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The specification of permissible defect sizes in welded metal structures

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Summary
The eventual goal of much fracture research is to facilitate the economic design and construction of fracture-proof structures, yet the frequent criticism of practising engineers is that this issue is evaded most by those whose knowledge of fracture mechanics is such that they would also be most competent to help. The link is most likely to be provided through specifications of permissible defect sizes, prepared in combination by fabricators, inspectors and researchers. The paper discusses how such specifications might strive for rigour, in combination with flexibility and practical simplicity of application, through a two-class system distinguishing the plane stress and plane strain modes of operation.

Introduction

The array of knowledge, now recognised under the heading of fracture mechanics, had its humble origin in the investigation of casualty fractures. The international character of this science has depended largely upon experience gained from their emergence in a statistical distribution, in almost all countries of the world. In former times the injection of new funds for fracture research depended upon the occurrence of some new casualty; nowadays the idea is better established of mounting continuing programmes of research with the object of fracture prevention. Although of obvious benefit, this organisation of work carries with it the danger of separating the investigators and the research from the realities of the fracture situation in the industrial world.

With the increased rate of development of constructions, in scale and variety in the recent past, the task of advising on fracture precautions in new ones, which was formerly in the hands of the engineers who designed them, together with the expert bodies who classified and insured them, has been shared to an increasing degree by those engaged in experimental fracture research. The sheer weight of evidence produced by this research, often directed to particular types of structure, made it inevitable that a descriptive science should develop. At the present time no one human mind could comprehend all without the benefit of such. Nevertheless, if a science has been created, and if the preventive aspect of fracture research is replacing a more hand-to-mouth existence, it is necessary to remind ourselves that this is not a science pursued for the better contemplation of nature. It has a direct objective in fracture prevention, and all those who pursue it have a responsibility to apply it fully in this way.

If there is a gulf between the study of fracture mechanics and the real world of casualty fractures, the responsibility for it cannot all be placed upon the scientist. No assurances of anonymity, it would seem, have been sufficient to persuade some organisations to release details of their casualty investigations to those who could make valuable use of them, or even to persuade them to have them investigated. Where such climates of opinion exist concessions are required on all sides if the next step is to be taken, of applying new knowledge to create a specification framework for fracture prevention. This is now timely.

Radiography was the principal tool of non-destructive testing fifteen years ago, and it was of such obliquity and cost of application that specifications could be framed in terms of complete absence of detectable defects in the sparingly used but carefully preserved and documented photographic records of those times. There were those who earnestly believed that a radiographically welded construction had no defects, and that fractures required no defect nuclei. Such illusions have been shattered by the advent of large scale development of ultrasonic and other methods of non-destructive testing, and such has been the shock of discovery in this way of the scale of the imperfections, even in exemplary welded constructions of considerable cost, that their wholesale condemnation to the scrap yard has sometimes been contemplated. The lesson of these events is that acceptance standards for tolerable defects must be drawn up. The inspector cannot be expected alone to bear the burden of arbitrary definition of acceptable defects. He needs experimental evidence, classified in a scientific manner.

The notch ductility test is the hinge-pin with regard to all assessments of tolerable defects, and fracture mechanics is the means of interpreting the test results for all manner of sizes and shapes of structure and defect. There is no finality in the development of either of these, but sufficient progress has been made with both to permit the preparation of useful application specifications, taking them as they are now. For instance, one of the developments to be expected within the next five years is a mathematically quantitative appraisal of the state of stress in 3 dimensional, or finite thickness sharply notched members, of elastic-plastic material. This can be expected to illuminate more fully the manner in which there is a change from plane strain to plane stress conditions, as loads are progressively increased. Valuable as this information will be, it will not be expected to overturn the present concepts of the change from one regime to the other. Why therefore should we await this event, before embarking upon a specification?

