**British Steel plc**
Swinden Technology Centre

# DOCUMENT No. SINTAP BS/23

# SUMMARY NOTE: SINTAP TASK 5

# RECOMMENDATIONS FROM Y/T WORKING GROUP FOR SINTAP PROCEDURE

## 29th June, 1998

## 1. INTRODUCTION

During the past three months a group comprising the University of Cantabria, GKSS and British Steel has been assessing various aspects of the yield stress/tensile stress ratio (Y/T ratio) and the implications of this factor to the SINTAP procedure. Other issues related to, but not specifically addressed by this group, are also covered here. The specific issues under consideration are:

i) Estimation of Y/T from knowledge of yield strength (for possible extension of Lr cut-off at level 1, continuous yielding FAD).

ii) Estimation of N from Y/T (for use at level 2).

iii) Guidance on when to assume the presence of a yield (Lüders) plateau and, in such cases, what expression should be used to estimate it's length.

iv) Implications for structural assessments if upper yield stress only has been reported.

v) Guidance on appropriate factor for ensuring that overestimation of N at Lr>1 does not lead to a non-conservative FAD at Lr<1.

vi) Recommendations on m-factor for CTOD conversion to K.

This note summaries the progress made in these areas and the proposed expressions for use in the SINTAP procedure. Background information leading to these recommendations exists in the form of various draft reports. These are referred to here but the detail of the derivation of each expression is not covered in detail. Final versions of these background reports will be published soon. The recommendations given in the following were made after considerable discussions of these issues at the Task 5 meeting in London on 15/16th June.

## 2. Determination of Yield/Tensile Ratio from Yield Stress

For use of Level 1 of the procedure, only YS needs to be known. However, the relationship between YS and YS/UTS (know as "Y/T") will allow UTS to be estimated from YS thus enabling extension of $L_r$ to values greater than 1 in some cases. The proposed relationship (1) for estimation of YT from YS is:

$$\frac{\mathrm{YS}}{\mathrm{UTS}} = 1/\left[1+2(150/\mathrm{YS})^{2.5}\right] \quad ...(1)$$

This relationship gives a conservative upper bound fit to data for various steels taken from databases available within BS, VTT, TWI and HSE.

Since expression (1) will be used for extension of $L_r$max in the case of level 1 of the procedure with continuous yielding this can be expressed as:

$$\mathrm{L}_{r\,\max} = 1+\left(\frac{150}{YS}\right)^{2.5} \quad ... (2)$$

The steels forming the data set on which this expression is based included ferrite-pearlite structural steels, high strength bainitic steels and austenitic stainless steels. The relationship is shown in comparison with data in Figure 1. This relationship is very conservative for austenitic stainless steels but provides a reasonable estimate for structural steels. (The data points for the austenitic stainless steels lie outside the range shown in Fig.1.)

## 3. Determination of Strain Hardening Exponent (N) from Yield/Tensile (Y/T) Ratio

At Level 2 of the procedure, the strain hardening exponent for the material is determined from the yield stress/ultimate tensile stress ratio (Y/T) for subsequent determination of the FAD at $L_r$>1. The conclusion reached in Task 5 is that the N value should be determined from the true stress strain curve, as is convention, and the interim position reached was that N can be represented as a simple linear function of Y/T:

$$N = 0.5\left[1-(Y/T)\right] \quad ... (3)$$

The N values used to derive expression (3) were determined in the conventional manner; from YS to UTS, using true stress and strain. However, further work within SINTAP(2) has demonstrated that there is the possibility that less conservative results could be obtained than when using higher levels of the procedure when using this approach; the reasons for this lie not in the relationship between N and (Y/T) but in the relationship between the linear regression fit to the stress-strain data and the actual stress-strain curve. It has been demonstrated(2) that the fitted stress-strain curve for certain examples of steel can overestimate the actual stress-strain curve at low plastic strains. This is due to the influence of the points at high strains, towards UTS, distorting the overall fit of the regression line. The overestimate of stress in regions of low plastic strain is particularly important for the SINTAP procedure since this is the critical region for many structural assessments. This potential problem is shown schematically in Fig. 2. It should be noted that the question is not one of the determination of N form Y/T but on the method used to calculate N; the aim of this current analysis is not to redefine the method of calculating N but to ensure that the method for estimating N from Y/T is such that analysis of all cases will lead to decreasing conservatism with increasing level of assessment.

