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SINTAP

**SUB-TASK 2.1 REPORT: THE SIGNIFICANCE OF THE
YIELD STRESS/TENSILE STRESS RATIO
TO STRUCTURAL INTEGRITY**

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SUMMARY

THE SIGNIFICANCE OF THE YIELD STRESS/TENSILE STRESS RATIO TO STRUCTURAL INTEGRITY

British Steel plc

The trend towards the optimisation of the useful weight of structures has led to the use of increased strength materials. In this context high strength steels (YS >450 MPa) have a significant potential contribution which still remains largely unrealised. This is predominantly due to design code limitations, the upper allowable limit of yield stress/ultimate stress ratio being particularly severe. This report presents a review of current literature on the origins, causes and structural significance of high Y/T ratios in steels.

Treatment of Y/T in design codes, the origin of the limits and current thinking on acceptable limits are first reviewed. The reasons for higher Y/T ratios in steels and the relationships between Y/T and other parameters, principally the strain hardening exponent, are then assessed. The structural significance of Y/T is then reviewed with reference to the influence of cracks and the behaviour of high Y/T steels in buildings, bridges, pressure vessels, tubular structures and pipelines. The treatment of the Y/T ratio in assessment codes is then addressed with particular reference to R6, BSPD6493 and the engineering treatment model. As final steps, conclusions and recommendations for further work are made.

The report provides a status review on this subject and forms the basis for the direction of further work within the SINTAP project.

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THE SIGNIFICANCE OF THE YIELD STRESS/TENSILE STRESS RATIO TO STRUCTURAL INTEGRITY

British Steel plc

1. INTRODUCTION

1.1 Background

One of the principal objectives of many modern steel structures is the optimisation of useful weight by increasing the strength of the material, thereby improving the economical efficiency of the design. In addition, some types of structures can only be realised through lightweight design either due to the limitations in methods of installation, or the necessity for mobility. Despite the fact that many designers are now beginning to appreciate the advantages in using high strength steels (HSS), the full exploitation of the potential for such steels remains largely unrealised. In the current context, the term 'high strength steel' is used for steels of yield stress 450 MPa and above. A qualitative indication of the use of such steels⁽¹⁾ is shown in Fig. 1. The percentage of such HSS in use in offshore fixed steel structures has increased from 8% in 1985 to 40% in 1995⁽²⁾.

One of the principal obstacles to the increased use of HSS are the severe restrictions placed on them in design codes. Of these, the yield stress/ultimate tensile stress (Y/T) ratio limits are particularly restrictive and severely limit the advantages to be gained by using HSS. One of the principal driving forces leading to the introduction of such limits is the lack of clearly defined guidance on the influence of the Y/T ratio. Hence, quantification of the effect of Y/T ratio on structural behaviour is currently lacking leading to subsequent reduced user confidence in higher strength steels. One of the reasons for current limitations is the often wrongly perceived significance of Y/T ratio. A low Y/T ratio (typically <0.7) has been traditionally regarded as providing a safety margin against failure by plastic collapse or fracture in the post-yield area.

Improvements in production process and new developments in alloy compositions have led to a new generation of high performance HSS produced by the TMCR, AC or Q&T route. Such steels, with yield strengths up to 1000 N/mm² have Y/T ratios in the range 0.8 to 0.95, compared to 0.5 to 0.7 for conventional normalised steels. Schematic stress-strain curves of a number of different steels are shown in Fig. 2. The reason for this is that modern compositions and processing routes have had less effect on the ultimate tensile strength than on impeding the movement of dislocations which in turn governs the yield stress. Consequently, the Y/T ratio is higher for modern steels. The typical relationships between yield strength and Y/T ratio are shown in Fig. 3 from different sources^(3,4). Since a low Y/T ratio has formerly been considered as providing a high capacity for strain hardening, and a safe margin against fracture, concern has been expressed over the capacity of modern high strength grades to give reliable behaviour in service. A clear assessment of the role of Y/T ratio on the accuracy of the outcome of defect assessment procedures is therefore required in order to revive the current interest of the construction industry in HSS. A number of studies are either planned or underway which aim to clarify the situation of Y/T ratio in steel design codes. However, these do not address the treatment of Y/T ratio effects in defect assessment procedures.

1.2 Purpose of Review

The purpose of this review is to establish the current state of knowledge on the effects that the Y/T ratio has on the mechanical/fracture behaviour of steels, from the published literature. The process routes and behaviour of HSS are assessed and the relationships that exist between tensile parameters highlighted. The treatment of Y/T ratio in assessment codes is also reviewed and the limitations outlined. Finally, areas where knowledge is lacking are identified and suggestions for further work made; these will then be included in Task 2 of the SINTAP Project.

2. TREATMENT OF YIELD/TENSILE RATIO IN DESIGN CODES

In conventional structural design the working stress is usually taken as a proportion of the yield stress; typical values are 60% YS in normal loading and up to 80% in severe loading⁽⁴⁾. The Y/T ratio is largely irrelevant for such elastic cases. More recently, structures have been designed using plastic design concepts whereby the ability of the structure to yield and redistribute load without catastrophic failure is required. In such cases the post-yield behaviour of the steel assumes an increasing importance.

In engineering terms the parameter selected to idealise the ability to withstand plastic loading is the Y/T ratio. This parameter provides a basic measure of the capacity for strain hardening of the material, it is not the Y/T ratio per se which is the governing factor but it is readily measurable from information contained in a steel test certificate and can

be related to the strain hardening exponent (n), the exact relationship between Y/T , n and other tensile parameters is discussed later, suffice to say at this stage that n decreases as Y/T increases. To this end various restrictions were introduced to ensure adequate plastic deformation capacity. These include upper limits to Y/T , design stress expressed as a limit of UTS, a given % of uniform elongation and a given length of yield plateau.

The first limit on Y/T was introduced in the 1960s⁽⁵⁾ for tubular joints. The requirement was that Y/T must be less than 0.67. Although this empirical requirement is now known to be too severe and the original dataset incomplete⁽⁴⁾, it has remained the limiting value in one design code. Other codes have limiting Y/T ratios up to 0.90 as shown in Table 1. It has been recommended that all codes with maximum allowed Y/T ratios of 0.67 or 0.70 should be raised to at least 0.8⁽⁶⁾. In addition, in the design code for tubular joints, the maximum assumed capacity is taken as 0.67 UTS when $Y/T > 0.67$. In such a case a 50% increase in strength only gives an allowed increase in design capacity of 10%.

Clearly such limits are unnecessarily restrictive for many modern steels which although having high Y/T ratios can also exhibit high toughness and extensive elongation before fracture. Although the Y/T ratio is an indication it should not be used in isolation. Clearly the definition of a steel's performance solely in terms of Y/T without reference to strain hardening exponent (n) is an over simplification. In Fig. 3, a TMCR steel ($YS \approx 400 \text{ N/mm}^2$) a Q+T steel ($YS \approx 500 \text{ N/mm}^2$) and a Q+T steel ($YS \approx 800 \text{ N/mm}^2$) have similar Y/T ratios but widely differing strain hardening exponents. To treat all three steels in a similar way, as would be the case using Y/T as the parameter, would be oversimplistic. It is necessary to consider Y/T , strain hardening and elongation parameters to gain a full understanding of these steels and to treat them correctly in design codes and structural integrity assessment codes.

3. TENSILE PARAMETERS OF MODERN STRUCTURAL STEELS

3.1 General Aspects of Steel Processing

For many modern structures a reduction in dead weight is required. The steel industry has taken account of this desire for lightweight design by developing high strength weldable structural steels with minimum yield strengths up to 1000 N/mm^2 .

To achieve minimum yield strengths up to 460 N/mm^2 , use is made of alloyed and unalloyed low carbon steels. By controlling the temperature and deformation time, normalising rolled steel can be produced. The material condition achieved is equivalent to that following a normalising annealing and it is also possible to keep within the desired mechanical property values after subsequent normalising. If the final rolling takes place in a temperature range in which the austenite no longer recrystallises then it is termed thermomechanical controlled rolling (TMCR). In this case material properties are produced which cannot be achieved by heat treatment alone. TMCR attains a good combination of strength and toughness properties and thin plates with higher minimum yield strengths up to approximately 700 N/mm^2 can be produced by TMCR alloyed steels.

The effects of TMCR and normalising rolling can be intensified by means of follow-on accelerated controlled cooling. Depending upon the cooling rate and cooling stop temperature, the term used is accelerated controlled cooling or direct quenching, after which tempering can also be performed if necessary. These steels meet the highest property requirements, with minimum yield strengths up to 960 N/mm^2 possible, even when greater plate thicknesses are involved. Accelerated controlled cooling increases the yield strength without significantly impairing the toughness and this effect can be exploited in order to reduce the alloy content, i.e. with a lower carbon equivalent. The weldability, especially of thick plates, is consequently improved. For higher strengths still use is made of quenching and tempering. Tempering conditions can be adjusted to meet the required balance of strength and toughness. Yield strengths in excess of 1000 N/mm^2 can be achieved.

Figure 4 depicts the relationship between the carbon equivalent and yield strength of plates produced by the different methods⁽⁷⁾. Accelerated controlled cooling permits a carbon equivalent reduction of 0.05% compared with TMCR and at least 0.1% compared with normalising for the same strength level.

The combination of strength and toughness in modern processed steels is primarily achieved by promoting a fine grain size. In non-Q+T steels this is achieved by a fine ferrite-pearlite microstructure with, in the case of the TMCR steels, a network of dislocations, while in Q+T steels it is provided by the quenched and tempered bainitic matrix with additions of alloying elements to improve hardenability. The strain hardening exponent, n , which is typically inversely proportional to Y/T ratio, decreases with increasing levels of substitutional solutes, with decreasing grain size and with increasing volume fractions of second phase.

3.2 Relationships Between Y/T and Other Parameters

3.2.1 Choice of Parameter

Because the shape of the stress-strain curve varies for different steels, Fig. 2, several related effects may be implied from the Y/T ratio. Such properties include:

- Yield/tensile difference
- Strain hardening exponent
- The length of the yield plateau (if one exists)
- Local elongation (elongation in the necking region)
- Uniform elongation (total elongation less local elongation)
- Elongation at UTS

The reported mechanical properties for plate material are usually limited to the yield point, the ultimate tensile strength, the percentage elongation and reduction in area. This information alone provides little indication of the obtainable deformation capacity of the material in the presence of a defect. However, a careful analysis of the shape of the stress-strain curve in its plastic deformation stage may give a better estimation of such behaviour. Generally, it is found that for increasing yield strengths, both the yield point elongation and the strain hardening rate decrease. For HSS, the rate of strain hardening, n , is not constant over the full range of uniform plastic strain, its value is initially large but diminishes rapidly after a small amount of plastic straining. In these cases, two different values of n should be assigned. However, the determination of the strain hardening rate involves a relatively elaborate testing procedure and it may be more convenient to approximate its value using the all inclusive Y/T ratio⁽⁸⁾.

In addition, it is not only the shape of the stress-strain curve beyond yield which is important but also the presence or otherwise of a Lüders Plateau (yield point elongation). Yield point elongation is desirable in facilitating early relief of constraint at the crack tip and thus on the crack tip opening⁽⁹⁾. Alternatively, unless the material is truly brittle, strain hardening at the crack tip may cause remote yielding after the yield stress is reached in the cracked section. A low strain hardening rate (or a high Y/T ratio) will make it difficult to transfer part of the applied load or plastic deformation to the remote plate sections.

3.2.2 Estimates of Strain Hardening Exponent

Since the Y/T ratio is easily determined but the strain hardening rate (n) is the actual parameter determining performance, a relationship between such parameters is useful. A relationship between Y/T and n is shown in Fig. 5 for a number of normalised, TMCR and quenched and tempered structural steel plates⁽⁹⁾.

Barsom and Rolfe have derived an estimation scheme for determining the strain hardening exponent from yield stress, described in Ref. 10. The n value is determined by assuming a continuous true stress-strain curve and taking true strain at maximum load to be equal to n . The correlation is given below.

$$n = \left(\frac{103.4}{\sigma_y} \right)^{\frac{4}{3}} \quad (\text{MPa}) \quad \dots (1)$$

where the stress-strain equation is given by:

$$\frac{\epsilon}{\epsilon_0} = \frac{\sigma}{\sigma_y} + \alpha \left(\frac{\sigma}{\sigma_y} \right)^{\frac{1}{n}} \quad \epsilon > \epsilon_0 (\alpha + 1) \quad \dots (2)$$

$$\alpha = \frac{n}{\epsilon_0 \epsilon} \left(\frac{\sigma_y}{\sigma_u} \right)^{\frac{1}{n}} \quad \dots (3)$$

Denys et al⁽¹⁰⁾ have plotted data for X60 linepipe material together with other data, shown in comparison with the Barsom and Rolfe correlation in Fig. 6. It is claimed that the correlation will underestimate the length of the Lüders Plateau. The true strain at UTS under uniaxial tension is equal to $n^{(11)}$, a feature which facilitates the estimation of n . Figure 7 shows true and engineering strain at UTS v n and shows a reasonable correlation independent of whether true or engineering strain is used.

