_{II}}{G}\left(1-\nu\right)\sqrt{\frac{2r}{\pi}} = \frac{2K_{II}}{E}\left(1-\nu^2\right)\sqrt{\frac{2r}{\pi}} \qquad (4)$$

where E is the Young's modulus, $\nu$ is Poisson's ratio and G is the shear modulus.

### *Thermoelastic Stress Analysis*

Thermoelasticity is based on the fact that under adiabatic and reversible conditions, a cyclically loaded structure experiences temperature variations that are proportional to the sum of the principal stresses [9]. These temperature variations may be measured using a sensitive infra-red detector, the signal from which, S, is related to the first stress invariant by the following equation:

$$\Delta(\sigma_1 + \sigma_2) = AS \qquad (5)$$

where A is a calibration constant. An expression for this first stress invariant in the region of the crack tip can be derived from stress field equations and used to determine the stress intensity factors. The stress intensity factor value obtained from thermoelastic analysis is equal to the range of the stress intensity factor, $\Delta K$, that occurs at the crack tip due to the applied cyclic load. TSA gives the actual crack driving force and therefore will give the effective stress intensity factor range experienced by the crack tip rather than that which is applied.

## Experimental procedure

### *Specimen preparation*

A 45° starter notch was spark eroded into a cruciform specimen, shown in Fig. 1 and the specimen was then loaded in a Denison Mayes 100 kN biaxial testing machine, in order to perform the fatigue crack propagation test. The advantage of using a biaxial test and the cruciform specimen with a 45° crack is that by changing the applied load on the two axes it is possible to generate all types of mixed modes from pure mode I (when the four actuators of the biaxial machine apply equal loads at the same time), through mixed modes I and II, to pure mode II (when one pair of actuators push and the other pull with equal load amplitudes at the same time). A Personal Computer with a PCI – 6035 National Instruments card and the LabVIEW software was used to control the biaxial machine. A computer program was written to command the signal on the X and Y axes of the test machine. An equibiaxial sine load of $P_{xmin}$=8.21 kN, $P_{xmax}$=45.1 kN and $P_{ymin}$=8.21 kN, $P_{ymax}$=45.1 kN was used for precracking, a successive loading $P_{xmin}$=0 kN, $P_{xmax}$=37 kN and $P_{ymin}$=0 kN, $P_{ymax}$=37 kN with $K_{II}/K_I$=1 (Fig. 2) was used to propagate the mixed mode crack to a half length of 9 mm.

