Selection of steels according to their Charpy V properties in order to avoid brittle fracture

B.de Meester (Belgium)

1. Background

I.1. The classification of steels based upon the Charpy V transition temperature is now widely accepted and included in ISO standards. The genesis of current practice for the selection of steels in welded constructions based on the Charpy V transition temperature was the systematic analysis of brittle fractures of all welded structures built during World War II and in particular of ships of the U.S. Navy. Since then, the complexity of welded constructions has grown considerably. The accumulated service experience with these constructions, the extensive research and development programs, the considerable amount of work produced and of information treated by the classification societies and other interested bodies have been introduced progressively in various codes of constructions, recommendations and other specifications.

1.2. The various construction codes nowadays in use, particularly the pressure vessel codes, all contain a procedure to select steel for low temperature applications. All of them use Charpy testing as a means to check whether the steel to be used is suitable, i.e. meets the minimum required impact energy (or, in the case of very high strength steels, minimum required lateral expansion) at a specified temperature. In the older codes (U.S.A., Germany, Austria) the relationship between minimum design temperature of the construction and the temperature of the Charpy test is direct. The wall thickness does not influence the selection.

In the sixties, after publication of the Wells wide plate tests, more modern pressure vessel codes developed. Reference is made to the proposal of ISO/TC 11 of September 1971. The codes of the U.K., the Netherlands, Norway, Switzerland, Australia and Sweden give material selection graphs which are based on (or on combinations of) experience and wide plate tests. The French Code is very much based on linear elastic fracture mechanics. These codes have graphs for as-welded and for post-weld heat treated constructions and often for different tensile strength levels. When the minimum design temperature and wall thickness are entered in the relevant graph the required steel type is indicated, characterized by a minimum required Charpy energy at a specified temperature. In this case the Charpy test is related indirectly and merely is quality control test.

The code for steel bridges in the U.K. is largely based on elastic-plastic fracture mechanics and also uses the Charpy test as a means of quality control.

I.3. Over the past twenty years fracture mechanics theories have undergone considerable development and significant progress has been made. It is now possible to relate through computation a critical flaw size to the geometry and service stresses of a structure when the toughness of the material is measured by appropriate fracture mechanics tests. Fitness for purpose analysis has been successfully applied for many practical applications.

It is worthwhile to note that as a result of these sometimes very sophisticated calculations, the criteria used to prevent brittle fracture are expressed as follows : the material of the structure must have at the service temperature a toughness higher than the calculated result taking into account the stresses, the geometry of the workpiece and the flaw size.

In spite of considerable amount of work and interest in this topic throughout the world, there are still some differences between specialists on the best theoretical refinements to be used in practice. The current position of IIW on this matter has been summarized in the published document IIS/IIW-707-82 "Reservations with respect to the application of elastic-plastic fracture mechanics to welded structures". More recently, the published document IIS/IIW-795-84 "Weld metal fracture toughness. Reply agreed by Commissions IX and X at the IIW Annual

Doc. IIS/IIW-1020-88 (ex doc. IX-1445-86) submitted to Commission IX "Behaviour of metals subjected to welding" of the IIW.

Dr. de Meester is Associate Professor at the Catholic University of Louvain, B-1348, Louvain-La-Neuve, Belgium.

Assembly, Trondheim 1983, to a question from Commission II at Ljubljana 1982" was devoted to the Characterization of weld metals from the point of view of their susceptibility to brittle fracture.

1.4. The first Chairman of Sub-Commission IX-F: "Recommendations relative to steels for welded constructions", M. Bonhomme (Belgium) started work on the classification and choice of steels. The last document issued under his Chairmanship was doc. IX-1042-77 which is a collection of earlier recommendations, some of which are now considered as classical. In this document, however, the last chapter is missing. This last chapter was intended to give advice on which grade of steel (B,C,D,E) to select for a structure in order to obtain a sufficient degree of safety : that is the brittle fracture safe design based upon Charpy V requirements. The very first draft of this chapter was based upon good practice and the best engineering judgment. It was, mainly an empirical approach.

