Measurement and analysis of fatigue crack deformation on the macro- and micro-scale

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ABSTRACT. The paper describes an experiment which performs in-situ loading of a small compact tension specimen in a scanning electron microscope. Images are collected throughout a number of successive loadincg cycles. These are then analysed using digital image correlation (DIC) in order to produce crack flank displacements as a function of load. This data is then compared with a simple elastic approach, and it is concluded that elastic-plastic analysis is required in order to accurately capture the displacements close to the crack tip. A simple approach due to Pommier and Hamam is therefore employed. This gives a better representation of the data, but predicts a variation of crack tip displacement, ρ, which is difficult to explain from a physical perspective. The need for a more sophisticated analysis of the data is therefore highlighted.

KEYWORDS. Crack Tip Displacements; Digital Image Correlation; Elastic-Plastic Fracture Mechanics.

INTRODUCTION

The understanding of fatigue crack propagation is an essential pre-requisite to safe operation of many engineering structures and systems. Most damage tolerant life prediction approaches are based on the application of experimental crack propagation data to the real system. For example, the Paris Law [1] is frequently used to apply experimental da/dN vs delta K data to service loads and to the system geometry. However, most experimental data is obtained for constant amplitude loading whereas engineering systems frequently experience non-uniform loading. The presence of history effects in fatigue crack propagation is well known and this means that life prediction under service loading conditions remains a challenging problem in many cases. A detailed understanding of the crack tip response to a range of load histories is the key to improvements in this area.

Recent work at Oxford has been presented at the Forni di Sopra [2,3] and Malaga [4] IJ Fatigue/FFEMS workshops and has concentrated on the use of digital image correlation to measure and analyse the displacements fields around a crack. Our work has made use of a long-range optical microscope to examine deformations in a region within 0.5 mm of the crack tip. Analysis of these deformations has allowed stress intensity factors to be calculated and crack closure assessed. In the current paper we will seek to extend this approach by reporting measurements taken during in-situ loading of a fatigue crack in a scanning electron microscope. This permits more detailed examination of the displacement field in the neighbourhood of the crack tip.

MACROSCOPIC MEASUREMENTS

Our earlier work on the measurement of crack tip displacement fields has employed a long range microscope, focused on an area approximately 600 x 400 μm close to the crack tip [2]. A number of images were captured at intervals during the loading cycle, and digital image correlation carried out using a public domain Matlab script produced by Erbl et al [5]. The data obtained were processed in a number of ways, but a particularly convenient means of presenting the results is to determine the experimental stress intensity factor by comparing the measured crack tip opening displacements with those predicted by an elastic model. The crack flank displacements for an elastic crack are given by

$$u_i = \pm \frac{4K_I}{E}\sqrt{\frac{r}{2\pi}} \tag{1}$$

where K_I is the elastic stress intensity factor, E is Young's Modulus, and r is the distance from the crack tip. Hence, a plot of u_i against $\sqrt{r}$ should yield a straight line and the stress intensity factor can be extracted from the gradient. Fig. 1(a) shows results from a typical experiment conducted under constant amplitude loading. The dotted line represents the theoretical variation of elastic stress intensity factor with load for the size and type of specimen used (a standard Compact Tension specimen). It will be seen that the experimental results broadly follow the theoretical ones, and that the slope of the load vs K line is very similar. However the experimental results exhibit an offset, and the experimental K values are lower than predicted. This may be interpreted as being due to plasticity induced crack closure, which causes superposition of an additional negative residual K term (K_r). It can be seen from the results that the crack does not open until about 0.5kN of applied load (approximately 25% of the maximum load).