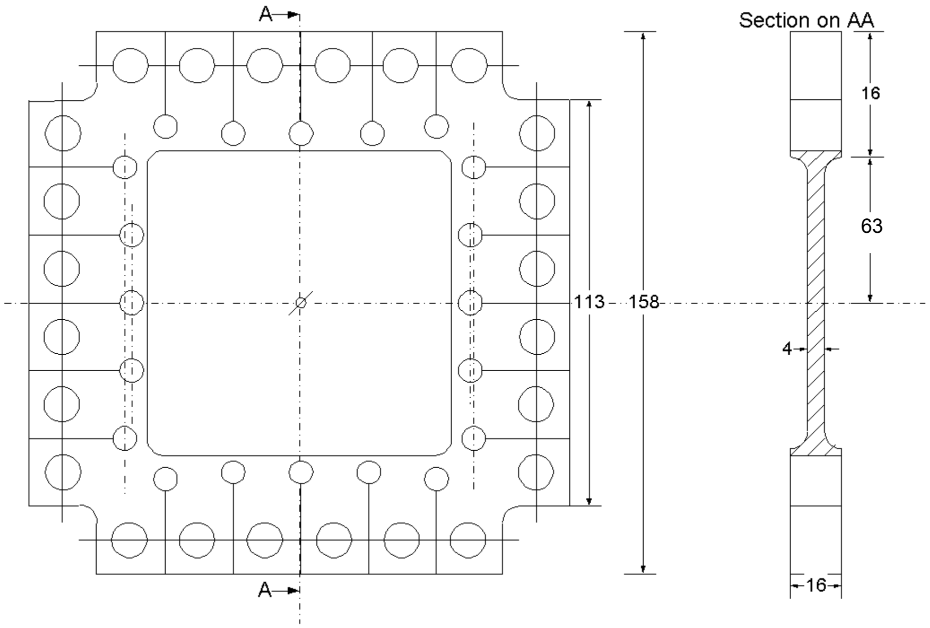

Figure 1. The cruciform specimen with starter notch

A frequency of 5 Hz was used for the crack propagation tests, at which the machine gave a satisfactory response. The shape of the load waveform and the response of the load cells were checked using two, 2 - channel oscilloscopes. A traveling microscope was used to measure the crack length in the tests.

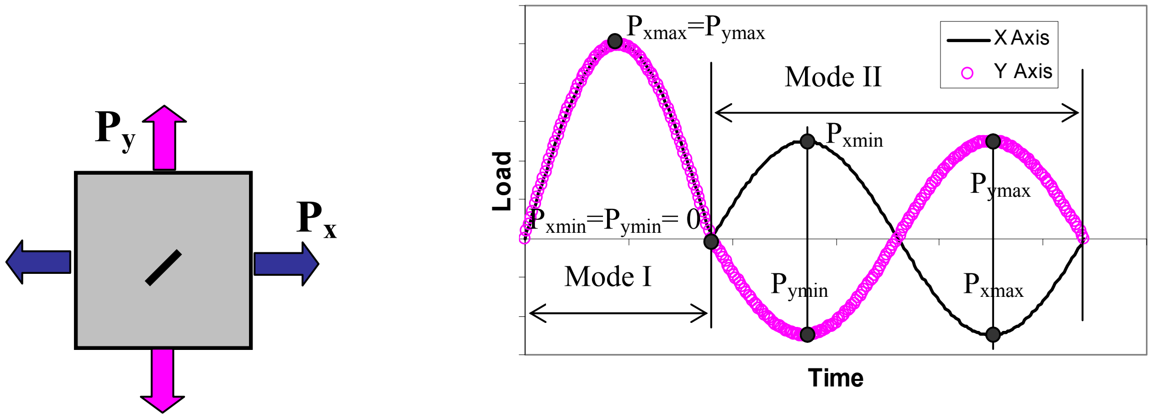

Figure 2. The successive loading cycle for $K_{II}/K_I=1$

***Thermoelastic Measurements***

The thermoelastic measurements were performed using a DeltaTherm 1000 system, manufactured by Stress Photonics Inc. (USA). The applied cyclic load, with sine waveforms, was lower than the load used for fatigue crack propagation in order to prevent crack growing and branching during the thermoelastic measurements. The infrared camera acquires thermal images from the specimen surface. A lock-in amplifier correlates the signal from the detector with a reference signal taken from one of the loading cells of the biaxial machine. A computer and DeltaVision software control the aquisition process.

Six different combinations of the applied loads on the X and Y axes of the test machine where used with R ratios of 0, 0.1, 0.2, 0.3, 0.5 and 0.7 (Table 1). A frequency of 8 Hz was needed for thermoelastic measurements to ensure the adiabatic conditions required. In order to study the effect of the R ratio for all cases the applied mixed mode ratio was constant at applied $\Delta K_{II}/\Delta K_I=0.45$.

Table 1 Applied loads for the thermoelastic tests

| R – ratio | Loads for thermoelastic measurements | | | |
|---|---|---|---|---|
| | $P_{xmin}$ [kN] | $P_{ymin}$ [kN] | $P_{xmax}$ [kN] | $P_{ymax}$ [kN] |
| 0 | 0.00 | 0.00 | 4.21 | 12.29 |
| 0.1 | 0.41 | 1.20 | 4.18 | 11.90 |
| 0.2 | 1.10 | 3.04 | 5.40 | 14.96 |
| 0.3 | 1.80 | 5.40 | 6.04 | 17.98 |
| 0.5 | 3.98 | 12.00 | 8.02 | 23.62 |
| 0.7 | 9.16 | 27.90 | 13.12 | 39.50 |

Thermoelastic data was collected from the specimen surface around the crack tip using a zoom lens in wide - angle position, and the parameters of data acquisition were: integration time: 3.25 min, electronic shutter: 98 %. The surface of the specimen was sprayed with matt black paint in order to provide uniform emissivity.