From this time on, the brittle fracture safe design of welded constructions remained on the working programme of the Sub-Commission IX-F. To give in a simple fashion general guidance for the selection of the base material to be welded, based upon Charpy V requirements, taking into account the recent advances in fracture mechanics, the experience gained from practical applications and the best available empirical relationships between toughness properties of structural steels evaluated by fracture mechanics and Charpy V impact energy, is considered as an important objective. To carry out a full fracture mechanics analysis can be a complex and relatively expensive process. Even though the cost can often be recovered in critical and important constructions, there are many applications for which it cannot be economically justified.

I.5. This paper is intended to present the current state of the discussion within Sub-Commission IX-F. Two methods have been more thoroughly taken into consideration. The first is based upon the linear elastic fracture mechanics theory and leads to requirements expressed in terms of a testing temperature at which a minimum Charpy V energy of 28 Joules would be measured. The French pressure vessels code (CODAP) is largely based on the application of this method. The second is based upon elasto-plastic theory and leads to requirements expressed as a minimum Charpy V energy level at the service temperature. The code for steel bridges in the U.K. is developed according to this philosophy. These two methods are presented, compared and discussed in this paper.

II. Presentation of the methods for the selection of steels according to their Charpy V properties

II.1. The method based upon linear elastic fracture mechanics

This method was originally proposed by M.Sanz (France) of IRSID (Steel Research Institute). Using experimental data produced in France, as well as other data from the literature, it is shown that there exists a linear relationship between the temperatures at which K_{1c} is equal to 100 MPa/m, designated $TK_{1c=100}$ (°C) and the temperatures at which the Charpy V energy is equal to 28 Joule, designated TK28 (°C). It has the very simple following form (Fig. 1):

$$TK_{1c=100} = 1.4\ TK28. \quad (1)$$

It is valid according to the authors when the fracture is due to a cleavage mechanism. This relationship appears to be original because the correlation is found between temperatures rather than between levels of toughness in different tests at a given temperature.

This relationship is further extended to other fracture toughness levels, so that one obtains :

