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SINTAP

CONTRIBUTION TO SUB-TASK 2.3: ASSESSMENT OF THE OCCURRENCE AND SIGNIFICANCE OF YIELD PLATEAUS IN STRUCTURAL STEELS

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SUMMARY

ASSESSMENT OF THE OCCURRENCE AND SIGNIFICANCE OF YIELD PLATEAUS IN STRUCTURAL STEELS

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Within the current revision 3.0 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 an estimate of the length of the plateau, should one be assumed to be present, is also required. This note details work carried out to enable the above two characteristics to be defined. It is divided into the following sections.

- The Yield Point Phenomenon
- Test conditions favouring a yield plateau
- Structural loading conditions favouring a yield plateau
- Metallurgical factors influencing occurrence of yield plateau
- Estimation of length of plateau
- Analysis of test data to assess structural significance

Interim guidance for the SINTAP procedure is presented, although it should be emphasised that this is an interim report prior to the full availability of test data from Sub-Task 2.3 (Yield/Tensile Ratio). However, the structural significance of the yield plateau appears to be relatively minor and limited to certain specific material/configuration/loading/crack depth combinations. It is therefore not necessary to incorporate this aspect into a structural assessment in a completely conservative manner as their appearance is mainly a feature of small tensile tests.

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CONTENTS		Page
1.	BACKGROUND	3
2.	THE YIELD POINT AND YIELD POINT ELONGATION PHENOMENA	3
3.	TENSILE TEST CONDITIONS FAVOURING A YIELD PLATEAU	4
4.	STRUCTURAL LOADING CONDITIONS FAVOURING THE FORMATION OF A YIELD PLATEAU	4
5.	METALLURGICAL FACTORS INFLUENCING THE YIELD PLATEAU	4
5.1	General Observations	4
5.2	Analysis of British Steel Dataset	5
5.3	Analysis of ECSC Dataset	6
6.	INTERIM SINTAP GUIDANCE FOR SELECTION OF APPROPRIATE FAD AT LEVELS 1 AND 2	7
7.	ASSESSMENT OF THE LENGTH OF THE YIELD PLATEAU	7
8.	IMPLICATIONS TO THE FAILURE ASSESSMENT DIAGRAM (FAD)	8
9.	EFFECT OF YIELD PLATEAU ON LARGE SCALE TENSILE BEHAVIOUR	8
9.1	Specimen Types and Materials	8
9.2	Results	9
9.3	Discussion	11
10.	CONCLUSIONS AND RECOMMENDATIONS	12
10.1	Occurrence of Yield Plateau	12
10.2	Structural Relevance of Yield Plateau	12
	REFERENCES	13
	TABLES	14
	FIGURES	F1

ASSESSMENT OF THE OCCURRENCE AND SIGNIFICANCE OF YIELD PLATEAUS IN STRUCTURAL STEELS

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1. BACKGROUND

The occurrence of the yield, or Lüders, Plateau in the stress-strain curve of a structural material can greatly influence the performance of the material in structural applications involving loading beyond yield stress. Irrespective of whether a Failure Assessment Diagram (FAD) or Crack Driving Force (CDF) approach is used to analyse a defect-containing structure, a decision must be made as to whether the material should be analysed assuming a discontinuous stress-strain curve (i.e. with a yield plateau) or assuming a continuous curve. For the lower levels of the SINTAP procedure this decision must be made based on data commonly available on a steel test certificate; namely process route, composition, heat treatment and yield stress.

Little guidance is currently available for potential users of the SINTAP procedure as to when a yield plateau should be assumed and what its structural significance might be. In this note an analysis of the effects of steel composition and processing routes has been made to enable qualitative guidance to be given to enable the correct type of stress-strain curve to be assumed. In addition, when the plateau is assumed a conservative estimate of its length is also required. The data have therefore also been assessed to enable a conservative (upper-bound) estimate of the plateau length as a function of yield stress. Finally, an analysis of test data was carried out to determine the conditions necessary for the yield plateau to be structurally significant.

The results of this analysis are presented here together with areas where further guidance needs to be developed.

2. THE YIELD POINT AND YIELD POINT ELONGATION PHENOMENA

Many materials such as structural steels, titanium and tungsten alloys frequently show a yield point phenomenon during the tensile test. The stress drops suddenly from the upper yield point to the lower one, about which it fluctuates until a specific value of strain, namely the Lüders strain, is reached. The deformation process in this strain range is regarded to be a series of local plastic flow events, oriented at 45° ⁽¹⁾, and propagating through the specimen to its end prior to the start of global strain hardening. Figure 1 shows this phenomenon and gives definitions of the terms used subsequently in this note.

The yield point can be produced in all common metallic microstructures provided that interstitial elements are present and that correct test procedure is adopted. The pinning of dislocations by interstitial atoms, the stress required to unpin these dislocations and their subsequent speed and density are the interrelated factors which affect the occurrence and length of the yield plateau. Furthermore, since different atoms have differing effects on the mobility of dislocations, and the position of these atoms relative to the dislocations is a thermally activated process, it follows that the yield point phenomenon is a function of both steel composition and heat treatment rather than the absolute strength of the material itself.

The ease of movement of dislocations through the crystal lattice is fundamental to the occurrence or otherwise of the yield plateau. The force required to move these dislocations is known as the Peierls-Nabarro Force (P-N-Force). In Face-Centred-Cubic metals the P-N force is low and a yield point and plateau are rarely observed. In Body-Centred-Cubic metals the P-N force is significant and sharp yield points followed by a Lüders extension are frequently observed.

3. TENSILE TEST CONDITIONS FAVOURING A YIELD PLATEAU

The attainment of a sharp upper yield point and subsequent plateau can be promoted by certain test conditions, irrespective of the characteristics of the material. In particular, the following conditions favour the formation of the yield plateau⁽²⁾:-

- An elastically rigid (stiff) testing machine.
- Careful axial alignment of the specimen.
- Specimens free from stress concentrations.
- High loading rate.
- Low temperatures.

The test machine stiffness is particularly important since a perfectly soft machine does not allow a load drop and hence will not permit a sharp yield drop after the upper yield point has been reached, Fig. 2.

Even taking data for ambient, or near-ambient temperatures and conventional slow strain rates it is clear that the trends in yield plateau occurrence cannot be attributed solely to material characteristics; significant scatter in results is therefore anticipated and as such only trends, or at best a conservative bound, for the data can be ascertained.

4. STRUCTURAL LOADING CONDITIONS FAVOURING THE FORMATION OF A YIELD PLATEAU

Although a yield plateau may be observed in the tensile test, it is usually the case that such behaviour will not be exhibited in a structural component, although the geometry of the component and the loading mode will influence the behaviour in this respect. This is further complicated by the concept of local and global collapse.

Plateaus tend to be suppressed by any situations with non-uniform strain; for example bending or defective components. For cracked components the yield plateau is generally not exhibited unless the configuration has very low constraint, and for a plateau to be favoured, the loading must be predominantly tensile. A general summary of the loading conditions necessary for the yield plateau to play a significant role in overall structural behaviour are summarised in Table 1. These issues are further addressed in Section 9, where data from a range of structural steels have been investigated.

5. METALLURGICAL FACTORS INFLUENCING THE YIELD PLATEAU

5.1 General Observations

The general trend for the occurrence and length of the yield plateau is that as yield strength increases the likelihood of obtaining a yield plateau decreases as does the length of the plateau in the cases that one is obtained. The typical trend in the shape of the stress-strain curve with increasing strength is shown in Fig. 3. However, this trend is not a function of strength per se, but more a function of the alloying system used in the steel and the heat treatment used to achieve the properties. Since certain alloying elements are also used to enhance strength it does however follow that the yield point and plateau are indirectly related to yield strength. The length of the yield plateau has been related to the grain size through a Hall-Petch type relationship⁽¹²⁾, where the yield point elongation is proportional to $K (\text{grain size})^{-1/2}$, where K is a factor depending on test conditions.

The mobility of dislocations in steels is particularly influenced by the presence of interstitial atoms and their availability for the locking of dislocations. In steels the main interstitial elements are carbon, nitrogen, boron and hydrogen with the first two having a particularly strong effect on mobility of dislocation and the second two only a weak effect. If carbide or nitride formers are added, reducing the level of interstitial atoms that are potent lockers of dislocations by forming an atmosphere around them, then continuous yielding will be promoted⁽⁴⁾. These elements are:

- Nitride formers: Al, Si, and B
- Carbide formers: Mo
- Carbide and Nitride formers: Cr, V, Nb and Ti.

Hence, it is apparent that certain alloying systems will tend to minimise the potential of forming a yield plateau and, furthermore, these systems will usually be associated with specific strength levels. Furthermore, any process which induces plastic strain, such as cold forming or temper rolling, will often remove the yield point and associated plateau, although the phenomenon can be recovered by ageing of the steel. A number of datasets have been assessed to investigate the relationship between alloying system/heat treatment and the attainment of a yield plateau. A summary of the dataset from BS, which comprises predominantly the steels being studied in SINTAP Task 2, is shown in Table 2, while a similar dataset taken from the contribution of IEHK⁽⁵⁾ to a collaborative ECSC project is given in Table 3.

5.2 Analysis of British Steel Dataset

For the BS steels analysed, detailed in Table 2, the following general trends are observed:

Effect of Boron: Boron addition, made for Q&T grades to improve hardenability, tends to lead to a continuous stress-strain curve with no yield plateau, especially when used in conjunction with Mo.

Effect of Titanium: In B-steels the boron only confers hardenability if it is protected from forming nitride. Therefore all the N must be combined with another element and titanium is often added for this purpose to form Ti-N. This is able to lock dislocations and therefore leads to the formation of a yield plateau.

Effect of Mo: Molybdenum, also added to increase hardenability in Q&T steels, tends to favour a continuous stress-strain curve. (Comparison of Steels 1, 3 and 13.) Steel 3 is particularly interesting in this respect since this was a Q&T composition but tested in the Normalised condition: The absence of the yield plateau in this steel demonstrates that it is the composition and not the process route which affects the occurrence of the plateau since normalised steels of conventional composition would normally show a yield plateau.

Effect of Nb: Niobium, usually added for precipitation strengthening in TMCR steels, will generally favour a yield plateau unless it is in combination with other elements such as Mo.

Effect of V: Vanadium forms carbides on grain boundaries and therefore tends to favour the formation of a yield plateau.

Effect of Heat Treatment: Any heat treatment process tends to favour the formation of a yield plateau. Steels 13 and 14 have essentially the same composition but different heat treatments: the as-quenched steel has no plateau while the tempered steel has. This is further supported by data for pure iron-carbon alloys which show a clear relationship between heat treatment time and yield plateau length, Fig. 4. It will be noted, however, in Fig. 4 that the length of the plateau increased with increasing strength level for this steel. This is probably due to the fact that the heat treatment used is one for precipitation hardening (low temperature) which increases strength rather than the more conventional tempering heat treatment.

Effect of Welding: Heating cycles, such as those experienced by HAZs, tend to lead to a continuous stress-strain curve irrespective of the fact that a yield plateau may have existed in the parent material.

