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Review of Traditional Design Codes and their Relevance in Relation to Fracture [and Discussion]

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Review of traditional design codes and their relevance in relation to fracture

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A review of the traditional design codes, in the context of fracture prevention, is made by considering the requirements of British Standards relating to low temperature storage tanks and quality pressure vessels. The use by the codes of the results of wide plate testing in controlling permissible sub-zero design temperatures is discussed together with the effects of heat treatment on material toughness and residual weld stresses. An estimate is made of stress levels implied by code requirements both below and above the threshold for the onset of creep effects. The activities of manufacture, inspection and testing are considered for their contributions to fracture prevention. The general techniques of fracture assessment (two-criteria approach and the c.o.d. approach) are simplified by restricting the scope to code-designed structures, so that flaw assessment charts can be produced. The charts are used to estimate stable flaw sizes under sub-zero and ambient temperature conditions, with comment made on the elevated temperature situation. Finally, a survey is made of techniques available to assess flawed components under creep conditions, which meet the requirements of the appropriate codes. While a comprehensive methodology is not yet available, an example is given of a flawed cylinder under creep conditions that would be applicable provided that the material remained ductile.

1. Introduction

Traditional codes applicable to the heavy engineering industries cover a wide spectrum of industrial application and have evolved over many years, reflecting the advances in technology within those industries. The relevance of codes in fracture prevention may be illustrated by considering two British Standards applicable to the production of quality structures, which also require a significant volume of weld metal in the fabrication process. A standard for quality pressure vessels has been selected, British Standard 5500 (1976), since much of the fracture analysis work and material toughness testing has been related to pressure components. Thick sections and complex geometries are quite often involved, so that the control of flaws is important when welding is carried out on components that exert a high level of restraint during solidification of the weld pool. As a contrast, British Standard 4741 (1971) has been included since it covers refrigerated storage tanks for products such as propane, with a minimum temperature of −50 °C. Carbon–manganese steel plates are often used, so that the material could well operate in the transition region where toughness varies rapidly with temperature. Clearly, fast fracture could be a potentially dominant failure mode. In addition to these formal standards, use has been made of the extensive materials testing carried out for the production of North Sea offshore structures. These tubular structures include complex node geometries, which must be assessed for fracture at a design temperature of −10 °C.

Code requirements must be comprehensive in their scope of application or they will be restrictive to the industry for which they are intended. As an example, a pressure vessel code needs to cover a wide range of temperature to give adequate applicability, and typically this

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could be from below ambient to 480 °C for carbon and low alloy steels. When this temperature range is considered from a flaw stability aspect, the fracture mode extends from the transition region to the fibrous upper shelf and continues into the region of creep crack growth and void formation. The present status of fracture mechanics is such that a uniform and rational treatment of code requirements cannot be given throughout this whole range, with components under creep conditions being particularly difficult to assess. It is also to be expected that the widely used carbon and low alloy steels will require a yielding fracture mechanics approach, even at the low temperatures of the refrigerated storage tanks. In this situation the more straightforward and compact linear elastic methodology does not provide a realistic basis for relating code requirements to fracture prevention.

2. Code requirements

Design is just one of the code-related activities that contribute to the control of reliability of structures containing flaws, but total requirements must be broadly based and comprise:

(*a*) material selection and control of properties, especially those that determine toughness;

(*b*) control of stress levels appropriate to the material under load;

(*c*) requirements for fabricating techniques, especially the depositing of weld metal and post-weld heat treatment;

(*d*) inspection by appropriate non-destructive examination;

(*e*) testing the structure under load before subjecting it to service conditions.

Clearly, the final tolerance of the structure to flaws will depend largely upon the cumulative effect of all of these activities in contributing towards fracture prevention. Consideration in some detail is therefore given to the individual areas of activity.

2.1. *Charpy impact requirements*

Materials have traditionally been selected on the basis of tensile properties, suitability for welding, corrosion resistance, etc. Indeed, this still largely applies, but if fracture is a concern then the British Standards for materials permit a Charpy V requirement to be added to the material order. It is generally agreed that Charpy values do not have a direct relevance in defining critical flaw sizes, although correlations with fracture toughness are now being proposed for use under linear elastic conditions. The application of fracture mechanics to structural situations has been under intensive development for well over a decade, so that in this situation the codes have taken a direct approach and utilized experimental data as a basis for framing requirements for low-temperature structures. The wide plate testing reported by Woodley *et al.* (1964) was assessed and it was in fact found that this work could be correlated with Charpy values so that a code-orientated methodology was then available.

