FRACTURE CONTROL IN WELDED STEEL STRUCTURES

A. A. Wells

The Welding Institute, Abington Hall, Cambridge, England

ABSTRACT

Fracture studies of welded steel structures in the two decades after the second world war required an emphasis on the analysis of casualties. There has since been sufficient progress to allow the lessons learned to be applied to fracture control. There have been notable successes, for instance with ocean structures, and it can be claimed that the engineering designer now has available a range of techniques for application to ensure structural integrity. They can be summarised as fitness-for-purpose assessments which embrace metallurgy, mechanics, non-destructive testing and quality assurance.

Fracture mechanics methods have been very useful both in the analysis of casualties and in providing methods for fracture control in new structures, but it needs to be recognised that different approaches are required for these two applications. Furthermore, different approaches may still be required to assert fracture control with different classes of structure. The paper makes use of recent experiences in an attempt to create a perspective.

KEYWORDS

Fracture mechanics; fitness for purpose; steels; structures; welded joints; fracture tests; toughness; brittle fracture; crack initiation; crack propagation.

INTRODUCTORY REVIEW

Fatigue fractures have been common in engineering structures from the earliest times, and they still are too common. Fatigue is a vast subject, far beyond the scope of this review, and it afflicts other than welded structures, although there are special areas of significance when welding is used. Among these are the cases of fillet welded joints, and mechanical engineering components required to have very long lives (say $>10^8$ stress applications) as in reciprocating engines. Linear elastic fracture mechanics applied through fatigue crack propagation laws has been efficacious in providing the designer of welded structures with methods of control. No further comment will be offered, except to counsel that there are worthwhile rewards for designers who worry about fatigue from the commencement of design development; it is rare to have to call the experts under crisis conditions when that step has first been taken. Forethought may cost money, but it is manifestly cheaper than a casualty, perhaps associated with secondary or consequential damage, followed by replacement and repair.

Brittle fractures of welded steel structures are much rarer than fatigue failures, as a result of which there is also a dearth of first-hand experience, particularly among welding craftsmen. The monolithic character of welded structures can lead to transmission of cracks and creates the need for care. Both these factors are evident in the treatments accorded to welded attachments, which have caused the downfall of otherwise carefully made constructions on numerous occasions. Welding craftsmen usually work with integrity, but they are often put under considerable pressure to conduct minor repairs; their customers also want them to weld this to that, because the two have come apart in use or abuse. It is difficult to persuade a welder that a post-weld heat-treated pressure vessel may be endangered when it is required to weld bracket attachments inside it to support additional structure for product treatment, or that a ship can break in two if exposed and damaged portions of bilge keel are cut out and rewelded without due care during a hurried ship repair. The normal view of the craftsman would be that the structure exists to carry the attachments. Casualties from these causes are usually less than once-in-a-lifetime experiences for the craftsman; the responsibility for avoidance rests more with the supervisor who should have acquired knowledge and experience to avoid such situations, but even the supervisor may be subservient to managements with other pressing responsibilities. Obviously, structural safety cannot be the sole concern of the welding craftsman, or even that of the supervisor. It is the proper function of quality assurance, in method and implementation, to avoid the development of such situations of vulnerability, and a high degree of effective communication is required to apply it. Again, the subject of quality assurance is too substantial to treat in this review, which will alternatively trace the stages in development of brittle fractures in welded steel structures, from initial defects to unstable propagations. It will then review this knowledge towards the goal of adequate fracture control.

It is very well-known that ferritic steels exhibit transition temperatures, above which there is an absence of cleavage in the exposed microstructure, hence of tendency towards brittleness, and below which there is a risk of brittle fracture. A transition range of temperature is exhibited in the equally well-known Charpy V notch impact test. The transition temperature is exhibited even more sharply and clearly in the Tipper notched tensile test, which uses slow loading on specimens of full plate or section thickness, and widths five or more times greater. Cleavage type fracture is induced in this test by incorporating a pair of Charpy V type notches, and the test is assessed on the percentage of cleavage appearance in the fracture cross-section. It is of considerable interest to note that the strength of steel exhibited in the Tipper test is in no way influenced by the fracture appearance; it may even be increased as temperature is lowered. The inception of the Tipper test would have heralded the end of the brittleness problem in an ideal world. The difficulty is that the needs of the engineer in terms of larger structures, structural cross-sections and higher yield strengths, and in terms of lower operating temperatures and higher rates of loading can always easily outstrip the capacity of the steelmaker to provide suitable materials. This is as true today as it was forty years ago, in spite of great achievements in steelmaking practices; the sights are raised every time an improvement in steelmaking is introduced.