5.3 Analysis of ECSC Dataset

5.3.1 Compositional and Heat Treatment Aspects

The ECSC dataset comprises high strength steels produced predominantly by the Q&T route, Table 3. For these steels the yield plateau occurrence can again be explained in terms of the presence of interstitial alloying elements able to cause the atmosphere around the dislocations.

In Set 1 the Q&T treatment was enough to create the yield plateau, and although the two steels have approximately the same composition they have different yield strengths due to varying temper treatments. For the steels in Sets 2 to 5, the tempering treatment in the lower yield strength variant of each composition was sufficient to create the conditions necessary for a discontinuous yielding behaviour even though both Boron and Molybdenum were present.

In sets 6 and 12, the high Vanadium levels coupled with what can only be a very light tempering treatment (if one was used at all) has led to the trend of continuous yielding behaviour. This behaviour is further expected when the Molybdenum addition is also considered.

In set 7 two steels of the same composition but different process routes (Q&T and DQT) are compared. The yield plateau is absent for the Q&T steel but is present when the steel is processed by the DQT route, the latter route not employing any reheating after rolling.

For the steels in sets 8 and 9, tempering has been used to achieve a yield stress of approximately 800 MPa and a discontinuous yielding curve is obtained despite the presence of the elements usually associated with the presence of a plateau (Mo and B). In rows 10 and 11 the presence of Ti and Nb respectively, coupled with a high Molybdenum level leads to the absence of a plateau despite a tempering heat treatment.

5.3.2 Significance of Test Temperature

Generally, these results shows that decreasing test temperature from room temperature to -40°C has caused a decrease in the size of the yield plateau, and in some cases its complete disappearance. This is in some contrast to claims that decreasing temperature leads to increasing length of the yield plateau⁽⁶⁾. However, the temperatures required for this effect are very low, -120 to -196°C and at these temperatures the yield stress is very high. The possible explanation for this fact may be related to the high stress required for yielding, potentially activating the secondary slip systems and leading subsequently to enhanced plastic deformation. In addition, an increase in the strain rate enhances the temperature effect such that the plateau length increases with only a modest reduction in temperature, Fig. 5⁽⁶⁾.

6. INTERIM SINTAP GUIDANCE FOR SELECTION OF APPROPRIATE FAD AT LEVELS 1 AND 2

Based on the analysis presented in Section 5, the assumption of whether a steel should be assumed to have continuous or discontinuous yielding behaviour can be made with knowledge of:-

- The process route used.
- The composition.
- The yield strength.

The selection criteria are shown by means of a table (Table 4). The criteria for selection or otherwise of a FAD assessing a yield plateau are based on the influence of yield strength, composition and heat treatment on the yielding characteristics as discussed in previous sections. (It should be noted that areas of uncertainty in the final column of this table are marked in brackets.) This should be used in conjunction with Table 1 to assess whether, in the case of discontinuous yielding, this is relevant to the structural conditions being assessed. When it is suggested that a plateau should be assumed its length should be estimated according to the recommendations given in Section 7.

One remaining aspect of contention is that assumption of the presence of a yield plateau will lead to a more conservative FAD: however, those steels with yield plateaus tend to have higher strain hardening exponents than those without and it may therefore be over conservative not to allow for this hardening in a structural analysis. This aspect is addressed in Section 9, where it is demonstrated that strain hardening following the yield plateau is only present in a large scale cracked component if the yield point elongation is low.

7. ASSESSMENT OF THE LENGTH OF THE YIELD PLATEAU

Due to the number of variables influencing the yield plateau phenomenon it is not possible to derive a unique relationship relating its length to metallurgical or mechanical factors. Bearing in mind the level of the procedure for which this information is required (i.e. not the highest accuracy level) it follows that a conservative bound to available data will be appropriate. Three data sets were analysed for this purpose; the BS and ECSC data shown in Tables 2 and 3 and data received from GkSS⁽⁷⁾. In all cases data at temperatures significantly above or below room temperature have not been included. The length of the plateau was plotted as a function of yield strength; although this is not the only factor influencing the plateau length it is a readily available data input for the lower levels of the procedure. The resultant plot is shown in Fig. 6(a).

For an upper bound description to these data a simple set of equations can be derived: the equations conservatively relating the length of the yield plateau (ϵ_1) to yield strength (YS) are:

$$\text{For } YS < 500 \text{ MPa, } \epsilon_1 = 0.05 \quad \dots (1)$$

$$\text{For } 500 < YS < 1050 \text{ MPa, } \epsilon_1 = -(0.000091 \text{ YS}) + 0.0955 \quad \dots (2)$$

$$\text{For } YS > 1050 \text{ MPa, } \epsilon_1 = 0 \quad \dots (3)$$

However, considering the proposals made elsewhere within the SINTAP procedure for relating tensile parameters such as Y/T ratio (Yield Stress/Ultimate Tensile Stress) and N (Strain hardening exponent) it is felt that the use of the upper bound relationship described in expressions (1-3) would be unduly conservative. Consequently, the following expression is proposed and represents a reasonable fit to the data when the range of parameters affecting the relationship is considered:

$$\epsilon_1 = -(0.0000375 \times YS) + 0.0375 \quad \dots (4)$$

The line representing this relationship is shown in comparison with the aforementioned data set and the upper bound relationship in Fig. 6(b).

For the purposes of the SINTAP procedure it is recommended that Equation (4) is expressed as:

$$\epsilon_1 = 0.0375 \left(1 - \frac{YS}{1000} \right) \quad \dots (5)$$

8. IMPLICATIONS TO THE FAILURE ASSESSMENT DIAGRAM (FAD)

Using the two estimation schemes proposed in Section 7, and assuming Young's Modulus = 210 GPa, the effect on the FAD was assessed⁽⁹⁾. The FAD derived from the R6 Option 1 was compared with the R6 Option 2 FAD, Fig. 7(a). At $L_r = 1$, there are two values of K_r for the R6 Option 2 FAD for materials showing discontinuous yielding. Because of the proposed schemes for determining the length of the yield plateau and the expression used to calculate the FAD, the lower of the K_r values at $L_r = 1$ ($(K_r)_{L_r=1}^{\text{lower}}$), varies with yield strength. The relationship is shown in Fig. 7(b) for the upper-bound estimation scheme (Equations (1), (2), (3) and the best-estimate scheme (Equation (4)). The value of $(K_r)_{L_r=1}^{\text{lower}}$ for the upper-bound scheme shows little sensitivity to yield strength below $YS = 500$ MPa, due largely to the constant value of ε_1 proposed for this range of yield strength in expression (1). At $YS = 1050$ MPa, $(K_r)_{L_r=1}^{\text{lower}} = (K_r)_{L_r=1}^{\text{upper}}$ since the material is then assumed to show continuous yielding behaviour (i.e. no yield plateau, expression (3)). For the 'best-estimate' scheme, as represented by Equation (4), the predicted values of $(K_r)_{L_r=1}^{\text{lower}}$ are higher than the equivalent values determined using the upper-bound scheme; the greatest difference lies in the YS range ~500-800 MPa.

9. EFFECT OF YIELD PLATEAU ON LARGE SCALE TENSILE BEHAVIOUR

9.1 Specimen Types and Materials

Within Sub-Task 2.3, data are available for parent plates which enable the stress-strain characteristics of three specimen types to be compared. These are:

- Conventional small scale tensile specimens used for determining tensile properties.
- Centre-Cracked-Tensile (CCT) specimens containing surface notches of various geometries.
- Wide plate specimens with surface notches

CCT and wide plate specimen designs are shown in Fig. 8. The data currently available are for a range of materials of varying stress-strain characteristics with and without yield plateau, as summarised in Table 5. All tests were carried out at -20°C in pure membrane loading. These data have only been analysed in this current work in terms of global stress-strain characteristics as calculated from load and diametrical clip gauge readings for the tensile tests, and load and LVDT readings for CCT and wide plate tests. Localised strains and crack opening responses in the latter two test types are not addressed here but will be covered in detail in the Sub-Task 2.3 report. Furthermore, selected tests on HAZ-notched CCT and wide plate specimens will be reported later in Sub-Task 2.3.

Further data have also been supplied⁽⁹⁾ for an A533B wide plate, an edge-cracked wide plate for 50D material but with a simulated structural attachment and welded surface cracked tensile panels of a similar geometry to those shown in Fig. 8 (100 mm wide) but with different mis-match levels.

9.2 Results

9.2.1 355EMZ 25 mm Plate

Tensile, CCT and wide plate test results are available for this material. The principal observations made on comparison of these data are:

- The two tensile tests for this material showed significantly different behaviour; one continuous and one discontinuous, Fig. 9. The 0.2% PS determined from the continuous curve was 315 MPa, the LYS determined from the discontinuous curve 473 MPa.
- Comparison of the two tensile test results with CCT data is given in Fig. 10(a and b) for strains up to 5% and 1.5% respectively. A yield-point is just discernible for notch Types A and C. The maximum stress achieved in the CCT tests exceeds the measured 0.2% PS but does not reach the measured LYS, Table 6.
- Comparison of the tensile results with the wide plate test is given in Fig. 11(a and b) for strains up to 15% and 1.5% respectively. The wide plate loading curve deviates from the elastic line at a stress of ~350 MPa, with a maximum stress in the wide plate equal to the UYS achieved in the tensile test

which showed discontinuous yielding. There was no evidence of a pronounced yield point in the wide plate test. However, the strain levels in the wide plate test lie within the yield point elongation strain range of the tensile test such that the wide plate did not reach the strain level necessary for hardening to commence.

9.2.2 355EMZ 50 mm Plate

Tensile and wide plate data are available for this material. The principal features of these are:

- Both the tensile tests showed very similar behaviour; yield points were present in both; average UYS and LYS values were 459 and 398 MPa respectively; one of the stress-strain curves is shown in Fig. 12.
- the wide plate loading curve is shown in comparison with the tensile test results for strains up to 5% in Fig. 13. Wide plate strain levels above 1.5% were not able to be recorded due to a technical problem. In this example, the wide plate does not achieve the UYS demonstrated in the tensile test, and the maximum load achieved was 9 MPa lower than the average LYS measured in the tensile test. There was no evidence of a yield plateau.

9.2.3 450EMZ 25 mm Plate

Only tensile and wide plate data are available at present and are reported here.

- Both repeats of the tensile test showed very similar behaviour, yield points being present in both tests and an average UYS and LYS of 515 and 482 MPa respectively. The change from the yield plateau to continuous hardening occurred at an engineering strain value of ~1.5%. One of the stress-strain curves is shown in Fig. 14.
- The wide plate behaviour is shown in Fig. 15(a and b). This plate showed some evidence a yield plateau in the wide plate loading curve with the plateau occurring at a stress of ~540 MPa between the yield strain and ~2%, beyond which slight hardening started to occur. The maximum stress achieved was 584 MPa, at which point the test was terminated due to exceedance of LVDT capacity.