The relationships between n and YS and n and UTS have been investigated for a number of strengthening mechanisms⁽¹²⁾, Figs. 8(a-b). The relationship is given by:

$$nS^p = C \quad \dots (4)$$

where S is yield stress or UTS and P and C are constants depending on strengthening mechanism and strength parameter as shown in Table 2. For grain refined and solid solution strengthened steels the derived relationship between n and YS is as shown in Fig. 9. The constants in Table 2 show that for a given strength level solid solution strengthening gives the most ductile steels followed by grain refining, precipitation strengthening, partial annealing and cold working. The correlation coefficients are higher for YS than for UTS in all cases.

In deriving relationships between Y/T and n it is noted in Ref. 13 that for a given steel composition Y/T is a function of n but YS and n are independent of carbon content up to ~0.15% whereas UTS is strongly influenced by carbon. The consequence is that Y/T and n have different relationships for different carbon levels and strengthening mechanism as noted in Ref. 13. A good relationship was obtained between n and LYS for steels with carbon content up to 0.13%, Fig. 10⁽¹³⁾.

Some suggest that the choice of n as parameter for determining strain hardening is inappropriate⁽¹¹⁾. For two materials with $d\sigma/d\varepsilon$ the same but with different yield strengths the calculated value of n will be higher for the lower yield stress material, Fig. 11. The ratio $d\sigma/d\varepsilon$, plotted as a function of the strain, Fig. 12, shows a family of curves which lie on a very similar line despite the fact that n varies from 0.05 to 0.26. The exponent n actually corresponds to the true strain at UTS, ε_u . Since increasing strength gives lower ε_u values it follows that n will also decrease.

A parameter also often used is N where:

$$N = \frac{1}{n} \quad \dots (5)$$

N is used particularly in fracture mechanics, in the small scale yielding regime the contour and size of the plastic zone can be determined as a function of N while in large scale yielding the relationship between J-integral and CTOD depends not only on geometry but also on N. However, N depends on the shape of the stress-strain curve and the yield stress. Figure 13(a) shows σ - ε curves for a number of steels with N between 3.6 and 13.5 according to the Ramberg-Osgood law. The parameter $d\sigma/d\varepsilon$ is nearly the same for all these steels. However, varying N but with constant yield stress produces a very different set of curves, Fig. 13(b). Hence, in Fig. 13(a) the difference in N is due largely to the difference in yield stress of the steels whereas in Fig. 13(b) the difference in the N values is due solely to the shape of the curves beyond yield. The two factors must be separated if the real material post-yield behaviour is to be quantified.

3.2.3 Relationship Between Y/T and Other Parameters

Some have questioned whether structural behaviour can be better viewed in terms of yield/tensile difference rather than Y/T⁽¹⁴⁾. As well as Y/T, the elongation capacity of steel is an important factor. This generally decreases as tensile strength increases although such generalisations do not take account of the fact that modern steels with mixed microstructures can give higher elongation values for a given tensile strength. The rotation capacity of beam-column connections, expressed as the plastic length fraction, was determined for a number of joints made in steels of varying tensile properties. The results are shown in Fig. 14, demonstrating that while Y/T difference can be used, Y/T is a more fundamental and continuous variable.

Separation of the total elongation in the tensile test into local elongation (in the region that necks) and uniform elongation (in the remainder of the specimen) has also been used to investigate sensitivity to Y/T of 1970's steels⁽¹⁵⁾. The data are shown in Fig. 15 together with more recent data for modern steels in the YS range 450-700 MPa. Clearly the 1970's data show that older steels

had a lower elongation for a given Y/T value and that modern steels cannot be described by this data set.

3.3 Influence of Microstructure on Y/T

The behaviour of modern steels is different to their older counterparts due to the processing and alloying developments which have led to microstructural changes. Such features include:

- Overall cleaner chemistry (reduced CEV)
- Finer grain size
- Reduced proportion of second phase

For steels showing only one line of single gradient in the $\log \sigma - \log \epsilon$ plot, the value of n has been found to be empirically related to grain size⁽¹⁶⁾, Fig. 16, and independent of carbon content.

$$n = \frac{5}{10 + d^{-\frac{1}{2}}} \quad (d \text{ in } \mu\text{m}) \quad \dots (6)$$

There is a rapid reduction in n for d less than 10 μm . The strength coefficient in the expression

$$\sigma = K\epsilon^n \quad \dots (7)$$

is strongly influenced by carbon content and grain size, but insufficient data exist for the grain size correlation. However, the general relationship linking K to grain size has been expressed as

$$K = A + Bd^{-\frac{1}{2}} \quad \dots (8)$$

where A and B are constants for a particular steel. K is linearly dependent on carbon content, the ratio Y/T increases as grain size decreases since grain size has a much larger influence on the yield stress than the UTS.

4. STRUCTURAL SIGNIFICANCE OF YIELD/TENSILE RATIO

4.1 Influence of Cracks

The influence of the strain hardening exponent (n) on fracture propagation depends on the fracture mode. Generally, the energy required for ductile fracture increases with increasing n ⁽¹⁷⁾. At temperatures where the material is relatively ductile and the development of a critical strain is required for fracture, high strain hardening increases the energy required to produce failure. In the transition regime and below, however, a critical stress law is valid and a low rate of work hardening may enhance the resistance to crack propagation⁽¹³⁾.

The Y/T ratio and n values also affect the spread of yielding in tension loaded plates⁽⁶⁾. The presence of cracks modifies the shape of the stress-strain curve such that interactions between applied stress, crack depth and n dictate the plate behaviour. For deep cracks the strain hardening may not be sufficient to enable gross section yielding, leading to confinement of yielding to the cracked section and in the presence of a macroscopic crack, the shape of the stress-strain curve will be modified. During plastic deformation a reduction in both the yield point elongation and the strain hardening rate will occur, while for long cracks the yield point elongation can be completely suppressed. The stress-strain response will gradually change with increasing crack size.

For a material with little or no distinct yield point elongation and which strain hardens only, the spread of yield occurs essentially as symmetrical zones in a direction of about 45° to the tensile axis on either side of the crack axis. The direction of these yielding bands is dependent on the material's strain hardening response and the length of the crack. For a material of high initial strain hardening (or with a low Y/T ratio) the orientation of the yielded zones will effectively approach the direction of 45° to the tensile axis, whereas a low strain hardening rate (or a high Y/T ratio) will produce plastic zones which have an orientation closer to the crack axis.

Relationships between crack opening and strain in cracked plates for a material with high work hardening and a yield plateau and a material with low work hardening and no yield plateau are shown in Fig. 17⁽¹⁸⁾. Experimental work confirms the trend, demonstrating that higher crack opening at a given strain will result from a material of low work hardening rate.

4.2 Buildings and Bridges

4.2.1 General Trend

The use of higher strength steels in buildings and bridges is only advantageous when the design is not deflection-limited (since the stiffness and hence deflection of steel is relatively independent of yield strength). The main driver is the move towards taller buildings and longer span bridges. Y/T is important in such structures when:

- (i) Plastic design is used
- (ii) The ability to yield when the ultimate limit state is approached
- (iii) The structure must be earthquake resistant

Most of the recent work addressing the structural significance of Y/T ratio in bridges and buildings has been in Japan largely due to the necessity to withstand severe earthquakes. Such conditions require typically connection rotation capacities of seven times that required at yield moment, while general plastic design for bridges and buildings in the USA requires a capacity of three.

4.2.2 Bending Members

Studies on bending members⁽¹⁹⁾ indicate that the rotation capacity tends to decrease with increasing yield/tensile ratio, and that it can affect the final failure mode. However, all applications do not require the same level of rotation capacity, and it is not necessary to maximise the rotation capacity for each one. If required levels are established, analytical and experimental studies can determine the maximum yield/tensile ratio that would provide that capacity. Also the mode of failure can be controlled. For example, flange width-to-thickness ratios and web depth-to-thickness ratios can be selected that will allow a member to reach its required strength and rotation level, but that will ensure plastic local buckling before reaching the strain required for tension flange rupture.

4.2.3 Compression Members

Available data on columns⁽²⁰⁾ suggests that, provided the stress-strain curve is not overly rounded, the strength of columns with yield/tensile ratios up to about 0.95 can be reasonably predicted with the present relationships that are used for other steels. The same conclusion holds for local buckling strength for stresses up to the yield point. However, if a short compression member of given proportions is compressed beyond the yield point level, the maximum average stress that can be reached in proportion to its yield strength, tends to increase with decreasing yield/tensile ratios of the steel. However, if such post-yield behaviour is needed, it can be realised by decreasing width-to-thickness ratios of flange and web elements.

4.2.4 Tension Members

For bolted tension members, if it is required that gross section yielding controls failure rather than net section rupture, greater yield/tensile ratios require greater ratios of net-to-gross section area. However, most specifications do not require that gross section yielding control the design. For bolted members of the same geometry and bolt pattern the Y/T ratio determines if yielding in the gross area occurs before fracture of the net area⁽²¹⁾. In addition, the bolt holes cause stress concentrations leading to early yielding. High Y/T ratio steels usually reach yield load when uniformly stressed but may fail to do so in the presence of a hole. Figure 19 shows the effect of Y/T on achievable elongation in a 500 mm long, 80 mm tension member with a 22 mm diameter hole, clearly showing a reduced elongation for increasing Y/T ratio⁽¹⁹⁾. Results for tapered members⁽¹⁹⁾, Fig. 20, show a rapidly reducing elongation capacity for Y/T ≥ 0.85 , although increasing ratio of net width:gross width for a tapered member gives reduced plastic capacity regardless of Y/T ratio⁽²¹⁾, Fig. 21.

4.2.5 Industry Experience

The required deformation capability depends on the application. Cold formed structural members fabricated from steels with yield/tensile ratios up to 0.93 have been used successfully for many years. Indeed, members with yield/tensile ratios up to 1.00 have performed adequately in tests and have been used for a limited range of applications⁽²²⁾.

The high strength structural steel, A514, has performed well in bridge and building applications, even though the yield/tensile ratio based on measured properties range up to 0.93 or 0.95. Thus, provided a reasonable level of total

ductility is maintained, steels with yield/tensile ratios up to about that level can be effectively used in most design applications⁽²²⁾.

For more demanding applications such as seismic design, lower yield/tensile ratios would be desirable. Japanese steels developed for seismic applications have a minimum yield/tensile ratio of 0.80 for yield strengths from 50 to 65 ksi, and 0.85 for a 100 ksi yield strength steel. However, studies have not specifically shown that such ratios are the highest values that might be acceptable for the application.

4.3 Pressure Vessels

The effects of strain hardening and yield/tensile ratio on the burst strength of pressure vessels has been studied⁽²³⁾. This was aimed at more effective utilisation of the yield strength of high strength steels. Based on plastic instability the following equation was derived for cylindrical vessels.

$$P_B = \sigma_u F \ln W \quad \dots (9)$$

where

- P_B = burst pressure
- σ_u = UTS
- F = correction factor
- W = OD/ID

F is given by

$$F = \left(\frac{0.25}{n+0.227} \right) \left(\frac{e}{n} \right)^n \quad \dots (10)$$

where n = strain hardening exponent and e is the log base ($n = \epsilon_{UTS}$ as shown previously).

Figure 22 shows the factor F for cylindrical and spherical vessels as a function of n . The burst pressure decreases as ϵ_{UTS} , and therefore n , increase. Higher strength steels therefore tend to burst at a higher proportion of their tensile strength than lower strength steels. The trend has also been experimentally confirmed. One feature also pointed out is that plastic strain concentration at sharp geometries is higher in a low work hardening steel than a high work hardening one. More attention must therefore be paid to geometrical effects in higher strength steels.

4.4 Tubular Joints

Multiplanar tubular joints are frequently used in tubular structures such as offshore jackets, towers and long span roofs. The effect of Y/T ratio on the static strength of tubular joints is complicated by geometrical factors such as plane of bending, joint type (K, cruciform etc.) and ratio of chord to brace inner and outer diameters. For K-joints loaded by the chord, increasing Y/T from 0.55 to 0.91 gave a 20% reduction in load capacity⁽²⁴⁾ (normalised for yield stress differences), Fig. 23. Finite element studies of capacities of X-joints with five assumed material stress-strain laws⁽³⁾, has demonstrated a number of features as shown in Table 3. In particular, for a constant yield stress of 350 MPa, decreasing the Y/T ratio from 1.0 to 0.66 enhanced the ultimate joint capacity by only 6%. A similar analysis with 450 MPa yield stress shows only a 1% capacity enhancement. The joint capacity was also found not to increase linearly with yield stress since geometrical factors contribute to the overall behaviour. However, where a yield plateau precedes strain hardening, the capacity is 7% less than that associated with continuous yielding. Both yield stress and Y/T need to be considered in assessing theoretical capacities of tubular joints. However, tentative guidance is suggested in Ref. 3 that a restriction to $Y/T \leq 0.85$ would still be safe based on FE and experimental work. A value of 0.8 is quoted elsewhere⁽⁶⁾.

