FRACTURE ANALYSIS OF A SUSPENSION BRIDGE LINK EYE

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Critical crack opening displacement values obtained for samples of wrought iron taken from a chain link out of the bridge and compared with the results of an elastic/plastic finite element analysis of the chain link eye, showed an adequate margin of safety against fast fracture.

Predictions using experimentally determined threshold stress intensity factors indicated a visibly detectable tolerable crack size.

INTRODUCTION

The Clifton Suspension Bridge, opened in 1864, is a wrought iron structure. The suspension chains are made of flat plate eye bars joined together by pins.

In 1971 the Bridge Trustees instructed their consulting engineers, Howard Humphreys and Partners, to carry out an appraisal of the resistance of the Bridge to fatigue failure. This decision was prompted by the report that the collapse of the Point Pleasant Bridge over the Ohio River in the USA had been caused by the propagation to failure of a fatigue crack in a steel eye bar chain link.

Fatigue Appraisal. Several areas of high load concentration were identified and all were eliminated as sites of potential fatigue failure except the eye ends of the river chains where they were joined to the tower saddles. At these points analytical and

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experimental studies showed that the rotation of a link about its pin caused an effective eccentricity of the line of action of the load of approximately ± 15 mm with a consequent fluctuation of ±33.6 N/mm^2 in the maximum stress, which occurred at points on the inside of the eye approximately 75^o from the axis of symmetry to the link, Fig.1. Prior to erection each link had been proof tested and the whole bridge had also been proof tested with a 42% overload. The consequent residual compressive stresses induced at the inside of the eye were judged to reduce the mean stress ratio to 0.49 at which this stress fluctuation would be acceptably below the fatigue limit.

Fracture of Wrought Iron. Wrought iron anchor chains used on ships were known to be subject to brittle failure, but this had been associated with the hardening caused by abrasion in use and the subsequent strain ageing. However, the failure of a railway bridge in Eire in December 1975 showed that fast running fracture leading to collapse could be initiated from a locally applied impact load. Because of this the appraisal was extended to determine the critical length of a crack in the chain eye for a fast fracture to be initiated and to examine the possibility of a pre-existing crack growing to this length.

FIRST PHASE OF THE INVESTIGATION

The use of wrought iron in major structures had effectively ceased by the end of the 19th century and it is no longer manufactured commercially. Although fatigue data has been obtained in recent years (mainly for the appraisal of the large number of railway bridges which are still in use) no fracture mechanics data are available. The Clifton Bridge is a historical structure and a memorial to its original designer I.K. Brunel. There is, therefore, a reluctance to deface the structure by removing parts of it for making test pieces and it was decided to use samples of iron of a similar age to that at Clifton which were available from reconstruction work at the Brittania and Menai bridges. The former was a piece of 16 mm thick hammered plate and the latter part of a 25 mm thick rolled chain link.

Calculation of Stress Intensity Factors for the Chain Link Eye. Stress intensity factors (K) for plane strain conditions were obtained using the BERSAFE finite element program developed by Hellen et al (1). The eye was modelled as a 2-dimensional body and triangular and quadratic elements were used together with special additional elements at the crack tip.

A radial through thickness crack was assumed, starting at the inside of the eye and extending along a radial line at 75^o to the axis of symmetry of the link (the line of maximum stress determined in the fatigue appraisal). Solutions were obtained for

5 crack lengths, for axial loading and for loads with eccentricities of ± 15 mm. It will be seen from Fig. 2 that the value of K does not change significantly for crack lengths between 15 and 60 mm. Funds available for this stage of the investigation were unfortunately insufficient to permit an elastic-plastic analysis.

Fracture Toughness Testing.

The thickness of the material available for testing was considered to be too small to obtain a plane strain fracture toughness K_{1c} value. Because, the thickness of the eyebar link, 25 mm, was the same as that of the Menai link material it was decided to deduce K_c values, for comparison with the analytical K values,from the results of COD tests as prescribed in BS 5762: 1972 (2). This standard is based on the use of a bend test, however, because of the very limited amount of material available the smaller compact tension specimen (CTS) was preferred so that a larger number of specimens would be obtained. All the samples were oriented so that the notch would lie perpendicular to the direction of rolling of the plate and normal to the plane of lamination. The Brittania plate showed no ductility in a static tension test and as attempts to grow a stable crack in the CTS failed this material was discarded.

