

FRACTURE MECHANICS ANALYSES OF STATIC AND
DYNAMIC FAILURES ASSOCIATED WITH WELDING

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DECLARATION

I declare that this thesis is my own unaided work, except where due reference is made to others. It is being submitted for the Degree of Doctor of Philosophy to the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University.

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21st day of March 1986.

SUMMARY

This thesis reports on a programme of experimental work designed to examine, in a quantitative manner, the relationship between predicted and observed behaviour of welded joints containing defects, under both static and dynamic loading. Thereby, the aim has been to provide further insights into the effective application of current methodologies and techniques of describing, and improving, the service life of typical welded structures and components.

In the first part of the investigation the aim has been to address serious concerns which persist relating to the inherent inaccuracies of ultrasonic NDT procedures, as well as operator variables, at the level required for the reliable application of fracture mechanics to many safety critical applications. The object has therefore been to investigate ultrasonic detection variability, and its influence on fracture mechanics predictions of the performance of defect-containing structural weldments.

Firstly, therefore, discrete artificial weld defects, simulating lack of fusion, were introduced into a series of thirty test plates of a medium strength structural steel. Two welding processes (MMA and SAW) were used, and the mechanical properties and the CTOD fracture toughness levels were established for the weld metal, heat affected zone and parent plate of each weld type, in both the as-welded and stress relieved condition. Each defective weld was then examined non-destructively, using ultrasonics, by fourteen different operators (of variable experience) in order to obtain predictions of defect geometry and position. No restriction was placed on the type of equipment that could be used, and no specific sizing technique was stipulated.

Twenty of the test plates were then destructively tested, in the as-welded condition, under controlled four point bending; the failure load of each test plate was recorded, and the defect parameters (length, height and depth) were accurately measured from the resulting fracture surfaces. Very considerable -

and indeed disturbing - variation was observed, both between operator predictions and between predicted and actual defect parameters. Indeed, it would not have been possible to judge, from these UT predicted defect sizes which of the defects was the most critical. The remaining ten test plates were then subjected to a second series of ultrasonic inspections, wherein the operators were given more information with regard to the defect type and, in addition, a set procedure for sizing the defects was stipulated. Much more accurate predictions of defect size were obtained in this second test programme, with the result that the most critical defect could have been evaluated on the basis of these ultrasonic predictions. Thus, the results obtained in these two inspection programmes serve as a guideline for performance assessment criteria in NDT, as well as for procedures to be adopted to ensure that the most effective defect size estimations are established for subsequent use in fracture mechanics assessments.

The ultrasonic data obtained in the two inspection programmes were then used in conjunction with two widely applied failure assessment procedures, viz: the COD design curve approach of British Standard's PD 6493 and the U.K. Central Electricity Generating Board's Two-criteria or R-6 Method, in order to study the effect of ultrasonic defect sizing inaccuracies on fracture mechanics predictions. The analytical methods used in the two assessment routes were validated by performing a sensitivity analysis; this also served to indicate the relative defect tolerance of the four weld metals. Such a technique could have particular application to material selection in the fabrication industry, in addition to evaluating the effects of a stress-relief heat treatment on the defect tolerance of welded structures.

The results obtained indicate compatibility between the two approaches to failure assessment, and a considerable tolerance to the significant variation observed in the defect size predictions of the initial UT programme was found in the estimation of failure conditions. The improved accuracy in the defect sizes obtained in the second UT inspection resulted in more precise fracture mechanics

estimations of defect criticality.

In the second component of the study, based on a consideration of a typical, representative case study, the objectives have been to examine current engineering application of welded joints under dynamic loading, firstly, in regard to the inter-relationship between weld detail design and actual fatigue strength, and the influence of traditional weld dressing procedures; and secondly, the role of fracture mechanics in describing/predicting the actual fatigue behaviour of welded joints. Finally, much contradictory information and opinion exists concerning the use of quantitative fractography in failure analysis, which becomes even more confused in weld microstructures, and this aspect was addressed in some detail.

In the first instance therefore, a test facility was established to examine the factors affecting the fatigue strength of four non-load-carrying fillet welded details. It was shown that, even in good quality welding, small defects could be readily introduced at the weld toe. These defects caused a dramatic reduction in fatigue strength of the fillet welded detail, but could easily and reliably be removed from the weld toe by mechanical dressing techniques. The results of tests performed on specimens which had been ground or peened after welding clearly demonstrated the efficacy of these cost-effective techniques which increased the endurance limit to such an extent that crack initiation occurred remote from the weld. There were, however, instances where fatigue crack initiation occurred from the weld toe of dressed specimens within a few million cycles of the starting stress range. These results therefore served to indicate that the practical implementation of grinding or peening operations must not be followed by an automatic increase in operating stresses, without appropriate controls and periodic in-service inspections.

