FATIGUE OF WELDED COMPONENTS AND STRUCTURES - CURRENT STATUS

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INTRODUCTION

Structural components such as in bridges, cranes, engines, pressure vessels and offshore structures are often subjected to cyclic loading. Fatigue failures generally occur at stress concentration sites in the components. The geometrical and metallurgical states of welds make them prone to fatigue failures owing to stress concentrations caused by weld shape and discontinuities, Moreover, welding introduces unfavourable tensile residual stresses, often of yield magnitude, which increases the severity of the applied fatigue loading. As a result, both applied compressive and tensile stresses can be equally damaging. In addition, the existence of defects in weld eliminates the fatigue crack initiation stage, and hence, the life is predominantly governed by fatigue crack propagation. Therefore, fatigue is one of the major factors determining the life of welded structures. In this report, the current status of developments towards the design rules including fracture mechanics concept, post weld improvement techniques and influence of weld defects on fatigue behaviour are briefly reviewed. Recent understanding about repair welding of fatigue cracks in components with the view to extending the life of the components is also highlighted.

Fatigue Design Rules

Fatigue design rules for welded structures employ S-N curves based on data obtained from fatigue tests on welded specimens. These rules provide a series of S-N curves and a detailed classification system. Fig 1 shows the IIW design S-N curves for welded joints in steel (1). Each curve refers to a particular mode of fatigue failure in specified joints. The S-N curves are expressed in terms of the nominal stress range in the region of potential fatigue cracking. Full stress range is used regardless of applied mean stress in order to account for the presence of high tensile residual stresses in welded joints. However, this approach provides only basic information and is being reviewed with a view to make it more comprehensive. Correct choice of S-N curve is also significant; for a given stress range, the IIW design curves predict lives which vary by over 20 times. This emphasises the need for classification systems which are comprehensive as well as clear and unambiguous. Current rules are not sufficiently comprehensive for all applications, something which IIW seeks to improve.

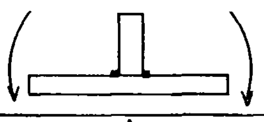
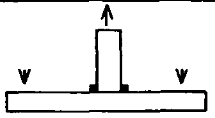
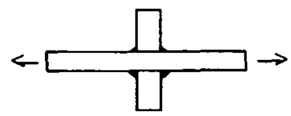
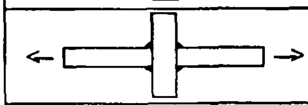
Immediate plans are to :

Extend the present classification system to cover other welding processes (e.g. electron beam, laser, friction, resistance) and other joint configurations (e.g. tubular joints in sheet material, round bars)

Provide guidance in the influence of stress relief and applied mean stress

Introduce scale effect correction, related to plate thickness and other relevant joint dimensions

TABLE 1
IMPROVEMENT DUE TO VARIOUS POST WELD TREATMENTS [13]
Material : E 690 steel, No. of cycles; 2 x 10^6

TYPE OF JOINT	TESTED CONDITION	$\Delta\sigma$ (MPa)	IMPROVEMENT (%)
	AW TD SP	207 360 392	-- 74 89
	AW TD SP	136 220 288	-- 62 112
	AW TD SP	132 218 267	-- 65 102
	AW TD SP	139 230 240	-- 58 72

AW - as welded; TD - TIG dressing; SP - shot peening.