In pre-cracking the test pieces it was found that the force had to be raised from the value of 12.5 kN, prescribed in BS 5762, to 15kN to start the crack. In some cases fracture occurred, in others excessive crack tip plasticity caused extensive yielding before fracture in the subsequent COD test rendering it void. It was also difficult to achieve uniform crack growth, possibly because of the inhomogeneous structure of wrought iron.

Initially the crack length was measured optically, but later the back face strain (BFS) technique developed by Deans and Richards (3) was used.

The COD tests were done at $-18^{\circ}C$ which was the calculated minimum effective bridge temperature for the Clifton Suspension Bridge.

Estimation of Fracture Toughness (K_c). A value was estimated for the applied load (P_i) at which slow crack growth appeared to start and the corresponding value of crack opening displacement (δ_i) was calculated.

For this purpose, in the absence of any guidance for relating clip gauge displacement to CTOD for a CT specimen, the expression given in BS 5762 for the SEN bend specimen was used. Values of δ_i were converted to K_c using the expression, developed by Burdekin and Stone (4):

$$K_c = (\delta_i \sigma_y E)^{\frac{1}{2}}$$

where σ_y is the yield stress of the material and E its Young's modulus. These values which were thought probably to be conservative ranged from 50 to 59 $MNm^{-\frac{3}{2}}$. The largest calculated values of K for a 25 mm crack varied from 28.9 $MNm^{-\frac{3}{2}}$ when the load was axial to 32.6. $MNm^{-\frac{3}{2}}$ for the maximum eccentricitiy of +15 mm. This material could be expected to provide an adequate margin of safety against the initiation of a fast running crack. These results indicate that, if the material in the bridge was similar to that in the Menai link then it was probably acceptable, but if it was similar to the Brittania plate then it was not acceptable.

SECOND PHASE OF THE INVESTIGATION

A wide range of fracture properties had been shown to exist between the two samples of wrought iron so that the results that had been obtained could not be regarded as a satisfactory basis for an assessment of the safety of the bridge. It was therefore decided to remove a chain link from the bridge to provide material for further COD tests and also to carry out an elastic-plastic finite element analysis of the eye to determine crack opening displacements.

Selection of samples from the bridge. As removal of a link at the tower saddle was impracticable a search was made for a link representative of the saddle links which was accessible for removal. Although most of the links are re-used from the demolished Hungerford Bridge the saddle links, and some others, were made specially for Clifton. Records showed that some of the new links were located near mid-span. Chemical tests were made on samples from the shoulders of suitable links and showed that the sulphur and phosphorous contents, which have a deleterious effect on toughness,were in the normal ranges. Analysis showed that the phosphorous content of the link removed was 0.31% which was above average. As the eye-ends of the links are joined to the shafts by hammer welding the two are not necessarily of the same material. Specimens were therefore taken from the eye-end only. Four CTS pieces were cut around the line of assumed crack propagation (Fig. 1) and others in the shoulder and shaft of the link.

CTOD Tests. A number of CTS pieces were cut from the link eye in the locations shown in Fig.1 and tested at $-18^{\circ}C$ using the BS 5762 procedure. The results were analysed in two ways to obtain the crack tip opening displacement corresponding to fast crack extension:-

1) By using the pop-in value

2) By partially unloading the specimen at various positions on the load/displacement curve and using the elastic unloading slopes to detect any changes in compliance which indicate crack extension.

The values of CTOD from the tests which gave valid results obtained from method 1) ranged from 0.055 mm to 0.16 mm, and by method 2) from 0.068 mm to 0.268 mm

The BERSAFE programme was used to extend the elastic stress analysis to consider plastic effects at the crack tip. Whereas superposition allows an elastic analysis to be performed with unit loads and the results scaled appropriately a plastic analysis must model the relationship between yield stress and the load stress exactly .

The yield stress was determined experimentally using four specimens cut from the eye material. The values of yield stress obtained ranged from 195 MNm^{-2} to 217 MNm^{-2}. The minimum value was used in the analysis. The position of the load used was that that had caused the maximum K value in the elastic analysis. A crack length of 102 mm was used as the elastic mesh was available for modification.

The results indicated a plastic zone extending 2 or 3 elements from the crack tip indicating that the mesh was fine enough. The crack tip opening displacement was then determined by plotting the relative displacement of adjacent nodes on each face of the crack and reading off the maximum value in the plastic region.

Assessment of results. The lowest measured CTOD value for the material exceeded the calculated value for the chain eye by a factor of 1.72; if the average value 0.130 mm is taken the factor becomes 4.81. On this evidence the margin against the possible development of a fast running crack can be regarded as adequate.