9.2.4 450EMZ 50 mm Plate

The 50 mm plate of the same grade of steel described in 9.2.3 showed similar, but not identical behaviour:

- Both tensile tests showed yield points, one example is given in Fig. 16, with average UYS and LYS 533 and 529 MPa respectively.
- The wide plate stress-strain curve, Fig. 17, was elastic up to a stress of ~550 MPa, which is equivalent to the average UYS for this material. However, unlike the 25 mm plate, the wide plate then demonstrated slight hardening continuously beyond yield without a plateau.

9.2.5 StE690 25 mm Plate

This plate is a high strength quenched and tempered steel for which tensile, CCT and wide plate tests have been completed.

- Both tensile tests carried out for this material showed continuous yielding, with an average 0.2% PS value of 673 MPa. One of these tensile curves is shown in Fig. 18.
- CCT tests carried out on this material showed similar characteristics to the tensile test, Fig. 19. There was little difference in the loading curves for the three different notch geometries; for the specimen with which Type A, considerable noise was present on the test record, this is not associated with the specimen behaviour.
- The wide plate behaviour of this material is similar to that of the CCT panels in that there is no evidence of a yield point, Fig. 20. The loading curve deviates from elastic behaviour at a stress of ~475 MPa, and a maximum stress of 760 MPa is achieved prior to fracture. Fracture occurred only after 7 mm of ductile tearing.

9.2.6 A533B Wide Plate

Figures 21 and 22 show tensile test and surface-cracked wide plate results respectively for an A533B 50 mm thick plate⁽⁹⁾. The crack depth/plate thickness ratio was 0.5. The tensile test shows a Lüders Plateau but the wide plate loading curve is nearly continuous throughout.

9.2.7 50D Plate With Structural Attachment

Figure 23 shows stress-strain curves for a 50D structural steel (S355J2 to BS EN 10025) at three different test temperatures⁽⁹⁾. Results of a wide plate test incorporating a welded edge attachment with a crack in the vicinity of this attachment, are shown in Fig. 24. The stress-strain curves demonstrate a Lüders Plateau but the wide plate load-displacement curve representative of a structural configuration does not show a yield plateau.

9.2.8 Welded Plate Specimens Incorporating Varying Mis-Match Levels

Figure 25 shows stress-strain curves for two different base materials and a weld metal used in a mis-match study⁽¹⁰⁾. Base material M01 is a 25 mm thick 450 EMZ plate and M02 is a 25 mm thick grade 690 plate, both produced by the Quenched and Tempered route. All the stress-strain curves exhibit Lüders Plateaux. Results of 'mini-wide plate' specimens are shown for various mis-match conditions and crack configurations in Fig. 26. None of these tests showed a Lüders Plateau.

9.2.9 Other Materials Within Sub-Task 2.3

Within Sub-Task 2.3 tensile, CCT and wide plate data are also being generated but at the present time data sets are incomplete so a full analysis cannot be made. The full extent of data which will be covered in the final report are summarised in Table 7.

9.3 Discussion

The full data sets from the Sub-Task 2.3 test matrix will be reported in the final report for this sub-task. However, for the data assessed in this report, the following observations can be drawn.

For the case of a material exhibiting both continuous and discontinuous yielding in repeats of tensile tests, the structural behaviour in a configuration containing a crack is best approximated by the LYS. The 0.2% PS, determined from the continuous stress-strain curve is too conservative while the UYS is an overestimation of the capacity of the material in a large scale structural loading situation.

The 355EMZ 25 mm plate, which in accordance with Table 4, would be predicted to have a yield plateau, also showed slight evidence of a yield point and plateau in the CCT tests for the notches A and C. Notch B, the deepest and longest crack, did not show a plateau.

For materials which demonstrate a yield plateau length of 4-5%, the wide plate test shows a flat yield curve, Figs. 11(b) and 13, with very little hardening; this is presumably due to the wide plate elongation lying totally within the strain range of the yield plateau shown in the conventional tensile test. For materials which have only a small yield point elongation, the wide plate test in one case (thin, low constraint, specimen) shows the same behaviour since the yield point elongation lies within the wide plate elongation range, Fig. 15(a). For similar material but higher constraint (same a/B ratio but thicker) material, the yield elongation in the wide plate test is not present, Fig. 17.

Data for an A533B steel, a 50D steel with welded attachment and 450/690 grade steels with different mis-match levels show that although the small scale tensile test may show a yield plateau, this is not manifested in the wide plate test.

The current analysis suggests that for materials exhibiting a small (e.g. <2%) yield point elongation in the conventional tensile test, a similar plateau followed by onset of hardening may be present in the behaviour of a cracked plate of low constraint when loaded in tension: for higher constraint the plateau is absent and hardening commences directly after yielding. For materials with larger yield plateaus (2-5%) the behaviour of a cracked plate in tension is similar to that of an elastic-perfectly plastic material.

10. CONCLUSIONS AND RECOMMENDATIONS

10.1 Occurrence of Yield Plateau

Prior to completion of the full Sub-Task 2.3 work programme, interim recommendations have been made for the treatment of yield plateaus, and their structural significance has been investigated for the case of tension loading.

The yield point and yield plateau phenomena in steels have been investigated in terms of the influence of steel type, composition, heat treatment and test conditions. Two criteria have been assessed:-

- (i) When to assume that a yield plateau should be present.
- (ii) Whether the length of the plateau can be estimated from knowledge of the yield strength.

These criteria are necessary information inputs for Levels 1 and 2 of the SINTAP procedure.

Data for a range of steels have been investigated with a view to defining the metallurgical criteria which dictate whether a yield plateau should be assumed: Recommendations have been made for a procedure which guides the user to the final choice of type of stress-strain curve.

In the case where a plateau should be assumed, a best-estimate fit to a large data set should be used to estimate the length of the plateau. The expression proposed gives a plateau length of 3% at a yield stress of 200 MPa and decreases linearly to zero at a yield stress of 1000 MPa.

10.2 Structural Relevance of Yield Plateau

An analysis of tensile, centre-cracked-tensile (CCT) and wide plate data for a range of structural steels with and without yield plateaus has been made. Large scale structural behaviour, as represented by the wide plate test, can only be conservatively predicted in terms of load bearing capacity when the lower yield stress is used for the analysis (in the case that a yield point is present). For small yield point elongation (<2%), the plateau can sometimes be exhibited in low constraint configurations in tension prior to hardening, whereas in higher constraint (thicker specimens) hardening occurs without the plateau. For larger yield plateaus, the behaviour of large scale wide plate tests approximates to that of an elastic-perfectly plastic material. Analysis of a tension-loaded wide plate with a structural attachment and of tests with varying mis-match levels have shown that the yield plateau is largely irrelevant for these cases. It is concluded that since the yield plateau seems to be largely a feature of the small scale tensile test it is not necessary to account for it in the FAD in a completely conservative manner.

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 2. H. Conrad, Acta Met, 1963, 11, 75.
 3. G.E. Dieter: 'Mechanical Metallurgy', McGraw Hill Publishing, 1988, ISBN 0-07-084187-X.
 4. E.O. Hall: 'Yield Point Phenomena in Metals and Alloys', Macmillan & Co. Ltd., 1970.
 5. T. Nießen: 'Development of High Strength Steels (450-1000 MPa) with optimised Y/T Ratio for High Loaded Applications', IEHK-RWTH, Technical Report No. 4, Contribution to ECSC Contract 7210-KA/124.
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 7. U. Zerbst: 'Additional Data for Y/T-N Approximation', Fax, 29th January 1998.
 8. Y-J. Kim: 'Comments on BS/23 Summary Note: SINTAP Task 5', Fax, 24 June, 1998.
 9. C.S. Wiesner: 'SINTAP Task 2: Lüders Band in Tensile Specimens Compared to Wide Plate Tests', 16 June, 1998.
 10. H.G. Pisarski: 'The Effect of Weld Metal Mis-Match on Structural Integrity Assessments - Experimental Studies', Report 220010/12/44, August, 1994.
- C.D.

TABLE 1
STRUCTURAL CONDITIONS FOR SIGNIFICANT INFLUENCE OF YIELD PLATEAU

Component and Crack Geometries	Loading		
	Predominantly Tensile	Predominantly Bending	~Equal Tensile and Bending
Thin Wall, Shallow Crack	√	X	()
Thin Wall, Deep Crack	√	X	()
Thick Wall Shallow Crack	X	X	()
Thick Wall, Deep Crack	X	X	()

√ = Yield Plateau Structurally Significant
() = Significance Uncertain
X = Yield Plateau Structurally Insignificant

**TABLE 2
BRITISH STEEL DATASET**

Steel ID	BS Reference	Grade	LYS or 0.2% PS	Heat Treatment	Alloying System				Yield Plateau
					Mo	Nb	Ti	V	
1	Y6X190	StE690 ⁽¹⁾	768	Q&T	0.150	0.032	0.029	<0.005	No, due to H. T. and alloying
2	Y7X77	355EMZ	449	TMCR	<0.005	0.022	<0.005	<0.005	Yes, due to the TMCR
3	Y7X78	Experimental Steel (355) ⁽¹⁾	300-368	Normalised	0.21	<0.005	<0.005	0.050	No, high hardenability, the treatment may cause a quench effect
4	Y6X105	355EMZ	381	TMCR	<0.005	0.021	<0.005	<0.005	Yes, due to the TMCR
5	Y6X136	450EMZ	465	Q(930/1'45") T(650/3'25")	0.16	<0.005	<0.005	0.050	Yes, due to tempering
6	Y7X76	StE690 ⁽¹⁾	680	Q(930/50") T(580/1')	<0.005	0.034	0.038	0.063	No, high hardenability and low tempering temperature
7	Y6X158	355EMZ	458	Gleeble	<0.005	0.021	<0.005	<0.005	No, due to Gleeble
8	Y6X201	450EMZ	400	Gleeble	0.16	<0.005	<0.005	0.050	No, due to Gleeble
9	Y7X120	450EMZ	464	Q(930/35") T(625/34")	0.14	<0.005	<0.005	0.050	Yes, due to tempering.
10	Y7X175	Weld	540	Weld					Yes.
11	Y7X176	Weld	485	Gleeble	0.14	<0.005	<0.005	0.050	No, due to Gleeble
12	Y7X100	450EMZ	494	Q(930/35") T(625/40")	<0.005	<0.005	<0.005	<0.005	Yes, due to tempering
13	Y7X100	StE690 ⁽¹⁾	802	Q(930/30") T(580/34")	<0.005	0.037	0.026	0.050	Yes
14	Y7X100	ABRAZO 400 ⁽¹⁾	993	Q(930/38")	<0.005	0.037	0.025	0.064	No, due to quenching

⁽¹⁾ = Boron Treated to Improve Hardenability
 TMCR = Thermomechanically Controlled Rolled
 Q = Quenched
 T = Tempered
 (/) = Heat Treatment, e.g. (930/50") = 930° C for 50 min