4.5 Pipelines

Welded pipelines are one of the few structures which are subjected to plastic strains during their installation, for example laying of sub-sea pipelines (design strain $\approx 0.8\%$) or soil movement in onshore pipelines (design strain $\approx 0.5\%$). The post-yield fracture behaviour of the steel is therefore particularly important in linepipe steels.

Deformation capacity of linepipe without defects shows a steadily decreasing circumferential failure strain as Y/T increases⁽²⁵⁾, although even at $Y/T = 0.95$ the minimum failure strain is still $\sim 2\%$. In the presence of defects, pressure bearing capacity reduces slightly with Y/T up to 0.91, Fig. 24(a) and (b), although the reduction is not significant.

Generally, work on cracked pipe body specimens has shown the following:

- The effect of increasing defect depth on tolerable defect length is more significant than the increase in Y/T ratio from 0.80 to 0.90.
- The tolerable defect length for deep defects (above 40% thickness) is relatively little influenced by the Y/T ratio between 0.85 and 0.95.
- The tolerable defect length for shallow defects (20% thickness) reduces significantly (by 50%) from $Y/T = 0.90$ to 0.95.

Overall, there is therefore little influence of Y/T on defect tolerance in pipelines up to a value of about 0.90.

5. TREATMENT OF YIELD/TENSILE RATIO IN ASSESSMENT CODES

5.1 Failure Assessment Diagram (FAD) Approaches

5.1.1 General

The yield/tensile ratio affects the FAD in a number of ways:

- Shape of FAD
- Cut-off level of the FAD
- Definition of flow stress of the material

There are four generic FADs in use at present within the framework of R6⁽²⁶⁾ and BSPD6493⁽²⁷⁾. These are shown in Fig. 25 and are collectively:

- An inherently conservative FAD for use in preliminary screening analyses, Fig. 25(a).
- A generalised FAD, based on either yield stress or flow stress, but not accounting for work hardening, Fig. 25(b).
- A generalised FAD, based on yield stress, and allowing for work hardening, Fig. 25(c).
- A material specific FAD, based on the material's stress-strain response, Fig. 25(d).

Revisions to both R6 and PD6493 have led to the definition of appropriate FADs as detailed in Table 4. The influence of Y/T ratio on these FADs is discussed in more detail below.

5.1.2 R6 Failure Assessment Diagrams

R6 Rev3 option 1 (generalised) and option 2 (material specific) FADs are shown in Fig. 25(b) and (c) respectively. A comparison of the two FAD types has been made previously⁽²⁸⁾ where stress-strain curves of a range of materials, Fig. 26(a), were used to derive option 2 FADs. These option 2 FADs are shown in comparison to the option 1 FAD in Fig. 26(b). Care is suggested when using option 1 for materials demonstrating a yield plateau, since for such materials option 2 predicts a sharp drop in the FAD at $L_R \approx 1$. It is claimed⁽²⁸⁾ that this is only a realistic description of the tension case. However, pre-cracked specimens in tension do not tend to show yield points and Lüders plateaux irrespective of the presence or otherwise of such features in the stress-strain curve of the conventional tensile test. The practical significance of the yield plateau in real structures therefore needs to be addressed.

The Rev3 FADs differ from the Rev2 through the adoption of a plastic collapse parameter based on σ_y rather than σ_F , giving respectively L_R and S_R plastic collapse parameters. The Rev2 curve is similar to the Rev3 option 2 curve when elastic-perfectly plastic behaviour ($\sigma_i/\sigma_y = 1$) is demonstrated. Curves corresponding to varying levels of σ_i/σ_y can be plotted as Rev3 curves on Rev2 axes and vice versa, Fig. 27. When strain hardening capacity is low, assumed to be the case as $\bar{\sigma}/\sigma_y \doteq 1.0$, there is little difference between the Rev2 and Rev3 curves.

5.1.3 BSPD6493 Failure Assessment Diagrams

Revisions to BSPD6493 are ongoing and have resulted in reclassification of the FADs as described in Table 4. The following discussion relates to the draft version of BSPD6493, 1996⁽²⁹⁾. The principal influence of Y/T ratio is on the selection of FAD at level 2 and the definition of L_R cut-off.

For the generalised FADs, material of 'low work hardening', defined as $\frac{\sigma_f}{\sigma_y} \leq 1.2$, should be assessed using the level 2 option 1 FAD, Fig.25(b), where:

$$\sqrt{\delta_r} \text{ or } k_r = \frac{\sigma_y}{\sigma_f} L_r \left(\frac{8}{0.2} \ln \sec \left(\frac{\pi \sigma_y}{2 \sigma_f} L_r \right) \right)^{-0.5} \quad \dots (11)$$

This is equivalent to the PD6493 1991 level 2 method. Materials with $\sigma_f > 1.2 \sigma_y$ may also be assessed but with σ_f limited to $1.2 \sigma_y$. Rearranging the formula gives the value of Y/T at which the definition of flow stress changes to be 0.71. Furthermore, if the material exhibits a yield plateau an L_R cut-off of 1.0 is applied meaning that plastic collapse is predicted for stresses above yield. This point needs further considerations since metallurgical factors favouring high work hardening rates, deemed advantageous in many respects, also favour the formation of yield plateaux. In addition, yield plateaux in real structures may often not occur, or their length is reduced, when a crack is present. In fact, wide plate tests on steels with and without yield plateaux⁽¹⁸⁾ show that those with tend to show a plateau in the CTOD-strain behaviour such that crack opening is shielded due to deformation being concentrated in the plastic straining of the plate. This is advantageous in minimising the crack opening.

The FAD for high work hardening materials, Fig. 25(c), is recommended for materials where $\frac{\sigma_f}{\sigma_y} > 1.2$, or when Y/T > 0.71. The equation is:

$$\sqrt{\delta_r} \text{ or } K_r = [1 - 0.14 L_r^2] [0.3 + 0.7 \exp(-0.65 L_r^6)] \quad \dots (12)$$

The curve can also be used for low work hardening materials but will provide a lower bound. The L_r cut-off, L_r^{max}, is given by

$$L_r^{\max} = \frac{\sigma_f}{\sigma_y} \quad \dots (13)$$

The material specific FAD, applicable to all materials, is given by:

$$\sqrt{\delta_r} \text{ or } K_r = \left(\frac{E \epsilon_{ref}}{L_r \sigma_y} + \frac{L_r^3 \sigma_y}{2 E \epsilon_{ref}} \right)^{-\frac{1}{2}} \quad \dots (14)$$

where L_r^{max} is as per Equation (13) and ϵ_{ref} is true strain at a true stress of L_r σ_y .

The L_R cut-offs and the selection of FAD is based on the Y/T ratio indirectly. This is a simplification since previous data has shown that for Y/T increasing from 0.86 to 0.91 the strain hardening exponent can decrease by a factor of 4. Linking of Y/T with n for different steel classes should clarify such relationships.

The derivation of crack driving force curves using the level 2 option 1 method enables prediction of the relationship between applied stress and resulting crack driving force parameter (K or

CTOD). Such predictions can be used to assess structural or wide plate behaviour or to assess the influence of parameters such as residual stress. Such curves tend to overpredict the crack opening for a given applied stress, which is expected since the method is conservative.

However, a stress-based curve reaches its limit of applicability at stresses $\approx \sigma_y$. This is because the level 2 approach predicts failure by plastic collapse when $S_R > 1.0$ such that the required CTOD to prevent failure tends to infinity. A strain based approach provides more information on the behaviour of wide plates and structures since these behave as approximately elastic-perfectly plastic materials with a level stress-strain curve after yield which gives an increasing CTOD for a constant level of stress. With reference to pipelines, PD6493 has been criticised⁽¹⁰⁾ because it cannot readily estimate straining capacity which is being used increasingly in pipelines and other structures; strain-based plastic collapse solutions would help overcome such limitations.

A further influence of Y/T in PD6493 is at level 3 where the relationship between σ_I and K_I is dependent on constraint and work hardening. Guidance is given on correction factors for 'low' and 'high' work hardening although the definitions of low and high are ambiguous.

5.2 The Engineering Treatment Model

The Engineering Treatment Model (ETM) developed by GKSS⁽³⁰⁾ can be used for estimating the CTOD, J-integral, load line displacement and limit load of flawed structures. It is particularly applicable for the determination of crack driving force curves. It is divided into two parts, calculations for contained yielding and predictions for the fully plastic state. The first part is applicable between $0.5 \leq F/F_y \leq 1$ and the second part is applicable between $1 < F/F_y \leq UTS/Y_S$. F_y is the yield load which for tension is taken as the load corresponding to $0.9 \sigma_y$.

In the contained yielding state the CTOD is calculated by:

$$\delta = \frac{K_p^2}{EYS} \quad \dots (15)$$

where δ is CTOD (or δ_s) and K_p the stress intensity corrected for plasticity.

For the fully plastic state the ETM formulation is:

$$\frac{\sigma}{\sigma_y} = \left(\frac{F}{F_y} \right)^{\frac{1}{n}} = \left(\frac{J}{J_y} \right)^{\frac{1}{n+1}} = \frac{\epsilon}{\epsilon_y} \quad \dots (16)$$

This formulation is shown in Fig. 28.

Hence, the ratio of instantaneous value to yield value of CTOD, load, J-integral and true strain are related through the strain hardening exponent, n . The strain hardening exponent in the ETM is determined from a log-log plot of the yield point (0.2% PS) and the ultimate tensile stress. The slope of the straight line through the points $(\sigma_{0.2\%}, \epsilon_{0.2\%})$ and $(\sigma_{UTS}, \epsilon_{UTS})$ gives the strain hardening exponent, n . It is noted however⁽³⁰⁾ that this formulation only gives good approximations for power law hardening materials. It is suggested that work is needed to assess the influence of ETM defined n , as opposed to conventional n , on the accuracy of predictions. This is planned within SINTAP.

The ETM is similar to the EPRI handbook in that use is made of a reference point (σ_y, ϵ_y) or (F_y, ϵ_i) up to which elastic solutions apply and beyond which values are obtained by extrapolation into the fully plastic regime by a magnification factor related to the strain-hardening exponent.

5.3 Influence of Y/T on Crack Driving Force Predictions

Both BSPD6493 and the ETM can be used to assess the predicted influence of Y/T on the crack opening response of tensile panels. Figure 29 shows the results of PD6493 level 2 analyses for a constant geometry cracked plate in tension in a material of constant UTS but varying yield stress and therefore varying Y/T. The stress axis is normalised by dividing by yield stress. The effect of Y/T varying in the range 0.5 to 0.8 is less significant than in the range 0.8 to 0.9. At a Y/T of 0.8 the predicted crack opening tends to ∞ at a normalised stress of 0.95 whereas for a Y/T of 0.9 this occurs at a normalised stress of 0.83.

An analysis for the same geometry made with the ETM is shown in Fig. 30 for a constant yield stress but n_{ETM} varying between 0.05 and 0.30. Particularly notable features are the fact that wide plate CTOD is only predicted to increase rapidly once significantly above yield stress and the fact that n varying from 0.2 to 0.3 has little influence on predicted driving force curves. These factors are to be further investigated within the project and compared with real data for parent plates in the yield strength range 275 to 800 MPa.