Further experimental studies also demonstrated clearly the potential for synergistic interaction between undercut defects and hard heat affected zones, to the considerable detriment of fatigue life. Further, through an evaluation

of the influence of mean stress, residual stresses in the welds/materials of the types under consideration were shown to have minimal influence on the fatigue performance.

An important component of the fatigue testing programme was to establish the preferential crack initiation sites by macroscopic examination. This served to substantiate the findings of the endurance limit testing programme, since both the as-welded and dressed specimens which exhibited relatively low endurance limits were seen to fail from weld toe defects. Both the potential drop and the compliance methods were evaluated as crack depth monitoring techniques but, in order to calibrate these indirect methods, it was necessary to mark the crack front at various stages during crack propagation, either by heat-tinting, or by varying the applied stress range, so as to give characteristic "beach-marks". However, these crack front marking techniques, although useful in monitoring the progressive crack front shape development during crack propagation, affected the correlation between frequency and crack depth. It was further shown that the potential drop method cannot be easily applied to these specimens, due to the fact that the probes had to be attached on either side of the weld, and the electrical spacings were not reproducible. Crack propagation rates were calculated in the beach-marked specimens, and these were plotted as a function of the fluctuating stress intensity. These results indicated that the fatigue cracks in these welded details were propagating at near-threshold growth rates, and at these low growth rates fatigue striations could not be resolved on the fracture surfaces.

Accordingly, the last series of fatigue tests were performed on conventional compact tension specimens, machined in such a way that the fatigue crack grew in either unaffected parent plate, or in weld metal. These tests were carried out at loads which gave crack propagation rates in excess of 10^{-7} m/cycle; at these relatively high crack propagation rates, striations were easily resolvable under the scanning electron microscope. The macroscopic growth rates were accurately monitored by using both optical and potential drop techniques, and

these growth rates were compared to the fatigue striation spacing measurements. The results of this last series of tests indicated that the fatigue striation spacing tended to underestimate the actual crack propagation rate, and thus could not generally be used as a reliable estimate of the cyclic stress intensity at the crack tip without appropriate - and case specific - corrections.

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CHAPTER ONE

INTRODUCTION AND MOTIVATION

1.1 Static Testing of Defective Weldments

One of the fundamental requirements of any engineering structure is that it should not fail in service. It must also be recognised that there may be several possible modes of failure, all of which can be affected by the presence of a defect or flaw. It is widely accepted (for example see references 1,2) that "all structures contain flaws", and, based on this premise, it is often necessary to perform some procedure for assuring structural integrity, preferably at the design stage.

Weldments, weld cladding and weld repairs are each a source of potential defects of various types and hence sites for the initiation of both stable cracks (propagating by fatigue, stress corrosion cracking or ductile tearing, for example) or unstable cracks (propagating by fast, brittle fracture). Thus, many engineering structures enter service with some pre-existing weld defect, and often critical assessments of the structural components may be necessary, if failure is to be avoided. All-welded designs present further complications to integrity assessments in that most metallurgical defects associated with welding will occur in the weld metal or heat affected zone of the joint and, unless post-fabrication stress relieving heat treatments are performed, these will generally be regions of high residual stress. Such stress relieving procedures, although reducing the level of static stresses, may modify the mechanical and fracture behaviour of the material in which the defect is sited, and this may have an adverse effect on the defect tolerance of the structure. In addition, of course, a crack in a welded structure is likely to cause more extensive damage than in bolted or rivetted structures, since the crack can readily propagate from one plate member to the next.

Various methods are available to describe the significance of such defects by fracture mechanics and, under structural elastic-plastic conditions for example, one can employ the COD design curve approach of the British Standards' document PD 6493 (3), the U.K. Central Electricity Generating Board's Two-Criteria or R-6 method (4), or the J-integral based approach of the Electric Power Research Institute of the U.S.A. (5). Although the basic approaches differ, each does require appropriate evaluation of the material fracture properties, together with an accurate description of prevailing stress conditions. However, this information will only indicate tolerance levels for defects under specific conditions, and input data with regard to pre-existing defect type, position and size is required for the evaluation of structural integrity. Clearly, the accuracy with which the service conditions, material properties and defect parameters are established is a crucial factor in the accuracy of the overall assessment.

