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The reliability of welded structures—some contributions of Commission X of the IIW

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1. Introduction

In many of the expanding range of applications of welded structures, failure of the structure could lead to serious risks to life or health or to serious financial losses, for example due to equipment outage. There is therefore a growing interest in increasing the reliability of such structures by so designing, manufacturing and inspecting them that the risk of failure is reduced to a practical minimum. In many cases, it is recognised that such improved reliability can be economically worthwhile to the purchasers of the equipment, even when its attainment leads to higher first cost. The importance of such improvement in reliability is recognised throughout the work of the International Institute of Welding and many of the Commissions devote much of their work to this aspect. Limitations on time and space prevent a full review of all such work, and in this lecture I can only give a few examples taken from the recent work of Commission X, these examples being chosen to illustrate a theme rather than for their individual importance. I hope, however, that colleagues within Commission X and in other Commissions will accept this as a general acknowledgement of the contribution of their work to improved reliability.

There are three main ways in which a welded structure may cease to perform its function. It may deform excessively by stretching, bending or buckling; it may develop a leak so that it is no longer serviceable as a containment or pressure barrier; it may suffer gross separation by tearing or fracture so that it can no longer carry the imposed loads. The prevention of excessive deformation has been the basis of engineering design for many years, and most of the existing design codes are aimed at this aspect. Nevertheless, improvements in detailed aspects are being made continuously, as is indicated by the continued work on design aspects in Commission XV "Fundamentals of welding design and fabrication for welding" and in much of the work on pressure vessels and piping, Commission XI "Pressure vessels, boilers and pipelines". More recently, there has been some use of welded structures at temperatures at which creep deformation may occur, and this topic was reviewed in depth at a Colloquium organised by Commissions IX "Behaviour of metals subjected to welding" and XI in Toronto in 1972.

Considering next the possibility of leakage, one major cause of such leakage can be penetration of the containing metal by a growing fatigue crack. The problem of fatigue and the definition of rules to prevent leakage or failure from fatigue is the prime object of the work of Commission XIII "Fatigue testing". Another possible cause of leakage is localised penetration by corrosion, a subject discussed in detail in 1975 at Tel Aviv in the Public Session organised with the help of Commission IX.

The most dramatic form of failure is of course that of separation of the load-carrying components by fracture or by tearing. Apart from the fatigue aspect covered by Commission XIII, traditional design takes care of such failures by the prevention of the excessive deformation

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which in structural materials of adequate ductility precedes fracture, provided that there is no strain-localising flaw or defect in the structure. The problem of which we are forcefully reminded by the occasional major failure is that, in the presence of a sufficiently large crack-like defect, such failures can occur at loads permitted by the relevant design specifications, usually as a result of fast fracture with only small amounts of overall deformation.

Several of the Commission of the IIW are doing work relevant to this aspect, either by reducing the incidence of cracking (Commissions II "Arc welding", IX, XII "Flux and gas shielded electrical welding process") or by improving their detection and repair (Commission V "Testing, measurement and control of welds"). The important contribution of Commission X to the improvement of reliability is essentially that of improving our understanding of how to prevent fracture in welded structures in the presence of local crack-like defects. The following discussion will concentrate on this aspect.

2. The effect of defects on failure conditions

An important source of information on the factors leading to failure of welded structures is the examination of causes of actual failures. This aspect has been covered by Sub-Commission D "A co-operative international study of fracture, other than fatigue fracture in both fabrication and service"*, which has obtained technical details of about 100 failures and analysed them to identify the factors which led to the failures, this work relating primarily to failures in structural steel. Most of the cases occurred at moderate or low nominal stresses, within the ranges usually considered safe for the structures concerned.

The initiation of failures was almost always associated with notch efleets due to discontinuities either inherent in the design or arising from accidental damage or from flaws introduced by welding. There was an increased risk of failure with materials of low notch toughness, regard less of whether the low toughness resulted from a poor initial choice in relation to the structure thickness and service conditions, deterioration in fabrication, heat treatment or service, or the local reduction by the effects of welding which can be pronounced in structures that have not received post-weld thermal treatments. In addition to this effect of welding in modifying the local properties and in possibly introducing crack-like defects, welding could also increase the risk of failure by introducing thermal and residual stress. Many of these aspects have been confirmed by conclusions deriving from tests done under more controlled conditions on large welded steel plates. An inportant monograph on this topic by *Hall*, Kihara, Soete and Wells (1), produced as a result of Commission X collaboration, reviews authoritatively the work in this field up to 1967. Its conclusions are as relevant today as when they were written. Speaking of measures to reduce the risk of failure in welded steel structures, the authors said "Foremost would be selection of a material (through screening studies) which would be notch tough at or below the expected service temperature, yet which is weldable (without deterioration of properties), if welding is to be employed, and not susceptible to extreme ageing effects. The design would include careful consideration of the fabricated structure in terms of the base material and the welded structure as a whole, with careful attention being given to the possibility of local flaws, or the propensity for such fractures to run even a short distance shoud they occur in any event. Normally, non-destructive inspection techniques would be employed during fabrication, such as X-ray or radiography, ultrasonics, and magnetic techniques. These techniques alone, as is well known, do not guarantee that tiny flaws which can be sources of cracks cannot still exist, and in some cases they do not always detect larger flaws. Good design normally includes proper attention to the elimination of flaws, structural discontinuities and high residual stress, especially in situations involving significant structural constraint. If conditions warrant, both in size of the structure and cost considerations, it is common to consider removal or at least amelioration of the residual stresses in the structure. Residual stresses may be reduced by postheating procedures, or alternatively in many cases by mechanical stress relief (loading to a stress level greater than the expected service level).

These important topics of (a) definition of notch-toughness to provide more effective methods of material selection, (b) identification of the size of defects which may be a serious risk, and (c) devising appropriate treatments to reduce residual stress and local notch embrittlement effects have been the main features of the work of Commission X in recent years.