6. CONCLUSIONS

The significance of the yield/ultimate tensile strength (Y/T) ratio on the fracture behaviour of steels has been investigated by means of a literature review. The principal areas assessed are the origins of the concern over Y/T ratio, the interrelationships between tensile parameters, the structural significance of the Y/T ratio and its treatment in assessment codes. The main conclusions are as follows:

1. Limits to the Y/T ratio were introduced into design codes based on the behaviour of 'first-generation' high strength steels and the notion that a high Y/T value equates to poor fracture performance. Modern steels give higher elongation values for a given strength level and Y/T ratio and the initial concern is of low relevance to modern steels.
2. Modern steels produced via controlled rolling or quenching and tempering generally have Y/T in the ratio 0.8-0.95 compared to 0.65-0.75 for normalised steels. A high Y/T ratio is generally associated with a low work hardening rate, n ; the relationship is however neither linear nor consistent.
3. Current design code limits for Y/T vary between 0.67 and 0.90. There is general agreement that values of up to 0.85 are satisfactory in conventional structural applications and values up to 0.95 in specific cases. However, these limits have not yet found their way into design codes.
4. Of the various parameters applicable to the post-yield regime, the yield tensile ratio, strain hardening exponent, local elongation (Lüders strain) and strain at UTS are the most relevant parameters for structural integrity assessments.
5. Numerous estimates of n are available; most rely on the assumption that $f(\sigma_y, n) = \text{constant}$. Such correlations are promising, particularly when different constants are used for different strengthening mechanisms. Furthermore, the strain at UTS appears to give a reasonable estimate of n .
6. The presence of cracks modifies the shape of the stress-strain curve; crack depth and n dictate the extent of this. The yield point may be suppressed and a Lüders band not obtained. The latter effect can however be observed in the CTOD-strain response where a plateau of CTOD can be achieved beyond yield in steels showing a Lüders plateau in the conventional tensile test.
7. The significance of Y/T in buildings and bridges is only relevant for cases of earthquake resistance in the former and plastic design in both structures. Design rotation capacities (maximum rotation/yield rotation) of connections are typically 3 for general plastic design and 7 for severe earthquake design. The rotation capacity tends to decrease with increasing Y/T ratio although geometry and thickness also have a major influence.
8. For tension members gross section yielding rather than net section fracture is the preferred failure mode. Achievable elongation in the presence of holes such as bolt holes is very sensitive to Y/T. For

tapered members, strong sensitivity is only noted above Y/T at ~ 0.85 . However, industry experience suggests steels with values of Y/T up to 0.95 can be used without problem.

9. In the case of pressure vessels, burst pressure has been found experimentally to increase with decreasing strain hardening exponent.
10. For tubular joints, decreasing Y/T from 1.0 to 0.66 at constant yield stress has been found to enhance the ultimate joint capacity by only 6%. Tentative guidance suggests an upper limit of Y/T of 0.85.
11. Work on defect-containing pipelines has demonstrated that the effect of increasing defect depth on tolerable defect length is more significant than increasing Y/T . For deep defects there is little influence of Y/T once above 0.85. For shallow defects there is significant influence once above Y/T of 0.90.
12. A number of FADs are currently available which incorporate the Y/T effect indirectly through limits on flow stress definition. Others are generated using actual stress-strain data. Both the shape of the FAD and the plastic collapse parameter cut-off depend on the Y/T ratio. Industry experience with these methods is wide but the influence of high Y/T steels on the suitability of the FAD parameters needs assessing.
13. The Engineering Treatment Model (ETM) incorporates an estimated strain hardening parameter in its approach. The method therefore predicts different behaviour for steels with the same yield strength but varying n . The method is of significant interest in its ability to characterise behaviour of steels with varying Y/T ratios and n values.
14. Crack driving force curves based on BSPD6493 suggest relatively little influence of the effect of Y/T in the range 0.5-0.8 but a significant influence above this level. Similar curves based on the ETM show a systematic effects of n at all levels.

7. FUTUREWORK

Future work on the subject of yield/tensile ratio within the SINTAP project should concentrate on the following aspects:

1. Establish relationships between yield strength, Y/T, strain at UTS, n , composition and steel type to enable more accurate predictions of the relevant post yield tensile parameters.
2. Examine the relationship between conventionally defined n and the ETM-defined n and establish the significance of this on predictions.
3. Examine the significance of the yield plateau on behaviour of steels containing cracks.
4. Assess the interrelationship between crack depth and significance of Y/T.
5. Determine the influence of Y/T on the shape and cut-off limits of FADs and assess the accuracy of predicted crack driving force curves through comparison with the results from wide plate tests on different steels (parent plate).
6. Assess the potential of a strain-based FAD, methods of deriving such an FAD and how it compares with actual wide plate data.
7. Assess the abilities of PD6493 levels 2 and 3 and the ETM to predict the crack driving force curves of parent plate wide plate tests.
8. Link with Task 1 to assess the influence of Y/T in welded joints and the effect on the significance of mis-match.

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TABLE 1
LIMITS TO Y/T RATIO IN ACCORDANCE WITH VARIOUS DESIGN CODES

Code	Limitation YS as Proportion of UTS	Application
API RP2A (Pipeline)	0.67	Tubular joints
HSE Guidance Notes (Offshore)	0.70	Tubular joints
BS 5950 (Buildings)	0.84	All components
NS 3472 (NPD) (Offshore)	0.83	All components
EC3 (Buildings + Bridges)	0.92	All components ($E_{UTS} \geq 15 E_{cy}$)
DnV (Offshore)	0.85 0.75	Except tubular joints Tubular joints ($\sigma_y > 500 \text{ N/mm}^2$)
AISC (Buildings)	0.90	Grade 50 ksi beams
Dutch Rules for oil and gas pipelines (Pipelines)	0.85 0.75	Acceptance Strength calculations
BS 5400 Pt 3 Draft (Bridges)	0.74 0.83	All steels $\sigma_y < 390 \text{ N/mm}^2$ All steels $\sigma_y > 390 \text{ N/mm}^2$

TABLE 2
PARAMETERS FOR PREDICTION OF STRAIN HARDENING EXPONENT
FROM STRENGTH AND STEEL TYPE⁽²⁾

Steel Type	Strength Parameter			
	S = YS		S = UTS	
	P	C	P	C
Solution hardened	0.31	1.41	0.33	7.75
Grain refined	0.57	6.13	0.66	11.9
Precipitation hardened	0.90	39.8	1.15	284
Partially annealed	1.38	484	7.72	4743
Cold worked	4.77	2.66×10^{10}	23.4	∞

TABLE 3
PREDICTED RELATIVE LOAD CAPACITIES OF
CRUCIFORM JOINTS WITH RESPECT TO σ_y/UTS RATIOS⁽³⁾

σ_y (MPa)	UTS (MPa)	σ_y/UTS	Comments	Relative FE Load Capacity	Relative σ_y
350	350	1.0	Elastic-perfect plastic at baseline yield stress	0.945	1.0
350	525	0.66	Typical offshore structure steel with yield plateau	1.000	1.0
491	525	0.90	Higher strength steel ratio with yield plateau	1.276	1.4
491	491	1.0	Elastic-perfect plastic at higher yield stress	1.260	1.4
350	525	0.66	Typical structural steel with continuous yielding characteristics	1.066	1.0

TABLE 4
FAILURE ASSESSMENT DIAGRAMS: CURRENT STATUS AND NOMENCLATURE

Code	Figure Number and FAD Type				
	Fig. 25(a) Screening Level	Fig. 25(b) Generic FAD (Low Work Hardening)	Fig. 25(c) Generic FAD (High Work Hardening)	Fig. 25(d) Material Specific FAD	Full Tearing Analysis
R6	-	Rev 2 (S ₀ based)	Rev 3, Option 1	Rev 3, Option 2	Rev 3, Option 3
PD6493 1991	Level 1	Level 2 (S ₀ based)	Level 3, Option 1	Level 3, Option 2	Level 3, Option 3
PD6493 Rev 1995	Level 1	Level 2, Option 1	Level 2, Option 2 Level 3, Option 1 (tearing)	Level 2, Option 3 Level 3, Option 2 (tearing)	Level 3, Option 3

Frequency of Use

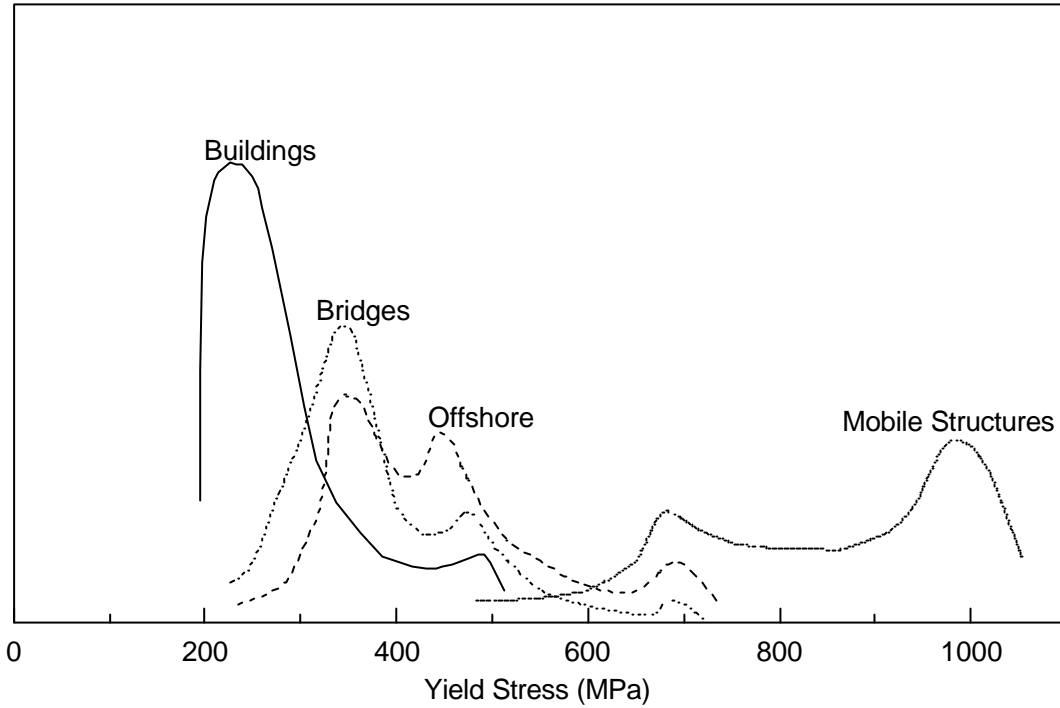


FIG.1

RELATIVE FREQUENCY OF USE OF HIGH STRENGTH STEELS

(D0672C06)

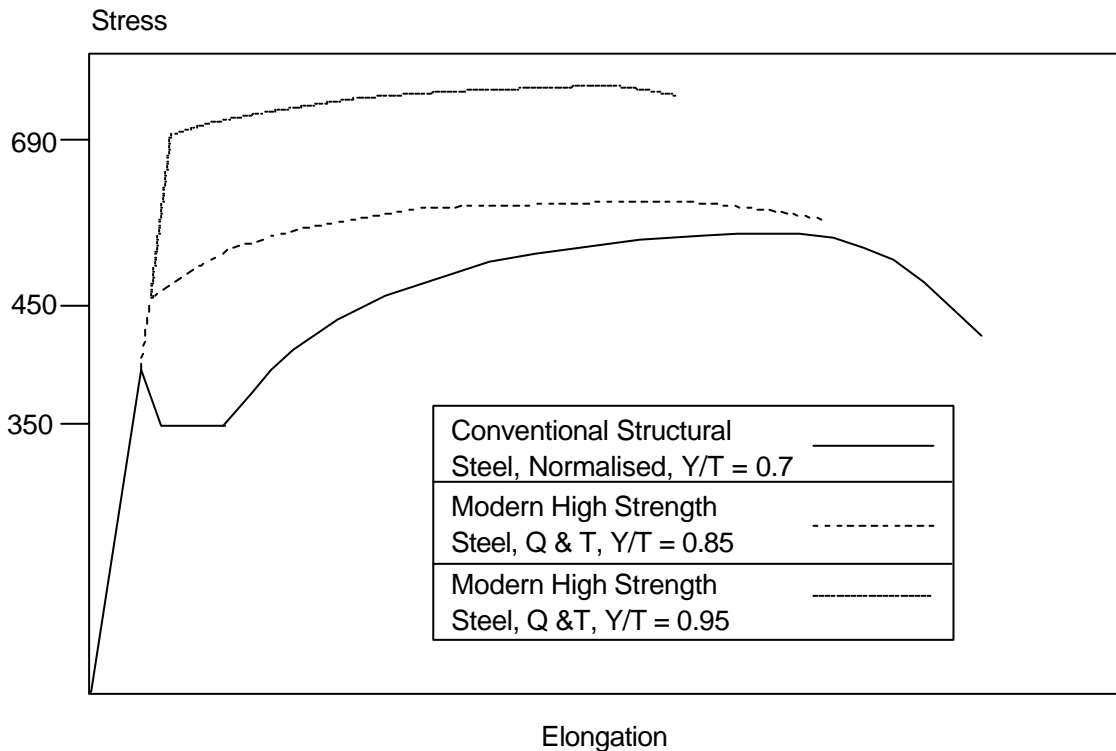
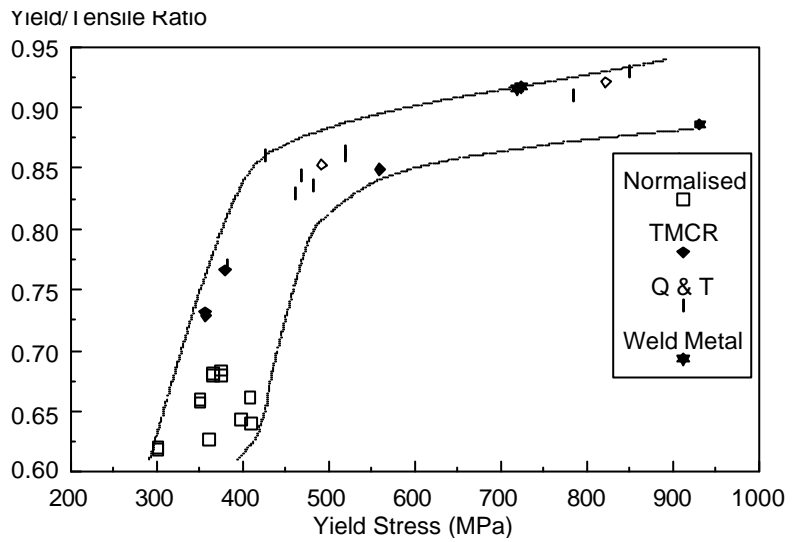


