Assessment Of Fracture Resistance In Welded Steel Structures

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This paper highlights different methods for the assesment of fracture resistance in welded steel structures. Fracture mechanics approaches have very useful in providing methods for fracture control in welded steel structures, but it needs to be recognised that different approaches are required to assert fracture control with different classes of structure.

A. INTRODUCTION

Weldments are often the most sensible parts of a structure with regard to crack growth and failure[1]. There are several reasons for this. Firstly, welds often contain material or geometrical defects or have an unfavourable shape causing stress concentrations. If cracks are not already present in the virgin weldment they are easily initiated and caused to grow during operation. Secondly, the temperature cycling of the material during the welding process sets up residual stress fields in the weldment. These stresses are superposed on the machanical stresses and thus affects both plastic flow and fracture behaviour of the weldment. Thirdly, weldments have very heterogeneous material properties. Thus the base material adjacent to the weld itself, the so called heat affected zone (HAZ), often has poor machanical properties.

Fracture studies of welded steel structures have received careful and extensive attention after the second world war. There has since been sufficient progress to be applied to fracture control and engineering designer now has available a range of techniques for application to ensure structural integrity[2].

Assesments of fracture resistance in welded steel structures normally involve the measurement of the notch and fracture toughness properties of various regions of the weld.

To acquire this information, engineers make use of fracture tests of various kinds with the objective of identifying the weakest link in the weldment[3]. However, different approaches may still be required to assert fracture control with different classes of structure. Thus, the selection of the most appropriate test method for the assessment of the fitness of weldments has been the most controversial and least resolved problems[4-6].

The present paper deals with the state-of-the-art progress in the assesment for the determination of fracture resistance in welded steel structures. However, no extensive descriptions of the testing procedure are contemplated. Instead, the emphasis has been placed on the advantages, limitations and applicability of each method.

B. Charpy V-notch impact testing

The simplest form of toughness testing is the charpy V-notch impact test. The advantage of this test is that there exists considerable experience and familarity apart from low cost and ease of replication[7]. However, the test result reflects the average notch toughness of a variety of microstructure encountered at the selected notch position in the weldment. The charpy test is thus not a reliable measure to detect the region of low toughness in the weldment. The test may only provide a qualitative assessment of toughness and in general, it is not possible with the charpy test to assess the significance of the toughness values measuerd with respect to the brittle fracture resistance of a structure[8].

Some of the drawbacks of the charpy test can be overcome by conducting instrumented fatigue pre-cracked charpy (IPC) tests. This test could be useful in quantifying the fracture toughness of local brittle zone in the absence of tough surrounding microstructure[6]. However, it is doubtful that the IPC test can fulfil the distinct role of a simple pass/fail test, primarily because it loses the simplicity and low cost advantages of the conventional charpy test[9].

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C. Crack Tip Opening Displacement (ctod) Testing

Unlike the charpy V-notch test, the result from CTOD test provides a fracture characterising parameter which enebles a structure's fracture resistance to be assessed[8]. Two specimen geometries are used for this test. The selection of one or the other geometry depends on the purpose of the test[10].

The preferred test specimen, having a B x 2B rectangular cross section and containing a through thickness crack (a / w = 0.5) is widely adopted. The B x 2B specimens provides a high degree of crack top constraint. The test result is normally used to measure the desired lower bound fracture toughness where the detailed design of the structure to be built may not have been finalised, particularly in the offshore industry, and consequently the toughness requirements necessary and possible location of fabrication / service defects are unknown. A drawback of this specimen geometry design is that the notch orientation does seldom represent the orientation of defects encountered in structures[10] The other specimen design is the subsidiary B x B surface notched specimen with the notch tip located parallel to the plate surface. The crack depth in the test specimen is chosen to represent a depth equal to or greater than the maximum expected crack depth in the structure. This specimen geometry may be used where the significance of surface defects needs to be assessed directly. Moreover, the surface notched B xB spacimen geometry allows to match the constraint in a more realistic way [5,10,11].

