THE WELDING INSTITUTE

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THE EFFECT OF REPAIR WELDS ON SERVICE PERFORMANCE

For: American Institute of Steel Construction Inc.
By : G. Slater

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SUMMARY

A literature survey has been carried out in an attempt to establish the current technical knowledge relating to the service performance of repair welds in the structural steel industry. It has been found that in general, repair welds perform satisfactorily, but there are a number of cases where a failure has been a direct result of a defective repair weld. This usually comes about because there are particular problems associated with making a satisfactory repair, as well as the general problems associated with making any weld, and these are often not fully appreciated or understood. More importantly, the literature has shown that many repairs, perhaps even the majority, that are required by existing standards, are unnecessary from a structural point of view. This is particularly true of repairs to slag and porosity. There is an urgent need for supplementary codes of practice dealing specifically with the need to repair, and also guidance on how to repair. Such documents would need to be readily workable, and a quality band approach has been recommended as the most suitable.

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1. INTRODUCTION

In recent years, many major research programmes have been conducted to establish the significance of weld defects with respect to structural integrity and the likelihood of differing modes of structural failure. As a result of this research it has become clear that conventional weld defect acceptance criteria are arbitrary or based on good workmanship, and rarely relate to the possible effects of the defects on performance. This means that many repair welds made in industry are unnecessary from a fitness for purpose viewpoint, and as such they have adverse consequences in terms of cost, without any benefit in terms of structural integrity. In fact, integrity may actually suffer as a direct result of the repair.

It has been estimated that unnecessary repair and re-repair typically add 10% to construction costs. These direct costs are not insignificant, and furthermore the consequential extra cost in terms of late delivery etc, can often exceed them by an order of magnitude. The quality of a repair weld will often suffer due to practical difficulties arising from working conditions which are less favourable than those under which the original weld was made. There is a danger of introducing new defects which are more harmful and less readily detectable than those which are being repaired.

The type of defect most commonly repaired is three dimensional, such as porosity and slag inclusions. It is no coincidence that these defects are of the type most easily found by volumetric non-destructive testing methods, but the less readily detectable two dimensional flaws such as cracks and lack of fusion, which tend to be much more detrimental to structural integrity, may go unnoticed and unrepaired. The advances in the performance of non-destructive testing methods over the years have meant that such a situation has become increasingly unlikely, but with the consequence that more and more innocuous defects are located and unnecessarily repaired.

Now that the structural significance of weld discontinuities is more fully understood and approaches to their assessment on that basis are documented there has been increasing use of these approaches to evaluate the need to repair in specific situations, particularly in high-risk applications such as the nuclear power industry. However, it must be remembered that at present, fitness-for-purpose evaluations are often complex and time consuming, and in a few situations the cost of such may outweigh the cost of the traditional repair approach.

The present report describes a study of the published literature relating to repair welding in the structural steel industry. From the information contained therein, it has been possible to evaluate the effect of repair work compared with the effect of the discontinuity in its unrepaired condition. This data, together with a knowledge of the capabilities of modern fracture mechanics techniques in assessing the significance of discontinuities, provides for most situations a basis for a more rational and cost-effective approach to repair welding than current design and fabrication codes allow.

2. THE REQUIREMENT FOR WELD REPAIR.

Welding as a method of joining two or more pieces of metal together is a universal technique. In virtually every manufacturing industry, from micro-electronics to shipbuilding, welding has its place, be it small or large. The quality of welding is as diverse as its applications. For example, the simple spot weld that fastens the handle to the lid of a trashcan does not have the same quality requirements as the weld that joins two halves of a main supporting girder of a road bridge, and the latter in turn has very different requirements to those of a nuclear pressure vessel. Each is expected to fulfil a requirement, although with differing degrees of reliability, since failure of the first does no more than inconvenience one or two people, whereas failure of the latter two may cause death, injury and hardship to many.

The quality of a weld depends on a number of factors, the choice of design, consumables, and welding process are three obvious ones. Perhaps a less obvious factor is quality assurance - is the completed weld exactly what was intended by designer and fabricator ? The answer is usually "not quite", and the next question is, "does it matter ?" If the answer to that question is "yes" then corrective action is required.

Weld quality is often expressed in terms of the shape, size, location and frequency of the "defects" present, as well as in terms of mechanical and metallurgical properties. The term "defect" though, is somewhat misleading, as it implies the presence of a degrading fault or flaw. This is sometimes, but not always, the case. A better word to use is discontinuity, which describes more accurately what the word defect is often used to describe, without the automatic implication of imperfection.

Discontinuities in welding are normally classified from the fabricator's point of view as one of five major categories, these being, in alphabetical order:

1. Crack or crack like.
2. Geometric.
3. Lack of fusion/penetration.
4. Porosity.
5. Slag.

Such discontinuities may arise from inadequate design and/or fabrication but some are inherent in the welding process, and this should always be taken into consideration. To make a weld totally free of any discontinuity is impossible. One should always strive to avoid the poor design or bad workmanship that accounts for the majority of weld discontinuities, but the pursuit of perfection should always be considered along with the expense it involves, and whether or not it is necessary. Once the presence of discontinuities in welding has been accepted as inevitable, the problem arises of defining what is and what is not permissible. A reputable manufacturer recognises his responsibility towards maintaining an appropriate degree of quality control over his products, as his customer would expect. As far as welding is concerned, the problem extends further than defining what is acceptable. It is often difficult to establish exactly what size and type of discontinuity is present, but this must usually be attempted before any judgement of acceptability is possible.

In brief, there are two basic tasks to perform. First, the quality of the weld, in terms of size, type, location and frequency of discontinuities, must be established. Then a decision must be made as to whether or not the quality is sufficient for the job in hand, and if not, what corrective measures are appropriate.

2.1 Common Types of Discontinuities Associated With Welding

As stated earlier, weld discontinuities can be placed into one of five major categories. These categories are normally ranked in decreasing order of severity of their effect on the integrity of a welded structure (1) as follows: 1, crack or cracklike; 2, geometric; 3, lack of fusion/lack of penetration (LOF/LOP); 4, slag; and 5, porosity.

The reasons behind the order of ranking relate to the effect of the discontinuity on service performance, and will be considered in detail in Section 4. The usual causes of the various types of discontinuity are discussed below.

2.1.1 Cracks or Cracklike Discontinuities

Cracklike fabrication defects normally result from unsuitable materials and/or welding procedure, and are exacerbated by poor workmanship. Solidification cracking is caused by high thermally induced strain acting on insufficiently ductile weld metal, but this is very rare in structural steelwork nowadays. Hydrogen cracking can occur in the heat affected zone (HAZ) or weld metal, the former being the more common. It is caused by hydrogen diffusion from contaminated weld metal which embrittles the microstructure to such an extent that only a low level of strain results in fracture. Low hydrogen electrodes and submerged arc fluxes have been developed to combat hydrogen cracking, but possibly the most common cause is the usage of damp electrodes or fluxes. Lamellar tearing is a form of cracking associated with the presence of planes of non-metallic inclusions in the parent plate which reduce the transverse ductility to a level insufficient to accommodate thermally induced strain. This problem is most prevalent in heavy sections or highly restrained joints and can be avoided either by careful joint design, or preferably by using better quality steel.

In general, cracks or cracklike discontinuities are a result of incorrect or inadequate selection of materials, consumables, or procedure, and are sometimes beyond the control of the welder. This has important ramifications where inspection and quality control are concerned, as will be explained later.

Cracks are probably the most common type of service induced discontinuity. It has been estimated (2) that 90% of all structural failures result directly from fatigue cracking, or brittle fracture following on from fatigue cracking. Both types of failure normally initiate from a fabrication induced discontinuity, but not necessarily one that was cracklike. Stress corrosion cracking is an environmentally produced cracklike discontinuity which, as the name implies, is a product of corrosion acting on stressed metal.

2.1.2 Geometric Discontinuities

A geometric discontinuity in this context is a sudden change of shape or a surface irregularity. Weld profile is usually considered as a geometric discontinuity, although most are inherent in the design, for example, sudden changes of section at a weld joint, or the provision of a permanent backing bar beneath a single sided butt weld. Misalignment is a common source of geometric discontinuity not directly associated with the weld, as is angular distortion. The weld profile discontinuities in particular can be classified (3) under the following headings:

1. Undercut.
2. Concavity or convexity.
3. Excessive (or insufficient) reinforcement.
4. Poor reinforcement angle.
5. Overlap.
6. Burn-through.
7. Shrinkage.
8. Surface irregularity.

Some labels are interchangeable in certain circumstances, such as 2, 3 and 7. The term "reinforcement" although in common usage, is somewhat misleading in that it implies a beneficial effect, although in terms of stress concentration, the converse is true. The term overfill is generally the more accurate. All the above are directly within the control of the welder, and are consequently favoured areas of inspection where workmanship is under examination. Also under the control of the welder, but not directly associated with the weld are stray arc strikes and weld spatter.

Service induced geometric discontinuities are rare, the only likely one being pitting as a result of corrosion attack.

2.1.3 Lack of Fusion and Lack of Penetration

These discontinuities have been placed in their own category, for although they are usually planar, they differ from cracks in that their extremities are relatively blunt. Their nature and appearance are self-evident from the titles, and they are both indicative of incorrect welding procedure, poor workmanship, poor joint design, or a combination of these. Lack of penetration can be deliberate, as in a partial penetration butt weld. Lack of side-wall fusion can be through-thickness, especially in single pass weld. Lack of inter-run fusion is a phenonemon associated with multi-pass welds, and is usually no more than one weld run deep at any particular location.

2.1.4 Slag Inclusion

Buried slag inclusions occur predominantly in multiple-pass welds, and may be intermittent or continuous. This type of discontinuity is largely process controlled, and is influenced particularly by choice of flux/electrode and weld geometry. The former influences the formation of slag and the latter influences its detection and removal. For example, a well-rounded weld bead in a deep narrow preparation is much more likely to trap slag along the weld toes than a flatter weld bead in a more open joint. The presence of buried slag is often indicative or poor workmanship, because although the formation is a function of process and consumables, most slag should normally be removed by the operator before the next weld pass is made. This is especially true of manual processes. Thus inspection and detection of slag is widely used as a control of weld quality with respect to workmanship.

2.1.5 Porosity

Porosity is usually spherical, or "worm-hole" which is essentially tubular. It may be scattered or clustered, and buried or surface breaking. It results from gas in the molten weld metal failing to escape completely to the surface. The formation of the gas usually arises from the presence of contaminants on either the consumable or the metal surfaces, and also from failure of shielding gas (GMA processes) or loss of flux (submerged arc or SMA processes). As such, it is a result of inadequate cleanliness and is indicative of poor weld procedure or workmanship. Like slag, porosity levels are often used as a guide to the standard of workmanship achieved.

It is interesting to examine the effect of welding process alone on the preponderance of the various types of defect. Sandor (1) considered five processes widely used in American shipyards, and ranked the discontinuity types in decreasing order of frequency of occurrence (Table 1). For submerged arc welding, the most frequent type was LOF/LOP. For the other four processes, slag or porosity or both were the most frequently occurring types of discontinuity.

2.2 Methods of Detecting Weld Discontinuities

Having accepted the fact that a production weld is almost certain to contain discontinuities of some description, a judgement must normally be made as to whether or not the discontinuities are acceptable. There are two major reasons for this: Firstly, the presence of certain types of discontinuity is indicative of inadequate control of material or welding procedure or poor workmanship. Detection of these discontinuities at an early stage in fabrication can lead to immediate corrective action and thus avoid further deterioration of weld quality. Secondly, certain discontinuities may impair the performance of the finished assembly, and for that reason they may not be tolerable. Before a judgement can be made, it will be neccessary to identify the type of discontinuity, locate its position, and estimate its size. This can be done by some kind of destructive testing, but this has obvious disadvantages and is rarely practicable. By far the most common methods of defining discontinuities fall under the title of non-destructive testing, or NDT. (sometimes called non-destructive examination, NDE; or non-destructive inspection, NDI).

There are many types of NDT in use in the structural steel industry, the most common ones being:

1. Visual inspection.
2. Dye penetrant.
3. Magnetic particle.
4. Radiography.
5. Ultrasonic testing.

Each has its own advantages and disadvantages depending on individual circumstances. These will now be outlined.

2.2.1 Visual Inspection

Visual inspection is by far the most commonly used method of NDT. As well as deliberate inspection by qualified inspectors, most concientious workers directly involved with fabrication will be visually inspecting the job, before, during and after fabrication, and making corrections where necessary as an inherent part of their work, although they may not regard it as "inspection". It is the most appropriate method of checking for weld profile and geometric discontinuities, although its accuracy and repeatability can vary considerably. One factor which affects this is the skill and training of the individual inspector. Other factors include access, lighting, and surface condition of the material. When inspecting for undercut, Jubb (4) points out that, "good access for welding usually means good access for visual inspection and these conditions are more likely to lead to the discovery of undercut. The type, direction and intensity of lighting coupled with the surface condition of the material are major factors in visual inspection. It is far easier to see and measure undercut after shot blasting in a well lit painting bay, than to find it on rusty steel in a weakly lit fabrication shop, when the works is keen to clear the item as ready for painting".

Aids to visual inspection which most inspectors use include a portable light source, a small mirror, some kind of weld profile gauge, and a low power magnifying glass. These make the detection of quite small surface discontinuities possible. As well as geometric discontinuities, surface breaking porosity can be found, but surface breaking cracks will not often be visually detectable. Where single sided butt joints are made, the root surface will not always be accessible, and obviously, buried discontinuities cannot be detected visually. For these, volumetric NDT techniques such as Radiography and Ultrasonic testing must be used.

2.2.2 Dye Penetrant and Magnetic Particle

These methods of NDT are limited to detecting cracklike surface breaking discontinuities. In a way, they may be considered as an extension of visual inspection, since they enhance the appearance of the above type of discontinuity so that they become visible to the naked eye, whereas they may not have been visible normally. Of the two, magnetic particle inspection is the more sensitive.

2.2.3 Radiography

Radiography is a technique in which a sensitive film is exposed by radiation emanating from a radioactive or X-ray source and passing first through the joint to be examined. Voids such as porosity, and non-metallic inclusions such as slag are more transparent to the radiation than solid metal, and thus a radiation path containing such discontinuities has less attenuation and produces a stronger image on the film. To be successful, this technique requires good control of exposure and development of the film. Access to both sides of the joint is desirable, but in relatively simple joints such as a pipe girth weld, the technique can be just as effective when the exposure is made through both walls when access to the inside is not possible. On more complicated joints, it becomes increasingly difficult to obtain a satisfactory exposure of the weld in question without undue interference from other material. This is especially true of fillet welds.

The method is good for detection of buried volumetric discontinuities, such as slag and porosity. It can indicate geometric discontinuities such as "waggon track" root concavity in pipe welds. However it is unlikely to detect crack-like discontinuities, unless the planes of these happen to lie within a few degrees of parallel to the beam direction. The length of the discontinuity is easily determined, but the thickness in the depth direction is almost impossible to estimate, although an experienced operator may be prepared to pass judgement based on the relative densities of the radiographic image (5, 6). It tends to become less sensitive as thickness increases (6) and cannot position the discontinuity relative to the surfaces of the joint being examined.

2.2.4 Ultrasonic Testing

Ultrasonic testing relies on the principle that the propagation of sound waves through a nominally homogeneous material is altered by discontinuities within the material. Surface boundaries, both external and internal (as present at cracks, LOF and LOP, slag and porosity), act as reflectors to the ultrasound, and detection of these reflections indicates the presence of a discontinuity. However, surface effects and metallurgical conditions such as coarse grain boundaries (7) can also produce signals which may be erroneously interpreted.

The effectiveness of ultrasonic testing compared with radiography depends on many factors. Ultrasonics becomes progressively more effective with increasing thickness, except where clusters of porosity are concerned (6). It is much more successful at detecting planar discontinuities such as cracks, LOF and LOP. It can locate the position and depth of a discontinuity, as well as its length, although the accuracy of such measurements has been a source of some controversy (8-14). This has come about for a number of reasons. Firstly, ultrasonic testing is a relatively new method of NDT, which has developed rapidly in recent years. Secondly, the accuracy depends greatly on the skill and experience of the operator. There is much more scope for subjective interpretation of ultrasonic signals than for radiographic records, largely because ultrasonic methods have the potential to reveal much more information about the discontinuity. Unlike radiography, ultrasonic testing does not normally provide a hard copy of results, so all decisions will normally have to be made by the operator on site. As Young (6) points out, boredom, lack of personal comfort, presence of danger, personal problems and other stress conditions can have significant influence on the performance of the ultrasonic operator. Ref. 15 is a comprehensive and up to date report on the current capabilities of ultrasonics as a method of sizing discontinuities.

2.3 Codes of Practice and Assessment of Discontinuities

There are Codes of Practice and Standards relating to just about every aspect of design and manufacture, including welding, relevant to most industries. They are usually written and maintained by national bodies and their purpose is to set standards of quality and safety to which manufacturers and purchasers can easily relate. Codes of Practice for welding and acceptance standards for welding discontinuities were first developed when industrial use of welding was in its infancy. They were pioneered in the American petroleum industry, particularly by the American Society of Mechanical Engineers, the American Standards Association and the American Petroleum Institute. At the time, little was known about the engineering significance of weld discontinuities, and the standards tended to concentrate on what was considered to constitute a level of good workmanship, coupled with some knowledge of the quality that had given satisfactory service in the past.

The advent of industrial radiography presented code bodies with something of a dilemma: large discontinuities were revealed in most welds; far larger than those which had caused certain dramatic failures in the recent past, but no worse than those found in older fabrications which had stood the test of time. Some authorities adopted a very strict approach which demanded that all radiographic indications should be repaired. Most, however, without any background upon which to evaluate the true significance of these discontinuities, adopted purely arbitrary acceptance levels. Even today, most acceptance levels defined in codes and standards are merely an attempt to define the normal limits for practical welding - a standard which an average welder should, with reasonable care, be capable of achieving. They must also take into account the practical limitations of NDT in detecting and measuring discontinuities.

Basic NDT capabilities have improved considerably over the years, and because of this there has been a tendency to generate more rigorous acceptance standards which demand much more from the welder. In parallel with these devlopments, there have been great advances in welding technology, which to some extent have allowed these greater demands to be met. However, it has also resulted in larger, more complex, and more ambitious welding projects to be attempted, which increase the difficulty of both making a good weld, and subsequently inspecting it. Because these developments rarely keep in step, there is a tendency for imbalance between quality, inspection, and standards to develop. These can be exacerbated by the often considerable inertia of code bodies when trying to keep up with advances in technology. Consequently standards of different countries intended for the same applications often vary considerably in their demands.

