Consultancy and Expertise in Quality, Materials, Agreement and Systems

A METALLURGICAL APPROACH OF THE PARAMETERS AFFECTING THE FRACTURE BEHAVIOUR OF BASE HETAL AND WELDED COMPONENTS

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FOREWORD

The setting-up of quantitative relationships between specific properties based on fracture mechanics theories and materials characteristics obtained through quality control tests is from many years an objective of the steel industry.

A well-known approach in this regard was proposed by SANZ in 1980 and is based on correlations between temperatures derived on the one hand from the Linear Elastic Fracture Mechanics and the K_{Ic} concept and on the other hand from the Charpy V test.

The interest of such correlations is clear since these provide a guidance for the selection of materials with regard to avoidance of brittle failure and they help in specifying in the standards suitable and realistic requirements based on test procedures easy to perform and daily applied by the steel producer. Updating regularly those simple models is also necessary owing to the constant evolution in steel quality and the need to ensure the right calibration with the most modern materials.

The hereunder reported activities in the field of resistance to failure fit with the above mentioned target and aim at considering the relevance of standard quality control tests to the actual fracture resistance of modern steels. Considering the toughness achieved by the present structural qualities, an elasto-plastic failure behaviour has to be considered. Developments of fracture mechanics theories have been observed those last years in this regard but it must be accepted that the now available concepts still fail in predicting accurate performances of welded components. Taking those limitations into account, the approach was to adopt indisputable test procedure and acceptance criterion, namely the wide plate test and the yield criterion proposed by SOETE and DENYS several years ago and now worldwide recognized as valuable and reliable concepts.

The results provided by this procedure were then related to standard materials characteristics such as Charpy V energy, tensile strength and yield stress, as well as hardness values along the heat affected zone of welded joints. The model which has been developed that way helps in anticipating the potentialities offered by modern steels for structural design and in detailing the metallurgy of welding of those new grades. A further asset offered by the present model is to promote the application of wide plate tests for the appraisal of the fitness for purpose of welded components since it releases the constructor from the need to carry out medium size fracture mechanics tests, while it gives him the possibility to readily optimize the successful achievement of wide plate tests by easy screening procedures.

SUMMARY

This document describes the development of a model which computes the fracture behaviour of wide plates from material characteristics easily accessible in quality control tests.

As far as only base metal is concerned, the material entry data are the Charpy V energy, the tensile strength and the yield stress.

For welded joints, the evolution of the Charpy energy and of the hardness in the heat affected zone and its surrounding is to be considered together with the base metal yield stress.

The application of this model to the appraisal of the critical defect size at full yield or of the fracture stress as a function of defect length is illustrated not only on proper experimental results but also with some data from other laboratories.

It is highlighted how this model can help in understanding the experimental results of wide plates and in optimizing the selection of weld metal and of heat input. Finally, it is shown that this model is a tool to promote the use of high strength modern steels as well as the tough performance of successful wide plate tests.

1. Introduction

A fracture safe design of metallic structures involves a set of requirements to be fulfilled which among others regard the proper selection of materials, the definition of suitable fabricating conditions, the set up of efficient control operations, the application of an adequate maintenance. The question is indeed to check whether the fitness for purpose is ensured at every stage occurring before or during the construction and along the service life.

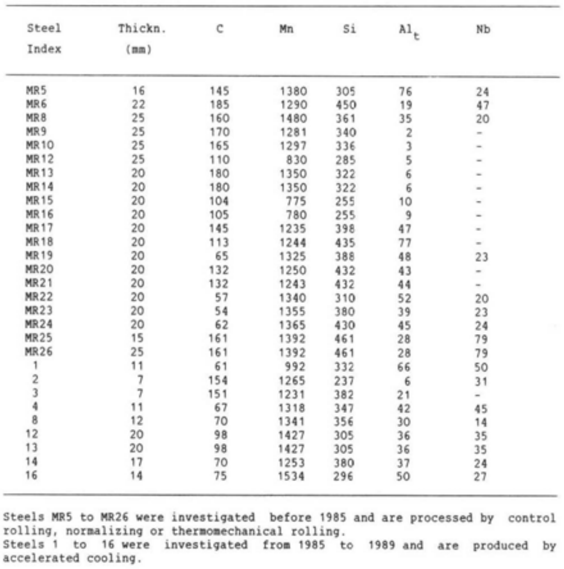
Specific tests can be applied in this regard. Some of them use medium size cracked specimens in full thickness, and request for an appraisal of their results a careful analysis based on different fracture mechanics theories or concepts. Another procedure is to investigate the resistance to brittle failure of large scale specimens the behaviour of which is comparable to that of a real component. Wide plate tests are in this regard a long standing well-proven technique (1, 2, 3) whose concept may be linked with the early documents on fracture mechanics (4) and which is suited to the applicability of simple and reliable criteria of structural integrity (5). Results of wide plate tests constitute also the reference data for the set up and calibration of several multi-purpose design curves or theories (6, 7). Such large scale trials bring moreover a relevant appraisal about the properties of structural steels in the as received or welded conditions (8, 9).

The above recalled great field of applicability for wide plates highlights the interest of a frequent use of those tests to appraise in all necessary cases the safety of metallic structures. It goes, however, without saying that the evaluation of large scale specimens requests appropriate experimental equipments and a suitable time planning. To encourage the application of this technique, it is therefore worthwhile to promote in the mean time models which can efficiently help in anticipating the wide plate results and achieving the best fracture behaviour. Such models could advantageously use as an experimental set of entry data the results of quite classical and usual quality control procedures such as tensile tests, Charpy V values or hardness measurements. Works have been carried out to achieve this objective. This document draws a survey about those investigations.

2. Description of experiments

Test material is low carbon microalloyed modern structural steel in plates or flanges of sections with a thickness comprised between 6 and 25 mm produced by thermomechanical rolling or accelerated cooling. The level of yield stress ranges from 330 to 540 MPa. Many of those products display a moderate tensile to yield ratio, i.e. between 1.11 and 1.30 and excellent toughness properties. Tables 1 and 2 list respectively the chemical composition and the mechanical properties of the investigated products.

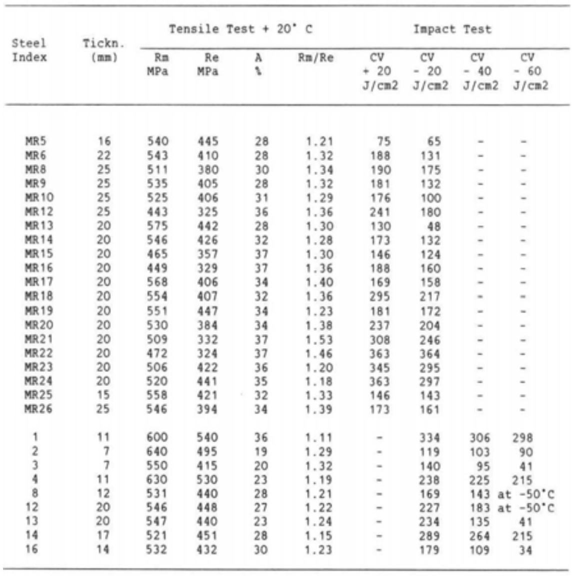
Welding of the material was conducted by the submerged arc process using a basic flux, and different types of weld metal listed in Table 3.