Cotton (1967) describes the manner in which this correlation was obtained; in outline, the wide plate tests involved tensile loading to failure of large plates containing welds which were notched by saw cuts before welding. The tensile loading induced an average mean strain of 0.5% in the plates, so that the pre-existing flaws were subject to both applied and residual stresses. A range of material thickness was tested, so that the temperature for fracture initiation was obtained for each plate thickness. In addition, the testing was carried out with the welds either in the as-welded or the heat-treated condition, so that the work can be classed as type testing of a simple welded structure.

The experimental data were then correlated with Charpy values, so that they then provided a set of criteria that could be presented as formal code requirements. Both the storage tank and pressure vessel codes being considered here have these requirements presented graphically and correlate the parameters design temperature, material thickness and Charpy requirements for both the as-welded and heat-treated conditions.

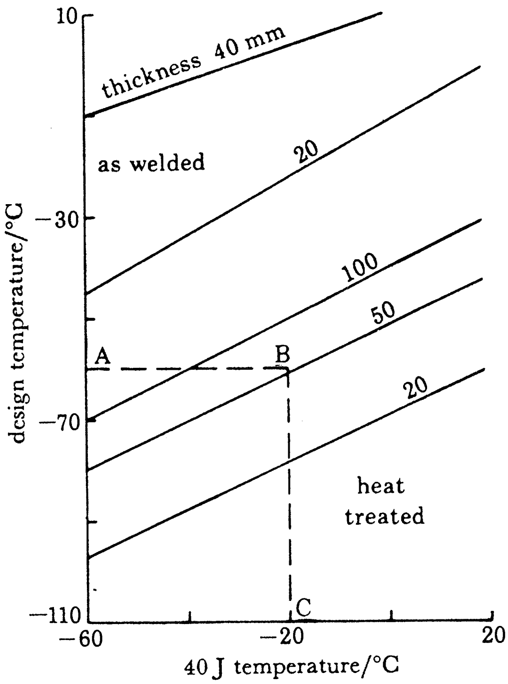

FIGURE 1. Code requirements for Charpy energy.

Figure 1 shows this presentation and is applicable to the general class of carbon and carbon–manganese steels. Path ABC represents a design temperature of −60 °C in conjunction with 50 mm plate and heat-treated welds, so that an impact value of 40 J would be required at −20 °C in the material chosen. From a visual comparison of the two families of curves, it is evident that heat treatment lowers the permissible design temperature significantly. A typical reduction of about 60 K is to be expected and this is due to the cumulative effects of improvement in material toughness and reduction in residual stress due to the heat treatment.

It would seem that a re-evaluation of the wide plate tests, concentrating on the effects of heat treatment, would be well worth while. Both linear and yielding fracture mechanics require estimates of the self-balancing residual weld stresses, and present estimates may be difficult to justify on a technical basis. Factual evidence from the wide plate testing might help to improve the application of the generalized techniques for fracture assessment, as presented by Dawes (1978) and Milne (1978).

2.2. *Limitations on stress levels*

It is well established that fabricated steel structures can safely operate at loads in excess of those that induce only elastic response, so that some material may be under post-yield conditions. The traditional design codes have always recognized this situation, but the extent by which the elastic load can be exceeded is often not apparent from the text of the design clauses. Judgement has been used by the code committees depending upon the component involved,

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and while consideration would have been given to the existence of flaws, fast fracture would not be explicitly included. The response to load of flaw-free structures is still central to code philosophy. However, code development away from the traditional set of design requirements to an approach based more on stress analysis enables estimates to be made of stress levels inherent in code designs. In the context of pressure-retaining components, code designs would have stresses below yield in the so-called membrane regions. These are regions of uniform geometry, such as a cylindrical shell, where the loading is taken by membrane action. When rapid changes in geometry occur, elastically calculated stresses will normally exceed yield. An example of these so-called discontinuity regions would be the junction between a cylindrical shell and a smaller diameter radial cylinder (nozzle).