It used to be said that British Standard specifications embodied established good practice, but this attitude is logically indefensible, for an object within the specification cannot simultaneously be improved and established, so that progress could be stultified by such an interpretation. There are many

precedents where good sense has prevailed to absorb into BS specifications improvements arising from experimental and theoretical research, rather than established practice. Hence, there is nothing to prevent a specification for tolerable defects from being similarly absorbed, and nothing save our own inertia to thwart us from embarking upon the task now.

Modes of failure

Among the fracture hazards for most metallic structures that are already properly proportioned for the loads they have to bear are those due to fatigue, brittleness, creep and stress corrosion. All of these involve the extension of nucleated cracks. The size at which a nucleus is recognised as such may lead to discussion; in general, the metallurgist can assert more relative influence on events than the engineer, as the nucleus becomes smaller. Of the four modes, brittleness is the one most closely associated with unstable complete rupture. Although not the most prevalent mode, it tends to be regarded as of great importance because of its potential destructiveness. The remaining three modes mainly represent slow crack extension, whereby the rate of occurrence is dominant. Of these, fatigue is the most widespread. It has become recognised more recently that precise distinctions within these three are less important than to be able to measure and compare the relative resistances to crack movement by these modes, within the same fracture mechanics framework that is already applicable to brittle cracking. The evidence in favour of this is now ample.

As far as specification of acceptable defects is concerned, a reference framework is envisaged in which there is an observed crack defect size or length, and a critical defect size for unstable fracture. The permitted defect size will be less than the critical by a margin dependent upon (1) the estimated life growth due to the agencies of slow crack extension in the appropriate environment, (2) a margin for measurement and assessment error. In an acceptable structure the observed defect sizes will again be less than the permitted values for each position in the structure, according to geometry and loading pattern. The existence of viable stress analysis procedures for possible crack configurations is accepted as a prerequisite.

The nature of defects

Defects can be intrinsic to a material, such as lamination, to a process, such as a forging roke, or to both as in a welded joint, where heat affected zone cracking may be combined with lamellar tearing. Defects can be crack-like, or voluminous, as with slag inclusion or porosity in welding. By contrast, the treatment of a defect in terms of fracture mechanics is restricted to a plane, simple geometrical shape of infinite edge sharpness, in material of uniform elastic-plastic properties. The gulf between actuality and idealisation is large, but by no means daunting, because every case can be classified between two extremes. Thus, a collection of distributed pores can be described in terms of an enveloping circular or elliptical crack, with plane normal to the stress direction. This is usually the most conservative assumption. At the other extreme, the group could be represented by one or more spherical cavities, whose effect on the elastic-plastic strength of the member would be no greater than the proportional loss of cross-section would indicate. Adherence to one or the other of these extremes would be conditioned by existing experimental evidence from tests on specimens containing such defects. This would probably indicate the first assumption to be appropriate to heavy sections, as at the core of a large forging, where triaxial tension during cooling has the effect of converting such porosity groups into crack networks, and the second assumption to the majority of cases, in thin sections of material or welded joint.

The shape limitations for calculable plane defects have been extensively discussed [1] as has the extension to elastic-plastic conditions [2]. The advent of elastic-plastic computer programmes for crack problems has extended the range within which solutions should soon be available [3].

The principle of extremes can be used to assess the significance of defects in locally metallurgically damaged material of reduced toughness, in the sense that real behaviour will lie between that for the defect embedded in uniform fields of damaged and undamaged material. This assertion has, for instance, been tested in many studies of the fracture of notched and welded wide plates [4]. The effect of residual stresses can be taken into account by assuming that the operative stress field is always at least of yield point magnitude.

When these formalised approaches are fully considered, certain of them will be found to yield results that are incompatible with practices now established. Some specifications, for instance, allow slag inclusions or stringers of small cross-sectional dimensions as acceptable defects, provided that they are below a certain length aggregating many times their thickness. The teaching of fracture mechanics would alternatively be that no distinction could be drawn between a length/width aspect ratio of about 2 or 3, and infinity. However, one reason for the present ruling is that a long slag inclusion represents a consistent welding process fault, which should be eliminated in the interests of overall quality. Compromise between conflicting claims has to be established when writing any specification, where there are also the subjective elements of practical experience to be accommodated, and can be anticipated as necessary in the present case.