3. Some theoretical aspects

The studies of failures and large scale tests have shown that the failure stress in the presence of a defect decreases with the increasing size of the defect, depending also on a property of the material called fracture toughness. Formal relationships between these parameters have been sought in order to enable prediction of the failure stress of particular structures containing known or

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*Doc. IIS/IIW-61-60 "Co-operative study of brittle fracture in service" and IIS/IIW-160-65 "Provisional report on an international investigation of brittle fractures".

assumed defects from material properties data obtained from carefully-defined laboratory tests. In the general case such formal relationships are complex and difficult to derive without simplifying approximation. One such approximation that can often be applied, especially to large structures made from materials of thick section, high strength and relatively low fracture toughness, is that failure precedes general yield. In such cases, the well-developed Linear Elastic Fracture Mechanics can be applied, based on the concept that failure will occur when the local stress intensity factor (K_1) near the tip of defect exceeds a critical value (K_1C), this parameter K_1C becoming a measure of the fracture toughness of the material. The stress intensity K is related to the applied stress σ and the defect size parameter (a) through a relationship of the general type $K=F(\sigma\sqrt{a})$. A detailed methodology for the protection of welded pressure vessels against non-ductile failure has been defined in Appendix G of Section III of the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code, 1974 Edition. This Appendix spells out the detailed procedure to be used including the method for calculating the stress intensity factor K_1, reference values for fracture toughness (K_IR) of specified materials, and for the size and shape of postulated "design defect", considered to be very large when compared with the sensitivity of modern non-destructive testing techniques.

Whilst this treatment has been a major step forward in fracture assessment, it is recognised that the approach is not valid in many of the general engineering applications involving materials of this section, lower strength and high fracture toughness. In such cases, some form of Elastoplastic or General Yield Fracture Mechanics is required, and the Commission X Working Group on Fracture Mechanics Theory is currently concentrating its efforts largely on the assessment of various proposals that have been made to fill this need.

One of the main approaches to this problem was described by Wells in his Houdremont Lecture (2) and assumes that failure will occur when the local displacement at the crack tip (the Crack Opening Displacement—COD or σc) exceeds a critical value σc which is a material property. Work on this approach continues, together with that which makes use of advances in the methods of stress analysis in the crack tip region to derive an elasto-plastic stress intensity factor K_1P (see for example the work of Chell (3). Another approach of great current interest attempted to reduce the uncertainties which arise from concentrating attention on the complex area at the crack tip by determining around the crack the "Path independent integral (J)" which can be defined as the change in potential energy for a unit extension of crack length (4). The concept is that failure occurs when J reaches a critical value J_1C which is regarded as a material property.

4. Estimation of defect significance

One of the most important reasons for following fracture mechanics work in Commission X is to provide a better understanding of the engineering significance of flaws and defects so that inspection acceptance levels can be based on rational judgement rather than on subjective experience. Such an approach has been encouraged by the growing sensitivity and reliability of non-destructive examination (NDE) techniques and represents a major change in philosophy in the use of NDE to provide a specific safeguard against the presence of dangerous defects, these being defined on the basis of "fitness for purpose" arguments, rather than to form part of a general quality assurance scheme. Such an approach can be justified on reliability grounds since weld repairs are often themselves the source of further defects or of detrimental changes in local material properties, particularly if the materials involved show progressive grain growth on each cycle or if post-weld heat treatment is not possible. Moreover, an important improvement in reliability could arise from the fact that such an appraisal directs attention to the most important aspect of improving quality, that is, to reducing the number of significant defects, particularly large crack-like flaws or lack of fusion. From the fabricators' viewpoint a rational basis for acceptance standards makes sound economic sense. As evidence for this statement there is the data collected by Salter and Gethin (5) from 599 main seam welds totalling 60m in length. By current inspection acceptance standards, 806 defects had to be repaired, but analysis of these showed that only 19% were planar defects such as cracks or lack of fusion; even pessismistic "fitness for purpose" standards of acceptance would have reduced the number of repairs from 806 to 153 and the number of repaired seams from 258 to 70.

"Fitness-for purpose" acceptance standards related to fast fracture aspects have been put forward in several parts of the world following the Public Session of the 1962 Annual Assembly in Toronto, and the continued efforts of Working Group of Commission X working in conjunction with Commission V and its Sub-Commission F "Welding defects and their significance". In the USA the 1974 Edition of the ASME Boiler and Pressure Vessel Code, Section XI (In Service Inspection) gives a detailed specification of the methods for judging acceptability of any flaws found by NDE during such inspections. The specification covers first the standardisation of ultrasonic calibration procedures and of reporting levels, the methods for determining a single size parameter for an irregularly-shaped defect, and the methods and inputs to be made in the fracture mechanics calculation of acceptability. The method is based on Linear Elastic Fracture Mechanics (LEFM) using input data from the large scale Heavy Section Steel Technology programme of fracture toughness, fatigue and pressure vessel tests of which the US Welding Research Council is one of the sponsors. The ASME XI specification is of course directed at nuclear reactor pressure vessels and the Working Group of Commission X has aimed at producing a proposal of more general applicability. A major paper prepared by this Group was published in 1975 under the title "Proposed assessment methods for flaws with respect to failure by brittle fracture" (6). This paper provides general rules from which more detailed specifications for particular applications can be derived. The flaws are categorised as planar defects such as cracks, lack of penetration or of fusion, and non-planar defects such as solid inclusions, gas pores, shape imperfections including undercuts. The two categories have different acceptability standards, those for the non-planar defects being derived from laboratory tests and experience, both with respect to the effect on strength in the direction normal to the applied stress, and with respect to the possibility of these defects hampering the effective inspection of the material, with the risk of failure to detect some dangerous planar defects. These considerations lead to the values shown in Table 1.

Table 1. Limits for inclusions and porosity

Inclusion length (max) as-welded	Inclusion length (max) stress relieved	Porosity percentage or projected area on radiograph	Individual pores diameter
No maximum length-Max height or width 3mm	No maximum length-Max height or width 3mm	5	e:4 or 6mm, whichever is lesser
-	e=thickness		

With regard to planar defects, the proposal defines the acceptability of a flaw in terms of a single size parameter a, and gives detailed rules for relating this parameter to real defects of different types and irregular shapes. The permissible value of a and the detailed method of calculation differ according to the total level of stresses in the region of the flaw. Primary, thermal, residual and peak stresses must be added together and if this sum gives a value less than yield, then the stress intensity factor (K) approach of LEFM is used, methods are proposed for dealing with stress concentration effects, with the bending effects associated with long flaws and with the differences between surface and embedded flaws. In cases where the total stresses exceed the yield stress (for example, as welded structures where the residual stresses alone are usually at yield stress level) the approach is based upon General yield Fracture Mechanics and the measurement of assessment of fracture toughness by Critical Crack Opening Displacement (σ_c). In summary, the flaw is regarded as acceptable if its equivalent defect size parameter a is less than a tolerable value $\bar{a}_m$ where
$\bar{a} = C(K_{1c}/\sigma_y)^2$ where σ total $< \sigma_{y1}$
or $= C(\sigma/e_y)$ where σ total $> \sigma_{y1}$

The value of the constant C is taken from a curve given in the proposal and here reproduced as **Fig. 1**.