Although the Tipper test criteria may occasionally be unconservative for some applications, such as underwater explosively loaded constructions, or high-pressure line-pipe for natural gas transmission which can alternatively exhibit unstable ductile fractures, the fracture appearance criteria are in general too conservative, even for heavy high-pressure vessels in the power industries.

The Charpy V notch impact test has been retained as a completely empirical measure of notch ductility and transition temperature for quality control purposes, because of its low cost and ease of replication, but the Tipper test has been followed by many other type tests for steels and constructions, and their objectives are mainly to increase the latitude available to the engineering designer in several generic cases.

The tests of the second group attributed to W.S. Pellini (1983) and associates at the U.S. Naval Research Laboratory are primarily related to structural performance under explosive loading, and make considerable use of fracture appearance criteria. Nevertheless, the Drop Weight Test has also been widely recognised for application more generally to welded structures, and employs a brittle weld crack starter. The full implications of its use for heavy-section steels require further consideration because the test is usually conducted on reduced thicknesses in such cases.

The crack arrest tests of the third group (Boyd, 1970; Tipper, 1962) have the common objective to measure the limits of applied stress and temperature for arrest or continued propagation of brittle cleavage cracks which have first been initiated in an independent manner, either by use of a blow, or as in the Japanese double tension test by a subsidiary static load applied to an ear-shaped transverse extension of the fracture specimen. Such tests can be applied in principle to cross-sections of material of thickness as for the prototype structure, but they are not specially applicable to welded joints.

The fourth group of tests is based upon interpretation through fracture mechanics, and it is this group which best makes allowance for extremes of material section thickness. The well-known and most widely used is the plane strain fracture toughness test, or K_{Ic} test as standardised by A.S.T.M., and this has been conducted on rare occasions at thicknesses up to 0.4 metre, to give information that could not be obtained in any other way. Such tests are capable of sampling sections of welded joints, but interpretation in that case is not always easy. These tests do not have to be much modified to permit them to be used for materials which fracture under partially or fully plastic conditions, and are further discussed in this role. All the tests in each of these groups as defined could properly be described as material tests.

In spite of the importance of fracture toughness tests in the control of brittle fracture it has also been recognised over a long period that the three conditions needed to develop a brittle fracture casualty are,

1) the initial presence of a nucleating defect of sufficient size and sharpness,

2) the application of a field of tensile stress of sufficient magnitude to drive a crack, including weld residual stress where applicable, and

3) a spatial distribution of fracture toughness which can at all stages be overcome by the propagating crack.

Much progress has been made in improving non-destructive methods of examination for defects associated with welded structures, and this too deserves a separate review. It is now possible not only to detect most of such initial defects in the relevant size ranges, but also to size them for the purposes of structural quality assessment. The sensitivity of NDT is such that logically based decisions can be made as to whether to tolerate or repair defects, bearing in mind that repair sometimes introduces risk of degradation of the local fracture toughness properties, and can also extend fields of tensile residual stresses. Initial defects are sometimes revealed in strange shapes and combinations which could complicate fracture mechanics analyses, and it is appropriate to draw attention to published guidance from practice such as is now available in the British Published Document PD 6493. However, NDT grows in cost as it also becomes more effective, and is also subject to diminishing returns as the effort is increased; it would be a nonsense to suppose the possibility that all potentially significant defects could ever be located with certainty in large welded structures, or that none would appear during the life of a structure. There has to be a degree of crack tolerance, and preferably a comfortably large one. The amount of effort to be devoted to NDT, compared with that expended on raising the fracture toughness of the materials of construction, will always demand balanced decisions. Probability studies have contributed in recent years to reaching such decisions, and deserve further comment in relation to structures of widely different types.