The case for a two-class system of structures with respect to permissible defect sizes

It has become customary since World War II to classify steel structures with respect to the risk of brittle fracture in terms of a transition temperature, although this has been mainly interpreted as a material rather than a

structural property, assessed empirically. More recently, overwhelming evidence has been accumulated to show that transitional behaviour is recognisable in most materials (among the latest being carbon fibre reinforced plastics). It is primarily dependent upon yield or flow strength and thickness [2, 4]; temperature dependence is a by-product of variation with temperature of yield strength. For each material, oblique fracture planes are observed at below the critical thickness, and flat fracture planes above this thickness. For most, if not all materials, the toughness associated with oblique fracture is the greater.

The fracture plane transition is a faithful reflection of slip behaviour under sharp notched conditions in any material capable of supporting slip deformation. As loads are increased the first deformations are in the plane strain mode until such time as the yielded zones extend sufficiently far from the notch tip, in the direction normal to the notch plane, to accommodate oblique slip. The triaxial stress intensification associated with plane strain behaviour then gives way to plane stress. It is only in certain materials such as low strength steels that the two fracture modes are crystallographically separate, for reasons associated with the change of triaxial stress conditions at the transition. For instance, the corresponding changes in fibre reinforced plastics are from flat cracking, which passes from the matrix through the fibres under plane strain conditions, to oblique delamination under plane stress conditions. In certain high strength steels there is no metallographic or crystallographic distinction between the two fracture modes, although the measured toughness may increase when slip fracture becomes the alternative to opening mode flat cracking.

The almost universal increase of toughness associated with the plane strain/plane stress transition makes it important to recognise the conditions at which it occurs, and it will have been noted that these are defined solely in terms of stress and deformation, hence without reference to metallurgical or other fracture criteria for the material itself. It is therefore appropriate to describe the transition in the most direct possible terms, that is according to the ratio of yield zone size r_Y to section thickness T. Yield zone size, in the most general case, depends upon the shape of the enclave to be measured, which changes as the zone grows towards general yield so that the influence of other external boundaries of the body begins to be felt. Then, since an order of magnitude definition is all that is required, it is preferable to retain the simplest of the quantitative relationships of linear fracture mechanics, in terms of notional r_Y and section thickness T as follows:

$$\frac{r_Y}{T} = \frac{EG}{2\pi\sigma_Y{}^2T} = \frac{1}{2\pi T}\left(\frac{K}{\sigma_Y}\right)^2 = \frac{E\delta}{2\pi\sigma_Y T} \qquad (1)$$

bringing in all three of the alternative descriptions of cracking propensity, in terms of stress and strain, namely, crack extension force G, stress intensity (or stress field parameter) K and crack opening displacement δ. When $r_Y/T \geqslant 1$, there is fully developed plane stress. Alternatively, when $r_Y/T \leqslant (1/5\pi)$ (or, as designated in ASTM work, $T \geqslant 2{\cdot}5(K/\sigma_Y)^2$ there is fully developed plane strain. The intermediate transition range, involving a 16 fold change of G, or fourfold change of K, may seem to be very wide, but is often truncated in terms either of thickness or temperature, where the observed, almost stepwise, concomitant change of fracture toughness is taken into account. The experimental data, on which these numbers are based, is now quite thoroughly explored [2, 5].

For those whose assessment of notch ductility requirements is, perforce, in terms of the Charpy V notch test, a linear correlation between G_c and energy absorption, for the plane stress mode, is described in reference 2. By using this, Charpy V energy absorption values at the transition to plane stress can be calculated for sections of full thickness. An equally useful identity between crack opening displacement and the absolute value of notch root transverse contraction may alternatively be used.