Steel Index	Thickn. (mm)	C	Mn	Si	Al_t	Nb
MR5	16	145	1380	305	76	24
MR6	22	185	1290	450	19	47
MR8	25	160	1480	361	35	20
MR9	25	170	1281	340	2	-
MR10	25	165	1297	336	3	-
MR12	25	110	830	285	5	-
MR13	20	180	1350	322	6	-
MR14	20	180	1350	322	6	-
MR15	20	104	775	255	10	-
MR16	20	105	780	255	9	-
MR17	20	145	1235	398	47	-
MR18	20	113	1244	435	77	-
MR19	20	65	1325	388	48	23
MR20	20	132	1250	432	43	-
MR21	20	132	1243	432	44	-
MR22	20	57	1340	310	52	20
MR23	20	54	1355	380	39	23
MR24	20	62	1365	430	45	24
MR25	15	161	1392	461	28	79
MR26	25	161	1392	461	28	79
1	11	61	992	332	66	50
2	7	154	1265	237	6	31
3	7	151	1231	382	21	-
4	11	67	1318	347	42	45
8	12	70	1341	356	30	14
12	20	98	1427	305	36	35
13	20	98	1427	305	36	35
14	17	70	1253	380	37	24
16	14	75	1534	296	50	27

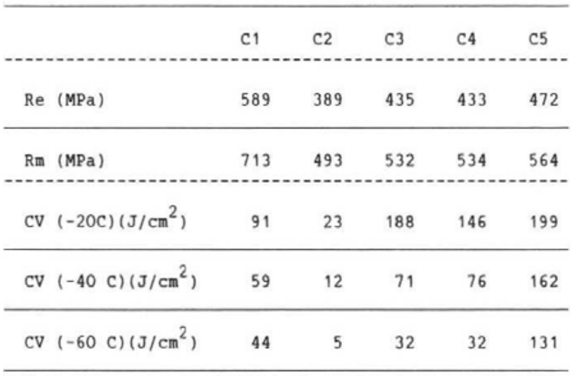
Steels MR5 to MR26 were investigated before 1985 and are processed by control rolling, normalizing or thermomechanical rolling.
Steels 1 to 16 were investigated from 1985 to 1989 and are produced by accelerated cooling.

Table 1. Chemical Compositions



Steel Index	Tickn. (mm)	Tensile Test + 20° C				Impact Test			
		Rm MPa	Re MPa	A %	Rm/Re	CV + 20 J/cm2	CV - 20 J/cm2	CV - 40 J/cm2	CV - 60 J/cm2
MR5	16	540	445	28	1.21	75	65	-	-
MR6	22	543	410	28	1.32	188	131	-	-
MR8	25	511	380	30	1.34	190	175	-	-
MR9	25	535	405	28	1.32	181	132	-	-
MR10	25	525	406	31	1.29	176	100	-	-
MR12	25	443	325	36	1.36	241	180	-	-
MR13	20	575	442	28	1.30	130	48	-	-
MR14	20	546	426	32	1.28	173	132	-	-
MR15	20	465	357	37	1.30	146	124	-	-
MR16	20	449	329	37	1.36	188	160	-	-
MR17	20	568	406	34	1.40	169	158	-	-
MR18	20	554	407	32	1.36	295	217	-	-
MR19	20	551	447	34	1.23	181	172	-	-
MR20	20	530	384	34	1.38	237	204	-	-
MR21	20	509	332	37	1.53	308	246	-	-
MR22	20	472	324	37	1.46	363	364	-	-
MR23	20	506	422	36	1.20	345	295	-	-
MR24	20	520	441	35	1.18	363	297	-	-
MR25	15	558	421	32	1.33	146	143	-	-
MR26	25	546	394	34	1.39	173	161	-	-
1	11	600	540	36	1.11	-	334	306	298
2	7	640	495	19	1.29	-	119	103	90
3	7	550	415	20	1.32	-	140	95	41
4	11	630	530	23	1.19	-	238	225	215
8	12	531	440	28	1.21	-	169	143 at -50°C	
12	20	546	448	27	1.22	-	227	183 at -50°C	
13	20	547	440	23	1.24	-	234	135	41
14	17	521	451	28	1.15	-	289	264	215
16	14	532	432	30	1.23	-	179	109	34

Table 2. Mechanical Properties



	C1	C2	C3	C4	C5
Re (MPa)	589	389	435	433	472
Rm (MPa)	713	493	532	534	564
CV (-20C)(J/cm^2)	91	23	188	146	199
CV (-40 C)(J/cm^2)	59	12	71	76	162
CV (-60 C)(J/cm^2)	44	5	32	32	131

Table 3. Weld metal Properties

Heat input was fixed as a function of thickness so as to cover a range of cooling times from 800 to 500°C (t8/5) comprised between 35 and 55 seconds. Tables and charts were used in this connection to fix the appropriate welding conditions (12) while several measurements of the cooling time were performed.

An example of joint preparation to achieve a straight as possible fusion line is illustrated in Figure 1 while the so obtained geometry of the heat affected zone is shown in Figure 2.

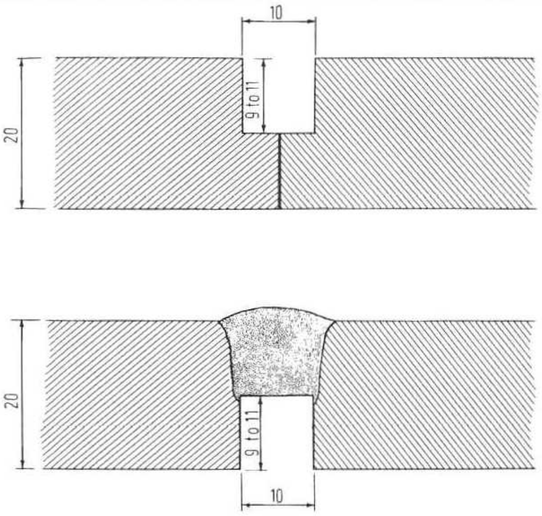


Figure 1. Joint Preparation

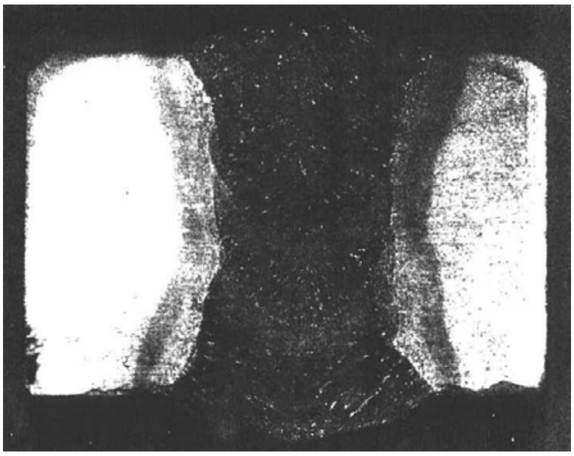


Figure 2. Macrography of a Welded Joint

3. The wide plate test

Figure 3 sketches classical dimensions of the specimens, which can be fitted with through thickness or surface defects.

Those specimens are tested in a 4000 kN tensile machine (Figure 4).