Welding defects may generally be classified as being one of two types: volumetric flaws, such as porosity and slag inclusions, or crack-like defects such as hydrogen cracking, hot cracking, lack of fusion or lack of penetration. The first type are relatively harmless and may even act to pin or arrest propagating cracks, although they are at the same time stress concentrators and hence likely crack initiation sites. Crack-like defects are more deleterious, since the stress intensity of any flaw is dependent on the root radius, and thus this group of defects cause the highest local stress intensities. In order to be able to investigate the effect of weld defects on the fracture mode of weldments, reliable techniques for fabricating welds containing such defects have had to be developed (6,7). It is worth noting that the production of a specific type of weld defect can be considerably more difficult than producing a sound weld!

When considering non-destructive testing methods to detect and size such defects, only two methods are really generally appropriate for the assessment of

internal conditions: radiography and ultrasonics (8,9). However, when examining planar defects, unless the major axis of the defect is within a few degrees of the X-ray beam axis, the defect will not be detected by radiography. In addition, radiography will not immediately assess the vertical height of the defect (the most important defect parameter from a fracture mechanics point of view (8)), even if it does manage to detect that defect.

Thus ultrasonics remains the only method suitable for detecting and sizing subsurface flaws of the type that are most deleterious to the continued safe operation of a structure and even this method has inherent limitations (2, 8-11). Indeed, it has been shown (8) that the possible cumulative errors in sizing defects using the 20dB drop technique are approximately 3.5mm on defect heights and approximately 5.2mm on defect lengths. Another study (11), has shown that there is apparently no correlation between ultrasonic echo amplitude and defect height.

In summary therefore, many engineering structures are fabricated by welding, and their performance can be significantly influenced by crack-like defects often present in welded joints. Fracture mechanics provides a useful, quantitative approach to the prediction of the behaviour of structures containing flaws, but its applicability depends to a large extent on the accuracy of the input data in the form of flaw sizing. Ultrasonic non-destructive evaluation is by far the most appropriate in such applications but serious concerns still exist in regard to inherent inaccuracies of the method, as well as operator variables, at the level required for many safety-critical situations. The object of this current work on the static failure of defective weldments, therefore, has been to investigate the ultrasonic detection variability and its influence on fracture mechanics predictions of the performance of structural weldments containing simulated lack of fusion defects. The results of this investigation are detailed in Chapters Two to Four, inclusive.

1.2 Fatigue performance of non-load-carrying fillet welds

As early as 1960 it was shown (12) that undercut defects at the toe of transverse fillet welds could cause a dramatic decrease in the fatigue strength of such details. The work of Signes, Baker, Harrison and Burdekin published in 1967, and which may be regarded as the "classic paper" in this field (13), showed that such weld toe defects, located at the point of maximum stress concentration in the detail, could have root radii less than 0,0001 inches (0.0025mm). More recently (14) it was calculated that the stress concentration factor of an undercut defect at the toe of a non-load carrying fillet weld could be as high as 27! It is apparent, therefore, that the notch severity of these defects result in the fatigue strength of weldments being reduced to a common level, irrespective of the yield strength level of the parent material (13,15).

In order to evaluate the significance of such observations, in practical engineering applications, it is appropriate to focus on one specific, but representative case study, namely the large, all-welded steel centrifugal fans (as fabricated by a certain manufacturer) which are used extensively for ventilation purposes in mines and for the supply of air to and the extraction of gas from boilers in conventional coal-fired power stations. The particular fans under consideration here may be double or single inlet, and are typically 3 m in diameter, with a rotating mass of up to 30 tons and operate in excess of 700 rpm. The fans are fabricated by welding the blades to the shroud plates and "centre sheet" (or "back sheet" in the case of a single inlet fan), and are then stress-relieved prior to transporting to the site of operation. Once in position, the fans are statically balanced, which involves welding "balance pads" to the periphery of the shroud plate. These mild steel balance pads are typically three quarters the thickness of the shroud plate, and may be up to 600 mm in length, depending on the mass required for balancing. The fans are then checked for dynamic stability and if any further balance pads are required, these are generally much smaller than the static weights. It should be noted here that this particular sequence of operation may not be followed for other

fan types, or by other fan manufacturers.