In order to assess the sensitivity of the value of N to the portion of the stress-strain curve from which it is derived, a series of analyses on nineteen different steels was performed using the true-stress strain curve from:

(i) YS to UTS
(ii) YS to mean of flow stress and UTS
(iii) YS to flow stress
(iv) YS to mean of yield stress and flow stress

The analysis was also carried out keeping the yield point fixed and non-fixed, and taking strain values with and without the elastic component. The work is reported in detail in (3, 4) and a summary of the results for the case of plastic strains only is given in Fig. 3. The three solid lines indicated are of the form:

$$N = \mathrm{x}\left[1 - (\mathrm{Y}/\mathrm{T})\right] \qquad \text{... (4)}$$

with x = 0.3, 0.4 and 0.5.

The dashed line indicated has a cut-off of N=0 for Y/T > 0.9. On account of the fact of the very limited hardening for materials with Y/T >0.9, the slight non-conservatism exhibited by the data for such steels in comparison with the lines which give N=0 at Y/T=1.0 is not relevant. The proposed relationship for determining N from Y/T is therefore:

$$\mathrm{N} = 0.3\left[1 - (\mathrm{Y}/\mathrm{T})\right] \qquad \text{... (5)}$$

A limited amount of analysis remains to be completed in respect of this (comparison of FADs) but this is not expected to lead to any major modifications to expression (5).

## 4. Treatment of Yield (Lüders) Plateau

Within the latest revision of the SINTAP procedure, selection of appropriate FAD/CDF (Failure Assessment Diagram/Crack Driving Force Curve) at Levels 1 and 2 ("Basic Level" and "Material Specific: Assumed N" level respectively) is dependent on the assumption or otherwise of the occurrence of a yield (Lüders) Plateau. In addition, at Level 2 a method for estimation of the length of the plateau, should one be assumed to be present, is also required. Preliminary work has been carried out(5) to enable the above two characteristics to be defined.

Selection of whether a yield plateau should be assumed for a particular steel should be made in accordance with Table 1. It is recognised that this approach is a "best estimate" and that there are other factors which also dictate whether a yield plateau should be assumed (such as loading rate and specimen design). When a plateau is assumed, its length should be estimated from the expression.

$$\varepsilon_l = -(0.0000375 \text{ x YS}) + 0.0375 \qquad \text{... (6)}$$

Although this does not represent an upper-bound fit to the data in Fig. 4, it is felt that expression(6) is a reasonable approximation given that a) expression (5) is a lower bound and the use of two lower bound expressions in combination would be unduly conservative; b) the fact that the plateau is rarely present in a large scale test(5,6); and c) the number of factors affecting the occurrence of the yield plateau is considerable and beyond the scope of such simplistic treatment.

For the purposes of SINTAP expression (6) is better expressed as:

$$\varepsilon_l = 0.0375\left(1-\frac{\mathrm{YS}}{1000}\right) \qquad \ldots (7)$$

A cut-off value of  for yield stress values of 600 MPa and above has also been suggested: However, the tensile data assessed show that some steels above this strength level can still show yield plateau. A cut-off for YS> 800MPa could be incorporated, but this will have only minor implications to the shape of the FAD. Hence, no cut-off is recommended.

## 5. Selection of Appropriate Yield Stress Value for Use in Assessment

Yield stress values for steels showing a yield point can be quoted as upper yield stress (UYS) or lower yield stress (LYS) while for steels showing a continuous stress-strain curve, yield stress is quoted as a proof stress (usually 0.2%, but sometimes 0.5%, depending on material specification). For the case of discontinuous yielding, the yield stress values quoted in steel test certificates are UYS values, whereas for structural applications the LYS must be used to ensure conservatism. The type of yield stress quoted in the test certificate is usually not specified. The potential unconservatism of using UYS for assessing structural behaviour is widely known and examples are given in(5).

In order to ensure that the load bearing capacity of a structure is not overestimated it is necessary to factor UYS values prior to use in an assessment. When the type of yield stress value is not known, the scheme for estimating whether a yield plateau is present (Table 1) should be used to determine whether a yield point is likely to be present for the particular steel. When it is predicted that the stress-strain curve will be continuous, the yield stress value quoted in the test certificate is likely to be the 0.2% proof stress and can be used directly in an assessment. When a discontinuous stress-strain curve is predicted, the yield stress value quoted in the steel test certificate is most likely to be the UYS and should be factored accordingly.

$$\mathrm{LYS} = 0.95(\mathrm{UYS}) \qquad \ldots (8)$$

Further data are to be assessed in respect of this proposed expression to cover plate, sections and linepipe products in structural steel grades. Alternatively, a partial safety factor approach may prove to be more realistic and less penalising to modern structural steels; this will be assessed in Sub-Task 2.3.

For the cases when yield stress is quoted for material with YS specified as a 0.5% PS this must also be factored accordingly, a case which also needs further assessment.