Estimates of inherent stress levels may now be presented as

$$\text{membrane regions,} \quad \tfrac{2}{3}\sigma_{\mathrm{y}};$$

$$\text{discontinuity regions,} \quad 2\sigma_{\mathrm{y}};$$

where σ_{y} is the yield stress. It will be noted that the value of $2\sigma_{\mathrm{y}}$ is based on elastic analysis and it will be seen later that the use of elastic stresses is in fact compatible with the application of the general methods of fracture assessment.

Above the creep threshold temperature the estimation of inherent stress levels in discontinuity regions is quite complex. Stress redistribution as a function of time occurs, so that it is only in membrane regions that a reliable estimate can be given as

$$\text{membrane regions,} \quad \sigma_{\mathrm{r}}/1.3,$$

where σ_{r} is the creep rupture stress in the service lifetime. Finally, it will be appreciated that the above estimates are for load-induced stresses; residual weld stresses are considered separately.

2.3. *Manufacture*

Manufacturing activities play an important role in structural integrity and yet the framing of specific code requirements in this area is quite difficult. The code writers must consider essentially shop floor activities, but the quality of a component relies largely on skills and experience, which cannot be quantified in code phraseology. This situation is particularly pronounced for welded structures, and to obtain a low incidence of flaws requires close attention to the manual or machine welding techniques being employed. This quality approach to production welding should be supplemented by non-destructive examination and the necessary weld repairs carried out. However, as tangible evidence of production capability the codes usually require the carrying out of welder qualification tests and the production of test plates during fabrication. While it is not possible to quantify these quality-related activities in the context of fracture prevention, it is clear that they must have a significant cumulative effect on structural integrity during service.

The manufacturing activities not only influence the incidence of defects but also subject the material to a history of strain which gives a self-balancing stress system within the structure before it is subject to operational loads. In addition, material properties can be modified during fabrication. Post-weld heat treatment is a most efficient means of alleviating both these occurrences by a single operation and this has already been shown in figure 1. Codes require strict control during heat treatment and specify permissible rates of heat up and cool down. Figure 2 shows the temperature–stress–time relations diagrammatically, starting with the material in the as-welded condition. The heat-up period reduces the stress system by plasticity effects, while holding the temperature constant allows further reduction by creep relaxation. At present there is no generally applicable method of quantifying the stress history and estimates are made of probable stress levels before and after heat treatment:

as-welded, 100 % of yield stress;

heat-treated, 10 % of yield stress.

These or similar estimates may be used to obtain total stresses (residual plus applied) required for the generalized techniques of fracture assessment.

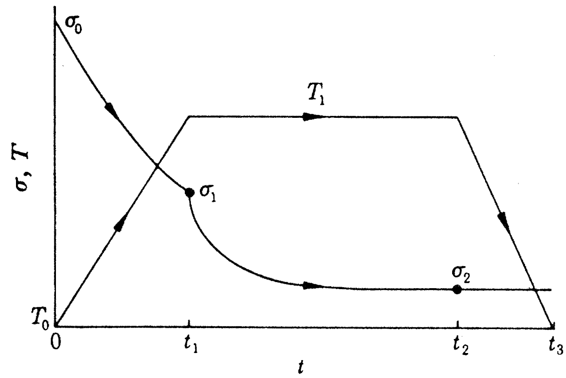

FIGURE 2. Post-weld heat treatment cycle. At time $t = 0$ the residual stress is σ_0 and the weld is at ambient temperature T_0, in the as-welded condition. At t_1 the temperature has increased to T_1 and the stress reduced to σ_1, by plasticity. Between t_1 and t_2 creep relaxation gives σ_2. Between t_2 and t_3 the temperature returns to ambient and σ_2 is the heat-treated residual stress.

The effects of heat treatment on weld metal toughness may be seen from the experimental work of Harrison *et al.* (1979). Crack opening displacement (c.o.d.) tests were carried out on weld metals suitable for the carbon manganese steel tubular structures used to support North Sea offshore production platforms. A c.o.d. of 0.12 mm at −10 °C was obtained without heat treatment. After this was done, the values ranged from 0.24 to 0.49 mm and it is interesting to note that the latter approached the parent plate c.o.d. Since this work was carried out for a specific purpose, the values are given here for illustration purposes only.

2.4. *Inspection*

The past decade or so has seen significant advances in the techniques of non-destructive examination, with particular improvement in ultrasonic testing and the interpretation of the indications obtained, which gives an evaluation of flaw position and severity. From a fracture viewpoint, the inspection capability should distinguish between voluminous and planar flaws.