TABLE 3
ECSC DATASET⁽⁴⁾

Steel Set	Ident.	Yield Stress	Main Alloying System								Heat Treatment ⁽²⁾	Lüders Strain (%)	
			Mn	Cr	Ni	Mo	V ⁽¹⁾	B ⁽¹⁾	Ti ⁽¹⁾	Nb ⁽¹⁾		RT	-40° C
1	D51	824	0.9	0.5	0.9	0.5	430	22			Q, T	1.85	1.47
	E56	947	0.9	0.5	0.9	0.5	420	20			Q, T	1.1	0
2	D52	780	1.2	0.5	-	0.3	280	16			Q, T	1.27	0.87
	E57	918	1.3	0.5	-	0.3	300	20			Q, T	0	0
3	D53	696	1.3	0.8	0.7	0.4	210	19			Q, T	0.88	0.75
	E58	947	1.3	0.8	0.8	0.4	210	19			Q, T	0	0
4	D54	722	1.3	0.8	1.2	0.5	230	23			Q, T	0.83	0.93
	E59	878	1.3	0.8	1.3	0.5	270	25			Q, T	0	0
5	D55	808	1.2	1.2	1.4	0.5	350				Q, T	0.72	0
	E60	951	1.2	1.3	1.4	0.5	410				Q, T	0	0
6	E65	931	0.7	0.5	1.7	0.4	600				Q, T	0	0
	E69	942	0.7	0.7	1.6	0.4	600				Q, T	0	1.7
	E70	1006	0.7	0.7	1.6	0.4	600				Q, T	0	0
7	D68	677	0.8	0.7	-	0.2	-				Q, T	0	0
	D71	720	0.8	0.7	-	0.2	-				DQ, T	1.0	0.95
8	D61	798	0.8	0.5	-	0.2	390	9	170		Q, T	2	1.9
9	D62	806	1.0	1.1	1.2	0.5	620				Q, T	1	0
10	D66	777	1.0	0.9	-	0.5	-	-	310		Q, T	0	0
11	D67	693	1.4	0.9	-	0.4	-	-		200	Q, T	0	0
12	E64	956	1.3	0.6	-	0.4	640				Q, T	0	0

⁽¹⁾ ppm

⁽²⁾ Q = Quenched, T = Tempered, DQ = Direct Quenched

TABLE 4
SELECTION PROCEDURE FOR DETERMINING WHETHER A YIELD PLATEAU SHOULD BE ASSUMED

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 addition	Conventional normalising	Yes
			Conventional normalising	Yes
	Controlled Rolled	EN 10113 compositions	-	Yes
			-	Yes
		EN 10113 compositions	-	Yes
			-	Yes
350 <YS 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 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

TABLE 5
TENSILE CHARACTERISTICS OF STEELS ASSESSED IN SECTION 9

Grade	Thickness (mm)	Process Route	Average YS ⁽¹⁾ at -20° C (MPa)	n ⁽⁴⁾	Yield Plateau
355EMZ	25	TMCR	315 [†] 473*	0.259	No ⁽²⁾ Yes ⁽²⁾
355EMZ	50	TMCR	398*	0.271	Yes ⁽³⁾
450EMZ	25	Q+T	482*	0.148	Yes ⁽³⁾
450EMZ	50	Q+T	529*	0.156	Yes ⁽³⁾
StE690	25	Q+T	673 [†]	0.105	No ⁽³⁾

⁽¹⁾ YS(*) or 0.2% PS^(†)

⁽²⁾ Two repeats show different behaviour

⁽³⁾ Repeat tests show same behaviour

⁽⁴⁾ Conventionally measured strain hardening exponent

TABLE 6
**YIELD STRESS VALUES COMPARED TO MAXIMUM STRESS VALUES ACHIEVED
IN CENTRE-CRACKED TENSILE AND WIDE PLATE TESTS**

Grade	Thickness (mm)	Tensile Test Values			Maximum Gross Stress Values ⁽¹⁾			
		0.2% PS (MPa)	UYS (MPa)	LYS (MPa)	CCT Notch A (MPa)	CCT Notch B (MPa)	CCT Notch C (MPa)	Wide Plate (MPa)
355EMZ	25	315 -	- 497	- 473	456 NF	439 NF	442 NF	496 NF
355EMZ	50	-	459	398	-	-	-	390 NF
450EMZ	25	-	515	482	(2)	(2)	(2)	584 NF
450EMZ	50	-	553	529	-	-	-	666 NF
StE690	25	673	-	-	735 NF	746 NF	755 NF	760 F

⁽¹⁾ F = Specimen Failure

NF = No Failure

⁽²⁾ Results Not Yet Available

TABLE 7
AVAILABILITY OF DATA FOR FINAL REPORT OF SUB-TASK 2.3

Material	Thickness (mm)	YS (MPa)	Process Route	Tensile Data	CCT Data	Wide Plate Data
S275J0	25	310	N	√	√	√
S355J2	25	380	N	√	√	
355EMZ	25	449	TMCR	√	√*	√
355EMZ	50	381	TMCR	√		√
450EMZ	12.5	494	Q+T	√	√	√
450EMZ	25	464	Q+T	√	√*	√*
450EMZ	50	465	Q+T	√		√
StE690	12.5	802	Q+T	√	√	√
StE690	25	680	Q+T	√	√*	√
StE690	40	770	Q+T	√		√*
ABRAZO 400	12.5	993	Q	√	√	√
ABRAZO 400	25	1160	Q	√	√	√

* Also HAZ Tests

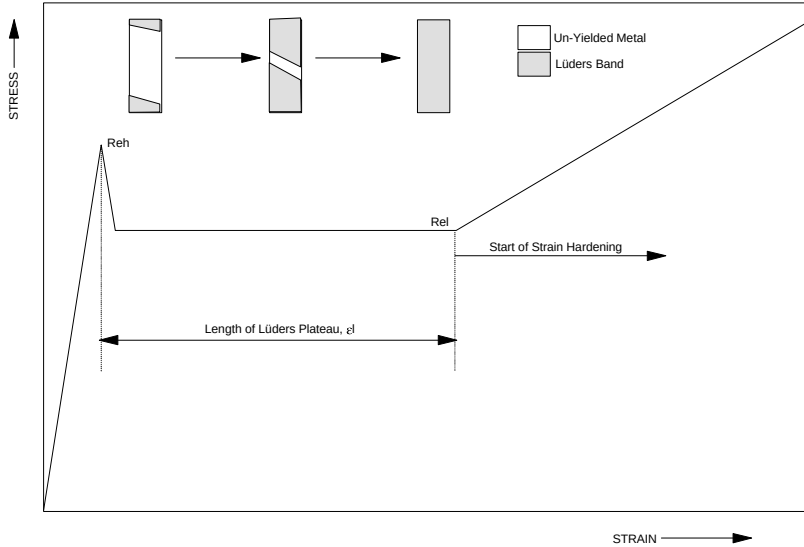


FIG. 1 THE YIELD PLATEAU AND ASSOCIATED DEFINITIONS (D0291E06)

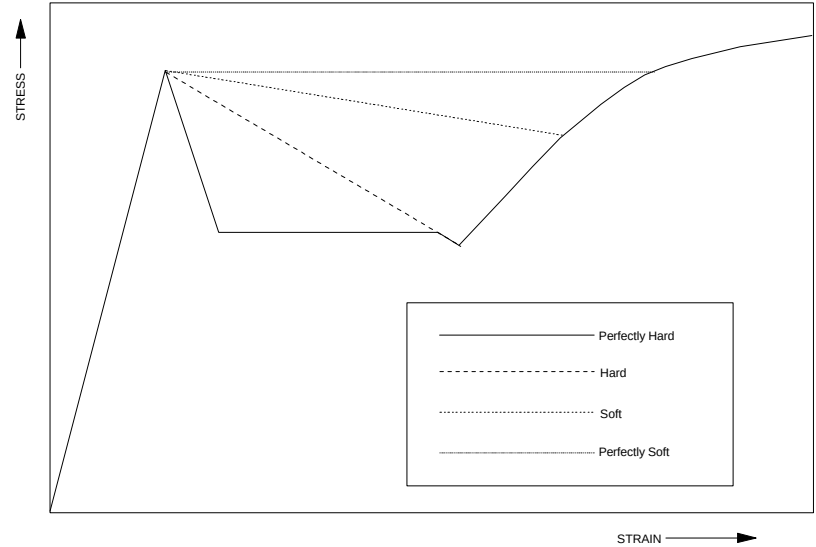


FIG. 2 SCHEMATIC INFLUENCE OF TEST MACHINE COMPLIANCE ON YIELD PLATEAU SHAPE (D0291E06)

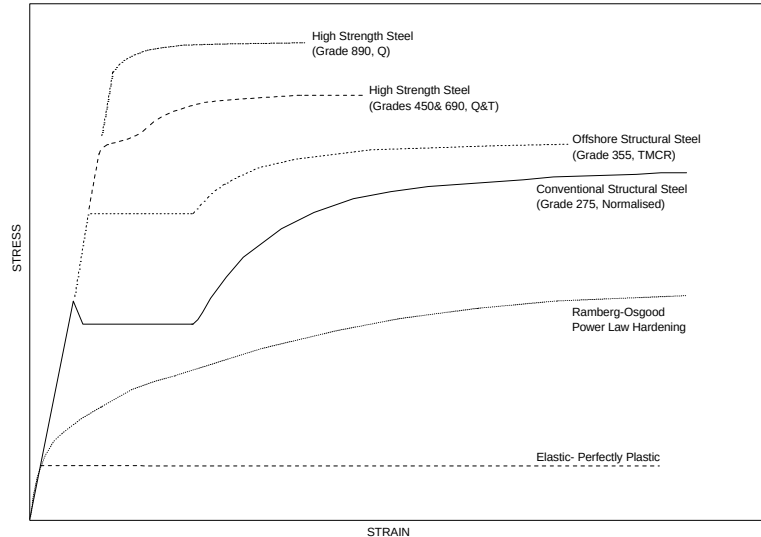


FIG. 3 TRENDS OF YIELD PLATEAU BEHAVIOUR AS A FUNCTION OF STEEL TYPE (D0291E06)

