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WELD METAL YIELD STRENGTH MIS-MATCH
Practical Considerations

Prof. Dr. ir. Rudi DENYS

Laboratorium SOETE,
Universiteit GENT (RUG)
St. Pietersnieuwstraat, 41, B 9000 Gent, Belgium

ABSTRACT

The article reviews the effects of weld metal yield strength mis-match on weldment performance. The discussions emphasize that the economic use of transversely loaded high yield strength steel weldments require consideration of the interactions between base and weld metal yield strengths, yield/tensile strength ratio, defect size and toughness. It is concluded that yield strength mis-match has an important effect on tolerable defect size and toughness requirements.

1 INTRODUCTION

Research into the fracture of welded structures in the last 50 years has dealt with a wide variety of problems. In the early days, the main concern was the prevention of brittle (elastic) fracture. As our knowledge of the factors controlling fracture has progressed, qualitative and quantitative (fracture mechanics based) weld defect acceptance standards and toughness requirements have been introduced[1-2].

Charpy V and CTOD toughness requirements as a means of brittle fracture control have essentially been developed for base metal evaluations. Specifications are generally based on the principle that the toughness required for the base metal should also be achieved for the weld metal and HAZ regions.

Users of toughness requirements assume implicitely that weldments are homogeneous plates or that the weld metal is 'stronger' than the base metal. For perspective, it is correct to emphasize that weld metals employed in low strength structural steel constructions do have adequate yield strength. The old type low strength steels are characterized by a low yield to tensile ratio which assures that weld strength qualification by transverse weld tensile testing warrants weld metal yield strength overmatching. For high strength steels, the condition of overmatching is not necessarily ensured[3].

For demanding applications, fracture mechanics concepts are used to define the fracture toughness level required to minimize the risk of brittle fracture. However, disagreement exists on the toughness levels needed to ensure fail save behaviour. Some experts feel that conventional fracture mechanics principles are adequate, others disagree and claim that weldment deformation/straining capacity not only depends on toughness [4-8].

Service experience and the accumulated results of model/large scale tests show that the straining capability does not solely depends on toughness. Undoubtedly, many structures in service today contain areas of low toughness and undetected weld defects but they continue to function satisfactory. The point is that in the early days of welding, designers failed to appreciate the beneficial effect of the overmatching weld metal yield strength on weldment performance.

Conventional designs do not directly address the weld metal yield strength mis-match and strain hardening effects on weldment performance. This is somewhat surprising because yield strength and strain hardening affect the onset of yielding and plastic strain distribution across a weldment. The other point, which also bears to this behaviour, relates to the load carrying capacity and thus the aspect of defect size.

When deformation or straining capability is required, it is not economic to focus material developments in terms of toughness. For instance, undue emphasis on toughness can badly distort the pattern of development of new high strength steels. Structural reliability of welded high strength steels depends on toughness, the degree of weld and base metal yield strength mis-matchs and, defect size. However, our understanding of these interaction is by no means complete at present[9-10].

2 WELD METAL MIS-MATCH

2.1 Base and weld metal combinations

A multiplicity of base and weld metal combinations are used to fabricate weldments. The base (YB) and weld metal yield strengths (YW), and the base (TB) and weld metal (TW) ultimate tensile strengths can be combined into 6 different combinations, Table 1. Combinations A, B and C represent weldments containing a weld deposit which is undermatching in yield strength. Combinations D, E and F contain overmaching weld metal.

Fig. 1 shows the corresponding deformation behaviours at failure. The hatched delineate the plastically strained region(s) while the dashed lines indicate the location of failure.

BASE - WELD METAL COMBINATIONS

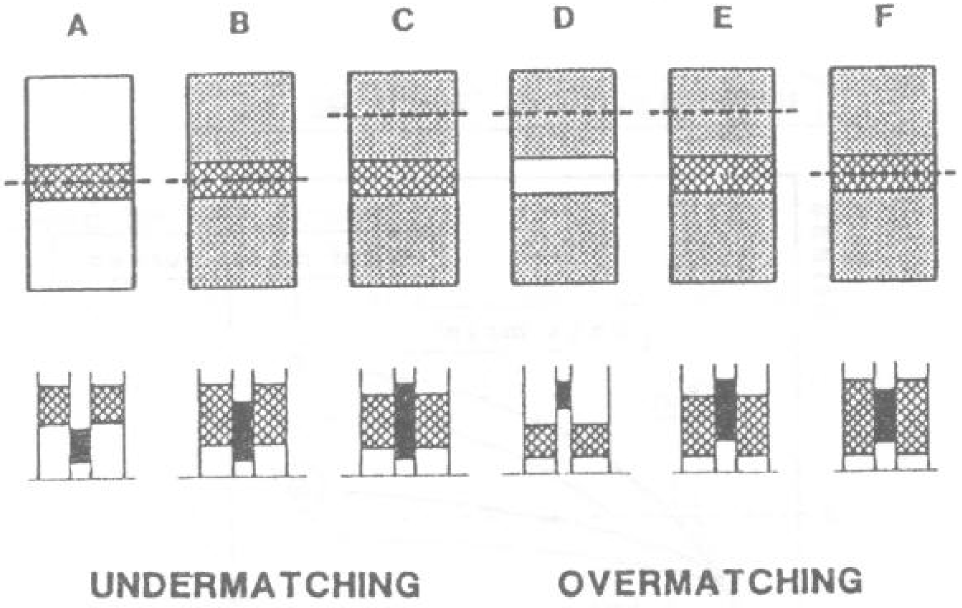

Fig. 1: Schematic diagram showing the basic base - weld metal combinations with indication of corresponding yielding pattern and failure location .

Fig. 1 illustrates that 5 out of the 6 combination will only fail after base metal yielding. The other important features to note are that base metal yielding in Combinations B and C is not excluded for yield strength undermatching weld metal. Weld metal failure is not excluded with overmatching weld metal yield strength (Combination F).

Combination	Sequence of phenomena	Type
A	YW < TW < YB < TB	Undermatching
B	YW < YB < TW < TB	
C	YW < YB < TB < TW	
D	YB < TB < YW < TW	Overmatching
E	YB < YW < TW < TW	
F	YB < YW < TW < TB	

Table 1 - Basic weld metal base metal combinations

Table 1 is based on the asumption that the yield and tensile strengths are exactly defined parameters. Unfortunately, this is not the case. Yield strength variability does not exclude different weld combinations for a particular steel delivered to a certain specified minimum yield strength.

Failure-deformation behaviour also depends on base and weld metal strain hardening capability, Fig.2.

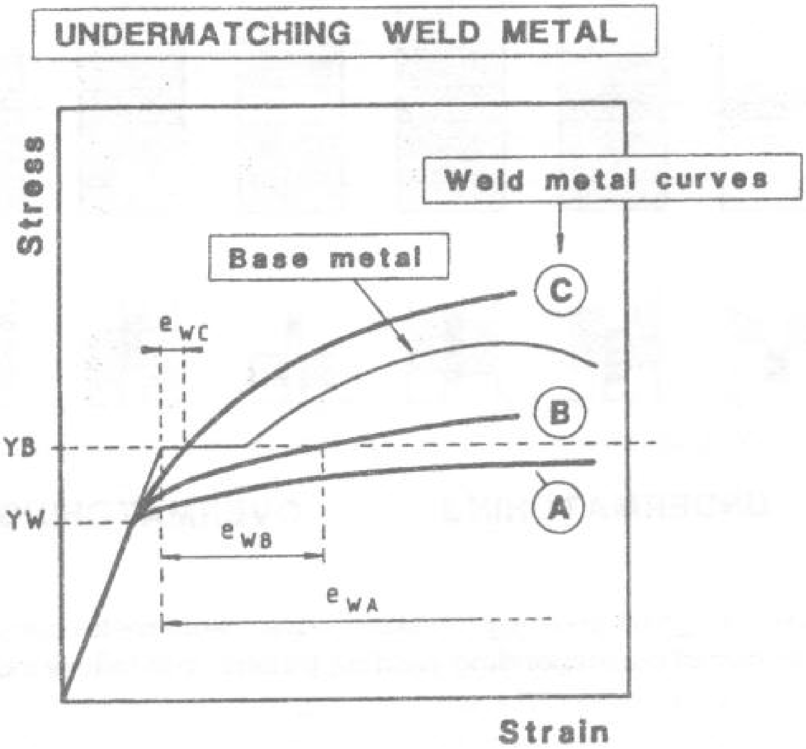

Fig. 2: Qualitative representation of the effect of weld metal strain hardening on weld metal strain, e_w, for an undermatching weld metal.

For undermatching high YS/TS ratio (low strain hardening capacity) weld metals, Fig. 2 illustrates that the probability of base metal plastic straining is low (Combination B) or even excluded (Combination A) and that decreasing strain hardening capacity requires significant weld metal straining (e_w) capacity to achieve base metal yielding. Conversely, weld metals having a high strain hardening capacity foster base metal plastic straining (Combination C).

2.2 Geometric effects on yielding behaviour

2.2.1 Weld reinforcement.

Weld reinforcement is a beneficial factor for statically loaded weldments. Weld reinforcement gives an increase in the cross section of the weld deposit which increases transverse strength.

Weld reinforcements might transfer the locus of failure from the weld metal area to the plate. For example, the root and cap weld reinforcements of an undermatching weld metal in thin plate can shield, just like in case of weld metal yield strength over-matching, the weld metal from (severe) plastic deformations.

2.2.2 Geometrical mis-match

The yield and tensile characteristics of weldments can be affected by geometrical mismatch between the welded plates. A loss of strength will occur as the offset distance or misalignment increases. In fact, misalignment creates an in-plate bending moment. The resulting stress raising action may be detrimental with a low yield strength weld metal.

2.3 Weld bevel (groove) design

The shape of the weld bevel preparation is primarily based on a combination of economics, access, plate thickness, effect of distortion and fabrication facilities[11]. Narrow groove bevels present an economical advantage over conventional geometries.