The fans are designed such that the only appreciable cyclic stresses arise from start-stop conditions, and the dynamic stresses during operation are generally presumed to be less than 20 MPa. Significant controversy therefore emerged from an investigation into the causes of a fan failure (16) when fatigue striation spacing measurements were made from the fracture surface. These quantitative results were used to estimate the service cyclic stress levels, and it was predicted that the cyclic stress amplitude was in excess of 100 MPa.

Accordingly, a comprehensive series of long term strain gauge tests were carried out on a similar fan during operation (17). Results here indicated that the cyclic stress ranges experienced under normal operating conditions were indeed below 20 MPa, but could, in certain circumstances approach 33 MPa. The mean stress during operation was measured at 150 MPa.

Initially, the balance pads were regularly stitch welded in position, such that they constituted non-continuous, longitudinal non-load-carrying fillet welds. However, the weld roots at the corners of these rectangular balance pads appeared to act as sites of stress concentration, since fatigue cracking which occurred in some of the fans were seen to be associated with these welds (16). Accordingly, the fan manufacturers introduced a specification for the welding of balance pads, which included rounding the corners of the attachment, applying a local pre-heat of 150°C, and welding continuously around the attachment.

However, when applying the Welding Institute's Design Rules (18) to these two details, it was apparent that both welds would be classified as "G" type joints and were thus expected to have similar fatigue strengths. Since in a year of continuous operation, these fans can experience in excess of 300 million cycles, there was some considerable concern with regard to the origin of the fatigue cracking, and the fatigue strength of the balance pad weldments.

Relatedly, and quite apart from the controversy resulting from the investigation

of the fan failure, there is some considerable confusion in the literature as to whether or not fatigue striations and applied stress cycles have a one to one correlation; and at what levels of alternating stress intensity (and growth rate) this ideal unitary relationship will be applicable.

In summary, therefore, this brief consideration of a typical, yet critical, engineering application of welded joints under dynamic loading highlights certain important aspects of more general relevance that have formed the basis for the second major component of the experimental work described in this thesis. The objectives of this work, therefore, have been to investigate the experimental fatigue behaviour of weld details having nominally the same design fatigue strength, as well as the relative influence of "well accepted" weld dressing procedures (see, for example, references 19-23) on the reality of fatigue performance. Arising from this has been a requirement to investigate the applicability of "laboratory-oriented" fracture mechanics descriptions of fatigue to actual fatigue propagation from service weld defects. Secondly, in the last two decades, the collective wisdom of many experts in the field have in most instances assumed that "classical" fatigue striations provide a quantitative indication of fatigue crack propagation rate. In practical situations the reality appears somewhat removed from this, and what studies there have been appear in conflict (see, for example, references 24-28). This has provided a good case for concluding this experimental programme, with a careful, quantitative fractographic investigation of fatigue cracks in and around welded joints.

* * *

Because of the nature of this work, and the different aspects of the programme, the format of this thesis is a little unconventional, since there is no introductory and all-encompassing Literature Survey, followed by Experimental Methods, etc., etc. Rather, each of the Chapters Two through Seven are relatively self-contained, each reviewing the literature appropriate to the

studies described and the conclusions drawn. Cross-reference between Chapters is made regularly, where appropriate, and reference is also made to the number of technical reports produced during the course of the investigation, where further detail can be found, if required. In this way it is hoped, and indeed intended, that the reader will be provided with a comprehensive yet readily assimilable appreciation of the work undertaken, and the results achieved.

CHAPTER TWO

ERRORS OBSERVED IN THE ULTRASONIC DETECTION AND SIZING
OF ARTIFICIAL DEFECTS IN FUSION WELDED JOINTS

2.1 Introduction and Background

2.1.1 The role of Non-Destructive Testing

The ultimate goal of Non-Destructive Testing (NDT) is to ensure reliability and safety without sacrificing economy. NDT is the generic term applied to those techniques which check structural integrity, or compliance of materials' quality to some set Quality Assurance standard, without in any way affecting the serviceability of the components so tested (2). Thus, in the fabrication industry, NDT has developed as a means of monitoring and maintaining quality, and to detect and reject defective components. The other, probably more important role of NDT is to monitor structures during service throughout the operational life of the component. All structural materials are inherently defective if they are inspected at sufficient sensitivity, and having recognised this fact, it is necessary to perform some kind of integrity assessment. Thus, by determining the fracture toughness of the material, together with the level of local stresses in the neighbourhood of the defect during service, the component can be either accepted or rejected as "fit-for-purpose" by comparing the defect size to the critical crack size, utilising the methodology that fracture mechanics provides.