It is of interest to note that the estimation of fracture toughness more appropriate to the actual welded structure can be obtained by attempting to model in the test specimen (i) the orientation of the crack likely in the structure and (ii) the constraint that crack will be subjected to. The orientation of the defect can be modelled by placing the notch in the weldment from the original plate surface. However, a very careful specimen preparation technique is necessary in order to ensure that a substantial part of the fatigue crack front is located in the particular test region of weldment in each test[8]. In order to ensure about placing the crack tip in the same region in each test, sectioning the specimens after the test to identify the microstructure sampled by the crack tip and in particular at the fracture initiation point is suggested. It should be recognised that if sectioning reveals that the region of suspected low toughness has not been sampled, further tests should be carried out. On the other hand the modelling of constraint is difficult to resolve. Constraint depends on a number of factors including crack depth, mode of loading and crack shape. It is difficult to quantify but usual practice, based on empirical observations, is to attempt to match the constraint in two ways. First by ensuring that the thickness of the specimen is the same as the structural section of interest, and secondly by ensuring that the notch depth is equal to or greater than the maximum expected in the structure. The use of shallow notches however may preclude the use of the standard CTOD formula given in BS 5762[12]. This formula is only valid for crack depth to specimen width (a/w) ratios in the range of 0.15 to 0.7, where a/w is less than 0.15 caliberation tests will be necessary to calculate CTOD. Alternatively, a double clip gauge technique may be employed so that by extrapolation the CTOD at the original fatigue crack tip can be estimated[13].

The main porblem lines in the wide scatter in CTOD test results and the translation of CTOD requirements for steel specification into fabrication specification[10,14]. However, improved methods for taking account of the stress gradients present at the welds when using the CTOD design curve have been proposed[13]. Recently, a method combining elastic finite element analyses and CTOD design curve has been used to assess the Ctod toughness requirements for an offshore plateform[15].

D. Fatigue CTOD test

In order to assure the integrity of welded structures, it is primarily important to know critical CTOD values of the most embrittled regions in the welded joints. However, the substantial scatter in the results of CTOD tests makes it difficult to determine the lowest CTOD values of welded joints and also prevents real analysis of structural safety. fatigue CTOD test[16,17,] on the other hand, enables to detect the minimum CTOD value in the welded joints easily. In this particular test, a CTOD test specimen is tested under cyclic loading which extends a fatigue crack from the initial kerf toward the HAZ through the weld metal. When the fatigue crack tip reaches close to the embrittle zone, brittle fracture may take place in the case where the applied CTOD value is larger than the critical value of the weakest region. When the applied CTOD is smaller than the critical CTOD value, a specimen will not be broken and a fatigue crack will propagate through the zone. The lowest value of critical CTOD can be expected to lie between the CTOD values calculated on these two specimense. The fatigue CTOD test has the additional advantage that the residual stresses need not be removed prior to the test[9]. The fatigue fracture toughness conformed well to the ordinary fracture toughness when the cyclic stress range is small. Moreover, the fatigue CTOD test should be carried out with a small cyclic stress range and with the cyclic frequency up to 10 Hz in order to evalute the fracture toughness of welded joints[18].

E. Wide Plate tests

In assessing how welds and weld defects might affect fitness for purpose, it is seen from previous discussion that one relies either on test results obtained from small test specimens such as charpy V-notch specimens and/or intermediate scale tests such as CTOD tests. However, these approaches, which are to be considered as a final goal, may pose serious problems[19]. Firstly, where the final decision depends upon the required impact properties, the criteria established for C and C-Mn steels (upon which most codes are based) may not be applied to modern tough materials without adequate justification from full scale behaviour. Secondly, where the application of single notch tip fracture toughness parameters such as CTOD etc. is recommended, it can be argued whether the CTOD design curve approach may be extrapolated to modern notch tough materials without making reference to full scale behaviour of original material.

