Application of digital image correlation to the investigation of crack closure following overloads

D. Nowell* and P.F.P de Matos

* Department of Engineering Science, University of Oxford, Parks Road, Oxford, OX1 3PJ, UK.

Instituto Superior de Entre Douro e Vouga, Rua António de Castro Corte Real, 4520-909 Santa Maria da Feira, Portugal.

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Abstract

This paper describes a set of fatigue experiments carried out on 6082 Aluminium CCT specimens. Crack propagation rates and crack opening loads were measured before and after a single overload in an otherwise constant amplitude loading sequence. Crack retardation was observed after the overload, and this was more significant in thin (3mm) specimens than in thick (25 mm) specimens of otherwise similar geometry. Digital image correlation and conventional strain gauges were used to monitor crack closure, and it was found that surface closure levels were similar in the two thicknesses of specimen. However, the thick specimens showed lower closure levels as detected by the strain gauges. This observation is consistent with the lower levels of crack retardation observed. A plane stress strip-yield model of crack closure was employed to simulate the experimental loading cycle and this showed qualitatively similar behaviour to that observed on the surface of the specimens.

Keywords: Fatigue; Crack Propagation; Crack closure; Overloads; Digital Image Correlation

1. Introduction

The concept of fatigue crack closure has been a stimulus for experimental work and modelling since Elber’s initial discovery of the phenomenon in the 1970s [1]. Initially there was a significant prospect that closure might explain some of the load-ratio and variable amplitude effects on crack propagation rate observed across a wide range of materials. However, this early promise remains largely unfulfilled. Partly, this is due to the difficulty in measuring crack closure accurately in a practical situation. Often an indirect measurement needs to be taken and closure inferred from this (e.g. by detecting a compliance change in the specimen). However, recent advances in digital image correlation techniques mean that direct measurements of surface closure are now possible from ordinary digital images of the crack tip region [2] and without requiring complex experimental techniques such as moiré interferometry [3]. These experimental advances provide a convenient means of exploring a practical industrial problem. Many engineering components are subjected to fatigue loading, and probably the majority of them are subjected to non-uniform load cycles. In contrast, the majority of laboratory experiments are carried out under uniform amplitude loading. For a given application, it is impractical to test specimens following the precise
sequence of loading suffered by the component (even in cases where this is known). It is therefore important to
device reliable means of predicting performance under variable amplitude loading from an understanding of material
behaviour under constant amplitude load.

The problem can conveniently be divided into two parts: first, prediction of initiation life. Here, simple
procedures such as Miner’s rule of cumulative damage [4] can sometimes be used. However, more sophisticated
approaches are being developed. These include explicit crystal plasticity models at the microstructural length scale,
which can be used to examine the accumulation of plastic strain under different cyclic loading conditions [5]. In this
paper, however, we intend to concentrate on the second aspect of the problem, the prediction of crack growth rates
once a macroscopic crack has nucleated. This is, of course, an important aspect of a damage tolerant assessment of
component life [6]. The Paris Law [7] is often used to predict growth rates as a function of applied stress intensity
factor range, and load-ratio corrections are sometimes employed [8]. However, this approach ignores load history
effects and it is well-known that these can be important [9]. For example, a large overload can retard fatigue crack
propagation caused by subsequent cycles and lead to an enhanced fatigue life.

The ultimate goal of research in the area of variable amplitude loading must be the prediction of fatigue crack
propagation rates for different aspect ratios of crack under entirely general loading conditions. However, this goal
represents a considerable advance from our current state of understanding and it is therefore appropriate to start with
a more modest objective. A number of authors have therefore examined the application of a single overload in an
otherwise constant amplitude loading regime (e.g. [10]). Crack growth rates can be measured before, during and
after the overload and compared to the predictions of models such as Newman’s strip yield representation of
plasticity-induced closure [11]. In the current paper, we aim to extend our previous work on the use of digital image
correlation to examine crack closure under constant amplitude loading conditions [2]. Closure levels and crack
propagation rates will be examined for compact tension test pieces subjected to constant amplitude loading with a
single overload. Measured crack opening loads will be compared with predictions from a simple strip-yield closure
model [12], similar in concept to Newman’s.