2.3.1 Weld metal width

The weld metal width-plate thickness ratio affects weldment yielding. Experiments on undermatched narrow gap weldments undertaken by Toyoda and Satoh [12] have shown that the overall straining capacity increases when the weld metal width (weld metal heigth perpendicular to the weld axix) is smaller than plate thickness. As pointed out by Kirk and Dodds[13], reducing weld metal width elevates also the stress for plastic flow but this effect cannot prevent weld metal strain concentration in the event of weld defects. In this case, weldment straining capacity for undermatching weldments can be low when weld metal or HAZ discontinuities occur[7].

2.3.2 Strain distribution

Little research has yet been done to investigate the interaction between weld bevel design and degree of weld metal yield strength mis-match. Work by Denys [14] has revealed that plastic strains are unequally distributed in and near under/overmatching V and K weld preparations, Fig. 3.

For *undermatching* weldments, the highest strains occur in the weld metal and HAZ regions. The HAZ strains at the root side are greater than the HAZ strains at the cap side, i.e. the smaller the width of the weld root (V bevel), the greater the strain in its adjacent HAZ (strain concentration effect) is. The strain accumulation in the weld root and its adjacent HAZ regions (V weld) can be relieved by using narrow groove (square-groove) weld bevel preparations. In the event of weld root defects, however, notch tough weld metal and HAZs will be needed.

For *overmatching* weldments the opposite effect is observed. The HAZ strains in the root region are smaller than those at the cap side. Note also that the HAZ strains in the overmatching weldment are smaller than the base metal strains (strain de-concentration effect).

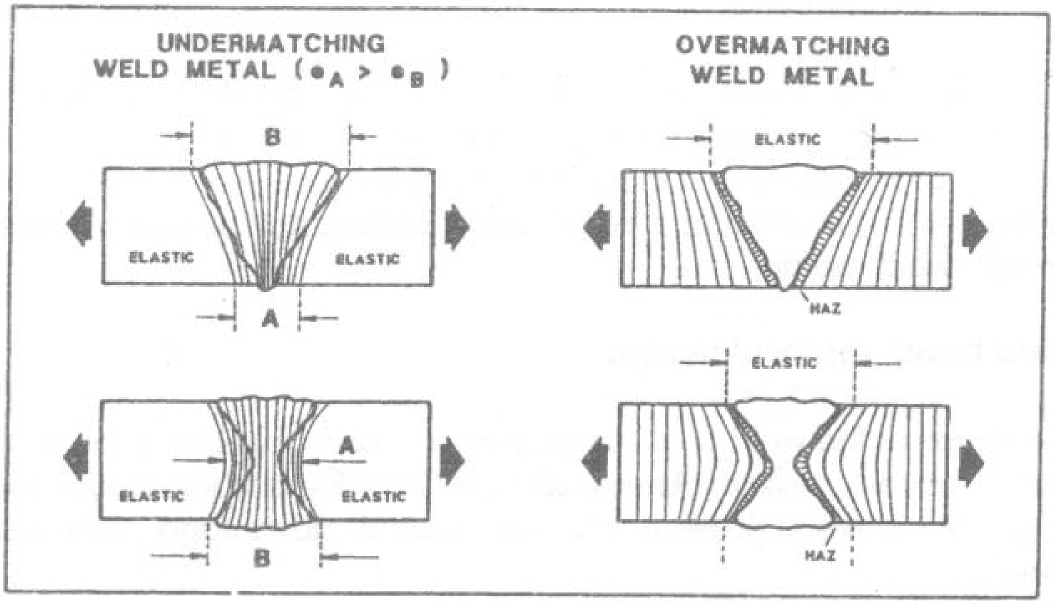

Fig. 3: Effect of weld bevel preparation on plastic strain density (hatched areas represent plastic deformed metal)

These observations permit to conclude that an overmatching single V weld bevel provides considerable protection of the weld metal root (including its HAZ) against plastic strains. This protection increases with increasing angle between the plate bevels. This solution is in conflict with economical considerations. However, whenever possible the included angle should be optimised to minimise strain concentrations in the weld root region. Evidently, the degree of strain de-concentration (weld metal overmatching) in the root area is not only a function of the weld preparation but also of the degree of overmatching.

2.4 Alternative weld groove designs

For high strength steels, it is a challenge for the manual metal arc welder to produce weld deposits that overmatch the base metal in yield strength and toughness. However, because of the trade-off between the level of weld metal yield strength mis-match, the angle of the bevel preparation and toughness, the problem can be overcome by using undermatching or matching (notch tough) electrodes for the weld root and highly overmatching (with moderate toughness) electrodes for the fill and cap passes in combination with a J (or U) groove weld preparation.

The notch tough undermatching/matching weld metal is effective to prevent weld root cracking. It's use is also beneficial in terms of welding productivity. The overmatching fill protects the weld root from plastic straining. The level of weld yield strength overmatching should be sufficiently high to prevent plastic strains from occurring in the root area, thus protecting weld imperfections from plastic strains. Experience with conventional steel weldments indicates that 25 to 30 % yield strength overmatching give tample protection when root defects are present[3].

3 WELD MIS-MATCH IN PRODUCTION WELDMENTS.

Theoretical considerations on weld metal mis-match are based on the assumption that the base metals on either side of the weld have the same yield strength. Production weldments, however, are hetereogeneous in that base metal yield strengths on each side of the weld deposit are different.

Hetereogeneous weldments are obtained when plates from different supplier or even plates from one single supplier are welded together. This heterogeneity affects the level of weld metal matching and consequently the required toughness for adequate weldment performance. In addition, when the base metal yield strength variability is significant, problems may arise in welding procedure qualification since compatible welding rods or wires are selected on the basis of the base metal minimum specified yield strength (SMYS).

3.1 Basic combinations.

Six weld metal base metal yield strength combinations can be identified for weldments made with a filler metal compatible with the base metal SMYS, Fig. 4.

In terms of weld metal yield strength matching, these combinations can be classified in the following three categories:

- *Matching weld metal yield strength (Combination 1)* - This combination refelects the design view of a weldment. The weld metal yield strength equals the base metal yield strength on either side (homogeneous weld), Fig. 4.
- *Undermatching weld metal yield strength (Combinations 3 and 6)* - The probability of weld metal yield strength undermatching depends critically on the overlap of the base and weld metal yield strength distributions, Fig. 5. Combination 3 occurs when two plates from the higher end of the yield strength distribution are welded with a filler metal qualified for plates from the lower end. Combination 6 occurs when a plate of the higher end is welded to a plate with a yield strength slightly exceeding the SMYS. These combinations are to be avoided since the applied strain will be concentrated in the weld metal.
- *Overmatching weld metal yield strength (Combinations 2, 4, 5)* - Combination 2 models the situation normally encountered in welding procedure qualification strength distribution. Combination 5 can occur when weld procedure testing was conducted on plates taken from the lower end of the yield strength distribution.

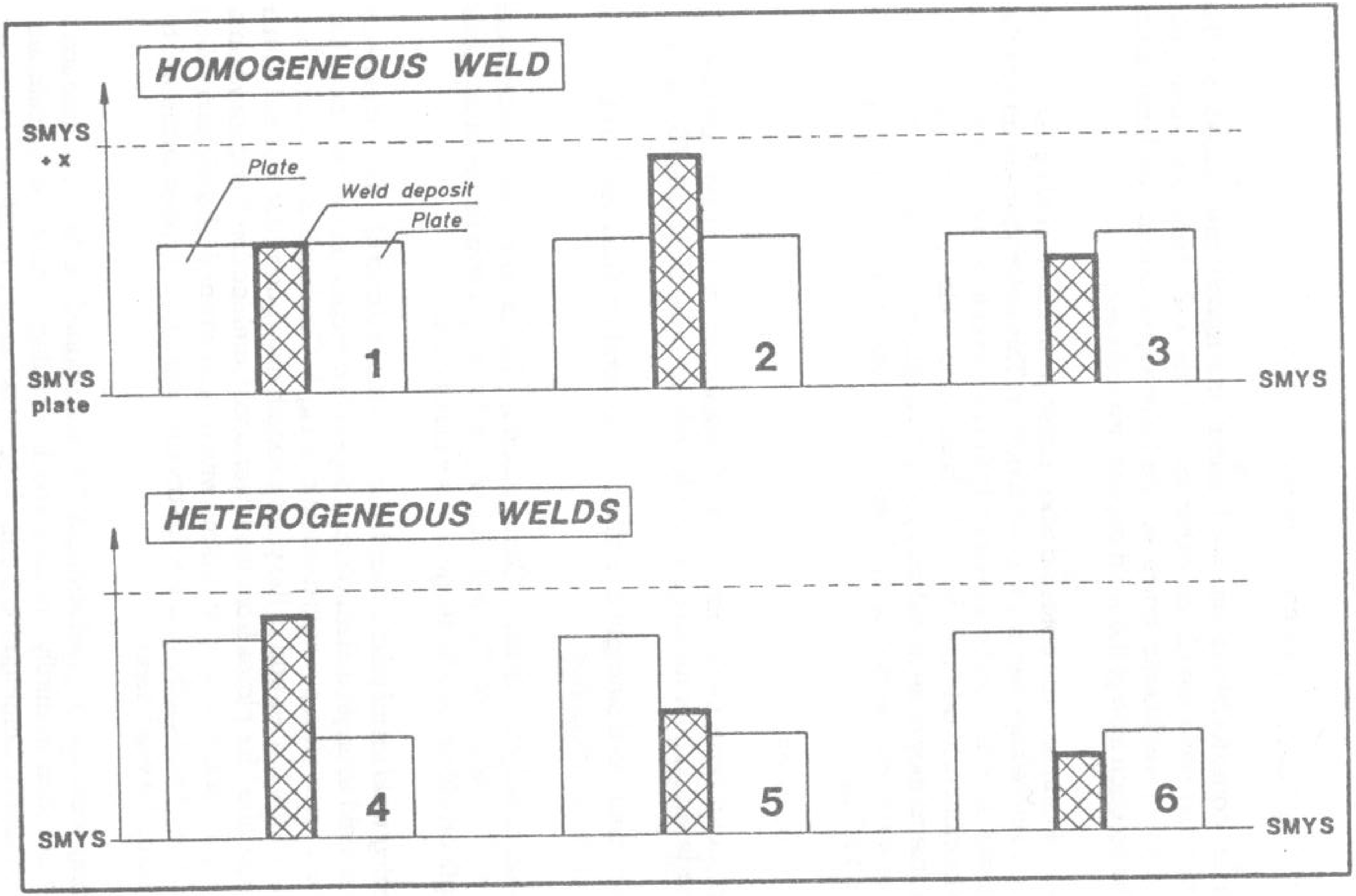

Fig. 4: Homogeneous (base metals have the same yield strength) and heterogeneous (base metals have a different yield strength) weldments. The height of the hatched areas represent weld metal yield strength.

