Crack closure - is it just a surface phenomenon?

N. A. Fleck and R. A. Smith

The fatigue crack closure response in the plane strain regions of a BS4360 50B steel specimen is evaluated. Compliance measurements using a new type of closure gauge, crack-mouth clip gauge and back face strain gauge show that the fatigue crack is closed for a significant portion (20%) of the load cycle. A sectioning technique is used to confirm that the fatigue crack is closed along the whole crack front, at zero load.

Key words: fatigue; fatigue crack closure; BS4360 50B steel; compliance measurement; sectioning technique

The phenomenon of fatigue crack closure leads to a reduction in the range of cyclic conditions at a fatigue crack tip because the crack faces can come into contact at positive values of external applied load. Several causes of this behaviour have been proposed, including: a) the wake of plastic deformation behind the advancing crack tip;[1] b) irregularities in surface topography of the crack;[2] and c) build-up of oxidation or corrosion products on the crack surfaces.[3] An understanding of the closure effect is useful for the accurate modelling of sequence effects in fatigue crack growth, where the applied load amplitude varies cycle by cycle, and much recent work has been performed to this end.[4] However, most of this research has been done on thin aluminium and titanium alloy sheets where the surface plane stress conditions at the crack tip extend through the sheet across the crack front.[1,5] Many engineering structures, for example pressure vessels, are fabricated from thick plate, and cracks which form are often not through cracks but are embedded and of thumbnail shape. It is therefore important to determine the closure response in the bulk plane strain regions of the material.

Indirect techniques for monitoring plane strain closure response include the electric potential method, ultrasonics and stress wave emission. Unfortunately, a mechanically open crack is *not* necessarily the same as an electrically or acoustically open crack, and so each method can give quite different results.[6,7] Compliance gauges, such as the back face strain gauge and crack mouth clip gauge, have also been used to deduce closure response at the centre of a specimen; such gauges may be over-influenced by surface behaviour and so yield unrepresentative closure information.

A new type of closure gauge has been developed by the authors which does not suffer from any of the above drawbacks. The device will now be described, together with some preliminary results.

NEW CLOSURE GAUGE

The gauge is used to monitor crack opening displacements just behind the crack tip, at the centre of a test-piece, Fig. 1. Essentially, the test is interrupted and two parallel holes of diameter 1.5 mm are drilled just behind the fatigue crack front. One hole is drilled to a depth 1 mm below the fracture plane, the other to a depth 1 mm above the fracture plane. A push-rod assembly is then fastened to the specimen. On

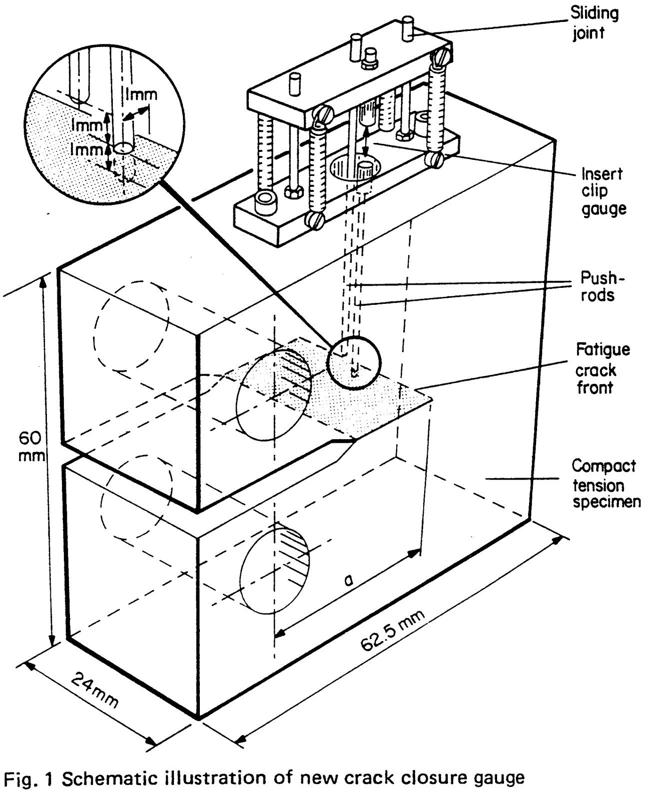


Fig. 1 Schematic illustration of new crack closure gauge

recommencing the fatigue test, the relative displacement of the hole bottoms is measured with a twin cantilever clip gauge, via the push-rods. The crack closure load may be deduced by locating the point at which a load/displacement trace becomes non-linear.