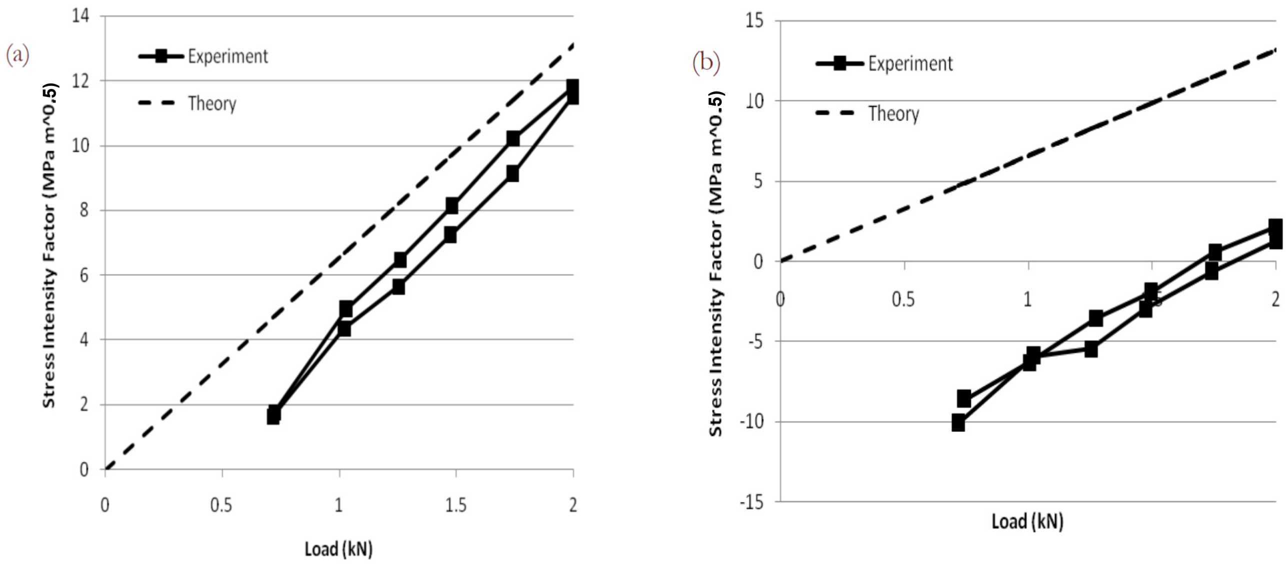

Figure 1: Variation of measured stress intensity factor with load for specimen CTF6 [4] (a) After constant amplitude loading and (b) Immediately after an overload.

Fig. 1(b) shows results from the same specimen immediately after a 50% overload cycle. Although the slope of the experimental line remains parallel to the theoretical one, these results exhibit some unusual features. In particular, negative K values are measured, which at first sight appears physically unreasonable. However, if there is a large plastic opening displacement at the crack tip, a crack shape of this form is possible, and closer inspection of the experimental results suggests that this is the measured deformation. The results presented here were obtained by analysing the relative displacement of 5 pairs of points from the recorded images, and the first pair is approximately 100 μm from the crack tip. In order to investigate the crack tip deformation in more detail, a novel experiment was therefore proposed, which involved in-situ loading of a small specimen in the scanning electron microscope.

MICROSCOPIC MEASUREMENTS

Experiments were conducted in the Laboratory for In-situ Microscopy and Analysis (LIMA), which is part of the Solid Mechanics and Materials Engineering Group in the Department of Engineering Science at the University of Oxford. The imaging device used was a Carl Zeiss Evo LS15 VP-Scanning Electron Microscope. The chamber of the SEM was large enough so that in-situ testing could be performed with a Deben testing stage similar to that shown in Fig. 2. A 5 kN load cell was attached to the testing stage and an extension rate of 1:25 mm/min was used for this testing. Computer software was used to set the drive parameters and to collect live data on the force applied and extension from the testing stage during loading. The specimen design was a modified compact tension specimen and the material used was aluminium alloy with a yield stress of approximately 320 MPa.

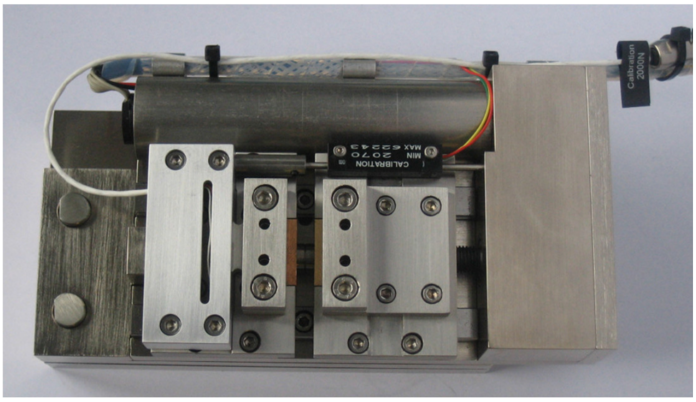

Figure 2: Deben In-Situ Microtest tensile & compression stage with a 2 kN load cell.