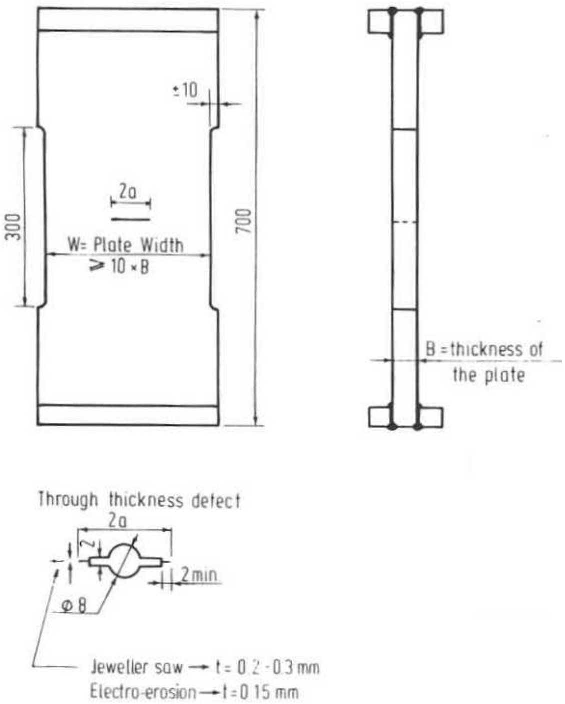


Figure 3. Wide Plate Test Specimen

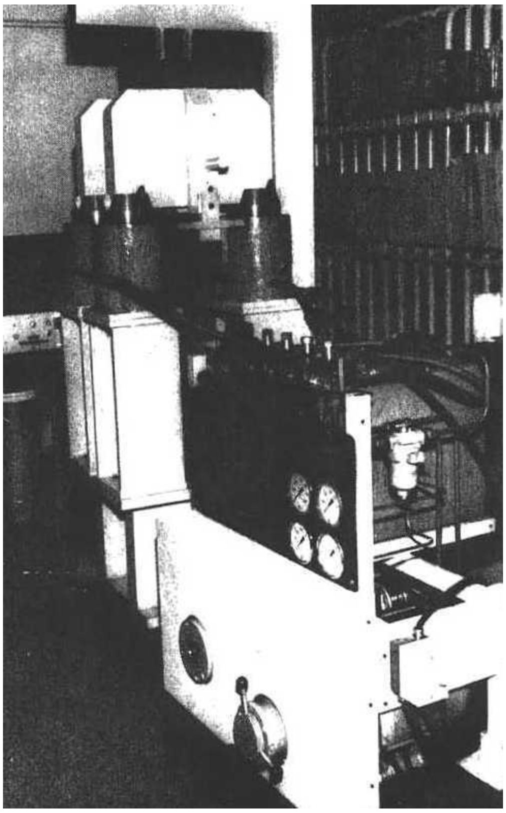


Figure 4. 4000 kN Tensile Machine

Through thickness defects are constituted of a central hole extended by two saw cuts of an appropriate length and terminated by thin 2 mm long notches, which were normally made with a jeweller saw; a tip radius between 0,10 and 0,15 mm was achieved that way.

Special attention was devoted to defect making and a procedure was developed by means of the electro erosion process, which allows to decrease this notch radius down to 0.075 mm. An example of such a very sharp notch is illustrated in Figure 5 under a semi-millimetric scale.

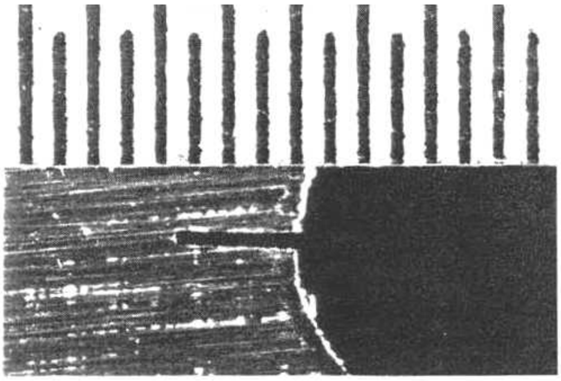


Figure 5. Sharp Defect by Electro erosion

Surface defects may also be investigated, which run over the entire width of the specimen under a given depth. Such defects were machined with a circular tool and then extended by fatigue under flexion loading in a 1000 kN actuator. Figure 6 shows a detail of the test equipment.

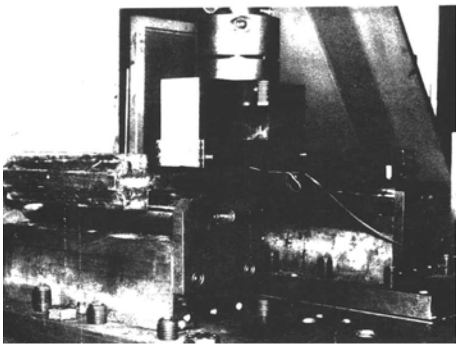


Figure 6. Fatigue Cracking

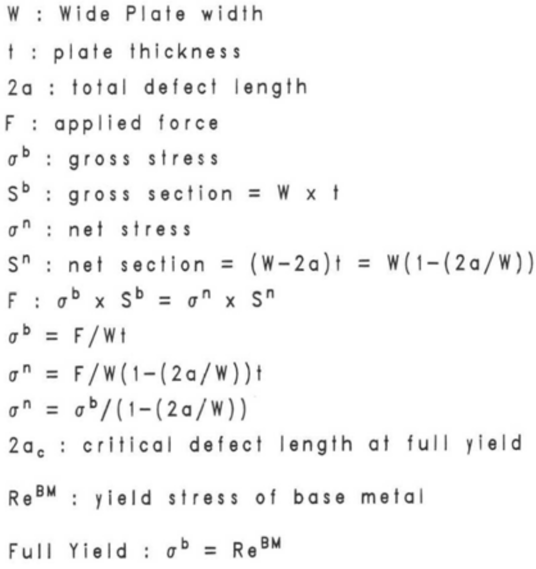
The following parameters are measured during the test:

- the tensile force;
- the overall elongation in the specimen axis on a 300 mm base length;
- the overall elongation at the specimen length side on a200 mm base length;
- the temperature of the specimen;

- the defect opening by means of a clip-gage;

Stresses in the wide plate test are computed from the force on two basis:
- that of the section not affected by the defect, this is the so called "gross section" from which the "gross stress" is derived;
- that of the section affected by the defect, this is the "net section" and the corresponding "net stress".

Some details are recalled in Table 4.



W : Wide Plate width

t : plate thickness

2a : total defect length

F : applied force

σ^b : gross stress

S^b : gross section = W x t

σ^n : net stress

S^n : net section = $(W-2a)t = W(1-(2a/W))t$

F : $\sigma^b \times S^b = \sigma^n \times S^n$

$\sigma^b = F/Wt$

$\sigma^n = F/W(1-(2a/W))t$

$\sigma^n = \sigma^b/(1-(2a/W))$

$2a_c$: critical defect length at full yield

Re^{BM} : yield stress of base metal

Full Yield : $\sigma^b = Re^{BM}$

Table 4. Wide Plate tests Basic Data

4. A quantification of the metal sensitivity to notch effect

Let be considered several wide plates taken from a same batch of steel and tested at lowered temperature with different sizes of the through thickness defect. It may obviously be expected a reduction of the net section stress at failure in the wide plate for increasing defect sizes since a larger defect induces a more pronounced stress intensity or a greater notch effect.

Figure 7 exemplifies the type of evolution which is observed during the experiments. It comes that the net section stress decreases linearly as a function of defect size. The slope of this evolution line can then be considered as a quantification of the sensitivity of the metal to a notch surrounded by a large ligament.

To elaborate this concept, it is advantageous to express that the net fracture stress in the wide plate would equate the tensile strength of the material in the absence of any defect. The following relationship can thus be written : σ^n_R = Rm.(1 - k.2a) in which Rm is measured at the test temperature. The parameter "k" in that relation will be considered as the notch sensitivity.

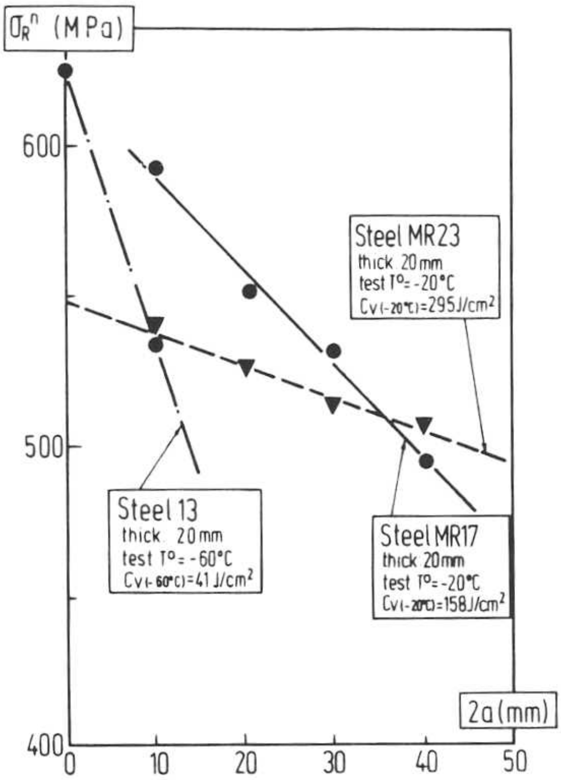


Figure 7. Net Section Stress vs. Defect Length

A fact that can be deduced from Figure 7 is that a steel with a better Charpy V energy shows a lower or more favourable notch sensitivity. It is therefore attracting to attempt to link both parameters through a quantitative relationship.