## 6. Recommended Expression for FAD for Continuous Yielding Material at Level 2 when $L_r \le 1$

A conservative estimate of N is required for Level 2 of the procedure to ensure that, at $L_r>1$, the FAD is conservative as compared to the material-specific curve. A consequence of underestimation of N at $L_r>1$ however is that the FAD at $L_r<1$ is overestimated: This is due to the necessity for continuity in the stress strain curve and the equation used to describe the FAD. The FAD for continuous hardening materials at Level 2 of the SINTAP procedure is given by:

$$f(L_r) = \left(1 + \frac{L_r{}^2}{2}\right)^{-\frac{1}{2}} \left[0.3 + 0.7\ \exp\left(-\mu\ \mathrm{L_r^6}\right)\right] \qquad \text{... (9)}$$

Analysis of stress-strain curves and corresponding FADs(7) led to the suggestion that μ would be best determined from elastic parameters, namely YS and E. The recommended expression is:-

$$\mu = 0.001(\mathrm{E/YS}),\ \text{(up to a maximum value of 0.6)} \qquad \text{... (10)}$$

when $\mu$=0.6, expression (8) is equivalent to the equation of the level 1 FAD.

## 7. Determination of m Factor

$J_{mat}$ and $CTOD_{mat}$ values of fracture toughness can be related through the expression.

$$\mathrm{CTOD_{mat}} = J_{mat} / (\mathrm{m.YS}) \qquad \text{... (11)}$$

Where m is the plastic constraint factor and YS the yield stress. The relationship is empirical but such that transferability between $J_{mat}$ and $CTOD_{mat}$ is within acceptable bounds(8). It is proposed that the SINTAP procedure will not incorporate a discrete CTOD route, but that CTOD-type data can be indirectly included via analysis using the m-factor described above(8). Within Task 3, recommendations were made for an estimate of m based on a range of steels assessed by various SINTAP members. The recommended m-factors(9) for use with yield stress values are:

m = 1.5 (for ferritic & bainitic steels)
m = 2.2 (for duplex & super-duplex stainless steels and weldments)

These recommended values of m-factors to convert $CTOD_{mat}$ values to $K_{mat}$ were all based on deeply cracked specimens with a/W>0.4. To check whether the recommendations apply to shallow crack specimens, analysis was carried out on shallow crack data on A533B steel (determined from J-values)(10). Expression(9) applies with

$$\mathrm{m} = 1.221 + 0.793(\mathrm{a_o/W}) + 2.751N - 1.418(\mathrm{a_o/W})\mathrm{N} \qquad \text{... (12)}$$

Hence, the effect of a/W on m is implicit in the above relation, based on the draft revisions to ASTM E1290 (Rev.4, Nov. 97), N is the strain hardening exponent. (Note that expression(12) replaces the old ASTM ratio quoted in ref. (8). The resulting dependency of m on a/W and N, using expression (12), is shown in figure 5.

The ASTM equation predicts m-values between 1.35 and 2.6, depending on a/W and strain hardening exponent.

Previous data collection for deeply cracked ($a_o$/W = 0.5) specimens reported in (9), gave values between 1.46 and 2.26 which is well in line with the values derived using expression (12). It should be noted that the duplex data which gave a mean m-value of 2.26 fit in with predictions from expression

(12) if their strain hardening exponent approximates to N=0.3, which is likely to be the case for this type of steel.

The recommended value of 1.5(9) is safe for all cases except for very low strain hardening steel with shallow cracks.

It is therefore proposed, pending a small amount of additional analysis, that if N and $a_o$/W are known, the m-factor can be determined from expression (12). If these parameters are not known, the current guidance of $m_y$=1.5 recommended in (9) should be applied but with the proviso that this value should not be used for low strain hardening materials (n<~0.05) with shallow cracked specimens ($a_o$/W <0.25), for which m=1 is recommended.

## 8. Summary

A summary of the proposed expressions and their applicability is given in Table 2. It is proposed that these should be considered as the recommended expressions for incorporation into the current SINTAP homogeneous procedure (written procedure and software) and for the basis of equations for subsequent development of the mismatch (heterogeneous procedure).

A. C. Bannister
**Welding & Engineering Metallurgy Department**

incorporating contributions from

Mr. J. Ruiz - Ocejo (UC), Dr. Y-J. Kim (GKSS), Dr. C. S. Wiesner (TWI), and from those present at the SINTAP Task 5 meeting held at HSE, London, on 15/16th June 1998.