The remaining major variable with respect to brittle fracture casualties and their concomitant in fracture control is the tensile stress field in magnitude and distribution, insofar as it influences crack travel. The early workers (Boyd, 1970; Tipper, 1962) were able to study a proliferation of casualties in the field. They learned how to identify many features in the appearances of casualty fractures which indicated the conditions of stress at the time of fracture. The contrasting appearances of initiating defects and the indications of cracking direction from chevron markings continue to be well-known, but there are others. For instance, smooth fracture appearances in cracks emanating from defects denote easy crack initiation and rough cleavage textures denote high applied stress initiations; transversely displaced chevrons in plate structures denote bending, and branching fractures usually denote high velocity cracks driven by correspondingly high stresses. It is often difficult to pick out the first event which led to a brittle fracture casualty, because of the chaos resulting from secondary damage, and these features are invaluable in classifying what to look for. Such features are of dominant importance, since a low stress crack initiation can indicate a faulty structure, whereas a high stress initiation may point to overloading from some extraneous cause. All structures have limits of performance with regard to overloading; the designer aims to equalise such limits in all the components making up a structure, and has to take into account several alternative failure modes in each case. In most cases it is inconsequential if a structural casualty exhibits zones of brittle fracture arising from overloading or secondary damage, since such is a mere alternative to plastic collapse in adjacent compression zones, or ductile tearing. No realisable degree of fracture toughness can hold together an overloaded structure.

Classes of structure are not alike in the external loading and stress levels which they should sustain without failures. It has never been suggested that vehicles, ships and aircraft should possess more than strictly limited resistance to accidental collision loading, since to overprovide would impair their principal modes of operation. Most pressure and storage vessels are built to withstand static loads which are well-defined and can be effectively limited, both intrinsically and by protective devices. Nuclear pressure vessels and those for high temperatures and pressures are in a different category, in that they must also safely sustain transient thermal stresses as well as pressure-induced stresses. Offshore platforms are in another different category because they must sustain wave loadings of wide variety without clearly defined upper limits, under conditions where initiating defects can grow by repeated wave loading.

The importance of correct identification of design stress and strain limits, which are neither too large nor too small, should not be overlooked in the development of fracture control procedures, and the lessons from past studies of casualties in the field should not be forgotten in setting these limits. It is perhaps not surprising that such should emerge as a principal lesson from this brief review, following periods of intense development, firstly of methods of measuring fracture toughness, and secondly of methods of non-destructive testing.

THE SIGNIFICANCE OF NOTCHED AND WELDED WIDE PLATE TESTS

The writer was privileged as long ago as 1952 to have access to a cylindrical oil storage tank casualty which provided an excellent model for the development and application of fracture mechanics, since the hydrostatic test loading was accurately known at the time of the event. The weld defect was large, being the result of an unsuccessful attempt to repair where a prober specimen had been extracted as a routine exercise to examine the through-thickness profile at one of the lower girth welds. The fracture extended above and below and the tank was destroyed. An earlier and comparable brittle fracture initiation had occurred from another transverse weld defect, but was arrested at a short length. The applied hoop stress was relatively lower at the time of this event. Linear elastic fracture mechanics in terms of the stress intensity K was not to be introduced until 1957, and so the analyses were performed using Irwin's crack extension force G, and problems of superposition of loading from applied and residual stresses were encountered, perhaps for the first time. This casualty demonstrated the different phenomena of crack initiation and propagation, and encouraged the prospect that the processes of crack extension and arrest could be followed with the use of fracture mechanics (Wells, 1952). The experience led in due course to the specification of the notched and welded wide plate test, and to the development of suitable test rigs of adequately large load capacities. The conditions for the occurrence of low stress brittle fractures were reproduced in the laboratory (Wells, 1956), using the same configuration as in the casualty, that is to say with the test weld parallel to the direction of pull, having an artificial transverse defect within its length. The artificial defect consisted of jeweller's sawcuts in the edges prepared for butt welding. These sawcuts were not melted out during welding, but the thermal plastic deformations imposed upon them by welding introduced severe damage of a strain ageing type. Crack initiation was thereby made to be relatively easy so that attention could be focussed upon subsequent propagation and arrest in the parent material. The distribution of stress intensity K for a symmetric crack extending from the weld is shown in Fig. 1, reproduced from the text book 'Brittle Fracture of Welded Plate' (Hall and co-workers, 1967). When the crack initiated in the presence of significant applied tension stress along the weld it is seen that K first increases to a maximum under the predominating influence of the tensile residual stress field associated with the weld, and a minimum value follows. Crack arrest can occur as a result of this minimum, just as has been observed on numerous occasions in structures. The arrest occurs in undamaged parent material whose fracture toughness may be considered to be unchanged with crack extension.