This task has been carried out and the conclusions are illustrated in Figure 8. It comes that an upper boundary of the experimental results can be defined and that a conservative prevision of the above defined notch sensitivity can be performed from the Charpy V energy measured at the same temperature and according to the same test direction. Some comments are useful in this regard.

It is worth mentioning first that the equation of the boundary curve - i.e. the "k.CV = 0.8" hyperbola - was set up since 1985 on the sole basis of the experimental points represented by full marks in Figure 8. The other open points were added later as a confirmation of this law and an extension to other steel qualities and to a wider range of temperature.

The second comment relates to the importance of the experimental work. The determination of the factor k as an appraisal of the notch sensitivity on a large scale basis needed about 200 wide plate tests for the 50 cases reported in Figure 8. This is obviously a significant piece of work. On the contrary, the corresponding determination of the Charpy V energy needed only the performance of about 150 small scale tests.

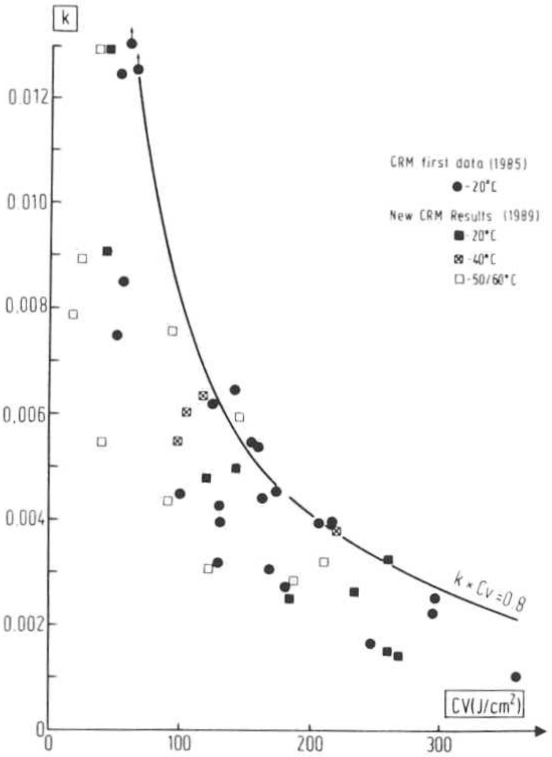


Figure 8. Notch Sensitivity vs. Charpy V Energy

The above mentioned relationship highlights therefore from now on the interest of small scale easy to perform standardized test procedures as a way, surely not to replace, but certainly to prepare, optimize and anticipate the results of wide plate tests.

5. Estimate of gross section fracture stress in wide plate

A nearly immediate application of the above defined concept consists in the computation of the gross fracture stress of a wide plate as a function of the defect size.

To do so, the gross fracture stress has first to be linked to the net section corresponding stress, as a function of wide plate width and defect length. The applicable relationship is recalled in Table 4.

$$\frac{\sigma^{b}_{r}}{Re^{BM}_{(T)}} = \left(\frac{Rm}{Re}\right)\left(1-\frac{0.8}{C_V}.2a\right)\left(1-\frac{2a}{W}\right)$$

$$= \left(1-\frac{2a}{W}\right) \text{ if } \frac{Rm}{Re}\left(1-\frac{0.8}{C_v}.2a\right)<1$$

σ^{b}_{r} : fracture stress estimated on the gross section of the specimen

$Re^{BM}_{(T)}$: yield stress of the base metal at test temperature

$2a$(mm) : total defect length

(Rm/Re) : tensile strength to yield stress ratio at room temperature

C_V (J/cm^2) : Charpy V at test temperature

W(mm) : width of the plate

Table 5. Computation of Fracture Stress

As a second step, it is useful to rationalize the gross stress in wide plate in terms of the yield stress of the material at the considered test temperature.

Table 5 lists the equation that is derived that way. The gross fracture stress divided by the material yield stress is thus a function of the defect size, the wide plate width, the Charpy V energy of the steel at the test temperature and the tensile to yield ratio Rm/Re. This material characteristic should as a rule be measured also at the test temperature. It comes, however, that for tough structural steels this ratio is not so much influenced by temperature in the range of +20 to -60°C. Therefore, it is attractive for simplification purpose to consider this ratio at the ambient.

A complement to improve the accuracy of the computation when large defects are considered can be brought provided the test temperature at the wide plate exceeds the fracture appearance transition temperature of the metal at the Charpy test (FATT temperature). Conditions are met indeed in those conditions to secure a fibrous type fracture at wide plate meaning that the net fracture stress reaches at least the yield strength. Another formulation for the computation of the gross stress for those large defects can then be used. It is listed in Table 5 which also contains the relevant information for the appropriate application of this model.

Examples of such computations are shown in Figure 9 and highlight the accuracy of those predictions. Figure 10 is a summary of all available results. It compares the experimental and computed gross fracture stresses corresponding to about 200 wide plates with defects sizes ranging from 10 to 50 mm sometimes up to 70 mm at temperatures between -20 and -60°C. Here again, a distinction has been made between the early results and the later ones to highlight the fact that the model developed in 1985 could be extended to other steels and a larger temperature range without any “retayloring”.

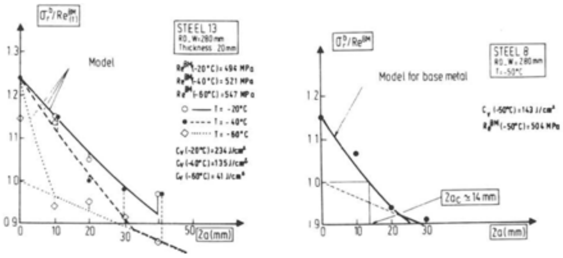


Figure 9. Wide Plate Test Results

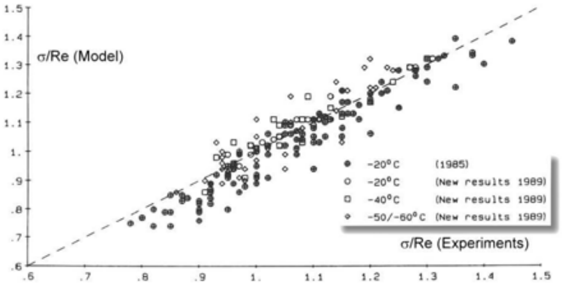


Figure 10. Fracture Stress, Computations vs. Experiments

6. Estimate of the critical defect length

The full yield or also so called gross section yield criterion is an appropriate and convenient way to derive a critical defect length (13). According to this concept, yielding of the metal occurs everywhere in the plate before failure, thus provides a field of plastic strains and ensures that way a safe fracture behaviour.