This, however, raises three important NDT requirements, and these are not always satisfactorily fulfilled (2,8). The first of these relates to reliability of defect detection, and since most inspections are, of necessity, carried out by manual techniques, consistent and accurate interpretation of results are required. The second is the need to determine, accurately, the size of the

defect, and the third requirement is the ability to monitor the growth of planar defects in service. These latter two will obviously aid the engineer in establishing whether or not the defect is larger than the critical crack size, and if not, to give some advance warning of when the crack is approaching this critical size.

However, design for subsequent inspection is rarely considered seriously, and in-service inspection is often influenced by economics and pressures of production schedules. High temperatures and the presence of lagging in process plants, radiation and contamination in nuclear industries and accessibility problems in fabricated structures and underground pipelines all contribute to the probability of inaccurate defect location and sizing. Thus, either the subsequent in-service inspection must be considered at the design stage, or alternatively, automatic continuous surveillance techniques must be developed such that the problems of manual in-service inspection will not continue to impair the accuracy of results.

2.1.2 The detection of surface flaws

The subject of NDT can essentially be divided into two classes: methods which will only detect surface breaking flaws, and methods which can both detect buried flaws and give information with regard to the defect height. In the first case, direct-view or "eyeball" techniques are still the basis for intelligent supposition (29). Techniques such as dye-penetrant examination and magnetic particle inspection (MPI) improve the visual contrast and hence the sensitivity; MPI is regarded as being the more sensitive for tight cracks and in addition can detect defects just below the surface, depending on the type of energising current (29,30). However, dye-penetrant is much more portable than MPI, since although hand-held energising prods can be used, a test bench facility may be necessary. In addition MPI can obviously only be used in ferromagnetic materials, and the induced magnetic flux lines need to be orientated at right angles to the defect (29,30). This latter disadvantage can

be overcome to some extent by, for example, universal polarisation (30). Eddy current testing can also be used to detect surface and near-surface flaws: however its use in the inspection of welded joints is limited due to the effects of metallurgical structure and surface profile on the results.

Various other techniques have been developed to increase the versatility of direct viewing, such as the use of optical borescopes, fibre optic viewing of inaccessible surfaces and miniature CCTV cameras for tube bore examination. Laser beam holography, tactile tests and infra-red or ultraviolet radiation studies produce characteristic surface profiles. However, widespread use of these methods have been curtailed somewhat by the prohibitive costs, when compared to dye-penetrant tests for instance, and also due to lack of portability and hence versatility (29,30). Furthermore, all the surface inspection techniques suffer the same drawback in that very little information with regard to defect height is obtained. Clearly, the defect height is the most important parameter in a fracture mechanics assessment of structural integrity, provided of course that there is no substantial loss of total load bearing area due to the presence of a very long crack (8).

2.1.3 The detection of buried flaws and the limitations of Radiography

The detection and sizing of subsurface defects is essentially restricted to ultrasound techniques and radiography (2,8,9,29-32). The latter technique is based on the ability of X-rays and gamma-rays to penetrate those materials that are opaque to white light, and any defect present will result in a variation in the intensity of the emergent beam (29). Both are electromagnetic waves with characteristic wavelengths, and whereas the gamma-rays are produced by a small source of radioactive material, X-rays are produced in a vacuum tube. Hence, although the principal of detection is the same for both methods, the equipment required for radiographic examination using X-rays is less portable, and hence less versatile.

A pictorial and permanent inspection record is the most obvious advantage of radiography; however, not all defects are detected. Radiography is most suited to the detection of volumetric defects, and a crack-like defect may well remain undetected if the major axis of the beam is not orientated to within a few degrees of the major axis of the defect, as shown schematically in Figure 2.1. It is doubtful that economic considerations would permit the use of radiography to detect lack of sidewall fusion, since, for a given length of weld, three shots would have to be taken to examine the weld effectively (8). In addition, radiography will reveal very little about the through-thickness dimension of the defect, although micro-densitometry may be used to measure the relative density of the image, and either by comparison or calculation give some information with regard to the defect height (30,33). Another technique which has been reported (34) to give good results without specialised equipment, is to take a pair of radiographs at slightly different incident angles, and to measure the width of the two images. A simple calculation then gives the defect height. Both these techniques, however, rely on the radiographic results being of a very high quality.

Other disadvantages of radiography are the stringent safety procedures imposed due to the potential health hazards from these types of radiation, and the requirement for darkroom facilities to develop the photographic plates. Thus, these two methods apart, the trend appears to be developing improved ultrasound procedures for subsurface flaw detection and sizing (2,8,9,29,30).