The feature which it is now desired to emphasize is that such an initiation event could not occur unless there were to be an initially steep upward

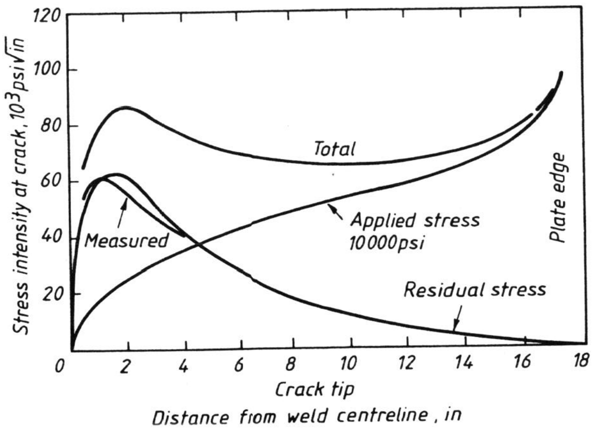

Fig. 1. Stress intensity distributions from weld residual stresses and applied stresses.

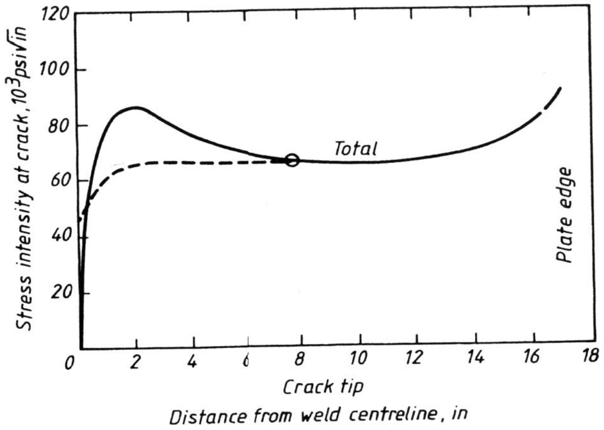

Fig. 2. Comparison of stress intensity and fracture toughness distributions.

gradient of fracture toughness through the weld and heat-affected zone, as shown by superposition in Fig. 2. There is a possibility that this necessary attribute of low stress fractures, in casualties as well as wide plate simulations of them, will be overlooked as attention is transferred to seeking improvements of the notch ductilities of weld metals and weld adjacent zones, using both Charpy V and crack tip opening displacement (CTOD) tests. Both these tests are sensitive with regard to sampling regions of substantial heterogeneity of toughness, as at welds, and high values of scatter can be experienced, including a proportion of low values. The scattered results may be plotted systematically on probability paper, and then used to calculate probabilities of fracture. However, this step is only meaningful for measurements near welds if the sequential steps of crack extension are fully considered. The most effective way of doing this is to consider the probability of the crack extending outside the residual stress zone into the parent material, as in Fig. 2. The true probability of fracture through crack extension is at least the product of the probabilities of each of the events, which have to be in sequence.

It is sometimes argued that no such obstacle would be offered to a crack running along a welded joint, since it could then follow a path continuously through aligned material of a possible low notch ductility. Such events have not been seen hitherto in casualties, and they are not readily demonstrated in wide plate tests using transverse instead of longitudinal welds, except under circumstances of general yielding and exhaustion of ductility. The most obvious explanations for the rarity of the event are firstly, that running cracks are themselves driven by tensile stresses, the normals to whose directions seldom coincide exactly with narrow paths of low notch ductility, and secondly, that crack extension along welds is not assisted by residual stresses.