Circulation

All SINTAP members

## References

1. R.A. Ainsworth SINTAP/NE/15, 'Compatability between Crack Driving Force and Failure Assessment Diagram methods', 9th March, 1998.

2. Y.-J. Kim & U. Zerbst, 'Further Note on Y/T Versus N for SINTAP Procedure', Fax 5th February, 1998.

3. J. Ruiz-Ocejo & F. Gutiérrez-Solana, 'On the Strain Hardening Exponent Definition and its Influence within SINTAP', SINTAP/UC/07.

4. J. Ruiz-Ocejo and F. Gutiérrez-Solana, SINTAP/UC/08, June, 1998.

5. A.C. Bannister, 'Assessment of the Occurrence & Significance of Yield Plateaus in Structural Steels', SINTAP/BS/19, 5th June 1998 (to be circulated).

6. C.S. Wiesner, 'SINTAP Task 2: Lüders Band in Tensile Specimens Compared to Wide Plate Tests', letter 16th June, 1998, SINTAP/TWI/53.

7. J. Ruiz-Ocejo & F. Gutiérrez-Solana, M.A. Gonzalez-Posada, SINTAP/UC/06.

8. J. Martin & R.W.J. Koers, 'CTOD Versus J-Integral as a Fracture Parameter', SINTAP/SHELL/07, 8th April 1998.

9. A.C. Bannister, 'Sub-Task 3.3 Report: Determination of Fracture Toughness from Charpy Impact Energy: Procedure & Validation', SINTAP/BS/17.

10. C.S. Wiesner, 'SINTAP Task 3: Kmat from CTOD for Shallow Crack Specimens', letter, 5th June 1998, SINTAP/TWI/52.

| Yield Stress Range (MPa) | Process Route | Composition Aspects | Heat Treatment Aspects | Assume Yield Plateau† |
|---|---|---|---|---|
| YS ≤350 | As-Rolled | Conventional Steels (e.g. EN 10025 grades) without microalloy additions | NA | Yes |
| | | | NA | Yes |
| | | Mo, Cr, V, Nb, Al or Ti present | NA | (No) |
| | | | NA | (No) |
| | Normalised | EN 10025 type compositions without microalloy additions | Conventional normalising | Yes |
| | | | Conventional normalising | Yes |
| | | EN 10113 type compositions with microalloy additions | Conventional normalising | Yes |
| | | | Conventional normalising | Yes |
| | Controlled Rolled | EN 10113 compositions | - | Yes |
| | | | - | Yes |
| | | EN 10113 compositions | - | Yes |
| | | | - | Yes |
| 350 <YS<br>500 ≥YS | Controlled Rolled | EN 10113 compositions | Light TMCR schedules (YS <400) | Yes |
| | | | Heavy TMCR schedules (YS >400) | (Yes) |
| | Quenched & Tempered | Mo or B present with microalloy additions Cr, V, Nb or Ti | Heavy tempering favours plateau | Yes |
| | | | Light tempering favours no plateau | (Yes) |
| | | Mo or B not present but microalloying additions Cr, V, Nb or Ti are (V particularly strong effect) | Heavy tempering | (Yes) |
| | | | Light tempering | (No) |
| | Precipitation Hardened* | | | |
| | | | | |
| | | | | |
| | | | | |
| 500 <YS<br>1050 ≥YS | Quenched & Tempered | Mo or B present with microalloy additions Cr, V, Nb or Ti | Tempering to YS < ~690 | (No) |
| | | | Tempering to YS ≥ ~690 | No |
| | | Mo or B not present but microalloy additions Cr, V, Nb or Ti are | Tempering to YS < ~690 | Yes |
| | | | Tempering to YS ≥ ~690 | (No) |
| | Precipitation Hardened* | | | |
| | | | | |
| | | | | |
| | | | | |
| | As-Quenched | All compositions | NA | No |
| | | | NA | No |
| | | All compositions | NA | No |
| | | | NA | No |

( ) = Some Uncertainty
* = Further Consideration/Data Needed
† = If Uncertain, Assume Yield Plateau