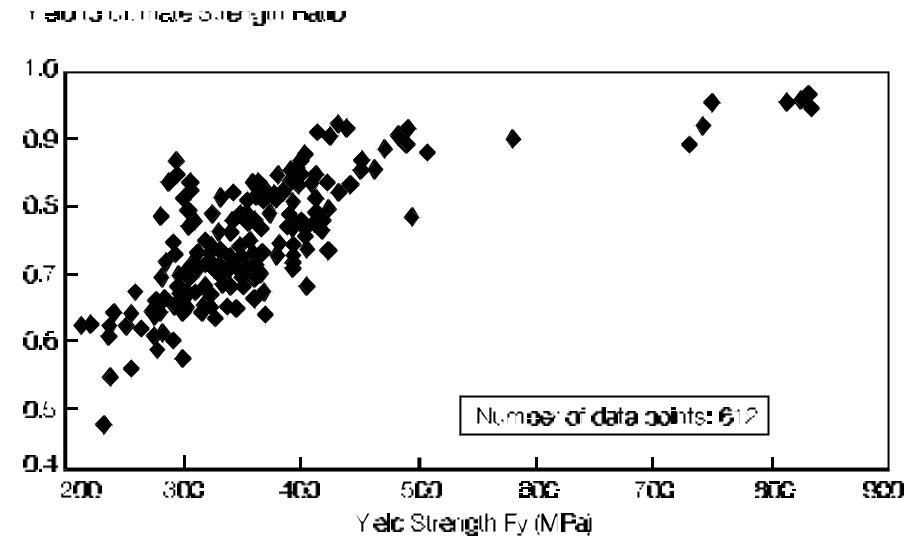
FIG.2

SCHEMATIC STRESS-STRAIN CHARACTERISTICS OF THREE STRUCTURAL STEELS

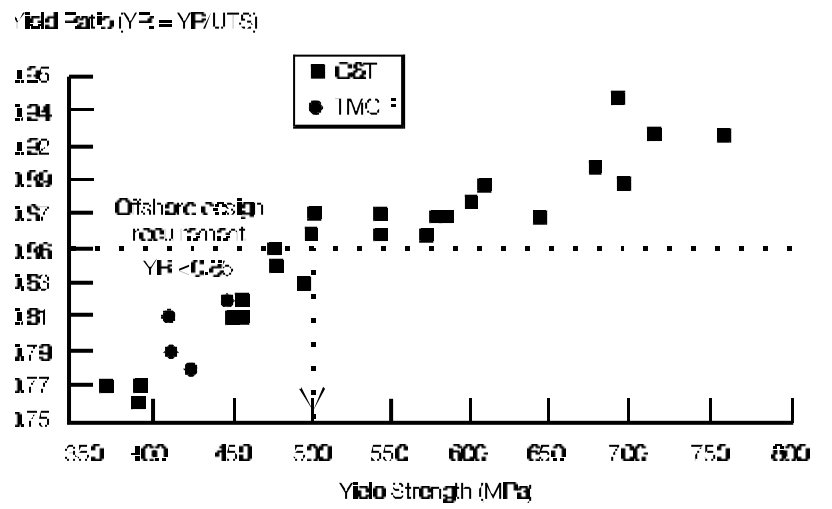
(D0672C06)



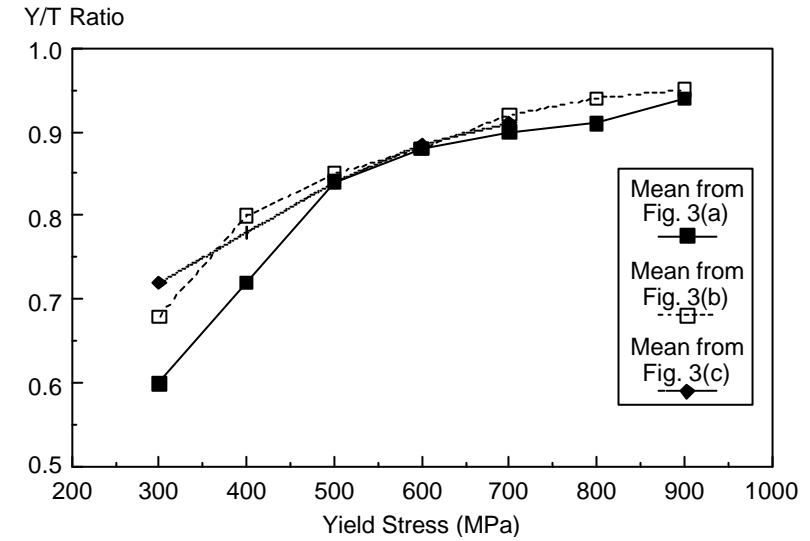
(a) Normalised, TMCR, Q&T Steels⁽⁹⁾



(b) Offshore Steels from a Tubular Joints Database⁽³⁾



(c) Offshore Steels⁽⁴⁾



(d)

Mean Lines for Data from Figs. 3(a), (b) and (c)

FIG. 3(a-d) RELATIONSHIP BETWEEN YIELD/TENSILE RATIO AND YIELD STRESS

(D0672C07)

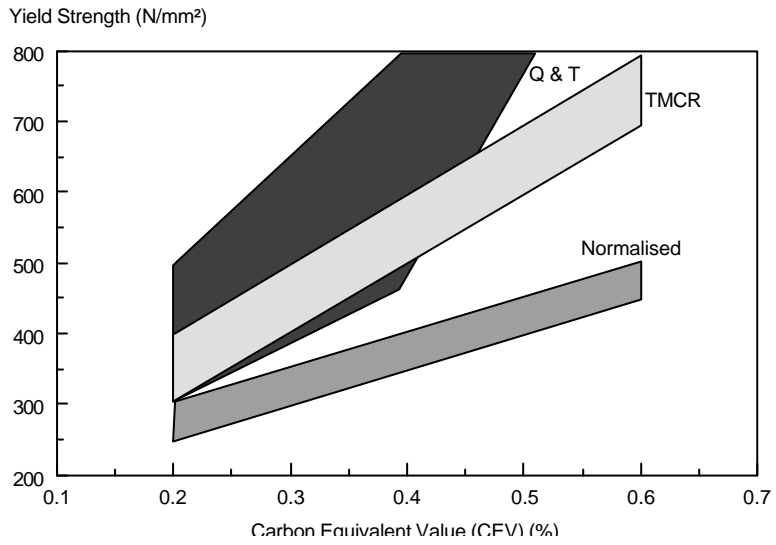
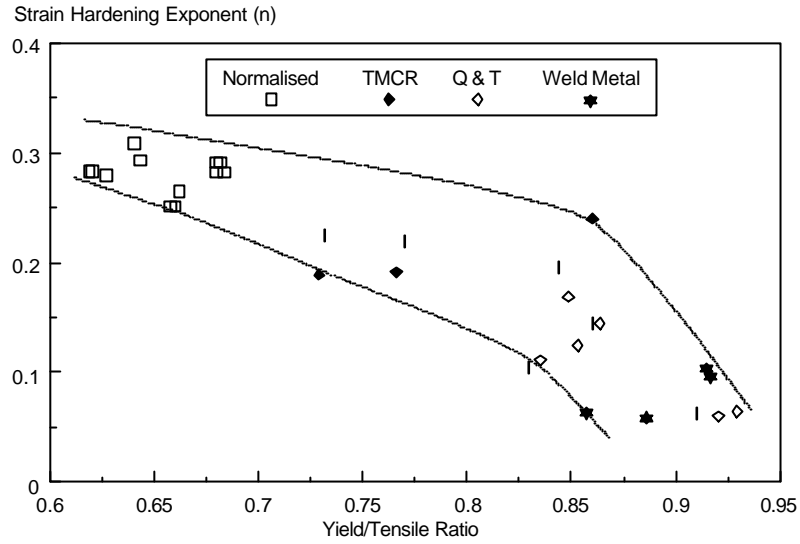


FIG. 4 ACHIEVABLE YIELD STRESS AS FUNCTION OF CARBON EQUIVALENT⁽⁷⁾

(D0672C07)

FIG. 5



RELATIONSHIP BETWEEN Y/T AND n FOR DATA SHOWN IN FIG. 3(a)

(D0672C07)

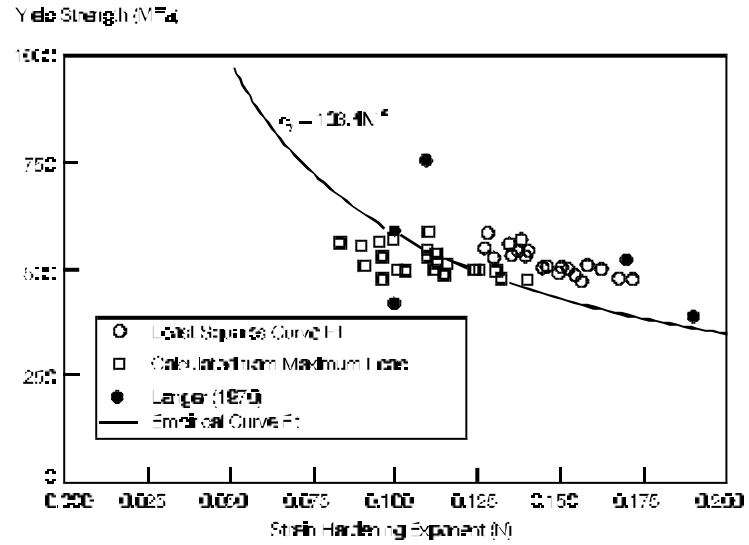


FIG. 6

RELATIONSHIP BETWEEN YIELD STRENGTH AND STRAIN HARDENING EXPONENT⁽¹⁰⁾

(D0672C07)

Strain at UTS

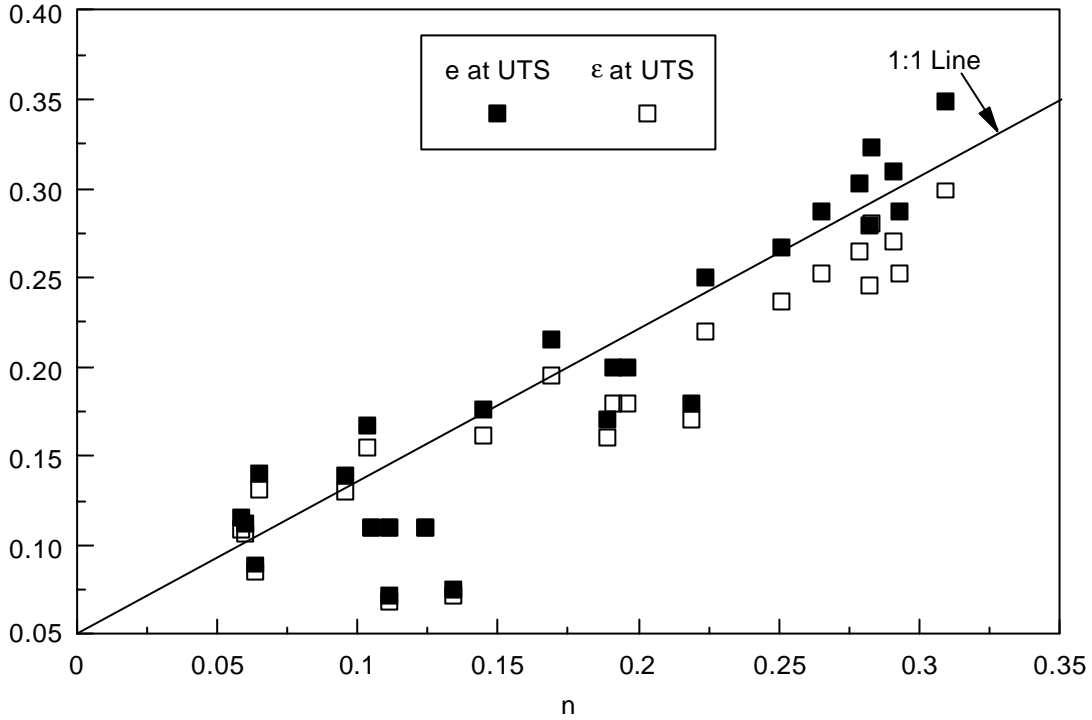


FIG. 7

STRAIN AT UTS v STRAIN HARDENING EXPONENT, n,
FOR VARIOUS STRUCTURAL STEELS

(D0672C06)