Some national standards based on the proposal have already been drafted (for example in Sweden and the UK) and experience is being gained with their application. The working Group has subsequently been looking into the problem of dealing with materials that in a fracture toughness test show a wide range of strains before fracture at which stable crack-growth occurs, particularly where this is coupled with a flat load/strain curve around the maximum load point. One proposal being examined is that under such circumstances the critical value should be the COD corresponding to 95% of maximum load. Extensions to the proposals to allow the use of J or other elastoplastic treatments are being considered.

5. Estimation and reduction of stress levels

The preceding discussion has emphasised that protection against non-ductile failure relies upon there being an appropriate balance of the three factors—maximum defect severity; stress applied to such a defect; material fracture toughness in the region of the defect. Commission X has made contributions in each of these areas. With regard to stresses, work has been done on the calculation and measurement of the local stresses residual from the welding process and on the reduction of such stresses by thermal and mechanical stress relieving treatments.

a) *Estimation of residual stresses*

Whilst it is a truism that yield-level stresses almost always arise in the vicinity of the weld in an as-welded sample, it is sometimes necessary to know in more

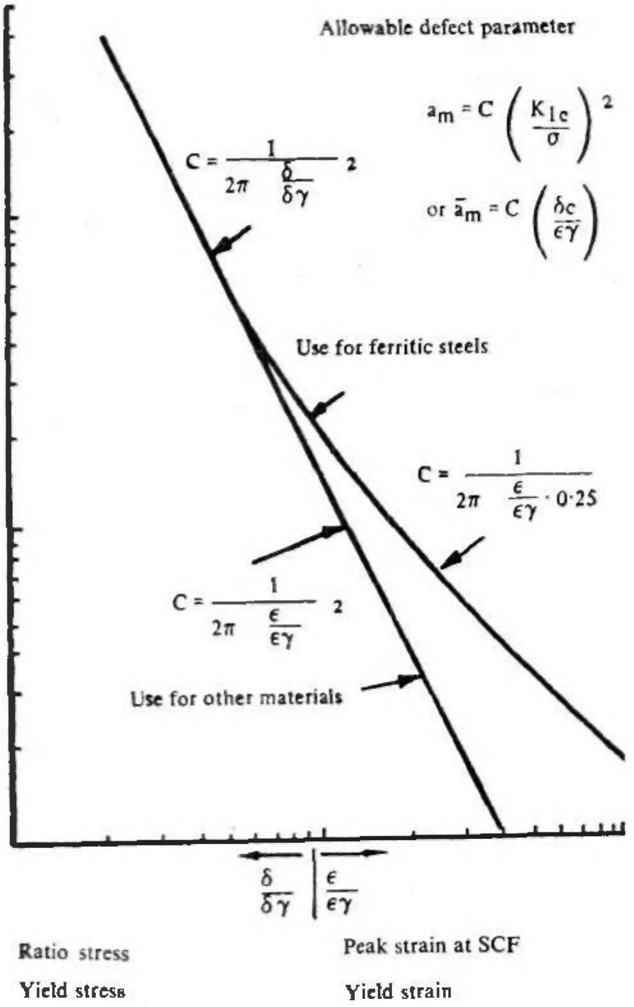


Fig. 1. Value of constant "C" for different loading conditions.

detail of the local levels of stress and strain and of their distribution. Improvements in stress and strain analysis, particularly those involving the use of such computer techniques as finite element or finite difference methods, are rapidly expanding our knowledge, and a Working Group on numerical analysis of stresses, strains and other effects produced by welding is considering this aspect. A state-of-art report by Masubuchi (14) emphasised the range of techniques and solutions available and the Working Group has prepared an annotated bibliography which should enable users to identify where solutions are available. Some examples of the topics covered include the estimation of residual stresses in aluminium alloy welds (8) and in a welded shaft overlap (9), transient and residual stresses in a multi-pass weld (10), residual stresses after gas cutting and welding high strength steel (12), residual stress in patch-welded circular plates (11) and the residual stresses due to a slit weld (13). An important extension to these studies is that of the estimation of the residual stresses near to the weld following post-weld stress-relieving treatments, since such information is important in flaw-significance calculations. A proposal has been made by Fujita et al (15) using the results of a conventional stress relaxation test to calculate the stress relief annealing in a rectangular plate.

b) *Measurement of residual stresses*

The interest in finding methods of calculation for residual stresses in as-welded and in stress-relieved weldments has arisen because most methods of experimental determination of such residual stresses involve the destruction of the specimen by progressive removal of layers of metal. Recently there has been a renewed interest in finding improved techniques for the experimental measurement of residual stresses, some of these methods under trial being non-destructive. A review by Schofield (16) and other papers presented to the 1975 Annual Assembly of the IIW highlighted their interest and led to the setting up of a new working group to assess and recommend methods for such measurements, particularly with respect to non-destructive techniques. Some of the methods described by Schofield were summarised in a Table (see Table II) and their various advantages and disadvantages compared. In many cases helpful results can be achieved by drilling small shallow holes in the vicinity of strain gauges, or making use of physical measurements from small balls located in such holes.

c) *Thermal stress relief*

It is well known that a post weld thermal treatment can improve the reliability of a welded structure by reducing the risk of brittle fracture. Part of this improvement results from the reduction of residual stresses and the role of such stresses has been demonstrated by Hall, Kihara, Soete and Wells (1). Early work of Commission X concentrated on the effect of the thermal treatment in reducing the residual stress, largely on the basis of tensile creep-relaxation tests and indeed most specifications are still based on this one parameter. More recently other effects of the thermal treatment have been recognised, some advantageous, some detrimental. A Commission X Working Group report in 1973 reviewed these aspects with particular attention to the effect on the mechanical properties of welded joints (17). The report starts by comparing the specifications then current in different countries (Table III). After discussion of various experimental results, the Working Group reached a number of important conclusions which are worth repeating as they have not all yet been acted