In the structural steel industry, the American code most relevant to design and fabrication is AWS D1.1 (16). This is a very comprehensive document, and it specifies acceptance levels for weld discontinuities according to three types of construction, these being buildings, bridges, and tubular structures. Limits determined by visual inspection are much the same for all three. Weld shape is judged qualitatively with the help of pictures, the only quantification being the maximum convexity for fillet welds (0.07 x face width plus 1.5mm maximum) and overfill for full penetration butt welds (3.2mm maximum). Cracks and lack of fusion are universally unacceptable. Limits on depth of undercut vary between 0.25mm and 1.6mm, and depend on a rather complex and arbitrary relationship between proportional length, direction of principal stress (longitudinal or transverse with respect to weld), and thickness. Piping porosity limitations are based on diameter and frequency in an equally complex and confusing fashion. Radiography defines limits based on maximum diameter of indication in association with weld size. For bridges and tubular structures, diagrams of radiographic images are provided as an aid to assessment, and for tubular structures alone, there is a distinction between rounded and elongated images. Ultrasonic inspection is based on four severity levels, and is defined by signal amplitude measurement. For tubular joints, assessment is very complex.

The requirements are largely arbitrary and based on workmanship, although some fitness-for-purpose concepts are present, for example, consideration of direction of stressing. The use of ultrasonic testing and its mention in the document is a relatively new addition, and as such is welcome, although some would argue that the type of testing technique and acceptance criteria are inappropriate (15).

In comparison, similar British codes are less informative than AWS D1.1. BS449 (buildings) (17) and BS5400 (bridges) (18) have virtually nothing to say about acceptance of weld discontinuities, although BS5400 does comment on joint misalignment. Here, the quality control stems from the welder approval and procedure approval codes, BS4870 and BS4871 (19, 20), the important difference being that the quality standards are only guaranteed on samples and test-pieces, rather than on the actual fabrication. The most widely used British code of fabrication containing some requirement for discontinuity assessment is the pressure vessel code BS5500 (21). The acceptance levels appropriate to two categories of construction are based on BS4870 and BS4871, and are broadly similar to those in AWS D1.1, but are less complex and consequently easier to interpret. BS5500 makes a rather innovative concession, "when acceptance levels different from those given in table 5.7 (1) have been established for a particular application and are suitably documented, they may be adopted by specific agreement", and "particular defects in excess of those permitted in table 5.7 (1) may be accepted by specific agreement between the purchasers, the manufacturer and the Inspecting Authority after due consideration of material, stress and environmental factors". This is an important advance over AWS D1.1 which has no flexibility, with effect that discontinuities deemed to be unacceptable must either be repaired or the product scrapped. Instead, BS5500 makes allowance for further assessment from a fitness-for-purpose viewpoint based on fracture mechanics before a final decision is made.

So far, little has been said about the recent trend towards fitness-for-purpose as a means of assessment of discontinuities and the few codes which utilise this approach, although it marks a radical change in assessment philosophy. It is now a generally accepted approach in the high risk industries such as oil, gas and nuclear power, and is gradually filtering through to the structural steel industry. The implications and importance of this will be discussed in section 4.

3. THE QUALITY AND ECONOMICS OF REPAIR WELDING

Having identified a welding discontinuity to be unacceptable according to the relevant code of practice, then, in most cases, corrective action must be taken to rectify the situation. In some cases, this can be achieved by removal of material. Dressing out of minor surface imperfections by grinding is an example. However, in the vast majority of situations, the removal of the unacceptable discontinuity has to be followed by further welding to complete the repair. It is rare to find any structural steel fabrication of moderate size and complexity that has been put into service without any repair welding being present. The vast majority contain repair welds of some description.

3.1 The Structural Integrity of Repair Welds

There are many cases on record where a dramatic failure has initiated from a poorly executed repair weld (Section 3.1.1.). This in itself is not indicative that repair welds are generally of a lesser structural integrity than production welds, for the simple reason that of all reported failures initiating from welds, repair welds form only a small proportion of the total. However, the percentage of repair welds as a proportion of total welding is also small. The ratios of repair weld failure to production weld failure and repair weld length/volume to production weld length/volume would be interesting statistics, but unfortunately they do not appear to be available. Two other factors which further cloud the issue should also be considered: firstly, most structures which contain repair welds perform satisfactorily in service. Failures are often reported, but successes tend to go unnoticed; and secondly, repair welds may be of a lower quality than production welds without causing a failure in a conservatively designed fabrication, or they may lie in a region which is relatively non-critical. To keep a true perspective of the causes of service failures of weldments, it is interesting to examine a collection of case histories of fatigue failures in welded constructions presented by the International Institute of Welding (22, 23).

Volume one (22) reported 65 failures collected between 1954 and 1967. Volume two (23) added a further 33 reports collected between 1967 and 1979. 34 of the reported failures related to rotating shafts, and are not relevant to this report. Harrison, in his analysis of the data (24) estimated that for normal welded structures, incorrect design or unforeseen service conditions accounted for about 75% of all primary causes of failure. The remaining 25% were identified as resulting from defective fabrication, and were mainly related to fillet welded joint details. Weld repair as a contributory cause of failure was not identified in any of the reported cases.

3.1.1 Case Histories and Laboratory Tests Pertaining to the Performance of Repair Welds.

As stated above, the majority of repair welds perform satisfactorily, and so they are never reported. Some instances where repairs do cause problems are treated confidentially and information is not available in the open literature. However, there are cases of repair welds causing failure which are well documented, and important lessons can be learnt from them.

One of the earliest and most widely reported repair weld failures took place in Fawley, England, in February 1952, when a large welded steel oil storage tank burst during the latter stages of a "full head" hydrotest. The failure was a continuous brittle fracture extending vertically through every strake of plating. Because of the wide interest in, and lack of understanding at the time, of that sort of failure, the manufacturers commissioned a full investigation, the results of which were made public (25).

As part of the routine inspection during fabrication, a weld prober was used to remove boat-shaped samples from a number of horizontal and vertical welds. One sample was found to contain a crack (all others were satisfactory), the extent of which was explored by removing a further four samples from the same region, the resulting grooves being repaired by welding. A crack from a prober repair occurred during filling, at a head of 10m. It extended vertically from a horizontal weld 375mm upwards and 225mm downwards. The tank was drained, the crack was chipped out using a pneumatic chipping hammer to a double vee preparation and re-welded. This repair proved to be of no further trouble, but after failure it was examined, and it was found that it contained cracks which were residual portions of the original crack not completely removed, as well as other defects.

The failure initiated from a weld prober repair in the first horizontal weld from the base. Examination of the repair revealed circular marks of the prober saw near the root of the outer weld. There was evidently a continuous cavity or defect, which may have been slag-filled, at the root of the outer weld, indicative of lack of root fusion. The root had been sealed on the inside by short runs of weld metal about 3mm thick, but no back chipping had been performed beforehand. The report makes the important comment, "the weld repairs of the grooves resulting from the removal of the prober specimens contained imperfections, and it would seem that the sound welding of these grooves presents difficulties".

A second well-documented case (26, 27) is that of the mobile jack-up drilling rig "Sea Gem", which sank in the North Sea on 27 December 1965, with the loss of thirteen lives. The rig was suspended from its legs by tie bars, flame cut from 76mm steel plate. Some weeks before the failure, two tie bars on number 12 leg broke between the spade end and the shank. These were replaced with spares, but no further action was taken to establish the reason for the breakage.

It was presumed that the final collapse resulted from similar brittle fractures of certain tie bars, such that those adjacent were overloaded, also failed, and so the breakage spread until the rig capsized. Many of the broken tie bars were recovered, and some showed evidence of weld repairs to gouges made during the flame cutting, and also clear regions of fatigue crack growth on the fracture surfaces. These repairs had not been post weld heat treated, and contained cracks and other defects from which failure had initiated. These defects were much more severe than the rounded gouges which they were supposed to repair. Further investigation showed that the majority of the steel used had inadequate impact properties at the operating temperatures involved.

Another widely reported case concerning both defective welding and defective repair came about following the fracture of one of the two main girders of the then recently opened I79 bridge near Pittsburgh, Pennsylvania (10). The majority of the heavy butt joints in the bridge were made using the electroslag process, which is particularly suited to the fabrication of such joints, and widely used in the heavy structural steel industry. It does, however, have a history of toughness and solidification cracking problems, and the very coarse grain structure makes ultrasonic examination very difficult.

Field examination of these electroslag welds in several bridges revealed a high incidence of repair welding. Repairs to the fusion line on both sides of the weld and both sides of the plate were found on virtually every weld examined. Also, up to 20% of the welds contained in-depth repairs varying from one quarter to full thickness. Multiple repairs were common, and where the repair was to the surface only, buried discontinuities had sometimes been left underneath. In the I79 bridge, the main fracture had initiated from a weld containing multiple in-depth repairs of several orientations, and uncorrected discontinuities of substantial size still remained. In another location, large slag pipes had been repaired by placing weld runs on the surface of the plate in order to cover the ends of the pipes. The resulting buried slag had subsequently passed ultrasonic examination.

It is apparent from the data that problems existed both in the initial fabrication and the non-destructive testing, as well as in the repairs themselves. The report identifies specific examples of unsuccessful repair as,

1. Weld repairs of defects in which penetration to the root of the defect was not achieved.

2. Weld repair of defects in which cracking extended beyond the edge of the repair area.

3. Weld repairs in which cracking of the weld repair material itself resulted in the necessity for multiple repairs.

These suggest that quality control during the weld repair process was also not what it should be and that the repair may sometimes have done more damage than it did good. Moreover, the properties of the weld metal deposited in some of these repairs was inferior to the electroslag weld which it replaced. In one notable instance, the repair weld metal had lower toughness and larger cracks than the electroslag weld in which the repairs were found.

Three more examples of failures initiating from repair welds were reported by Kahle (28). The first related to a failure of a gas transmission line, in which a repair had been made to the inside of a seam weld. Some 450mm of the root of the original submerged arc weld had been removed and repaired by the manual metal arc process. A brittle fracture had initiated in the heat affected zone of the repair. A metallurgical examination of the failure showed the exact cause to be HAZ embrittlement due to martensite formation as a result of inadequate control of heat input and cooling rate during repair. The second example was a similar failure in the same pipeline, differing from the first only in that severe undercut was associated with the repair.

The third case concerned a liquid gas holder, in which a 30mm crack appeared in a longitudinal weld after about 3 years operation. The fabrication documents showed that because of inconclusive radiographic reports, the inside of the longitudinal (submerged arc) weld had been built up with runs of manual metal arc weld. The crack was accurately located using ultrasonics, cut out from both sides, and repaired. A second crack developed about 30mm from the end of this repair, and only after further repair was a satisfactory radiographic report obtained. The gas holder was returned to service until a convenient occasion allowed a further radiographic examination of the repaired weld. This time, an 80mm long crack was detected just prior to breaking through the outer surface. This was repaired and the whole tank was thermally stress relieved, since it was believed that the high degree of restraint and associated thermal strain after repair was a contributory factor to the cracking.

All three of the above cases relate to welding and repair of high strength steels, but the problems encountered are not unique to those materials, and are worthy of consideration here.

The problem of creating further discontinuities during repair was investigated by Volkov (29). Three types of joint were considered, all full penetration butt welds, of between 26mm and 80mm thickness. The repairs were generally made to deep narrow gouges, and once again the problems of high restraint were evident. In all tests, more discontinuities were found after repair than were known to exist before repair (Table 2). Volkov goes on to attempt to define repair procedures relating the number of repair passes to the thickness of the joint, so that best possible control of thermal straining is achieved.

Kozulin (30) carried out some laboratory tests on multiple SMA repairs to submerged arc butt welds in low carbon steels. He recognised the need to repair defective regions more than once to obtain a satisfactory result in practice, and so in the tests, repairs were made two, three and four times, from one or both sides of the joint. Plate thickness was 14-50mm and defect removal was simulated by arc-air gouging. On some, the carburised layer was removed by grinding, and some specimens were welded to a rigid base plate to simulate structural restraint.

The impact toughness of the restrained specimens decreased on average by 20-25% and a further reduction was recorded on those specimens which had not been ground after gouging, the latter being attributed to the increase in carbon content of the repair weld metal, measured as 0.01-0.03%.

Other work pertaining to the toughness of repair welds was reported by Tenge (31), who performed CTOD tests for weld metal, the fusion boundary, and 1 and 2mm from the fusion boundary for both original weld metal and after weld repair. The lowest toughness values were for the repair weld.

If fusion between successive layers of weld metal is marginal, repair welding of such may cause some separation. Collins and Black (32) reported additional forms of cracking resulting from weld repair, one due to zinc contamination and another in which a massive repair weld caused delamination of the base plate.

Repair welding is often required to correct in-service fatigue cracking. A confidential investigation by The Welding Institute was carried out on a semi-submersible vessel operating in the North Sea. After three years of service, fatigue cracking was discovered in some of the chord to brace welds. In theory, a satisfactory repair would have allowed a further three years operation before the re-occurrance of cracking at the repaired regions. In practice, however, the repaired joints had cracked again after only several months operation. The reason for the poor fatigue performance of the repairs in this case was attributed to the unfavourable site conditions prevailing for the repair welding, making it difficult to achieve the same standard of workmanship as in the original joint, made in the fabrication yard. It should be pointed out that the repair weld satisfied the acceptance criteria applicable to the particular joint.

Some laboratory work has been carried out to establish the performance of repairs made to fatigue-cracked fillet welded attachments. Wylde (33) reported that part-through-thickness repairs gave fatigue strengths comparable to the non-repaired joint. However, the fatigue performance of through-thickness repairs was dependent on the quality of repair, and in particular the root region. One specimen in which the pre-existing fatigue crack was not completely removed produced a very low endurance. The point should also be made that repairs performed under less favourable conditions may well possess lower fatigue strengths than those reported by Wylde.

Boulton (34) performed fatigue tests on transverse and longitudinal non-load-carrying fillet welded joints in which fatigue cracks at weld toes were repaired by gouging out and re-welding. The results displayed a large amount of scatter, but on average the repaired joints exhibited a 75% decrease in fatigue life compared with the as-welded joints.

In contrast to the above, Boulton (35) performed further tests on similar joints containing weld toe fatigue cracks which had been repaired by simply welding over the crack, and found them to have a good fatigue performance. (This was a specific finding of this particular investigation and would not normally be recommended as good practice). The tests were carried out on 12.5mm thick specimens containing 6mm deep toe cracks which in effect become similar to lack of penetration defects as a result of the repair process. It was concluded that the ratio of buried crack depth to plate thickness was the dominant variable controlling the fatigue strength with a ratio of 0.5 representing the upper limit for a fatigue strength of the repair equal to that of the as-welded non-defective joint.

3.1.2 Practical Problems Associated With Making a Repair

The very fact that a repair weld is required is indicative that there were problems associated with making the original weld. These problems may be identified and overcome prior to repair, or they may still apply. In any case, there is usually some additional problem or difficulty particular to the repair itself, which must be overcome. In general, for a repair to be satisfactory, it must better the quality of the original defective weld, in conditions which are likely to be less conducive to good welding than those under which the original weld was made.

The literature has identified a number of problems associated directly with repair welding:

1. Incomplete removal of defect being repaired.
2. Introduction of further discontinuities associated with the repair.
3. Microstructure, material or toughness degradation.
4. Increased residual stress and distortion.
5. Inadequate repair and inspection procedures.

Most of the following comments have been drawn from Ref. 36:

3.1.2.1 Incomplete Removal of Defect Being Repaired

It is not uncommon for the defect under repair to be only partially removed, particularly when it is a crack-like planar defect. The remainder of the unrepaired defect may extend beyond the ends of the repair, or deeper into the material when a partial thickness repair is made. This is due in part to too great an accuracy being ascribed to the NDT techniques used to locate the defect, together with the problem that the material in the middle of the weld is usually in compression and the crack faces will be forced tightly together. It is a requirement of some standards that when gouging out defects the cavity should extend at least 25mm beyond the ends of the detected defect, yet incomplete removal still occurs. For this reason, it is good practice to inspect the excavated area before repair using either magnetic particle or dye penetrant to insure that all traces of the discontinuity have been removed.

3.1.2.2 Introduction of Further Discontinuities Associated With The Repair

The types of discontinuity which may be formed in a repair weld are on the whole the same as might be found in an original weld using the same process, which may well be the cause of the repair.

Hydrogen cracking is probably the most likely discontinuity to occur in repair welds, as a result of inadequate control of levels of hydrogen in the weld metal, and to a lesser extent inadequate levels of pre-heat and post-heat during welding. Solidification cracking is considered unlikely to be a problem when welding structural steels with ferritic GMA electrodes, except perhaps as crater cracks at the ends of weld runs. With gas shielded or flux cored wire repairs, solidification cracking may occur due to excessive dilution or poor bead profile, but is more usually a result of too fast a travel speed.

Lamellar tearing is more likely to occur during original welding rather than during repair, but may present problems in highly restrained situations. Gouging out an existing lamellar tear can sometimes lead to its propagation. Lack of fusion and lack of penetration are defects which frequently occur during repair welding, particularly when access is restricted, or positional welding is required, or a deep narrow cavity is to be filled. Gas shielded processes are generally more susceptible to this kind of defect than flux shielded processes, when "cold lapping" can occur if the operator uses a poor technique. Slag and porosity can generally be avoided by good welding practice, although some slight porosity is more or less inevitable in manual welding.

3.1.2.3 Microstructure, Material or Toughness Degradation

These properties are dependent on many variables, particularly filler and base material, weld process and procedure, heat input, etc. With regard to toughness, which is influenced by microstructure and material, there are no hard and fast rules governing the relationship between the toughness of the original weld and the repair. The only reliable means of estimating toughness is to measure it from tests on specimen repair welds made to simulate the precise conditions under which the real repair is made. It is often, but not always, the case that SMA repairs possess lower toughness than submerged arc welds to which they have been applied, and also that high restraint associated with repair in general can have a detrimental effect on toughness.

3.1.2.4 Increased Residual Stress and Distortion

Residual stress levels influence the structural significance of discontinuities, in relation to the likelihood of brittle fracture. Although residual stresses are likely to be high when a large degree of restraint is present, they are unlikely to be any worse than those present in any parts of the original weld which were also subjected to high restraint. The role of residual stress is important when an un-stress-relieved repair is made to a stress relieved structure, but since the majority of fabrications in the structural steel industry are left in the as-welded condition, the significance of repair residual stress is considerably reduced.

