THERMOELASTIC INVESTIGATIONS FOR FATIGUE LIFE ASSESSMENT

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Abstract

Thermoelastic data was collected from sharp slots in biaxially loaded steel specimens and the stress intensity factors ΔK_I and ΔK_{II} determined. Experiments of this type have not been attempted previously and the results were within 10% of theoretical predictions. The mixed-mode stress intensity factors were also determined from fatigue cracks under similar loading conditions and these results exhibited the symptoms of crack closure, since the experimental stress intensity factors were depressed compared to the theoretical prediction.

Introduction

The stress intensity factor value obtained from thermoelastic analysis is equal to the range of the stress intensity factor that occurs at the crack tip due to the applied cyclic load. This allows the actual crack driving force to be experimentally determined rather than being inferred from maximum and minimum stress intensity factors, which is the case with other experimental techniques. The background to crack analysis using thermoelasticity has been documented previously [1] and will not be repeated here.

Although accurate analyses have been performed for opening mode cracks and slots, only limited progress has been made for the determination of stress intensity factors for mixed-mode cracks using thermoelastic techniques [1-4]. The most recently published data on the subject [2] shows good agreement between theory and experiment for both K_I and K_{II} for central slots and cracks, and edge slots. However for mixed-mode edge cracks the differences between theory and experiment were up to 30%. The majority of the published data has been for cracks under predominantly mode I loading and the only data for predominantly mode II loading showed a difference between theory and experiment of up to 40% [1]. Although it is known that the majority of mixed-mode cracks found in engineering components eventually propagate as mode I cracks, in some cases such as turbine blades and rolling contact fatigue in rails, mixed-mode loading continues to dominate. Therefore this area of research is of importance and further testing is required.

All published experiments generate the mixed-mode conditions at a crack tip with the use of tensile loading of a plate containing a sharp slot or crack at an angle to the direction of loading. Biaxial loading of a sample has not been considered. The analysis of crack tip stress fields using thermoelasticity has been hampered also by the fact that, until recently, it has only been possible to use thermoelasticity to investigate crack tip parameters of stationary cracks, due to the limitations of single-point thermoelastic instruments such as SPATE (Stress Pattern Analysis by Thermal Emission). New instruments such as Deltatherm, which contain an array of detectors, enable thermoelastic data to be recorded in real time.

Therefore, it has been proposed that a thorough investigation be performed into the thermoelastic determination of mixed-mode crack parameters, with the aim of further developing a non-contacting experimental method for the assessment of fatigue cracks.

A series of experiments has been performed to determine stress intensity factors at the tips of cracks and slots under biaxial fatigue loading using a recently developed algorithm which utilizes thermoelastic data [1]. A new computer interface has been written to accept data from both SPATE and Deltatherm. Two areas from these tests will be discussed here. Firstly the determination of stress intensity factors from sharp slots under predominantly mode II loading. Secondly an investigation into the determination, using thermoelasticity, of stress intensity factors from fatigue cracks grown under biaxial loading conditions.

Stress intensity factors from sharp slots

Since the aim of the experiments was to evaluate the accuracy of the technique in determining stress intensity factors using thermoelastic methods, it was considered important to eliminate any other factors which may introduce errors into the results. From previous work it had been found that fatigue cracks may exhibit crack closure and this had the effect of depressing the value of ΔK calculated [5]. So in order to prevent these effects masking the accuracy of the technique, data was first collected from around a sharp slot rather than a fatigue crack.

The specimens were made from 150M36 steel and were a cruciform shape with a central spark-eroded slot inclined at 45°, of length $2a = 6$ mm, as in Figure 1. One side of the specimen was polished to enable any crack growth to be easily monitored using an optical microscope. The other side of the specimen was sprayed with a thin coat of matt black paint to increase emissivity and to obtain a uniform thermoelastic signal. The load was applied using a 100 kN Denison Mayes Biaxial Testing Machine. The shape of the load waveforms and the response of the load cells were monitored using two oscilloscopes and the reference signal was taken from one of the load cells.