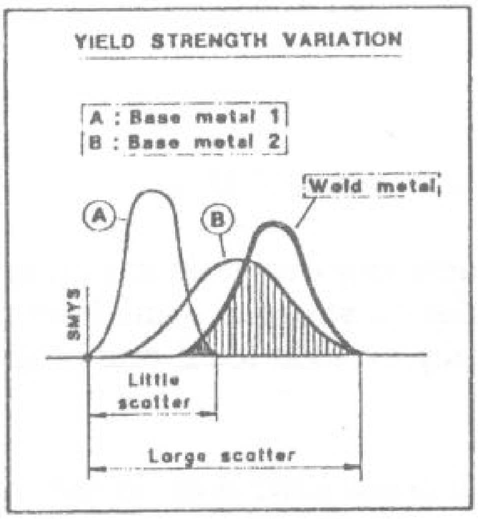

Fig. 5: Effect of base yield strength variation on weld metal matching (hatched area represents undermatching densitry)

3.2 Practical significance.

Combination 4 is favoured since it is very tolerant to weld and HAZ defects. For overloading situations, weld defects are fully shielded. Any plastic strain will be taken by one plate only, while the other plate and the weld deposit will be elastically strained [14].

The weld metal overmatching shielding effect in combination 2 is smaller. Weld defects are exposed to the applied strain from 'two sides'. The weld metal yield strength overmatching effects in combination 5 will be smaller than for combinations 2 and 4.

For critical applications facing HAZ/weld metal toughness problems, combination 4 provides a solution. By combining a low yield strength with a high yield strength base metal it can be assured that the plastic strains will be drawn on the high toughness lower strength base metal.

3.3 Qualification testing

Heterogeneous weldments requires re-consideration of the welding procedure qualification test requirements. Standard acceptance testing procedures may not indicate the real weldment quality. In particular :

(a) testing for weld metal strength should be conducted on plates from the higher end of the yield strength distribution.

(b) testing for toughness should be conducted on plates from the lower end of the yield strength distribution. In particular, testing should be concentrated on the

HAZ of the lower strength base metal because any plastic straining will be concentrated there.

4. ASSESSMENT OF STRUCTURAL INTEGRITY

Welded structures are normally designed to perform within the elastic stress range. The limitation of the design stress to some fraction of the base metal yield strength does not automatically exclude local and/or global (base metal) plastic deformations.

Given the fact that accodental, operational and functional loads causing significant plastic strains are random variables, it is a good practice to verify the safety margin associated with these conditions.

Conventional design criteria are inadequate to establish the relationship between defect tolerance and global plastic straining capacity. The point is that the theory of elasticity is used to design weldments, but, everyone should know that the structural intergrity of a welded structure is determined by its global plastic straining capacity. Textbooks on fracture control, however, do not provide information or guidelines.

4.1 Defect free weldments

Designed strain concentrations in defect free weldments are not a consideration. Weldments do possess adequate plastic straining capacity. For demanding applications, however, the global plastic deformation capacity of undermatching weldments might not be adequate when the applied deformations are concentrated in the weld metal area.

4.2 Defective weldments

Plastic straining tolerance decreases in the presence of weld defects. Depending on the level of weld metal yield strength mis-match, plastic straining capacity can be low when (unidentified) weld metal or HAZ discontinuity occur. Therefore, the effect of defects on weldment performance must be known for a correct understanding of the engineering significance of over- or undermatching weld metal yield strength.

To date, it is not possible to designate the level of toughness in terms of weld metal yield strength mismatch because toughness is complex function of many variables. Weld bevel design, defect size, defect position, strain hardening (yield to tensile ratio) capability and the applied performance requiremnet are important factors.

4.2.1 Stress based defect assessments.

A stress based defect assessment relates the design (fracture) stress of elastic magnitude to the toughness or flow stress of the defective cross sectional area.

Contained yielding - Defects in low toughness metals or service conditions entailing triaxiality might initiate fracture for contained crack tip yielding. For this condition, the fracture process is toughness controlled and elastic or elastic plastic fracture mechanics concepts can be used to derive tolerable weld metal/HAZ defects. For nominal (gross) or net section or fully yielded net section cross sectional stresses of yield point magnitude and beyond, elastic-plastic fracture mechanics does not apply.

Limit load behaviour - For uncontained (ligament or Net Section Yielding, NSY) yielding, limit load or plastic collapse principles are used. Plastic collapse defect assessment procedures require the nominal elastic stress and the (yield or) flow stress of the defective metal as input. For demanding weldments requiring straining capacity, plastic collapse defect assessment provides no solace because the analysis is nothing more than a net section stress analysis.

Limitations - Standard plastic collapse theories make no allowance for GSY. This restriction cannot be justified because GSY cannot be excluded for strain hardening materials. In addition, the published plastic collapse solutions are based on the assumption of homogeneous material behaviour. For weld metal defect assessments, it is conservatively assumed that the base metal yield (or flow) stress represents that of the weld metal. Thus, yield strength mis-match effects are not formally addressed.

4.2.2 Strain based structural integrity.

Traditional design and fracture mechanics theories ignore the effects of (gross) plastic strains exceeding the 0,2 or 0,5% level. One of the reasons is that the probability of elastic failure is low. This good record is due to the use of workmanship defect acceptance criteria and the undefined level of plastic straining capacity of low strength steels.

The ability of plastic deformation should be formalized and form the basis of design and defect acceptance. Further reasons why weldments should posses plastic straining capacity are that:

(a) field conditions may dictate the need for weldments which can undergo plastic strains without complete destruction of their serviceability.
(b) uncertainties in design and non destructive inspection cannot be excluded.
(c) tweld defects exceeding the workmanship limits must be considered possible.
(d) defects may grow in size by fatigue during the lifetime of the weldment.
(e) complex structures require a certain degree of plastic straining capacity to achieve their design strength (re-distribution effect).

These observations emphasize the point that a performance criterion has to be established which provides information for plastic service conditions.

Performance requirement - It is rational to require that a defective weldment can sustain remotely applied (gross) stresses of base metal yield strength magnitude[1]. Another way of saying the same thing is that a defective weldment which passes the base metal (gross section) yielding requirement can be accepted for demanding service conditions.

The question as to how much (elastic and plastic) strain should be required is a matter of design philosophy. Different fields of engineering require may also different performance criteria. For instance, the possibility exists that economic or operational considerations may lead to the conclusion that some level of elastic-plastic bahaviour can be adequate (stress based assessment).

Significant factors - Large scale laboratory tests provide ample evidence that failure prevention based on a plastic straining requirement is not limited to the toughness aspect. A strain based integrity assessment requires consideration of the pertinent factors that determine structural performance. The key factors are toughness, weld metal yield strength mismatch, defect size and position (weld metal/HAZ, buried or surface breaking) and, defect shape (through-thickness or part-through). Unfortunately, the scientific literature does not describe the interaction between these variables.

5 PLASTIC STRAINING BEHAVIOUR

The classical literature on 'fully' plastic behaviour does not recognize that two distinct modes of plastic collapse (or uncontained yielding) exist. Net Section Yielding[2] (NSY) occurs when plastic deformations are confined to the defective cross section. Gross Section Yielding (GSY) occurs when the applied stress exceeds the yield strength of the remote (defect free) metal.

Tests on steel plates demonstrate that large defects tend to produce NSY whereas small defects and capacity for strain hardening are beneficial for GSY[15].

Weldment GSY (base metal yielding), however, is a complex function of toughness, defect size, the capacity of the defective metal for strain hardening and the degree of weld metal yield strength mis-match. The complexity of the interactions is briefly discussed in the next sections.

5.1 NSY and GSY of plates.

The following provides elementary information on plate NSY and GSY. This information is essential for understanding the NSY and GSY behaviour of weldments.