2.1.4 Defect detection and sizing using Ultrasound.

Ultrasound techniques, while only one of the many possible NDT methods, are the most versatile, since ultrasonics can be used to detect and size surface defects as well as totally buried defects. The equipment itself is easily transportable, and both volumetric and planar defect may be detected. However, some approximate prior knowledge of the defect position and shape (29,35,36) will aid the operator to choose the correct probe angles and scanning

directions, as illustrated in Figure 2.2. In many instances, the probe choice can be made from an appreciation of the welding process, joint preparation and material used in the component. Although techniques for ultrasonic defect size estimation are still under development, those currently in general use for manual inspections are one of three types (37).

The first of these compares the reflection of unknown defects with machined reflectors in test-pieces, reference pieces or calibration blocks. In the DAC (distance amplitude curve) method, which is used as an ASME recommended procedure, a test block is fabricated from the same material as that undergoing inspection, with side-drilled holes at distances of $T/4$, $T/2$, and $3T/4$ from the surface being scanned. (T is the test block thickness, and ideally, is equal to the component thickness.) The diameter of the side drilled holes typically correspond to the maximum defect size that can be tolerated in the component. Defects are then sized with reference to the diameter of the side-drilled holes, and the depth of the defect is easily calculated, since the reference reflectors give rise to discrete reflections at different points along the DAC curve on the CRT screen, as shown in Figure 2.3. This is a relatively quick acceptance/rejection criteria, since the intensity of sound beam reflected by the defects will either be less than that of the reference reflectors (acceptable) or greater (rejected). However, this is obviously also the greatest limitation of the method, since real defects will not reflect the sound beam in the same manner as the smooth machined reference reflectors.

The DGS (distance gain size) method also relates the defect echo to that from a circular reference reflector. However, in the DGS technique, the relationship between echo height and beam path as a function of target size is produced by the manufacturer of the probe and not by the operator (as in the case of DAC). The third type of inspection procedure essentially requires the operator to, firstly, scan the edges of the defect with an imaginary defined line in the beam, such as the beam axis or the beam boundary; and secondly, locate the point of maximum signal reflection, and set this to 100% screen height. The probe is

then moved away from this position of maximum amplitude, decreasing the reflected signal by 6, 12 or 20 decibels (dB), which correspond to 50, 75 or 90% respectively, of the original screen height. The distance the probe must be moved away to achieve this decrease in signal amplitude can then be related to the defect size. Although the 6, 12 and 20dB drop techniques are similar, the 6dB is the most accurate (38), since in the 20dB drop method the final reference point is obtained when only 10% of the defect is in the beam path.

The limitations of the DAC and DGS techniques are obviously the comparison of signals reflected from real weld defects to those from idealised, machined defects, such as side drilled holes to simulate volumetric defects, and flat-bottomed holes to reflect the sound in the same manner as a planar defect. A comparative study performed on the ultrasonic response of machined slots and fatigue cracks (36) showed that for a receiver referenced or calibrated on machined slots an additional gain of between 10 and 34dB was required to reliably detect the true fatigue cracks. The dB drop methods, on the other hand, are affected by specimen geometry and weld reinforcement and may be less accurate in very thick sections (8). Additionally, the dB drop methods should only be used to size defects which are greater than the probe diameter. One further limitation is that the beam path is not regular, and therefore sizing near-surface defects (which may lie within the near-zone of the probe) is almost impossible (8). Indeed, it is apparent that the only way to reliably size a defect is to locate the opposite edges and measure the distance between them (9).

However, ultrasonic testing (UT) is becoming more essential in the construction and operation of modern, high integrity, engineering structures where it is being used to detect, measure and, in some cases, monitor the growth of flaws which would undermine plant safety (9). This has resulted in research efforts aimed at improving the existing (and developing new and better) detection and sizing techniques, and investigating the inherent limits of UT. Various researchers (2,8,9,10,31,39) have found that the most important parameter

affecting accurate defect sizing is the qualification of the personnel involved; it has also been shown that ultrasonic sizing techniques generally underestimate defect sizes (8,35,40).