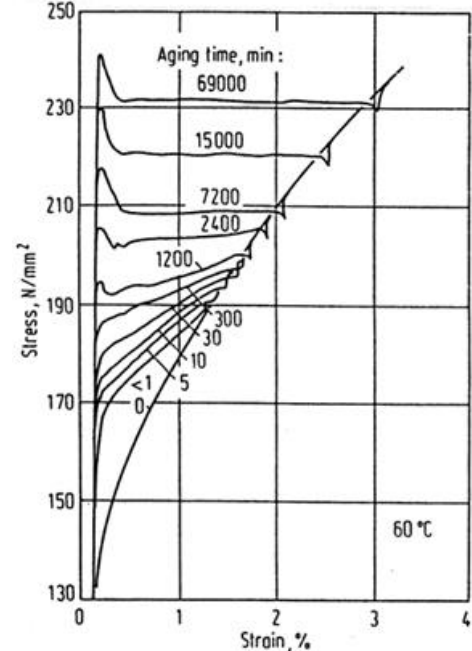


FIG. 4 INFLUENCE OF AGEING TIME ON YIELD PLATEAU FOR AN IRON - 0.01% CARBON ALLOY

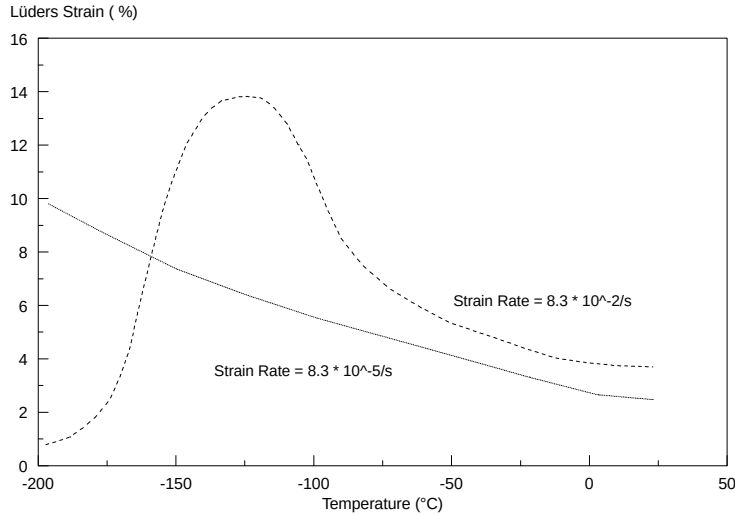
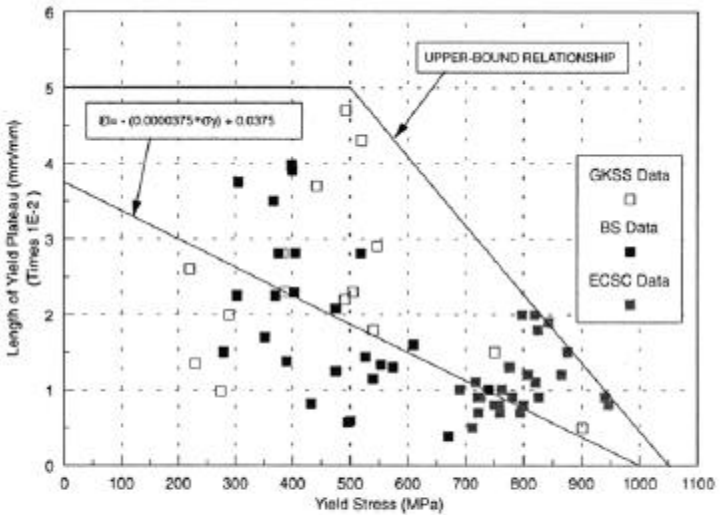
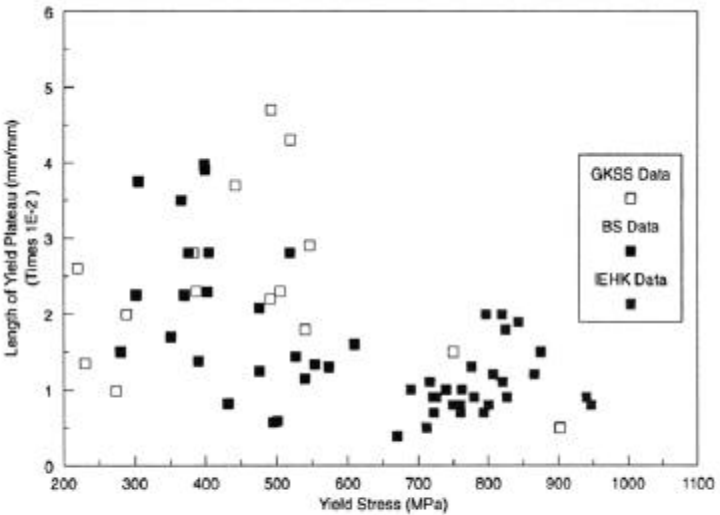
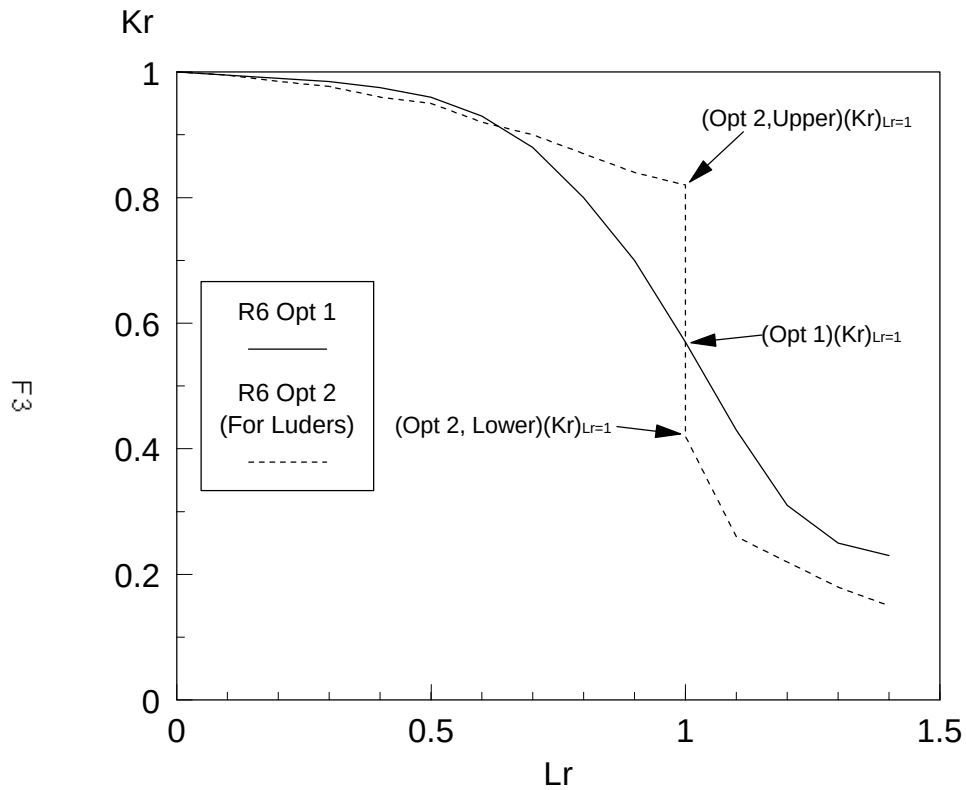


FIG. 5 INFLUENCE OF STRAIN RATE ON LÜDERS PLATEAU LENGTH FOR A 0.09% C STEEL (D0291E07)

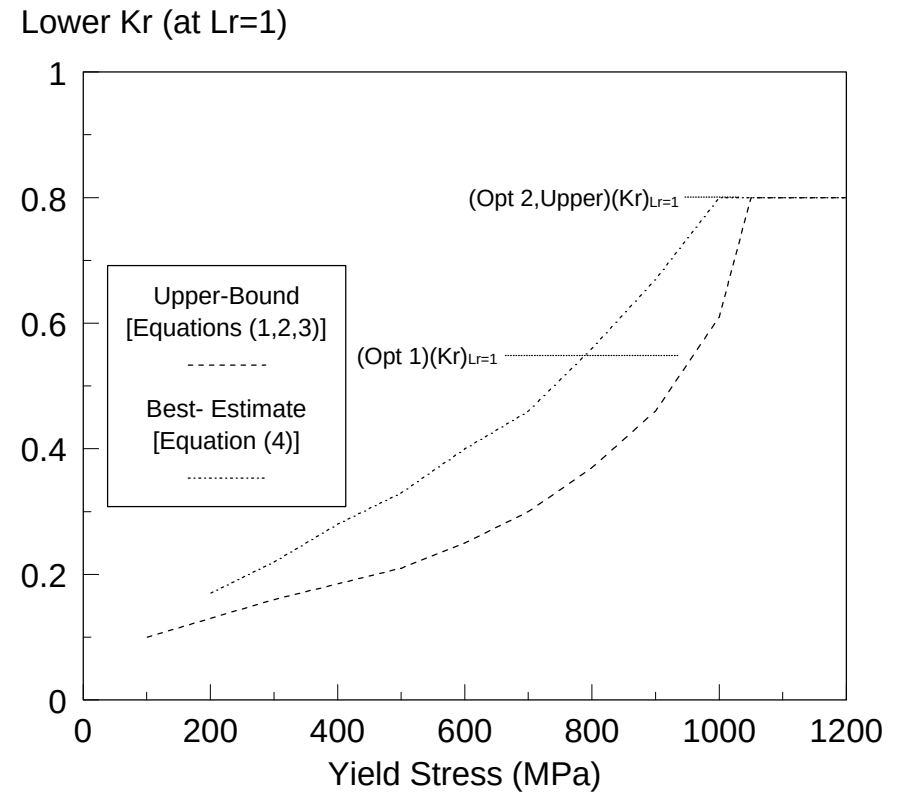


(a) Initial Data (D0291E07) (b) Proposed Estimation Method (D0291E07)

FIG. 6(a and b) LENGTH OF YIELD PLATEAU AS A FUNCTION OF YIELD STRESS



(a) FADs for Option 1 and Option 2 (Lüders) (D0291E07)



(b) Value of Lower K_r at $L_r = 1$ as a Function (D0291E07) of Yield Stress and Equation used to Estimate Yield Plateau Length

FIG. 7(a and b)