There are, or course, many objections of a scientific character to the Charpy V test construed in these terms, involving the devious character of the correlation, the use of impact, and the absence of a sharp notch in the test. However, most of these objections apply to attempts to use the correlation for situations where $r_Y/T < 1$, and this is to be emphatically discouraged, except where fatigue crack notches are employed in conjunction with a dynamically instrumented machine [6]. There is then a limitation to conditions where $r_Y/T_{cv} < (1/5\pi)$, or somewhat greater. T_{cv} is here the thickness of the Charpy specimen itself.

The subject of tests is further discussed below; for the time being it is to be concluded that a direct test for the quantities G_c, K_c or δ_c is to be preferred, with specimens of full section thickness if the transition region is to be explored. Attention must nevertheless be turned to the definition of the transition that might be adopted in a specification. One of the problems of exploration of the transition range is that the toughness measurements within it are susceptible to shape variations, both of notched specimen and actual structure with defects, in terms of the changes of triaxial stress intensification that they produce. These are now fairly well understood in these terms, sufficiently so to be sure that the effect can now be identified with many of the difficulties that were experienced during the past twenty years in obtaining correlations between small scale transition temperature tests and the brittle behaviour of actual structures. Although understood, the effects are too complex to be fully taken into account in any specification. Furthermore, the complexity is intensified where, as in most cases, the defects to be assessed are associated with locally embrittled material. The more conservative of the possible assumptions is then the only tenable one, namely, that plane strain conditions must be

assumed to apply up to the point of well developed plane stress, where $r_Y/T > 1$. This assumption carries the advantage that brittle behaviour with such a degree of notch ductility may be virtually discounted, provided that cracklike defects do no exceed plate thickness in any dimension for somewhat less if appreciable plastic deformation is to be accepted).

The plane stress class of structures, so defined, will accommodate a high proportion of those welded steel constructions now being put into use. They will be tolerant of some yield at design stress concentrations, will not necessarily require post weld heat treatment, or more than partial non-destructive testing. They will, however, require assurance that the notch ductility requirement is met in the weld metals and heat affected zones. The unified criterion now proposed for these structures will suggest limits of operation close to those now based on empirical transition temperatures, where these are also founded well in experience or semistructural scale tests in the laboratory. The advantage of the unified criterion is that it can be expected to apply equally well outside the areas of detailed investigation, and for other materials than steel. This arises from its fundamental basis in mechanics.

If plane stress structures are those that operate above a transition temperature, the significance of an alternative plane strain structure is equally clear with regard to operation below the transition temperature. There will always be some of these structures, of heavy section high strength materials. For instance, examples would be a 6 in thick construction of 55,000 lb/in^2 yield point or a 2 in of 100,000 lb/in^2, at a Charpy V value of less than 90 ft/lb. The specification would require them to be controlled on the basis of plane strain fracture toughness measurements, hence excluding the Charpy V test, even in the fatigue cracked, instrumented form, because the specimen is too small to support plane strain fractures for measurements up to the requisite toughness levels. Nevertheless, the treatment would be mainly conservative within the transitional region especially as the performance approaches plane stress. Defect control and design stress levels in such structures are discussed below.

Notch toughness tests for specification purposes

Experience of specification writing suggests that a flexible approach should be combined with the utmost simplicity of form. The breadth of application is increased if there is a background of scientific rigour. Application of these tenets suggests that the Charpy V test should be retained both for screening and quality control purposes, to distinguish the limits of plane stress qualification. The full thickness specimen test is then applied for procedure or qualification test in marginal cases. The latter test can be assessed in terms of the measured crack opening displacement as master variable, against which overall displacement, crack mouth displacement, or notch root contraction can be calibrated as convenient secondary variables. The criterion for initial notch sharpness, in terms of slit width, can be a value equal to or less than the COD to be measured, although fatigue cracking would be preferable, if the expense of it could be borne. The specification can afford to allow several alternative specimen shapes and loading configurations, as convenient, but recent collaborative experimental work has shown the need for carefully controlled and agreed measurement procedures.