**Table 1 : Selection Procedure for Determining Whether A Yield Plateau Should be Assumed**

**Table 2: Recommended Expressions for SINTAP Procedure**

| ISSUE | RECOMMENDED EXPRESSION | COMMENTS/APPLICABILTY |
|---|---|---|
| Determination of Y/T from YS | $\frac{\mathrm{YS}}{\mathrm{UTS}} = 1/\left[1+2(150/\mathrm{YS})^{2.5}\right]$ | Only valid for ferrous materials |
| Estimation of strain hardening exponent (N) from Y/T | $\mathrm{N} = 0.3\left[1-\left(\frac{\mathrm{YS}}{\mathrm{UTS}}\right)\right]$ | Potentially slightly non-conservative for Y/T>0.9 but this is of little practical significance. |
| Estimation of length of Lüders plateau ($\varepsilon_l$) | $\varepsilon_l = -(0.0000375\mathrm{xYS}) + 0.0375$ | For steels up to 800MPa YS. Above this value, $\varepsilon_l = 0$ may be realistic but not significant |
| Estimation of LYS when only UYS available | $\mathrm{LYS} = 0.92(\mathrm{UYS})$ | Further data to be assessed |
| Determination of μ factor | $\mu = 0.001(\mathrm{E}/\mathrm{YS})$ | Up to a maximum value of μ=0.6 |
| Determination of plastic constraint factor (m) | $\mathrm{m_Y} = 1.221 + 0.793\left(\frac{\mathrm{a_o}}{\mathrm{W}}\right) + 2.751\mathrm{N} - 1.418\left(\frac{\mathrm{a_o}}{\mathrm{W}}\right)\mathrm{N}$ (1) | -use (1) if $\left(\frac{\mathrm{a_o}}{\mathrm{W}}\right)$ and N known otherwise use (2) |
| | $\left.\begin{array}{l} \mathrm{m_Y} = 1.5(\text{ferritic / bainitic steels}) \\ \mathrm{m_Y} = 2.2(\text{Duplex, Super-Duplex}) \end{array}\right\}$ (2) | (2) not valid for N <0.05 with specimens for which $\left[\frac{\mathrm{a_o}}{\mathrm{W}}\right]$ <0.25. |