Examples of this classification of weld defect are: voluminous, flaws such as isolated pores and slag inclusions; planar, flaws such as cracks, lack of fusion and root penetration. The codes take a positive approach to planar flaws found during shop inspection and when these are reported they must be excavated and weld repairs carried out. Within specified limits, voluminous flaws are permitted by code rules, but they are not considered to be potential causes of fracture and are usually assessed on the basis of reducing the section thickness and giving a weakening effect to the structure. It therefore follows that when the general methods of fracture assessment are applied to a structure it is in the context of postulated planar flaws. Such an assessment could be based on the assumption that flaws still exist either because they are smaller than the sensitivity of the technique used or have, in fact, escaped detection during examination. Another basis for postulating flaws is that if a relatively large flaw can be shown to be acceptable, then this gives some reassurance that the results of any in-service inspection are unlikely to be the cause of concern for the safety of the structure.

2.5. *Testing*

The testing of structures usually takes the form of a pre-service overload, and this has certainly been the practice for pressure components such as vessels, boilers and tanks and is an integral part of British Standards. Much debate has taken place as to the role and effectiveness of an overload pressure test in giving tangible evidence that significant flaws do not exist. Indeed, the technical merits of overload testing are still the subject of differing views which essentially revolve around the following postulate.

If a structure survives an overload test then factual evidence has been produced that any flaws present are below critical sizes appropriate to the overload test. When the reduced service loads are applied, then a safety margin on fracture exists which is available for deterioration of material properties, crack growth, etc., during the service life. Further, this structural validation has been obtained without any fracture analysis being required so that estimates of material properties have not had to be made. Finally, should structural failure occur during overload, then this is a commercial hazard and not essentially safety-related, as such an occurrence would be in service.

Clearly, this appraisal has much to recommend it but certain features give cause for concern in case too much reliance is put on the reassurance derived from a successful test. The main concern is that the test gives an unknown degree of validation. If the service loading is dominated by loading of the same nature as that employed during testing, then service and test stress distributions at any flawed area will be similar and the optimum validation will be obtained. If, however, service loads are dominated by loading not simulated during the test then the stress distributions may differ considerably, giving a situation from which rational conclusions cannot be drawn. It seems reasonable to conclude that the overload test plays an important role in code requirements related to fracture, but conclusions drawn from a successful test must consider the overload–service load relation.

3. Application of code requirements

The main activities carried out during the fabrication of a welded structure have been considered in relation to code requirements. It will be evident that material toughness and stress levels, as implied by the codes, will dominate allowable flaw sizes. In general, toughness data applicable to the range of steels involved must be inferred from the open literature or other more restricted sources, but even this indirect approach often presents its own difficulties in attempting to obtain equivalent data. Since the codes make use of Charpy data, there is an incentive to obtain toughness values from the various correlations that have been proposed between toughness and Charpy energy. Care is needed in applying such correlations, and Pisarski (1978) has reviewed the work in this area. The stress levels are easier to quantify since estimates have already been made in §2 for both residual and applied stresses. In the numerical work that follows it will be assumed that welds have been subject to heat treatment, since this generally applies to structures with heavy weldments. The code implied stress levels may therefore be stated as

$$\text{membrane regions,} \quad (\tfrac{2}{3}+\tfrac{1}{10})\sigma_y;$$

$$\text{discontinuity regions,} \quad (2+\tfrac{1}{10})\sigma_y;$$

where σ_y is the yield stress.

The general techniques for fracture assessment below the creep threshold temperature have been presented by Milne (1978) and Dawes (1978), and both are applicable under post-yield conditions. They provide the following relations, respectively:

$$K_r = S_r[(8/\pi^2)\ \ln \sec(\tfrac{1}{2}\pi S_r)]^{-\frac{1}{2}}; \tag{3.1}$$

$$\left(\frac{\bar{a}}{\delta_c}\right) = \left(\frac{1}{2\pi}\right)\frac{E}{\sigma_y}\left[\frac{1}{\sigma/\sigma_y - 0.25}\right]; \tag{3.2}$$

where K_r is the ratio linear elastic stress intensity factor to the fracture toughness and S_r is the ratio of applied load to a plastic limit load of the flawed structure. For (3.2), $\bar{a}$ is the maximum allowable value of the half length of a through-thickness flaw and δ_c is the critical c.o.d. value; E is Young's modulus and σ the total (applied plus residual) elastic stress in the vicinity of the flaw.