Table II. Summary of methods for strain and restraint measurement

Name of technique	Approx. temp. limit (°C)	Advantages	Disadvantages
Electric resistance strain gauges	400	1. A well-known technique. 2. Simple. 3. Cheap—able to follow transient strains.	1. Temperature limited for use near welding.
Opto-mechanical gauges	300-1,000	1. Capable of high temp. strain measurement with suitable equipment.	1. Equipment often delicate and may be difficult to use.
Brittle lacquer	370	1. Gives a strain picture over large area. 2. Cheap and simple.	1. Temp. limited for use near welding. 2. Cannot measure transient strains. 3. No measurement possible during welding; i.e. before and after only.
X-ray diffraction	Room temperature	1. No contact with specimen. 2. Almost a point measurement.	1. Equipment bulky and expensive. 2. Cannot measure transient strains. 3. Measurement is made in immediate surface only and may give misleading results.
Moire fringes	Melting point of material to which grid is etched	1. Gives a strain picture over a large area. 2. High limit to temp.-etched grid not affected by welding except when melted. 3. Can measure elastic-plastic strains.	1. Incapable of following transient strains (except in special cases). 2. Time-consuming. 3. No measurement possible during welding, i.e. before and after only. 4. Totally destructive for internal strain measurements. 5. High quality surface finish required.
Holography and speckle pattern Interferometry	Room temperature	1. No specimen preparation. 2. Accurate. 3. Can measure elastic-plastic strains. 4. Can monitor transient strains with correct method.	1. Extremely sensitive to convection currents set up 2. by a heated body. 3. Small size specimens only. Lab method only.
Capacitance strain	600-800	1. Accurate, high-temp. strain gauge. 2. Small. 3. Easy to use.	1. Localised strain only. 2. Limited size of gauge length available (at present).
Hickson replica	Melting point of material on which lines are scribed	1. Can measure elastic-plastic strains. 2. Short gauge length. 3. Grid not destroyed by welding, unless melted.	1. Cannot measure transient strains. 2. No measurement possible during welding, i.e. before and after only. 3. High quality surface finish required.

upon by the specification writers. For example, the Group emphasised that post weld heat-treatment, whilst beneficial in respect to brittle fracture of weldments, to dimensional stability and to stress-corrosion resistance, can have detrimental effects in reducing the strength of parent plate, particularly if high temperature and long times of treatment are used. In low alloy steels there can be over-ageing effects, and general embrittlement, for example by the "temper-embrittlement" mechanism. Special problems arise for materials welded with high-energy processes or for materials which show significant strain-embrittlement which certain types of post-weld heat treatment can effectively remove. The choice of heat treatment conditions is thus a matter requiring careful consideration and the balancing of several factors. The Group advised that such treatments should be reduced to the minimum of time and temperature which would achieve the required aims, and stressed that many of the present specifications for carbon and micro-alloyed steels called for excessive temperatures and overprolonged soaking times. For low alloy steels, each of the effects mentioned above may be enlarged and further investigation is necessary to determine the optimum treatment.

The most important immediate task for this Working Group is to define the conditions when it can be recommended that post-weld treatment can be omitted. One particular aspect of practical importance relates to the amount of small attachment welds that can be allowed after the last thermal treatment; a special review of this topic was commissioned at the 1975 Annual Assembly. More generally, it is recognised that the risk of brittle fracture in some thin-section structures is so reduced that post-weld heat treatment can be omitted, but the requirements differ markedly between different countries. One attempt to put forward a rationalised basis for such aspects of a specification was put forward by Watanabe (18). He suggested that the limiting thickness for post-weld heat treatment should be that which would just tolerate without brittle fracture the presence of a crack of depth equal to half the plate thickness with an applied strain equal to the yield strain in material whose Charpy Fracture Appearance transition temperature (VTS) was 0°C. Using the experimentally determined correlations in this way he concluded that low alloy high strength steels of the HT60 grade did not need heat treatment if less than 50 mm thick, and the HT 80 grade did not if less than 38 mm thick. This proposal and others put forward subsequently (19) are being evaluated by the Working Group.

(d) *Mechanical stress relief*

In some welded structures it is impractical to consider thermal treatment for reducing residual stresses. In some cases all that can be done is to choose welding procedures and materials such that the detrimental effects of residual stress are minimised. In others it is possible to reduce the level of residual stress by the application of "mechanical stress-relief". To be more precise, the type of mechanical stress relief that has been shown to be effective is that involving the application of mechanical loads sufficient to cause some plastic deformation; other methods sometimes regarded as providing stress relief (peening and vibratory treatments) are of less proven value and will not be discussed further here.

The use of overstressing to provide mechanical stress relief was reviewed for Commission X by Nichols (21) with the help of many contributions from Commission members. It is important to distinguish between three separate uses of the overstressing techniques, namely:

(a) In structures not given a thermal stress relief, to reduce the level of residual stresses near to welds by producing local yield. By reducing such residual stresses, it is expected that the risk of fracture at a particular level of externally applied stress is also reduced.

(b) To demonstrate that a structure does not contain defects sufficiently large to cause failure on subsequent application under similar conditions of a slightly smaller service load. Whilst such an approach has always been qualitatively implicit in the proof test which is common to many design codes, of recent years various fracture mechanics approaches have made quantitative treatments on the basis.

(c) To remove the damaging effect of any defects which exist, for example, by work hardening the material at the tip of the crack to increase its yield strength, by producing local yield there which leaves a residual stress pattern and so reduces the stress at the tip of a crack under a given external load, by reducing the sharpness of the tip of a crack by the local yield. These effects would be expected to apply even to vessels which have already been thermally stress relieved unlike (a), and should have beneficial effects at temperatures lower than those at which the overstressing was done.

With regard to (a), mechanical stress relief becomes more complete the higher the overstress applied, be-