5.1.1 Failure stress

Defects reduce failure stress in proportion to their length (through thickness) or area (surface breaking or buried), Fig. 6a. Consistent with available experimental data, the equation relating failure stress, defect size, defective cross sectional area (l.d) and base metal ultimate tensile strength (TS) can be expressed as[1] :

$$\sigma = \alpha . TS . [1 - \frac{l.d}{t.w}] \qquad [1]$$

In Eq. [1], t = plate thickness, w = plate width and $\alpha < 1$. Eq. [1] shows that the failure stress decreases progressively with increasing defect dimensions. The maximum defect size, l_{gy}, for GSY is determined by putting the failure stress, σ, equal to the base metal yield strength, YS. For a given defect depth, d, Eq. 2 gives the maximum defect length, l_{gy}, ensuring GSY behaviour:

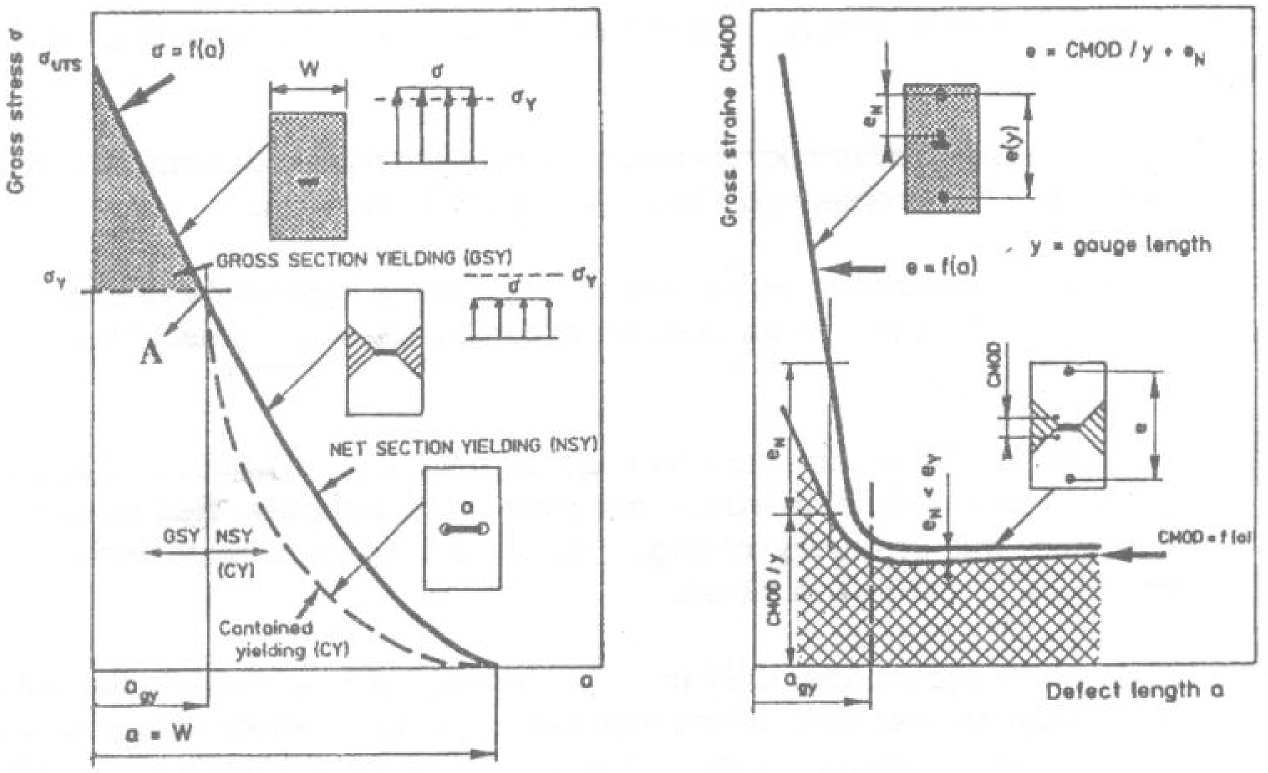

Fig. 6: Base metal gross (applied) stress, σ, gross (overall) strain, e, and CMOD dependence of defect length a

$$l_{gy} = \frac{t.w}{d} [1 - \frac{YS}{\alpha TS}] \qquad [2]$$

By substituting the YS/TS ratio, R, into Eq. 2, it can be verified that l_{gy} decreases with increasing R and thus with reducing capacity for strain hardening.

5.1.2 Failure strain

The transition from NSY to GSY is characterised by an abrupt change in straining capacity. For GSY, the applied deformation is distributed over the entire plate. The corresponding failure strains decrease gradually with defect size. For defects larger than lgy (NSY), failure strain and crack mouth opening displacement (CMOD) reach their 'minimum' value because the applied deformation is entirely consumed by the crack tip, Fig. 6b.

5.1.3 Toughness/temperature effects on NSY and GSY

Temperature has an effect on toughness and thus on the ultimate deformation behaviour. Also, defect size effects straining capacity as temperatures decreases. The combined effects of toughness and temperature on gross strain as a function of defect size is schematically represtented in Fig. 7.

For short defects (upper curve), four deformation behaviours can be distinguished at fracture:

(a) Elastic behaviour: fracture occurs with no significant plastic deformation at the defect tip (A); this problem can be solved by LEFM theories.

(b) Elastic-plastic behaviour: yielding is confined to the immediate vicinity of the defect tip (B and C); this fracture behaviour can be assessed by using the CTOD or J integral concepts.

(c) Plastic (NSY) collapse: the defective section has fully yielded in D. The gross strain increases with temperature and thus with toughness. This increase is limited and will gradually change into defect tip and plate yielding at temperature TD (strain transition).

(d) GSY: fracture occurs after GSY in E. Within temperature range E, the failure mode (fracture appearance) will change from cleavage to shear at temperature TA. The strain transition between NSY and GSY occurs at a temperature which is markedly lower than the fracture appearance transition temperature.

For long defects, a similar sequence of events can be identified Fig. 7 (lower curve). However, the gross strains for corresponding failure behaviours will be lower than for short defects whereas transition temperature TA will shift to higher temperature because of the increased defect tip constraint. Furthermore, since GSY cannot be achieved, it is evident that TD cannot be defined.

The practical significance of Fig. 7 is that the conventional definition of transition temperature depends on defect size. In particular, the ductility temperature TD could be used for material selection purposes. In other words, knowledge of temperature TD

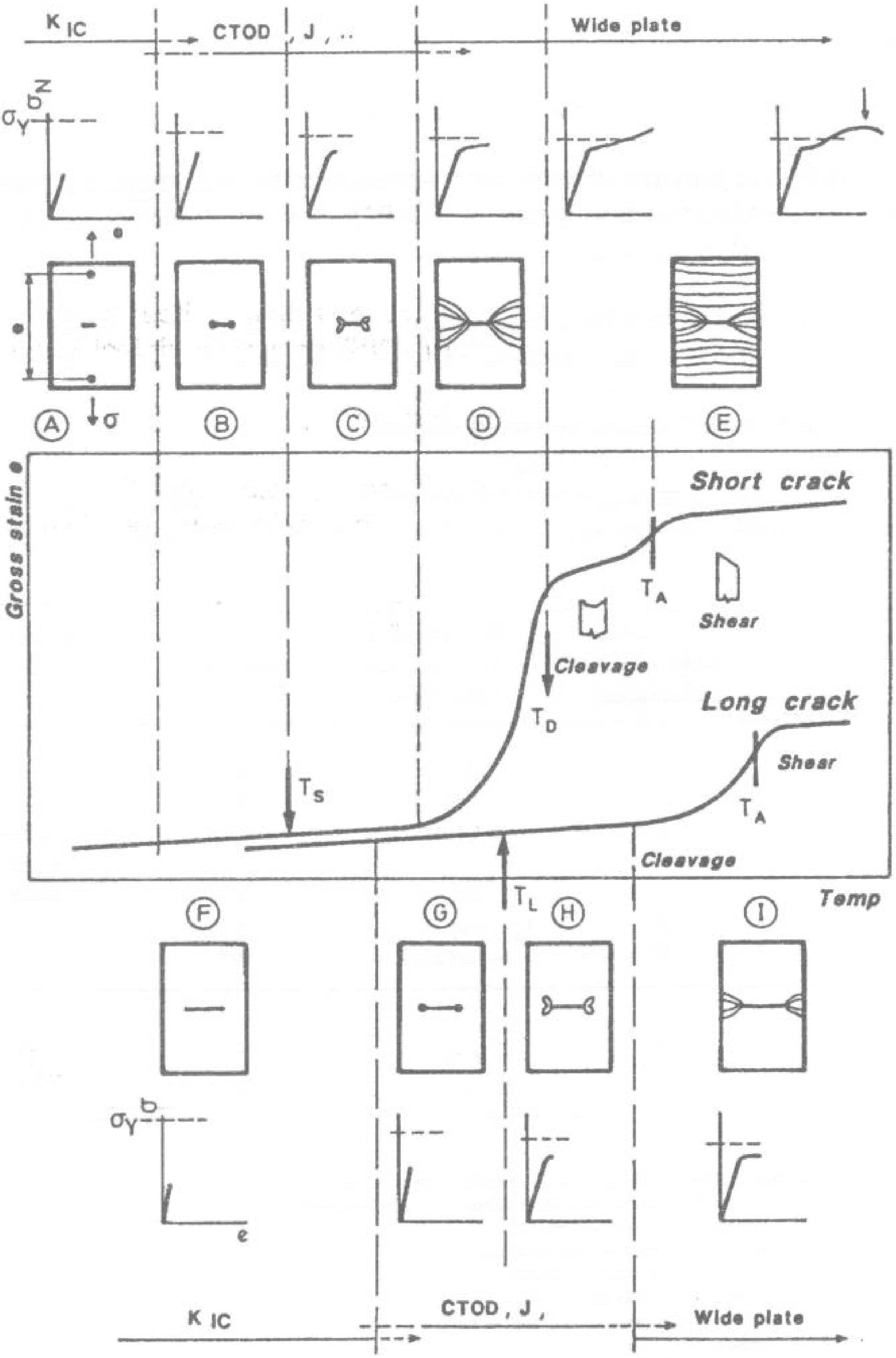

Fig. 7:Schematic representation of gross strain dependence on temperature and defect length.

would allow to verify whether GSY is a probable deformation mode for the selected design temperature.

5.2 NSY and GSY of defective weldments.

The yielding patterns of defective weldments differ from those for (homogeneous) plates. The possible yielding patterns are, together with their corresponding failure locations, defined in Table 2.

Table 2 shows that defect length l_{bm} defines the shift from base metal to weld metal failure whereas the transition from GSY to NSY occurs for defect length l_{gy}, Fig. 8.