Finally, the linear-elastic K distribution of Figs 1 and 2 may be modelled compactly if the influence of the tensile residual stress is considered to be contained by a uniform stress σ_Y applied over a total width 2b. The contribution from residual stress alone is then as follows, for instantaneous symmetric crack length 2a,

$$\text{When } 0 < a \leq b, \quad K = \sigma_Y\sqrt{\pi a}. \qquad\qquad (1)$$

$$\text{When } b < a, \quad K = \sigma_Y\sqrt{\pi a} \times \frac{2}{\pi}\sin^{-1}\frac{b}{a}$$

When the effect of uniform applied tensile stress σ is superimposed, with the added restriction that the sum of applied stress and residual stress is not allowed to exceed σ_Y, the total value of K may be represented as,

$$K = \sigma_Y\sqrt{\pi b} \times f\left(\frac{a}{b}, \frac{\sigma}{\sigma_Y}\right) \qquad\qquad (2)$$

where the first term is the reference value. The factor is readily calculated making use of equation (1) and is tabulated below,

$$\frac{a}{b} = \frac{\text{Crack length}}{\text{Average residual stress width}}$$

$\frac{\sigma}{\sigma_Y} = \frac{\text{Applied stress}}{\text{Residual stress}}$	1	2	3	4	5
0.5	1	0.94	1.05	1.16	1.26
0.55	1	0.99	1.12	1.24	1.36
0.6	1	1.04	1.19	1.33	1.46

The result of the calculation may be simply expressed, in that the possibility of realising crack arrest conditions is demonstrated at applied stresses up to 55% of yield stress for a parent material crack arrest fracture toughness of $\sigma_Y\sqrt{\pi b}$, where σ_Y is the reference value of residual stress and 2b is the average (total) width of the tensile residual stress zone. The particular value of fracture toughness for crack arrest to which reference is made is considered to be closely similar to the plane strain value K_{Ic}, for which the observed scatter for parent materials is relatively low.

This result may be considered to be well-founded, being compatible with the results of wide plate tests conducted over many years. Furthermore, crack propagation under the cited conditions does not involve crack velocities approaching those of Rayleigh waves, and stress redistribution during cracking is complete throughout. The application of LEFM with stresses locally as high as yield stress is defensible since the stress changes involve unloading from yield rather than additional plastic deformations.

It is interesting to note that the offered criterion involves a stress ratio which may be compared with the Robertson crack arrest stress, except that the latter has come to be regarded by some as a fundamental material property. Equation (2) shows that the usable stress ratio depends additionally upon the width of the residual stress zone. This offers an explanation for the relatively poor fracture experience with electroslag welds used in the as-welded condition where there have also been repaired defects. Such welds have very broad residual stress zones. Conversely, an excellent future prospect is offered for narrow gap pressure vessel welds, and large-thickness single-pass electron beam welds, both of which have narrow residual stress zones. For practical purposes, the tensile residual stress zone has a width 2b of about 5 melted widths for steel, but is less for multi-run welds.

It is again of interest to note that the U.K. design conditions for gas transmission pipes in relatively populous zones recognise a similar stress ratio criterion, which was reached after exhaustive experiment. The underlying philosophy is that the most serious hazard for such pipes under pressure is penetration damage from the bucket teeth of earth-moving equipments. It is considered that the criterion of equation (2) is likely to continue to provide for a high proportion of the welded steel structures that are built, or are likely to be built, excluding only those destined for the most arduous service. (Appendix)

ELASTIC-PLASTIC FRACTURE CRITERIA

It is a reasonable assertion that elastic-plastic fracture criteria such as CTOD and J (Knott, 1973) were initially sought to facilitate measurements of fracture toughness in laboratory specimens, since the necessarily smaller sizes of the latter give rise to elastic-plastic behaviour except for the more brittle material conditions. Much experience has confirmed that the corresponding behaviours of full-scale structures are more amenable to linear-elastic analyses, although there are exceptions.