In §2.2 it was stated that the estimate of inherent stress levels in discontinuity regions was based on elastic analysis although post-yield conditions existed. When applying (3.1) and (3.2) the stress in the vicinity of the flaw may be taken as the elastic value provided the yielding in the zone under consideration is contained by the surrounding elastic material. Most design situations do involve contained yielding at discontinuities, but judgement must be used in this respect.

These assessment methods are usually termed the 'two-criteria approach' and the 'c.o.d. approach' and have general application beyond the confines of code requirements. Equations (3.1) and (3.2) are now recast in more restricted forms, which can be used to illustrate the severity of flaws in code structures. The code implied stress levels after heat treatment are incorporated and the material flow stress is set at $1.25\sigma_y$ with E taken as $2\times10^5\ \text{N/mm}^2$. While surface flaws could have been considered, this would require assumptions for flaw aspect ratios so that a fully penetrating geometry has been selected. In the context of pressurized components, this type of flaw represents either a 'leak' situation (flaw stability) or a 'break' situation (flaw unstable) and so relates to ultimate safety. Proceeding on this basis, (3.1) may be presented as

$$K_{Ic} = 1.5(2l)^{\frac{1}{2}}\sigma_y, \tag{3.1a}$$

where $2l$ is the stable flaw length and the relation applies to membrane regions where the flaw is under uniform tension. Consideration has been given to the use of (3.1) for discontinuity regions but this was not proceeded with since K_r and S_r depend upon the specific geometry of the discontinuity. The codes cover a wide range of entirely independent geometries so that a 'typical' approach could be very misleading. Equation (3.1a) is presented in figure 3 for a range of $(2l)$ values. The c.o.d. approach may be used in both membrane and discontinuity regions so that (3.2) gives two relations:

$$\left.\begin{aligned} &\text{membrane region,} && \delta_c = 0.82\times10^{-5}(2\bar{a})\sigma_y; \\ &\text{discontinuity region,} && \delta_c = 2.9\times10^{-5}(2\bar{a})\sigma_y; \end{aligned}\right\} \tag{3.2a}$$

where $(2\bar{a})$ is the stable flaw length. The equations (3.2*a*) are presented in figure 4 for ranges of $(2\bar{a})$ values.

3.1. *Structures below the creep threshold temperature*

For purposes of illustration, the fracture characteristics of the membrane areas of low temperature components will be considered with reference to the chart given in figure 1. Path ABC shows that a design temperature of −60 °C and 50 mm plate, with heat-treated welds, would require a Charpy energy of 40 J at −20 °C in the material chosen. Such an impact requirement could be met by C–Mn steel to specification British Standard 4360 (1979) which has been chosen since Pisarski (1978) provides an estimate of K_{Ic} over a range of temperature in the transition region for this material. At −60 °C, K_{Ic} is estimated at 3200 N/mm$^{\frac{3}{2}}$ with a yield stress of σ_y = 400 N/mm² and figure 3 gives a stable flaw size of 30 mm based on the two-criteria approach.

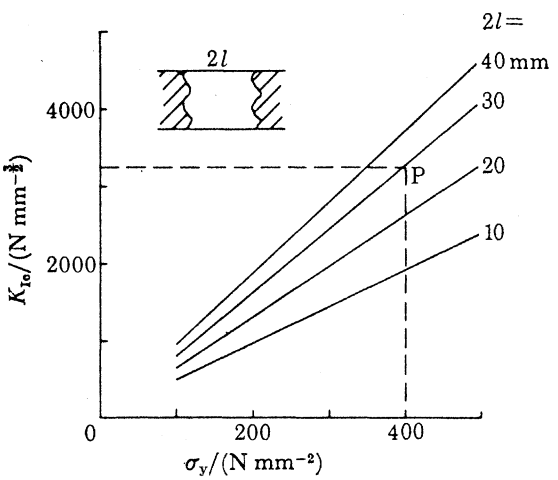

FIGURE 3. Flaw assessment by the two-criteria approach. Point P is given by C–Mn steel at −60 °C.