The specimen was pre cracked before being loaded on the Deben stage with the same tensile testing rig used for macroscopic specimen loading. The specimen was loaded at a frequency of 5 Hz, signicantly faster than could be achieved with the Deben testing stage. 17,000 cycles were applied to the specimen to grow the crack approximately 7mm at the same loads to be used for later testing on the Deben stage. Once pre cracked and placed on the Deben testing stage, the crack was grown slightly further to approximately 7:2mm before in-situ SEM images were captured. The maximum applied load was 1:25 kN and the minimum load was 0:125 kN, giving an R ratio of 0.1. A single overload cycle of 1:875 kN was applied as part of the experiment, but only constant amplitude results will be reported here.

Imaging was carried out using a secondary electron detector at an operating voltage of 15kV and working distance of 9mm and images were captured at a resolution of 3072 x 2304 pixels over an image area of approximately 215 μm x 161 μm. Images were taken every 0:125 kN to give 19 images for a complete cycle between 0:125 kN and 1:25 kN. The images were taken with the crack in approximately the same location within the image. To do this, the load was held at the desired value while the microscope stage and the electron bean were aligned with the crack before the next image was captured. Once images were collected, a series of sets of points were selected on either side of the crack and relative displacement was obtained using the DIC algorithm [5] for pairs of points within each set. Each set of points contained 2000 points (with 200 points in the horizontal x direction and 10 in the y direction), see Fig. 4. The procedure adopted therefore produced relative displacement in the y direction at 200 different x direction distances from the crack tip over the series of images. The points were distributed from close to the crack tip up to a distance of approximately 150 μm along the crack flanks. Displacement data could have been obtained with fewer points, however a large number of points were selected to reduce the chance that badly tracked points may influence the results. Due to the high resolution of the images, displacements around the crack were quite large at high loads when measured in pixels. Therefore, in order to better track the points, the area surrounding each point that is used for image correlation was increased from a 30 x 30 pixel square used in earlier work up to a 200 x 200 pixel area.

In addition to the images taken to analyse displacements around the crack tip, images of the full crack were captured in order to measure crack length for calculation of K. The loading was paused at the highest load of a loading cycle (1:25 kN), magnification reduced and a series of images taken along the full crack. These images were then fitted together using normalised 2-D cross-correlation with the Matlab Image Processing Toolbox to give an image of the full crack length to measure from. An example is shown in Fig. 5.

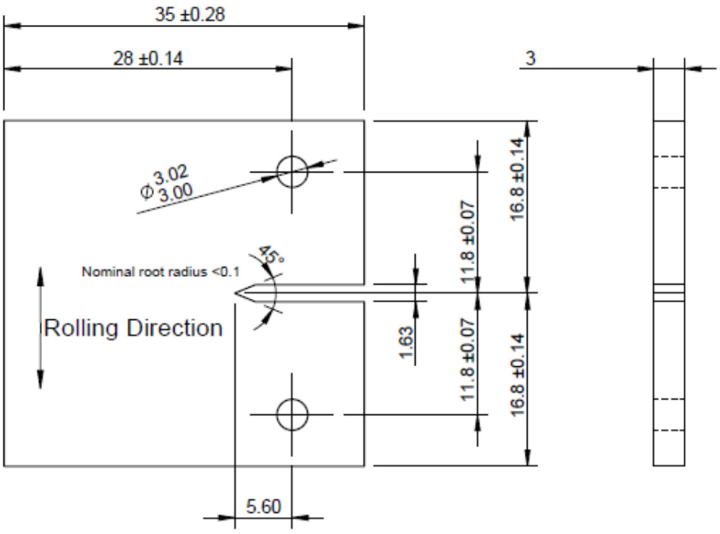

Figure 3: Dimensions (in mm) of specimens used for in-situ SEM testing. Specimens were cut from a sheet of aluminium alloy 6082-T6.