A sine load was applied at a frequency of 5 Hz and a load ratio, R = 0 along the two axes of the specimen in order to give the ratios of applied $\Delta K_{II}/\Delta K_I$ approximately equal to 0, 0.5, 1, 1.5, 2, and 2.5. At each load setting the thermoelastic data was recorded around the slot tip using a DeltaTherm 1550 system. Each data map was integrated over 4 minutes and a typical map is shown in Figure 2. The thermoelastic signal was calibrated using two orthogonal strain gauges located as in Figure 1. The signal was calibrated at regular intervals throughout the test programme since any change in ambient temperature can change the calibration constant. The stress intensity factor ranges, ΔK_I and ΔK_{II}, were determined from each set of data using a method based on the Muskhelishvili approach[1]. It was essential that the data was collected from within the singularity dominated zone and outside the plastic zone at the crack tip and this was ensured by incrementally masking the data close to the crack tip until linearity was reached. The slot was further extended to 2a = 12 and 18 mm and the same procedure repeated at each of these slot lengths.

The results of these tests are shown in Figure 3. The experimental data for both ΔK_I and ΔK_{II} compare well with the theoretical estimations for the longer slits. For the shortest slit, the linear elastic area in which the data could be collected was relatively small and this was thought to be the reason for the less favourable comparison with theory.

Fatigue crack growth

A series of tests were performed to determine the stress intensity factors from fatigue cracks under true mixed-mode loading using thermoelasticity. It is believed that no data of this type has been published previously. In order to prevent branching of the propagating crack, a successive load cycle which was developed by Brown et al [6,7] was applied. In this cycle, a mode I load is applied and removed before the fully reverse mode II cycle is applied, as shown in Figure 4. An attempt was made to record thermoelastic data under this load cycle, however it was found that the reference signal required for correlation with the thermal emission was crucial to successful data collection. The most common reference signal used in thermoelastic tests is the sine wave from which it is straightforward to calculate the change in the sum of the principal stresses. However under the successive load cycle difficulty was encountered in correlating the unusual reference signal with the temperature signal. This area of research is still under investigation. The current solution to this problem is to grow the crack under successive loading and then record thermoelastic data under a sine load similar to that used for the specimens containing slots. A typical thermoelastic scan is shown in Figure 5. The mode I stress intensities obtained from this fatigue crack data were comparable to those predicted by theory, but the mode II values were 10% lower in this case. For other cracks, the stress intensities were up to 30% lower than those predicted from theory. It was considered that these results exhibited the symptoms of crack closure, since the experimental stress intensity factors are depressed compared to the theoretical prediction [5] and further investigations into this phenomenon under biaxial mixed-mode loading are underway.

Conclusions

It has been shown that accurate stress intensity factors may be calculated from thermoelastic data under both mode I and mode II dominant, mixed-mode loading conditions.

Investigations have taken place into growth of mixed-mode cracks and recording data as the fatigue crack grows. Data can be recorded under a sine load, however the issue of successive loading is still under investigation.

Acknowledgements

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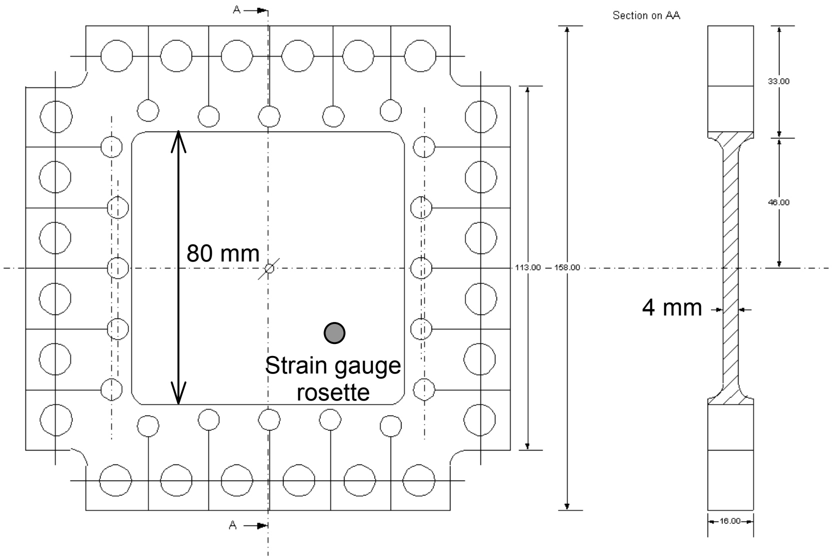