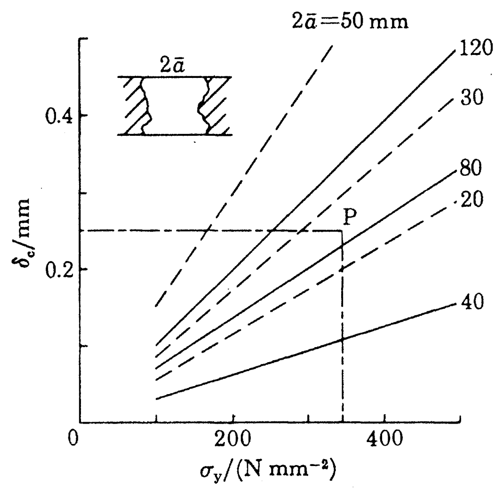

FIGURE 4. Flaw assessment by the c.o.d. approach. The full lines relate to membrane regions, the dotted lines to discontinuity regions. Point P is given by C–Mn steel at 10 °C.

Another example is provided by considering the same C–Mn material but now advancing the temperature to about 10 °C, when the toughness lies at the onset of the upper shelf and so is not too sensitive to temperature. A critical c.o.d. of 0.25 mm would be appropriate as a design value for use after heat treatment. With σ_y = 340 N/mm², figure 4 gives stable flaw sizes of 90 and 25 mm for membrane and discontinuity regions, respectively, based on the c.o.d. approach. To give adequate coverage to the range of temperature covered by the codes, consideration should now be given to flawed structures at elevated temperatures typified by pressure vessels in the process industries. However, it is not possible at present to do this in a quantitative manner, since flaw behaviour can now exhibit stable ductile extension. The significance of this on the load-carrying capacity of flawed structures at elevated temperatures must await the outcome of current work on this important aspect of flaw behaviour.

3.2. *Structures under creep conditions*

Certain British Standards, such as BS 5500, extend the scope of the requirements into the creep region. Essentially, the design rules applicable below the threshold temperature are still used, but the yield stress is replaced by the stress to rupture appropriate to the service life. Hence a time-dependent approach is used and consideration is now given to flawed structures under creep conditions, but as at elevated temperatures the technology has not yet been fully developed. Ellison & Harper (1978) have reviewed the position and emphasize that flaw behaviour depends upon three possible situations.

1. Brittle: flaw tip events govern and the stress intensity may correlate with the rate of flaw propagation.

2. Ductile: the material ahead of the flaw deteriorates with the growth of cavities associated with creep rupture. The flaw does not grow until rupture occurs at the tip with subsequent propagation through the previously damaged material.

3. Intermediate: applicable between these extremes and the parameter C^* appears to predict growth rates. The mode of failure is slow growth with the material ahead of the flaw being under creep conditions.

The ductile situation has been treated by Goodall & Chubb (1976) and the intermediate situation by Harper & Ellison (1977) so that the following relations can be presented.

Ductile:
$$P/P_L = \sigma_r/\sigma_y, \tag{3.3}$$

where P is the applied load, P_L the limit load of the flawed structure and σ_r the creep rupture stress for the service life.

Intermediate:
$$C^* = -\left(\frac{n}{n+1}\right)\left(\frac{P\dot{\Delta}}{BW}\right)\left[\frac{1}{m}\,\frac{\mathrm{d}m}{\mathrm{d}(a/W)}\right], \tag{3.4}$$

where n is the creep stress exponent, P applied load, $\dot{\Delta}$ displacement rate, m yield ratio (load for yield in flawed section to load for yield in unflawed section), a crack length, B specimen thickness, W specimen width.

It will be seen that (3.4) is presented in the context of fracture mechanics specimens, such as the compact tension specimen, and it is mainly for these geometries that the C^* parameter has been investigated.

As a final illustration, a thin cylinder containing an extended surface flaw and subject to a code-based internal pressure is shown in figure 5. The cylinder material is taken to be ductile under creep conditions and the constraint in the flaw area should be quite low so that a ductile situation exists and (3.3) may be used. Code design of such a cylinder would not of course recognize the presence of the flaw and would merely limit the plain membrane stress to $0.77\sigma_r$. The applied pressure would then be
$$P = 0.77\sigma_r(t/R)$$

and the limit pressure is
$$P_L = (1-a/t)(t/R)\sigma_y,$$

so that (3.3) requires
$$a/t = 0.23.$$

From this result it is seen that an extended surface flaw of perhaps 20 % of the thickness would be compatible with the code control of membrane stress under a creep ductile situation.