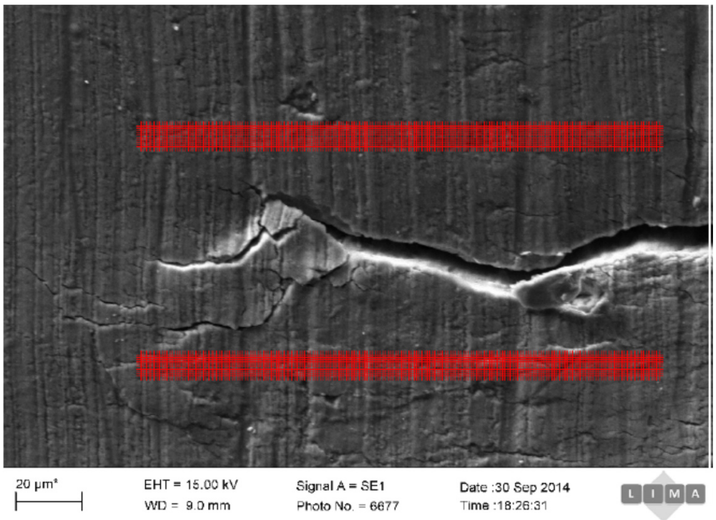

Figure 4: Typical image collected from the experiment at a load of 1:25 kN. Sets of points are selected on either side of the crack to measure displacements.

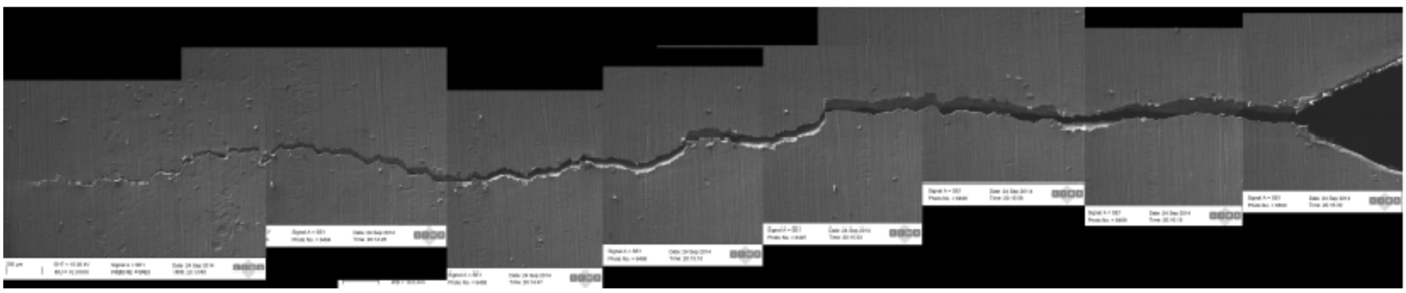

Figure 5: Series of images aligned to give an image of the full crack length at a load of 1:25 kN

RESULTS

As shown in Eq. (1), if an elastic model is assumed, a plot of log u_y vs. log r should be expected to give a straight line with a gradient of 0:5. This can then be used to obtain an experimental measurement of K. Fig. 6 shows a typical set of results obtained with a crack length (Measured from the notch tip) of approximately 7:2 mm. It will be apparent that the data falls into two distinct sets. Points more than about 25μm from the crack tip seem to give a good straight line fit, although the slope differs from 0.5 for all but the highest load. Points closer to the crack tip give a much shallower slope. It is instructive to compare this distance with the Irwin [6] estimate of plastic zone size.

$$r_p = \frac{1}{2\pi}\left(\frac{K}{\sigma_y}\right)^2 \tag{2}$$

where σ_y is the yield stress of the material. This gives a figure of $r_p \approx 330$ μm, for the maximum load, although the cyclic plastic zone size will only be about a quarter of this value. Hence, whilst an initial elastic analysis sheds some useful light on the problem, an elastic/plastic analysis is likely to be more appropriate at this level of plasticity. In common with our earlier work we will choose to employ a model proposed by Pommier and Hamam [7]. This partitions the total displacement field into elastic and plastic components. In terms of displacements along the crack flanks, the model leads to

$$u_y = \frac{8K_I}{E}\sqrt{\frac{r}{2\pi}} + \rho \tag{3}$$

i.e., that a constant plastic displacement component ρ is added to the elastic solution given in Eq. (1). In practice, of course the plastic deformation at the tip is unlikely to give rise to a constant deformation along the crack flanks, but close to the tip, Eq. (3) is a reasonable approximation. Plotting u_y against $\sqrt{r}$ should give a straight line with a gradient related to K and an intercept of ρ. The data in Fig. 6 is re-plotted in this way in Fig. 7.