As a consequence some authors [19-21] recommend the wide plate tests, resembling the actual structural detail and which are subjected to conditions that might be regarded as similar to those encountered in service. However, criteria for evaluating wide plate test performance are not well established. In addition, the interpretation of wide plate test data is complicated for the reason that account has to be taken of the effects of the degree of weld metal matching and the degree of crack tip constaint and the factors which affect those. Alternatively, the wide plate test results can be assessed using Gross Section Yielding concept[19,22] which aims to define a maximum tolerable defect size for gross section yield before fracture ensures. Thus, by applying the concept of gross section yielding to situations in which the elastic-plastic fracture mechanics is either invalidated or over conservative by excessive yielding (i.e. yielding beyond the so-called plastic collapse behaviour), one can have a realistic assessment of the integrity of welded structures. However, the wide plate testing is in particular recommended for expensive structures for which conservative defect tolerance levels may prove to be extremely expensive[19].

E. R. G. Assessment

Sometimes, real components are of complex shape, containing stress concentration and stress gradients. materials properties may vary from place to plate in the component, particularly in the vicinity of welds. The loading applied in service often cannot be defined precisely. The fracture analysis of such components cannot, therefore, be carried out with the same precision that can be applied to a laboratory test specimen. Linear elastic fracture mechanics is inappropriate for components, made of relatively thin material, with high fracture toughness and operating at temperatures well above the ductile / brittle transition. On the other hand, there is no satisfactory method of calculating the values of J or COD in complex three-dimensional geometries with stress concentration and stress gradient regions.

The two criteria method proposed by Dowling and Townley[23], provides a method of assessing the safety of such structures as mentioned above containing defects, making allowance for ductile behaviour. An analysis of the available experimental data showed that there are two extremes of behaviour. At one extreme, failure occured when the crack tip stress intensity factor reached the critical value K_{IC}. Failure load could be determined by linear elastic fracture mechanics. At the other extreme, significant plasticity had to be induced in the component before a sufficiently large crack opening displacement was achieved to cause failure. In the limit, the load carrying capacity could be determined from plastic collapse considerations, and failure was effectively governed by net section events. Between these two extremes of behaviour there was a transition region which could be adequately described by an adaptation of the Heald, Spink and Worthington[24] equation in terms of load rather than stresses.

$$\frac{L_f}{L_u} = 2\ \mathrm{Cos}\ {-1}\ \exp - \left(2\ {}_{l.K}^{\ 2} / 8\ {}_{L}\ \ u^{2}\ \right) \qquad (1)$$

Where, L_f is the failure load of the structure.

L_K is the failure load calculated by linear elastic fracture mechanics.

L_u is the collapse load of the structure determined from the limit analysis considerations.

The principles put forward by Dowling and Townley provided the basis for what has come to be known as the RG procedure, which is now widely adopted for the assessment of components containing defects. The formation of this assessment method was originally set out in the report by Harrison Etal[25]

The basis of the RG procedure is the failure assessment diagram, reproduced in Fig. 1. The Curve is derived from equation 1, but is plotted in terms of variables Kr and Sr, rather than L_f / L_u and L_k / L_u. This provides a diagram to carry out an assessment of a defective component, two calculations are required, which make use of linear elastic fracture mechinics and limit analysis. The liner elastic stress intensity factor 'K' is calculated for the service loads on the component. Knowing K_{IC}, the fracture toughness of the material, the value of $Kr = K_I/K_{IC}$ can thus be established. Sr is defined the most onerous load encountered in service divided by the load to cause plastic collapse. It is often sufficient to perform a classical lower bound limit analysis, using a rigid plastic material model, in which the yield stress of the model material is taken equal to the average of the yield and ultimate tensile strength of the real material.