<table>
<thead>
<tr>
<th>Nomenclature</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a )</td>
<td>Crack length, measured from notch tip</td>
</tr>
<tr>
<td>( a' )</td>
<td>Crack length, measured from loading axis (see Fig. 1a)</td>
</tr>
<tr>
<td>( E )</td>
<td>Young’s Modulus</td>
</tr>
<tr>
<td>( P )</td>
<td>Applied load</td>
</tr>
<tr>
<td>( P_{\text{max}} )</td>
<td>Maximum applied load</td>
</tr>
<tr>
<td>( P_{\text{op}} )</td>
<td>Crack opening load</td>
</tr>
<tr>
<td>( u_y )</td>
<td>Displacement in y-direction</td>
</tr>
<tr>
<td>( W )</td>
<td>Width of CT specimen (W= 60 mm)</td>
</tr>
<tr>
<td>( x, y )</td>
<td>Horizontal and vertical co-ordinates</td>
</tr>
<tr>
<td>( \nu )</td>
<td>Poisson’s Ratio</td>
</tr>
<tr>
<td>( \sigma_u )</td>
<td>Ultimate tensile strength</td>
</tr>
<tr>
<td>( \sigma_y )</td>
<td>Yield strength</td>
</tr>
</tbody>
</table>
2. Experiments

2.1. Experimental Configuration

The work described here forms part of a larger series of experiments, investigating the effect of specimen thickness on fatigue crack closure and crack propagation behaviour. The results for constant amplitude loading have already been reported [2] and we will concentrate here on the overload tests. Compact tension specimens were manufactured from 6082 Al alloy with the chemical composition given in Table 1. The alloy was age-hardened according to the T6 heat treatment and relevant mechanical properties are given in Table 2. Dimensions are shown in Fig. 1a. Three different thicknesses of specimen were used: 3, 10, and 25 mm. Figure 1b shows a schematic of the overall experimental configuration. Specimens are mounted in a servo-hydraulic fatigue testing machine and are instrumented in a number of ways. A ‘back face’ strain gauge is fitted, together with a crack mouth clip gauge (or ‘Elber gauge’). In each case these are used for conventional monitoring of crack closure by detecting differences in specimen compliance. In addition, an optical system is used to view one side of the specimen for subsequent digital image correlation calculations. This consists of a commercial webcam (chosen for low cost and ease of interfacing) coupled to a ‘Questar’ long range microscope. This combination gives a resolution of 640 x 480 pixels over a field of view of 595 x 446 μm. Hence, each pixel corresponds to an area of 0.93 x 0.93 μm. The microscope and camera are mounted on a translational stage with digital position readouts and can therefore be used to measure overall crack size and propagation rates. The other side of the specimen is viewed with a conventional video camera. This allows optical measurement of crack length and allows calculation of an average (through thickness) value.

Table 1. Chemical composition of Aluminium alloy 6082.

<table>
<thead>
<tr>
<th>Si</th>
<th>Fe</th>
<th>Cu</th>
<th>Mn</th>
<th>Mg</th>
<th>Zn</th>
<th>Ti</th>
<th>Cr</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.7-1.3%</td>
<td>0.5%</td>
<td>0.1%</td>
<td>0.4-1.0%</td>
<td>0.6-1.2%</td>
<td>0.2%</td>
<td>0.1%</td>
<td>0.25%</td>
<td>Balance</td>
</tr>
</tbody>
</table>

Table 2. Mechanical Properties of Aluminium alloy 6082 T6.