Figure 1 The cruciform specimen used for thermoelastic tests, showing the position of the strain gauge rosette and the spark eroded notch

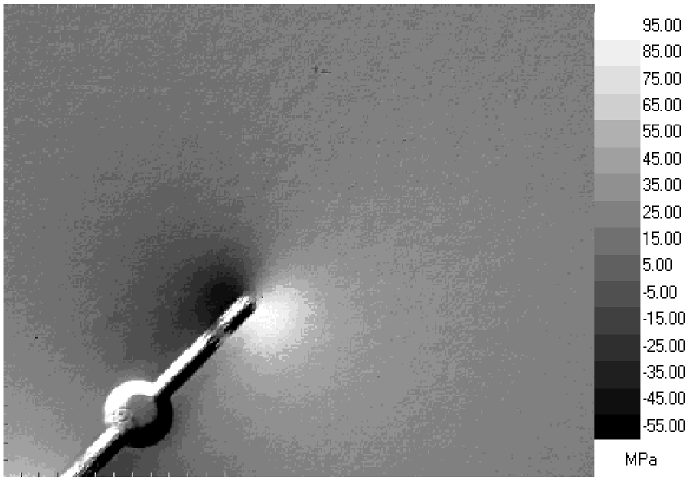
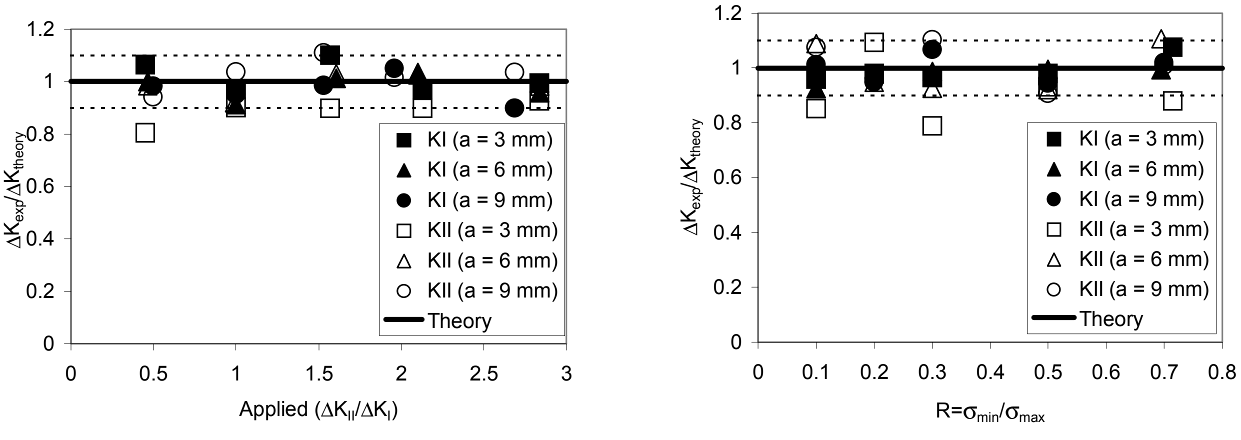


Figure 2 Showing the thermoelastic signal around a notch 2a = 12 mm, applied $\Delta K_{II}/\Delta K_I$ = 2; R = 0



(a) (b)

Figure 3 Plots of the normalised stress intensity factor versus (a) increasing applied $\Delta K_{II}/\Delta K_I$ at R = 0 and (b) increasing R ratio at $\Delta K_{II}/\Delta K_I$ = 0.5

