TWO-PARAMETER FRACTURE ASSESSMENT OF THROUGH-THICKNESS CRACKS IN AN ALUMINIUM BRIDGE STRUCTURE

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The bridge is a lightweight utility, fabricated using a weldable aluminium alloy. During laboratory fatigue testing, cracks were detected in the stem of the bridge main tension chord, where damage is most critical. The bridge sustained much longer critical crack lengths before failure than estimated from linear elastic fracture mechanics, using toughness data obtained from highly constrained specimens. To solve this discrepancy, three-dimensional elastic-plastic finite element analysis of the girder has been carried out. The cracked bridge girder is shown to be a low constraint geometry. Two-parameter theories are used to construct fracture toughness loci to match the toughness of the girder with that of low constraint specimens, leading to far better correlation between the numerical and experimental results.

INTRODUCTION

The Christchurch bridge is a lightweight and readily transportable twin-trackway bridging utility which can be rapidly erected to cover a range of emergency bridging requirements of up to 30m span. High strength aluminium alloys are used in fabrication to satisfy minimum weight/high strength requirements. Welding is favoured as the most cost effective method of fabrication. The design requirements of the bridge include the acceptance of initial or imposed defects which will reduce the safe fatigue life. The bridge comprises I-section fabricated vertical plate web girders. The chords of the girders are made from T-section extrusions between which are vertically stiffened shear plates. The T-section extrusions are attached to the web by longitudinal welds. The bottom T-section chords carry the high tensile stress produced by loading, and failure of any one of the tension chords would lead to catastrophic failure of the bridge.

An early large scale fatigue test programme of a single trackway of the bridge by Webber (1) showed that the crack responsible for initiating failure was along the

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weld attaching an intermediate stiffener to the stem of the T-section tension chord. The crack remained shallow while extending the full length of the weld, and then propagated to the mid-thickness of the stem. The crack then changed direction and started to grow downwards towards the flange of the tension chord and upwards towards the tapered end of the stem. At 17000 fatigue cycles (vehicle crossings), the through-thickness crack in the stem measured 99mm, at 22000 cycles the crack measured 205.5mm, and at 23000 cycles the crack penetrated the flange in a surface semi-elliptical form. This semi-elliptical crack then started to grow and it is believed that this caused final failure, at a net stress lower than the proof stress of the aluminium alloy. Figure 1 shows the variation of the crack growth in the Christchurch bridge girder with fatigue cycles. Another full scale test on a single trackway was conducted by Webber (2) to study the damage tolerance of the flange of the bridge girder. The bridge was artificially damaged by creating a 5mm saw cut in the flange of the bottom chord extrusion to cause a stress concentration that would accelerate failure and grow a fatigue crack at a predetermined position. The girder failed after 7695 cycles on the application of maximum live load. The crack had grown to a total length of 53mm.

Fracture toughness tests were carried out in (1) using compact tension (CT) specimens, cut from the extrusion under consideration, and conforming to British Standards BS-5447 to determine the plane strain fracture toughness, K_c, of the aluminium alloy. The minimum and typical K_c values obtained were 33 and 41MPa$\sqrt{m}$ (corresponding to a fracture toughness value of $J_c \approx 0.024$MN/m) respectively. A uniformly loaded rectangular plate of 100 $\times$ 25mm cross section, with an elliptical surface crack, was assumed to represent the tension chord in the absence of published solutions for the stress intensity factor, K, representing the actual chord section. The magnitude of the uniform stress was 150.5MPa which corresponded to that measured experimentally. In applying linear elastic fracture mechanics (LEFM) and substituting with the above data, Webber (1) predicted that the maximum crack length the bridge girder can sustain before failure is 24mm.

Clearly, the LEFM results presented above grossly underestimated the maximum crack length the bridge girder can sustain before failure. In this paper we study the I-section bridge girder, containing stem or flange cracks, using three-dimensional (3-D) elastic-plastic finite element (FE) models. In addition fracture toughness data obtained from experimentally tested and numerically analysed low constraint specimens (namely centre cracked, CCT, and shallow three-point bend, TPB) are summarised. Two-parameter theories (namely the J-T, after Hancock et al. (3) and the J-Q, after Shih and O'Dowd (4),) are used to construct fracture toughness loci using the specimens toughness data. The constraint parameters, T and Q, are then used to match the fracture toughness data of the specimens with the J-integral values evaluated from the I-section models.