5.2.1 Characteristic (tolerable) weld defects.

The values of l_{bm} and l_{gy} can be determined by comparing the failure stress with the base metal tensile strength (l_{bm}) or the weld metal yieldstrength (l_{gy}). The failure

Group	Base metal deformation behaviour[1]	Weld metal deformation behaviour[1]	Failure location[1]	Deformation mode[2]
I	P	gsy	B	Gross Section Yielding (GSY)
	P	nsy	B	
	P	e or ep	B	
II	P	gsy	W	
	P	nsy	W	
	P	e or ep	W[3]	
III	E	gsy	W	Net Setion Yielding (NSY)
	E	nsy	W	
	E	e or ep	W[3]	

1: Base and weld metal deformation and failure behaviours.

P	plastic base metal behaviour (Gross Section Yielding).
E	elastic base metal behaviour.
gsy	weld metal gross section yielding.
nsy	weld metal net section yielding.
e	elastic weld metal behaviour.
ep	elastic plastic weld metal behaviour.
B:	base metal failure.
W	weld metal failure.

2: Weldment deformation behaviour.

GSY	Gross Section Yieldng of the (whole) weldment
NSY	Net Section Yielding of the (whole) weldment

Table 2 Relation between deformation mode and failure location.

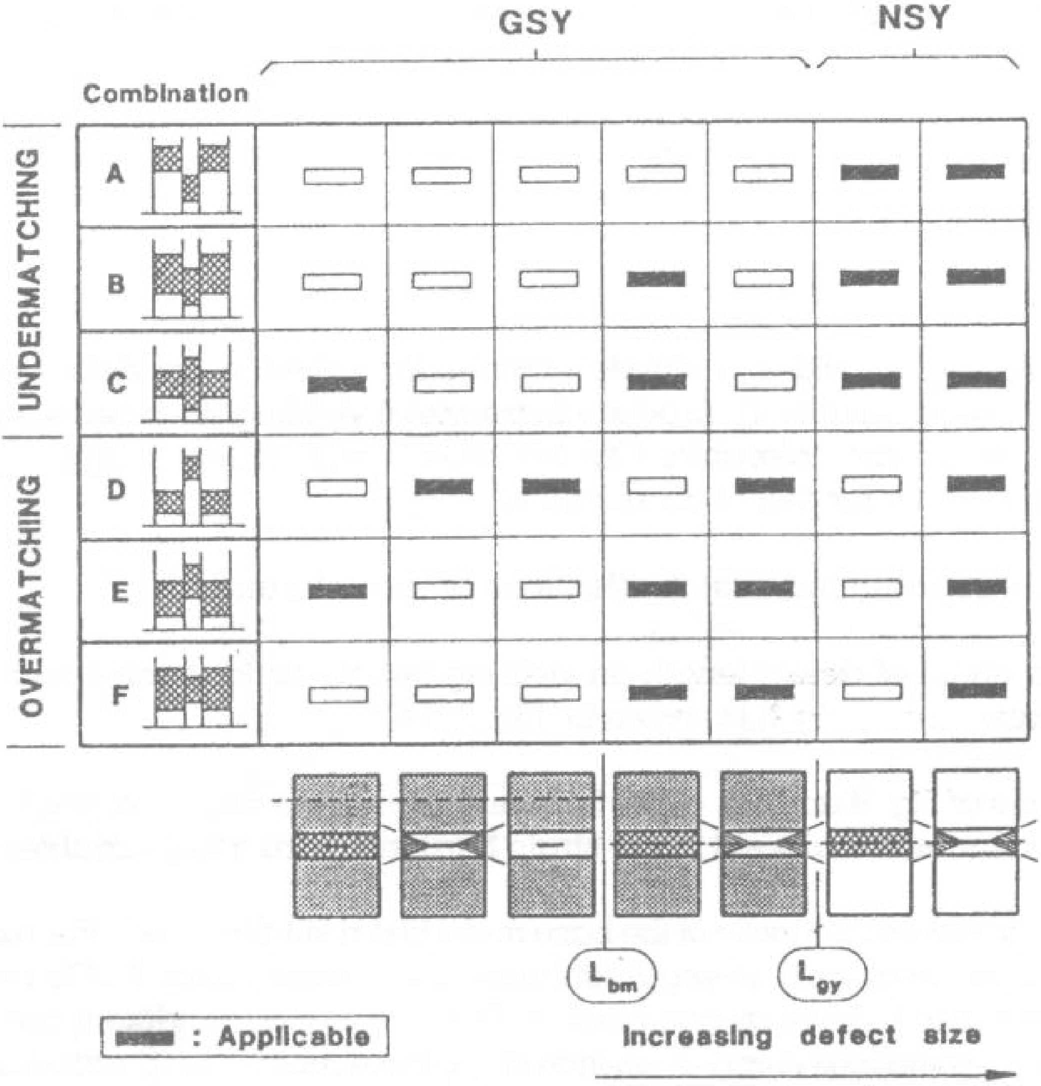

Fig. 8: Relationship between the degree of weld metal yield strength mis-match and defect length.

stress for a weld metal defect can be expressed as (see also Eq. 1) :

$$\sigma = \alpha . TW. [1 - \frac{l.d}{t.w}] \qquad [3]$$

Gross Section Yielding is achieved if the failure stress equals to the base metal yield stength. Hence, by substituting in Eq. 3 by the base metal yield strength, YB, one obtains:

$$l_{gy} = \frac{t.w}{d} [1 - \frac{YB}{\alpha TW}] \qquad [3]$$

The maximum length for which failure occurs in the base metal, l_{bm}, is found by substituting in Eq. 3 by the base metal tensile strength, TB :

$$l_{bm} = \frac{t.w}{d} [1 - \frac{TB}{\alpha TW}] \qquad [5]$$

Defect length l_{gy} provides a simple engineering criterion for defect acceptance because defects smaller l_{gy} produce base metal yielding. In other words, defects smaller than l_{gy} are tolerable. On the other hand, defect length l_{bm} is a too conservative index for defect acceptance.

5.2.2 Yield strength mis-match effects on defect tolerance.

The effect of defect length on yielding behaviour for each basic weld-base metal combinations, Fig 1, is shown in Fig. 8 [14].

The analysis of Fig. 8 and Eq. 4 and 5 illustrates that the degree of weld metal yield strength mis-match and weld metal strain hardening are a key variables for GSY.

The strain hardening capacity of the base metal has a similar effect. For example, for a given base metal yield strength, an increase in base metal YS/TS ratio causes combination E to behave as combination D, Fig. 8. For all weldment combinations, except for combinations A and C, an increasing base metal YS/TS ratio has a similar effect as increasing the level of weld metal yield strength.

6 GSY AND WELD METAL DEFECT ASSESSMENT.

The important feature of GSY is that it enables the development of alternative defect assessment strategies. GSY can be linked with existing fracture mechanics analysis methods. This observation is usefull because this possibilty enables to:

(a) appreciate the interactive effects of the pertinent variables on weldment performance

(b) formulate recommendation on the required toughness levels as a function of the degree of weld metal yield strength mis-match

(c) perform a fitness for purpose analyses of weld defects.

The knowledge of the interrelation between the base and weld metal stress-strain curves and the corresponding crack driving force (crack mouth opening CMOD)-strain behaviours enables guidelines to be developed (Section 7).

6.1 Weld metal stress-strain and CMOD-strain behaviour

The stress-strain (σ-e), the crack mouth opening displacement-strain (CMOD-e) curves and the coresponding weld metal deformation behaviours (yielding patterns) Fig. 9, provides the basic information to describe the effects of weld metal yield.