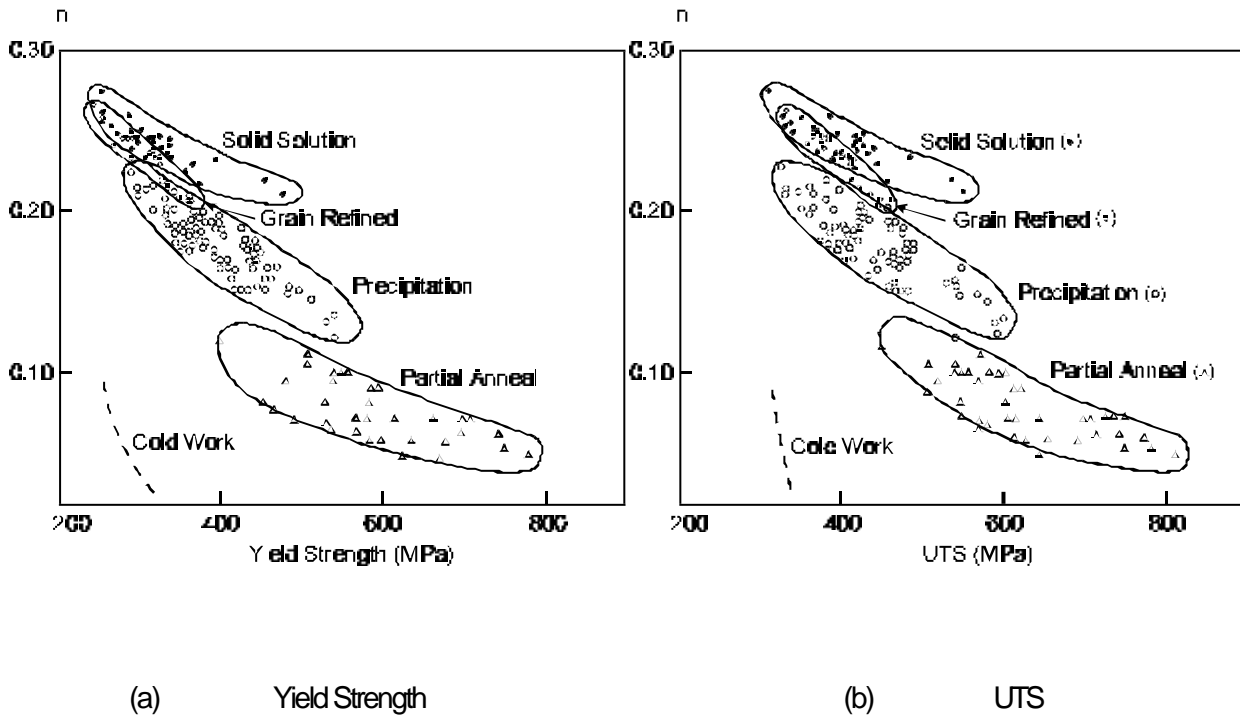


FIG. 8(a,b)

STRAIN HARDENING EXPONENT AS FUNCTION OF
STEEL TYPE⁽¹²⁾

(D0672C06)

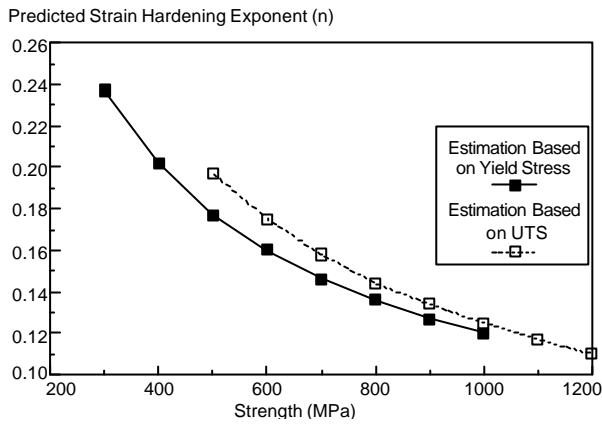


FIG. 9 PREDICTED n VALUES FOR GRAIN REFINED STEELS⁽¹²⁾ (D0672C06)

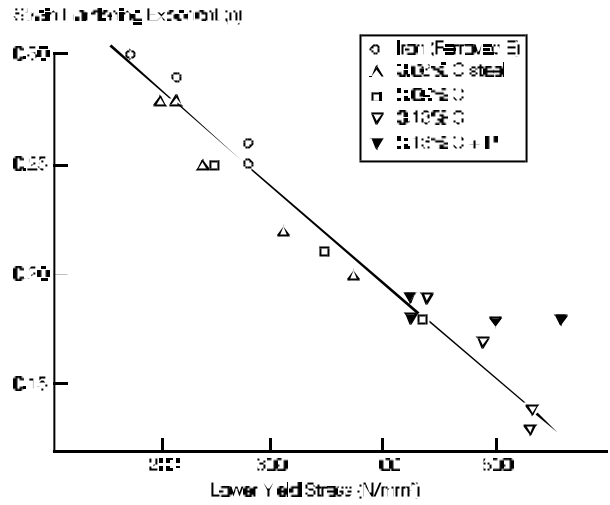


FIG. 10 n VALUES AS FUNCTION OF LYS FOR VARYING CARBON LEVELS⁽¹³⁾ (D0672C06)

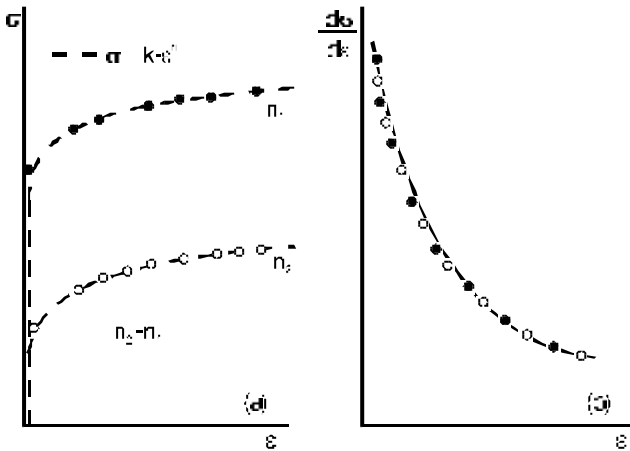


FIG.11(a-b) STRAIN HARDENING EXPONENT AND dd/de RATE FOR TWO STEELS⁽¹¹⁾ (D0672C06)

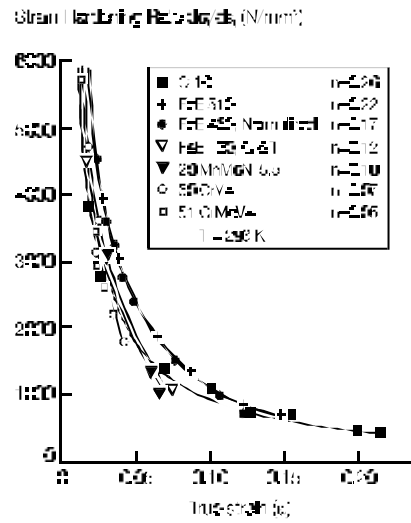


FIG. 12 STRAIN HARDENING RATE AS FUNCTION TRUE STRAIN⁽¹¹⁾ (D0672C06)

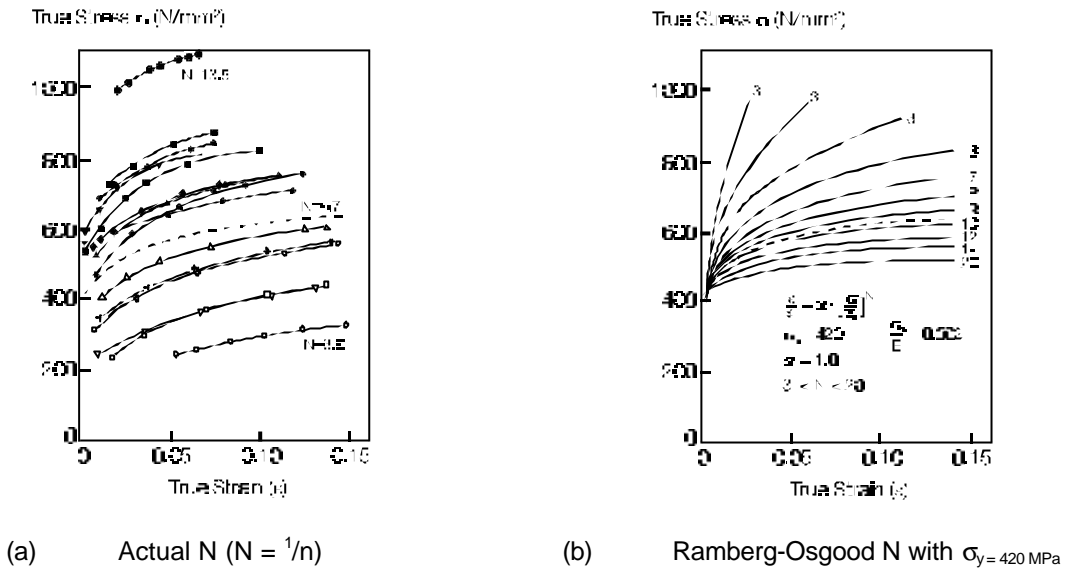


FIG. 13(a-b)

TRUE STRESS AS FUNCTION OF TRUE STRAIN⁽¹¹⁾

(D0672C06)

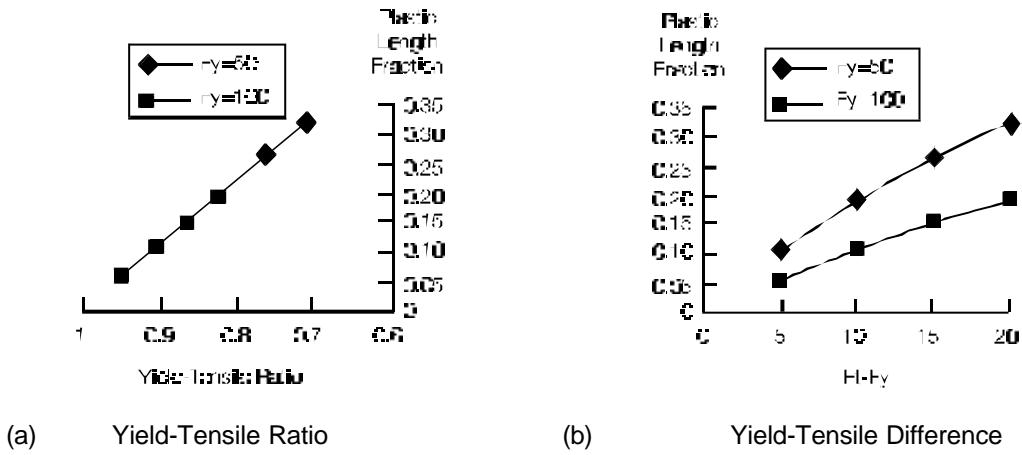


FIG. 14(a-b)

EFFECT OF TENSILE PROPERTIES ON BEAM COLUMN BEHAVIOUR⁽¹⁴⁾

(D0672C06)

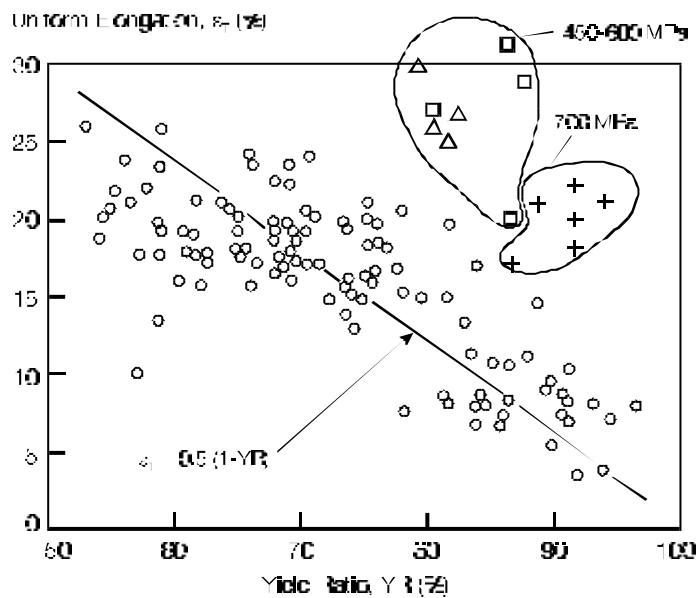


FIG. 15

EFFECT OF YIELD/TENSILE RATIO ON UNIFORM ELONGATION⁽¹⁵⁾

(D0672C06)