INVESTIGATION

Closure measurements

The plane strain closure response was determined for a 24 mm thick, 50 mm wide compact tension specimen,[8] made from BS4360 Grade 50B structural steel. The composition and tensile properties of the steel are listed in Table 1. A fatigue crack was grown at a constant rate of $\sim 10^{-4}$ mm/cycle by manually shedding the load to maintain a stress intensity factor range, ΔK, of 25 MPa $\sqrt{m}$ and a load ratio (= minimum load/maximum load) of 0.05. The

Table 1. Composition and tensile properties of BS4360 Grade 50B structural steel

Elemental composition (%)					
C	Mn	Si	P	S	Al
0.14	1.27	0.41	0.017	0.004	0.073

Properties*		
Yield stress	Ultimate tensile stress	Elongation
380 MPa	550 MPa	24%

*tensile properties relate to the roll direction

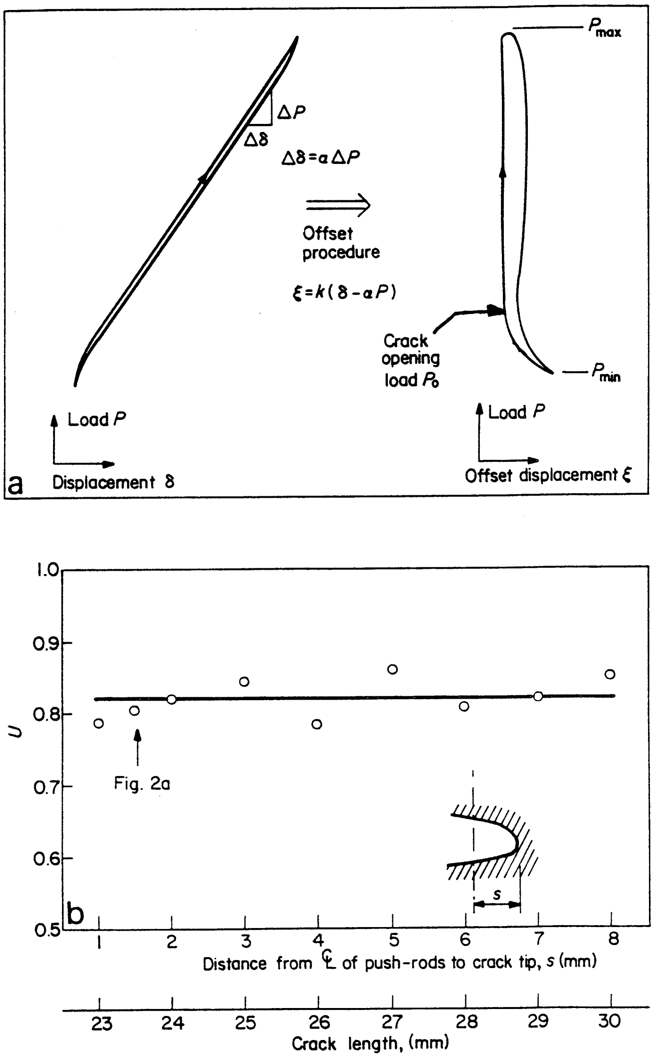


Fig. 2 Effect of distance from gauge to crack tip on closure response. (a) Load/displacement and load/offset displacement plots for a crack length of 23.5 mm; (b) closure parameter $U(= [P_{max} - P_0]/[P_{max} - P_{min}])$

test was interrupted, and the closure gauge mounted on the specimen, once the crack had grown from the starter notch (length = 15 mm) to a length, a, of 23 mm. On recommencing the test, closure readings were taken periodically, until the crack had grown to a length of 30 mm. Test frequency was reduced from 5 Hz to 0.02 Hz for closure measurements.