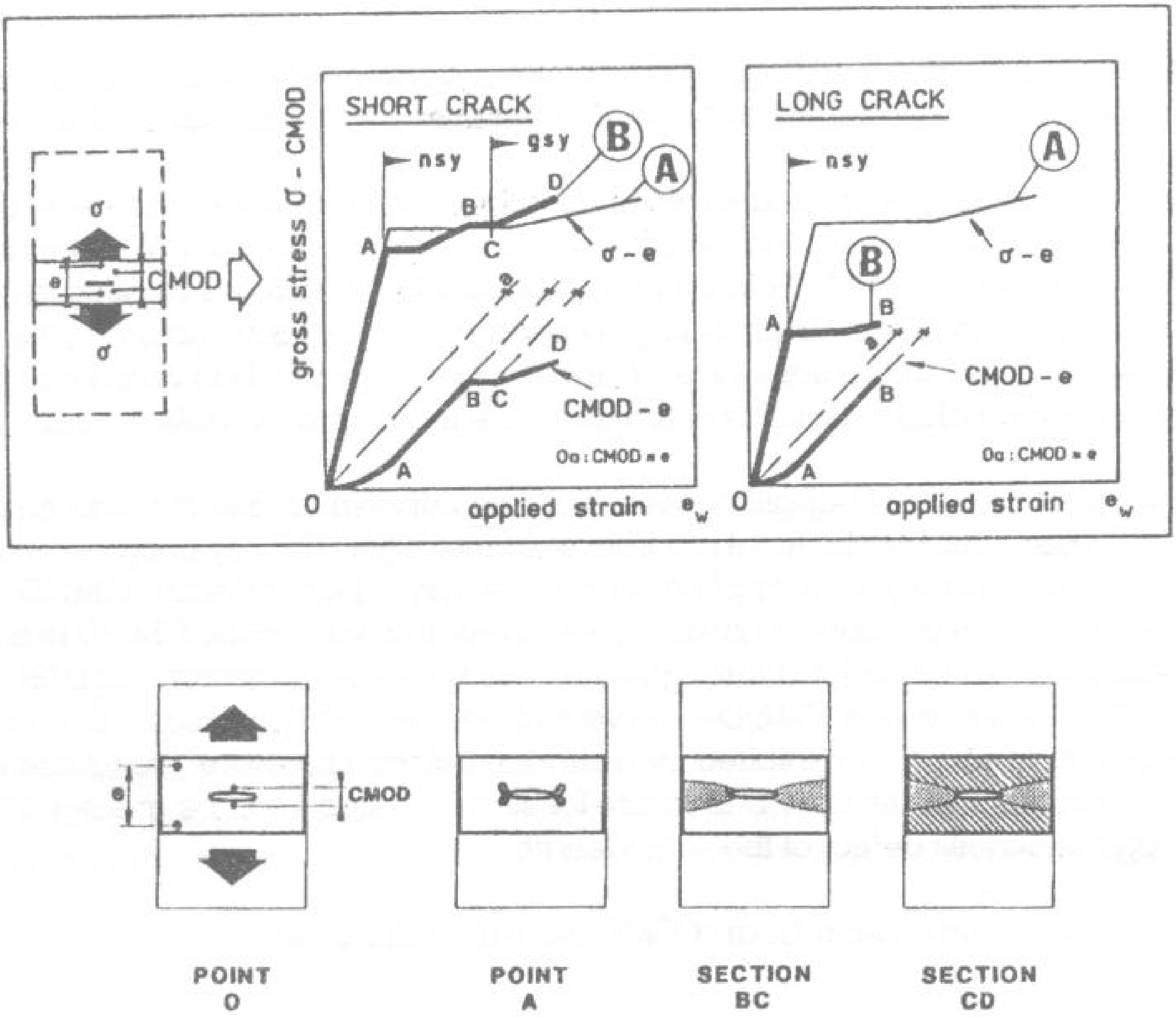

Fig. 9: Schematic presentation of the relationship between the applied stress, overall (gross) strain) and CMOD for weld metal GSY and NSY behaviour. Curve A is the (defect free) weld metal stressstrain. Curve B is the stress strain curve of a defective weld metal.

The stress-strain (-e), the crack mouth opening displacement-strain (CMOD-e) curves and the coresponding weld metal deformation behaviours (yielding patterns) Fig. 9, provides the basic information to describe the effects of weld metal yield strength mis-match on weldment performance, Fig. 10. For the case of a through-thickness defect, the sequence of events for a tensile loaded weld metal is as follows:

(a) Elastic tensile stresses produce local plasticity causing small crack mouth opening displacements, line OA.

(b) At and after the onset of NSY, the applied displacement is entirely transmitted to the crack tips (line AB). For long defects, the applied strain goes into the crack tips through the slip bands and the slope of the CMOD-e curve remains unaltered until fracture occurs (Fig. 9, right side). For short defects, the CMOD-e curve exhibits a similar behaviour at low plastic strains (line AB); at higher strains (line BCD), the slope of the CMOD-e curve decreases because of strain hardening effects.

(c) After Net Section Yielding, crack tip strain hardening causes, for the case of short defects, an increased resistance against CMOD so that GSY develops.

Once GSY occurs, the applied strain is absorbed by the remote base sections and CMOD remains constant during the Luders straining phase (line BC). With increasing applied stresses, the CMOD is no longer proportional with the applied strain, e, because of the applied strain is apportioned in the net and remote plate cross sections (line CD). In the case of GSY, the slope of curve BCD is controlled by the strain hardening characteristics of the defective metal and by defect size.

The shape of the CMOD-applied (overall) strain curve in the plastic loading range enables to distinguish weld metal nsy from weld metal gsy. For nsy (long defects), the CMOD varies linearly with applied strain. For gsy (short defects), CMOD is not uniquely related to the applied strain. Note further that the elastic CMOD is smaller for a surface defect than for a through thickness defect of the same length[8]. Thus, the position of the entire CMOD-e curve will be lowered because of the reduced resistance to plastic flow exhibited by a surface defect. Therefore, the failure stress and gross strain and, the CMOD at failure for surface defects will be greater than for a through thickness defect of the same length.

6.2 Weldment stress-strain and CMOD-strain behaviour

6.2.1 Definitions

The stress-strain curve of the defective weld metal, curve B, differs from that of the defect free weld metal, curve A, since weld metal yielding occurs at an applied (gross) stress level lower than that of the defect free weld metal, Fig. 9. The position of curve B with respect to that of the weld (curve A) or base metal (curve C) depends on defect size and degree of weld metal yield strength mis-match. The stress-strain curve of the defective weldment is represented by that of the (undermatched) base metal, curve C, as long as curve B lies above that of the base metal. For long defects or undermatching weld metal, curve B will be situated below curve C. In this case, the stress-strain behaviour of the weldment will be determined by the stress-strain behaviour of the defective weld metal only.

6.2.2 CMOD-strain behaviour

The mis-match changes the weld metal CMOD-applied stresses response.

When the weld metal stress-strain curve of the defective weld metal, curve B, is positioned between the (defect free) weld metal, curve A, and the base metal, curve C, stress-strain curves, the interaction between CMOD (curves D and E) and $e_{app(lied)}$ can be evaluated using curve C. The interaction between CMOD (curves D and E) and $e_{app(lied)}$ for a short through-thickness crack is as follows:

Section OE

For applied stresses up to the base metal yield strength, the CMOD corresponds with point E, Fig. 10 (curves D and E).

Section EF

With further straining, the stress-strain response of the weldment is characterised by curve C. The CMOD (curve D) will not increase between EF as the base metal has reached the onset of yielding and goes through the Luders straining phase. The corresponding CMOD-$e_{app.}$ behaviour (curve D) is represented by a horizontal line EF, Fig. 10. It should be noted that the strain at point F can be as much as the Luders strain and this can amount to 1 % and beyond.

Section FA

A subsequent increase in stress causes elastic the weld metal strains (portion EA on curve B) and base metal strain hardening (portion FA on curve C, Fig. 10). The CMOD versus e_w behaviour (curve E) will be linear while the CMOD versus e_{app} response (curve D) will rise at a slower rate due to the strain hardening of the base metal and the elastic staining of the weld metal. When fracture occurs at point A (elastic weld metal fracture), the fracture strain of the weldment will be as much as e_A.

Section AB

At point A there will be net section yielding of the weld metal. The CMOD-$e_{app.}$ (curve D) and the CMOD-e_w behaviours (curve E) will be coincident because all the strain is directed into the crack tip.

Section BC

Point B represents the onset of weld metal gsy. Further straining causes no increase in CMOD (weld metal Luder's straining).

Section CD

At point C, the weld metal has fully yielded (gsy) and further straining will cause strain hardening until failure, point D.

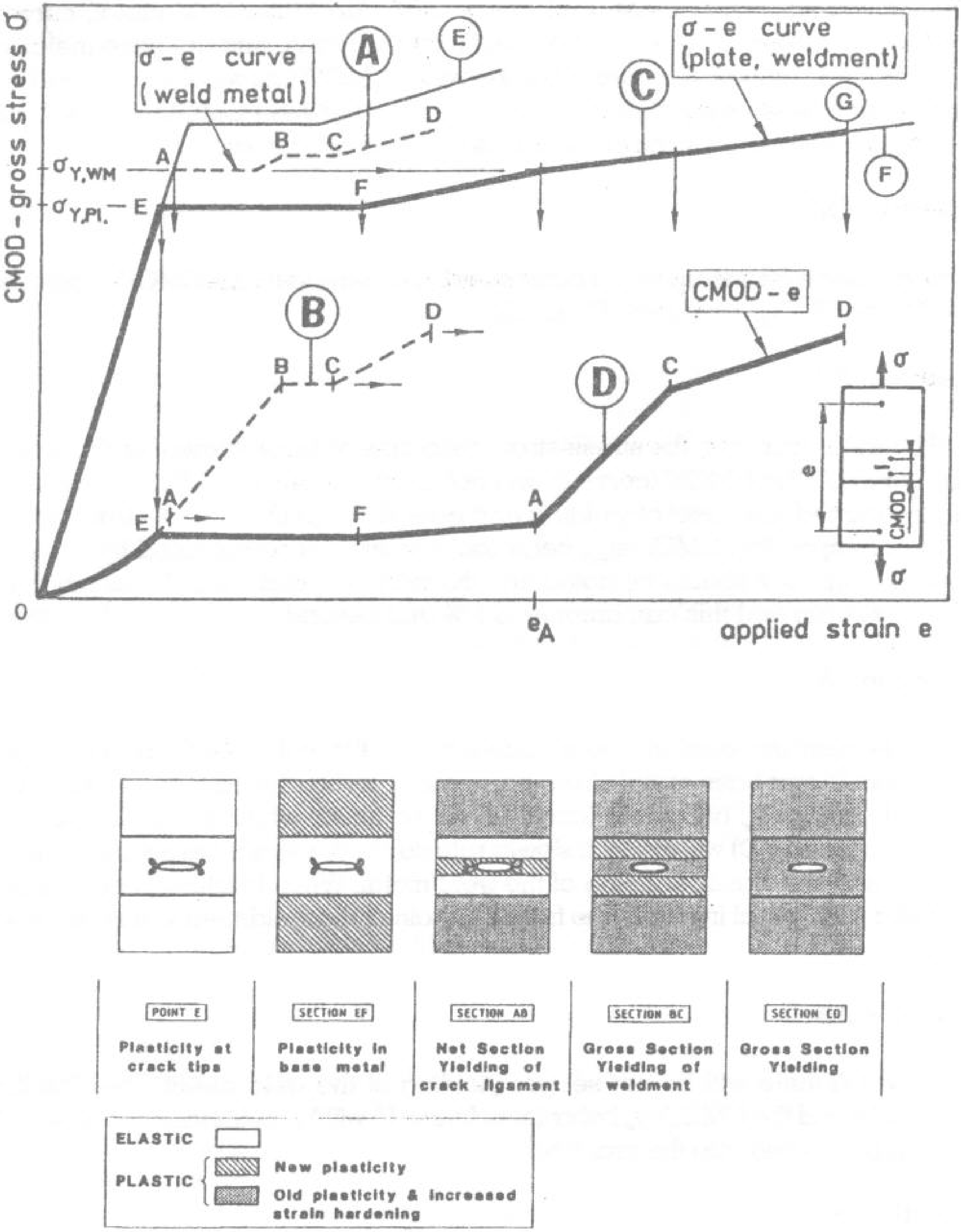

Fig. 10: Schematic representation of gross stress, σ, and CMOD dependence on applied gross strain $e_{app.}$ and weld metal strain e_w in a weld metal cracked tensile loaded panel with indication of the evolution of the plastic zone size. Curves A is the defect free weld metal stress-strain curve while curves B and E are the weld metal stress strain (e_w) and CMODstrain (e_w) responses of the defective weld metal. Curves C and D are stress strain and CMOD-strain response respectively for the whole weldment.