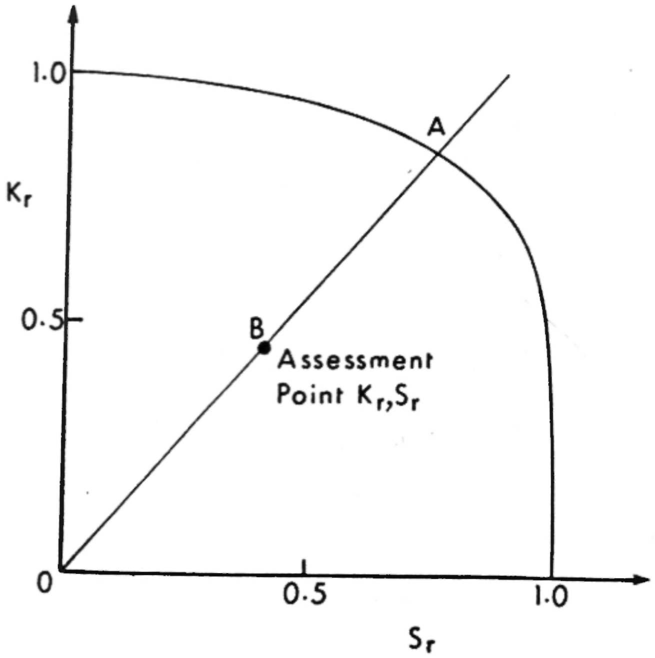

Fig. 1. The Failure Assessment Diagram

The point Kr, Sr is plotted on the diagram. If the point lines within the curve, initiation of fracture will not occure. The margin of safety with respect to load is the ratio OA/OB in Fig. 1.The calculations of Kr and Sr can be as approximate or precise as the situation demands. There are many occasions when an immediate check of intergrity is needed, so that the plant can be put back into production without delay. It is often possible to make simple but pessimistic assumptions about material properties and service loads, about crack sizes and shapes, about stress intensity factors and limit loads, and show that large margins exist against failure[26]. In other circumstances, where it is important to estimate the true margins, for example, where risk of failure has significant economic safety implications, more precise estimates may be needed. Thus, 3-dimensional finite element calculations can be undertaken to determine Kr, and special limit analysis solutions or model tests employed to estimate Sr. In addition the more precise investigations may require extensive material testing to determine the fracture toughness and tensile properties of the material, and a full exploration of the loads applied to the component in service, possible including plant measurements.

G. CONCLUSIONS

The foregoing discussions on the assessment of fracture resistance in welded steel structures revealed the following points :

1. Charpy V-notch impact tests can be used to appraise the quality of the weld.
2. Either CTOD or wide plate test data can be used to assess the significance of defects. However, CTOD data should not be used as a substitute for wide plate test data, the former being too conservative, to assess low-constraint or shallow crack problems.
3. Fatigue CTOD test is suitable for detection of minimum toughness of hetrogeneous materials as welded joints.
4. RG procedure can be applied to components of complex geometry and ensure desired degree of prediction against plant failure.

References

1. J. carlsson, 'Fracture Machanics for cracks in weldments', Proc. of the 6th Int. Conf. on Fracture, Vol.1, 1984, PP. 751-762.

2. A. A. Wells, 'Fracture Control in Welded Steel Structures', Proc. of the 6th Int. Conf. on Fracture, Vol. 1, 1984, PP. 763-774.

3. R. E. Dolby, 'Factors controlling HAZ and weld Metal Toughness in C-Mn steels', Proc. 1st Nat. Conf. on Fracture, 1979, PP. 117-134.

4. F. E. Walker, 'Fracture Toughness Testing : Present status of charpy V-Notch Impact and CTOD Testing'. Conf. Proc. the State of the Art in Materials Testing, Gent, Nov, 1986, PP. 29-42.

5. P. M. Bateson, S. E. Webster and E. F. Walker, 'Assessment of HAZ Toughness Using Small Scale Tests', Proc. of the 7th Int. Conf. on Offshore Mechanics and Artic Engineering, Vol. III, Houston, 1988, PP. 247-256.

6. C. Roger, 'A User's Perspective on Heat Affected Zone Toughness', Welding Metallurgy of Structural Steels, The Metallurgical Society, 1987, PP. 255-262.

7. R. Denys and H. I. Mchenry, 'Local Brittle Zones in Steel Weldments : An Assessment of Test Methods', Proc. of the 7th Int. Conf. on Offshore Mechanics and Artic Engineering, Vol. III, Houston, 1988, PP. 379-385.