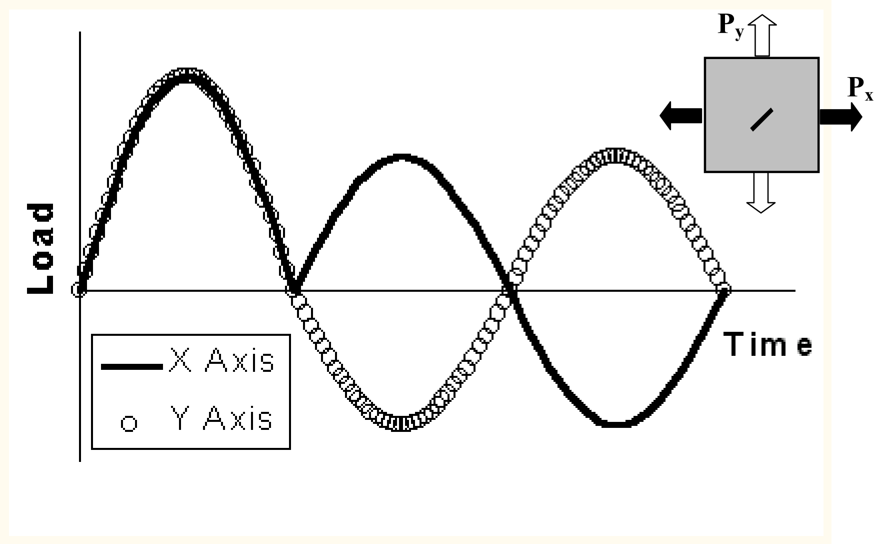


Figure 4 Successive load cycle for biaxial fatigue crack growth

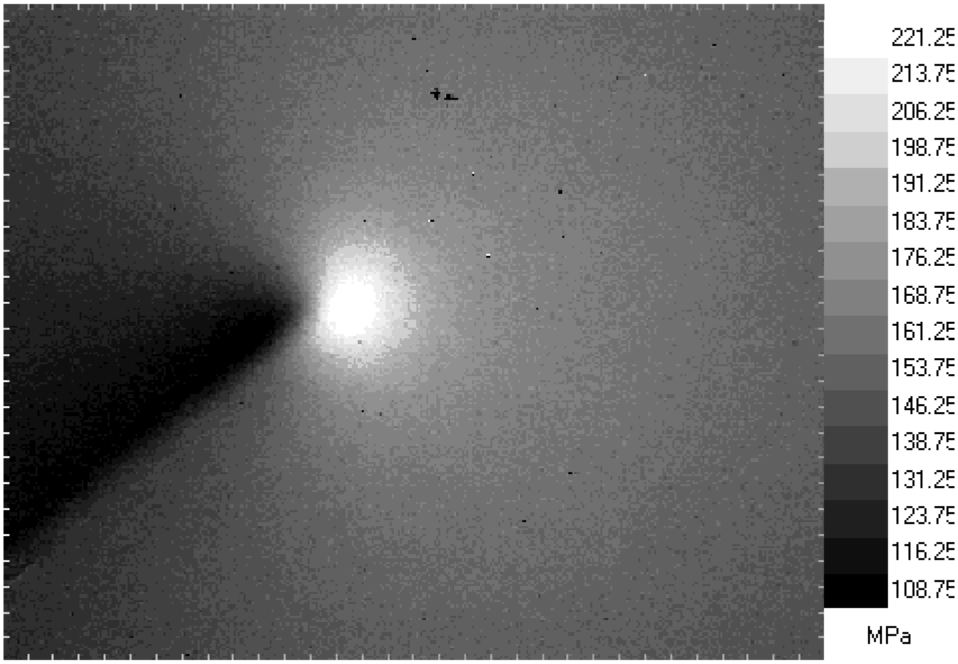


Figure 5 Thermoelastic data around a fatigue crack (a = 23.5 mm) under a mixed mode loading, $\Delta K_{II}/\Delta K_I = 0.43$, R = 0
Experimental results: $\Delta K_I = 4.170$ MPa√m; $\Delta K_{II} = 1.646$ MPa√m
Theoretical results: $\Delta K_I = 4.256$ MPa√m; $\Delta K_{II} = 1.829$ MPa√m
Difference between theory and experiment: $\Delta K_I = 2\%$; $\Delta K_{II} = 10\%$