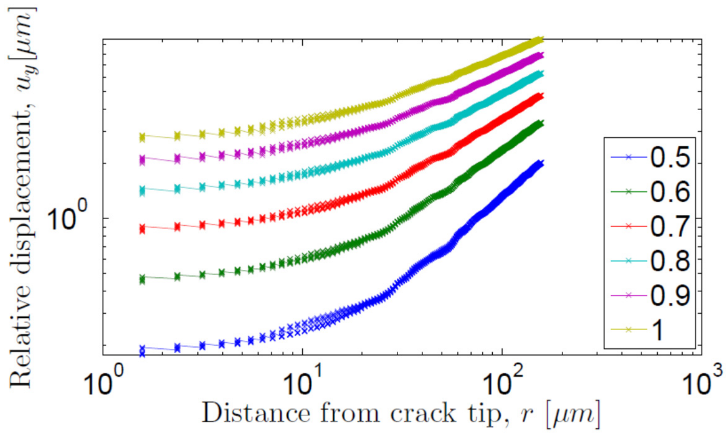

Figure 6: Variation of relative displacement (u_y) with distance from the crack tip (r) at five different values of load (P/P_{max}) during the loading phase of a loading cycle.

From Fig. 7 it can be seen that the data gives a good straight line fit for $\sqrt{r} > 5$ μm$^{0.5}$, i.e. $r > 5$ μm. The data can be used to plot the loading history in K vs ρ space. Pommier and Hamam [7] have suggested that the relationship should look like that shown schematically in Fig. 8. In particular, they suggest that in cyclic loading, such as the loop indicated by (C) in the figure, there is little change in ρ in the first part of each cycle. This observation can be used to explain the existence of a threshold ΔK in fatigue. It is postulated that, until the application of a certain level of ΔK, there is very little cyclic plasticity (characterised by $\Delta\rho$) and the crack does not grow. The experimental data is plotted in Fig. 9a, where it can be seen that the experimental loops are similar in general form to those predicted in [7]. However, there is significant variation in ρ throughout the cycle. In particular, ρ seems to continue to increase for a while after load reversal at maximum load (and similarly decrease for a while at the minimum load reversal). This feature is difficult to explain physically, and may simply be an artefact of the straight line fitting to the u_y vs $\sqrt{r}$ data. This is illustrated in Fig. 10, where it can be seen that fitting a straight line for the data corresponding to $P/P_{max} = 0.5$ leads to a negative value for ρ. This may be thought to be physically inadmissible, although it should be remembered that the datum image for the DIC is that at minimum load, rather than corresponding to the undeformed material. Hence, only variations in ρ are measured, not the absolute value.

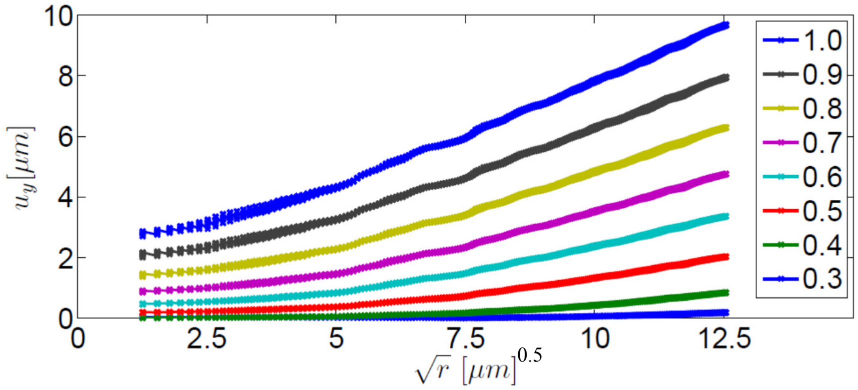

Figure 7: Variations of relative displacement (u_y) with distance from the crack tip (r) at eight different values of load (P/P_{max}) during the loading phase of a single cycle.

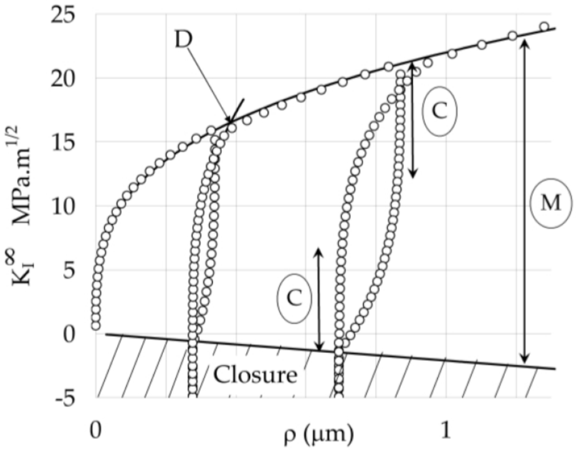

Figure 8: Pommier and Hamam's suggested behaviour in K vs ρ space [7]. Cyclic behaviour is indicated by the loop (C).