The CEGB R6 method of analysis (Harrison and co-workers, 1980) devised and used in the U.K. has provided a useful but limited extension of LEFM to deal with heavy pressure vessels and similar components for the power industries, which are distinguished by having well-defined plastic collapse loading characteristics. The method makes use of the elastic-plastic fracture criterion J to measure fracture toughness. The relationship $K^2 = EJ$ is then used in order to apply the data to extension of hypothetical defects in the structure, making use where convenient to do so of LEFM. This procedure has been useful in the assessment of transient thermal stress effects, and can also accommodate the levels of residual stresses found in stress-relieved constructions of heavy section.

The development of the CTOD test procedure took place somewhat earlier (Harrison, 1980; Wells, 1965). It was first aimed at the assessment of parent materials, and the design curves were developed and calibrated with the use of wide plate tests having saw-cut notches of different lengths, remote from welds. The limited objective of the CTOD approach has always been to predict the elastic-plastic extension to fracture in corresponding wide plate tests. This has been achieved through the experimentally verified

design curves, but attempts to synthesize design curves through the use of elastic-plastic computations have proved to be difficult. One of the reasons for this is that the conditions to be modelled in monotonic loading change from 2 to 3 dimensional in the range of most interest. Attention may be directed, however, to recent attempts to synthesize an alternative J design curve (Turner, 1983), since this promises to obviate the problem of a plastic constraint factor which changes continuously during elastic-plastic loading of any notched member of uniform finite thickness. Meanwhile, it has proved to be easier to standardise a CTOD fracture toughness specimen (BSI, 1979) than a similar specimen for J measurements of toughness.

Despite the reservations of early workers it was soon realised that the CTOD test could assist in the fracture toughness assessment of weld metals and heat-affected zones, and the test has been of great utility in detecting brittle crack-susceptible microstructures. These are found in association with welded joints to be as much or more dependent upon welding process variables than upon those characteristics of composition of metal and flux that are under the direct control of welding consumable manufacturers. Notwithstanding this burden upon the latter, considerable improvements have been won for such arduously loaded welded structures as those used offshore. Such has been the interest from users that there were proposals that the CTOD test should become part of standard requirements for the supply of welding electrodes and consumables. When the matter was jointly discussed in three interested expert Commissions of the International Institute of Welding in 1982 and 1983 a unanimous conclusion was reached that this should not be encouraged, for the reason cited above. It is hoped that the difficulty will be avoided, since there is already ample scope to apply notch toughness quality control to welding consumables using closely standardised quality control test conditions. The responsibility rests properly with welding fabricators to ensure that welding procedures are correctly chosen and monitored to ensure the production of a uniform quality of weld metal. This paper should have indicated with the necessary emphasis that notch toughness parity with parent material is not essential for welded joints to have a uniformly high resistance to brittle fracture, although parity is desirable if the loading of structures is such that there are several alternative mechanisms of initial slow crack growth, or the conditions of use are arduous in other ways.

These observations have a particular relevance to the repeated criticism that there is too much scatter in CTOD toughness tests, particularly at welds. The fault is not that of the test, which is sensitive, but can be attributed to the intrinsic heterogeneity of weld microstructures, arising from sharp gradients of composition, solidification, and thermal and plastic strain cycles. Very careful work in Germany (Ruge and Winkelmann, 1981) has shown that consistent results can be obtained even in welds, by very careful placement of the fatigue precrack front in CTOD tests in identical microstructures. The work also emphasizes a feature of CTOD and J toughness estimates, that they are relevant only to a small amount of crack extension. Insofar as the criticisms are levelled by those whose difficult task it is to assess the significance of scatter in applying quality assurance judgements to welded joints, the earlier observations in this paper may be relevant, concerning the limited significance of this scatter in terms of overall probability of failure.

Much remains to be done in the development of elastic-plastic fracture mechanics, since it is the key to further unification of notch toughness requirements for several different types of structure which are now treated in different ways. The technologists have shown readiness to pounce on each new development in the theoretical approach, once it can be brought to the stage of standardisation. That should be an encouragement towards further activity.

CONCLUSIONS

Fracture mechanics as it is applied to the fracture control of welded structures is not an elegant discipline, and may never be so. It is beginning to find a broad base, with the expectation of improvements to come, and it has acquired considerable importance in economic terms. In addition to the better unification which should be sought, two specific areas of need emerge from this review, and may be stated thus.