Distortion as a result of the action of residual stress is more likely to present problems, but in many cases it can be adequately controlled by careful manipulation of repair weld shape, size, sequence, and heat input, to establish a balanced welding procedure.

3.1.2.5 Inadequate Repair and Inspection Procedures

One aspect of this was highlighed above in consideration of the incomplete removal of defects, but all the above problems can be exacerbated by carelessness and lack of attention to detail when making a repair. Generally, tighter control of all welding parameters is required when a repair is attempted, but this is not always achieved. Cleanliness is important, as is the correct storage of low hydrogen electrodes, as mentioned above. Gouges made using arc-air tools should have the carburised layer ground off, and the resulting cavity should be smooth to facilitate inspection and the laying down of new weld metal. Stray arcs and hammer/chisel marks should be dressed off. Temporary attachments for jigging and suchlike should be carefully removed by grinding, and not just beaten off with a hammer.

There are other factors detrimental to repair procedures which are beyond the control of the operator. Access for repair may be poor compared with the access for the production weld. This may limit the choice of welding process purely from the point of view of accessibility, and also for health reasons: processes such as flux cored self shielded welding which produce a lot of fume may be unsuitable in an enclosed area. Field repairs, as distinct from repairs in the fabrication shop, will be positional, and environmental effects such as wind, rain and cold may hamper the welder by their inconvenience and the personal discomfort caused. On the whole, the above comments about access and environment are applicable to the inspection staff as well as the welding personnel.

3.2 Special Repair Techniques

In general, techniques used for repair welding follow normal welding practice and are adjusted to suit the individual circumstances of the repair. However, for critical applications, specific repair procedures have been developed. Although these would not normally be used in the structural steel industry, they are still relevant to repair of C-Mn steels, and are briefly discussed below.

3.2.1 Half Bead Technique

This technique was developed in the USA for repairing postweld-heat-treated fabrications, to give good HAZ toughness without postweld stress relief to the repair. This is achieved by tempering any HAZ in the structure to be repaired by heat from subsequent weld passes. The process is described in detail in ASME XI (37), based on the ASME III (38) repair weld procedure. In principle the half bead technique involves making a repair cavity by milling or grinding and putting on one layer of SMA buttering, using either a 3.2mm (ASME III) or a 2.4mm (ASME XI) diameter electrode. Following completion of the buttering layer, half of its depth is then ground off, and a second layer using larger electrodes (up to 4.0mm diameter) is deposited. The heat from the second pass is sufficient to temper any unfavourable microstructures in the first pass HAZ, and so there should be no unreheated HAZ regions. Fill passes can then be made with electrodes up to 4.0mm diameter. The cavity is overfilled and ground back to ensure that the last remaining passes have been tempered. The ASME codes demand very strict control of most welding parameters for this technique. A variation of this technique is being developed in which there is no need to grind away half of the first layer (39).

3.2.2 Repair Using Austenitic Consumables

The use of austenitic electrodes to make weld repairs has certain advantages, the most important of which is the much improved tolerance to hydrogen (40). Austenite has a much greater solubility for hydrogen than ferrite, and the diffusion rate of hydrogen in austenite is also much lower than in ferrite. Furthermore, austenitic weld metal is not sensitive to hydrogen embrittlement. Thus any hydrogen which has diffused into the HAZ during welding tends to diffuse back into the weld metal on cooling, which considerably reduces but does not eliminate the risk of HAZ cracking.

However, there are problems associated with this technique. Care must be exercised in selecting the most appropriate austenitic electrode. Dilution with a ferritic parent steel can produce less highly alloyed weld metal which could transform into martensite. Conversely, a wholly austenitic deposit must be avoided because of its susceptibility to solidification cracking. Also, the microstructure of the repair weld is such that ultrasonic and radiographic NDT of the finished weld is very difficult to interpret. Surface crack detection must be done with dye penetrant, since magnetic particle inspection is unsuitable.

3.3 The Economics of Weld Repair

In commercial industry, the economic viability of weld repair is next in importance to structural integrity. As well as the direct cost of making the actual repair, there are often hidden costs : the need for additional personnel for grinding, gouging, NDT and supervision, and the time involved, all add to the cost. Other costs stem from occupation of space, interuption of work schedule, and late delivery. Volkov (41) estimated that the total labour cost of repairing a defective region 100-200mm in length was 1.5-3.5 times greater than the labour cost of making 1m of the original weld (see Table 3). This is without any consideration of the need for repeated repairs to be made, although there is a 20-30% chance that any one repair will require re-repair (42). For particularly difficult welds, this increase in cost may rise to a factor of between 5 and 10 (43).

The position of the defect being repaired has a significant bearing on cost. Norman (44) estimated that the total repair time is 3-10 times more dependent on the depth of the defect than its length. This is especially significant considering the fact that a large proportion of defects occur in the weld root (i.e. at great depth). This also highlights the cost saving importance of making NDT inspections of root runs in thick joints before the weld is completed. It is clear that repair costs must rise if they are performed after fabrication process. An extreme example of this relates to repair of the Aleyaska pipeline (45). One particular repair had to be made to a weld in a portion of the pipeline which was laid across a river. A coffer dam was built to drain the river, and the repair, which involved local grinding of a weld cap to remove a cluster of pores, took about 3½ minutes. The estimated cost of that repair was about $3.5M.

The severity of the acceptance criteria also have a significant effect on repair costs, quite apart from the increased cost of performing more repairs. Lane and Briscoe (46) compared ultrasonic testing times for nozzle welds for 200mm diameter branches in boiler drums at two levels of acceptance. If the weld was defect free, 2 hours would have been required irrespective of acceptance criteria. If one or two defects were present, the additional time required to evaluate these would have been 1 hour for slag length acceptance levels of 25mm, or 6 hours for 6.9mm, assuming that the slag lengths were that small or smaller.

Other examples of repair costs have been quoted. Sandor (1) reported that in the American shipbuilding industry, the cumulative total amount of weld repair activity accounts for 10% of the overall cost of a ship. This works out to between $0.6M and $1.0M per ship (1981 values). Grant and Rogerson (47) studied repairs in three oilfield equipment modules. The labour for repair accounted for about 9% of the total construction labour, but only 10% of the repair labour accounted for removal of defects and making repair welds; the remaining 90% went on inspection of the excavation, supervision of the repair weld, and final re-inspection.

It is clear from the above that the direct cost of weld repair often pales into insignificance compared with the indirect costs of action by grinders, gougers, supervisory, and inspection staff, and the consequential cost of lost production time and space, penalty clauses, delayed delivery, etc. It should also be mentioned that the latter can bear much more heavily on the final customer than on the fabricator. There is much scope for reduction in cost, not only by reducing the amount of repair by better control of procedure and acceptance levels, but also by better timing of repairs.

4. AVOIDING UNNECESSARY REPAIR

It has been shown how the interaction of fabrication, inspection and assessment procedures in manufacturing industry can result in a requirement for weld repair. It is evident that a nominally "satisfactory" repair does not automatically guarantee an improvement in quality in terms of the service performance of the finished item. It is of course important to set and maintain standards of workmanship, but it must be remembered that the vast majority of structural steel fabrications are intended to meet requirements set in terms of service performance, rather than just provide a monument to the abilities of the fabrication team. Many repairs are performed simply to correct poor workmanship, despite the fact that the end result may have no influence on structural integrity, or may even be detrimental.

Standards and procedures have been developed over the years alongside welding and associated techniques, and have been based on workmanship criteria with the excuse that little was known about the effects of discontinuities on service performance. However, modern development of fracture mechanics and widening knowledge of weld behaviour in general mean that this excuse is no longer valid.

4.1 The Structural Significance of Discontinuities

The significance of weld discontinuities with respect to service integrity has been the subject of large volumes of published literature and a number of international conferences in recent years, of which Refs. 48-67 are just some examples. A large discourse on the subject would be out of place here, but there are, however, some general comments which are worthy of note. In section 2, weld discontinuities were categorised in decreasing order of severity as (i) cracks or cracklike, (ii) geometric, (iii) lack of fusion/penetration, (iv) slag, (v) porosity. The significance of these categories of discontinuity will now be considered.

Cracks are almost universally rejected in industry, due to their likely detrimental effects, and also because of their apparent unpredictability. The acuity of a crack tip causes a very large local stress concentration, which has two possible deleterious effects. Firstly it may give rise to a very short fatigue initiation period and subsequent rapid propagation. Secondly, in low toughness materials, the problem of instantaneous brittle fracture arises, and this may be exacerbated by high residual stress. The assessment of the brittle fracture risk can be difficult and complicated, as it requires a thorough knowledge of the mechanical and metallurgical properties of the material in which the crack lies, together with a full understanding of the local stress field. Surface breaking cracks are normally more detrimental than buried cracks, and the consequent exposure to the environment may increase their severity. If there is no fatigue or stress corrosion cracking, corrosion may blunt a crack tip, however. The performance of any crack, whether buried or surface breaking, is strongly influenced by its orientation with respect to the applied loading. A crack whose plane is normal to the applied load is likely to fare much worse than a similar crack whose plane is aligned parallel to the applied load. It has also been shown that the depth of a crack is much more significant than its length.

Geometric discontinuities normally act as stress concentrations, and thus enhance the likelihood of brittle fracture and increase fatigue crack initiation and propagation rates. It is primarily for the latter reason that control of weld bead shape is important. Heavy overfill of butt welds, for example, which was once considered to be "reinforcement", is in fact detrimental to fatigue strength. Gurney and Newman (68) showed the dependence of fatigue strength of transverse butt welds on overfill angle. Other work has shown that butt welds machined flush and having no internal discontinuities have a fatigue performance similar to plain plate. It is largely the same effect which accounts for the different fatigue design curves (69) for different joint categories, the highest classified joint detail being a machined butt weld, and the lowest being a load carrying fillet weld. Joint misalignment and angular distortion are other forms of geometric discontinuity, often neglected, which can result in very poor fatigue performance (70). Single sided butt welded joints are not classified from a fatigue viewpoint, because the enormous variation in root geometry can have a widely varying effect on fatigue life.

Another geometric discontinuity which influences fatigue strength is undercut. Jubb (4) explained that undercut can be classified as one of three basic types: (i) wide and shallow, where depth measurement is possible, (ii) narrow or very narrow, where depth measurement is difficult or impossible, (iii) shallow and narrow, not detectable visually or by NDT. Undercut tends to be judged solely on depth and length, and it is likely that type (i) would be most frequently rejected, whereas types (ii) and (iii) are potentially more harmful.

Joint geometry is a major factor as far as fatigue performance is concerned. Weld profiles and design are usually far more important than internal discontinuities. Although it is estimated that fatigue accounts for 90% of failures of welded structures which are subject to fluctuating loads in service, only a very small fraction can be attributed to buried defects. Where failures have occurred from buried non-planar defects, these defects have been very large indeed; and the structure was almost certainly not inspected before entering service. Lack of fusion and penetration are similar in nature to cracks, with the important distinction that they are often blunter, and this is why they are distinguished from cracklike discontinuities. It must be remembered though that some types of LOF/LOP have just as severe an effect on service performance as cracks themselves. Studies have shown that for transverse LOF which is parallel to the loading direction has a negligible effect on fatigue behaviour. Like a crack, LOF is most detrimental when it is surface breaking.

Slag is a relatively innocuous discontinuity by virtue of its rounded shape, and the fact that although it may be present in great length, it is rarely more than one weld run (∿3mm) deep. As was stated earlier, depth is far more deleterious than length for such discontinuities. Newman (74) showed that for pipe welds made on backing rings, even the presence of gross slag inclusions did not initiate failure during fatigue testing, the most common initiation site being the backing ring. Further work was carried out, investigating the fatigue performance of machined butt welds containing inclusions, made on 12.7mm plate (75). The results showed good correlation between inclusion length and fatigue strength although subsequent work suggested that it was not quite that simple. These tests highlight an important consideration as far as buried slag is concerned: if the weld has a nominally poor fatigue strength (e.g. pipe weld on backing ring, fillet weld, etc), then inclusions are not critical, whereas in a weld with a nominally high fatigue strength such as a butt weld with the overfill removed, effect of the inclusion may now be very significant.

The behaviour of porosity is very similar to that of slag, although in general, it is less severe. It is never likely to be a source of failure in structural steelwork, although it could conceivably cause failure when it is present in very large quantities, or in a high category joint such as a machined butt weld. In the latter case, experimental work (76, 77, 78) has shown a correlation between volume of porosity and fatigue strength. As with other defects, porosity is more detrimental when it is surface breaking than when it is buried. Perhaps the most important aspect of the presence of porosity is that it may mask a more serious planar defect when being examined by radiography or ultrasonics, and it is for this reason that some up-to-date codes require its removal. The same applies for slag inclusions, which have been known to have small cracks associated with their extremities.

4.1.1 Pressure Vessel and Shipbuilding Industries

Much of the above data has been derived from laboratory tests performed specifically to evaluate the structural significance of discontinuities, aided by some general knowledge of the problems encountered in industry. On the whole, feedback from industry relating to service performance of structures containing weld discontinuities is erratic and uncoordinated, but two notable exceptions are the pressure vessel and shipbuilding industries, where specific studies have been made.

It was reported (3) that in the period from 1958 to 1978 there were no catastrophic failures of pressure vessels conforming to ASME I and ASME VIII. In the USA, the disruptive failure probability has been estimated to be no greater than 10^{-5} per vessel year. The same figure shows up in Germany where more rigorous reporting is required. In Europe and the United Kingdom, between 1955 and 1963, only 1 out of 29 pressure vessel explosions was found to have been caused by a weld discontinuity, all others being attributed to operational errors (79). This suggests that the approach to design and manufacture of pressure vessels over the last 20 years has been very good, but a report by Salter and Gethin (80) showed that a lot of unnecessary work and expense due to repair was prevalent in the industry.

They examined the type and frequency of discontinuities repaired in the main seams of ferritic steel pressure vessels fabricated by three British manufacturers. Data was broken down into material thickness and composition, length and type of seam, and length, depth and type of discontinuity, which were divided into four categories: cracks, lack of fusion, porosity and solid inclusions. A total of 806 repaired discontinuities in nearly 1.5 miles of welded seam were recorded. Salter and Gethin estimated that all planar discontinuities required repair. All slag inclusions and porosity were considered acceptable, based on the reasonable assumption that the pressure vessel materials used had adequate toughness to tolerate small three-dimensional defects of these types. Whilst fatigue failure might have been a possibility from continuous lines of slag in vessels subjected to large numbers of stress cycles, the vast majority of vessels considered were designed within the fatigue limits set by BS 1515, so no special consideration of fatigue was required.

The results showed that of the 806 repaired discontinuities, only 153 in 70 seams totalling 896ft in length required repair. 81% of discontinuities, representing 87% of the volume of repair work, was judged to be innocuous. It must be appreciated that the non-repair of the 87% of discontinuities considered to be harmless, whilst providing a significant saving in cost, would not lower the integrity of the vessels. It was further noted that of the 19% of rejected discontinuities (all planar), a more thorough analysis was likely to have shown that even some of these would have had no effect on the structural integrity of the vessel concerned.

An example of a nonsensical approach to repair in shipbuilding is the repair of discontinuities found in welds when only a small percentage are inspected. Typically less than 5% of hull welds are examined volumetrically (X-ray), but discontinuities found in that 5% are often repaired, despite the fact that in the remaining 95% of welds, about 20 times that number of similar discontinuities are allowed to remain unrepaired. A study of defects in six large tankers (81) estimated that about 2000 planar defects were left in the unchecked welds in each ship. This was calculated from the known type and distribution of discontinuities in the tested welds (Table 4). The ships had been in service for 4 to 6 years at the time of the last damage report. None of the reported damage was related to an internal planar defect, but some cracks were related to repairs made to non-planar defects (Table 4). In summary, the report indicated that better joint design, along with better control of fit-up, misalignment and corrosion are a more effective means of fatigue fracture control than extensive inspection and repair of internal defects. The same conclusions were reached by Bokalrud and Karlsen (82) who applied probabalistic fracture mechanics in their theoretical evaluation.

A Japanese survey (83) conducted between 1950 and 1969 indicated that 75% of fatigue cracks which were found in decks and shell plates of ships had initiated at toes and roots of fillet welds, as a result of geometric discontinuity rather than any form of weld "defect". Once again, this highlights the disproportionate preoccupation with butt welds. More recent surveys of the U.S. shipbuilding industry (84, 85, 86) revealed that in-service failures were predominantly fatigue occurring mostly between the second and fourth year of service. The principal causes of failure were poor design details and undesirable joint misalignments. Weld discontinuities as an exclusive cause of fatigue ranked very low amongst the many causes. Furthermore, the ratio of non-weld-related causes of failure to weld related causes of failure was 6:1.

4.2 Fitness For Purpose

"Fitness for purpose" is a phrase that has come to be associated with the assessment of discontinuities with respect to their effect on the integrity of the structure in which they exist. More correctly, it is "engineering critical assessment" (ECA) which describes the route which is taken to establish the "fitness for purpose" of a structure in the light of the knowledge of discontinuities present and their likely effect. The approach is one which should lead to intrinsically safer structures because attention will be concentrated on the most important aspects of overall quality, particularly design and material selection. It may also lead to a relaxation in traditional acceptance standards based on good workmanship, and is often applied for that specific reason.

The concept of fitness for purpose was introduced by the President of the Institute of Welding, Edgar Fuchs, in his Presidential address (87) in 1961, linked with what was then known of the significance of weld discontinuities. The development of the fitness for purpose approach to the assessment of discontinuities initiated largely from two conferences held in London in 1967 and 1968 (88, 89). In the second, a paper by Harrison, Burdekin and Young (90) outlined what was probably the first acceptance standard for weld discontinuities based solely on a fitness for purpose approach. Developments in this philosophy over the next twelve years led ultimately to the publication in 1980 of the British Standards Institution document PD6493, "Guidance on Some Methods for the Derivation of Acceptance Levels for Defects in Fusion Welded Joints" (91), probably the most comprehensive document of its kind. This was followed by an international conference in London in 1981, "Fitness for purpose validation of welded contructions" (92). In the introductory paper at that conference, Wells (93) reviewed the historical development of fitness for purpose, emphasising how the recent advances in design, fracture mechanics and NDT, together with improvement in analytical capabilities due to computer controlled procedures, had permitted the development of this new technique.

The main aim of PD6493 is to provide a framework for the engineering critical assessment of discontinuities by well authenticated procedures, and it gives specific guidance showing assessment routes which could be adopted.

The modes of failure considered are:

Brittle Fracture
Fatigue
Yielding
Buckling
Corrosion/Erosion
Stress Corrosion
Leakage
Creep

The most detailed treatments are for brittle fracture and fatigue, as these are the failure modes principally affected by weld discontinuities.