The fraction of the load cycle for which the crack is open, U, (see Fig. 2) can be expressed as a function of the distance from the gauge to the crack tip. Typical load/displacement and load/offset displacement traces are included in the figure. The offset displacement is calculated by subtracting a fraction, α, of the load signal from the displacement signal such that the net response is zero for an open crack.[9,10] It was estimated that the fatigue crack is open for 82 ± 3% of the load cycle, independent of the distance from the gauge to crack tip.

To investigate the effect of drilling holes close to the crack front on the closure response, additional closure measurements were taken using a crack mouth gauge and back-face strain gauge. Again, the offset procedure was employed. Both gauges indicated a value for U of 80 ± 3%, independent of crack length and the introduction of the push-rod gauge. It was deduced that the holes have a negligible effect on the closure response. Further, it was concluded that the crack-mouth gauge, back face strain gauge and push-rod gauge indicate identical crack opening loads.

Metallography

After the fatigue crack had grown to a length of 30 mm, the test-piece was sectioned using a thin slitting wheel. The section plane lay 0.5 mm behind the crack tip, and normal to the direction of crack advance, Fig. 3a. After polishing the section plane with emery paper and diamond paste it was examined in a scanning electron microscope. It was observed that the fatigue crack was closed along the entire crack front at zero load, Fig. 3b and c, in agreement with the compliance measurements.

DISCUSSION

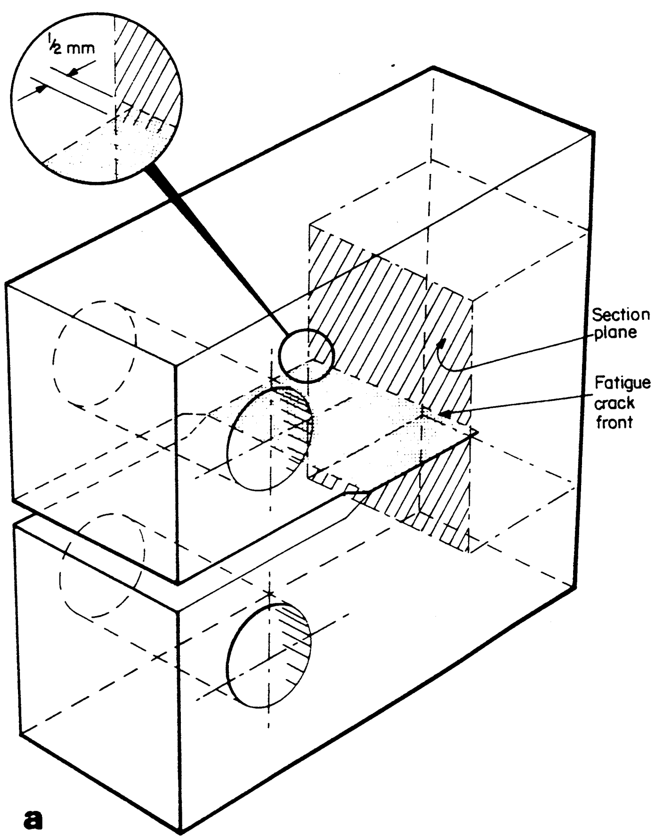
Lindley & Richards[11] used the potential drop method and the crack-mouth clip gauge to determine the plain strain closure response of a 1% carbon steel in the spheroidized condition. They found that the fatigue crack remained open for the whole load cycle, at both high and low load ratios. The specimens were sectioned normal to the direction of crack advance and 3 mm behind the crack tip; cracks were found to be closed at the surface of the specimen but open in the interior. The static and cyclic properties of the 1% carbon steel are similar to those of BS4360 structural steel, and so it was expected that the two steels would display similar crack closure responses. The discrepancy between Lindley & Richards' results and those of the present study must therefore be explained.