Note : t=thickness in in e=thickness in mm

Code	Furnace start temperature	Heating rate	Treatment temperature	Soaking time	Cooling rate	Finish temperature
ISO/TC II/SC 3 April 70 Draft/ Project 71	400°C	Max 220°C/h ou $\frac{220^\circ C/h}{t}$ ou 55°C/h t=maximum thickness	550—600°C	2mn/mm 30 mn mini 120mn maxi	275°C/h maxi $\frac{275^\circ C/h}{t}$ ou 55°C/h	400°C
BS 1113 tubes/pipe work t>20 mm 1969	300°C	Max. 200°C/h ou $\frac{200^\circ C}{t}$ ou 50°C/h	580—620°C	2 h/in maximum thickness	Maxi 250°C/h $\frac{250^\circ C/h}{t}$ ou 50°C/h	400°C
BS 1500 (1958) Pressure vessels applications	300°C	200°C/h ou $\frac{200^\circ C/h}{t}$	600—650°C 575°C—1,5 /h25 mn ou 550°C—2,5 h/25 mn 525°C—2,75 h/25 mn 300°C—6 h/25 mn 475°C—12 h/25mn	1 h/25 mn	250°C/h max $\frac{250^\circ C/h}{t}$	300°C
BS 3915 (1965) Pressure vessels	300°C	250°C/h ou $\frac{250^\circ C/h}{t}$	580—620°C	$a+\frac{b}{4}+\frac{c}{10}\geq 1$ ou a=h entre 600/620°C b=h entre 575/600°C c=h entre 550/575°C	250°C/h maxi $\frac{250^\circ C/h}{t}$	300°C
Din 17 155			A 37 – A 42 600/650°C A 48— 550/620°C A 52— 550/620°C			
ASME	310°C	Max 205°C/h ou $\frac{205^\circ C/h}{t}$ or 38°C/h	595°C 565°C 540°C 530°C 485°C	1 h/25 mn 2 h/25 mn 3 h/25 mn 5 h/25 mn 10 h/25 mn	235°C/h maxi ou $\frac{235^\circ C/h}{t}$ oy 38°C/h	310°C
Code chaudronnerie (France)	300°C	$\frac{500^\circ C/h}{e}$ maxi - 200°C/h	500—650°C	2mn/mm	150°C/h a 300°C/h	300°C
Technigaz (France)		2 h de 400 a 600°C 1 h de 600 a 640°C	640°C±10°C	2h	1 h de 640-600°C 3 h de 600-400°C	
Traitement des constructeurs de chaudiere		80 a 1000°C jusqu, a 300°C 60—80°C/h de 300 - 650°C	650°C	1 h/25 mn	80—100°C/h jusqu, a 300°C	300°C
ABC			620°C±25 C	1 h/25 mn	still air	315°C

coming virtually total once general yield occurs. For this purpose it is desirable to use the highest prestressing load practical without causing gross distortion or failure. The latter is made less likely if the prestressing is done at a temperature above the transition temperature of the steel (defined in such a way as to allow for the maximum plate thickness), if the level of preload is limited and if a prior non-destructive inspection indicates that the structure is free of major defects. It is well established that such treatments in fact do reduce residual welding stresses, and do increase the external stress needed to cause failure at temperatures in the brittle range. Most of the experimental work on the effect of overstressing relates to this application to as-welded structures, and leaves no doubt as to its beneficial effect. This work indicates that the gains accruing from the removal of high residual stresses far outweigh any detrimental side effects. Such prestressing even reduces the risk of failure from mechanical notches introduced into the structure near to welds after the overstressing operation, although any subsequent welding operation, of course, can increase the risk of failure again by reintroducing residual stresses. The beneficial effect of overstressing to mechanically stress relieve a structure is sufficiently established to make possible a recommendation that it should be accepted universally as a worthwhile procedure if thermal stress relieving is not possible. However, thermal stress relief is preferred, if it can be done, since this also removes metallurgical embrittlement near to welds and increases the ductility (so possibly reducing the extent of a failure) in contrast to mechanical stress relief in which only the failure stress is increased.

With regard to the use of overstressing as a final inspection tool (see (b) above), it must be remembered that this is only effective in so far as the overstressing reproduces and somewhat exceeds the loading conditions which will subsequently occur in service. The effects of distribution of load, rate of loading, temperature, thermal and other secondary stresses must all be considered. If these are all taken into account, it is difficult to see how such an overstressing can fail to be beneficial in increasing confidence in a structure. Provided that one only slightly exceeds service conditions, any detrimental effects must be very little different from any changes which may occur in any case in service. Such a procedure thus appears well justified although it must be repeated that it is only good insofar as it reproduces the actual service (and valid accident) conditions.

The use of overstressing at ductile temperatures to reduce the damaging effect of defects, even in the brittle range (c) above, is the most controversial, and the one for which there is the least experimental support. Such support must be obtained from tests on stress-relieved structures, or on plain unwelded notched specimens. The evidence suggests that the failure stress of such a prestressed specimen under conditions where failure occurs at low general stress levels (e.g. brittle temperatures) is at least as high and usually higher than the stress for failure of a similar unprestressed structure under similar conditions. In many cases the failure stress is as high as the prestress, but this does not appear to be so if very high prestresses are used. If sizeable defects exist which are just sub-critical at the overstressing conditions, some extension of the defect by ductile tearing may occur. The effect of reduced benefit under high loads, or just sub-critical loads, appears to result from so much local yield at the tip of a defect that on unloading, reverse yield occurs and the beneficial compressive residual stresses are not fully developed. Under such cases some reyield could occur at the crack tip on subsequent loading, and if the material has been embrittled (for example, by strainageing or hot straining) failure could occur. It thus appears desirable in this case (unlike the case of 'mechanical stress-relief') to limit the overstressing to a modest increase over that of actual service (say 20%) in which case it would appear that the treatment is effective. It is, of course, implied in the above discussion that the sense of the overstressing (i.e. tensile) is the same as that of service, since the reverse stress would have detrimental effects.

6. Assessment of fracture toughness

One of the most important aspects of defect assessment is that of establishing the relevant fracture toughness properties of the material in the vicinity of the defect. Recognition of this has been a major factor in recent developments in the appraisal of the large variety of fracture toughness and notched bar fracture tests that have been developed over the years, and a Working Group of Commission X has been concentrating on the standardisation of fracture toughness tests suitable for use in the quantitative assessment of defect significance. The first output from this group was the recommendation for standardisation of methods for the sharp-notch fracture toughness tests suitable for K_{1c} and COD measurement of conventional "static" rates of loading and these recommendations have been used in several countries. In the UK, for example, the British Standards Institution issued two Drafts for development (DD3 1971 and DD19 1972) for the K_1C and COD tests respectively. More recently the Group has reviewed the rates of strain typical of those applied to different welded structures and has concluded that most of the cases for dynamic K_1C and COD measurements can be covered by using the conventional specimens in hydraulic tensile machines of appropriate displacement velocity. A proposal for comment (20) was issued in 1975, and the final version is intended to be available in 1976. The work of the Group continues on three major topics:

(a) The development of recommendations for standard procedures for measuring J_1C.

(b) The development of recommendations for a small relatively cheap "quality-control" fracture toughness test, probably based on the use of an instrumented test on pre-cracked Charpy specimens.

(c) The development of recommendations for a standard fracture toughness test for weldments.