IMPLICATIONS OF ESTIMATION SCHEME FOR YIELD PLATEAU LENGTH ON FAILURE ASSESSMENT DIAGRAM⁽⁸⁾

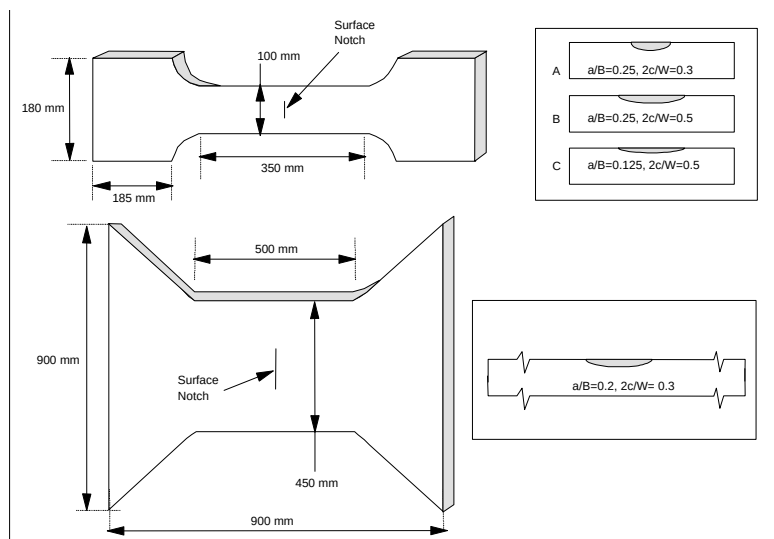


FIG. 8 DIMENSIONS OF CENTRE-CRACK-TENSILE(D0291E08) (CCT) AND WIDE PLATE SPECIMENS

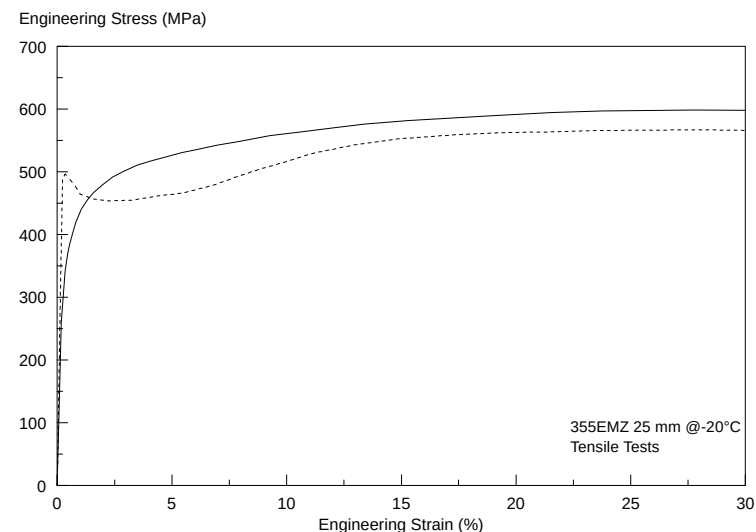
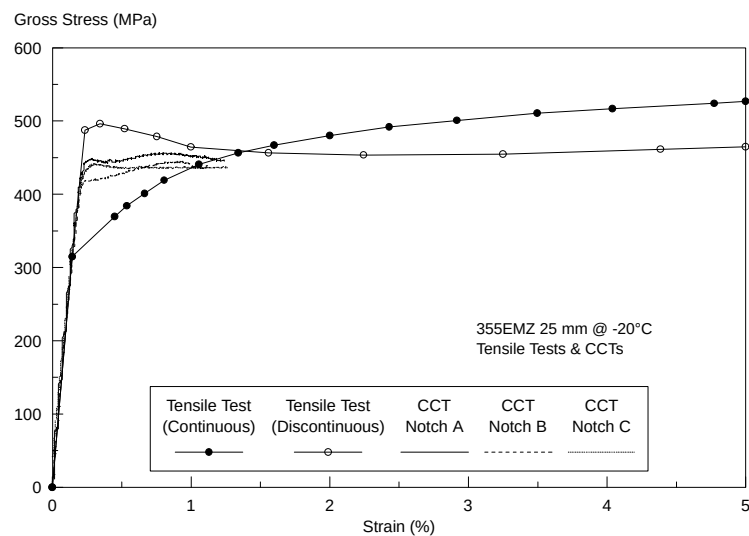
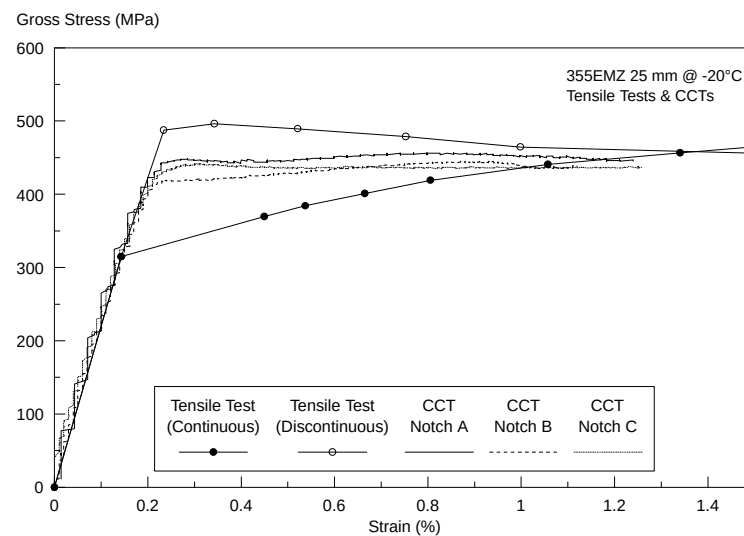


FIG. 9 ENGINEERING STRESS-STRAIN (D0291E08) CURVES FOR 355EMZ 25 mm PLATE

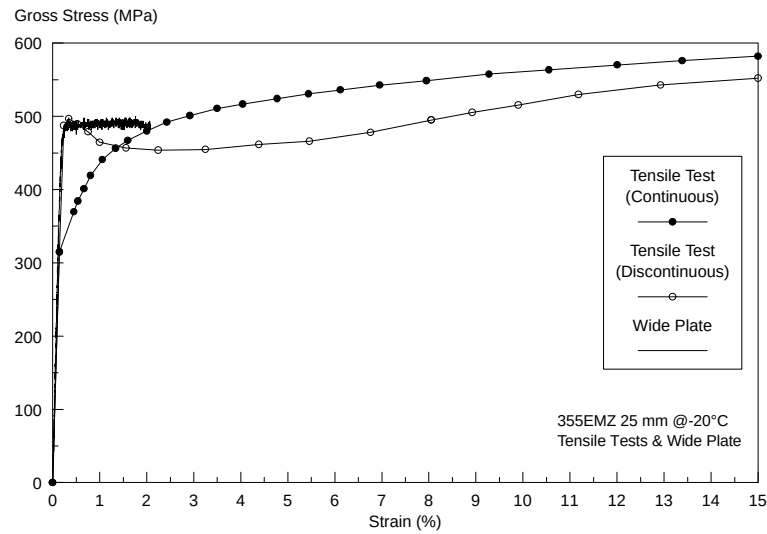


(a) Up to 5% Strain(D0291E08)

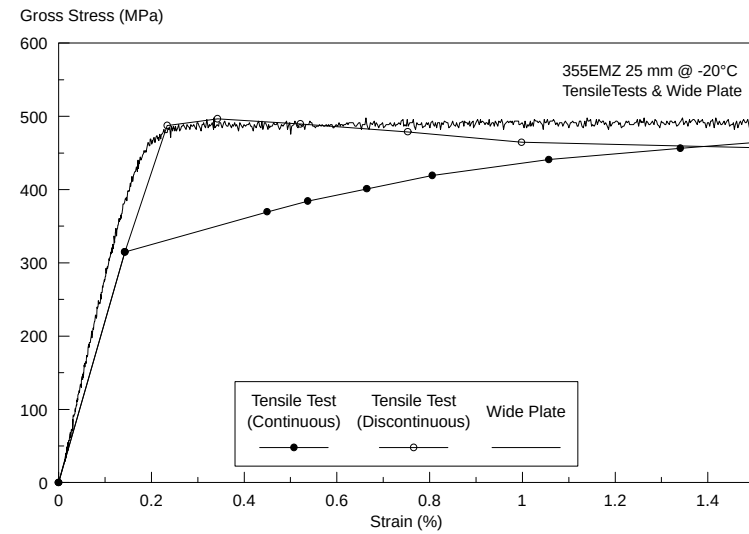


(b) Up to 1.5% Strain(D0291E08)

FIG. 10(a and b) COMPARISON OF TENSILE TEST AND CENTRE-CRACKED-TENSILE BEHAVIOUR OF 355EMZ 25 mm PLATE



(a) Up to 15% Strain (D0291E09)



(b) Up to 1.5% Strain (D0291E09)

FIG. 11(a and b) COMPARISON OF TENSILE TEST AND WIDE PLATE BEHAVIOUR OF 355EMZ 25 mm PLATE

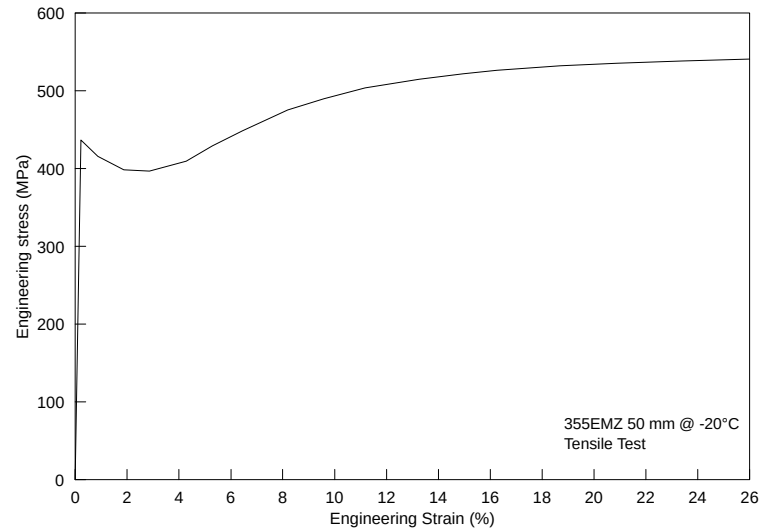


FIG. 12 ENGINEERING STRESS-STRAIN CURVE FOR 355EMZ 50 mm PLATE (D0291E09)

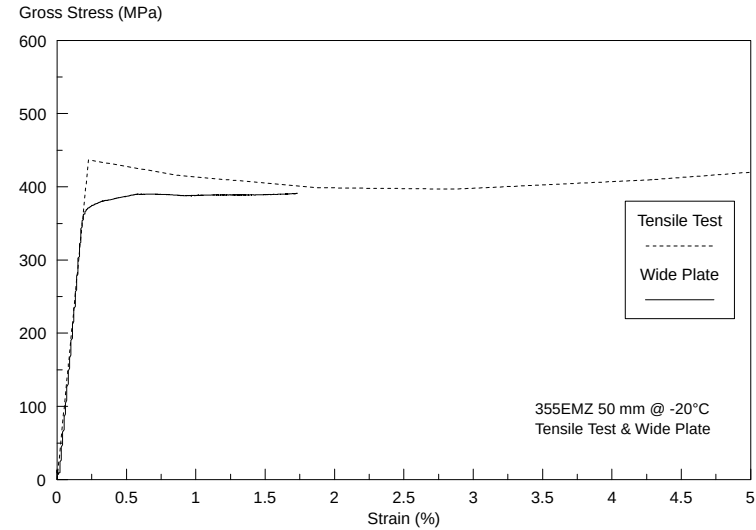


FIG. 13 COMPARISON OF TENSILE TEST AND WIDE PLATE BEHAVIOUR OF 355EMZ 50 mm PLATE (D0291E09)