3.3. *Summary of flaw sizes*

The stable flaw sizes that have been obtained for material toughnesses in the transition and upper shelf regions are presented in figure 6*a–c*. These flaws represent stable leakage for pressure components and for comparative purposes are shown located in 50 mm plate. While the fully penetrating flaw relates to ultimate safety during operation, surface flaws are more meaningful for non-destructive examination during fabrication.

The severity of surface flaws depends on the aspect ratio and the remaining ligament beneath the flaw so that material thickness is an important parameter. An appraisal of surface flaws in relation to code requirements is clearly beyond the scope of a review paper. Figure 6*d* shows the profile of the flaw given by the example of a cylinder under creep conditions. By considering only a simple geometry, a surface flaw has been treated but with consequent loss of generality.

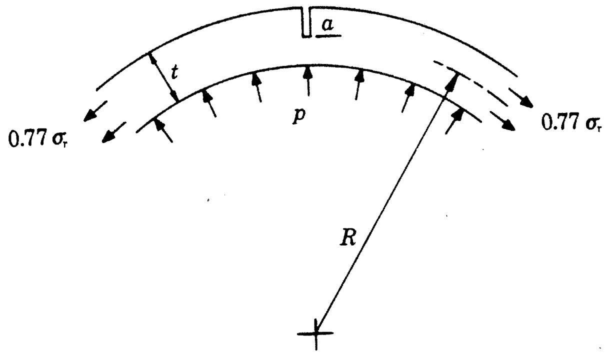

FIGURE 5. Flawed thin cylinder under creep conditions. The cylinder, radius R, thickness t, has a surface flaw depth a. Internal pressure p gives the code stress of $0.77\sigma_r$.

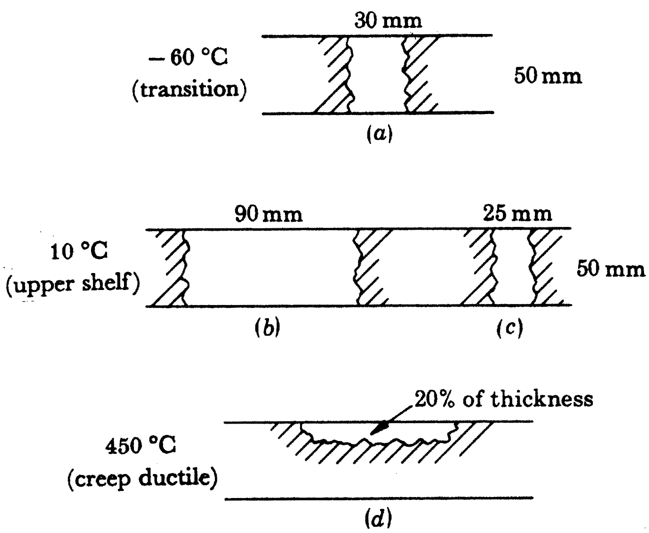

FIGURE 6. Stable flaw sizes from code requirements. The material is C–Mn steel with heat-treated welds. (*a*), (*b*) and (*d*) are based on membrane loading and (*c*) is adjacent to a structural discontinuity.

4. DISCUSSION

It is evident that the most fracture-orientated requirement contained in the British Standards that have been selected is the use of wide plate testing to control sub-zero design temperatures. When this requirement is related to the two-criteria approach in membrane areas, stable flaw sizes are quite large. A more comprehensive assessment would be well worth while since the same test results are also used in discontinuity regions. In the context of modern non-destructive examination, the flaw sizes in figure 6 seem quite massive. Since these are planar flaws, consideration of them must be compatible with the basic code philosophy, which does not permit such flaws when revealed during inspection. From this it follows that figure 6 is meaningful for flaws that have escaped detection or indeed occurred in locations not examined. The evolution of code requirements is to some extent motivated by satisfactory service experience or by a situation related to a safety hazard. However, such motivation can imply a variable and largely unknown level of reliability. For example, many code structures may well be suitable for increased loads while others may only just be adequate. The situation often only becomes manifest under safety-related events. Code evolution could be assisted if service experience were to be supplemented by application of the fracture assessment techniques to the requirements of appropriate traditional codes. It is suggested that this should be done by those responsible for the code; it would then not involve code users in the techniques.