Full yield is achieved when the gross stress in the wide plate exceeds base material yield stress at the test temperature. Should different defects of increasing size be considered at a same temperature, a critical defect length can be defined as soon as the above condition is no more fulfilled, in other terms when the ratio σ/Re equates one (Figure 11). Table 6 lists the equations from which the critical defect length can be computed according to the present model. It is an equation of the 2nd degree which as a rule admits two roots. One of them has, nevertheless, no physical meaning so that the solution is brought by the formula detailed in Table 6.

$$2a_c = \frac{W + 1.25C_V - \sqrt{(W + 1.25C_V)^2 - 5WC_V\left(1 - \frac{Re}{Rm}\right)}}{2}$$

$2a_c$(mm) : total length of the critical through thickness defect at test temperature

W(mm) : width of the plate

C_V (J/cm^2) : Charpy V at test temperature

Re/Rm : yield stress to tensile strength ratio at room temperature

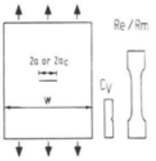


Table 6. Computation of Critical Defect

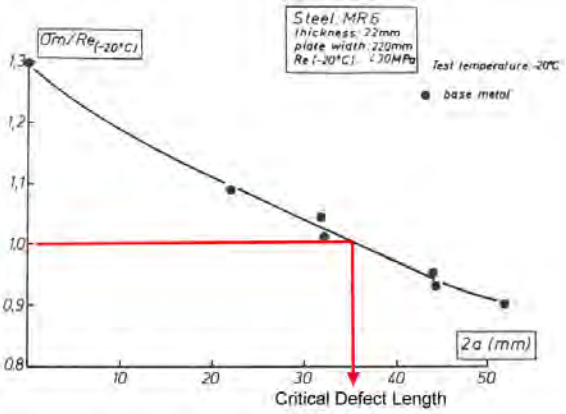


Figure 11. Through Thickness Defect in Wide Plate Tests

Figure 12 compares the estimates of the critical defect length with the experimental values and highlights the realistic and conservative agreement.

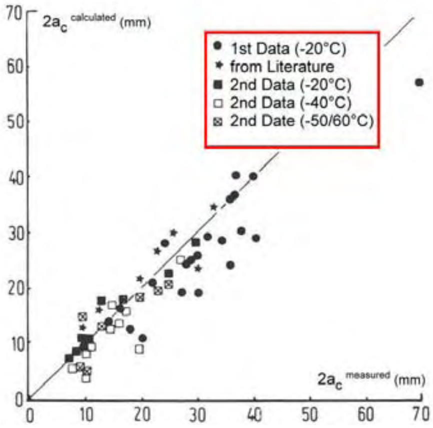


Figure 12. Defect Length, Computations vs. Experiments

This diagram calls for some remarks. It will be first mentioned that each point is, from an experimental point of view, the result of 4 to 6 wide plate tests. Then it is worth considering both sets of data: the black points correspond to the population from which the model was built while the open points relate to a second campaign performed after 1985 on other steels and at lower temperatures. The original model is thus confirmed. One notices, also the good agreement found in 1985 with experimental data reported in the literature. This point is extremely important for a calibration of a model. It will be discussed in more details in another section.

7. Physical significance of the model

Besides the mathematical relationships, the model expresses an important physical fact. It shows that the fracture behaviour of a large piece is governed by two material properties in an interactive way: the toughness, here expressed by the Charpy energy, the strain hardenability, here quantified by the tensile to yield ratio. Figure 13 illustrates this phenomenon in two significant cases and highlights the particular safe behaviour that is achieved by a material with a good toughness and a moderate tensile to yield ratio, as displayed by modern steels.

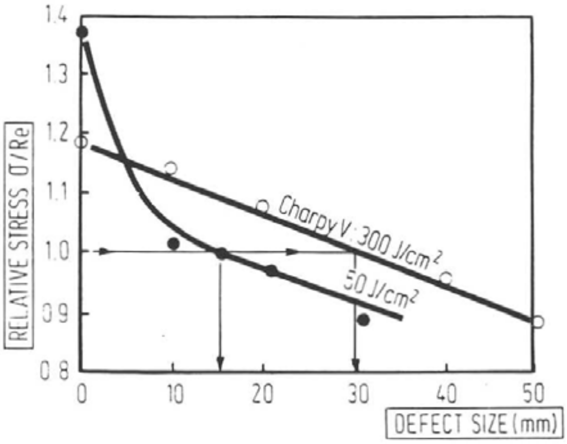


Figure 13. Fracture Behaviour

If the reserve of resistance over the yield stress depends indeed initially on the Rm/Re ratio, its evolution as a function of the defect length is governed by the material toughness, which fixes the slope of the curve.

The diagram and the model thus demonstrate that a specification for an elevated Rm/Re ratio as it is found in some codes, is not a guarantee for a safe fracture behaviour, because it does not take account of a possible presence of a sharp notch in the construction. On the contrary, this condition which from a metallurgical point of view is more easily fulfilled in materials with higher carbon content goes in a direction opposite to the development of high strength steels with improved toughness and weldability as those processed by thermomechanical rolling or accelerated cooling.

8. Extension to welded assemblies

In welded assemblies, the mechanical properties display sharp variations especially in the heat affected zone. This is a difficulty for the appraisal of the fracture behaviour because on the experimental basis the defect has to be actually located in the most critical zone of the test specimen, while for a correct modelling it is necessary to design how the local properties of the metal at the crack tip interfere with those far away from the defect and induce the global resistance to failure.

The model which is presented above, considers three metal characteristics: the Charpy energy, the tensile resistance and the yield stress. The first two ones are used to derivate a fracture stress when a sharp notch is present in the wide plate while the third one is necessary either to rationalize this stress in terms of the performances to be expected from the considered material or to compute the critical defect length according to the full yield criterion.

A possibility of extending this model to welded joints would therefore consist in considering the local Charpy energy and tensile strength of the steel at the crack tip while the yield stress of the base metal would still have to be kept. It is indeed the base metal which has to yield in the wide plate according to the adopted criterion. As regards the appraisal of the necessary local properties, Charpy specimens can be easily extracted in the heat affected zone, etched and notched at the right position, while hardness measurements can be performed to assess a local tensile strength. For weld metal, tensile specimens can even be performed.

Another peculiarity of the welded joint is, however, the existence of residual stresses, whose influence on the fracture behaviour is quite complex. Therefore, before looking at extending the model to welded joints, it is worth considering some effects induced by the residual stresses which may alter the influence of material properties.

9. Residual stresses and plastic yield of weld metal

Weld residual stresses are specially large in the direction of the bead and generally attain a value close to the yield stress of the base metal

They directly result from restraint effects occurring just after the welding cycle and which prevent the natural shrinkage of the weld metal. For similar reasons, high through thickness residual stresses are also to be expected. This means that in a welded joint free from external load, the weld metal is subjected to a field of large tensile residual stresses across the plate thickness and along the bead axis. For reasons of static equilibrium a reverse situation prevails at a certain distance from the welded area.

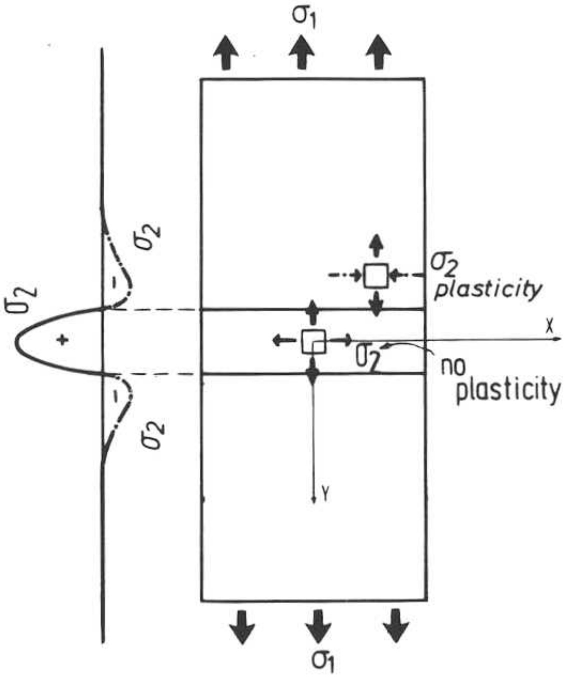


Figure 14. TRESCA's Criterion for Plasticity

Should an external load be applied to the assembly, a state of stresses similar to that one sketched in Figure 14 will develop. Plasticity criteria as those of TRESCA or von MISES tell that such a situation retards the plastic yielding of weld metal. This can play a significant role when the weld metal displays a lower yield stress than the base steel. In the absence of residual stresses, yielding would be expected to occur first in the weld while the base metal is still elastic. A finite element analysis of the question reported in Figure 15 confirms this statement. A same computation conducted with the assumption of residual stresses in the weld metal leads, however, to the situation reported in Figure 16 where weld metal yielding is prevented to a large extent. Such a situation prevails as long as base metal is loaded under its yield stress. Beyond this threshold, the simulation shows in Figure 17 that when the base metal starts to yield, large plastic strains suddenly take place in the weld.