The thermoelastic signal was calibrated using two orthogonal strain gauge rosettes bonded on the opposite side to the data collection, in a region of constant stress. All the test parameters (frequency, integration time, electronic shutter, zoom lens) were the same for the calibration test and for the thermoelastic measurements around crack.

The stress intensity factor ranges for each load condition were determined using the method developed by Tomlinson et al [10]. A Newton – Raphson iteration combined with the least squares approach was used to fit the equations describing the stress field around crack tip, based on Muskhelishvili's approach, to the thermoelastic data. The quality of the fit of the stress field equations to the experimental data is expressed by two statistical parameters, which are the mean and variance of the squared residuals.

The thermoelastic map obtained from each scan was interrogated at a number of points on radial lines radiating from the crack tip between an inner and an outer limit. The inner limit should mask the plastic, triaxial and non-adiabatic effects around the crack tip. The outer limit represents the maximum extension of the singularity-dominated zone [10]. Therefore, the data should be taken from a region governed by the laws of linear elastic fracture mechanics.

### *Replica Method*

The extent of closure was evaluated using the replica method. Replica material (acetate) of 0.1 mm thickness was used. The surface replicas were taken by spraying acetone on the specimen and then sticking replica material to the specimen. The acetone softens the acetate so that the image of the crack is reproduced on the replica.

For the half crack length of 9 mm the replica measurements were performed at the maximum and minimum load used for three of the thermoelastic measurements under predominantly Mode I conditions (the applied $\Delta K_{II}/\Delta K_I$=0.45) as in Table 2. The R ratios of 0.0, 0.2 and 0.5 were considered.

Table 2 Loads used for the replica measurements

| R – ratio | Replica R1 (minimum load) | | Replica R2 (maximum load) | |
|---|---|---|---|---|
| | $P_{xmin}$ [kN] | $P_{ymin}$ [kN] | $P_{xmax}$ [kN] | $P_{ymax}$ [kN] |
| 0.0 | 0 | 0 | 4.24 | 12.36 |
| 0.2 | 1.16 | 3.05 | 5.04 | 15.00 |
| 0.5 | 3.98 | 12.00 | 8.26 | 23.62 |

An optical image analysis system which links a microscope, a digital camera SONY CCM – M25CE and an image processing software was used to measure the relative displacements between the crack faces recorded by the replicas.
It was difficult to estimate the mode I crack closure ratio and mode II locking ratio at the crack tip itself, however some measurements of crack closure and crack locking effects were made near to the crack tip.

## Results

Figs. 3 and 4 show the theoretical solution of the stress intensity factor ranges $\Delta K_I$ and $\Delta K_{II}$, the experimental values determined by thermoelasticity and the effective values of the mode I stress intensity factor calculated with equations (4) and (5) from the replica measurements. All data are normalized with the theoretical values.