Although the analysis is a simplied presentation of the actual interactions, this method of analysis enables the weld metal yield strength and defect size effects on weld performance to be assessed. For instance, increasing crack lengths or decreasing lweld overmatching levels lowers curve B in Figure 10. If curve B lies below curve C, weldment performance depends on weld metal toughness, since all the applied strain goes into the crack tip or surrounding weld metal (Note also that a similar analysis can be mde for surface breaking defects).

6.2.3 Defect size and mis-match effects on CMOD.

The defect size and yield strength mis-match are shown in Fig. 11a (a fixed defect length is assumed). The following situation are assessed:

A: Highly overmatching weld metal,
B: Overmatched weld metal,
C: Undermatching weld metal.

Fig. 11a demonstrates that the resultant effect of increasing overmatching weld metal, curve A, is to decrease the CMOD for a given applied plastic strain. In this case, an undermatching weld metal requires more toughness than an overmatching weld metal. For applied strains smaller than the weld metal yield strain, however, the level of weld metal yield strength mismatch does not affect CMOD[15].

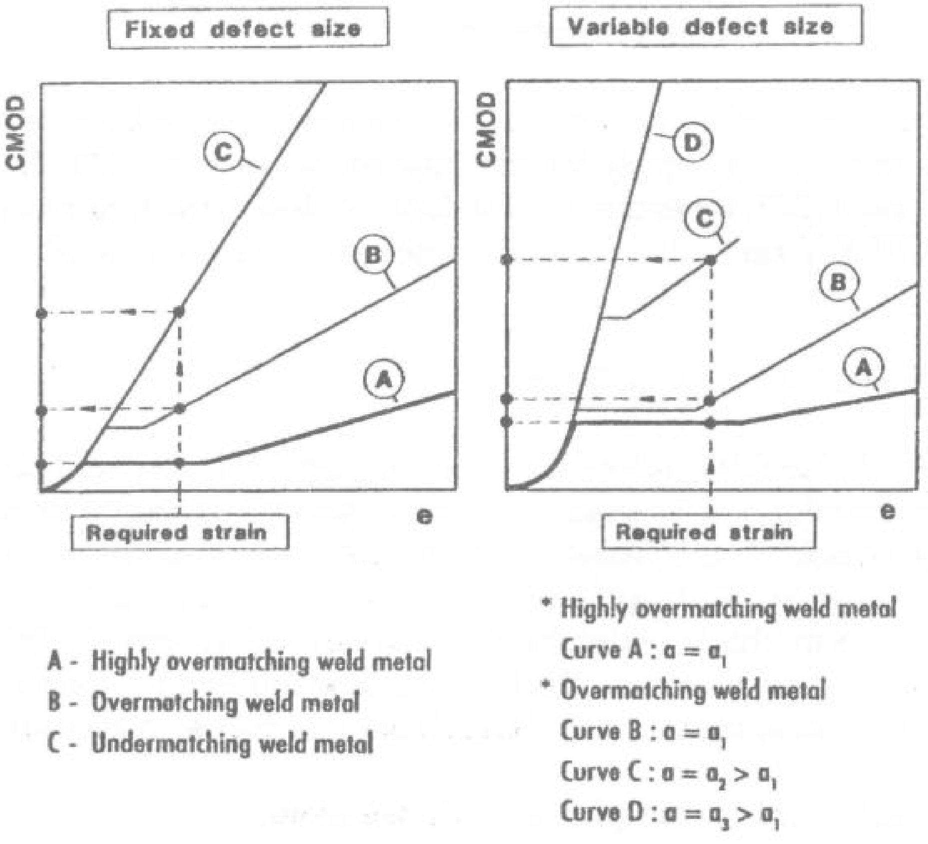

Fig. 11: Schematic illustrating the dependence of the CMOD on applied strain as a function of (a) the degree of weld metal overmatching for a fixed, $2a = c^{te}$, defect length and (b) defect length for a fixed level of overmatching (curves B, C and D)

The effect of increasing defect length and decreasing weld metal yield strength mis-match on CMOD is illustrated in Fig. 11b. In this Figure, the following definitions are used:

A: Highly overmatching weld metal containing a weld metal defect $a=a_1$,
B,C,D: Overmatching weld metal with $a = a_1$ (B), $a = a_2 > a_1$ (C), $a = a_3 > a_2$ (D).

Increasing defect lengths (curves B, C and D) cause greater CMODs for a given applied strain. The comparison of curves A and B further illustrates the effects of weld metal yield strength mis-match on CMOD for a given defect in terms of constraint. Increasing overmatching increases the level of elastic constraint thereby lowering the CMOD and thus the required toughness for GSY. Increasing defect length reduces level of elastic constraint which leads to higher CMOD.

6.2.4 Engineering significance of CMOD

The important quantity in the application of fracture mechanics concepts is CTOD and not CMOD. The engineering significance of the CMOD analysis can be appreciated by comparing the crack tip opening displacement (CTOD) as measured in the (highly constrained) three point bend test and the applied crack driving force for fracture (CMOD) occurring in a tension mode of loading. For a tensile loaded weldments, the overall constraint is lower than that found in the CTOD bend specimen. The ratio between the bend CTOD and tension CMOD for low toughness materials is approximately two. This ratio increases sharply with increasing notch toughness or decreasing defect length[27].

This observation enables to conclude that the observed interactions between CMOD and applied strain equally apply for the interaction between CTOD and applied strain. For weldment GSY, for example, a defect located in overmatching weld metal will need less CTOD than for the case of undermatching weld metal.

7. WELD DEFECT ASSESSMENTS

Failure for (tolerable) defect sizes producing GSY can be toughness (weld metal elastic or elastic-plastic weld metal behaviour) or strength dominated (weld metal gsy or nsy behaviour), Table 2. Thus, GSY or straining capacity can be obtained for moderate (low) toughness weld metal. This feature can be explored to develop alternative methods of defect acceptance. Fig. 12 summarises the various weld (HAZ) defect assessments paths in terms of weldment performance. The flow chart consists of a stress and a strain based integrity assessment branch.

7.1 Fracture mechanics and plastic collapse assessments

The stress based assessment can and is being used for design stress levels below plate yield strength (FM assessment). Conventional defect assessments are based on this condition. However, the FM methods of analysis have been developed

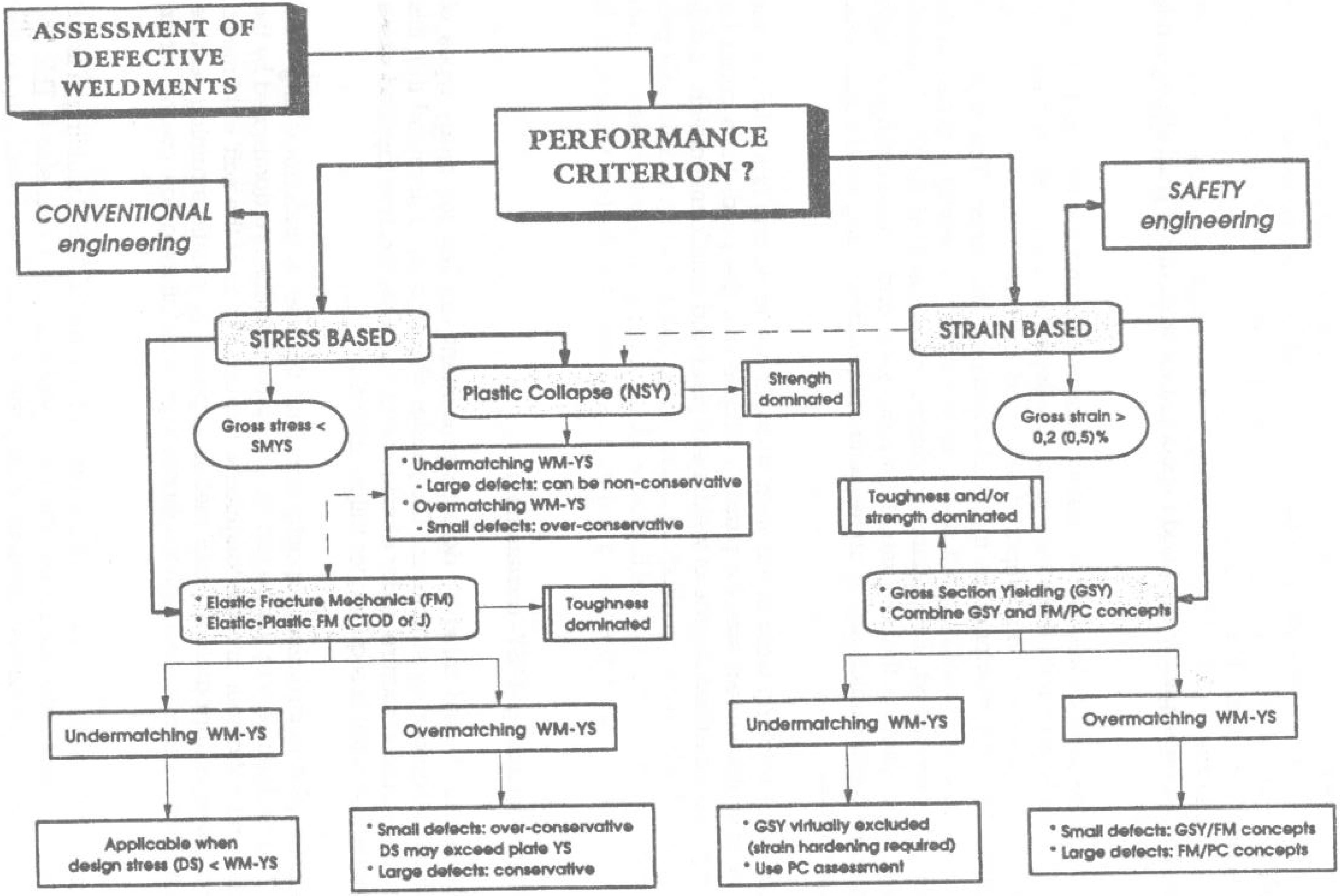

Fig. 12: Weld defect assessments, effect of performance requirement and weld metal yield strength mis-match.

prior to the development of 'tough' weld metals. Consequently, the user should know that the FM route is not always applicable. For example, experiments by Denys [16] have shown that a 30/40 J impact energy at design temperature for 3 mm deep and 7 times plate thickness long cracks in 25 mm thick weldments ensures plastic collapse. Furthermore, Fig. 12 (left branch, bottom) emphasizes the fact that FM solutions should be 'explicitly' modified to account for weld metal yield strength mis-match effects.