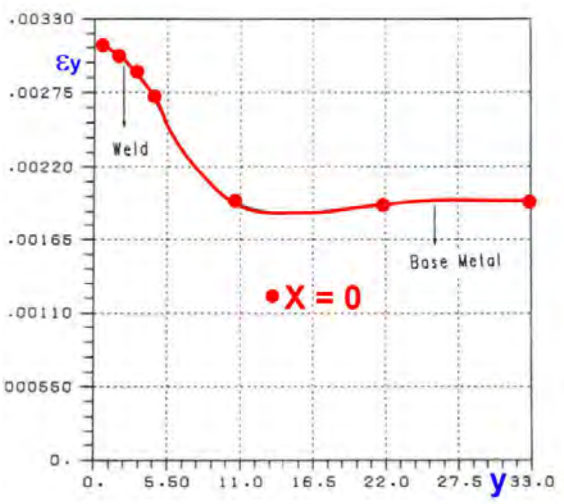


Figure 15. FEM Computation, Undermatching without Residual Stresses, Applied Stress: 405 MPa

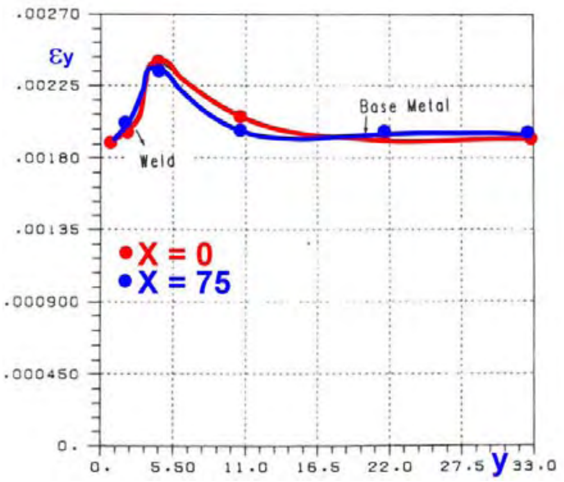


Figure 16. FEM Computation, Undermatching with Residual Stresses, Applied Stress: 405 MPa

It can therefore be concluded from those simulations, that residual stresses tend to "protect" a soft weld metal against yielding but this effect is temporary and vanishes when base metal starts to yield. Weld metal is then forced to quite rapidly develop plastic strains to accommodate this unstable situation. This indicates possible limitations coming from weld metal with strength properties largely different from those of base metal because of unstable conditions created with softer weld metal, or also of exacerbated residual stresses induced by too hard weld metals.

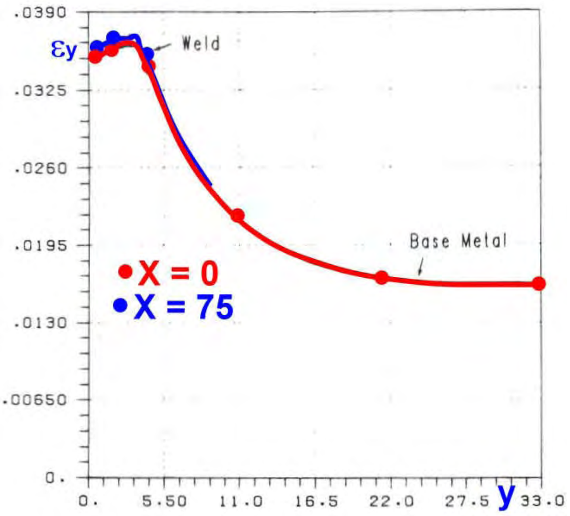


Figure 17. FEM Computation, Undermatching without Residual Stresses, Applied Stress: 440 MPa

The above computations highlight the complex role exerted by residual stresses which appear to be hardly modelled by simple approaches of fracture mechanics. Only models powerful enough to compute accurately the level of residual stresses after welding and to account for their evolution in external loading conditions seem liable to tackle this problem satisfactorily and to bring precise forecasts of the fracture behaviour.

From an experimental basis, it seems therefore appropriate to use fracture tests in which the residual stresses are actually present in the specimens at a representative level. Wide plate tests fulfil this requirement in this regard.

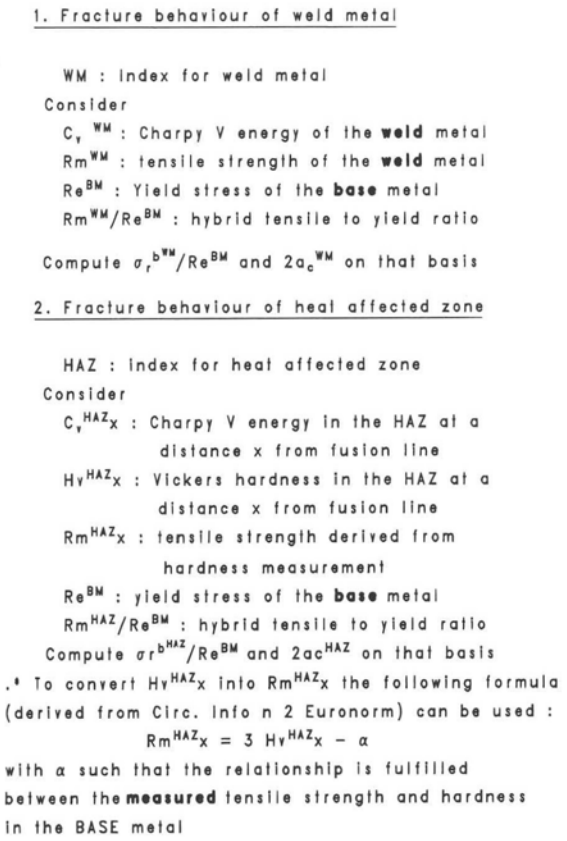
Those considerations thus fix the field of application for an extension to welded joints of the present model. It will not take precise account of the residual stresses but will try to derive a maximum of information from the mechanical properties of the fused metal, the heat affected zone and the base steel so as to anticipate possible problems at wide plate tests which would result from an inappropriate selection of weld metal or a non suitable welding procedure.

10. A concept of weld metal matching

A simple way to extend the model to welded joints is to consider that the defect affecting the wide plate is either located in the base metal or in the weld metal.

In the first situation, a fracture behaviour is predicted from the formulae listed in Tables 5 and 6 and using as entry data the parameters Rm, Re and CV of the base metal.

In the condition of a defect located in the weld metal, the relevant tensile strength and Charpy values are those of the weld metal while the yield stress of the base metal is still to be considered, since it is the reference data for the design of the welded component (Table 7).