The approach for fatigue seems to be generally accepted, but for fracture, alternative assessment routes have been proposed (94). Recent comparisons between a number of these (95, 96) have shown that, taking account of the different approaches to safety factors and stress gradients, the calculated discontinuity sizes are similar.

The assessment routes in PD6493, particularly for fatigue and fracture, rely heavily on the use of fracture mechanics, which is a relatively new analytical technique which relates the mechanical behaviour of metals to their material properties. The use of the document therefore requires the following information.

Discontinuity size, shape, position and orientation.
Structural and weld geometry.
Stresses and temperatures including transients.
Tensile properties.
Fatigue, corrosion fatigue and fatigue crack propagation data.
Fracture toughness (K_{IC}, J, CTOD).
(Creep data).
(Corrosion data).

Few of these are controversial, but the provision of toughness data for welds is subject to debate. Fracture toughness varies widely with different materials, welding consumables and welding procedures. It also varies according to position in a welded joint. Ideally, toughness data would be collected from welding procedure test plates as required, where these exist, and in some cases it is possible to estimate the appropriate data from the results of Charpy tests. Other problems arise in the establishment of (i) discontinuity size, shape, position and orientation, and usually (ii) operating stresses. The former is dependent on the accuracy of NDT, which is a subject of debate. A particular problem has been the undersizing of defects by certain commonly used NDT techniques (15, 97). The latter cannot always be determined accurately, if at all. Obviously, any known inaccuracies in the data can be overcome by using conservative values, but this may result in totally unrealistic result, thus defeating the object of this type of assessment. Also, in some situations where the economics of assessment and repair are the main criteria, it may be cheaper and more appropriate to use conventional assessment techniques. One possible criticism of PD6493 is that its complexity makes it difficult to understand for those not fully conversant with fracture mechanics. Consequently, The Welding Institute has published a number of "users guides" in its Research Bulletin (98-101).

It is beyond the scope of this document to provide a full account of the principles of fracture mechanics and its application to welded structures, which is a complete subject in itself. Similarly, a long description of PD6493 would be inappropriate: such information is available elsewhere (e.g. 102). Instead, six examples of the successful use of the fitness for purpose assessment of discontinuities, as quoted by Harrison (41), are reproduced here.

Case 1: The Aleyaska Pipeline

The most often quoted example of the benefits of a fitness for purpose approach compared with the use of traditional acceptance criteria is the Aleyaska Pipeline (44). When 400 miles of this line had been completed the radiographs were audited. About 10% of the girth welds were found to contain discontinuities which should have been rejected on first inspection according to API 1104 (103). An engineering critical assessment (44,104) showed that all the defects were innocuous and this in the end was accepted by the U.S. Department of Transportation who waived the repair requirements for some welds. However, because of time constraints, the majority of welds were repaired before the waivers were issued, at a cost of about $90M,nearly 20% of the cost of that portion of the line.

Case 2: Power Generation Industry

Engineering critical assessment for weld defects has been used to great advantage in the power generation industry. Toft and Yeldman (105) describe cases where fracture mechanics was used to assess defects in United Kingdom Central Electricity Generating Board boilers. Timing of repair is important in such plant. Must it be done immediately ? Can it be deferred until the next shutdown during a period of low demand or, possibly with suitable in-service monitoring, will the plant survive for its design life without repair ? The running costs vary with demand, (106) a day's running cost on an AGR during a high demand period being about $300,000, reducing to $180,000 when demand is low. James et al (107) describe an engineering critical assessment of small defects found, just prior to commissioning, in welds in Advanced Gas-cooled Reactor AGR steam generator piping systems. This showed that the defects could remain without any detrimental constraint on station operation. Repair would have delayed commissioning of all four units affected by at least a year. These four units would cost about $2400M so that the loss in interest charges alone would be, say $300M. An alternative to repair was to downrate the stations, but this was equally undesirable economically. An approximate estimate of the daily cost of such downrating for the four units would be up to $240,000 depending on demand and on other operational constraints.

Case 3: Beatrice Pipeline

This case has many similarities to that of the Aleyaska Pipeline. The Beatrice Pipeline is 16in. diameter, ½in. thick, with submarine and land sections 12 miles and 28 miles long respectively. After the line was laid, an audit of the girth weld radiographs revealed many defects which should have been repaired according to the acceptance criteria of BS4515. Of course this state of affairs should never have been allowed to occur, but an extenuating circumstance was the record speed at which the line was laid and the consequent pressure on the radiographic team. Be that as it may, the owners had to decide whether the line could be operated or must it be entirely replaced, the only viable alternative for the submarine section. Fortunately BS4515, unlike the then existing version of API 1104, provides for these circumstances by permitting ECA to be made for defects falling outside the normal quality control levels, provided all the parties agree. This was done for the girth weld defects using the procedures of PD6493. It was shown, to the satisfaction of the Licencing Authority, that the defects were tolerable and agreed that the line could be operated. The value of this decision can be tied directly to the cost of a replacement for the line estimated at $26M.

Case 4: North Cormorant Jacket

At a late stage in fabricating the North Cormorant offshore platform buried chevron cracks (weld metal hydrogen cracks) were found in submerged-arc longitudinal and girth seams in the tubulars used to make the large inter-sections (nodes). The tubulars, which were up to 100mm thick, had been made by one subcontractor. A second subcontractor had welded brace stubs to these to make the nodes which were then postweld heat treated (PWHT). The main contractor had received the nodes and welded them into the jacket. The chevron cracking was first found during UT of one of the circumferential erection welds, when the NDT Technician had to probe through the end of the longitudinal seam of the node, where this intersected the erection weld. Further UT probing revealed that 20% of seam welds were affected. Repair of the defects would have had disasterous consequences for the construction programme. The structure would have had to be dismantled, because in situ PWHT of the repair welds was impossible. It was therefore decided to carry out an ECA of the defects. Fortunately the welding procedures were pre-qualified on a CTOD basis and excellent values were obtained at $-10^{o}C$. The defects were assessed for resistance to fracture and fatigue using the methods of PD6493 and found to be quite innocuous. It was decided, with the concurrence of the certifying authority, to allow construction to proceed.

The value of this decision can only be estimated, but it can be assumed that, without it, delivery would have been delayed for at least twelve months because launch in the summer weather window would have been missed. With a total investment in the North Cormorant field of $500M, the loss in interest charges alone would be about $70M.

Case 5: A Mine Shaft Lining

The shaft of the Boulby potash mine is some $\frac{3}{4}$ mile deep. It passes through a layer of sandstone $\frac{1}{2}$ mile thick which contains water at pressures which increase with depth up to 90 bar. To sink the shaft and line it, it was first necessary to freeze the sandstone. The shaft lining has two 45mm thick steel shells with the space between being filled with concrete. Late in fabrication, UT of one of the horizontal girth welds indicated cracks, which were identified by metallography as HAZ hydrogen cracks. This finding called into question the original inspections and seven additional welds were reinspected by UT. Five were cracked. Some of the cracking was in the outer shell and some in the inner shell in positions where the interspace had already been concrete filled. Attempts were made at repair but these were abortive because of the difficulties involved, in particular, for those welds already backed by concrete. An ECA of the defects was therefore conducted. Because of the very high water pressure in the sandstone, failure of the lining would have had serious consequences. Although after completion of the shaft, the lining would be in compression, axial tensile stresses could develop from thermal gradients set up as the frozen sandstone thawed out and rose to ambient temperature. In addition, tensile residual stresses transverse to the weld could reach yield locally.

The assessment was made using the procedures of PD6493. The only conceivable failure mode was brittle fracture. CTOD tests were performed at -30°C, the minimum temperature of the frozen sandstone, on specimens notched in the HAZ of a weld sample from the lining. Analysis based on a minimum CTOD of 0.31mm indicated that long buried cracks, up to 10mm deep at midthickness, could be tolerated. This was considerably larger than any of the defects located by NDT and it was decided to continue lining the shaft, but with welding procedures revised to eliminate the original causes of the cracking. The mine has now been in use for several years without any problems at these welds.

Case 6: Pipe Girth Weld Defects in a Chemical Plant

After construction of a piping system for the transfer of hot gases small cracks were found to exist in some of the site butt welds. These welds were made on to backing rings and the cracks which were about 1mm high were at the root. Although under normal operation the system will be hot, it was remotely possible for it to be pressurised cold. It was decided that, if the system survived the statutory pressure test, the defects would not be repaired. However, the pipes were refractory lined and for this reason the owners wanted to test the system pneumatically rather than with water. However, if it could be done pneumatically the welds could all be tested simultaneously and this would save about one week. Because of the energy stored in a pneumatic test the owners wanted to have reasonable confidence that failure would not occur. CTOD tests on sample weldments gave a minimum value of 0.09mm. The methods of PD6493 indicated a maximum tolerable surface flaw 8mm deep x 80mm long at the proposed pneumatic test pressure of 1.3 x design. Since this was considerably larger than the actual defects it was decided to proceed with the test which was successful. The system has been in operation now for several years. The economic significance of this case was that, if a hydrostatic test had been carried out, at least one week would have been required to dry out the refractory lining before the whole plant could be brought on stream. This relatively short delay would have led to a loss of revenue of $2.5M.

5. A RATIONAL APPROACH TO REPAIR OF WELDS

The literature has shown that, to a greater or lesser degree, the traditional approach to repair, encompassing all aspects of design, fabrication, inspection and correction, is at best out of date, and at worst incorrect. There are problems associated with the making of a satisfactory repair, due largely to an ignorance of the special requirements demanded to achieve a good repair: these problems can be overcome in most situations if certain precautions are taken and certain procedures are followed. However, the area in which most progress can be made relates to the decision-making process by which a repair is called for. There is considerable scope for improvement in this area with a likely net result that far fewer repairs would be required.

5.1 Assessing the Need for Repair

It has been shown that the traditional standards for assessment of discontinuities in welds do not on the whole relate the effect of the discontinuity to service performance and hence they are inappropriate for establishing a requirement to repair. They are, nevertheless, very useful for setting standards of good workmanship which should be achievable, and are applicable to general quality assurance procedures. Rather than modify these standards so that they provide alternative assessment levels for use when considering the need to repair, it would be easier and less confusing to have a completely separate standard, solely applicable to the assessment of repair requirements. It is very important to maintain a distinction between the standard of quality that a fabricator should achieve, and the standard of quality that guarantees structural integrity. Otherwise, because the latter is often less severe than the former, any confusion of the two separate objectives may lead to a general lowering of workmanship standards, which is clearly undesirable.

For general use in structural steel industries, a repair standard must allow assessment of discontinuities to be made at shop floor level on a go-no go basis. PD6493, for example, is too specific as it is designed to assess each discontinuity separately, requiring a wide range of information and extensive attention of the design team in the process. In its present form it is best suited for use in high risk industries such as nuclear power, where the establishment of structural integrity must be made at any cost. However, it has also been used extensively in the structural steel industry, particularly for offshore constructions. The best form of repair standard is probably one which allows the designer to select one of perhaps five or six quality bands for each specified type of weld, each quality band having different limits of acceptance for discontinuities - limits than can be quickly and easily checked by the inspector during fabrication.

The standard must contain sufficient data to allow the designer to select the correct quality band based on his knowledge of service requirements. He should not need to be an expert in fracture mechanics, fatigue, metallurgy, etc, to do this. In the structural steel industry, it is reasonable to assume that design and material selection can be established by the designer so that risk of failure by corrosion, stress corrosion, creep, gross yielding buckling and collapse are avoided. Thus the quality bands need only cater for the two primary modes of failure, fatigue and brittle fracture.

The effect of discontinuities on fatigue performance is now fairly well understood, so it should be possible to establish quality bands which permit differing sizes of discontinuities to be accepted according to the design stress range, required number of cycles, and joint type used. To establish the fracture tolerance of discontinuities, some knowledge of toughness is required. Toughness is a quantity about which it is difficult to generalise, but it may be possible to provide minimum toughness values by a probablistic approach based on empirical data, at set levels of confidence (similar to the S-N approach for fatigue). These toughness levels could be either (i), global; or (ii) related to specific combinations of material/consumable/process. The latter is probably the better approach, and could be verified by Charpy data from test plates made during fabrication (the provision of test plates for toughness evaluation at the fabrication stage is in any case a sound procedure to adopt, if there is any possibility of a more rigorous fracture analysis being required at a later date, e.g. evaluation of in-service cracking), or ideally by the more thorough route of crack tip opening displacement (CTOD) testing.

Having established an appropriate quality band based on fatigue and fracture requirements, the maximum permissible sizes for planar discontinuities, lack of fusion/penetration, slag and porosity relevant to that band are automatically defined. Because of the complex behaviour of cracks and similar planar discontinuities, it is likely that in this simplified approach, they will only be permissible if good toughness can be guaranteed in service.

Geometric discontinuities must be given full treatment, since it is apparent from the literature that weld profiles, misalignment, etc are among the most common causes of failure. The intrinsically poor structural performance of fillet welds compared with butts may require a separate quality treatment of each. Undercut must also be given careful consideration.

Slag and porosity are generally harmless in all but the highest quality welds, and should rarely require repair unless grossly outside the conventional limits set by good workmanship standards, or there is a suspicion that they are masking more serious discontinuities. This is the area which requires most immediate attention, since the literature has indicated that slag and porosity, the most innocuous of all discontinuities, are the most often repaired. In structural steelwork, the typical levels of slag and porosity encountered are never likely to be a direct cause of failure. Once this is understood and accepted, it may lead to the use of more economical high productivity welding processes which at present are excluded because of the relatively high levels of porosity associated with them.

When defining the limits for the quality bands careful consideration should be given to the resulting limitations imposed by each band on the acceptable size of discontinuity. The type and capability of the NDT methods that will be required are relevant here, and a sensible approach will result in economical inspection requirements. For example, great cost saving could be achieved if the lowest quality band set limits on discontinuity sizes that could be checked solely by visual inspection. The higher quality bands will no doubt require some volumetric inspection, but at least the designer will have the choice of weighing the cost increase resulting from use of better and more expensive design/materials to a saving on inspection labour because a lower quality band (and hence greater discontinuity tolerance) has resulted.

Specification of maximum discontinuity dimensions should also take into account the capability of volumetric NDT methods. Although depth is considered a more important parameter than length for buried defects, length is usually the most easily and accurately measured dimension, so if tolerances could be related to length only, a lot of NDT could be avoided. For example, slag can be reasonably assessed on length since its depth and width are rarely greater than 3mm. Similarly, porosity is rarely ofgreater diameter than 3mm, so radiographic assessment could be on a percentage projected area basis. Planar defects could possibly be conservatively assessed on length using the assumption that they are through thickness. On the whole, the current approach to NDT seems to require too much (or the wrong sort) in many circumstances. Fillet welds, because of their inherent geometric discontinuities, should never require evaluation of non planar buried defects. It is in any case difficult to use radiography and ultrasonics on fillet welds. There is instead a need for more basic visual inspection, especially during fabrication, to help maintain standards and identify and correct problems as and when they arise, rather than at completion of fabrication. (Ref. 108 gives a good guide to visual inspection methods and application).

No part of the above route is radically new or controversial - the difficulties arise only when choice and quantification of the relevant parameters is attempted. Harrision, Burdekin and Young in their 1968 conference paper "A Proposed Acceptance Standard for Weld Defects Based Upon Suitability for Service" (90) came as close to defining a simple workable document as anyone else since, although it is believed that similar documents have been prepared for in-house use in certain specialised industries (the author knows of one example being a British crane manufacturer). Because it is of such direct relevance to this study, it has been reproduced in full in the appendix. It is possible that developments in the welding world since that paper was written would alter some of its content, but on the whole it still serves as an excellent example of what is required today. The only real criticism is that (like PD6493) for planar discontinuities specific examples must be individually assessed to establish the minimum quality band which is capable of tolerating them. The more workable approach is the reverse, in which a given quality band stipulates size limits for a few broad categories of planar discontinuity, despite the inherent conservatism of this approach.

5.2 How to Repair When Necessary.

Ultimately, the best way of avoiding the requirement to repair is to set and maintain high standards of design and fabrication, but inevitably mistakes are made that must be corrected by repair. Code requirements for repairs usually ask for procedures and final quality that match the original requirements, and say little else. After consideration of the host of problems specific to making a weld repair (Section 3) it would seem that this is inadequate, and that far greater attention to detail is required for repair, compared with that used for initial welding. If a high quality repair is required, special attention should be given to the following points:

1. Before commencing a repair, first establish the cause of the initial defect. This may give important clues to potential repair problems, and may indicate that the initial procedures are inadequate.

2. For correction of geometric defects such as poor weld profile, undercut, etc., a dressing technique such as grinding should be used as an alternative to additional welding whenever possible, even if a slight reduction on thickness results. The benefit in terms of fatigue strength due to grinding far outweighs any small increase in nominal stress due to removal of material.

3. Excavate a clean, smooth-walled, well shaped cavity. Careful design of cavity shape together with good procedures will minimise distortion due to repair and the likelihood of introducing new crack-like LOF/LOP discontinuities.

4. Make sure the defect is fully removed, using the appropriate NDT technique (MPI or dye penetrant).

5. Give consideration to the risk of introducing new planar discontinuities during repair. To avoid hydrogen cracking, use basic coated electrodes (which need careful drying) or other low hydrogen processes. Consider the need to use preheat - a repair will often require more preheat than the original weld; for example, positional welding may have a much lower arc energy than the equivalent flat welding technique. Also, maintaining the pre-heat for a few hours after welding will help to diffuse out the hydrogen before the weld cools to a temperature at which it may crack. Consider that an expensive process that requires little or no preheat (e.g. GMA or austenitic welding) may be the most economical in the long run.

6. If the repair is being made to a stress-relieved weld, post weld heat treatment may be required, or alternatively the half bead technique may be used.

7. Temporary attachments should be fitted and removed in a sensible fashion.

8. Thorough NDT of the repair may be essential.

With consideration of the above points, together with education of designer, welder and inspector to make them aware of the potential problems particular to repair welding, it should be quite feasible to produce a sound and satisfactory repair.

6. CONCLUSIONS

Weld repairs, although very low in the list of causes of structural failures do, nevertheless, directly cause failure from time to time. There are two major reasons for this: firstly, there are particular problems associated with weld repair that are often not fully considered or understood, and this may lead to a repair whose quality is not as good as expected;secondly, and more important within the structural steel industry, repair is often performed on structurally innocuous discontinuities, and this, in combination with the first may lead to a repair that is structurally much less sound than the original weld that was the subject of the repair. However, with a better understanding of the problems and requirements inherent in repair welding, in the majority of situations it is possible to make a satisfactory repair. Similarly, with a better understanding of the structural significance of discontinuities, the majority of repairs could be avoided completely.