With regard to the fracture toughness testing of weldments, a joint Working Group 2912 "Brittle fracture tests on weld metal" with the participation of delegates from Commission X gave detailed attention to methods for assessing weld metal. This concluded (22) that the specification of a Charpy value of 3.5 Kgm/cm² gave adequate protection for many structures. Where hazard assessment led to the need for more rigorous treatment, there was the proposal to use a special drop-weight test on welded specimens (the Niblink test) for dynamically-loaded structures, and the COD test for statically loaded structures. Commission X has widened the study to that of weldments including the heat affected zone, and round-robin tests are in hand to assess the effectiveness of specimen geometries proposed by Dolby and Archer (23).

7. The presence of defects

The final parameter involved in the attainment of high integrity is that of the avoidance of crack-like defects. In part, of course, this depends on the selection of fabrication procedures which will minimise the production of defects, and most of these are dealt with in other IIW Commissions. Commission X has however made some contribution to the assessment by other groups of the risk of crack-formation by providing methods for estimating the stress distribution during welding, an important factor in the assessment of risk of cracking during fabrication and in the interpretation of practical welding tests to assess procedures and materials for susceptibility to cracking. A paper by Satoh, Ueda and Matsui (24) is typical of the work discussed in Commission X and particularly concentrates on the Tekken weld cracking test widely used in Japan. This work emphasised that it is necessary to consider plastic strain as well as stresses with respect to weld cracking. It was also found that the preheat temperature required to prevent weld cracking depended greatly on the location of the weld in the Tekken test (Fig. 2). Similar work involving evaluation of restraint intensity was used to determine the best welding procedures for minimising the risk of cracking in real structures such as pressure vessels, building frames and turbine casings.

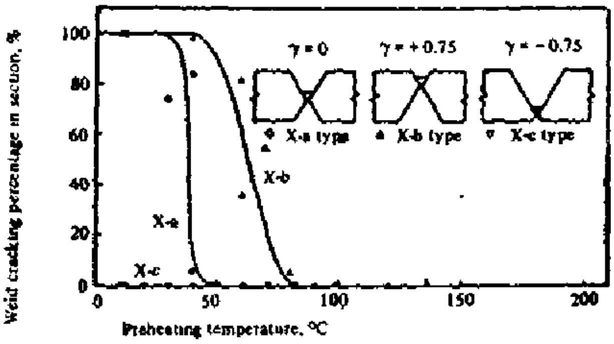


Fig. 2. Effect of eccentricity of weld on critical preheating temperature required for preventing weld crack in Tekken type specimens, (HT—80 steel, Q=17000 J/cm, plate thickness 30 mm).

An aspect of crack-prevention of direct concern to Commission X is that of choosing conditions for thermal post-weld heat-treatment such that reheat cracking during such heat-treatments does not occur. One form of such cracking is the brittle cracking which can occur if an as-welded component of low notch-toughness is subjected to high thermal stresses which can add to the residual stresses and so initiate brittle fracture from stress concentrations or smaller defects (25). Control of heating rate or of furnace loading temperature can be specified to reduce this risk, which is believed to be the cause of the crack which initiated a major failure in the Cockenzie steam drum (26). More recently there has been great interest in the high-temperature reheat cracking which can occur due to low stress-rupture ductility near to welds in alloy steels.

Turning to reheat cracking, recent work has led to considerably increased understanding of the factors involved in the assessment of the susceptibility of materials to the form of reheat cracking which occurs at higher temperatures. Vinckier (27), who is Chairman of an energetic Working Group on this topic for IIW Commission X, has reviewed the various tests, dividing them into assessment tests based on stress relief of formalised welded assemblies, tensile tests on weld-simulated specimens and simulation tests of the stress-relief cycle on weld-simulated specimens. Table IV is reproduced from Vinckier's paper, in which he compared and discussed the tests and presented results on 45 steels using a high temperature tensile test and stress relief simulation tests, both using simulated weld specimens. These tests demonstrated that the fractures were all intergranular and followed the prior austenitic grain boundaries, cracks starting by initiation at microvoids in the boundaries (Fig. 3.). The results showed only general similarity in their dependence in steel composition to the proposals of Nakamura and of Ito-Nakanishi (Fig. 4). Vinckier concluded that where possible susceptible steels should be avoided for applications in which they could be subjected to reheating in welding, either in heat-treatment after welding or in subsequent service. If this is not practical, then he suggests that :

(a) Tensile tests should be carried out at stress relief temperatures on weld simulation specimens heated to 1350°C. A minimum ductility of 20 % reduction in area should be required.

(b) The design should be checked to avoid as much as possible built in stress raisers and to allow adequate NDT inspection of all joints.

(c) By modifying the welding procedure (weld dressing, temperbeads, raising preheat temperature, etc) cracking in susceptible microstructures can sometimes be avoided.

(d) Careful NDT inspection should take place after stress relieving the structure and again after final pressure testing.

The Working Group studies formed part of the input into an authoritative review by Vinckier and Pense carried out for the US Pressure Vessel Research Council (28) relating to the particular form of reheat cracking which occurs when one layer of weld metal or weld-deposited cladding is deposited on another layer or on the parent plate. The review concluded that this in practice was a problem of one type of steel (A508 Class 2) and a change of steel specification to A508 Class 3 or A533 steel could markedly reduce the frequency of such cracking. This view was confirmed experimentally by Vinckier and Dooge (29) (Fig. 5). Where the more susceptible steel must be used, the avoidance of high heat input welding techniques can significantly reduce the risk, as can the subsequent re-normalising heat treatment of the heat affected zone material.

A final contribution of Commission X to the reduction of the possibility of significant defects remaining in a welded structure is in the development of the specialised non-destructive testing techniques using acoustic emission detectors. The interest of Commission X in this technique arose because its members made use of it to detect crack initiation during fracture toughness tests. The realisation that it could provide an overall inspection tool led to a Colloquium on this topic being organised jointly with other Commissions

Table IV. Tests to determine the susceptibility to reheat cracking

Stress relief of welded specimens		Tensile tests at high temperature		Stress relief simulation tests	
BWRA ring	(a)	Stress relaxation	(g)	Slit tube	(l)
Restrained butt weld	(b)	Gleeble specimen	(f)	Fracture Mechanics	(m)
Restraining jig	(c)	Dead loss stress rupture	(j)	Bend specimen	(n)
H-type restraint	(d)	Implant specimen	(k)	Elastic strain	(0)
Strained root bead	(e)			Plastic strain	(p)
Lehigh restraint	(f)				
CTS specimen	(g)				
Notched U-bend	(h)				