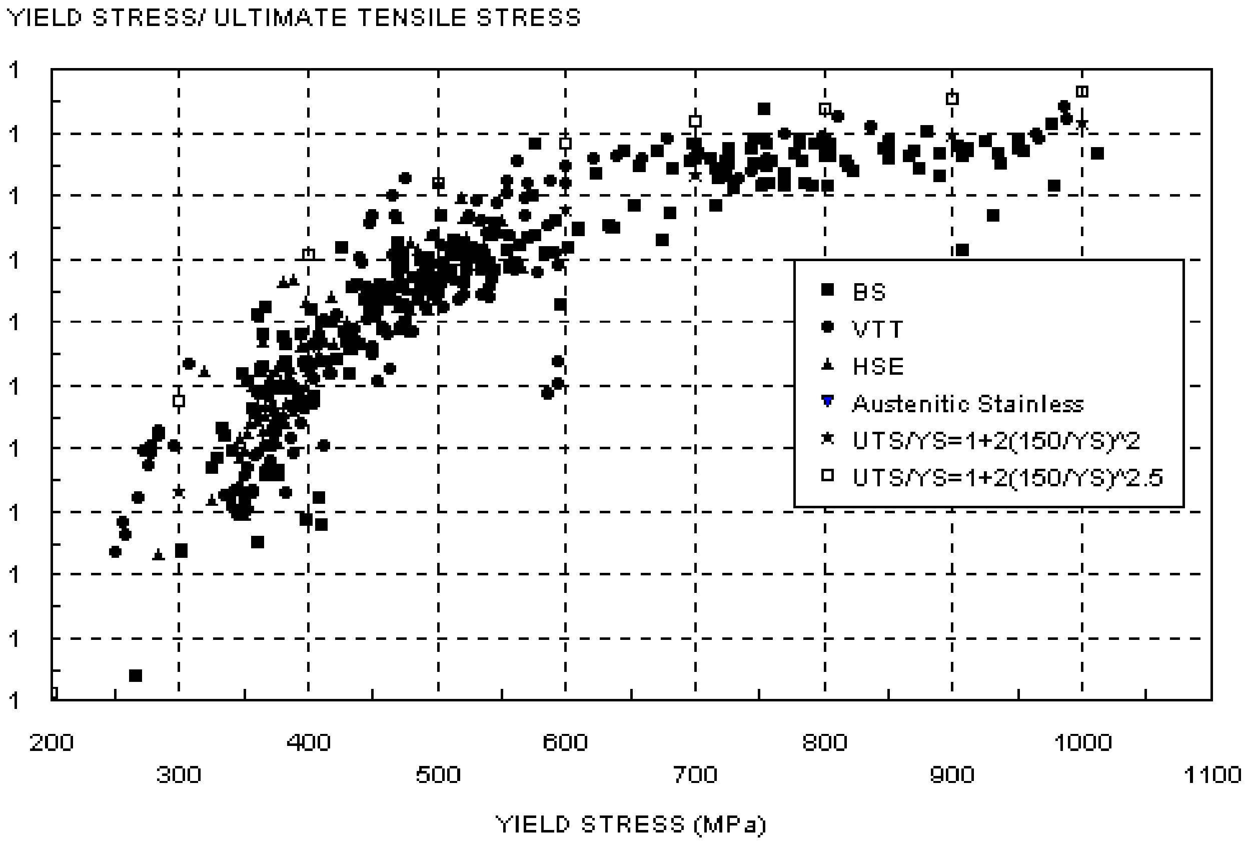

Fig. 1. Prediction of YS/UTS from Yield Stress

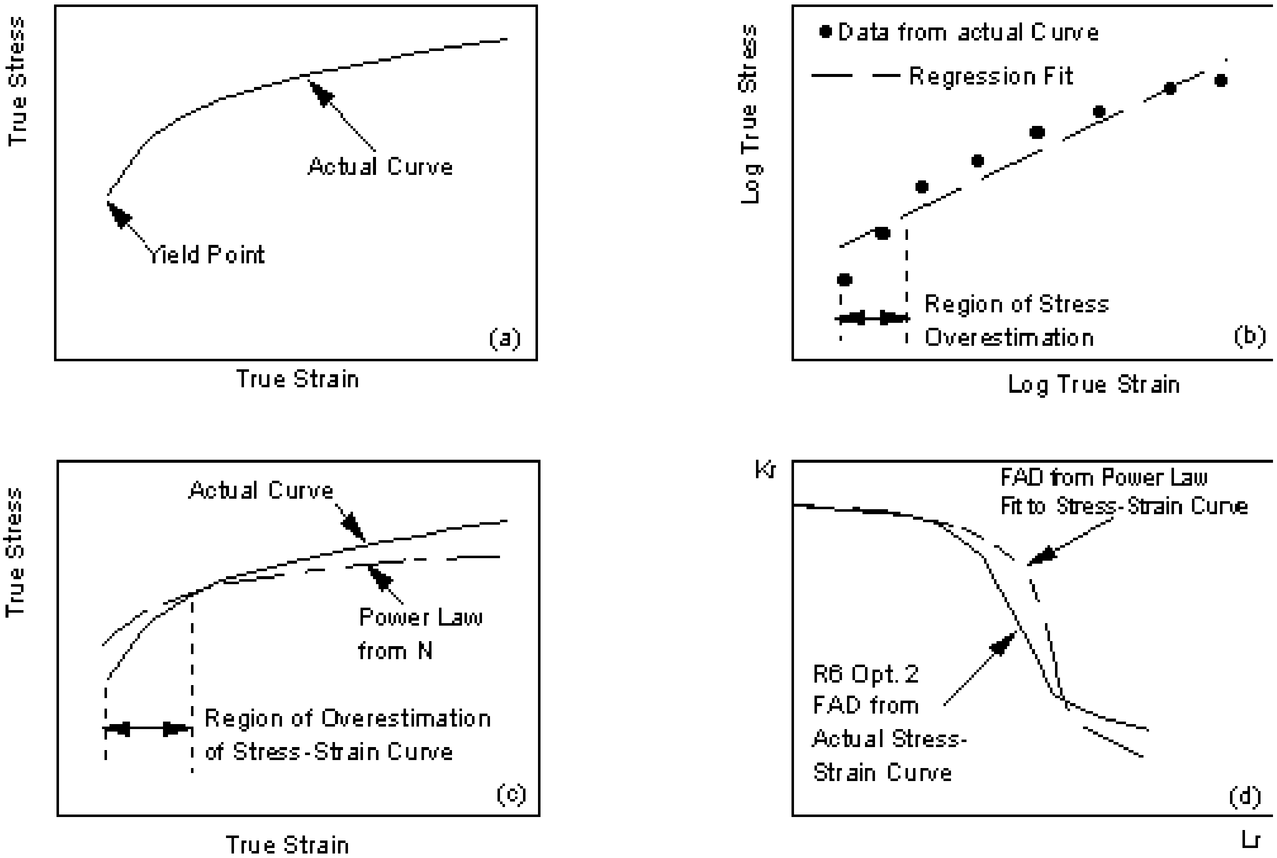

Fig. 2. Schematic of Potential Conservatism Arising from Use of Conventionally Defined N