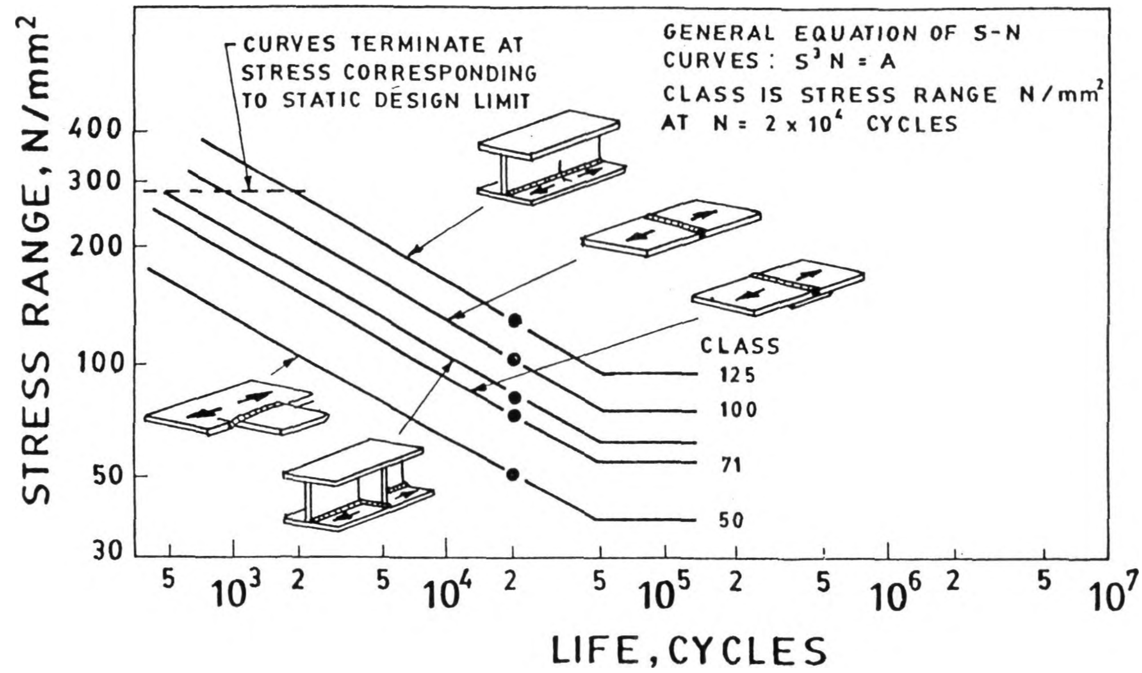


Fig 1 . Typical IIW design S-N curves and corresponding weld details showing site of cracking and loading direction considered

Cover other materials (e.g. aluminium, stainless steel)

Fatigue loading in components during service can arise from many different sources. Accurate prediction of service load spectrum is often difficult. Underestimation of service stresses or negligence of certain sources of fatigue loading during design are therefore, highly determental and can lead to premature fatigue failure. Thus it is imperative to anticipate all sources of fatigue loading and to quantify the service stress spectrum as accurately as possible. Experience from previous similar structures or records based on measurements on prototypes or existing structures may be used for realistic prediction.

Problems can also arise in determining the nominal stresses used in fatigue design. The presence of secondary stresses, grometric stress concentrations and multi-axial or combined loading complicates determination of nominal stress. Detailed stress analysis techniques can be employed to determine complex stress distributions. In particular, determination of the local stresses at the possible sites for fatigue crack initiation eliminates the problems associated with estimation of nominal stress to be used in structures involving complex load spectrum and joint design. This local stress concept is somewhat similar to the hot spot stress method used in tubular joint design which incorporates the stress concentration influence of the joint [2-5]. This approach leads to the use of an unified S-N curve instead of a series of curves.

Significance of weld flaws

Imperfections present in welds affect the fatigue performance of the structure. The extent to which the defect influences life depends on the type, size and location in the weld joint. The concept of **"fitness-for-purpose"** is currently adopted as a basis for the acceptance of welding flaws whose presence does not impair the fatigue performance which is required for intended purpose [6,7]. In order to assess the severity of weld flaws, and to take account of these imperfections in design fatigue test data has to be generated on weldments containing defects.

Weld defects such as porosity, slag inclusion, lack of fusion and incomplete root penetration provide alternate sites for the initiation of fatigue crack. Another harmful imperfection is misalignment, which arises during fabrication, either as axial misalignment or angular distortion. This introduces secondary bending stresses and hence it does not provide alternate site for crack initiation, but enhances the severity of existing stress concentration.

Several studies have focussed on the effects of various flaws on fatigue performance of welded joints [8-11]. It is shown that reduction in life due to misalignment could be correlated with additional bending stresses which arise out of various type of misalignments [8]. The influence of weld defects on fatigue behaviour of type 308 SS welds has been investigated at Kalpakkam [11]. It has been found that type and location of flaws determine fatigue life.

Fracture Mechanics Approach for Fatigue Design

Fatigue lives of nominally sound welded joints are determined by crack propagation. Therefore, fracture mechanics (FM) concept of fatigue crack growth can be used to predict the fatigue life. This approach is based on the integration of Paris Law, i.e., the relationship between crack growth rate (da/dN) and the stress intensity range (ΔK). Fatigue life, N of the specimen containing a crack of initial depth, a_i which can propagate to a_f before failure can be given as,

$$(1/C)\int_{a_i}^{a_f} da/(Y\sqrt{\pi a})^m = S^m N$$

One of the major advantages in adopting FM approach as a design method is the use of specific materials properties (i.e., C, m, a_i), geometries and loads (Y). The initial flaw size, a_i is an important factor, which must be properly defined. The determination of a_i is generally related to the capability of non-destructive testing (NDT) techniques. Based on metallurgical evidence, it is found that cracks originate from flaws of depth ranging from 0.05 to 0.4 mm [12,13]. Such small-sized