<table>
<thead>
<tr>
<th>Young’s Modulus, E (GPa)</th>
<th>Poisson’s ratio, ν</th>
<th>Yield stress, σy (MPa)</th>
<th>Ultimate Tensile Strength, σu (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>70</td>
<td>0.3</td>
<td>323</td>
<td>330</td>
</tr>
</tbody>
</table>

Fig. 1. (a) specimen geometry; (b) experimental configuration.
2.2. Digital image correlation

The basic principles of digital image correlation are well-known (see, e.g. [13]) and space considerations preclude a detailed description of the method here. A number of images are captured, and the displacement of regions in each image are calculated relative to a reference image (e.g. the first in the series) by maximizing a normalized cross-correlation function. Whilst it is possible to evaluate ‘full-field’ displacements in this way, the process is computationally intensive, particularly when a large number of images need to be processed. For the current purposes it is sufficient to evaluate displacements at a number of pairs of positions (one location each side of the crack) at five different distances from the crack tip. This is shown schematically in Fig. 2a. A public domain Matlab routine written by Eberl and co-workers [14] was used to carry out the digital image correlation in the current study. Images were recorded at a constant framing rate of 30 fps whilst the specimen was cycled at a reduced frequency of 0.25Hz. 360 frames were extracted from each video, corresponding to three full cycles of loading and these were employed for the digital image correlation calculations. Figure 2b shows a typical captured image, illustrating the positions of the measurement points relative to the crack tip. A typical variation of relative displacement (i.e. displacement of the point $L_1$ on one side of the crack relative to the corresponding point on the other side) is shown in Fig. 3 for point pairs $L_1$ to $L_5$, located 100 to 500$\mu$m from the crack tip. It may clearly be seen that the behaviour is similar for each pair of points. For low loads there is no change in relative displacement, indicating that the crack is closed at this position, whereas for higher loads, there is a linear variation, showing that the crack is open. Points further away from the tip (e.g. $L_5$) open at lower loads than those which are closer (e.g. $L_1$), demonstrating that the crack ‘peels open’ from the mouth towards the tip.

Fig. 2. (a) schematic showing DIC measurement points; (b) Typical recorded image, showing position of crack tip and measurement points.

Fig. 3. Variation of relative displacement, $u_{x}^{\text{relative}}$ with normalized load, $P/P_{\text{max}}$. 
3. Results

A total of five overload experiments were carried out within a programme of 20 constant amplitude experiments [2]. Details of the experimental parameters used are given in Table 3. In each case, a crack was grown under constant amplitude loading at an R-ratio of 0.1 or 0.125, until its length exceeded 5mm. A single overload cycle was then applied, with 100% overload (i.e. the peak load of the overload cycle was twice that in the constant amplitude phase. Crack lengths were monitored optically before and after the overload in order to calculate the crack growth rates, and digital image correlation was carried out periodically to determine the crack opening load by examining the variation of relative displacement with load for the L1 pair of points, as shown in Fig. 3. Figure 4a shows the variation of crack length, a, with number of cycles for the 3mm specimens, compared to experiments where no overload was applied [2]. The retardation effect of the overload cycle can clearly be seen. Similar data for the 25mm thick specimen (CTT2) is shown in Fig. 4b. It will be apparent that the effect of the overload is much smaller in the thicker specimen. The medium thickness specimens (CTMT4/6) showed a similar effect, but with a retardation of 40000 to 80000 cycles, i.e. between the values observed for the ‘thin’ and ‘thick’ specimens.

Table 3. Parameters used for overload experiments.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Thickness, mm</th>
<th>Const amp loading, kN</th>
<th>R-ratio</th>
<th>100% overload</th>
<th>Fatigue life, N cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTF6</td>
<td>3</td>
<td>2.0</td>
<td>0.25</td>
<td>0.125</td>
<td>29500</td>
</tr>
<tr>
<td>CTF8</td>
<td>3</td>
<td>2.0</td>
<td>0.25</td>
<td>0.125</td>
<td>29000</td>
</tr>
<tr>
<td>CTMT4</td>
<td>10</td>
<td>6.0</td>
<td>0.60</td>
<td>0.1</td>
<td>45000</td>
</tr>
<tr>
<td>CTMT6</td>
<td>10</td>
<td>6.0</td>
<td>0.6</td>
<td>0.1</td>
<td>60000</td>
</tr>
<tr>
<td>CTT3</td>
<td>25</td>
<td>12.5</td>
<td>1.25</td>
<td>0.1</td>
<td>170000</td>
</tr>
</tbody>
</table>

Fig. 4. Variation of crack length with number of cycles; (a) 3mm thick constant amplitude and overload specimens; (b) 25mm thick specimens.