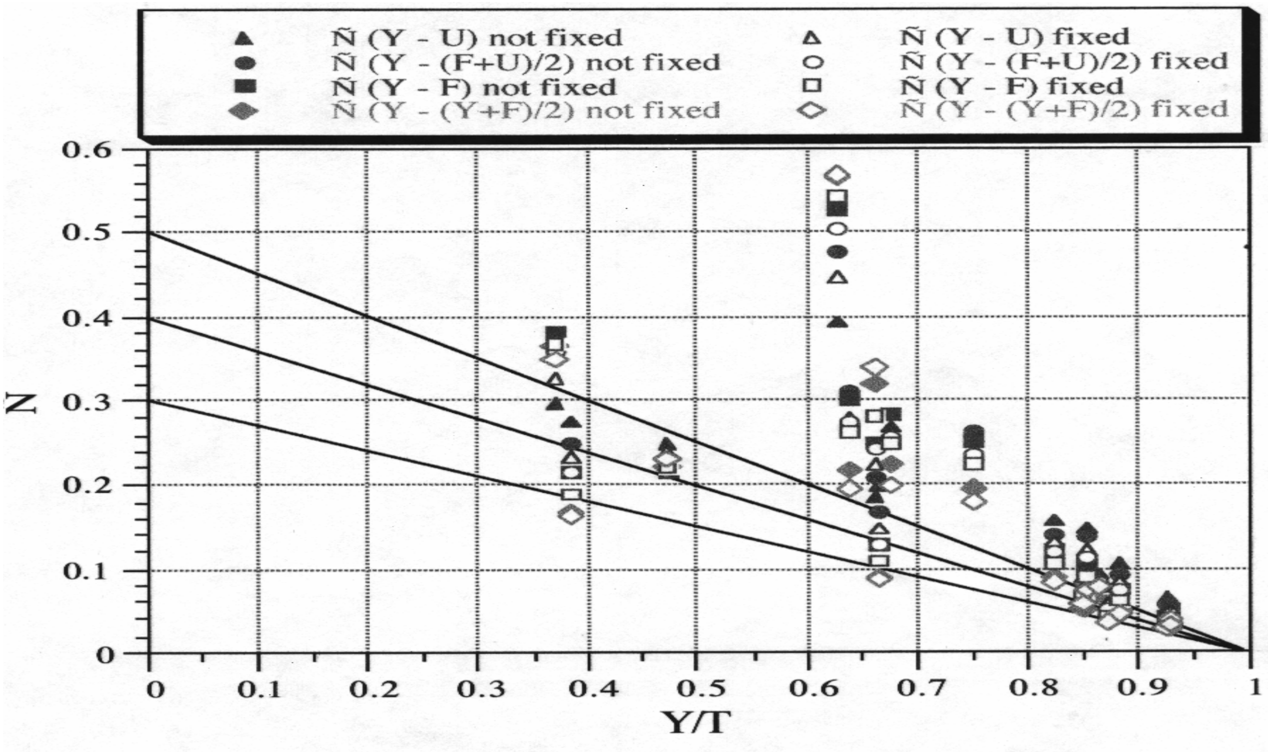

Fig. 3. Prediction of N from YS/UTS : Effect of Portion of Stress-Strain Curve used to Define N (Plastic Strain Only)