In the case of weldments, both the screening and full plate thickness tests, where the latter are necessary, would be performed additionally on weld and heat affected zone material, in the appropriate condition of heat treatment.

A variety of alternative plane strain toughness tests have each been specified by ASTM and confirmed by intensive recent work in the U.K. All are based upon full thickness, fatigue notched specimens, assessed through fracture load measurements. They are capable of giving precise results, because of the large standardisation effort that has been devoted to them. It is necessary, however, to draw attention to difficulties that arise in the transition region. The plane strain measurement capability is lost in this region, although this would be acceptable with specimen thicknesses equal to those to be used in service. Unfortunately, the specimens also tend to exhibit general yield before fracture, so that a straightforward toughness measurement cannot be made from the fracture load using the calculation methods of linear elastic fracture mechanics. Resort must therefore be made to additional measurements, of crack opening displacement type, in this region.

It would appear likely that this disadvantage could be removed in the near future by utilising the temperature wave method of direct measurement of fracture work [7, 8, 9]. By this means it is possible to remove the dependence upon an inference of toughness from the critical value of crack extension force, calculated at the point of instability. The effect of overall yielding before instability can thereby be excluded. Furthermore, by sampling the fracture work rate in the very early stages of crack propagation, it is possible, at least with steels, to make dynamic plane strain toughness measurements right through the transition zone, in terms of temperature as in Fig. 1. The diminished dependence upon specimen geometry, conferred by the temperature wave method, also permits the use of specimens naturally cracked at weld deposits, and promises to provide the fabricator with a full sized test specimen which is cheap to make and test in a robust fully instrumented form, and which is capable of sampling critical material at a welded joint in terms of a measurement of scientific rigour. If such a specimen is also assessed in terms of through thickness contraction it is capable of providing crack initiation data uniformly over the range from plane strain to plane stress.

Critical defect sizes

(a) *Plane stress*

Although these have been discussed [2], to the extent of experimentally verified theoretical values, with different crack shapes and overall plastic strain levels, some simplification would be required for specification purposes. For instance, crack shape effects could be considered as of second order significance, and it could be tacitly assumed that no material with superfluous notch toughness would be employed in practice, for economic reasons. A short table of ratios of crack size to plate thickness would then suffice, in terms of the required overall plastic strain tolerance. In assessing the latter, for instance in pressure vessels, there would be regard for the design strain concentrations at the time of overload proof test, but only those strain concentrations would be considered, having sufficiently large extent to contain a defect within a zone of substantially uniform strain (e.g. nozzle openings). Strain concentrations of small extent, such as those at the toe of a fillet weld, would be lumped with the defects which they might generate.

(b) *Plane strain*

If, as in most cases, the realisable plane strain fracture toughness is less than the marginal value for plane stress, it is clear that the defect tolerance is substantially reduced. Indeed, almost the only way in which to retain such tolerance is to limit concentrated stresses to elastic values, hence design stresses to conservative values of the order now used. This might be an implicit feature of the specification. Even under these conditions, critical defects will often be much smaller than plate thickness in size. However, the complicating effect of thickness is then reduced, and the simplest critical crack size treatments of linear fracture mechanics can be used. Under these circumstances, crack shape effects will be worth taking into account.

Permissible defect sizes

A considerable quantity of data now exist on crack growth rates due to fatigue, both in virgin materials [10] and welded joints [11], and due to stress corrosion in selected high strength materials [10, 12]. In view of the small defects and comparatively low stress ranges studied, much of the data appertain to plane strain but, for technological purposes, the effects of translation to plane stress, and of mean stress, could be considered to be of second order for specification purposes. Moreover, many data suggest minimal effects of change of composition and heat treatment within metals represented as elements. The few data available for creep rupture crack extension [13] suggest elevated temperature values in excess of those for brittle fracture at room temperature, after the metal has been simultaneously exposed to heat and plastic strain. It should therefore be possible to compile tabular data for crack size growth ratios in a specification in a less complex manner than for the fatigue of welded joints in so far as that is dealt with in BS 153.