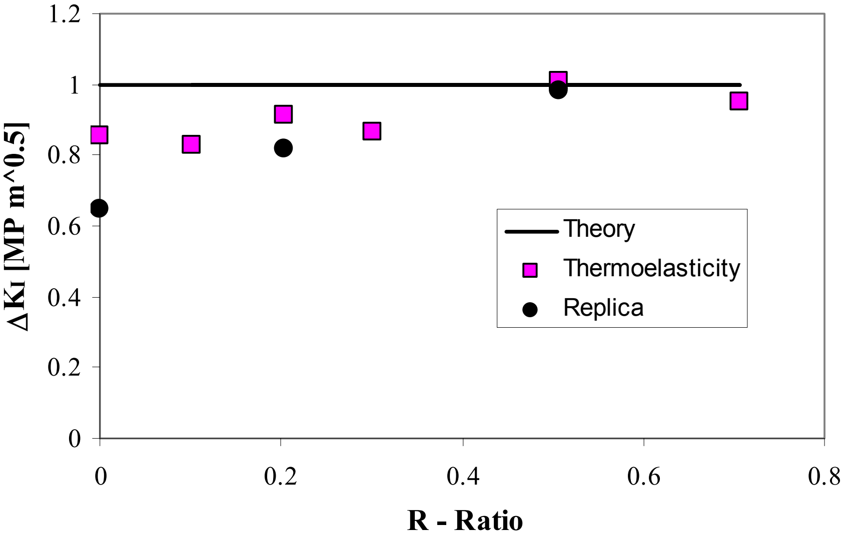

Figure 3. Theoretical, experimental and effective variation of the stress intensity factor $\Delta K_I$ against R – ratio, for an applied $\Delta K_{II}/\Delta K_I$=0.45

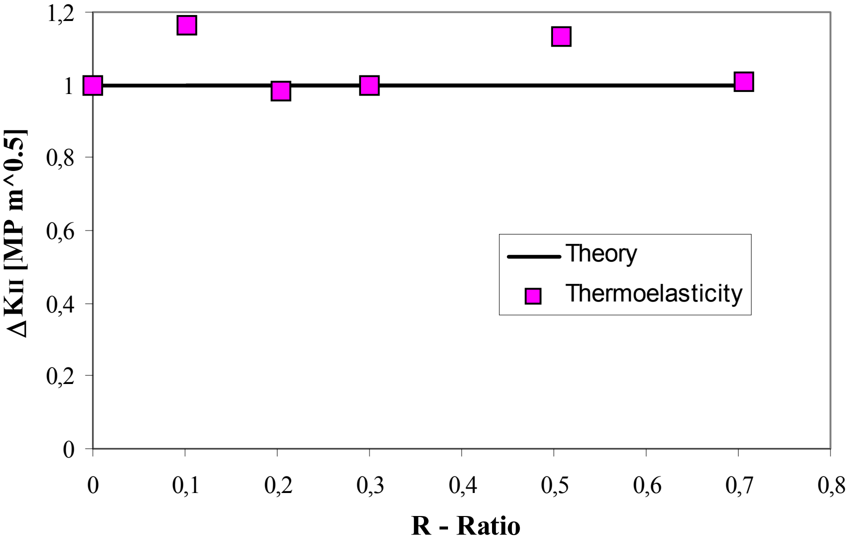

Figure 4. Theoretical and experimental variation of the stress intensity factor $\Delta K_{II}$ against R – ratio, for an applied $\Delta K_{II}/\Delta K_I$=0.45

The surface replicas were used to measure the opening displacements, but not the sliding displacements due to the very small amount of sliding displacement produced by the predominantly mode I applied loads. The measured maximum and minimum opening displacements from the replicas were higher than the theoretical ones. This can be explained by the plastic deformations left by the successive loading cycle used for crack propagation. The thermoelastic measurements were performed at lower applied loads in order to prevent the crack branching during the data acquisition.

It is obvious from Fig. 3 that the closure effect appears for R – ratio values smaller than 0.5 and is not present above this value because the minimum applied load of the cycle is large enough to completely open the crack.

The comparison between the theoretical, the experimental (obtained by thermoelasticity) and the effective values (obtained from replicas method) of the stress intensity factor $\Delta K_I$ highlights that the experimental results obtained by thermoelasticity represents the driving force for crack propagation. However, the experimental values of the stress intensity factors obtained by thermoelasticity are below the theoretical ones but above the effective values obtained taking into account the closure using the replicas, Fig. 3. A possible explanation of this is that the closure effect is over estimated as suggested by Sadananda et al [11]. Further investigations need to be performed to check if the effective stress intensity factor based on the concept of partial crack closure by Donald et al [12] fit better with the experimental values obtained by thermoelasticity.

## Conclusions

Effective stress intensity factors for a mixed mode crack, propagated using a successive loading cycle, have been evaluated using thermoelasticity and surface replicas. A sinusoidal loading cycle with applied $\Delta K_{II}/\Delta K_{I}=0.45$ was used in order to determine the stress intensity factors by TSA. It can be seen that TSA could became a useful tool for investigating the crack closure effects. The result for the stress intensity factor range represents the crack driving force.

## Acknowledgements

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