1. Better definition is sought with regard to the fracture stress and strain expectations of different classes of welded structure, such as those which may be currently classified as
   - a) statically loaded with inherent limitations of loading
   - b) as at a) also with transient thermal loading
   - c) as at a) also with repeated loading
   - d) randomly loaded
   - e) impact loaded.
2. The need remains for elastic-plastic strain analyses of sharply notched plates of uniform finite thickness, in order to provide better bases for CTOD and J design curves.

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APPENDIX : COMPARISON OF CRACK INITIATION AND ARREST FOR WELDED JOINTS

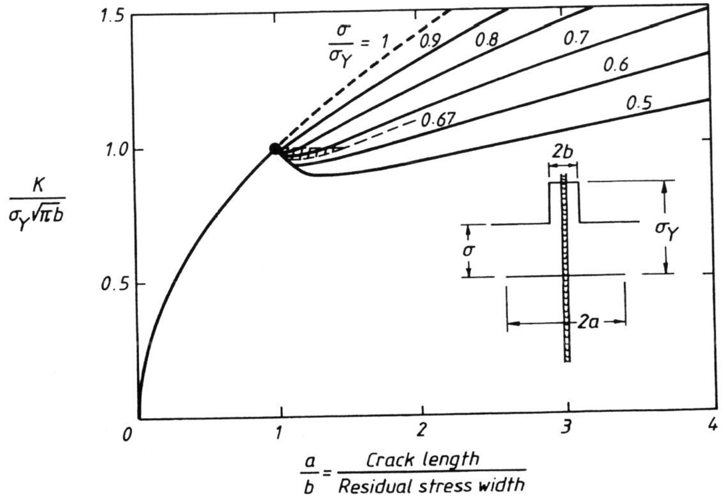

Fig. 3. Summary of crack arrest conditions for fractures influenced by residual stresses.

The full plot of equation (2) in the paper is shown in Fig. 3, from which it may be ascertained that conditions for crack arrest are still maintained at an applied stress σ with the ratio $\sigma/\sigma_Y = 2/3$ as for the design stress, provided that the arrest fracture toughness of parent metal is at least $\sigma_Y\sqrt{\pi b}$. This value may be compared in terms of δ (CTOD) with characteristic values for crack initiation as follows,

	δ		K
Crack initiation	$2\pi e_Y T$	$\longrightarrow$	$\sigma_Y\sqrt{2\pi T}$
Crack arrest	$\frac{\pi}{2} e_Y b$	$\longleftarrow$	$\sigma_Y\sqrt{\pi b}$

The reference value of CTOD for crack initiation with monotonic loading to the yield stress level has often been considered in terms of a through-thickness precrack of total length twice plate thickness T, and the value above is consistent with use at this stress level of the full value of the plastic zone crack length correction and plane stress conditions. e_Y is the elastic strain corresponding with uniaxial yield stress σ_Y. The cited value of K is the equivalent for these conditions.

Since the conditions preceding crack arrest are those of elastic unloading, the equivalent value of δ is tabulated for plane strain conditions, making use of a constraint factor of 2. It is also an appropriate value to consider for "pop-in" conditions, which are those of premature initiation quickly followed by arrest in the fracture toughness test.

T and b are independent variables, with T mainly influencing any change from plane strain to plane stress conditions. Nevertheless, b will usually exceed

T for welds in thin plates, and vice versa. There are other circumstances where residual stress considerations are unimportant, as in stress-relieved constructions, or where the conditions for crack arrest are easily established in as-welded cases, as with narrow gap welds where b<<T. It is worth noting that, under the circumstances dominated by residual stress effects, the occurrences of "pop-in" events during CTOD testing are likely to have little significance with regard to any effect that they might have in reducing the resistance to unstable fracture. However, there may be a greater significance for "pop-in" in other circumstances, dependent upon loading conditions and the required degree of fracture resistance.

These nuances deserve attention when new standards using fracture mechanics methods of fracture control are prepared for welded structures, bearing in mind the wide range of structural types and service conditions to be embraced.