Crack Extension Under Fatigue Loading

The possibility of the intiation of a fatigue crack having already been examined the growth of a pre-existing crack by fatigue loading was considered.

Crack growth tests. Two tests were done using compact tension test pieces with a load range equivalent to the axial load moving over the full range of eccentricity giving correct stress intensity factor ratio (R_K) of 0.77. Figure 3 shows the crack growth rate (da/dn)v.ΔK curve for one sample for which a threshold stress intensity factor range of ΔK = 230 $Nmm^{-\frac{3}{2}}$ (7.27 $MNm^{-\frac{3}{2}}$) was obtained. A value of ΔK_{th} = 200 $Nmm^{-\frac{3}{2}}$ (6.33 $MNm^{-\frac{3}{2}}$) was obtained for the other specimen.

Estimation of longest non-propagating crack. The elastic finite element analysis showed that ΔK increased slowly as the crack length increased. For the shortest crack length (a) used in this analysis (12.5 mm) ΔK = 6.92 $MNm^{-\frac{3}{2}}$. In the light of the values of K_{th} obtained experimentally it must be assumed that all cracks longer than 12.5 mm are likely to grow under fatigue loading.

An estimation of the situation for cracks shorter than 12.5 mm was made using ESDU Data Item 81029(5) which gives values of K for single through cracks in round ended lugs. Taking the same overall dimensions as for the Clifton link a value of K = 21.6 $MNm^{-\frac{3}{2}}$ was obtained for a 25 mm crack, compared with 28.5 $MNm^{-\frac{3}{2}}$ given by the finite element analysis. Values calculated for other crack lengths when scaled up by the factor 28.5/21.6 compared well with the finite element results, so that it was felt justifiable to use this procedure for calculating K for cracks shorter than 12.5 mm. For the lowest value of K (11.0 $MNm^{-\frac{3}{2}}$ for a = 1 mm) ΔK was obtained by assuming that its variation about the mean would be the same as that of the stress at the inside of the hole. Values of ΔK for values of K between this value and that for a = 25 mm were obtained by interpolation. The lower of the two values for ΔK_{th} (6.33 $MNm^{-\frac{3}{2}}$) was found to be associated with K = 25.3 $MNm^{-\frac{3}{2}}$, which would be generated by a crack length of 8.9 mm.

Taking a reduced ΔK of 6.33/1.5 = 4.22 $MNm^{-\frac{3}{2}}$, to allow for the restricted data and uncertainities in the calculations the length of the shortest crack that would be propagated by the maximum load fluctuations is 5 mm.

COMMENTS

Decisions concerning the safety and residual strength of a standing structure have commonly to be made on limited evidence. In this case the problems were aggravated by the absence of any relevant fracture data for wrought iron, which has not been manufactured for structural use for many years. The decision to remove a link from this historic structure was made with reluctance and provided an only limited number of test specimens.

The conclusion of the investigation was that the risks of failure of the structure by fatigue or brittle fracture were acceptably low. This conclusion is reinforced by the knowledge that the chain links for the bridge were proof load tested before erection and it is most unlikely that a 5 mm crack on the inside of the eye would not have been noticed at this stage. The maximum load fluctuations are caused by extreme wind conditions and diurnal temperature changes, greatly exceeding those due to traffic loading; their frequency is therefore comparatively low so that the extension any pre-existing crack to date would be of the order of 5 mm only.

Should a crack have extended so that the remaining ligament of the eye was unable to support the load the highly redundant nature of the suspension system, with its many alternative load paths, would have restricted the damage to this local area.

Compressive residual stresses exist around the hole in the link eye caused by the proof loading of the bridge. Because of these residual stresses the effective stress intensity factor ratio (R_K) for the link eye, for cracks shorter than 25 mm at least, will be less than the value of 0.77 used for the crack growth test peices which were essentially free of residual stress. Values of the threshold stress intensity factor (ΔK_{th}) obtained from these tests are therefore likely to be pessimistic.