Plastic collapse predictions use the defect dimensions and the remote (nominal) applied stress to calculate the stress level developed in the defective (net) cross section. This stress level is then compared with a notional flow stress derived from the stress-strain tensile behavior of the material containing the defect. The value of the flow stress is greater than the yield stress, so the strain hardening capacity of the material is incorporated. For failure conditions characterised by (NSY) plastic collapse, the problem is that the use of the plate yield and tensile strengths might over-estimate (undermatching) or under-estimate (overmatching weld metal) weld metal flow stress.

No doubt, overmatching weld metal yield strength overmatching has a favourable effect on tolerable defect size for plastic collapse but, the predictions could be, depending on the certified degree of weld metal yield and tensile mis-match, unduly conservative. This has also an effect on the required toughness for plastic collapse. Note finally that for weld metals of limited work hardening, the usefulness of known flow stress definitions in predicting failure conditions of defective weldments is limited[17].

7.2 Plastic straining -GSY- assessment.

The strain based integrity defect assessment applies for many types of conventional engineering structures. The reader should also understand that this assessment excludes fracture under elastic conditions. Overloading (applied stress > plate yield strength) is required for failure initiation.

The need for plastic straining capacity can limit the use of undermatching weld metals. The problem is that the performance characteristics are dominated by the load-extension behaviour and the toughness characteristics of the 'soft' weld metal. Thus, defective undermatching weld metals exposed to plastic straining require adequate strain hardening and high toughness to prevent failure at low overall strain levels.

While a minimum toughness is required to obtain base metal (GSY) yielding, it is not always realized that, even for an overmatching weld metal, defect size is THE key factor. Increasing defect size is detrimental from the point of view of strength, i.e. the beneficial effect of overmatching decrease with increasing defect size.

Inasmuch the weld metal toughness exceeds the toughness transition, an overmatching weldment permits more straining than an undermatching weldment. From this viewpoint, it is attractive to ensure weld metal yield strength overmatching because it is then possible to allow relaxation in weld metal toughness requirements. Conversely, the tougher the weld metal is, the lesser the necessity to aim for overmatching. Unfortunately, little practical information exists to formulate practical recommendations.

8. UNDERMATCHING OR OVERMATCHING WELD METAL YIELD STRENGTH ?

There are conflicting opinions about the use of undermatching and overmatching weld metals. The choice depends on technical and economic factors and, the consequences of failure. Beyond the economic considerations, some say that we must accept undermatching weld metal, others believe that the use of undermatching weld metal must be excluded. In fact, both are right. The fact that some engineers make no discrimination between the design conditions and the actual performance characteristics of as-built weldments is at the origin of the disagreement[18-21].

The author is of the opinion that straining capacity is a critical requirement. This opinion is based on the fact that Charpy impact requirements for certain critical applications (e.g. pressure vessels) have been derived from large scale tests which had to satisfy a straining requirement (4 times yield strain[1]) which is, in to-day's terminology, nothing more than plate yielding.

The discussions on this subject will not come to an end, unless scientists involved in modeling and numerical analyses recognise that:

(a) the deformation characteristics of weldments made of 'low strength steels' differ from those in high strength steel weldments.

(b) with the introduction and use of the newer high strength steels (Specified Minimum Yield Strength > 450/500 MPa) it is becoming difficult to find matching weld metal with high toughness levels (the toughness requirement of SMYS/10 can be a severe requirement for low temperature applications).

(c) the differences between certified and actual plate/weld metal yield strengths can be significant.

However, the discussions can be concluded when elastic service conditions can be ascertained. In this case, weld metal mis-match is not direct issue. Undermatching weld metals can be accepted when they are fully documented. The use of overmatching weld metal might be more expense, however, the increased costs may be more than offset by savings from decreased costs for quality control, inspection and lifetime surveillance.

9 RESEARCH ASPECTS OF WELDMENT EVALUATION.

The trend to high yield strength steels poses the problem of weld joint efficiency in terms of strength and deformation capability. Laboratories all over the world are studying this problem. These studies vary in scope from highly theoretical to intensely practical.

9.1 Analytical approach.

Many researchers are of opinion that analytical models can be developed to predict the complex relationships between toughness, yield strength mismatch, groove design and weld defects on weldment performance. Whether this ambitious objective can be achieved is open to debate.

Published information is misleading. Comments on weld metal matching effects are derived from idealized weld geometries and material properties. Analytical models must address the effects of the manufacturing and material variations. Thus, the solutions are only as good as the data and assumptions on which the calculations are based. The other general points that require consideration are that:

(a) researchers involved in modeling do not produce experimental data or do normally not validate their predictions with large scale experiments. And, if they do so, they frequently underestimate the effects of defect size.

(b) despite the many papers written on this subject, we are still waiting for guidelines and simple rules from which the industry can benefit.

9.2 Experimental approach.

The importance of coupling testing and modeling in the evolution of design or defect assessment procedures cannot be over-emphasized. Consideration must be given to differences between drawing table, laboratory and field weldments.

Industrial experience demonstrates that the weldment performance levels of high yield strength steels depend on factors such as material variability, welding conditions and many other factors which cannot always be identified. Heterogeneous weldments can serve as an example. The other point about the experimental approach is that it is often the only way to obtain information which can be immediately used.

9.3 Solution.

One may not lose sight of the ultimate objective which is to provide simple guidelines. Therefore, analytical/numerical methods require experimental evidence to justify their use. To establish confidence, weldments of significant size fabricated according to practical production techniques should be evaluated. In particular, test specimens should be tested under a stress system that satisfactorily simulates service. The test conditions must equal or exceed the conditions that are likely to be encountered in the field. Too many times, however, tests supply information which is often misleading. For example, what is the engineering significance of the CTOD test for low crack tip constraint (shallow crack) situations in thin section plates.

9.3.1 Small scale testing

Small scale tests test cannot be used to investigate the performance characteristics of overmatching or undermatching weldments as they measure a local property. Small scale tests can only be used after calibration with large scale/wide plate tests. In this connection it should be noted that the calibration approach was used in the 1960s to establish CVN requirements[1] and in the 1970s to develop the CTOD design curve[22]. Since then, however, we are using materials with different characteristics.

9.3.2 Large scale testing

The large scale or wide plate test can be considered as a intermediate step required to tie the results of small scale test or analytical predictions to the performance of welds as component parts of structures. Insight into the relationship between toughness, weld metal yield strength mismatch and defect size can only be derived by considering the wide plate test.

10 FUTURE

The conflicting opinions on the weld metal matching issue calls for a critical examination of contemporary knowledge. Apart from the economic considerations, the number and complexities of the various factors affecting the choice between undermatching or overmatching weld metal makes this a difficult task.

The information necessary for establishing the performance levels of weldments fabricated with todays high yield strength steels cannot be derived from past experience. The properties of modern high yield strength steels and their companion weld metals differ from those we used in the past[23]. More information is required than that given by the tests hitherto used because the companion filler metals do not always attain the same high level of weld metal yield strength overmatching as observed in weldments made of conventional steels. Furthermore, a high yield strength weld metal is usually less tough so that the tradeoff between strength and toughness should be considered.

Fracture control procedures based on toughness might no longer be conservative. The straining capacity of a weldment depends not only on local toughness, but equally on the difference between the weld and base metal yield strengths, the yield to tensile ratio and defect size. In addition, with the much greater diversity of loading conditions and the possibility of accidental overloading it is natural that the criteria used to evaluate the strength and deformation capacity of weldments in the past must be re-examined. This incentive requires consideration of many factors. The primary factors that need to be considered include:

(a) the base and weld metal yield strength variability.
(b) the yield to tensile (YS/TS) ratio because high YS/TS ratio materials have inadequate strain hardening capacity to redistribute local deformations.
(c) the effects of forming operations and welding procedures on the base and weld metal yield strengths. For example, hot forming might cause a downwards shift of yield strength whereas cold forming cause an increase.
(d) defect position (weld metal/HAZ, buried or surface breaking), defect shape (through-thickness or semi-elliptical) and defect size.

Also, the potential presence of a low yield strength weld metal in a high yield strength steel poses problems of performance evaluation.

11 FINAL COMMENT

Further research should be directed to the development of simple but realistic procedures which have the capabilitiy for characterising the interaction between weld metal yield mismatch, defect size and toughness. Because of the complexity of this issue we need more experimental information which must be translated in simple guidelines.

In addition, understanding of the deformation behaviour of practical heterogeneous weldments and the development of an engineering test capable of identifing the actual degree of weld metal matching would greatly contribute to the knowledge and the assessment of weld metal yield strength effects on weldment performance.

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