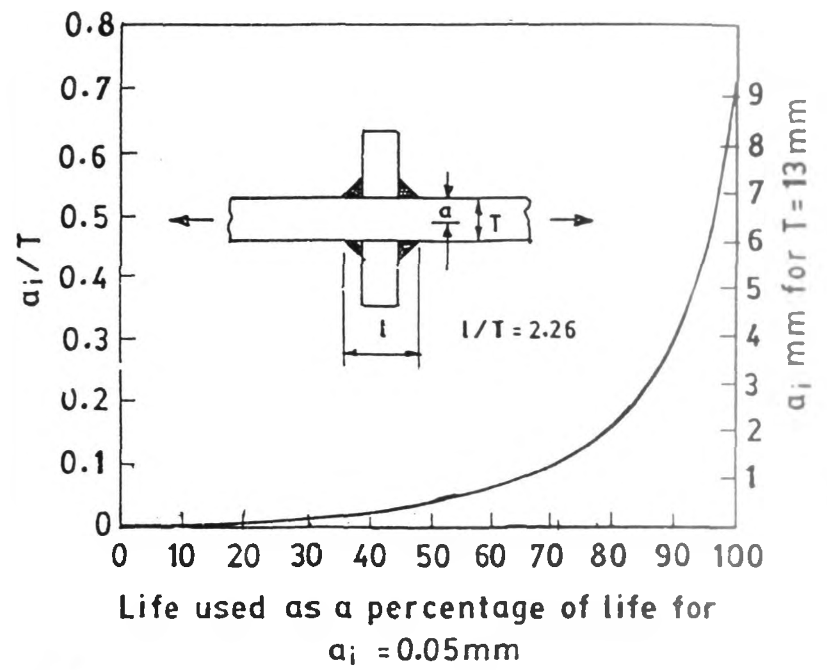


Fig 2 Influence of initial flaw depth on fatigue life predicted by fracture mechanics, assuming da/dN = C (ΔK)

flaws are undetected by conventional NDT methods. If one assumes a_i based on realistic detectable limit $a_i \simeq 1$ mm), then life prediction will be highly conservative. Figure 2 illustrates a typical example of fracture mechanics prediction for a fillet weld toe crack [14]. It is clearly seen from Fig 2, that for a = 1 mm, this approach assumes that only 30% of the potential life is remaining. Therefore, realistic life prediction is possible by FM approach by assuming the initial crack length, a_i value based on metallurgical examination. Such a knowledge becomes then important for each specific case until NDT method which detect much smaller flaws become available.

Another advantage of FM is that crack growth under variable amplitude loading could be modelled accurately including stress history effects and treating stresses below constant amplitude fatigue limit more precisely using the threshold stress intensity factor[14].

Improvement Techniques

A crucial feature of weld from the view point of fatigue is the weld toe and in general, fatigue cracking from the toe region results in poorest fatigue strength. Improvement methods developed to enhance fatigue lives of welds are primarily based on two approaches [15]: (1) To reduce the stress concentration factor at the toe by dressing (grinding, machining or remelting) and (2) to reduce the effective applied tensile stress range by introducing compressive residual stress (shot, hammer or needle peening). Table 1 lists the improvement in fatigue life due to various post weld treatments[15]. Modification of the surface region near weld toe delays fatigue crack initiation since the probable sites for crack initiation are removed. Adoption of such techniques provides greatest benefit in the high cycle regime where crack initiation period is significantly high. In addition, improvement techniques appear to offer the opportunity to use higher design stresses in high cycle fatigue applications and utilise high strength materials to advantage. It is important to study, however, the effects of mean stress in joints subjected to stress improvement techniques.

Repair of Fatigue Cracks

In recent times, there is growing interest in extending the lives of plants and structures, containing fatigue cracks [16] This can be achieved by performing repair welding on the premature fatigue cracks. At present, there is very little guidance in standards on repair methods and the fatigue performance of repaired joints. For this reason, Commission-XIII has recently formed a new Working Group with the specific task of producing recommendations on methods suitable for repairing fatigue cracks, application of these methods and what fatigue life can be expected after the repair.

Summary

This report briefly summarises present understanding of fatigue design and assessment methods for welded structures and components. Current design rules provide guidance on the estimation of the fatigue lives of welding structures. However, refinement is needed in areas like assessment of cumulative damage, improvement in stress analysis and correlations between weld quality and fatigue. Futher, accurate estimation of loading and service stress spectrum are necessary for realistic life prediction. Fracture mechanics approach can be employed for accurate life prediction of weld joints. There is need to improve NDT methods for assessment of small-sized flaws, so that more reliable predictions can be made. Post weld improvement techniques can be very effective. However, standardisation is needed in this area.

There is need to involve more laboratories in the country in studies related to fatigue of welded components and structures. One way to achieve this would be to highlight periodically the importance of this topic through discussion meetings, publications of summaries of current status in this area and inviting industries to fund this important activity.

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