8. H. G. Pisarski and R. J. Pargeter, 'Fracture Toughness of Weld Heat Affected Zones (HAZs) in Steel Used in Constructing Offshore Platforms', Proc. Second Int. Conf. on 'Welding in Energy-Related Projects', Toronto, Sept., 1983, PP. 415-428.

9. R. M. Denys, 'Fracture Control and Local Brittle Zones a General appraisal', Conf. on 'Weld Failures', London, nov., 1988, PP. 133-149.

10. S. J. Squirell, H. G. Pisarski and M. G. Dawes, 'Recommended Procedures for Crack Tip Opening Displacement (CTOD) Testing of Weldments', The Welding Institute, Abington, Doc. 7807, 02/86/486.2, 1986.

11. H. G. Pisarski and R. J. Pargeter, ' Feature Toughness in HAZs in Steels for Offshore Plateforms', Metal construction, Vol. 16, 1984, PP.412.

12. BSI. BS 5762 : 'Crack Opening Displacement (COD) Testing', British Standards Institution, 1979.

13. M. S. Kamath, ' The Cract Tip Opening Displacement (CTOD) Design curve : Some Proposals for Incorporating Stress Gradient Effects', The Welding Institute Conference on 'Fitness for Purpose Validation of welded contruction', London, 1981.

14. K. J. Rodgers, 'Heat Affected Zones - A Fabricators Viewpoint', Proc. of the 7th Int. Conf. on Offshore Machincs and Artic Engineering, Vol.III, Houston, 1988, PP. 191-198.

15. I. J. Smith, H. G. Pisarski, h. Ellis and N. J. Prescott, 'Assessment of Fracture Toughness Requirements for the Deck Structure of the hutton Tension Leg Flat from using Finite Elements and the CTOD Design Curves', 14th Annual OTC, Houston, USA, PAPER OTC 4430, 1982.

16. K. Tanaka, M. Sato and T. Ishikawa, 'Fatigue CTOD and Short Crack Arrest Tests', Int. Conf. on Fracture Toughness Testing Methods, Interpretation and Application, 1982, Paper 18.

17. T. Yokobori and T. Aizawa, 'A Proposal for the Concept of Fatigue Fracture Toughness', J. Japanese Society for Strength and Fracture of Materials, 1970, Vol.5, PP. 54-58.

18. T. Inshikawa and K. Tanaka, 'Development of Fatigue CTOD Test for Investigation of Brittle Regions in Welded Joints' Proc. of the 6th International Conference of Fracture, 1984, Vol 5, PP.3311-3320

19. R. M. Denys, 'Defect Assessment Based on Gross Section Yielding in wide Plate Tests', Proc. of the 6th Int. Conf. on Fracture, 1984, Dec., Vol.5, PP. 3615-3622.

20. H. G. Pisarski and E. F. Walker, ' Wide Plate Testing as a Back up to the CTOD Approach', TWI Rwport for the Department of Energy, 3915/4/86.

21. H. G. Pisarski, 'Philosophy of Welded Wided Wide Plate Testing for Brittle Fracture Assesment', The Fracture Mechanics of Welds, 1987, Mechanical Engineering Publications, London, PP. 191-208.

22. R. Denys, ' The Effect of Defect Size on Wide Plate Test Performance of Multipass Welds with local Brittle zones', Welding Metallurgical Society, Warrendale, 1987, PP. 319-334.

23. A. R. Dowling and C. H. A. Townley, 'The Effects of Defects on Structural Failure : A two-criteria Approach', Int. J. Pres. Ves. Piping, 1975, Vol. 3, P. 77.

24. P. T. Heald, G. M. Spink and P. J. Worthington, 'Post Yield Fracture Machanics', Mater. Sci. Eng., 1972, Vol.10, P. 129.

25. R. P. Harrison, K. Loosemore and I. Milne, 'Assessment of the Integrity of Structures Containing Defects', CEGB Report R/H/RG, 1976.

26. C. H. A. Townley, 'Practical Methods For Assessing Defects in Components', Proc. of the 6th Int. conf. on Fracture, 1984, Dec., PP. 3499-3506.

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