REFERENCES

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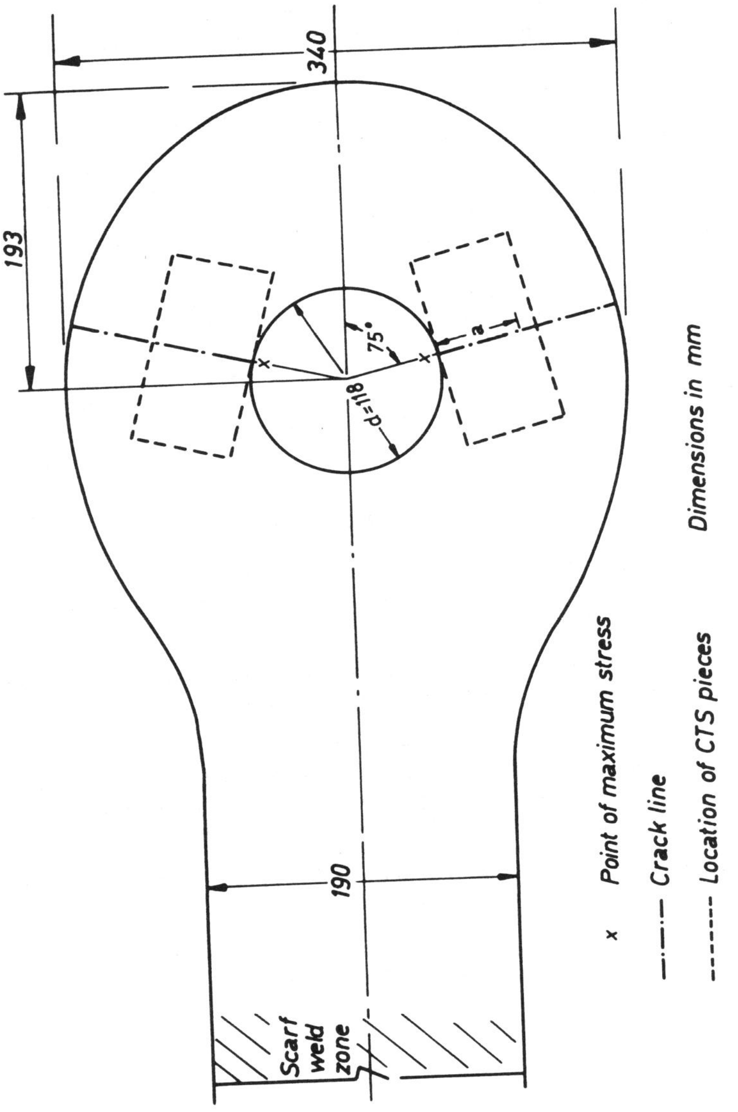

Fig. 1. Geometry of link eye

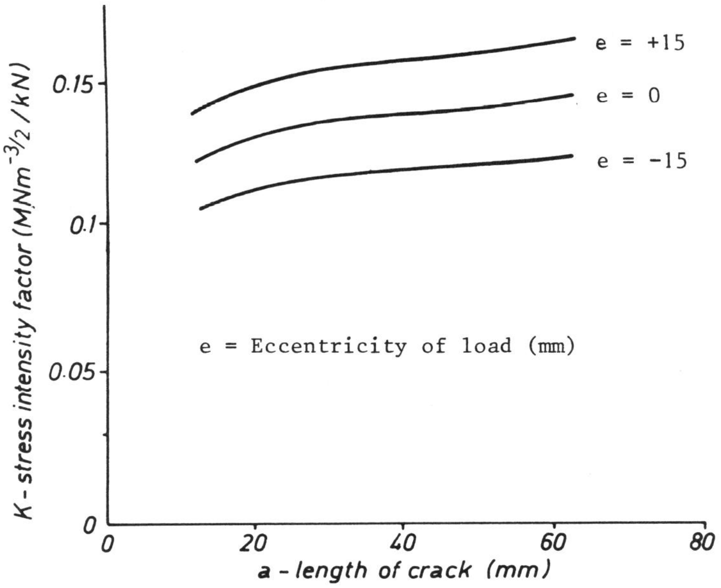

Fig. 2. Stress intensity factors for radial crack in link eye

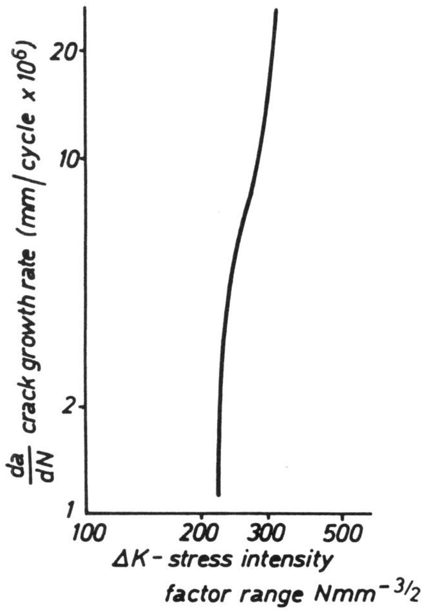

Fig. 3. Crack growth rate curve for wrought iron