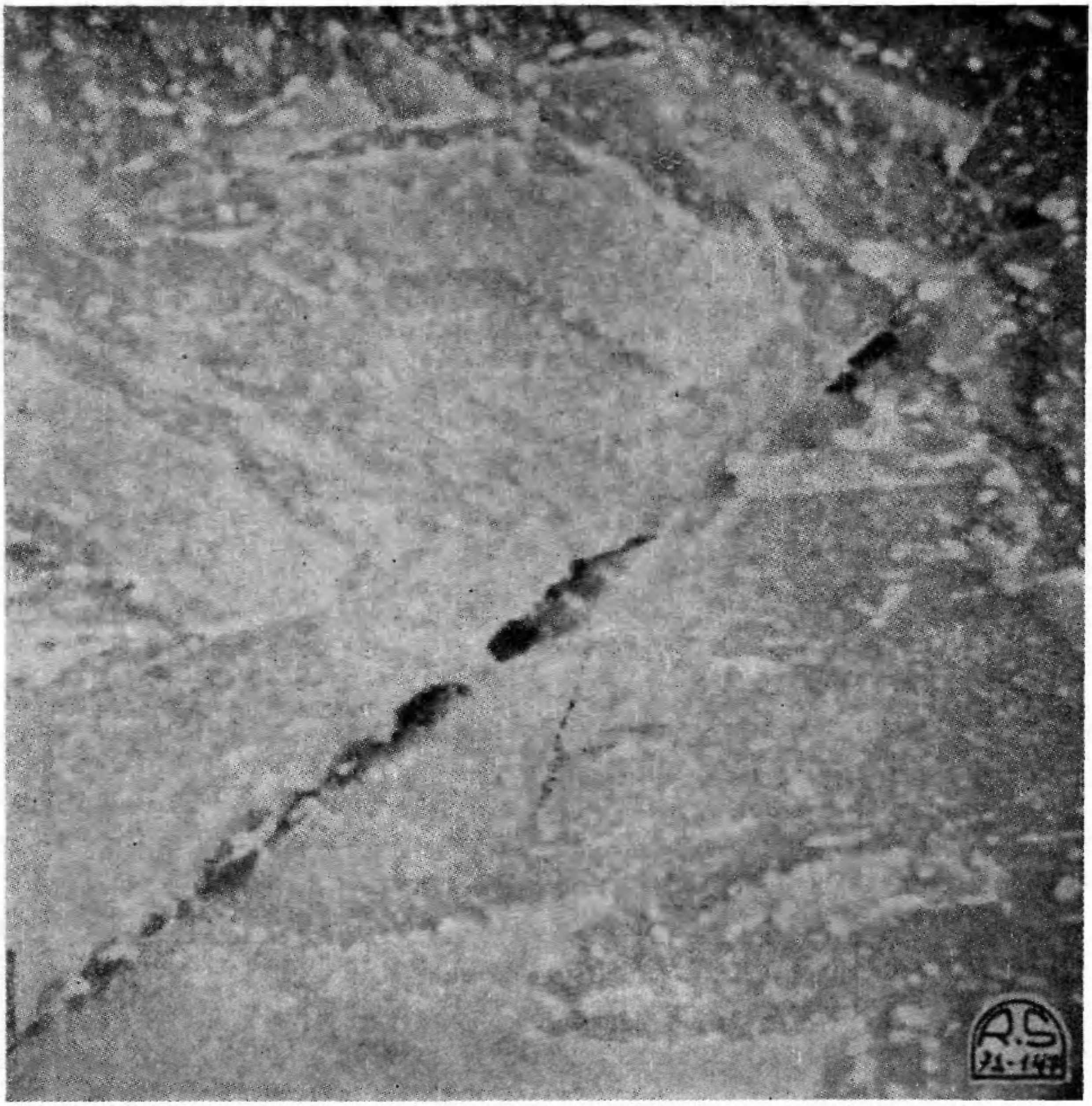


Fig. 3. Scanning electron micrograph of etched metallographic cross section. Steel no. 12.

at the Tel Aviv Annual Assembly in 1975(30), and these papers together provide a convenient state-of-the-art summary. In brief, acoustic emission is the transient elastic wave generated by the rapid release of energy in a material associated with the local redistributions of stress and strain that are frequently the first step towards failure of a material in a welded structure. Equipment to detect such emissions, to analyse them and locate the initiating sources has been developed to the practical application stage and standardised testing techniques are being developed. Whilst the method can be applied to detect defects as they form during welding, there can be many sources of signals other than defects, so that it is more easily applied to TIG and electron beam welding where the absence of slag and the minimum of oxide formation and metal transfer minimise interfering noises. Another aspect of application during fabrication is to the detection of delayed hydrogen cracking and of reheat cracking. However, the application of most immediate interest is that of detecting pre-existing defects as they are loaded in a proof test, for example, the over-pressure test frequently applied to pressure vessels and piping. A difficulty is that at present it is impossible to characterise a defect

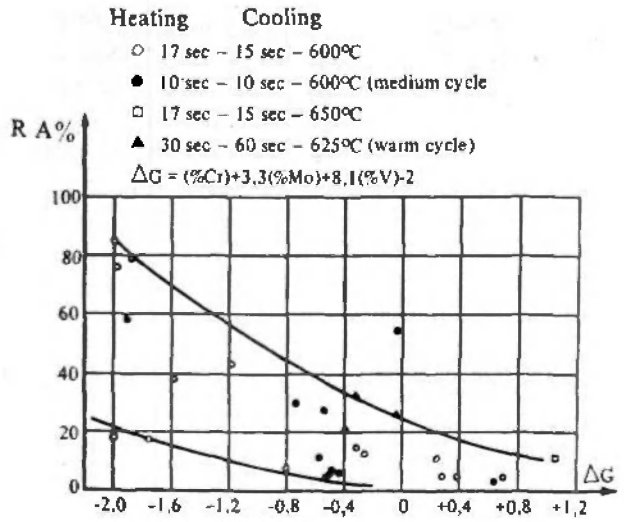


Fig. 4(a). Reduction in area at stress relief temperatures after weld simulation cycle to 1350°C in function of > G value after Nakamura et al.