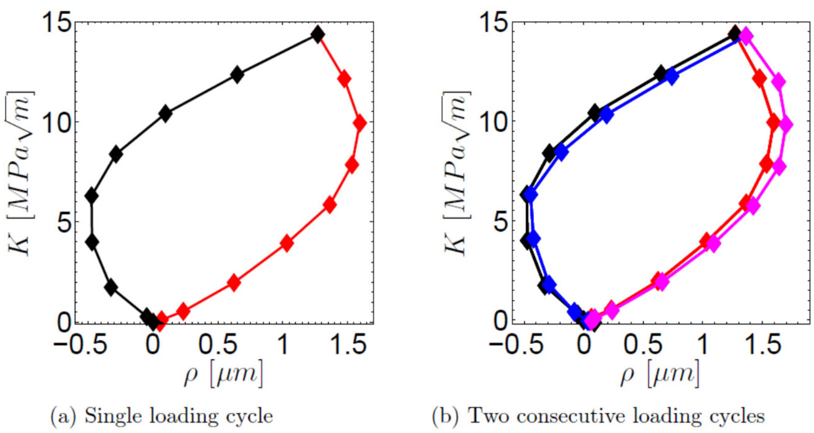

Figure 9: Variation of K and ρ for loading cycles. Loading phase [black] and unloading [red] are shown for the first cycle. In Fig. 9b a second cycle of loading [blue] and unloading [magenta] is included.

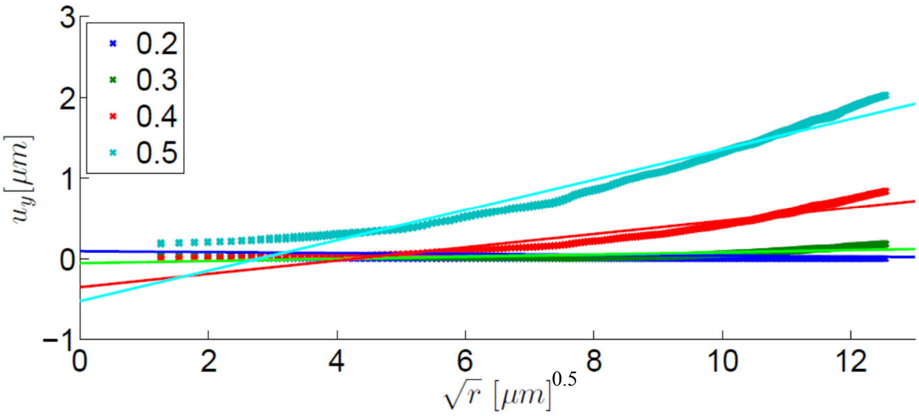

Figure 10: Variations of relative displacement (u_y) with distance from the crack tip (r) at four different values of load (P/P_{max}) during the initial loading phase of a single cycle. A line of best fit produced with a least squares method is included for each load in the matching colour.

Finally, in Fig. 9b, data from two consecutive loading cycles are presented. It will be seen that the cycles are very similar, illustrating the reproducibility of the technique. However, a small increase in ρ can be seen between the first and the second cycle, corresponding to the accumulation of damage at the crack tip and, possibly, crack tip extension.

CONCLUSIONS

The paper has presented a technique for in-situ loading of a small compact tension specimen in a scanning electron microscope. It has proved possible to take high quality images of the area close to the crack tip during complete loading cycles. Constant amplitude data are reported here, but images from a single overload cycle have also been captured. Digital image correlation has been used to analyse the data using both an elastic and an elastic-plastic approach. Unsurprisingly, the elastic approach does not model the measured displacements well, particularly close to the crack tip. An elastic-plastic approach provides a better fit, but there are still deficiencies in capturing deformations close to the tip. This may be partly because the existence of the process zone at the tip affects the displacements measured at the grid locations, and these may no longer represent purely crack flank displacement. A more sophisticated elastic-plastic model is almost certainly in order to model the data more accurately, but the experiment had demonstrated the capability to measure displacements close to the crack tip which will be useful in calibrating other models.

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