It is proposed that previous investigations failed to observe crack closure in thick specimens, for the following reasons:

1) The closed crack increment at minimum load is small (less than 3 mm). Unless the specimen is sectioned near to the crack tip the closed crack will not be found. In the present investigation, the crack was closed 0.5 mm behind the crack tip at zero load.

2) The crack mouth gauge can detect crack closure only if careful attention is paid to the elimination of electrical noise and an offset displacement procedure is employed.[10]

3) The potential drop method is unable to detect crack closure for steels in air. An insulating oxide film prevents any change in specimen resistance on closure of the fatigue crack, and so the technique is invalid.[6,10,12]



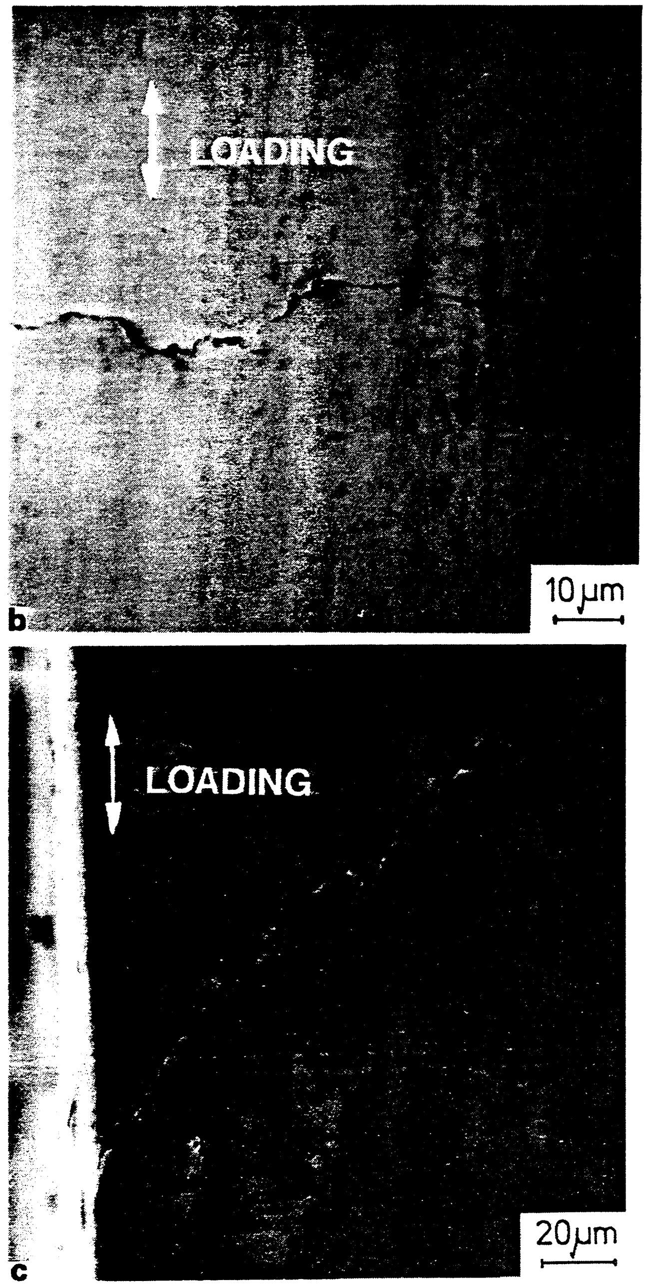


Fig. 3 Section taken 0.5 mm behind crack tip of BS4360 test-piece: a) sectioning technique; b) view at mid-thickness of specimen; and c) view at surface of specimen

CONCLUSIONS

Crack closure is not just a surface phenomenon, but can also occur in the bulk (plane strain regions) of a test-piece. In particular, fatigue cracks in BS4360 50B steel may be closed for a significant portion (20%) of the load cycle.

A new compliance technique has been developed which is capable of monitoring the crack closure response at the centre of a specimen.

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