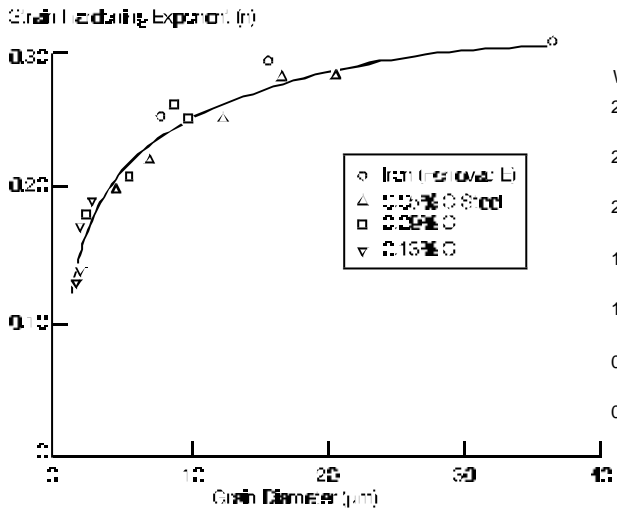


FIG. 16 INFLUENCE OF GRAIN SIZE ON STRAIN HARDENING EXPONENT⁽¹⁶⁾ (D0672C06)

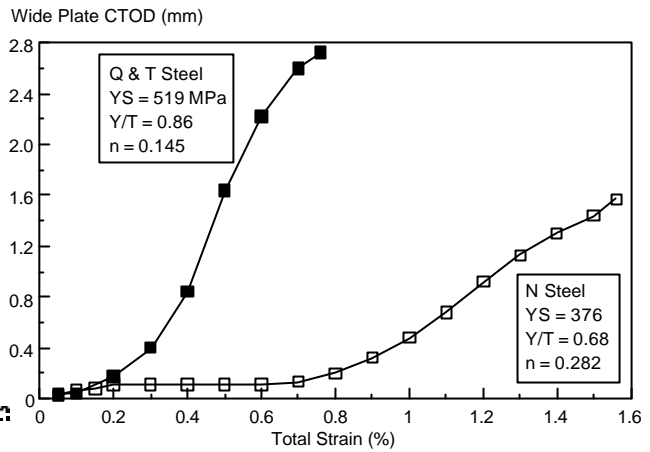


FIG. 17 WIDE PLATE CTOD v STRAIN FOR LOW AND HIGH Y/T RATIO STEELS⁽¹⁸⁾ (D0672C06)

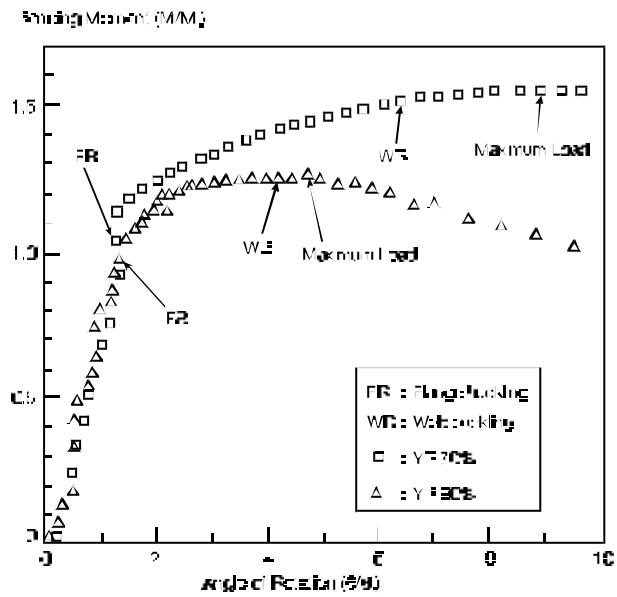


FIG. 18 CANTILEVER BEAM BEHAVIOUR FOR DIFFERING Y/T RATIO STEELS⁽¹⁹⁾ (D0672C06)

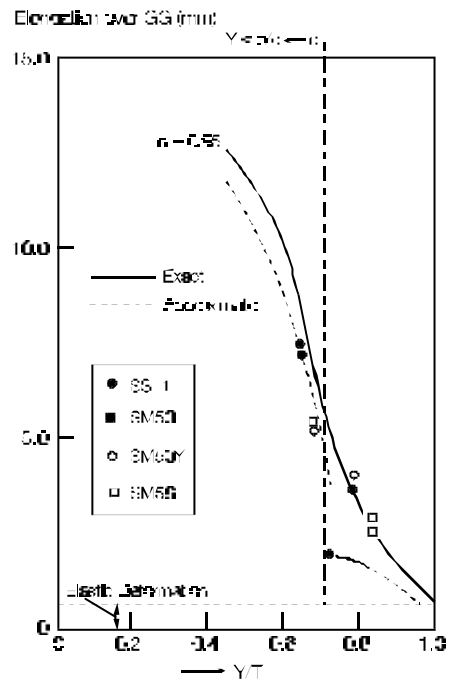


FIG. 19 EFFECT OF Y/T ON ELONGATION CAPACITY OF TENSION MEMBER WITH HOLE⁽¹⁹⁾ (D0672C06)

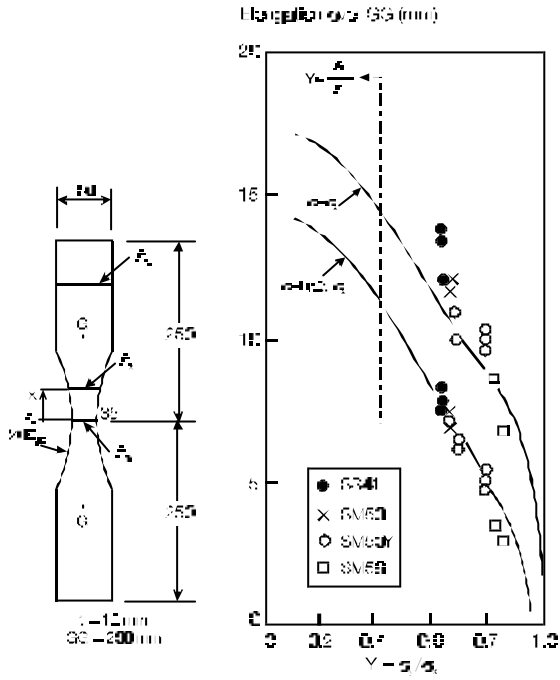


FIG. 20 EFFECT OF Y/T ON ELONGATION CAPACITY OF TAPERED TENSION MEMBER⁽¹⁹⁾ (D0672C06)

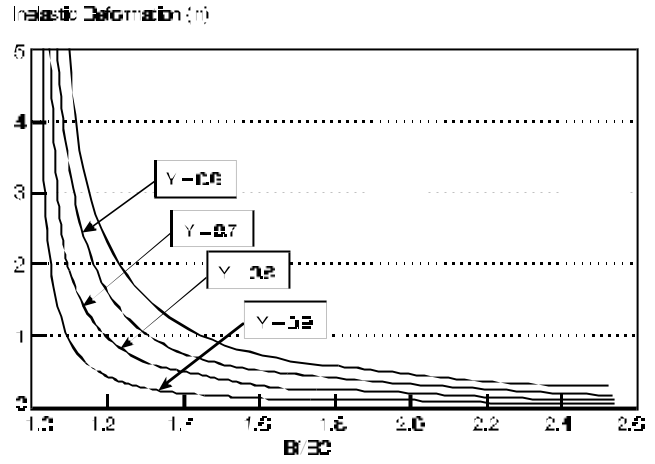


FIG. 21 PLASTIC DEFORMATION OF TAPERED MEMBERS WITH VARYING Y/T RATIO⁽²¹⁾ (D0672C06)

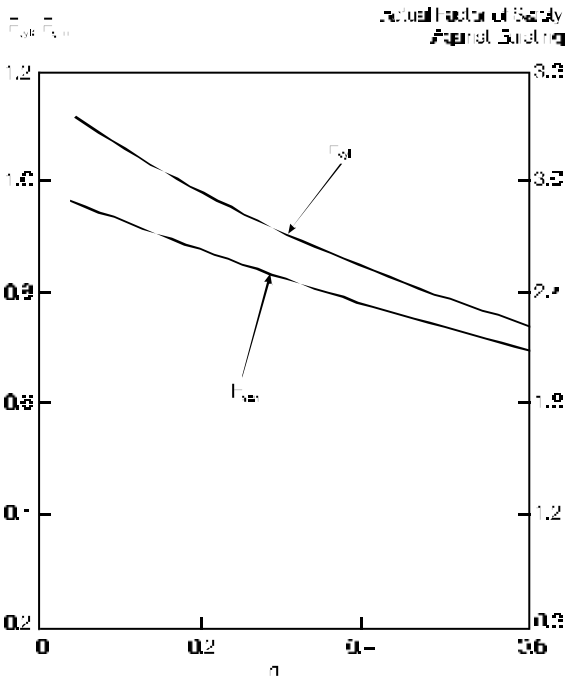


FIG. 22 EFFECT OF STRAIN HARDENING EXPONENT ON BURST PRESSURE⁽²³⁾ (D0672C06)

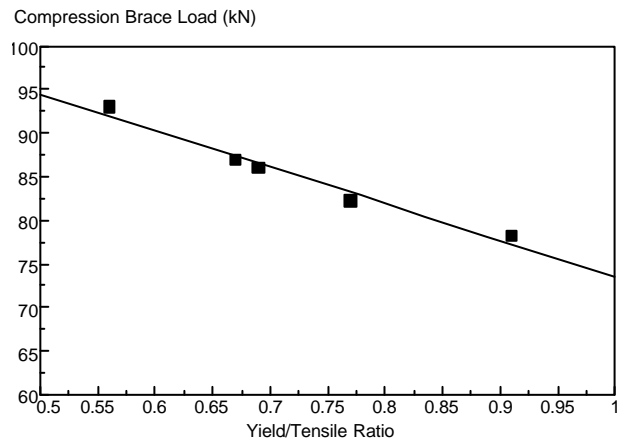
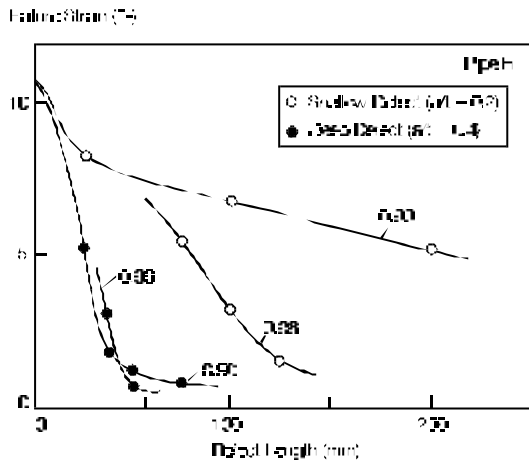
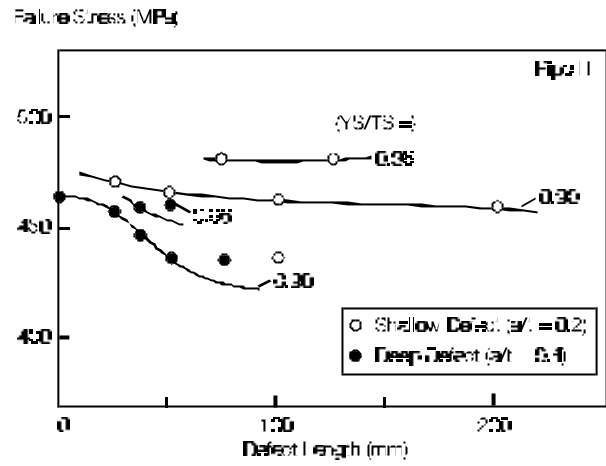


FIG. 23 COMPRESSION BRACE FAILURE LOAD AS FUNCTION OF Y/T⁽²⁴⁾ (D0672C06)