Of the new techniques currently being developed, most noticeably the trend is towards replacing manual inspection with automatic data collection and processing techniques. Adaptive learning network systems utilise microcomputers and recognise defect types from the characteristics of the reflected sound beams which are digitised to form a network, the output of which depends on the different input parameters in various forms (9). Acoustic holography is another example of this type of data processing system; both the signal amplitude and the phase of the echoes are monitored (41). Possibly the best ultrasonic imaging method (42) is the Synthetic Aperture Focusing Technique (SAFT), which provides a high resolution image. This enhancement is brought about by synthesizing the focal properties of a large aperture, focused transducer by making a series of measurements with a small aperture transducer, scanned over a large aperture. Clearly, the development of such sophisticated techniques require significant cooperative input from engineers, mathematicians and physicists as well as the ultrasonic experts.

Most manual techniques, such as the DAC, DGS and decibel drop, operate in a pulse-echo mode, in which a single probe emits the ultrasound beam, and receives the reflected wave. The time of flight diffraction (TOFD) technique, on the other hand, relies on a second probe detecting the ultrasound that is diffracted from the tips of a defect or crack. Measurement of the wave propagation times will enable the operator to locate the diffraction sources, and hence locate and size the defects (43,44).

2.1.5 Summary

Clearly, as ultrasound is required to detect and size those defects which fracture mechanics has shown to be structurally critical, the future development

of improved UT techniques will be closely linked to the growing importance of fracture mechanics assessments of component or structural integrity. As noted towards the beginning of this Section, adequate access to the component is necessary for complete inspection. The first requirement of defect detection using ultrasound is that the beam must pass through the appropriate regions of the component, and this will be severely curtailed if adequate access is not allowed. Modest changes at the design stage can circumvent this, and more effective inspections will result from a growing appreciation by engineers that constraints upon inspection must be considered during design (9).

The remaining Sections in this Chapter report on the results of a defect sizing evaluation programme, performed as part of a study of the influence of ultrasonic detection variability on fracture mechanics predictions of the performance of structural weldments containing simulated lack of fusion defects.

2.2 Experimental Details

A series of thirty welded test plates were fabricated from ROQ-tuf AD 690, a medium strength (690 MPa yield strength) structural steel, using both the Manual Metal Arc (MMA) and the Submerged Arc (SA) welding techniques. (The specified chemical compositional ranges and mechanical properties for this steel are shown in Table 2.1.) A procedure was developed whereby discrete, artificial weld defects, simulating lack of fusion, could be introduced, reliably and reproducibly, into each weld, as shown in Figure 2.4. As already mentioned, the production of specific weld defects can be difficult, and the procedure used in this work will be detailed in Section 4.1.2, to follow. These defects were made intentionally large, so as to facilitate the subsequent ultrasonic detection and sizing, as well as being smooth and relatively tight, so as to simulate crack-like defects from a fracture mechanics point of view. The test plates were machined to remove plate scale and proud weld metal, in order to provide a flat surface for the ultrasonic transducers.

An ultrasonics test programme was then initiated whereby fourteen independent operators attempted to size the defect in each plate as accurately as possible. (Due to time constraints, however, not all fourteen operators inspected each of the thirty plates). The operators were informed that there was one major defect in each plate and that this defect had a minimum length of 40mm. and a minimum height (in the through-thickness direction) of 5mm. This was to prevent the operators from sizing the smaller, extraneous porosity or slag inclusions associated with some of the welds, as had been indicated in the preliminary X-ray examination of the test plates. In this initial "round-robin" defect sizing exercise, there were no limitations whatsoever on the equipment to be used by the operators. Furthermore, each operator was free to choose whichever sizing procedure he felt was best suited to sizing these defects.

On completion of this preliminary inspection programme, twenty of the thirty plates were tested to destruction under controlled, four point bending conditions. The failure loads recorded for each specimen, and the defect sizes were measured from the resulting fracture surfaces. As will be shown in Section 2.3.1, to follow, there was some considerable variation, both between operators and between actual and predicted defect sizes. It was apparent that these defects are not representative of the size of defects that the operators would expect in welds of this size, based on past experience. A second test programme was therefore initiated, wherein the operators were given a specific sizing procedure, in addition to a more detailed explanation of the type and location of the defects. The results of this second "round-robin" exercise are detailed in Section 2.3.3.

2.3 Results and Discussion

2.3.1 The initial inspection programme

Figures 2.5, 2.6 and 2.7 show the range in UT predictions of defect heights, lengths and depths respectively for each of the thirty test plates. In each

case the magnitude of the relevant defect parameter, as measured from the fracture surface is indicated, and although the actual defect parameter increases from left to right in these Figures, it is clear that the range of ultrasonic predictions do not increase correspondingly. This is a worrying point since, if faced with a series of unknown size defects, it may not be possible to gauge, from ultrasonic test results, which of the series is the most significant defect. It is also evident from Figure 2.5 that some of the operators disregarded the information given to them at the start of the programme when they were told that the minimum defect height in any test plate was 5mm. (This point will be discussed more fully in Section 2.3.2 to follow).