In most current standards, the demand for repair is based on the failure to achieve good levels of workmanship - this is an inappropriate approach, as it takes little or no account of the service performance of the structure in the presence of discontinuities. In a few cases, this approach may be unconservative, but in the vast majority of cases it is very over-conservative, with detrimental effects on cost, and also on structural integrity, if the repair is poor. Workmanship standards serve a valuable purpose in maintaining quality, but there is a pressing need for alternative standards giving guidance on when to repair discontinuities. This is particularly true for slag and porosity, considered to be the most innocuous of all discontinuities, yet the most frequently repaired. In nearly all cases, repair to slag and porosity in structural steel fabrication is totally unneccessary.

The present knowledge of the effects of discontinuities on structural integrity, together with the aid of the relatively new disipline of fracture mechanics, should permit the formulation of an acceptable and readily usable standard for assessing the need to repair, although there are still some grey areas in which further work would be desirable. Such a document would in general greatly reduce costs, whilst at the same time providing a firmer guarantee of structural integrity. The quality band approach seems to be most favoured in the literature, and the appendix contains one such approach which could provide a basis for a working document.

A further aspect of repair welding which requires close consideration is inspection and NDT. Recent rapid developments in NDT technology have meant that current practices are to some extent irrational and not as cost effective as they could be. A rational approach to repair welding must take account of the present capabilities and limitations of NDT, and make sensible and economic use of them.

7. RECOMMENDATIONS

1. There is a requirement for a new and more rational approach to repair of weld discontinuities, based on fitness for purpose, and tailored to suit the structural steel industry so that it can be simply and easily used.

2. There is sufficient knowledge and data available already on which such a document could be based, but there are some areas, particularly low cycle fatigue behaviour, generalised fracture toughness guidelines, and non-destructive testing capability, which would benefit from further study.

3. To produce a document that is both reliable and practical would ideally require close cooperation between both the experts in the relevant engineering disiplines and the industrial manufacturers by whom the document would be used.

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TABLE 1. Frequency of occurrance of types of discontinuity according to process, in US shipyards (from ref. 1).

Welding Process	Discontinuity type, in decreasing order of occurrence
Manual Metal Arc	1. Slag
	2. Porosity
	3. LOF/LOP
	4. Undercut
	5. Others
Submerged Arc	1. LOF/LOP
	2. Slag
	3. Porosity
	4. Others
Flux Cored Arc	1. Slag
	2. Porosity
	3. LOF/LOP
	4. Others
MIG (solid wire)	1. Porosity
	2. LOF/LOP
	3. Others
MIG (self shielded)	1. Porosity
	2. Slag
	3. LOF/LOP
	4. Others

TABLE 2. Defects in welded joints revealed by repeated inspection (29).

Preliminary evaluation of weld, in numbers (defects remaining in weld)	Technological operation preceding repeated inspection	Number of defects revealed by repeated inspection	Type of repeated defects	Comment
<u>Austenitic steel, 26mm in thickness (radiography)</u>				
3	weld repair austenitising	5	Cracks, length 1.5-6.5mm	In the vicinity of welded groove
2 (permissible)	The same	2	Slag inclusions, 1.2 x 1.5mm; 1.5 x 1.8mm with tears	In the seam
2 (permissible)	The same	4	Acute-angled slag inclusions; 2 x 1.5mm; 2.2 x 2.0mm	In the seam
3	The same	5	Cracks, length 6.0-75mm	In the vicinity of welded groove
<u>Pearlitic steel 20K, thickness 70-80mm (ultrasonic inspection)</u>				
3	Weld repair, heat treatment	22	Crack, length 4.0-6.5mm	In the vicinity of weld groove (confirmed by radiography)
2 (permissible spots)	Repair mechanical treatment	12	Long defects	In the seam
2 (permissible spots)	Repair, heat treatment	5	The same	The same
3	The same	38	Cracks, length 12-150mm	In the vicinity of weld groove

Contd.../....

TABLE 2 Continued

Preliminary evaluation of weld, in numbers (defects remaining in weld)	Technological operation preceding repeated inspection	Number of defects revelealed by repeated inspection	Type of repeated defects	Comment
Pearlitic steel 12Kh1MF, 70-80mm in thickness (ultrasonic inspection)				
2 (permissible spots)	Repair,heat treatment	45	Long defects, increase in pulse height	In the seam
2 (permissible spots)	The same	24	A crack 15mm long	In the vicinity of welded groove
3	Repair	12	A crack 40-85mm long	The same
3	Repair	19	A long defect	In the seam

TABLE 3. A comparison of the cost of repair compared with the cost of the original weld, from Volkov (41).

Technological operation	Operator	Average labour content (hours) in relation to the thickness of components		
	Profession	18mm	30mm	40-45mm
		Norm- hour	Norm-hour	Norm-hour
Marking of defect according to flat detector image	Machinist	0.50	0.50	0.50
Grinding of defective area with periodical marking according to flaw detector image	Machinist	0.60	1.00	1.20
Radiography of ground weld region	Radiographer	0.20	0.24	0.32
Photoprocessing of X-ray image (preparation of film, charging and discharging of cassettes, development)	Photographic assistant	0.078	0.078	0.078
Welding of ground defective weld region	Arc Welder	0.238	0.47	0.75
Dressing of welded-up region by pneumatic polisher	Machinist	0.03	0.03	0.03
Ultrasonic inspection of repaired weld region	Ultrasonic equipment operator	0.14	0.14	0.14

Contd.../....

TABLE 3 Continued

Technological operation	Operator / Profession	Average labour content (hours) in relation to the thickness of components: 18mm	30mm	40-45mm
		Norm-hour	Norm-hour	Norm-hour
Radiography of repaired weld region	Radiographer	0.24	0.32	0.43
Photoprocessing of X-ray image	Photographic Assistant	0.078	0.078	0.078
Polishing of repaired weld region and HAZ for surface inspection	Machinist	1.00	1.00	1.00
Luminiscent or dye penetrant inspection of repaired weld region	Operator in luminiscent inspection department	0.75	0.75	1.00
Total		3.258	3.89	4.82
Labour content of welding 1m of seam	Welder	0.95	1.88	3.00

NOTE. The calculation was conducted according to norms of machine building plants. The depth of defect location was taken at 75% of the component thickness (the most frequent case).

TABLE 4. Analysis of discontinuities in welded ship hulls (ref. 81).

Table 4a. Summary of NDT results from hull testing of six ships of size 250 000-260 000 tdw

Joints	Total length of hull welds, m*	Length of tested weld		Number of internal planar defects found
		Total	In cruciform joints	
Deck	9 643	1 438	310	450
Side shell	10 208	680	146	184
Bottom shell	8 595	2 110	390	495
Transverse bulkhead	1 246	23		4
Longitudinal bulkhead	5 305	72		23
Webs	23 531	136		52
Longitudinals	14 674	1 026		227
Bottom plates	1 260	496	331	68
Total	74 462	5 981	1 177	1 503

*Machine welded joints

Number of defects inspected/m in cruciform joints $= \frac{1503}{5981} \times 2 = 0.5$

Number of defects in cruciform joints = 1177 x 0.5 = 588.5

Number of defects inspected/m except cruciform joints $= \frac{1503 - 588.5}{5981 - 1177} = 0.19$

Number of defects left/ship $= \frac{0.19\ (74\ 462-5981)}{6} = 2169$

Table 4b. Summary of registered damages during service from the same six ships

	Number of damages					
	Cargo Space		Fore-body		After-body	
	Crack	Deformation	Crack	Deformation	Crack	Deformation
Side shell	2	4		2		1
Bottom shell		3				
Transverse bulkhead	4	1			1	
Wash bulkhead	1					
Web on side shell						1
Web on transverse bulkhead	1					
Side longitudinal		1				1

None of the damages can be related to internal defects in welds.

APPENDIX A

00503

A PROPOSED ACCEPTANCE STANDARD FOR WELD DEFECTS BASED UPON SUITABILITY FOR SERVICE

By J. D. Harrison, F. M. Burdekin, and J. G. Young

SUMMARY

The standard outlined in this paper sets out means of stipulating sizes of defect which can be permitted to remain in welded structures without preventing the structure from performing its required function. The requirement to specify limiting defect sizes is placed upon the designer, and the limits are to be set at the design and material selection stage. The inspector is asked to ensure that the requirements of the designer are met. Where interpretation is required this is the function of the designer.

It is assumed that material selection has been correctly carried out to prevent failure by corrosion, stress corrosion, and creep, and that the design is adequate to prevent failure by gross yielding, collapse, or buckling. Defects of such a size that the remaining ligament is loaded to a mean stress level above yield are obviously unacceptable. The standard caters mainly, however, for the cases of fatigue cracking and brittle fracture.

A summary of the requirements of the standard is given in Table II with reference to other tables and figures where necessary. Five basic qualities of fabrication (V-Z) are listed for which maximum sizes of planar defects (cracks, lack of fusion, lack of penetration), slag inclusions, and porosity are given.

For fatigue-loaded structures the designer is required to stipulate the necessary quality for the particular design stress level from Fig. 1, after taking account of the inherent fatigue strength of different welded details. The limiting levels of porosity and slag inclusions are then shown in Table II, and those for planar defects must be derived from Figs 3 and 4.

To prevent failure by brittle fracture the designer must stipulate the use of materials (including all regions of welded joints) to tolerate both initial welding defects and cracks developing in service. The limits for the qualities V-Z under fatigue loading are chosen so that fatigue cracks will not grow to a size exceeding the plate thickness. For such loading the designer is required to stipulate materials with adequate fracture toughness to tolerate through-thickness cracks of length twice the plate thickness. In structural steels this may be done either by a transition temperature approach or by a fracture mechanics approach. Requirements for the former are given in Table II, where the designer must choose between prevention of fracture initiation (referring also to Figs 5 and 6 for C-Mn steels), and prevention of fracture propagation. The fracture mechanics approaches must be used in all cases where transition temperatures are not applicable, and the relationships between maximum crack size, working conditions, and material fracture toughness are given in Tables V and VI for linear elastic and crack opening displacement (COD) approaches respectively.

The Authors are with The Welding Institute.

INTRODUCTION

The basis of acceptance criteria for weld defects in existing applications standards appears to be arbitrary. Such standards, which are not related to service requirements, will in some cases lead to structures which are unsafe and in others to unnecessary and possibly even deleterious repair work. For example, in the case of a shaft built up by welding and subsequently machined, nothing short of excellence will do. This is because the small defects in an average weld will act as the greatest stress raisers present and will initiate fatigue failure at approximately 70% of the fatigue strength of the unwelded shaft. However, in a building structure subjected only to static loading in which there is no risk of brittle failure, all but the most gross defects are acceptable.

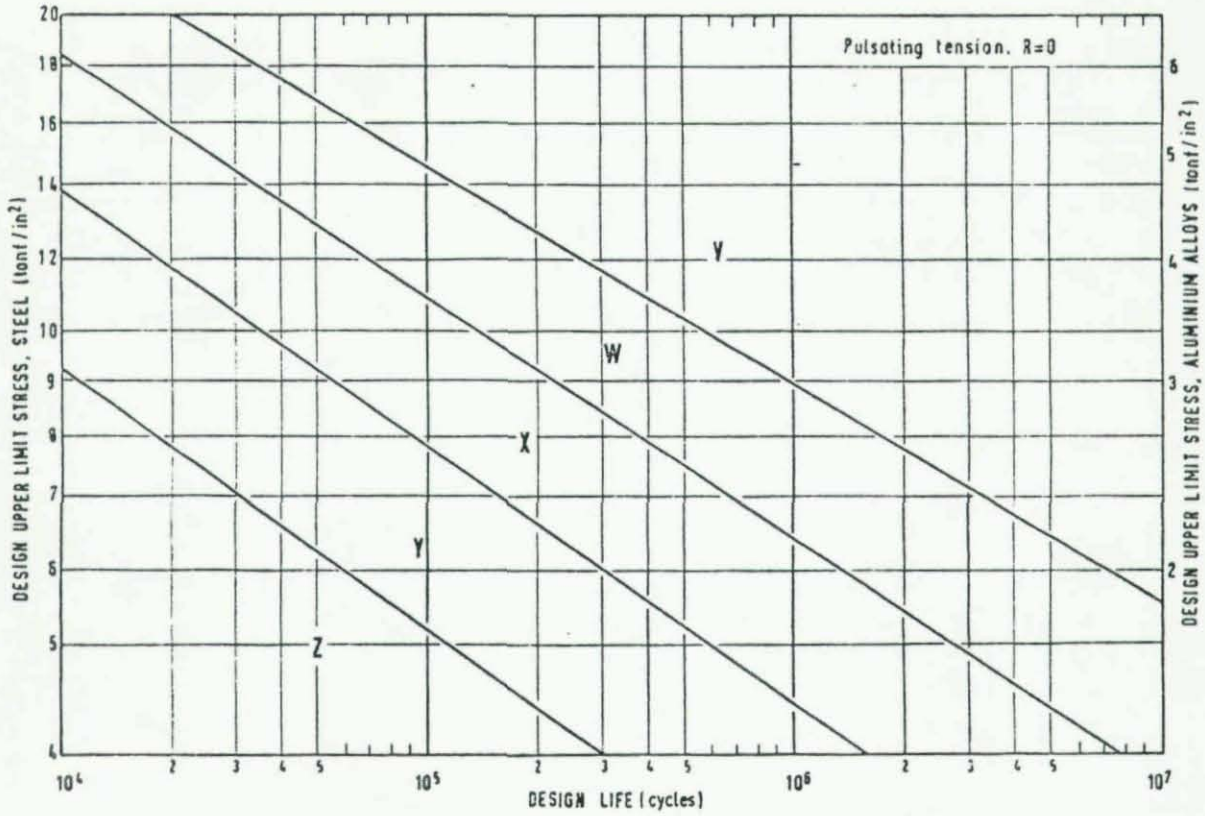


Fig. 1 - Quality levels with stresses multiplied by appropriate safety factors

Repair welds are usually not made under such favourable conditions as were present when the original weld was deposited. For example, the repair weld will often be made in a narrow groove and, therefore, under conditions of high restraint. Insufficient attention may be paid to preheat and small gauge electrodes may be used. Such conditions lead to an increased risk of cracking. One may therefore have removed an easily detectable but harmless defect, e. g. a cluster of pores, and substituted a planar defect which is both harmful and difficult to detect. Therefore, quite apart from economic arguments, there is good reason for basing acceptance standards for weld defects on the effect of defects on service performance.

Because of the economic and technical advantages, the acceptance standards outlined in the present paper are based solely on the question of whether or not any particular defect introduces a risk that the structure will be prevented thereby from fulfilling its intended function.

An earlier paper by the present authors [1] reviewed in detail the information available for assessing the significance of defects on structural performance. The present paper goes a step further in presenting the information in a form which should enable designers to specify those defects which can be tolerated in particular structural applications and those defects which must be repaired.

PHILOSOPHY

The proposed standard, based as it is on 'fitness for purpose', assumes that there is a thorough knowledge of the service conditions in terms of temperature, stress, and cyclic life. Since this knowledge will normally be available to the designer but not necessarily to the inspector, the former should be responsible for specifying the appropriate quality so that a minimum of engineering judgement is required of the latter. This approach also ensures that the fabricator is aware of the standards to be met and so can base his estimates on a realistic standard of fabrication.

In assessing the effect of defects on service performance the information required is the critical size of defect to prevent the structure from carrying out its service duties. This may occur by final failure of the structure by brittle fracture or by overloading when the net section is greatly reduced, or it may occur by leakage in pressure containing equipment, or by distortion. It is also necessary to know whether growth of defects is going to occur in service by fatigue or stress corrosion. Given this information the initial size of defect which can be tolerated may then be estimated and this can be compared to the size of defect which can be detected with reasonable accuracy. Obviously the type of defect and the location and orientation of defects will have some influence on their effect, and the standard assumes the worst orientation to be relevant. It is assumed in this standard that appropriate materials to avoid stress corrosion have been selected, although the brittle fracture requirements can be used to cater for stress corrosion cracks through the thickness with a length up to twice the thickness. No guidance is given in the standard for avoidance of welding or heat treatment cracking, since this is outside the terms of reference. Creep is not considered since the effect

TABLE I - Safety factors

Line between areas	Unfactored stress (tons/in^2) at		Factors at		Factored stress (tons/in^2) at	
	10^5 cycles	2×10^6 cycles	10^5 cycles	2×10^6 cycles	10^5 cycles	2×10^6 cycles
V - W	20.0	9.2	0.72	0.85	14.5	7.8
W - X	13.5	6.2	0.82	0.87	11.0	5.4
X - Y	9.0	4.2	0.86	0.89	7.75	3.75
Y - Z	6.0	2.8	0.88	0.90	5.25	2.5

of defects on this form of failure is small. No detailed consideration of corrosion is included.

Several laboratory investigations have shown that static tensile tests on weldments containing defects may not permit a true assessment of the significance of these defects under service conditions. Natural defects are notoriously difficult to reproduce realistically in laboratory trials. It is now well established, however, that fatigue tests on butt welds with the excess weld metal removed are extremely sensitive to the presence of defects and can show quite clearly the different effects of different defects. Thus, in addition to providing information on the rate of growth of defects under fatigue loading for direct application to structural performance, results from fatigue tests can be used to indicate the relative severity of different forms of defect.

Coupled with the information derived directly from fatigue tests, fracture mechanics analyses provide a powerful means of assessing the relationships between crack size, rate of growth of fatigue cracks and size of crack for unstable fracture. Fracture requirements in the proposed standard are based upon requiring materials to have adequate fracture toughness to tolerate a crack of length equal to twice the plate thickness. This means that in fatigue-loaded structures it is possible for fatigue cracks to develop provided they do not exceed a length approximately equal to the plate thickness. The fracture toughness requirements also mean that in pressure-containing equipment leakage should occur and be detected before fracture occurs.