There would appear to be much to commend in the attempt [14] to correlate this ratio with the corresponding ratio: measured or calculated proof load to the structure working load, in the selected environments of fatigue, stress corrosion or high temperature thermal fatigue and creep. This is tantamount to attributing a notch toughness degradation ratio dependent upon environment. It might be tempting to apply the same philosophy to notch toughness degradations arising at welded joints, but a modicum of reflection will show that this is undesirable, at least in medium and low strength steels, because such degradations are not confined to crack tips, and therefore lead to unstable rather than slow crack growth.

It will be noted that there are no safety margins interpolated in BS 153 for fatigue failure, and this is defensible because the fatigue is a slowly occurring event. Furthermore, the proper place for an overall margin arises in the design load factor. Although the latter question should be discussed when framing a specification, it is suggested that the same approach should be adopted as in BS 153, subject to a minimum crack growth ratio of 2, to allow for uncertainties in structures in which fatigue, stress corrosion or creep rupture slow crack growth are assumed not to occur.

Conclusions

The above discussion may conveniently be summarised by formulating the draft specification in a tabular manner (Table 1). It is fully anticipated that any such table eventually emerging from the patient and conscientious deliberations of a drafting committee will scarcely resemble Table 1, but the task has to be commenced in a small way. If Table 1 serves as a nucleus and stimulus, the attempt at compilation will have been worthwhile.

References

1. PARIS, P. C. & SIH, G. C. *ASTM,, S.T.P.*, vol. 381, p. 30, 1965.
2. WELLS, A. A. *British Welding Journ.*, vol. 15, no. 5, p. 221, 1968.
3. WELLS, A. A. *Engineering Fracture Mechanics*, vol. 1, no. 3, 1968.
4. WELLS, A. A. *British Welding Journ.*, vol. 12, no. 1, p. 2, 1965.
5. WESSEL, E. T. *Engineering Fracture Mechanics*, vol. 1, no. 1, p. 77, 1968.
6. RADON, J. C. & TURNER, C. E. *Journ. Iron and Steel Inst.*, vol. 204, p. 842, 1966.
7. WELLS, A. A. *Welding Research*, vol. 7, no. 2, p. 34r, 1953.
8. WELLS, A. A. Trans. N.E. Coast Inst. Engrs. and Shipbuilders, vol. 71, p. 277, 1955.
9. MONTGOMERY, D. & WELLS, A. A., to be published.
10. JOHNSON, H. H. & PARIS, P. C. *Engineering Fracture Mechanics*, vol. 1, no. 1, p. 3, 1968.

11. HARRISON, J. D. Welding Institute Rept. RB/E20/68. To be published.
12. BROWN, B. F. *A.S.T.M., Materials Res. and Stds.*, vol. 66, p. 129, 1966.
13. WELLS, A. A. & McBRIDE, F. H. *Canadian Metallurgical Quarterly*, vol. 6, no. 4, p. 347, 1967.
14. NICHOLS, R. W. *British Welding Journ.*, vol. 15, nos. 1 and 2, pp. 21 and 75, 1968.