1. Fracture behaviour of weld metal

WM : Index for weld metal
Consider
C_v^{WM} : Charpy V energy of the **weld** metal
Rm^{WM} : tensile strength of the **weld** metal
Re^{BM} : Yield stress of the **base** metal
Rm^{WM}/Re^{BM} : hybrid tensile to yield ratio

Compute $\sigma_r{}^{b^{WM}}/Re^{BM}$ and $2a_c{}^{WM}$ on that basis

2. Fracture behaviour of heat affected zone

HAZ : Index for heat affected zone
Consider
$C_v{}^{HAZ}x$: Charpy V energy in the HAZ at a distance x from fusion line
$Hv^{HAZ}x$: Vickers hardness in the HAZ at a distance x from fusion line
$Rm^{HAZ}x$: tensile strength derived from hardness measurement
Re^{BM} : yield stress of the **base** metal
Rm^{HAZ}/Re^{BM} : hybrid tensile to yield ratio
Compute $\sigma r^{b^{HAZ}}/Re^{BM}$ and $2ac^{HAZ}$ on that basis
.• To convert $Hv^{HAZ}x$ into $Rm^{HAZ}x$ the following formula (derived from Circ. Info n 2 Euronorm) can be used :

$$Rm^{HAZ}x = 3\ Hv^{HAZ}x - \alpha$$

with α such that the relationship is fulfilled between the **measured** tensile strength and hardness in the BASE metal

Table 7. Application to Welded Joints

Used that way, the model brings the fracture stress evolution of both weld and base metals as a function of defect size and the respective critical lengths at full yield.

Figure 18 presents different situations which can appear as a function of the respective properties of the base material and the weld metal. Here comes a new concept of matching from. It is self-explanatory looking at those diagrams. Matching of weld metal to base steel is achieved when fracture behaviour as a function of defect length is similar for both components of the welded assembly. Critical defect sizes at full yield are also comparable in that situation.

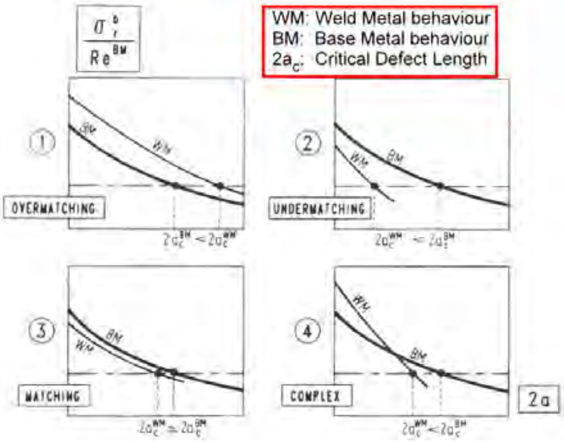


Figure 18. Different Matching Conditions

Should one of these metals supersede the other in terms of resistance to failure, over- or undermatching conditions would then be met. There is also one situation referred to as "complex" where the ranking depends on the defect size.

This fracture oriented definition of matching can bring useful information. Two examples are given to support this statement. Figure 19 plots the results of different wide plate tests when the defect was located in the weld metal.

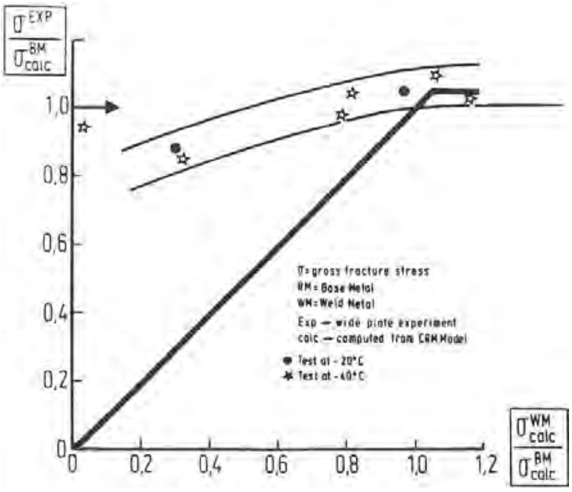


Figure 19. Defect in Weld Metal

Abscissa reports the ratio between the fracture stresses computed from the model for weld and base metals, in other terms it expresses the degree of matching. Ordinate bears the ratio between the experimental gross fracture stress measured at wide plate and the computed value relating to the base metal. Different observations can be made in this diagram. First of all, in the area where matching is achieved, i.e. for abscissa comprised between 0.8 and 1.2, the experimental fracture stress is close to the computed value (ordinate of the concerned points close to 1).

This means that in such conditions, a good evaluation of the fracture behaviour of an assembly with a defect in the weld metal, is brought by the model. For marked degrees of undermatching (abscissa near to 0.3), the model brings deliberately too conservative results, looking at the gap between experimental results and the so obtained estimates. This discrepancy is a direct consequence of the residual stresses and of their protective temporary effect on the weld metal commented in section 9 in undermatching conditions. Rather than a lack of accuracy, this feature of the model could be considered as a warning of a potentially unsafe situation. When looking in Figure 20 on experimental results and fracture simulations for different defect sizes in wide plate assemblies welded with undermatching conditions, it comes first that in no case the expected fracture behaviour of the base metal is achieved.

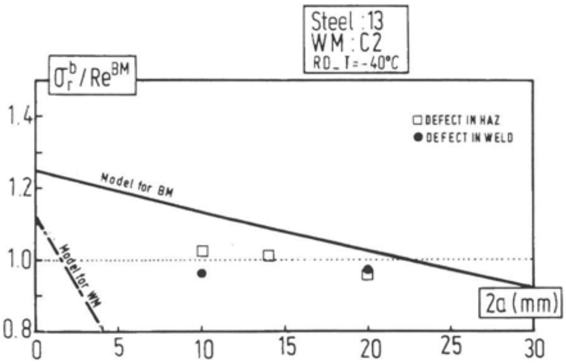


Figure 20. Undermatching Conditions

As a second fact, the fracture stress stays at a constant level and does not depend on the defect size. This could be rather surprising were the constant level not precisely equal to the base metal yield stress. Such results are therefore consistent with the simulations by finite element analysis which show that residual stresses suddenly relax when base metal yields and that the temporary protection brought to the weld metal drops immediately. If the latter displays a poor toughness, it cannot support this situation and fails in a brittle manner.

11. Computation of the fracture behaviour of welded joints

For an application of the model to welded assemblies, it is necessary to compute the fracture behaviour not only for the weld metal but also for the heat affected zone. To do so, the local values of the Charpy energy and of the tensile strength inside HAZ are also to be generated. Charpy specimens may in this regard be extracted, etched to reveal the fusion line and notched at the requested distance. This procedure brings the evolution of the toughness through the heat affected zone.

Vickers hardness measurements can be easily performed on the above specimens before they are fractured so as to give, after a suited conversion, an image of the tensile strength distribution in the affected zone. Both local parameters CV and Rm are thus measured from the weld metal to the base metal and can be used together with the yield stress of the parent steel to calculate the fracture behaviour of a welded component. Details about the achievement of such computations are listed in Table 7.

Examples of such computations are shown in Figure 21 in two cases, the first one corresponding to a heat input which induced in a butt joint of 17mm thick plates a cooling time between 800 and 500°C of 35 seconds, the second one relating to a higher heat input and a cooling time of 55 seconds. Before going further in the description of those experiments, it is worth recalling that the so called t8/5 cooling time is a convenient parameter to define the range of suitable welding conditions. In this regard, it was shown previously (14, 15) that too long weld cooling times impair the HAZ properties and induce a poor fracture behaviour. The limit not to exceed with classical steels was found to be around 60 s. The here reported experiments thus correspond to a quite acceptable cooling time on the one hand and to a boundary case on the other hand. The diagrams in Figure 21 plot the three respective evolutions of the Charpy energy in the weld metal, the heat affected zone and the parent steel, of the hardness which is then converted into a tensile strength and a "hybrid" tensile to yield ratio, and finally of the computed critical defect length. The accuracy of the so achieved defect size computation is exemplified by the points corresponding to the experimental results. It is clear that such diagrams are useful to appreciate the suitability of the applied welding conditions. It comes here that those corresponding to a cooling time of 35 s lead to a favourable fracture behaviour of the heat affected zone while the welding conditions whose t8/5 parameter is at the boarder line induce a degradation in the HAZ, as it could be expected.