The results can be re-plotted as crack growth rates (da/dN) against crack length (Fig. 5a) or against stress intensity factor (calculated using a standard expression for CCT specimens), Fig. 5b. Figure 5a, is particularly useful, as it shows that the retardation effect is particularly significant for the next 2mm of crack growth following the overload, when growth rates are close to zero. Further, growth rates do not fully recover until the crack has grown to a length of approximately 12 mm (i.e. 7mm after the overload). These distances are much larger than the plastic zone size (which is approximately 0.5 mm according to Irwin’s analysis (plane stress). Hence, the level of retardation cannot simply be explained by the need for the crack to grow through a plastic zone with enhanced levels of residual stress.
It is illuminating at this stage to examine the crack closure measurements. Figure 6a presents the variation of crack opening load with crack length for one of the 3mm thick specimens, as determined by the back face and crack mouth (CMOD) gauges. It can be seen that both gauges give similar results. Before the overload, crack is fully open at about 30% of the maximum load. Immediately afterwards, the opening load falls to 12.5% of $P_{\text{max}}$, indicating that the crack is fully-open, due to the additional plastic strain ahead of the crack tip. However, as the crack starts to grow, the opening load increases rapidly, approaching 80% of the maximum, before slowly returning to pre-overload levels. This data is qualitatively similar to that reported elsewhere in the literature (for example by Yisheng and Schijve [10]). A similar picture is observed using the DIC measurements (Fig. 6b), which indicate the situation on the surface of the specimen. Similar data for the 25mm thick overload specimen are shown in Fig. 7. The DIC data (Fig. 7b) shows that the situation at the surface is rather similar to that for the thin specimens. However, the strain gauge data (Fig. 7a), which ‘averages’ through the thickness, shows very different behaviour. Crack opening loads are lower before the overload, and there is no sign of the sharp reduction shortly afterwards. Similarly, opening loads do not increase greatly as the crack grows and the overload plastic zone recedes along the crack wake. Comparison of figures 6 and 7 suggests that surface closure levels (as measured by DIC) are similar in the two specimens, but the thicker specimen has a lower overall closure effect due to the larger proportion of the crack front which is in plane strain conditions. Once again, space considerations preclude presentation of the results for 10mm thick specimens, but these lie between the two extremes presented here.
4. Modelling

A number of different approaches may be used to simulate the experimental results. It is appropriate to assume that the principal phenomenon giving rise to the observed overload effect is that of plasticity-induced crack closure [6]. This may, of course, be modelled by a finite element method, but this approach is likely to be computationally-demanding. It will be necessary to accurately represent crack-tip plasticity and contact along the crack length. A large number of loading cycles will need to be simulated, even if the crack is allowed to advance more quickly in the simulation (e.g. by releasing a pair of nodes each cycle) than in the real physical problem. This features lead to a highly-complex non-linear model, even in two dimensions. A further difficulty arises in detecting the crack opening load, where different methods can give significantly different results [15]. An alternative is to use a simple 2D ‘strip-yield’ model, similar to that proposed by Newman [11]. A quadratic programming formulation [12] allows automatic identification of open and closed regions on the crack faces, and evaluation of a residual stress intensity [15] at minimum load permits evaluation of the crack tip opening load without the need to take small load increments. The model described in [12] was therefore applied to the load history of specimen CTF6 (Table 3). It should be noted that the strip yield formulation used applies to a centre-cracked plate geometry under uniform far-field stress and it is therefore necessary to define an equivalent stress, based on the loads applied in the real CCT specimen. This was achieved by matching the stress intensity factor at the overload crack length, leading to a maximum far-field stress of 0.2\(\sigma_y\). It should be appreciated, however, that the evolution of the stress intensity factor with crack length will be different in the two geometries, so that the model should only be taken as a qualitative prediction of specimen behaviour. Figure 8 shows the variation of opening load with crack length, as predicted by the model.