ASSESSMENT OF CRACKS IN THE BRIDGE GIRDER

The 3-D FE models of the full I-section bridge girder comprised of four models containing different through-thickness stem cracks corresponding to those found in the real structure between 17000 and 22000 cycles, and six models containing different flange cracks corresponding to those found in the real structure up to failure at 7695 cycles. The FE models were meshed using reduced integration twenty-noded isoparameteric brick elements degenerated at the crack front to wedge elements. The nodes at the crack front were coincident but independent. All models shared the same "spider web" mesh design surrounding the crack front. Mesh refinement was such that the smallest element was 1/980 of the crack length. A typical finite element mesh of the I-section girder containing a through-thickness stem crack, with details of the crack front region, is illustrated in Figure 2. Symmetry boundary conditions were applied on the models where applicable, and the load was applied as a linearly variable stress with maximum tensile and compressive values at the lower and upper T-section chords respectively, as determined from the experiments. The stress-strain curves were modelled up to failure using true stress-ln strain values measured during tensile experiments.

Different fracture parameters (namely the J, T and Q) were evaluated for the I-section models when the strain levels at the bottom of the tension flange reached values corresponding to those measured during full scale experimental testing of the bridge. The fracture parameters were evaluated at mid-thickness of the models, where conditions of plane strain were most dominant. The T-stress and Q-value were evaluated at a distance of $2J/\sigma_{ys}$, ahead of the crack front, where σ_{ys} is the yield stress. The opening stress fields at a distance of $2J/\sigma_{ys}$ ahead of the crack fronts of all the bridge girder models studied here fall below that of the HRR, by more than 10%, indicating loss of single parameter characterisation (J-dominance) of the stress fields. The T-stress and Q-value of all the bridge models were negative indicating that the bridge geometry containing through-thickness stem or flange cracks is a low constraint geometry. The stress fields of the different bridge models are best characterised in terms of the J-T or J-Q theories. As the functional relationship between the fracture toughness, J_c, and the constraint parameters (T or Q) is unknown, specimens of different geometries incorporating a wide range of crack front constraint are needed to quantify it.

APPLICATION OF FRACTURE TOUGHNESS LOCI TO THE GIRDER

Low constraint fracture specimens were tested by Henry et al. (5), and values of J_c were measured. In addition corresponding T and Q values were calculated using published 2-D solutions. The specimens were then modelled numerically in 3-D using the material stress-strain curve. The numerical and experimental J_c values agreed within 10%. Figures 3 and 4 show the variation of the numerical J_c values with constraint as indexed by the T-stress and the Q-value respectively. Low constrained geometries showed up to an eight-fold increase in fracture toughness over the J_c values of 0.024MN/m obtained by Webber (1) from highly constrained CT specimens. Figures 3 and 4 also illustrate the upper and lower toughness boundaries of the data. Toughness data higher than the upper boundary will indicate failure, while those within the boundaries are safe.

The *J*-integral values for the different I-section bridge girder models are matched with the toughness data of the low constrained specimens using the T and Q as illustrated in Figures 3 and 4 respectively. Both the results of the lower (towards the tension chord) and upper crack fronts of the stem models are presented. The *J* values of the bridge models are within the upper toughness boundaries, except for the deepest flange cracked model. For this cracked configuration, experimental results showed that the crack started growing unstably on the application of the maximum live load. Two-parameter theories are successful in indexing the constraint of both the bridge girder and the small test specimens, providing an explanation of the ability of the girder to sustain longer cracks than predicted by LEFM and fracture toughness data from CT specimens. The bridge girder is a low constraint geometry, and this loss of constraint accounted for the increase in toughness over the values from the CT specimens.

CONCLUSIONS

The bridge girder under investigation is a low constraint geometry. Within the framework of two-parameter theories, fracture toughness loci were constructed using experimental and numerical results of low constraint geometries, enabling the comparison of the data from the specimens and bridge girder models to be compared on the same graph. The results of the bridge girder models were within the upper boundaries of toughness data. This show that the bridge girder can sustain much longer cracks than predicted by LEFM. This enhanced fracture capabilities are due to the loss of constraint.