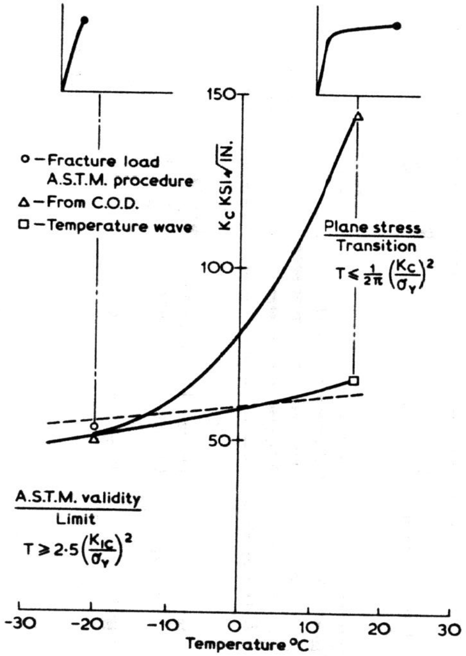

Fig. 1. Temperature wave and other toughness measurements for a mild carbon steel 2 in thick.

Table 1
Trial specification for permissible defect sizes in welded metal structures

Procedure or estimate	Notch toughness: Test description	Notch toughness: Measurement variable	Working temperature criteria for base material, weld metal and HAZ: Plane stress	Working temperature criteria for base material, weld metal and HAZ: Subtransition, or plane strain
SCREENING and QUALITY CONTROL	10×10 mm CHARPY V impact test. 2 mm notch.	$\frac{W}{A}$	$\frac{W}{A} \geqslant \frac{4\pi\sigma_Y^2 T}{E}$	$\frac{W}{A} < \frac{4\pi\sigma_Y^2 T}{E}$
PLANE STRESS QUALIFICATION (where any Charpy V m'ment is less than plane stress limit)	FULL THICKNESS Sharp notched slow bend or compact tension test. $\rho < \frac{\pi\sigma_Y T}{E}$, or fatigue crack.	Standard: δ_e Calibrated sub-standards: Crack open end displacement Root transverse contraction	$\delta_e \geqslant \frac{2\pi\sigma_Y T}{E}$	$\delta_e < \frac{2\pi\sigma_Y T}{E}$
PLANE STRAIN QUALIFICATION	ditto but fatigue cracked only.	Fracture load/unit thickness, Crack open end displacement. } K_c	—	K_c up to offset yield limit. (ASTM, STP 410 procedure)
	FULL THICKNESS weld cracked drop weight bend test.	Temperature wave G_c	—	G_c for whole joint. Limits to be specified later.
	Correlations			
CRITICAL DEFECT SIZE	Uniform applied elastic or plastic strain, and section thickness only.		$\frac{e}{e_Y}$: 1, 2, 5, 10 $\frac{a}{T}$: 0·84, 0·24, 0·074, 0·034 Minimum $\frac{e}{e_Y}=2$ for as-welded structures.	—
	Uniform applied elastic stress, measured notch toughness, and crack configuration.		—	$a = \frac{EG_c}{\pi\sigma^2} = \frac{1}{\pi}\left(\frac{K_c}{\sigma}\right)^2$, or equivalent for given crack configuration.
CRACK GROWTH RATIO	Ratio of proof loading to applied loading, and number of applications of applied load for fatigue growth, or notch toughness degradation in environment for stress corrosion, and creep with thermal fatigue.		Ratio 2; otherwise dependent upon compiled experimental data.	
PERMISSIBLE DEFECT SIZE			*Critical defect size* / *Crack growth ratio*	
CONCESSIONS, or LIMITATIONS			Rounded defects may be assessed on loss of cross-section alone, in non-fatigue loaded structures.	Welded structures to be efficiently heat treated, and non-destructively tested after. Yield not permitted at design stress concentrations.

W – Charpy V impact energy: in/lb. A – Charpy V specimen ligament area (8×10 mm) = 0·124 in². σ_Y – yield strength: lb/in². σ – applied stress.
E – elastic modulus: lb/in². T – section thickness: in. ρ – notch tip radius: in. δ_e – critical crack opening displacement: in.
G_c – notch toughness: lb/in. K_c – critical stress intensity: 1000 lb/in² in. a – crack half length: in. $e_Y = \sigma_Y/E$. e – applied uniform strain.

Permissible defect sizes in welded metal structures