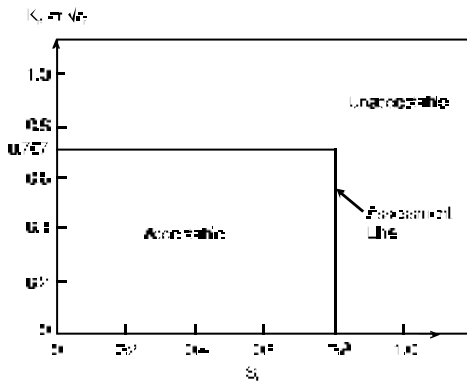


a) Failure Strain

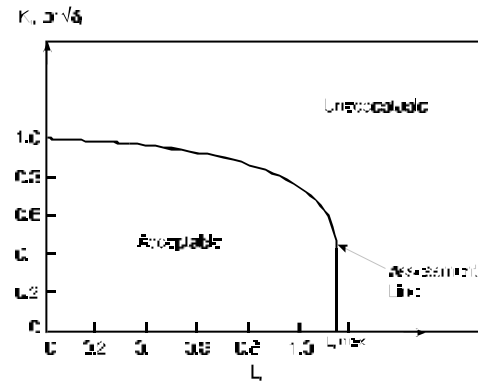


(b) Failure Stress

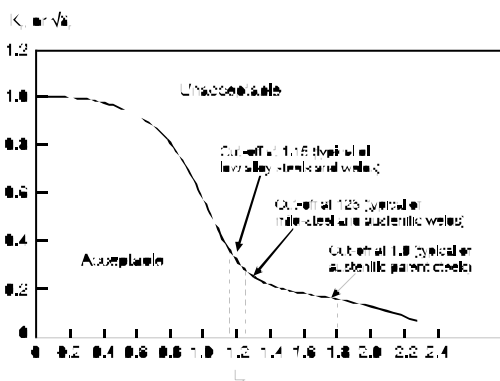
FIG. 24(a-b) EFFECT OF Y/T AND DEFECT LENGTH ON WIDE PLATE BEHAVIOUR⁽²⁵⁾ (D0672C06)



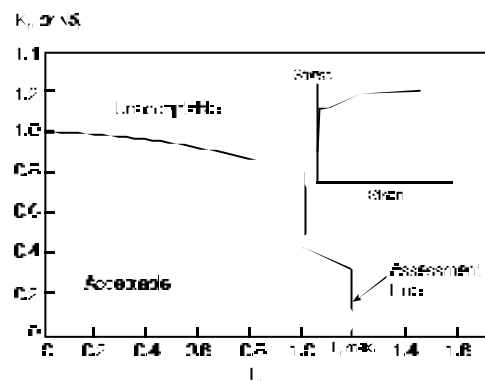
a) Level 1 Failure Assessment Diagram



(b) Level 2 Generic FAD for Low Work Hardening ($\sigma_1 \leq 1.2 \sigma_y$) (Curve plotted is for $\sigma_f = 1.15 \sigma_y$ typical of low alloy steels and welds)



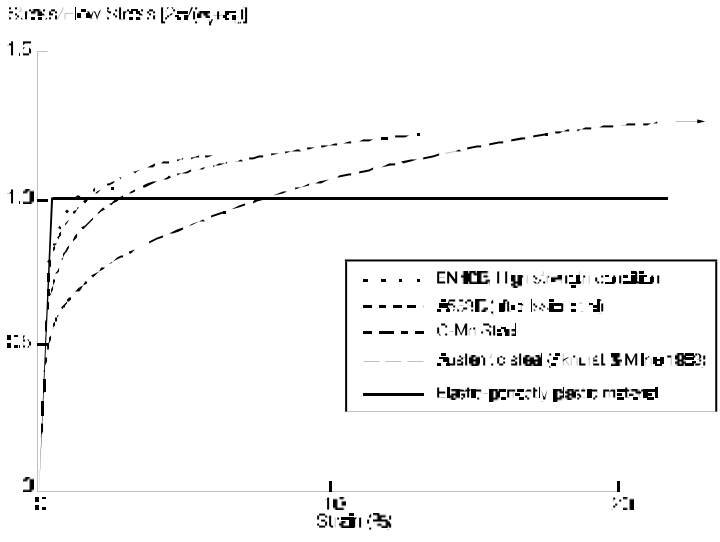
(c) Level 2 Generalised FAD particularly relevant to higher work hardening materials ($\sigma_1 < 1.2 \sigma_y$)



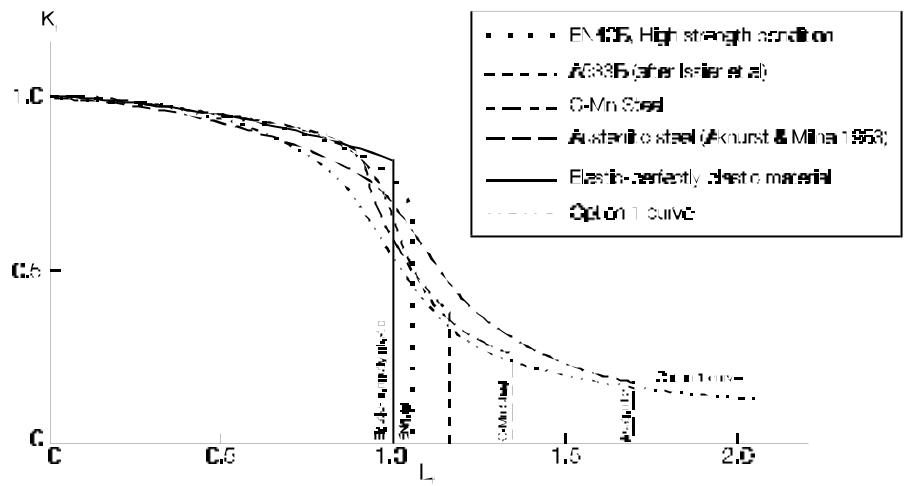
(d) Material Specific FAD

FIG. 25(a-d) FAILURE ASSESSMENT DIAGRAMS AS PER DRAFT REVISION TO BSPD6493⁽²⁹⁾

(D0672C06)

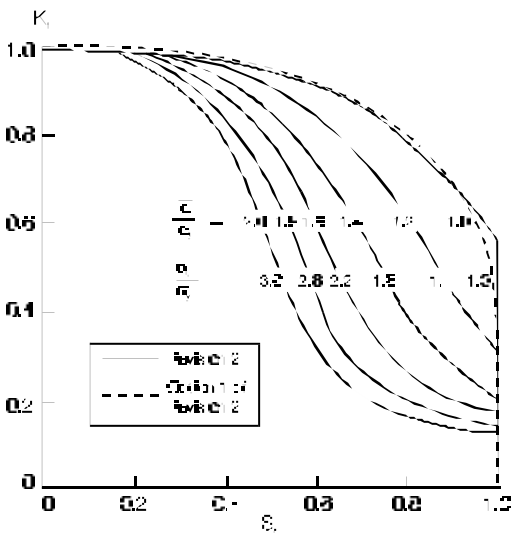


a) Engineering Stress-Strain Data

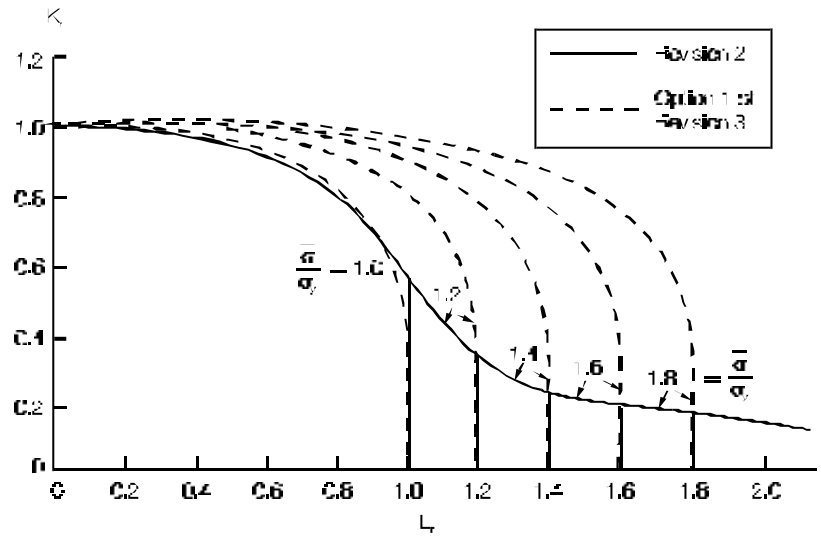


(b) Resulting FADs

FIG. 26(a-b) DEVIATION OF R6 FAILURE ASSESSMENT DIAGRAMS⁽²⁸⁾ (D0672C07)



a) Rev 3 Curves on Rev 2 Axes



(b) Rev 2 Curves on Rev 3 Axes

FIG. 27(a-b) FAILURE ASSESSMENT DIAGRAMS (D0672C07)

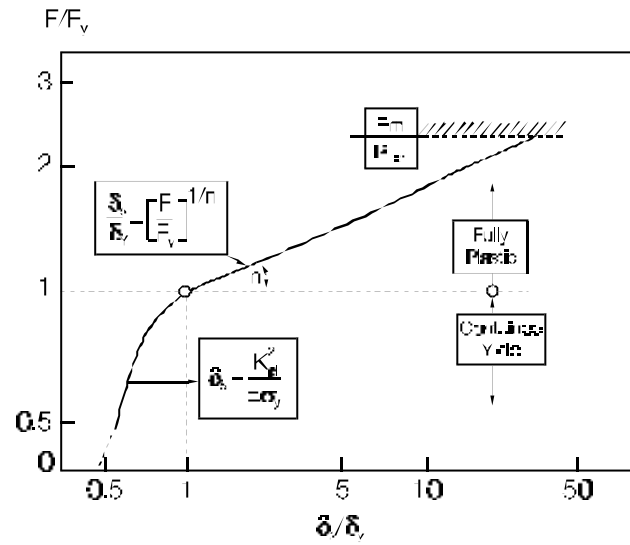


FIG. 28 KEY FEATURES OF THE ETM (D0672C07)

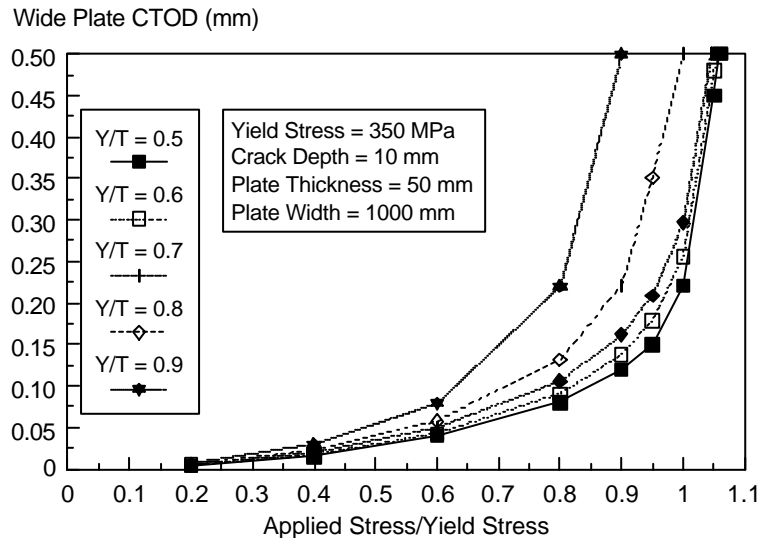


FIG. 29 EFFECT OF YIELD/TENSILE RATIO ON CRACK DRIVING FORCE CURVES ACCORDING TO BSPD6493 (D0672C07)

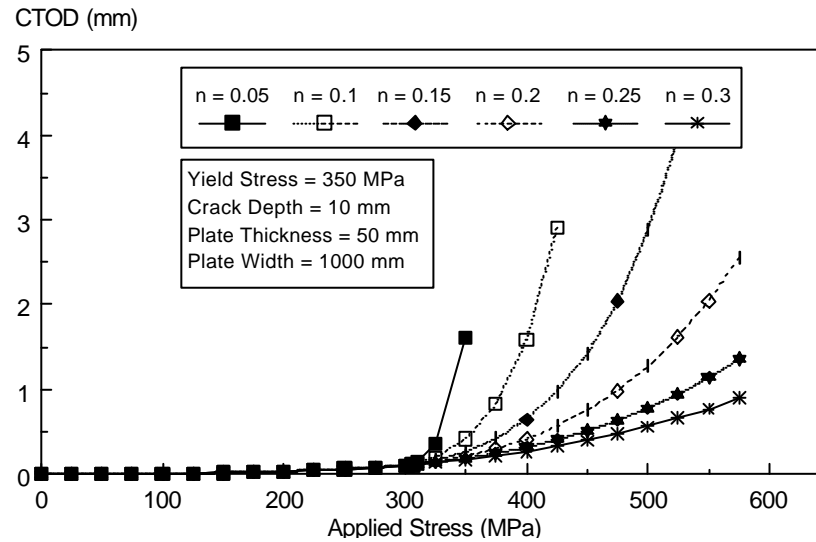


FIG. 30 EFFECT OF VARYING n ON CRACK DRIVING FORCE CURVES ACCORDING TO ETM (D0672C07)