An important component of this work was to attempt to identify the sources of any errors that may arise in the UT predictions of defect sizes. Therefore, each operator was asked for an estimation of his error in each of the parameters. It is worth pointing out that whereas some of the inspectors gave error estimations in terms of mm displacements, others quoted their errors in terms of a percentage. Clearly, when defect heights of 1mm were obtained from some operators, a scatter band of + 10% is somewhat optimistic. It is felt that error estimations should have always been given in terms of mm displacements, but at the time, it was difficult to obtain any error estimation from some operators.

Figures 2.8, 2.9 and 2.10 illustrate the disparity between the predicted errors and those calculated from comparing actual defect sizes with those estimated by each of the operators, either as a percentage or as a mm displacement. It is clear from these Figures that the actual errors are, in most cases at least twice (and in some cases four times) the error estimated by the operators themselves. In order to obtain some indication of the origin of these errors, the average error of each operator was plotted as a function of the number of years experience they have had in the NDT field. These results are shown in Figures 2.11, 2.12 and 2.13; although the data is far too scattered to attempt any regression analysis, it appears that the two operators with 20 or more years

experience have more consistently low average errors relative to the other operators. In the case of defect length predictions (Figure 2.12) it will be seen that four of the operators with less than 5 years experience had lower average errors than their more experienced counterparts. However, this was not the case in the defect height and depth predictions.

This information on comparative errors is summarised in Figure 2.14, which indicates the fraction of the total number of plates inspected by each operator in which the defects were oversized or undersized, thereby illustrating the ability of each operator to size the defects within his estimated scatter band. This is seen as a very important concept, since if the operator can place reliable limits on the accuracy of his measurements, these can easily be incorporated in the fracture mechanics assessment, and this will result in more accurate predictions of defect criticality. This schematic diagram (Figure 2.14) indicates the general tendency to undersize defect heights and lengths, and oversize defect depths, although this last effect may be a manifestation of the tendency to undersize defect heights.

2.3.2 Possible sources of errors

Consideration of the results obtained necessitated a review of the preliminary test programme, on the following basis. Firstly, these artificial flaws are really too large to be considered representative of the natural weld defects the inspectors would expect to find, based on previous experience, in welds of this size. It could justifiably be pointed out that these defects were, in all cases, far in excess of any code limitation, and that an inspector would in practice reject the weld rather than attempt to size such a gross defect. Secondly, it is apparent that the absence of information concerning the exact weld preparation would be sufficient cause for the operator to refuse to make any assessment of defect type, or the location in the weld. (When one considers all these factors, however, it is perhaps surprising that the operators did not estimate more "realistic" sizing errors for their results!)

It will be recalled from Section 2.2 and Figure 2.4, that these defects were machined into the weld preparation prior to fabricating the joints. The interior of the defects were thus smooth machined faces, and clearly, would give rise to a reduced signal intensity relative to that reflected from the top and bottom edges of these artificial defects. Thus if, for instance, the operator was using the 6 or 20dB drop techniques to size the defects, he would be able to record the required decrease in signal intensity by moving the beam from the top (or bottom) edge of the defect to the centre of the defect, as illustrated in Figure 2.15.

It would therefore be possible for these artificial flaws to appear, ultrasonically, as two isolated defects, and having been instructed to size only one defect per test plate, the operators would choose one of the defect edges, thereby considerably underestimating the defect height. Clearly, if the interior of these manufactured defects gave a decreased reflected signal, it is reasonable to assume that all the sizing methods used would have been affected in the same way. Thus, whether the operator used the dB drop technique, or the DGS or DAC methods, which compare the signal intensity from the defect to that of a reference reflector (eg. a side-drilled hole or machined slot), having been instructed to size only the major defect in each plate, it is possible that the operator will size one of the defect edges, whichever appears to give the largest reflected signal intensity.

It was thought, therefore, that by instructing the operators to locate the top and bottom edges of the defect, and to record the distance between these points as the defect height, that much more accurate results would be obtained. (It is, in fact, becoming more widely appreciated (9), that the only generally reliable way of measuring the extent of a defect is to locate the opposite edges and measure the distance between them). This procedure would also only measure the two parameters, depth and height, of the defect that are critical from a fracture mechanics point of view, and the defect length could easily be measured

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