FATIGUE CONSIDERATIONS

The general procedure adopted has been to divide structures into a number of arbitrary levels of required quality based on the design stress and required cyclic

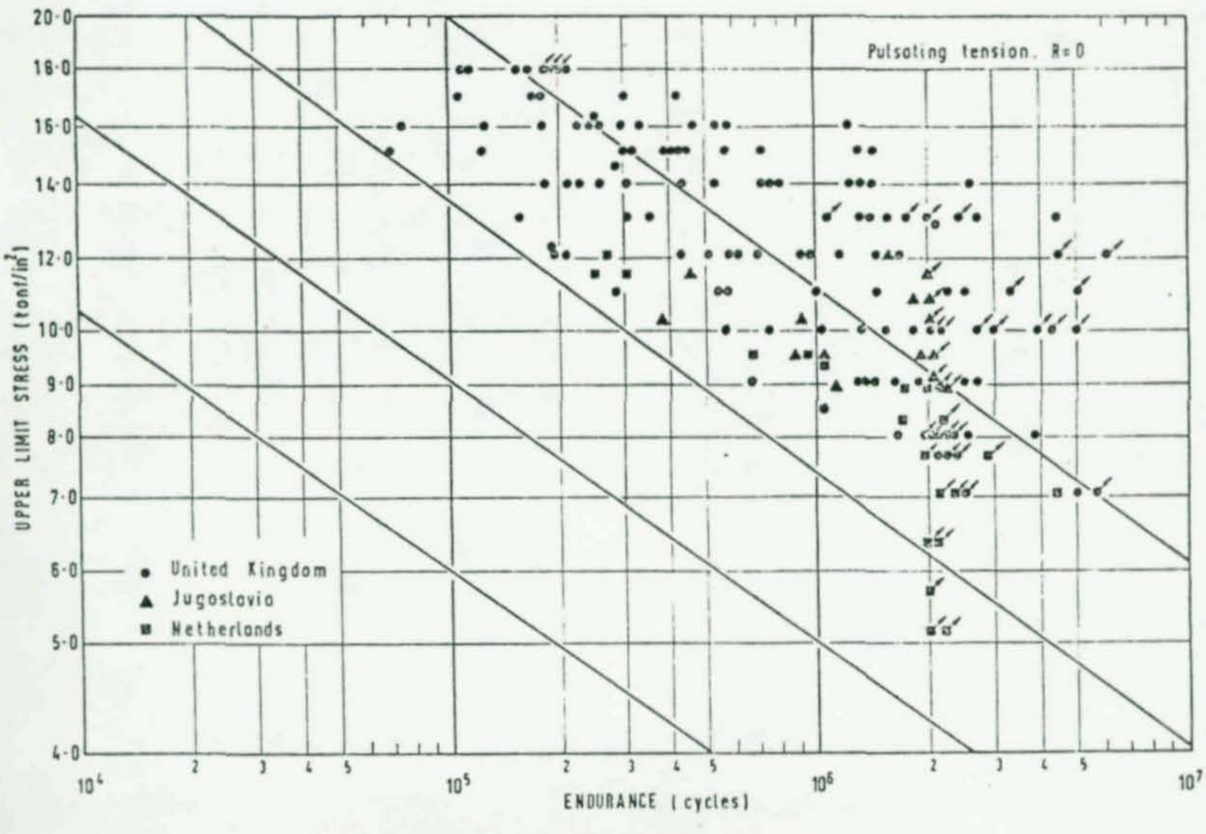
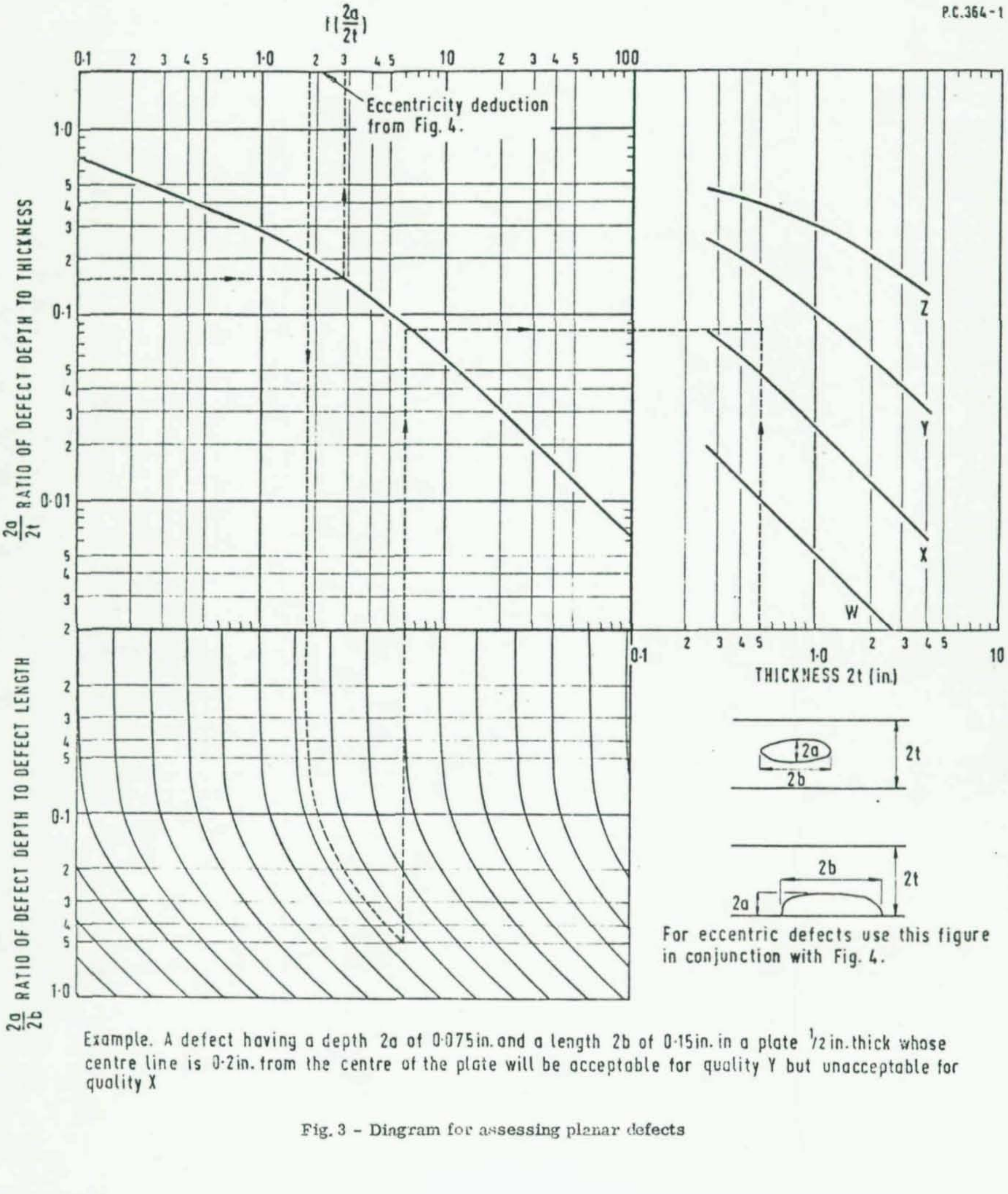


Fig. 2 - All test results for rutile welds containing slag inclusions not more than 3/8 in. (10mm) long

life. These quality levels are defined as areas in the S-N diagram. They are divided by straight lines with a slope of $-\frac{1}{4}$ since this conforms with a theory developed elsewhere to deal with lack of penetration defects. [1] This slope is also found to be suitable for other types of defect. Using always the lower limit of the scatter band of all known test results, the critical size of defect which might just cause failure in each area was then determined. The acceptance standard can then be stated in terms of the maximum allowable size of each type of defect for each of the five quality levels.

If the areas and the appropriate defect sizes were used as they stand there would be no factor of safety in the standard. In order to allow for ignorance of the exact size of the defect present, the applied stress level and the required life, an approach similar to that used in BS153 and described by Gurner,[2] is suggested here. Because the consequences of ignorance are likely to be more serious at high stress than at low stress the factors applied are graded. The actual factors are arbitrary and would in any particular applications standard be the responsibility of the drafting committee. The stresses at



Example. A defect having a depth 2a of 0·075in. and a length 2b of 0·15in. in a plate ½in. thick whose centre line is 0·2in. from the centre of the plate will be acceptable for quality Y but unacceptable for quality X

Fig. 3 - Diagram for assessing planar defects

TABLE II - Summary of maximum defect sizes and fracture toughness requirements

Fabrication quality	Permissible design stress	Planar defects, cracks, etc.	Slag inclusions (steel) length, in.		Porosity % vol.	Basic joint geometry	Fracture requirements				
							Transition temperature (steels)			Fracture mechanics	
							Initiation				
			As-welded	Stress relieved			C-Mn	Others	Propagation	Linear elastic	General yielding
V	See Fig. 1.	0	0	0	0	See BS 153	No defects permitted			See Table V	See Table VI
W		See Figs 3 and 4	1/16	$\frac{1}{4}$	3		For thickness 3in, temp. 100°C limited only by bulging or net area. For other conditions use Figs 5 and 6. Where not covered use fracture mechanics	Fracture mechanics approach required	Select steel and weldments so that minimum service temp. is above D. W. T. T. transition, or 35°C above nil ductility temperature.		
X			3/8	No maximum	8						
Y			No maximum	No maximum	20						
Z			No maximum	No maximum	20						

which each of the lines cross the 10^5 and 2×10^6 abscissae are multiplied by the arbitrary factors selected and the points so obtained again joined by straight lines in the log S - log N diagram. The resulting Fig. 1 is the one which is used in determining the quality level required for an actual structure. In deriving Fig. 1 the factors actually used are given in Table I.

As an example, the designer of a steel structure required to survive 10^5 cycles at a stress range of 0-9 tons/in^2 would know from Fig. 1 that the required quality was X.

For low cycle fatigue, i. e. cyclic lives $<10^4$ cycles, it is conservative to consider the relationships between design and stress and quality to be the same as those at 10^4 cycles.

In the fatigue tests on which the standard is based, fatigue cracks grew until the stress on the remaining net section was sufficient to cause ductile fracture. In order to ensure that the results of such tests can be applied with safety to an actual structure, it is necessary to specify that the material has sufficient toughness to enable it to tolerate a crack, whose length approximates to the material thickness, without there being a risk of brittle fracture. The necessary toughness levels are given in the standard.

LIMITATIONS ON THE APPLICABILITY OF THE FATIGUE CRITERIA

Material

It has been found in general that the fatigue strength of welded joints at long lives is independent of the tensile properties of the particular material involved. All welds of the same type in steels varying widely in tensile strength have the same fatigue strength beyond about 10^5 cycles. The same applies to welds of the same type in aluminium alloys. Therefore, although the fatigue tests on which the standard is based have used only mild steel and a small number of aluminium alloys, it is not considered necessary to restrict the application of the standard to these materials. In fact it would be reasonable to apply it to steels having tensile strengths up to 50 tons/in^2 and aluminium alloys up to strengths of 25 tons/in^2.

In general it is found that for similar joints and defects the fatigue strength of aluminium alloy welds are approximately one third of the strengths of steel welds. Figure 1 can be applied to both materials making use of the appropriate stress scales.

Thickness

Some of the rules in the proposed standard take account of thickness (lack of penetration) and some do not (slag inclusions). In tests on welds containing slag inclusions it has been found that for a given size of defect the strength for thicker material is either as great as or greater than for thinner material. There is therefore no necessity to impose an upper limit on thickness. However, since the converse will apply it would be unsafe to apply the rules to material thinner than the smallest thickness used in the tests. This thickness was $\frac{1}{2}$ in.

Joint geometry

The majority of fatigue failures which occur in service are associated with design features and not with weld defects in the normally accepted sense. It is assumed that any structure which is to be subjected to fatigue loading in service has been designed on the basis of fatigue strength inherent to the geometric details employed (using for example the fatigue clause in BS 153). The effect of designing to such a clause is to rule out, for most practical cases, the higher quality levels. For example, structures with fillet-welded attachments either with the fillet weld lying transverse to the direction of stress or with the fillet weld end in the stress field will not require a quality level greater than X.

The effect of stress ratio

The standard as outlined here is based purely on pulsating tension loading $\left(\frac{S_{min}}{S_{max}} = R = 0\right)$. However, there is sufficient information in the literature on the effect of different values of R to enable the effect of this variable to be allowed for in drafting any particular code. For example, a number of diagrams similar to Fig. 1 could be produced for the different values of R. It is suggested that the quality levels should remain the same throughout, the stress ranges appropriate to each quality being adjusted according to the value of R. It is known that for $R = -1$ the stress range for $R = 0$ can be multiplied by a factor of about 1.25 and for $R = +0.5$ it can be multiplied by a factor of about 0.85. Ranges for other values of R can be obtained by extrapolation and interpolation from these known values.

Secondary bending

The analysis used in deriving the rules does not make allowance for secondary bending which could occur with long surface defects in flat plates.

Surface defects in such instances would be more damaging than similar defects in structures where secondary bending is resisted, e.g. circumferential butt welds in pipes, and the allowable defect sizes would therefore be reduced. Analysis of this configuration has not yet been carried out.

DERIVATION OF ACCEPTANCE LEVEL FOR DEFECTS

Slag inclusions (applicable to steel only)

It has been found that good correlation can be obtained between the length of a slag inclusion and fatigue strength. This is not because the other dimensions (in particular the height measured through the thickness) are considered to be immaterial, but because, by reason of the way in which a slag inclusion occurs, these other parameters do not vary widely. A standard based on length will anyway be conservative because it is based on results for inclusions whose heights cover the range of practical values and a lower limit to the test results has been used. The acceptance levels were evolved by plotting all available test results. The results were plotted in order of increasing defect size. In this way, the lower limit of the scatter band was gradually moved downwards. The critical defect sizes were taken to be those for which one or more of the results fell in the next lowest quality band. Figure 2 includes all the results obtained by a Working Group of Commission XIII of the IIW for defects whose lengths were less than or equal to 3/8 in. It will be seen that no failures occurred in quality band X. On the next increment in size, however, some results did fall in this band; 3/8 in. is therefore the critical size for this quality. Stress-relieved welds can tolerate larger defects than as-welded joints and it may be considered worthwhile to take advantage of this fact.

The maximum allowable defect sizes determined in this way for the five quality levels are given in Table II.

Uniform porosity (steel and aluminium alloys)

The parameter characterising uniform porosity has been taken to be the percentage reduction in cross-sectional area. Good correlation has been found by a number of investigators between this parameter and the percentage reduction in fatigue strength. An approach similar to that used for slag inclusion has been employed, plotting on a diagram similar to Fig. 2 results for increasing percentages of porosity. Results for aluminium and steel have been analysed. The resulting allowable levels of porosity are shown in Table II.

Since for most practical purposes with fatigue loading qualities V and W cannot be used, about 8% porosity will usually be allowable. This is in fact a very high level and indicates the relative harmlessness of this type of defect compared, for example, with weld geometry. A 20% porosity would be to all intents and purposes impossible to achieve by any practical welding process.

A useful method of determining the percentage of voids for uniform porosity from a radiograph has been described by Houldcroft et al.[3]

Linear porosity (steel and aluminium alloys)

This is a defect which should be treated with caution. As such it is probably insignificant, but it is frequently an indication of lack of fusion. If the latter type of defect can be identified and its depth measured, or if its depth can be assumed from the details of the joint preparation, it should be assessed on this basis referring to the relevant clause in the standard. Only if the linear porosity can be shown not to be associated with lack of fusion should it be treated as porosity pure and simple and assessed on the basis outlined in the preceding paragraph.

Planar defects (steel and aluminium alloys)

This heading may be taken to include all the following defects :

Cracks, lack of penetration, oxide inclusions in aluminium alloy welds, lack of side wall fusion , lack of interrun fusion, and lack of root fusion.

Undercut and root concavity can also be treated as defects breaking the surface under this heading, since they will certainly have small crack-like defects at their roots.

In the past it has been conventional, with a few exceptions, to reject welds containing any of these defects. This has been very reasonable since such defects are the most deleterious of all. However, it is known that practically

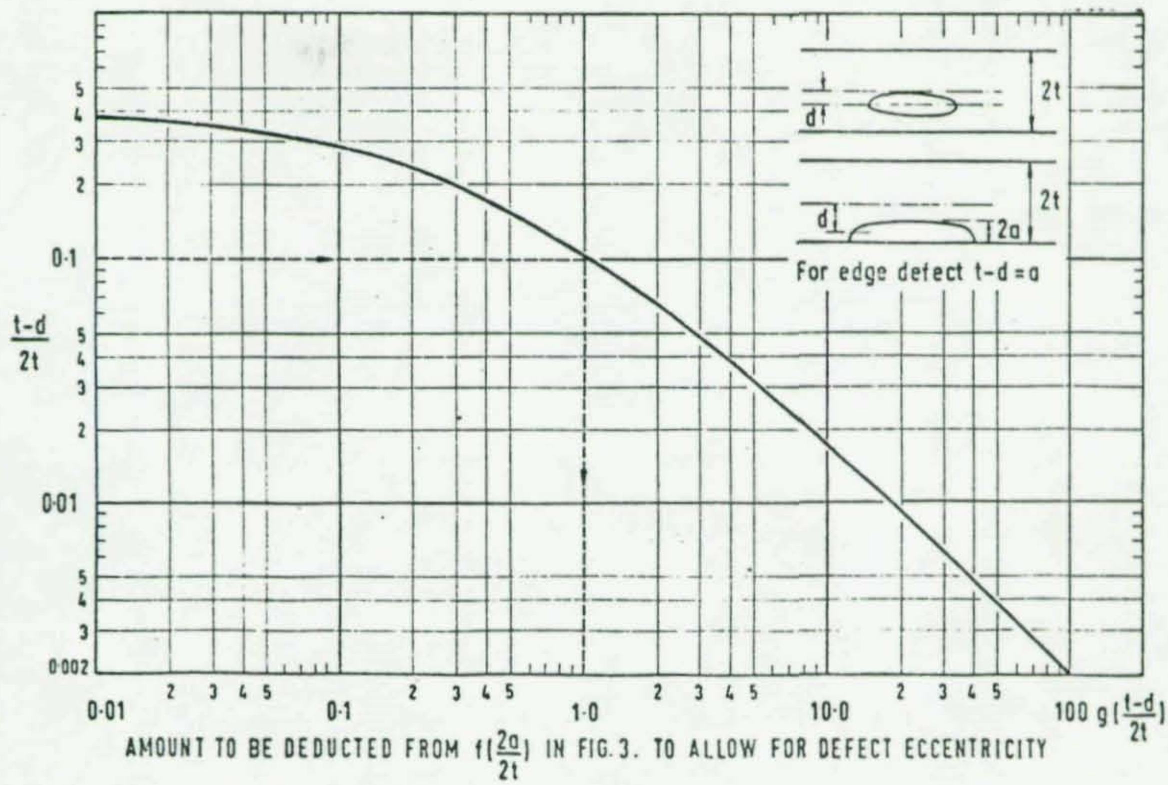


Fig. 4 - Eccentricity allowance

every weld that is made contains planar defects of one kind or another, but in most cases in the past these have been small enough to be undetectable. Structures containing them have given quite satisfactory service. With the improvements which are taking place all the time in NDT techniques, and also the increasing use of destructive examination of sample welds, it is becoming clear that a standard which seeks to reject all planar defects is no longer practical. Here again a decision must be taken as to whether the defect is large enough to impair the serviceability of the structure. However, considerable care in NDT should be exercised when assessing such defects in view of their severity.