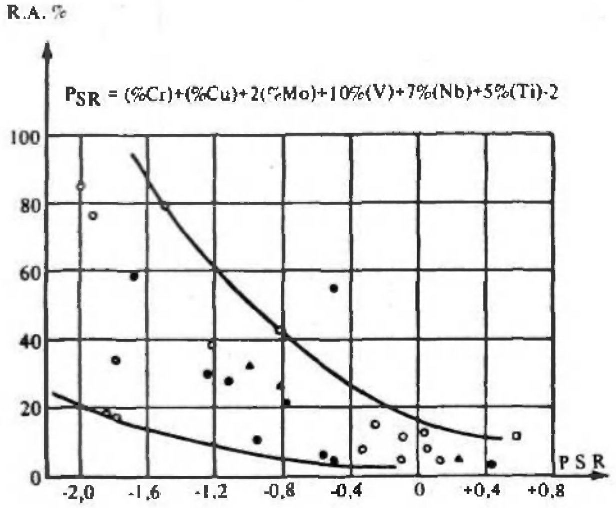


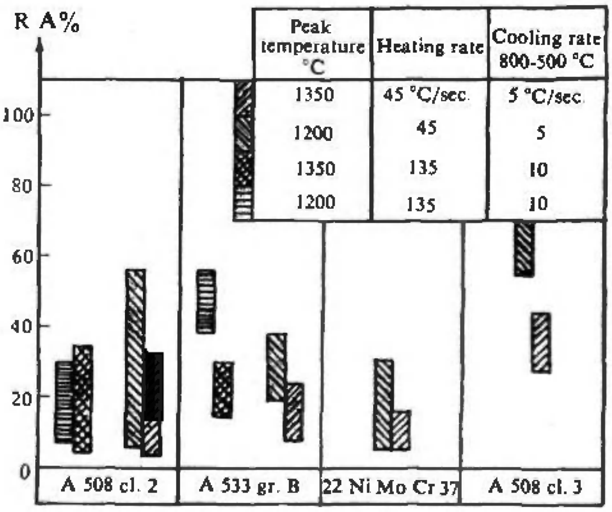
Fig. 4(b). Reduction in area at stress relief temperatures after weld simultation cycle to 1350°C in function of P value after Ito-Nakanishi.

from such acoustic emission signals: tests on large vessels have shown pronounced acoustic emissions from minor defects and surface effect whilst large crack-like defects have sometimes failed to produce signals. The amplitude of acoustic emissions can be dependent on metallurgical structure and is more pronounced in strong, brittle materials than in many common structural materials. Acoustic emission detectors can also be fitted to operating structures for surveillance of selected regions of interest, for example those likely to sustain high loads of a cyclic nature. Such techniques are being applied experimentally to a number of structures in which high integrity is required.

7. Quantitative assessment of level of integrity achieved

Whilst undoubtedly the work described above should lead to significant improvements in the integrity of weld structures, it is difficult to demonstrate this quantitatively because of the difficulty of providing evidence of the quantitative level of integrity achieved. Studies of failure rates of actual components or of experimentally-tested assemblies are unlikely to help because of the very large number of components required to establish the failure rate where this is very low; for example in many cases a failure rate as low as one in a million component/years is required. Recently attempts have been made to obtain improved estimates by studying the individual factors that can lead to failure, breaking these factors down into constituent stages and obtaining statistical evidence on the individual stages from sources other than the limited information on component behaviour in service or large scale tests. If one can be satisfied, as indeed one can for some types of welded structure, that the only residual risk of failure is that due to the risk of fast fracture, then such a probability assessment can be based on a fracture mechanics approach. This is the approach being followed by a new Working Group of Commission X concerned with probabilistic fracture mechanics. An example of such an approach has been given by Becker and Pedersen (13).

This approach suggests that since fast fracture will only occur if the applied stress intensity factor K_1 exceeds the critical value for crack extension K_{1c}, then the probability of failure is equal to the probability that at any point in the vessel the actual K_1 equals or



	Peak temperature °C	Heating rate	Cooling rate 800-500 °C
▨	1350	45 °C/sec	5 °C/sec
▨	1200	45	5
▨	1350	135	10
▨	1200	135	10

Fig. 5. Reduction in area in % at stress relief temperature after weld simulation cycle to 1200 and 1350°C.

exceeds a particular value K^x, and that the actual material property in the region where this stress intensity factor is applied is less than or equal to K^x, where K^x assumes all values between zero and infinity. The probability that the applied stress intensity factor K_1 exceeds a certain value must take account of the uncertainty in real stress field under different conditions, the probability that cracks of different sizes exist in the vessel, and the probability of variations in stress intensity factor due to crack geometry. The probability that the material property will be less than a certain value must take account of the actual spread in material toughness in any material, of any uncertainties arising from the experimental determination of the local variations due to welding and fabrication and of differences due to the possibility of the use of wrong materials or non-standard manufacturing procedures.

As the other probability approaches, the difficulty in its application is mainly one of finding verifiable input data. With regard to the relevant stress transients, in reactor technology considerable effort has been applied to establishing these for particular plant conditions and designs, but assessment of the likelihood of low-probability abnormal events requires considerable judgement. The next step in determining the stress intensity factor distribution is to estimate the numbers of defects of specific sizes which may have been left unrepaired in the vessel, in other words to provide a crack distribution function. This distribution itself depends on two different practical skills—the ability of a particular fabrication process to produce a vessel with a low incidence of large defects and the ability of non-destructive examination procedures to detect any such defects so that they can be repaired. There are few observed data on either aspect, and further work is very desirable to establish the defect distributions arising from different fabrication processes, and that left after particular non-destructive examination.

The other material properties of importance are yield point and fracture toughness; in contrast to the information on yield point, the information on variations of fracture toughness is limited, particularly with respect to data from other than the Charpy V-notch test. The Becker and Pedersen paper uses estimated distribution functions in each of these areas and applies the results to those cylindrical sections of a BWR vessel which are free from structural discontinuity. They consider that, for a mean stress of 26.0 ksi the failure probability over 40 years operation is as low as 2.5×10^{-8}, the failure probability being almost constant with time. There are many potential developments of such an approach both with respect to methods of analysis and with respect to experimentally-justified input data. Perhaps such detailed appraisal can be justified only for some of the most sophisticated of welded structures. The method is at present best regarded as one to highlight the areas where further technological development is most likely to lead to improvements in integrity.

8. Closure

The preceding paragraphs have indicated that the International Institute of Welding through the work of its Technical Commissions can make a real contribution to improved integrity and reliability of welded structures. The particular examples have been taken from the work of Commission X and it is a pleasure to acknowledge the contributions made to this work by present and past members of the Commission, and especially the chairmen of the various Working Groups and Sub-Commissions.

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