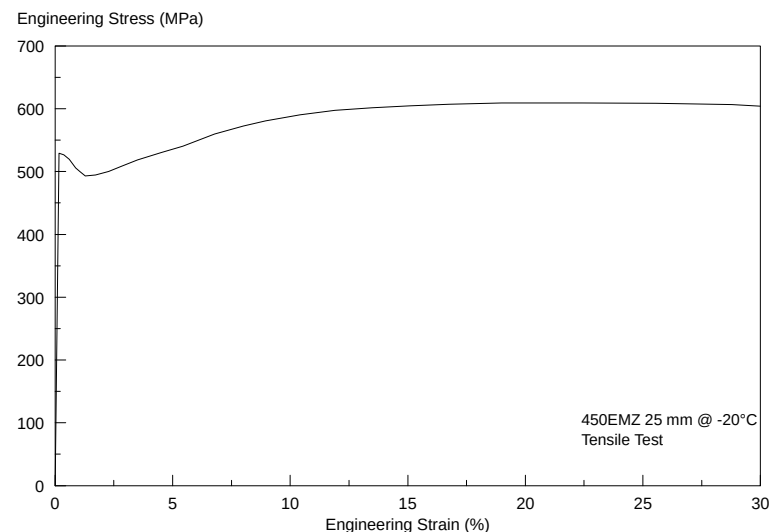
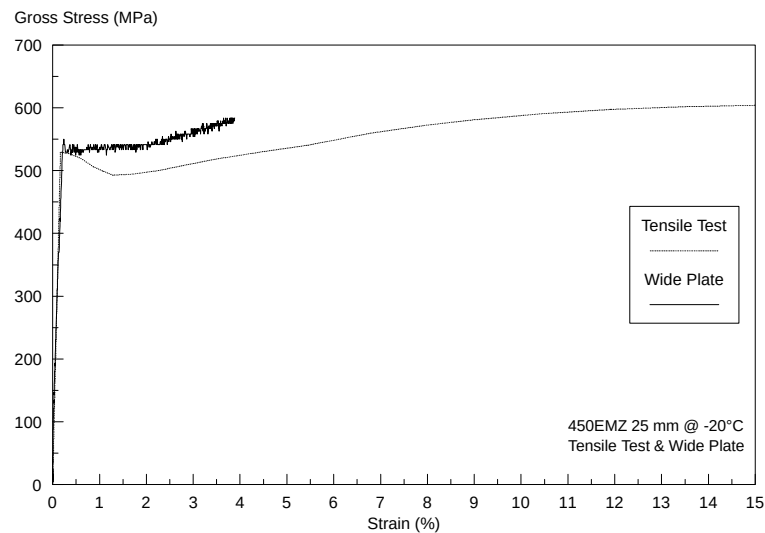
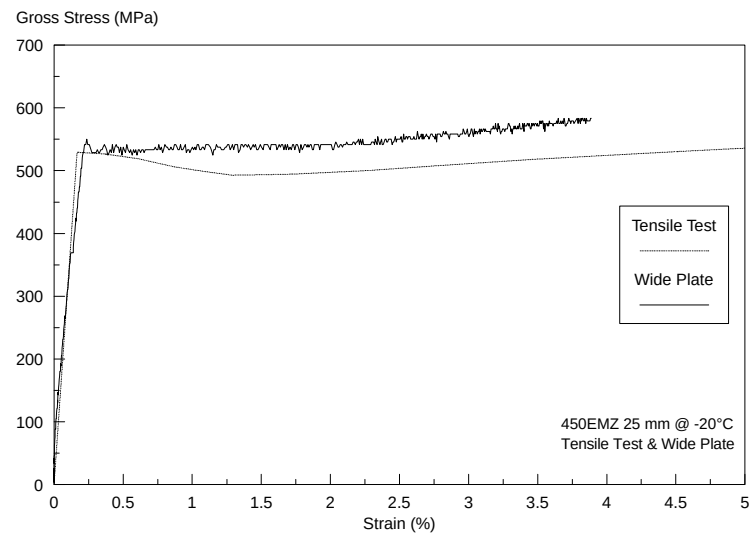


FIG. 14 ENGINEERING STRESS-STRAIN CURVE FOR 450EMZ 25 mm PLATE (D0291E10)



(a) Up to 15% Strain (D0291E10)



(b) Up to 5% Strain (D0291E10)

FIG. 15(a and b) COMPARISON OF TENSILE TEST AND WIDE PLATE BEHAVIOUR OF 450EMZ 25 mm PLATE

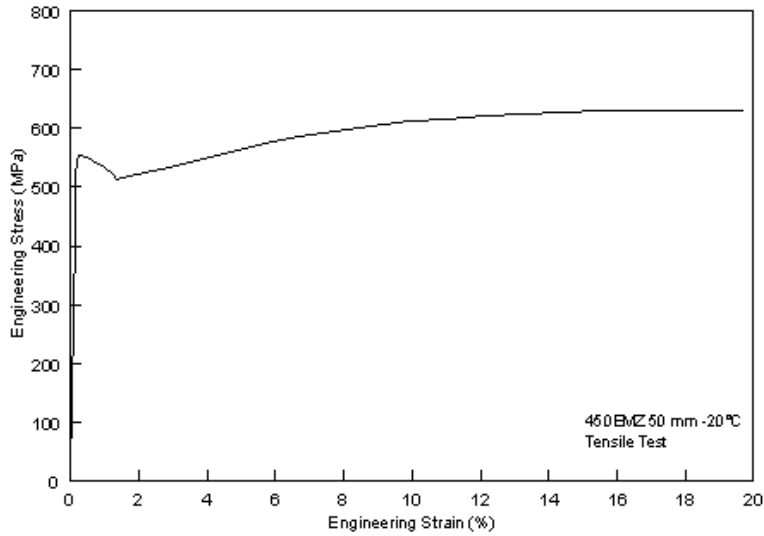


FIG. 16 ENGINEERING STRESS-STRAIN (D0291E11)
CURVE FO 450EMZ 50 mm PLATE

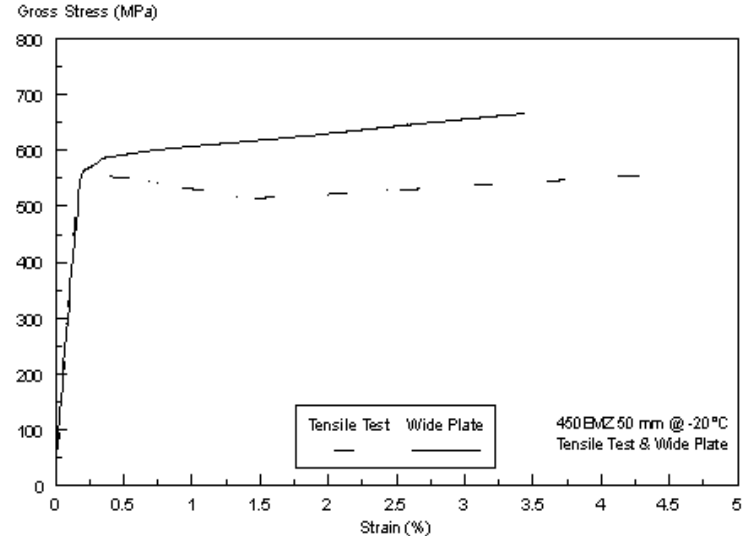


FIG. 17 COMPARISON OF TENSILE TEST (D0291E11)
AND WIDE PLATE BEHAVIOUR
OF 450EMZ 50mm PLATE

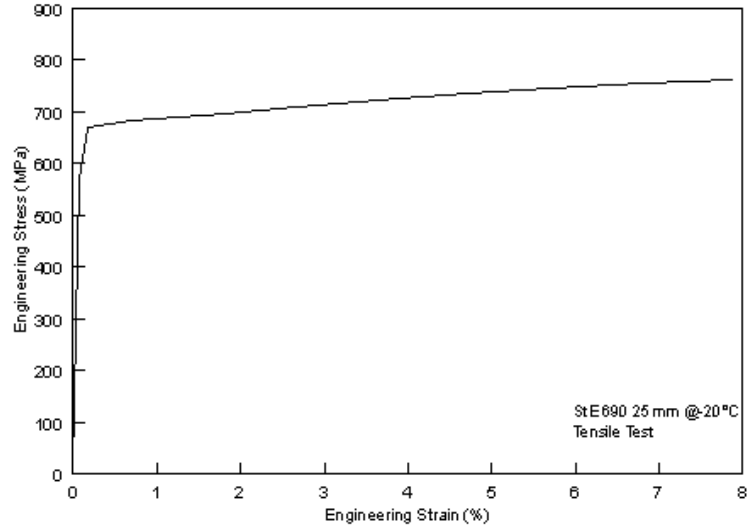


FIG. 18 ENGINEERING STRESS-STRAIN (D029E11)
CURVE FRO StE690 PLATE

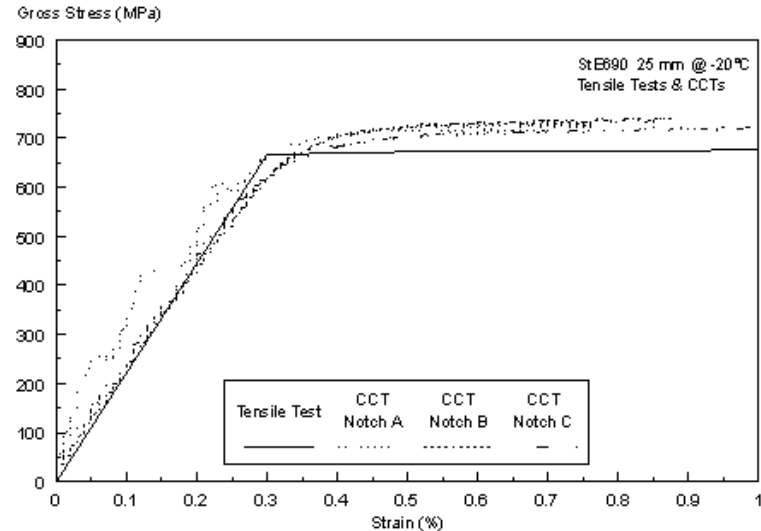


FIG. 19 COMPARISON OF TENSILE TEST AND (D0291E11)
CENTRE-CRACKED-TENSILE
BEHAVIOUR OF StE690 PLATE

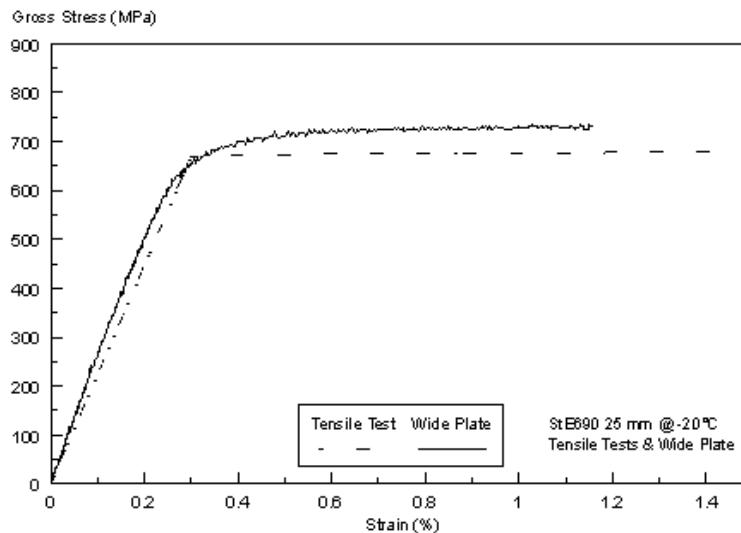


FIG. 20 COMPARISON OF TENSILE TEST AND WIDE PLATE BEHAVIOUR OF StE690 PLATE (D0291E11)