It is perhaps worth noting that the rules which have been derived for crack-like defects can be applied to other types of defect, if, for example, difficulties of identification arise since the planar defect is the most severe.

A theory, which is well supported by experimental evidence, has been evolved on which rules for planar defects can be based. Such rules cannot be as simple as those outlined above for porosity and slag inclusions since they depend in a rather complex way on defect height, length, position, and material thickness. The theory will not be discussed here except to say that it was partially outlined in the authors' previous paper[1] and is based on the observed connection between rates of fatigue crack propagation and the instantaneous value of the fracture mechanics stress intensity factor, K.[4,5]

Rules based on this theory can best be expressed in diagrammatic form. Figure 3 gives the basic rule which was originally derived from defects near the centre of thickness. Figure 4 gives the correction to be applied for off-centre defects. The way in which these diagrams are used can best be illustrated by means of an example. Suppose that one wanted to assess the significance of a defect having the following dimensions and position in a plate whose thickness 2t was $\frac{1}{2}$ in.

Defect height, $2a = 0.075$ in.
Defect length, $2b = 0.15$ in.
Distance between defect centre line and plate centre line, $d = 0.2$ in.

First, $\frac{2a}{2t} = \frac{0.075}{0.5} = 0.15$ is calculated and using the upper left hand part of Fig. 3 the function $f(\frac{2a}{2t})$ is found, a function which is derived from the crack propagation equations. In the case of this example $f(\frac{2a}{2t}) = 2.8$.
Next, the expression $\frac{t-d}{2t} = \frac{0.25 - 0.2}{0.5} = 0.1$ is calculated, and from Fig. 4 the eccentricity allowance $g(\frac{t-d}{2t})$ to be deducted from $f(\frac{2a}{2t})$ is determined. In this case $g(\frac{t-d}{2t}) = 1.0$.

It is to be noted that as d approaches zero, i.e. $\frac{t-d}{2t} \rightarrow 0.5$, $g(\frac{t-d}{2t})$ becomes small. Also for defects with small values of $\frac{2a}{2t}$, $g(\frac{t-d}{2t})$ may be negligible compared with $f(\frac{2a}{2t})$.

In the present example the corrected value of $f(\frac{2a}{2t}) = 2.8 - 1.0 = 1.8$.

The next step is to allow for defect shape. The value of $(\frac{2a}{2b})$ is calculated. In this case $\frac{2a}{2b} = \frac{0.075}{0.15} = 0.5$. The parallel curves in the lower left hand part of Fig. 3 are followed from the corrected

TABLE III - Allowable defect heights 2a for various qualities, thicknesses, and degrees of eccentricity. (Values given are for defects in which $\frac{2a}{2b}$ is small)

Quality	Thickness 2t, in.	Central Defect d = 0, 2a in.	d in.	2a in.	d in.	2a in.	d in.	2a in.	d in.	2a in.	d in.	2a in.	Edge defect (t-d = a) 2a, in.
Z	0.5	0.19	0.15	0.16									0.12
	1.0	0.28	0.3	0.25	0.4	0.18							0.14
	2.0	0.38	0.6	0.36	0.8	0.28							0.19
Y	0.5	0.080	0.15	0.076	0.2	0.061	0.23	0.039					0.033
	1.0	0.10	0.3	0.090	0.4	0.080	0.46	0.057					0.038
	2.0	0.11	0.6	0.11	0.8	0.10	0.92	0.080	0.96	0.060			0.040
X	0.5	0.023	0.15	0.023	0.2	0.020	0.23	0.017	0.24	0.013			0.009
	1.0	0.024	0.3	0.024	0.4	0.023	0.46	0.021	0.48	0.018	0.49	0.014	0.009
	2.0	0.024	0.6	0.024	0.8	0.024	0.92	0.023	0.96	0.022	0.98	0.018	0.009
W	0.5	0.005	0.15	0.005	0.2	0.005	0.23	0.005	0.24	0.004	0.245	0.004	0.002
	1.0	0.005	0.3	0.005	0.4	0.005	0.46	0.005	0.48	0.005	0.49	0.005	0.002
	2.0	0.005	0.6	0.005	0.8	0.005	0.96	0.005	0.92	0.005	0.98	0.005	0.002

TABLE IV - Allowable defect heights 2a for various qualities, thicknesses, and degrees of eccentricity. (Values given are for defect in which 2a = 2b)

Quality	Thickness 2t, in.	Central d = 0, Defect 2a in.	d in.	2a in.	d in.	2a in.	d in.	2a in.	d in.	2a in.	d in.	2a in.	Edge defect (t-d = a) 2a, in.
Z	0.5	0.36											0.27
	1.0	0.59	0.3	0.39									0.34
	2.0	0.90	0.6	0.68									0.57
Y	0.5	0.20	0.15	0.16									0.14
	1.0	0.31	0.3	0.27									0.20
	2.0	0.42	0.6	0.38									0.24
X	0.5	0.095	0.15	0.087	0.2	0.072							0.50
	1.0	0.12	0.3	0.11	0.4	0.098	0.46	0.070					0.61
	2.0	0.13	0.6	0.13	0.8	0.12	0.92	0.094					0.62
W	0.5	0.028	0.15	0.027	0.2	0.025	0.23	0.021	0.24	0.016			0.012
	1.0	0.028	0.3	0.028	0.4	0.027	0.46	0.024	0.48	0.020	0.49	0.016	0.012
	2.0	0.028	0.6	0.028	0.8	0.028	0.92	0.027	0.96	0.024	0.98	0.020	0.012

value of $f(\frac{2a}{2t})$ until the horizontal line appropriate to this value of $\frac{2a}{2b}$ is reached. From this point a vertical line is projected back to the original curve. This in effect gives an equivalent value of $\frac{2a}{2t}$ for a continuous defect at the centre of thickness. In this case the equivalent value is 0.08. A horizontal line is now projected at this value into the right hand part of the diagram to meet the vertical line for the appropriate thickness. If the point so determined lies below the curve for the quality required the defect is acceptable, but if it lies above the curve it is not acceptable. In the example given the defect would be acceptable for quality Y but not acceptable for quality X.

Defects which break the surface are treated in just the same way as other defects but in this case the eccentricity deduction will be considerable.

Some idea is given in Tables III and IV of the sizes of defect obtained using these diagrams :

(i) for a long defect, i.e. where $2b \gg 2a$, and

(ii) for a short defect where $2b = 2a$.

Multiple defects (slag inclusions and planar defects)

Whether or not adjacent defects interact depends on the distance between them. Based on work carried out elsewhere on lack of penetration defects,[6] the following rule can be derived.

If the distance between the ends of two adjacent defects is greater than :

(a) 2.25 times the thickness of the material, and
(b) 1.25 times the length of the larger defect each defect shall be considered separately. If, however, the distance between the ends of two defects is less than either of the above values, they shall be considered as a single defect having an overall length equal to the distance measured between the two extremities of the defects.

FRACTURE CONSIDERATIONS

In most materials the problem of preventing brittle fracture is mainly one of selection of materials for tension regions with adequate toughness to tolerate defects of a size likely to occur in fabrication and/or service. In structural steels the situation is complicated by the fact that, because of their sensitivity to strain rate, they have a lower resistance to propagation of a moving crack than to initiation of fracture from a stationary crack. It is thus possible to base material selection requirements for steels upon either resistance to fracture initiation or resistance to unstable fracture propagation. In general, past experience has relied upon the transition with temperature of resistance to brittle fracture, without a clear distinction as to whether this transition referred to fracture initiation or to fracture propagation. This standard provides for both alternatives so that the choice is made by the designer. In general, selection of materials based upon prevention of fracture propagation is the safest philosophy since it accepts and caters for the fact that, in welded structures, there may be some locally damaged regions which could lead to fracture initiation. Material selection based upon prevention of fracture initiation from pre-existing defects requires a careful assessment of the resistance to fracture of all regions of a weldment. This arises because, in practice, the initial defects of concern occur as a result of welding, so that the tips of the defects will usually be located in material changed or produced by the welding process. As described previously, to cater for fatigue-loaded structures it is necessary to stipulate adequate toughness to tolerate through-thickness cracks with a length of twice the plate thickness. This also ensures that leakage will occur before fracture in pressure-containing equipment. Some guidance is also given in the standard, however, for the relationship between fracture toughness and defect size so that an assessment of the significance of cracks can be made for non-fatigue situations.

Whilst the transition temperature approach has been extremely successful in structural steels it does not provide quantitative information on the relationship between stress level, defect size, and material fracture toughness. This information is best derived by fracture mechanics approached, which are not limited to structural steels in their application, but can be used on all materials. The fracture mechanics approaches are not incompatible with the transition temperature approach since it is found that the fracture toughness determined by fracture mechanics tests on full thickness material increases rapidly as the temperature increases through the transition range.

LIMITATIONS OF APPLICABILITY OF FRACTURE APPROACH

In determining transition temperatures for resistance to fracture initiation in structural steels the test results must be obtained from tests which satisfy a number of requirements.

Transition temperatures - thickness effect

It is found that for different thicknesses machined from the same initial thickness, the temperature range over which a transition in fracture toughness occurs is lower for thinner material. This geometric effect of thickness means that, to determine realistic transition temperatures for a given material, tests must be carried out at the full material thickness.

Strain rate effects

Where a transition temperature for resistance to fracture initiation is to be assessed it is essential to reproduce the strain rate relevant to the structural application. Thus, for pressure vessel applications, where the rate of loading is invariably static, it is sufficient to carry out fracture toughness tests in a normal slow loading test machine. However, for application to earthmoving equipment or ships, for example, where some degree of impact loading may occur, the rate of loading used in the tests must reproduce that from service.

Local material effects

When considering resistance to fracture initiation it is essential to carry out fracture toughness tests to ensure that all regions of the weldment have adequate toughness. In most cases this can be achieved by carrying out tests on specimens taken from a procedure test plate with either sharp notches or fatigue cracks introduced after welding. It has been found, however, that in C-Mn steels, when defects occur during welding and are present during subsequent thermal cycles from later welding runs, severe local embrittlement may occur at the defect tips by a strain ageing mechanism. It is therefore prudent to carry out fracture toughness tests in which specimens taken from procedure test plates are also subjected to strain ageing, either by mechanical prebending or by simulating the presence of a defect and then welding over the top to produce natural strain ageing.

Cracks at the edges of openings - long cracks

Radial cracks at openings need special consideration. When such cracks are small they will be effectively located in the field of stress concentration due to the hole. Longer cracks may behave as if they had a total length including the hole diameter in the uniform general stress field. Cracks with a length greater than 0.2 x the diameter of the opening should be considered as the dividing mark, and to have an effective length equal to the actual length added to the diameter of the opening.

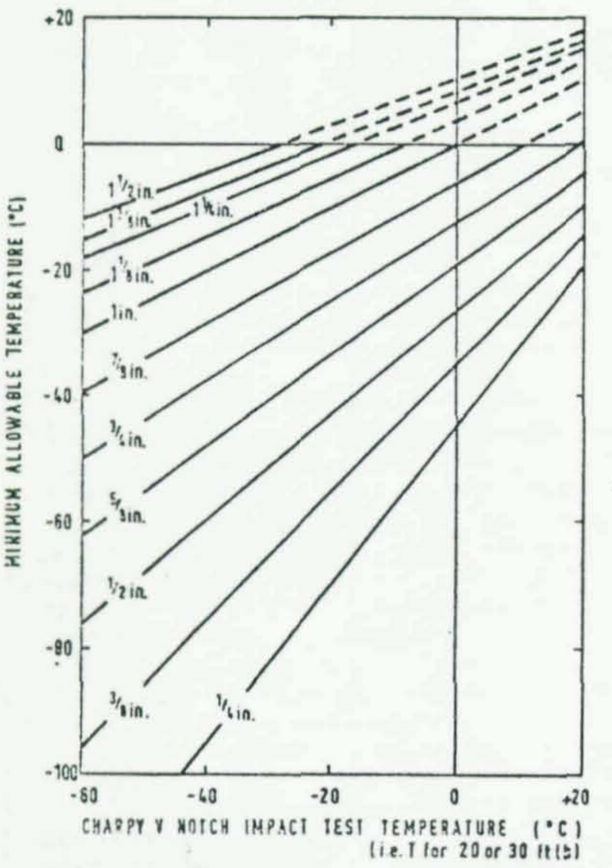


Fig. 5 - Minimum temperatures for different thicknesses of C-Mn steels in the as-welded condition

With long cracks nearly through the thickness in pressure vessels, bulging effects occur which cause failure at a lower pressure than would be the case for a flat plate situation, and which can cause failure well below the yield stress even above a transition temperature.

The important parameter controlling this bulging is $a/\sqrt{Dt}$ where D is the vessel diameter and 2t is the material thickness. Significant bulging effects will occur for values of $a/\sqrt{Dt} > 0.5$ at 0.75 x general yield pressure for the vessel, for $a/\sqrt{Dt} > 1.0$ at 0.67 x general yield, and for $a/\sqrt{Dt} > 1.5$ at 0.5 x general yield. The fracture mechanics relationships given below do not allow for bulging effects.

FRACTURE TOUGHNESS REQUIREMENTS

In certain thicknesses of some materials it can be assumed that there is sufficient inherent fracture toughness to tolerate both initial welding cracks and fatigue cracks completely through the thickness to a length twice the plate thickness. For the purpose of this standard aluminium alloys up to 2 in. thickness, with a proof stress less than 15 tons/in^2, and operating at a design stress below two thirds of the proof stress of the weakest region of welded joints, do not require special consideration for risks of brittle fracture. With structural steels the designer is required to decide on either a transition temperature approach or a fracture mechanics approach as described below. For all other materials the fracture mechanics approaches should be used. The requirements are based on planar defects :

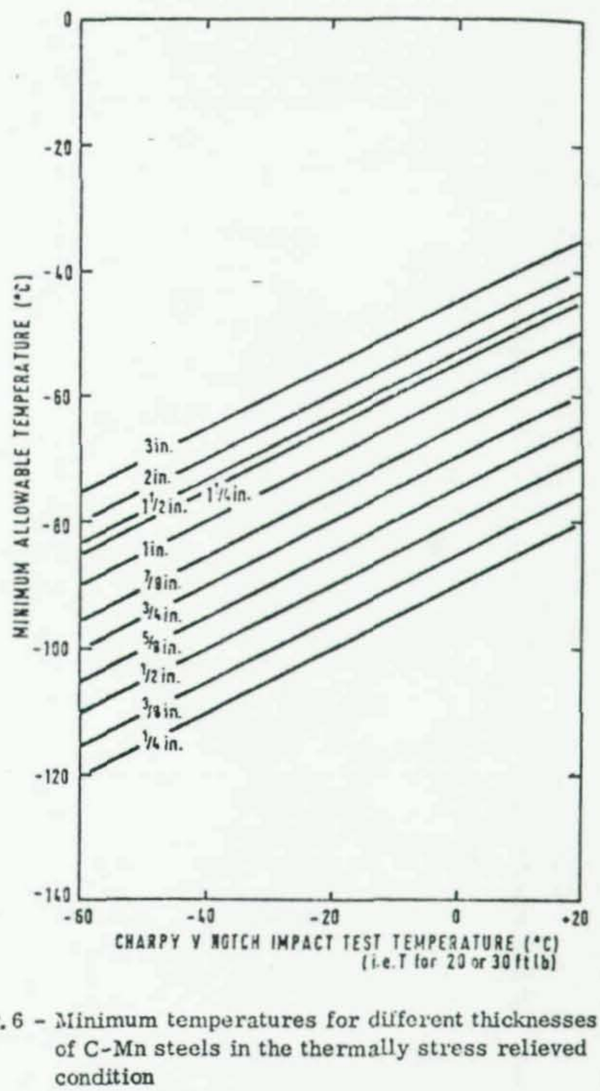


Fig. 6 - Minimum temperatures for different thicknesses of C-Mn steels in the thermally stress relieved condition

all defects may be treated as planar for fracture considerations but it will usually be found that non-planar defects are insignificant.

Transition temperature approaches (structural steels with yield stress less than 30 tons/in^2)

The designer must stipulate whether the initial material selection is to be based upon resistance to fracture initiation or on resistance to fracture propagation. For fabrications subjected to shock loading, or in cases where the consequences of failure are particularly hazardous the propagation approach should be used. In other cases the initiation approach should be adequate.

Prevention of fracture initiation. In cases where the toughness levels given below cannot be achieved it is necessary to stipulate quality V, i. e. no defects can be accepted. In such cases there must also be an adequate safety margin against fatigue to ensure that fatigue cracks do not develop.

It can be assumed that, provided materials have been selected on the basis of realistic transition temperatures, there will be adequate tolerance for initial welding cracks and for through-thickness fatigue cracks developed in service to a length twice the plate thickness when operating above the transition temperature. The minimum permissible temperatures for materials which show transitional behaviour with temperature can be based either upon results of notched and welded wide plate tests or upon results of COD tests. When considering initial welding cracks it is necessary to take account of possible embrittlement from welding by carrying out tests on parent plate, HAZ, and weld metal, as well as to assess susceptibility to strain ageing damage. For C-Mn steels up to 3 in. thickness operating always above 80°C no consideration of brittle fracture is required. The minimum temperatures permitted by this standard without further experimental work for different thicknesses of C-Mn steels are given in Figs 5 and 6 for the as-welded and stress-relieved conditions respectively. These limits are based upon correlations between Charpy V-notch impact tests and notched and welded wide plate tests, and are chosen to take account of local yielding at stress concentrations such as nozzles in pressure vessels. For steels with a yield strength up to and including 18 tons/in^2 the energy absorption at the Charpy V-notch test temperature for use in Figs 5 and 6 should be 20 ft lbs, while for steels with a yield strength between 18 tons/in^2 and 30 tons/in^2 the appropriate Charpy energy absorption should be 30 ft lbs. To operate at the minimum temperatures permitted it is necessary that the weld metal should give a minimum Charpy energy absorption of 30 ft lbs at 0°C (BS639 grade 2), since this was the quality of weld metal used in the wide plate tests on which the limits in Figs 5 and 6 are based. The limits are not applicable to single run high heat input processes unless it is shown that the Charpy energy absorption in the HAZ 0.05 in. from the fusion boundary is not worse than the weld metal requirement. For notch ductile steels Charpy energy absorption figures are supplied by the steelmaker on the millsheets. For BS15 steel, a Charpy energy of 20 ft lbs at +10°C can be assumed for thicknesses up to $\frac{3}{4}$ in., and for BS968 plate material values of 20 ft lbs at -15°C can be assumed up to thicknesses of $1\frac{1}{4}$ in. In all cases not covered by the above remarks fracture mechanics or COD tests should be carried out on specimens from weld procedure test plates to determine the transition temperature, taking account of the points made under 'Limitations of applicability of fracture approach'. These results may then be used quantitatively to derive a more accurate relationship between defect size and conditions for failure.