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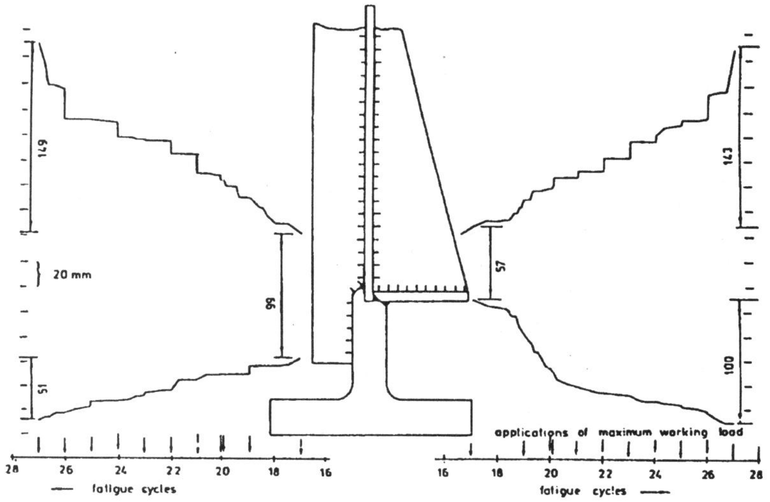

Figure 1 Variation of crack growth in the bridge girder stem with fatigue cycles

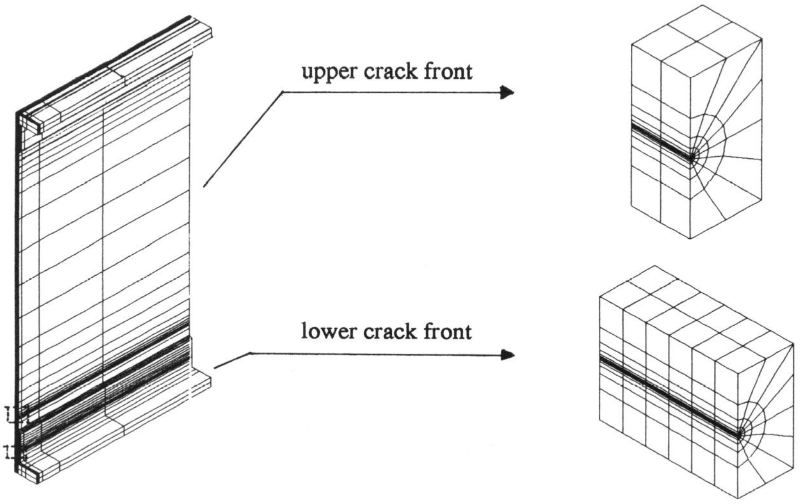

Figure 2 Typical three-dimensional finite element model containing through-thickness stem crack, lower and upper crack fronts are enlarged.

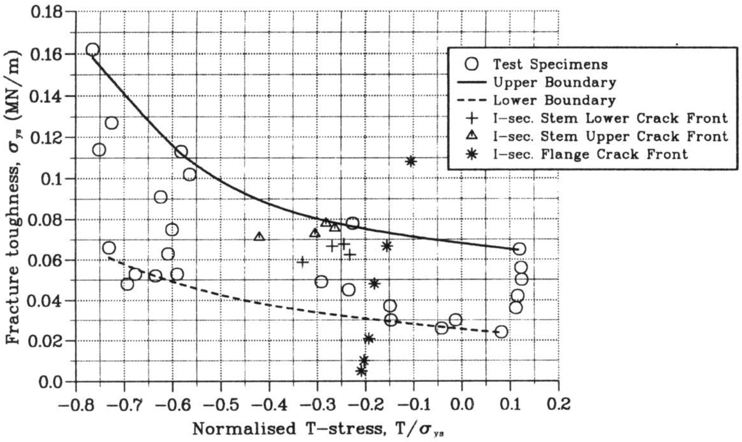

Figure 3 Variation of the fracture toughness with the normalised T-stress for the test specimens. The *J* values of the I-section girder containing cracks are shown

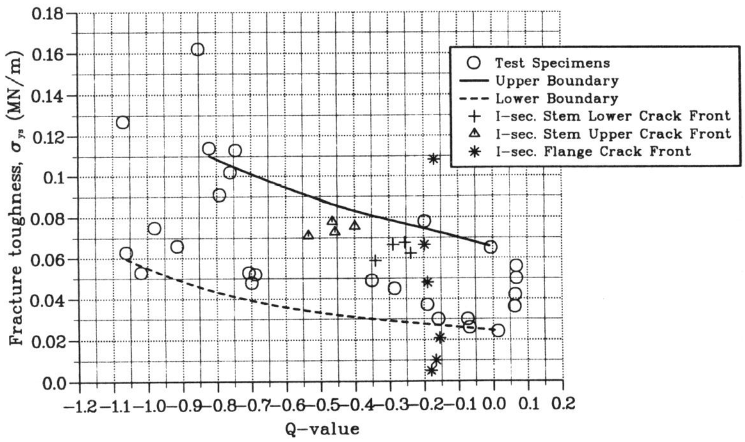

Figure 4 Variation of the fracture toughness with the Q-value for the test specimens. The *J* values of the I-section girder containing cracks are shown