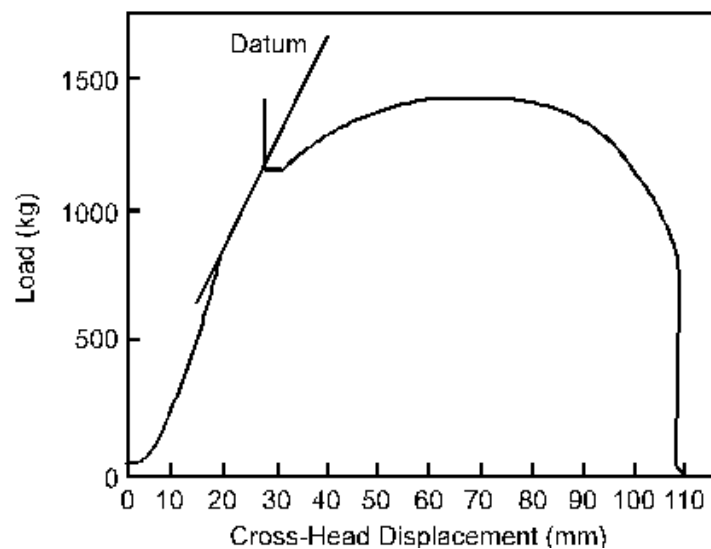


FIG. 21 LOAD v CROSS-HEAD DISPLACEMENT (D0291E11) TRACE FOR LONGITUDINAL TENSILE TEST FOR A533B (50 mm PLATE)⁽⁹⁾

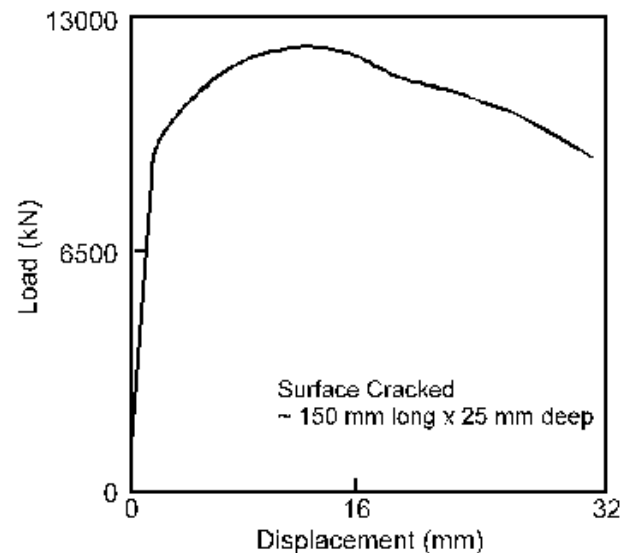


FIG. 22 LOAD v TRANSDUCER DISPLACEMENT (D0291E11) FOR A533B (50 mm PLATE) SURFACE CRACKED WIDE PLATE TEST ($a/B = 0.5$)⁽⁹⁾

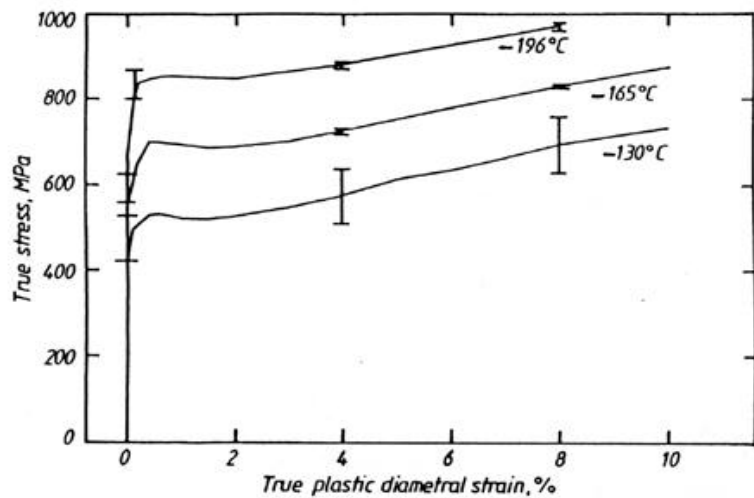


FIG. 23 TRUE STRESS - TRUE PLASTIC STRAIN CURVES FOR BS 4360 GRADE 50D⁽⁹⁾ (D0291E12)

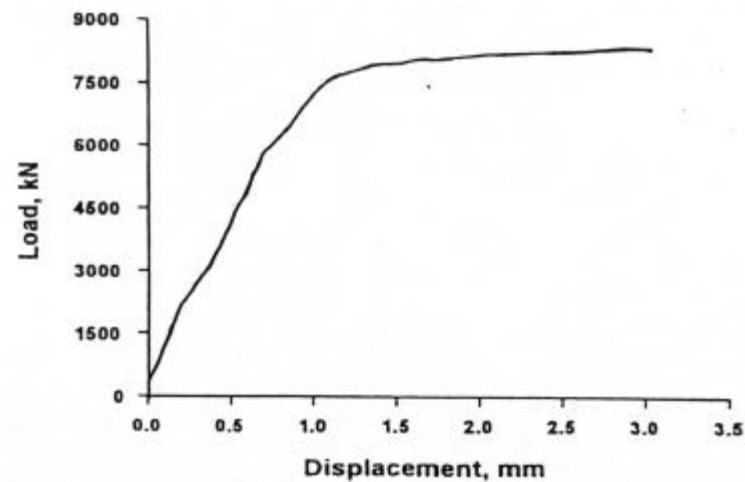


FIG. 24 LOAD-DISPLACEMENT TRACE FOR BS 4360 GRADE 50D WIDE PLATE WITH EDGE WELD⁽⁹⁾ (D0291E12)

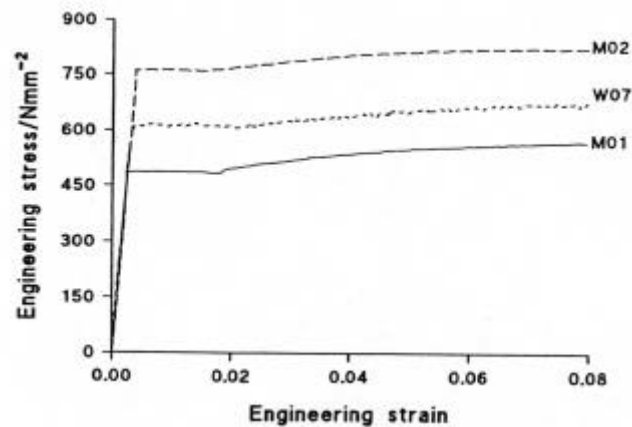


FIG. 25 ENGINEERING STRESS-STRAIN CURVES FOR PARENT PLATE AND WELD METAL USED IN MIS-MATCH STUDY⁽¹⁰⁾ (D0291E12)

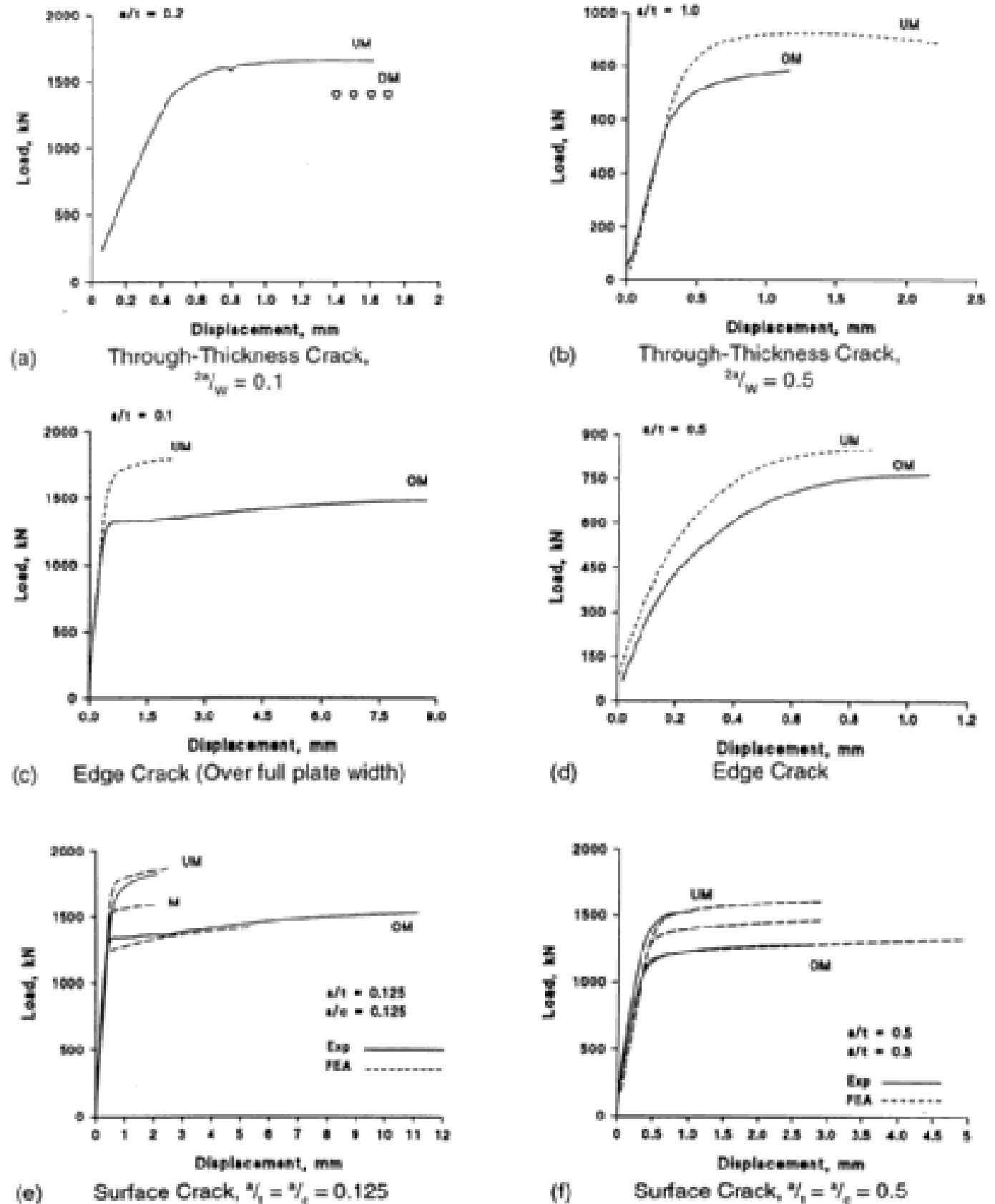


FIG. 26(a-f) LOAD-DISPLACEMENT CURVES FOR MINI WIDE PLATES OF VARIOUS MIS-MATCH LEVELS AND TEST CONFIGURATIONS⁽¹⁰⁾ (D0291E13)