Prevention of fracture propagation. To select steels for prevention of fracture propagation the simplest method for steels with a yield strength up to about 30 tons/in^2 is to determine the crack arrest curve by carrying out drop weight tests to locate the nil ductility temperature, or transition direct. Provided the minimum operating temperature is at least 35°C above the nil ductility temperature of all regions or above the drop weight tear test transition of all regions, there will be sufficient fracture toughness to tolerate cracks of length twice the plate thickness. Correlations between these tests and the Charpy V-notch impact test have not been systematically co-ordinated at present and this standard requires either drop weight tests or drop weight tear tests to be carried out when design against propagation is stipulated.

Linear fracture mechanics

For the case of a crack extending to both plate surfaces with a length greater than the plate thickness in uniform stress regions remote from boundaries, the relationship between stress intensity factor K, stress normal to the crack plane σ, and half crack length 'a' is given by $K = \sigma\sqrt{\pi a}$. This can be assumed to apply to curved shells as well as flat plate situations provided the crack length does not exceed twice the plate thickness. In regions of stress concentration, σ should be taken as the nominal stress x the stress concentration factor. For surface or embedded cracks of less than 0.7 x the plate thickness in depth, the important dimension is the crack height, as in the fatigue considerations for planar defects. In these situations it is necessary to stipulate an equivalent value of the parameter 'a' for fracture toughness considerations. For embedded cracks, remote from both surfaces by at least 15% of the thickness, 'a' should be taken as half the maximum crack height. For cracks which approach to either surface within 15% of the thickness 'a' should be taken as the full value of the maximum crack height. The effect of crack length for cracks of height less than 0.7 x thickness is small and the crack height is the only dimension required for the fracture section of this standard. For cracks of height greater than 0.7 x thickness the crack length becomes the dominant factor, and 'a' should be taken as half the crack length. With these provisions the relationship $K = \sigma\sqrt{\pi a}$ may then be applied to situations of through-thickness surface or embedded cracks. These simplifications are not as accurate as the relationships used in the fatigue analysis for planar defects, but are sufficient for the present purpose.

The fracture toughness of a material is the critical value of K at fracture, and the minimum value for relatively thick material is called plane strain fracture toughness and given the symbol K_{Ic}. Recommended procedures to measure plane strain fracture toughness (K_{Ic}) are now well established.[4, 9]

In principle the methods are applicable to all materials, but in practice the thickness and size of laboratory specimens necessary to maintain the validity of the elastic analyses for many materials may be greater than the thickness of interest or the size which can conveniently be tested.

It is not considered worthwhile to take advantage of the lower stress levels necessitated by fatigue considerations to permit a reduction in fracture toughness requirements, although analyses for this could easily be carried out. This assumption represents a considerable safety factor. For a design stress based on two-thirds of the yield stress the toughness level necessary to support a through-thickness fatigue crack of length twice plate thickness is :

$$K_{Ic} = 2/3\ \sigma_y \sqrt{2\pi t},\ \text{i.e.}\ \left(\frac{K_{Ic}}{\sigma_y}\right)^2 = 2.6\,t,\ \text{where the}$$

thickness is 2t. This toughness level is outside the range of validity of current plane strain toughness testing techniques, indicating that some alternative to linear fracture mechanics is necessary for the severe requirements of tolerating cracks of length twice plate thickness at a stress level of two-thirds yield.

For non-fatigue situations it would still be a desirable objective to have adequate toughness to tolerate a crack of length twice plate thickness, particularly in pressure-containing equipment, so that leakage occurs before fracture. This will not always be possible, however, since the cost of materials with such toughness levels will often be uneconomic compared to increased

TABLE V - Fracture toughness/crack size relationship permitted for valid linear fracture mechanics techniques

	Design stress two thirds of yield stress		
Max. crack size	Stress relieved	As-welded or stress relieved +SCF 3.0	As-welded + SCF 3.0
a_{max}	$0.5\left(\frac{K_{1c}}{\sigma_y}\right)^2$	$0.1\left(\frac{K_{1c}}{\sigma_y}\right)^2$	$0.15\left(\frac{K_{1c}}{\sigma_y}\right)^2$

inspection requirements. Where valid plane strain fracture toughness tests can be carried out the maximum values of 'a' permitted by this standard are given in Table V. The tests must be carried out on parent steel, HAZ, and weld metal from a procedure test plate, at a rate of loading appropriate to the structure, to determine the significance of defects in these different regions.

General yielding fracture mechanics

In the previous paper by the authors [1] an account was given of the COD techniques of general yielding fracture mechanics. The basis of this approach is that for a particular combination of material, thickness, temperature, and loading rate, fracture initiation is found to occur at a critical value of COD. This approach provides an extension to linear fracture mechanics, so that fracture mechanics tests on one type or the other can be used to measure the resistance of a particular material to fracture initiation by laboratory tests. The measurement of critical COD values on different regions of a weldment must be carried out only taking account of thickness and strain rate effects, and using instrumentation calibrated and proven to give accurate COD values. A check on the COD values can be obtained from notch root contraction measurements before and after fracture which should be roughly equal to the COD measurement. In C-Mn steels tests should also be carried out on specimens prestrained by opening and then closing the notch by 0.006 in. at 250°C, to assess possible damaging effects of hot straining at pre-existing defects during welding.

It remains to be shown what level of COD the material will be asked to withstand in a structure of a particular material at given stress level and defect size combinations. An indication of the relationship between COD, stress level, and defect size can be obtained from the analysis of the strip yielding model of a central crack in an infinite plate under uniform stress. This analysis is in effect an extension of the well-established analyses of linear fracture mechanics, and gives the following relationships between COD (δ), yield stress (σ_y), yield strain (e_y), applied stress (σ), and half crack length (a):

$$\delta = \frac{8e_y a}{\pi} \log \sec \frac{\pi\sigma}{2\sigma_y}$$

The parameter 'a' should be taken to have the same significance as for linear fracture mechanics for the case of surface and embedded cracks. For the case of a design stress of two-thirds of the material yield stress the above expression reduces to :

$$\delta = 2e_y a$$

Experimental measurements of COD at different stress and strain levels in edge notched wide plate tests [7] and in spherical vessels [8] show that, provided the crack length does not greatly exceed twice the thickness and bulging effects do not occur, this expression is conservative. These results also show that for the case of residual + design stresses or for design stress + stress concentration effects with an SCF of 3.0 (as at nozzles) the relationship between COD and crack length is covered by $\delta > 2\pi e_y a$, and for the case of design + residual stress + stress concentration effects it is covered by $\delta > 3\pi e_y a$. These expressions are summarised in Table VI in terms of the maximum value of 'a' permitted by this standard for different COD levels.

TABLE VI - Fracture toughness/crack size relationships permitted for general yielding fracture mechanics techniques

	Design stress two thirds of yield stress		
Max. crack size	Stress relieved	As-welded or stress relieved +SCF 3.0	As-welded + SCF 3.0
a_{max}	$0.5\left(\frac{\delta}{e_y}\right)$	$0.15\left(\frac{\delta}{e_y}\right)$	$0.1\left(\frac{\delta}{e_y}\right)$

For fatigue loading situations the parameter a_{max} for crack size in Table VI should be replaced by the material thickness, 2t, to give values for the toughness level necessary in all regions of fabrications to tolerate the presence of fatigue cracks.

EXAMPLES

In order to demonstrate how the requirements of this standard should be applied three examples will be given.

Example 1

The first case to be considered is a steel press frame. Since there is no British Standard directly relevant the customer has asked for the frame to be designed to BS 153. The region of particular interest concerns a simply supported I beam with a central point load, fabricated from BS 968 steel with 2 in. thick flanges and a ½ in. thick web. The press may have to operate at temperatures down to +10°C. The flanges contain transverse butt welds and the web-to-flange weld is made by a continuous automatic process with cope holes located at the butt welds in the flange. These cope holes are positioned at one quarter and three-quarters of the length of the beam. Stiffeners are welded to the compression flange and to the web only and are cut away so that they do not come below the neutral axis.

The worst detail for welded tension regions is the weld end associated with the cope holes. In the fatigue clauses of BS 153 this detail would be designated as Class F. The required fatigue life of the press is 2×10^6 cycles. The maximum design stress permitted by BS 153 for such a detail is 5 tons/in^2 and the maximum stress permitted for continuous automatic longitudinal fillet welds (Class B) is 11 tons/in^2. At the mid-span position of the beam a stress level of 10 tons/in^2 is required by the design and this is within the BS 153 limit. At the one-quarter and three-quarter length positions the maximum stress is 5 tons/in^2 which is again acceptable. Referring to Fig. 1 of this standard Quality V construction is required for mid-span regions and no defects are permitted. However, Quality X construction is adequate for regions between cope holes and the ends of the beam. Thus the transverse butt welds in the flange which are in this region must satisfy Quality X. Table II shows the maximum sizes of different weld defects which can be permitted for these conditions. In general there is no need to inspect the welds on the compression side.

This example emphasises that it may be possible to call for different qualities at different locations in a structure provided that adequate communications exist between designer, fabricator, and inspector.

With regard to fracture properties BS 153 requires clause 15 of BS 968 to be stipulated for thicknesses above $1\frac{1}{4}$ in. In effect this stipulates a transition temperature based on previous satisfactory experience. Table II and Fig. 5 do not permit the use of thickness above $1\frac{1}{2}$ in. unless Quality V (no defects) is stipulated or fracture mechanics tests are carried out. In the case of this example a further check is required since the designer wishes to permit fabrication of the flange butt welds to Quality X and to allow for the possible development of fatigue cracks. Fracture mechanics tests are required to demonstrate adequate resistance to fracture initiation. The COD tests should be carried out on 2 in. square specimens, e.g. full flange thickness, and from Table VI should be required to show COD levels given by $\delta/e_y = 13.3$, i.e. a COD of 0.024 in. at +10°C to tolerate fatigue cracks of length twice the flange thickness. To check on risks of fracture from initial weld defects prestrained specimens should also be tested, although in this case it is sufficient to ensure that the transition temperature in the COD tests is below the minimum working temperature of +10°C. In this example the requirements for limiting weld defect sizes because of fatigue loading completely override other considerations on initial defect sizes. This will always be the case where fatigue loading to long lives has to be considered.

Example 2

Considerable interest was aroused by a report of a failure of a 6 in. thick low alloy steel pressure vessel on hydrostatic tests in December 1965. The initial defect size which led to complete fracture was a triangular crack of the order of 0.4 in. in height, completely buried some 0.8 in. below the surface. This is within 15% of the thickness from the surface so that the appropriate value of the parameter 'a' is the full crack height 0.4 in. Fracture toughness tests on the weld metal carried out since failure gave an estimated K_{1c} value of 53000 psi $\sqrt{in.}$ The yield stress of the weld metal was found after failure to be approximately 110000 psi. This gives a value of $(K_{1c}/\sigma_y)^2$ of approximately 0.23 in. The report of the investigation into this failure concluded that the heat treatment applied was probably not sufficient to relieve residual stresses. Referring to Table V of this standard the appropriate maximum permitted value of 'a' for the as-welded condition would be 0.15 $(K_{1c}/\sigma_y)^2$, i.e. 0.035 in. If the heat treatment had been sufficient to relieve residual stresses without any concomitant improvement in toughness, this standard would permit values of 'a' of only 0.12 in. Had it been possible for the effects of low stress-relief temperatures on the fracture toughness of the particular weld metal composition to be known, the information given in this standard would have indicated the sizes of crack which would be unacceptable.

Example 3

A somewhat similar pressure vessel failure occurred in June 1966 with the fracture on site proof test of a boiler drum in the power station at Cockenzie. In this case the initial defect for the final fracture was about 14 in. long and extended $3\frac{1}{2}$ in. from the plate surface. In this case the appropriate value of the parameter 'a' is $3\frac{1}{2}$ in. The report of the investigation into this failure indicated that the heat treatment had been correctly carried out so that the vessel was fully stress relieved. The large crack which acted as the initiation point was located in parent material and Table VI of this standard indicates that, to tolerate cracks of this size in material with a yield stress of 65000 psi, the steel would have had to show a critical COD of $e_y a/0.5 = 0.017$ in. This is the order that was obtained in tests at The Welding Institute on 6 in. thick steel of the type involved in the failure, again indicating that the requirements of this standard are not unrealistic compared to service performance.

DISCUSSION

It is now clear that the subject of weld defect acceptance standards cannot be treated in isolation. It is an integral part of the total process by which the customer is assured of getting the product quality he requires at the quoted price and delivery whilst at the same time allowing the fabricator to make a reasonable profit. This process is known as quality control and is a primary management function. All too often it is regarded as an informal and democratic process but the number of disasters or near disasters which have occurred in welded fabrications due to human error must surely have demonstrated that management must not rely upon informal contacts between experts which may or may not take place and which go unrecorded. It must establish a definite liaison procedure within its organisation which will be strictly followed in every instance.

It is still held in some quarters that any attempt to specify acceptance standards for defects will inevitably result in a relaxation in standards and open the door to poor workmanship. These people feel that acceptance or rejection should be based on the good engineering judgement of the inspector. The approach suggested constitutes in our view a rationalisation rather than a relaxation of standards and involves a total approach to the process of design and construction. The final inspector is at the wrong end of the fabrication process to be able to decide acceptance standards. Acceptance standards must be decided before the beginning of the fabrication process and the key man will be the designer since he is the only individual who knows the material he is specifying, the stresses he is using, and the duties to be performed by the fabrication. The number of designers with sufficient knowledge of the welding metallurgy of all the materials with which they are likely to be concerned, in the capabilites of the welding processes to be employed, and in the abilities of the proposed inspection methods to detect significant defects, is very few. With the growing complexity of the science of welded fabrication the number of such universal experts is likely to diminish; consequently the approach becomes a team effort in which the designer involves the metallurgist, welding engineer, and inspection specialist.

Management's job is to establish a check list of the factors to be considered in the total process and to establish formal mechanisms by which it is informed that each stage has been considered and of the decisions taken. The contents of such a list will vary with individual circumstances since experts may not be available within an organisation and outside experts or consultants may need to be involved. The following example is based on the assumption that the design and fabrication are to be carried out under one roof :

1. Customer submits an outline of requirements.
2. Designer discusses possible methods and materials with the customer.
3. Designer discusses material problems with the materials scientist.
4. Designer discusses welding problems with the welding engineer.
5. Designer discusses inspection methods with the chief inspector.
6. Resolution of problems on test methods and acceptance criteria.
7. Preparation of detailed design and submission to fabrication manager for approval.
8. Submission after modification to customer for preliminary approval.
9. Submission of detailed design and estimates of cost and delivery to customer.

Stages 1 and 2 need no further comment and at this point it will be clear whether or not fatigue has to be considered. Stage 3 is one of the more important and will include selection of parent materials and welding consumables with advice from materials suppliers and consideration of the weldability and corrosion resistance of the materials selected. It is at this stage that it will be clear which approach to design and hence to defect significance is valid; whether it should be fatigue, transition temperature, or fracture mechanics, or whether the materials are so inherently docile that control of welding defects is not a significant part of quality control. The designer will learn of the types of metallurgical defects which could arise. In the case of unknown materials or materials supplied to a wide or incomplete specification, it will be necessary to carry out laboratory tests to define essential properties. At the completion of this stage the designer will know what defects he can tolerate.

The discussion with the welding engineer, stage 4, will concern fabrication problems associated with the weldability of the chosen materials, e. g. the need for preheating and/or stress relief and the methods to be used to control it, and the choice of process and procedure for economical fabrication. Information on the technological (welding process) defects which might arise and methods to limit their occurrence will also be featured at this stage.

In stage 5, the designer will discuss with the chief inspector, the inspection methods to be employed, both in process and after completion, in the light of the information on possible defects received from the metallurgist and welding engineer. The NDT engineer will be required to answer searching questions on the defects which may be detected, positively identified, and accurately measured, using the various techniques at his disposal. He will have to be more precise than in the past as he has in some cases not only to determine the length of a defect but also its height and position within the thickness. It may be necessary at this stage for the inspector to inform the designer that inspection techniques of sufficient sensitivity are not available, and the original choice of material may thus be untenable because of the inability to detect defects which may give rise to failure.

It is suggested that stage 6 should be a general discussion between designer, aided by his materials, welding, and inspection colleagues, and the customer's inspecting authority on the problems of interpretation of test methods and weld quality acceptance standards. It is seldom that a Standard or Code of Practice exists which exactly meets requirements and it will often need to be rewritten or modified to suit a specific fabrication. A scientific approach to weld defect acceptance criteria as promulgated in the present paper will usually need modification in the light of commonsense. For example, a particular type of defect which is perfectly acceptable on the basis of the information on this proposal, may interfere with the detection of an unacceptable defect by the particular NDT methods in use.

Stage 7 involves the preparation of the detailed design with information on all the processes to be used and the quality of welds required. This is submitted to the fabricating shops in toto for confirmation that it can be made with the selected material in the chosen way and that it can be inspected to the standards required. Stages 8 and 9 need no comment.

A possible approach to the problem of deciding on the significant sizes of defect which can be tolerated under a particular set of circumstances has been suggested in this paper. Several steps can now be taken to augment this suggestion and to enable realistic applications standards and codes of practice to be prepared :

(a) Establish a more comprehensive list of terms for defects with definitions (BS 499, Part 3 deals only with defects revealed by radiography)

(b) Define the essential parameters describing a defect in terms of its size and its position within the welded joint.

(c) Obtain clear information from NDT experts on the ability and limitations of their respective NDT techniques to detect, identify, and measure each of the defects listed in (a)

Such activity is proceeding internationally under the auspices of Commission V of the International Institute of Welding but it will be a long time before an International Standard can be promulgated. It is suggested that it is not too early for BSI to be considering this essential groundwork simultaneously with an attempt to use the suggestions in this paper for the preparation of an applications standard for a limited specific field to establish their feasibility.

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