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Discussion

Sir Hugh Ford, F.R.S. (*Imperial College, London, U.K.*). I should like to raise the question of transient thermal stresses in pressure vessels for higher pressure ranges, for example for the vessels in polyethylene plants and the like. Such vessels are subject to rapid discharge of their contents when a relief device lifts and discharges the vessel content, often at high temperatures, into thick-walled ducting. It seems to me that the standard codes do not provide adequately for the design of the side entries of the vessels for such discharges, particularly since the plants are often exposed sites with winter temperatures of −30 °C. During operation, they and the relief port ducting may be subject to temperatures of 250–300 °C or more.

Has Mr Poynor any views on the way that codes should be interpreted in this type of application? The consequences of fractures would be extremely serious.

I should also like his views about the advisability of initial pressure testing being carried out at temperatures such that the vessel steels are well above the transition.

There are also deficiencies in the standard codes – both A.S.M.E. and B.S.I. – regarding the design of the end closures and cover plates, especially where these have a number of non-central entries.

J. F. Poynor. Sir Hugh Ford's contribution raises fundamental issues in the relation between code rules and the prevention of fracture in high-pressure cylinders, subject to thermal transients in the region of the side entries during rapid discharge of the vessel contents. Since the standard codes are based on crack initiation rather than a specific fracture assessment the code philosophy can be summarized as follows.

In the region of a side entry the bulk material surrounding the entry should remain elastic during the transient and the codes would require the use of a shakedown approach, with pressure as well as thermal stresses being considered. It may well be that this requirement is in fact met by vessels for polyethylene manufacture, where autofrettage would give elastic recovery on release of pressure so that, in code terms, shakedown under pressure is ensured. With the differing patterns of stress distribution generated by pressure and thermal loadings, it is unlikely that shakedown will be violated under the combined effects, so that the bulk material will respond to load in a stable manner. With the bulk situation established, the codes would then assess the material local to the cross-bore on a basis of high strain fatigue data and the expected number of transients in the vessel life. The stabilizing constraint of the bulk material validates the use of constant strain range data. After a consideration of code interpretation on a crack initiation basis, the wider issue of fracture prevention in high-pressure equipment is of interest. The standard codes have been widely used with medium-strength steels where the yield stress would be about 300–400 N/mm^2. Such steels have high toughness, which, together with modest operating stress levels, implies quite large stable flaw sizes in the context of modern n.d.e. The code philosophy of not requiring a formal fracture assessment is therefore realistic. Thick-walled vessels for polyethylene production must use higher strength materials and, typically, Vibrac V30 ($2\frac{1}{2}$ NiCrMo alloy steel) has often been used. The yield stress would now be about 750 N/mm^2 and with increasing yield stress the toughness is reduced, so that stress intensities at flaw tips are increased by the higher stress levels and at the same time the critical value is reduced, giving quite small stable flaws. The traditional code philosophy may not now be adequate, so that a flaw assessment approach could be a vital part of rules intended for these severe applications.

Concerning the temperature of initial pressure testing, the codes suggest a minimum hydrotest temperature of 7 °C governed by the testing medium rather than material toughness aspects. However, at 7 °C most of the code materials would have a toughness located at least at the onset of the upper shelf, but it may be that some code materials could in fact be in the transition region. Since a hydrotest is a controlled load cycle with essentially constant metal temperature throughout the vessel, testing in the transition region should be an acceptable procedure. Toughness would seem to be the salient parameter and code requirements for material selection and fabrication control have given a technically acceptable situation in this respect. Considering now the high strength steels and thick walled high pressure containers, the increased stress levels and reduced toughness implies a more critical situation. It would be advisable to carry out the pressure test at a temperature giving maximum toughness with the material under upper-shelf conditions. This conservative approach may require warming of the vessel and the existence of temperature gradients. Careful temperature control would be necessary to ensure all material is in the upper shelf condition.

The design of end closures and cover plates containing several non-central penetrations involves a complex geometry somewhat beyond the scope of component design rules as presented in the codes. If these and similar complex geometries are not included as specific assemblies, then some of the latest codes (BS 5500 and A.S.M.E. III) contain general assessment criteria. To some extent the codes have moved away from a policy of providing detailed component design rules on a comprehensive basis. Code development has provided criteria based on shakedown, limit analysis and fatigue presented in a form that requires only an elastic stres analysis for these essentially inelastic modes of material loading. In this way, vessel geometry is not restricted, although the end cover assembly would require a computer analysis to obtain the distribution of elastic stresses.

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