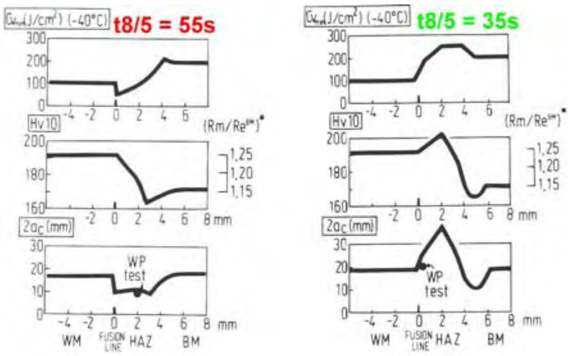


Figure 21. Fracture Behaviour of Welded Joints

Another application of the model is reported In Figure 22 and it applies to a set of wide plate tests carried out on welded joints with different steels, weld metals, heat inputs and defect sizes.

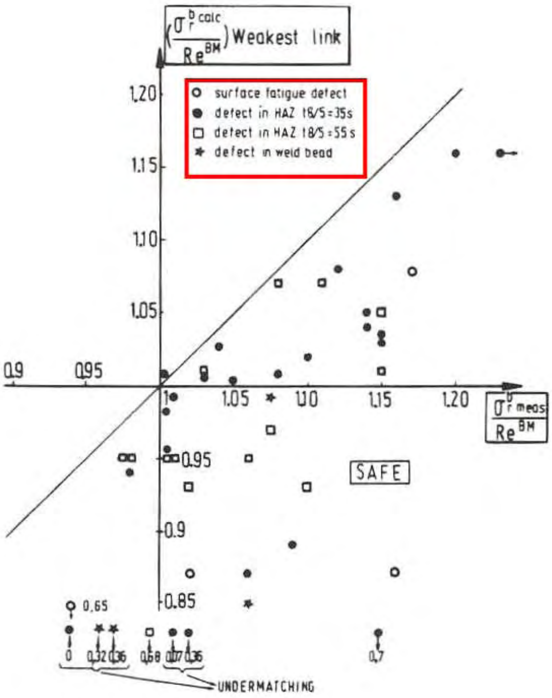


Figure 22. Model applied to Welded Joints

The fracture stress of the wide plate is here considered, either measured from the tests or computed according to a weakest link concept. This simply means that the lowest fracture stress derived from the Charpy and tensile to yield ratio of weld metal, base metal and HAZ is taken into account. It comes that the model gives in all cases a conservative estimate and in most instances a realistic prediction. Only the cases corresponding to marked undermatching situation appear too conservative, but this question was already discussed above.

12. Application of the model to external test results

Results of wide plate tests performed in other laboratories are valuable data to appreciate the validity of a model. To illustrate this, Figures 23 and 24 are extracted from publications of the Technical University of AACHEN (7, 8) and compare the experimental German results of wide plates in different base metals to the computations made by the present model. As it can be seen this validation applies too for very tough modern steels.

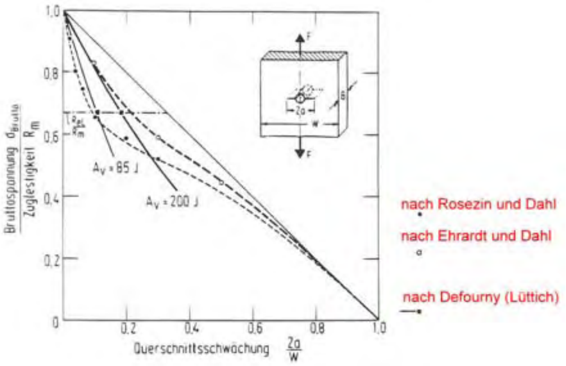


Figure 23. Excerpts from RWTH Publications

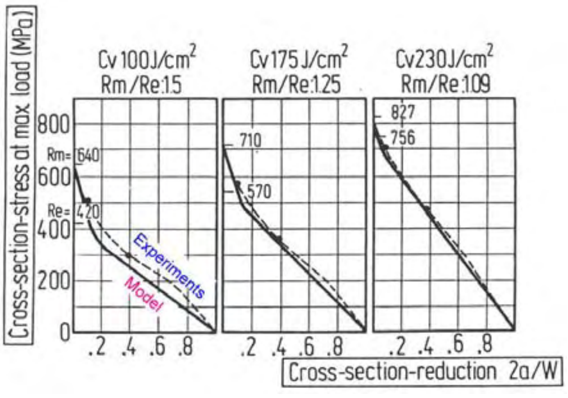


Figure 24. Excerpts from RWTH Publications

In a private communication from Denmark (16), reference was made to an application of the present model to two mild steels showing a specially poor toughness: 9 and 19 J. An analysis according to the LEFM approach was also made. While the present model led to respective defect critical sizes of 1.7 and 3.5 mm, the LEFM method generated the values of 2.4 and 4.5 mm, which are indeed in quite good agreement.

As regards welded assemblies, a comparison was carried out regarding the tests obtained in a British laboratory (17). As shown by Figure 25, the computations brought by the model for the fracture behaviour of the heat affected zone surround the experimental results of the wide plate tests. What is specially interesting here, beside the accurateness of the previsions, is the immediate understanding that the model gives of the apparently surprising scatter of the experimental results. As a matter of fact, the here observed gradient of the Charpy energy in the heat affected zone is the reason of the experimental variations of the fracture behaviour.

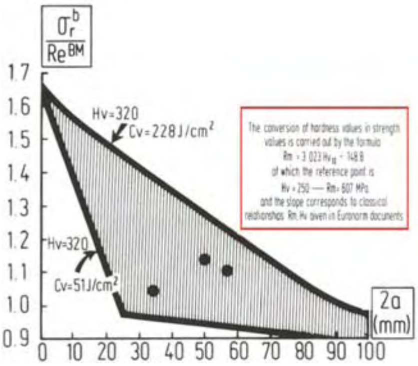


Figure 25. Comparison with British results

13. Conclusion

The model developed for the computation of the fracture behaviour of wide plates applies as well to base metal as to welded assemblies affected by sharp defects or cracks.

The fracture behaviour is expressed in terms either of the wide plate gross fracture stress as a function of defect length or of the critical defect size according to the full yield criterion.

The model applies to different steel qualities produced by classical rolling and possible normalization, thermomechanical rolling or accelerated cooling. The experienced temperatures range from -60°C to +20°C.

As far as only base metal is concerned; the material entry data are the Charpy V energy at the considered temperature and the tensile to yield ratio at the ambient. An evaluation of the resistance to failure is therefore immediately provided using quite classical steel characteristics, available from a current quality control.

For welded joint, the evolution of the Charpy energy and of the tensile strength in the weld area is necessary. Those data are also easily obtained from Charpy specimens sampled and notched in the base metal, the heat affected zone and the weld metal. Hardness measurements carried out on those samples before testing bring after a suited conversion the necessary tensile strength values. Yield stress to consider here is that relating to base metal which fixes the design stress of the component. A hybrid local tensile to base metal yield ratio is then used for the computations.

The applicability of this model in different situations is illustrated by comparisons between computations and results of experiments carried out in different laboratories.

The aim of this model is in no way to supplant or reduce the performance of wide plate or other large scale fracture mechanics tests. Such tests are indeed the only realistic way to appraise with accuracy the fracture behaviour. On the contrary, the present model is designed to easily bring relevant information which may help in readily succeeding large scale tests and avoiding fruitless and time consuming trials and errors. Indications to optimise a welding procedure such as the right selection of the weld metal or of the heat input are indeed derived from that model.

The model helps also in understanding the fracture behaviour observed at wide plates and therefore it contributes to reinforce the significance of experimental results.

Last but no least, this models highlights the potentialities of the modern high strength steels combining a high toughness to a moderate tensile to yield ratio.

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