The predictions in Fig. 8 may be compared with the experimental measurements presented in Fig 6. It is apparent that the measured and predicted behaviour is qualitatively similar. Specifically, comparing the predictions with the DIC measurements in Fig. 6b, it will be seen that the model gives slightly higher predictions of opening load throughout the loading sequence. The predicted opening load is 52% of \(P_{\text{max}}\), compared with a measured value in the region of 38%. Immediately after the overload, both model and measurement show that the crack is fully open \((P_{\text{op}} = P_{\text{min}})\). Closure levels then rise rapidly in both cases, so that the opening load reaches about 75% of \(P_{\text{max}}\) in the DIC measurements and 100% in the model. The steady state situation is recovered when the crack has reached about 140% of its pre-overload length, and again there is good agreement between the model and the measurements. However, it should be noted that the retardation in crack growth rate observed (Fig. 5a) appears to last a longer than this. The strain gauge measurements (Fig. 6a) show similar behaviour to the DIC results and also agree well with the model. For the 25mm thick specimen (Fig. 7), DIC measurements (Fig. 7b) are, as noted in the previous section, fairly close to those for the 3mm thick specimen, and are therefore in qualitative agreement with the model predictions. Strain gauge readings (Fig. 7a) predict lower levels of closure and do not agree with the model.
Fig. 8. Strip yield model: predicted variation of crack opening load ($P_{op}/P_{max}$) with crack length, before and after an overload cycle (conditions equivalent to specimen CTF6).

5. Conclusions

The paper has presented results from a number of experiments where crack growth rate and crack opening loads have been carefully monitored before and after a single overload in an otherwise constant amplitude sequence of loading. Three different thicknesses of specimen were tested, although only two are reported in detail here. Thin (3mm) specimens show high levels of closure, as measured by conventional strain gauge compliance methods. These are in good agreement with surface measurements obtained using digital image correlation. Crack opening loads increase rapidly following the overload, and do not recover to pre-overload levels until the crack has grown to about 150% of its pre-overload length. Thick (25 mm), and medium thickness (10mm) show reduced levels of closure, when assessed by strain gauge compliance, but DIC measurements give similar results to those for the thin specimens. This suggests that plasticity induced crack closure is primarily a surface effect, as is predicted by three-dimensional FE models [16]. This conclusion is borne out by the crack growth rate measurements, which show that the overload produced greater retardation in thin specimens than in thick ones. Hence, the effect of overload-induced closure is smaller in the thick specimens, as there is a greater proportion of the crack front which is unaffected by closure close to the surface.

A plane stress strip-yield model has been used to analyse the effect of a single overload and gives predictions which are qualitatively similar to the surface (DIC) measurements in the experiments. However, the model predicts higher crack opening loads than are observed in practice. This is almost certainly due to the two-dimensional nature of the model; in the thin specimen, even surface displacements will be influenced to some extent by conditions deeper into the specimen. Overall, the results highlight the complex nature of the fatigue crack closure phenomenon. Crack growth rates are influenced by the aspect ratio of the crack as well as by the loading history. Whilst simplified strip-yield models, such as that proposed by Newman [11] have a place in producing estimates of crack propagation behaviour in engineering components, they are more likely to be successful in thin sections (such as wing or fuselage skins), than in more complex geometries. Full finite element analysis of cracks in realistic components and under representative load history is unlikely to be practical in design assessments within currently available computing resources.

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References