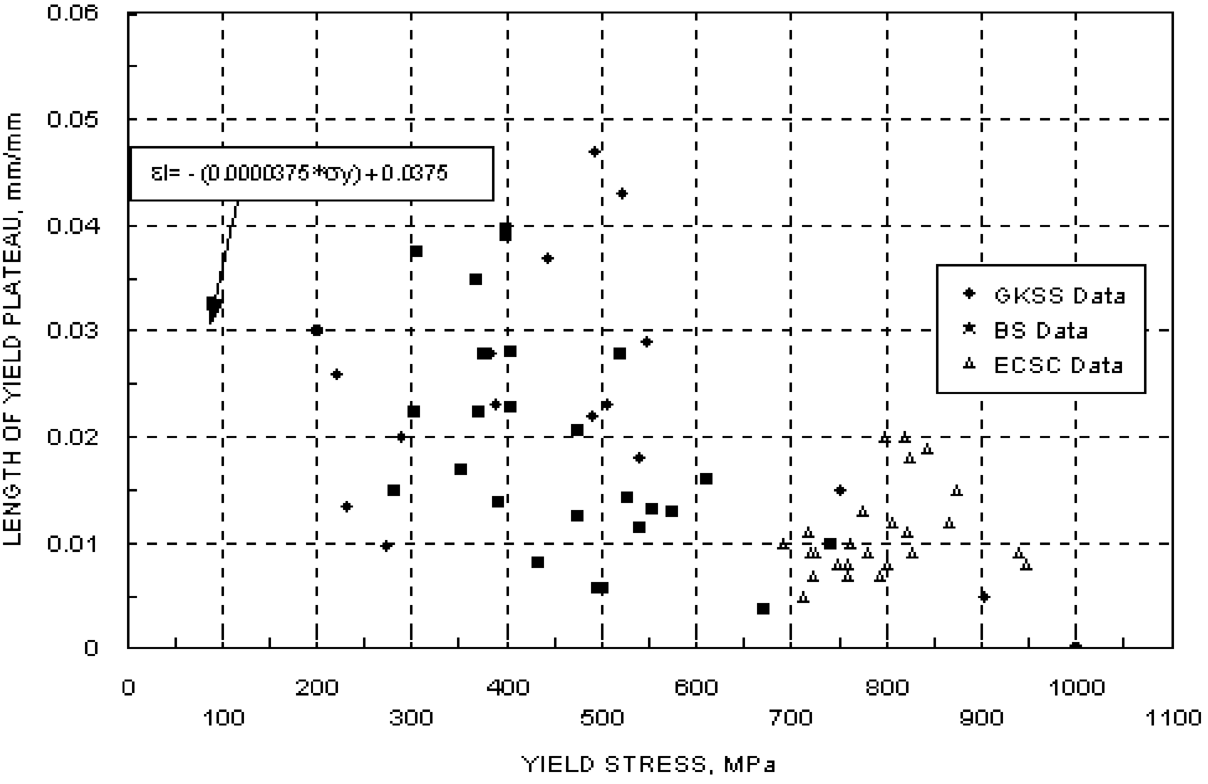

Fig. 4. Luders Plateau Length as a Function of YS and Proposed Expression for Estimation Purposes

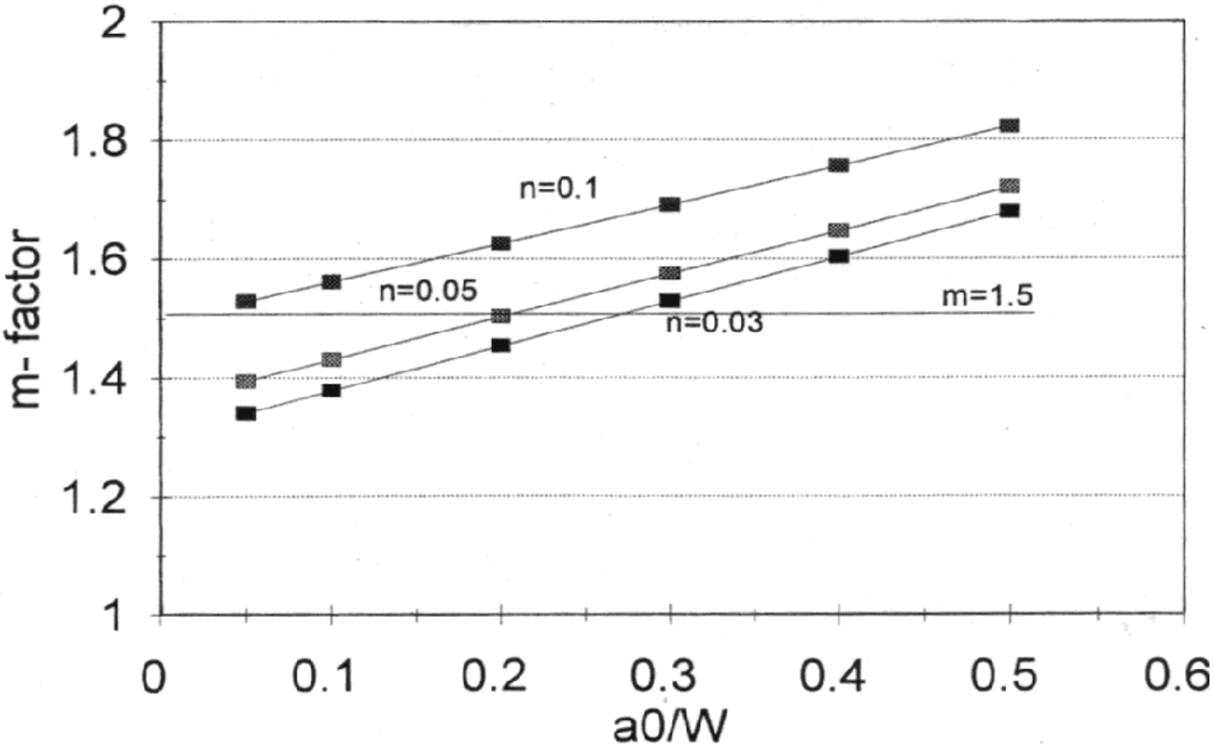

Fig. 5. M-Factors Predicted using ASTM E1290 Method for various N and a/W values