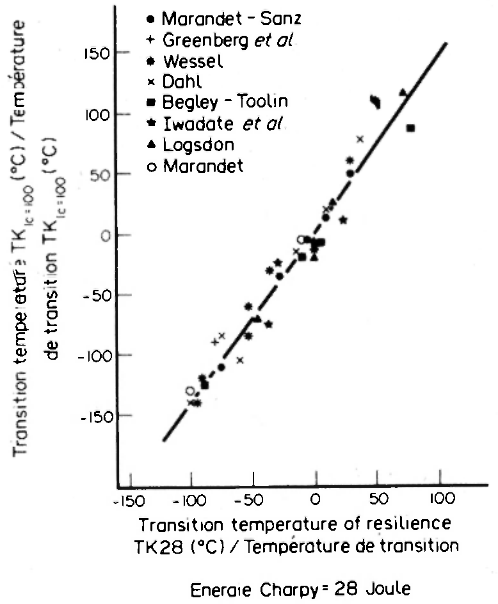


Fig. 1. Correlation between the temperature $TK_{1c=100}$ and TK28

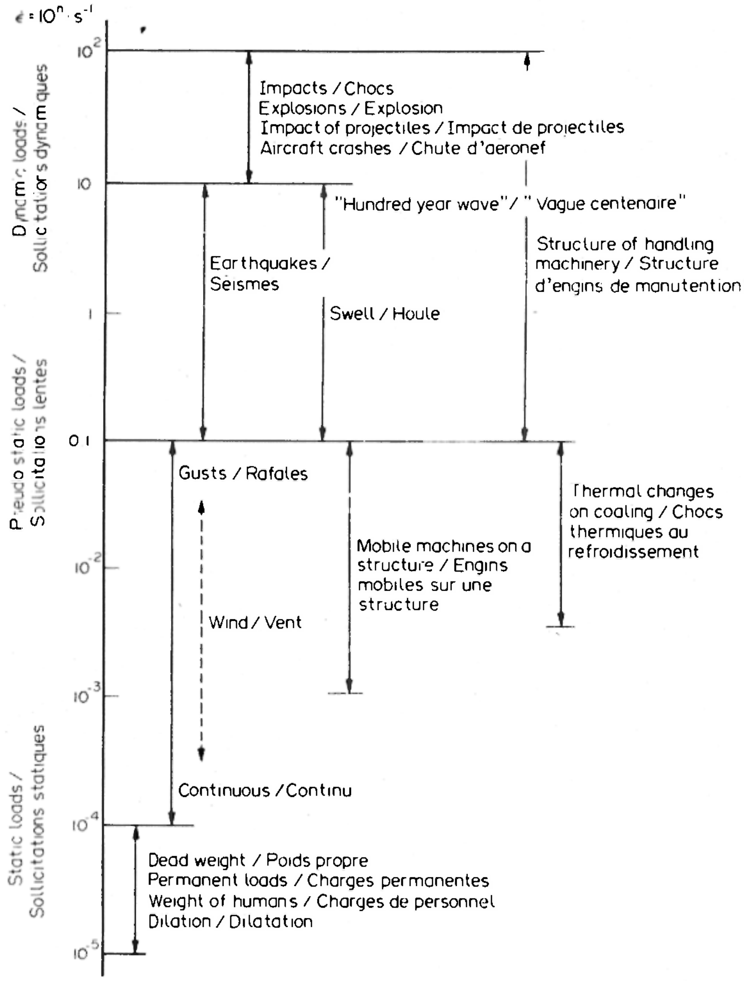


Fig. 2

$$TK_{1c=x} = 1.4\ TK28 + \beta\ (x). \qquad (2)$$

The principle of the method is that the design temperature must be higher than that for cleavage. Therefore as soon as the required level of K_{1c} is found through design considerations, the maximum temperature at which one should measure a 28 Joules Charpy V energy level can be calculated.

This method is further elaborated in order to take into account the loading rate since the above correlations were obtained at low K_{1c} testing speeds. Similarly, a correction taking into account the thickness of the stressed member is introduced. These adaptations have been done on the basis of experimental data. The final suggested requirement is expressed as follows:

$$T_s >= 1.4\ TK28 + \Delta T_v + \Delta T_e + \beta(\sigma_y) + \alpha(\sigma/\sigma_y) + 25 \qquad (3)$$

where :

- σ is the design stress (N/mm²).
- σ_y is the yield strength of the selected steel (N/mm²),
- T_s is the service temperature (°C),
- TK28 is the testing temperature (°C) at which a 28 Joules Charpy V must be measured.
- ΔT_e is a correlation term (°C) taking into account the thickness (e in mm) of the stress member :
  - = 0 if e < 110 mm
  - = 0.53e - 59 if 60 < e < 110 mm
  - = 0.97e - 85 if 30 < e < 60 mm
  - = 1.80e - 110 if 10 < e < 30 mm
- ΔT_v is a correction term (°C) taking into account the loading rate ($\dot{\varepsilon}$ = 10, 10^{-1}, 10^{-4} sec^{-1}):

$$\Delta T_v = (83 - 0.08\ \sigma_y)\dot{\varepsilon}^{0.17}$$

(In the absence of quantitative evaluation, the author recommends selecting ε = 10 sec^{-1} leading to the ΔT_v = 120-0.12.σ_y with σ_y<1000 N/mm² which is the correlation between static and dynamic (K_{1cd}) tests first suggested by Barsom and Rolfe. In other cases, Fig. 2 could be used as a guide.)

$\beta(\sigma_y)$ is a correlation term (°C) for the yield strength of steel, as found by the correlation expressed by Eq. (2).

$\alpha(\sigma/\sigma_y)$ is a correction term (°C) for the actual design stress lower than yield for stress relieved structures :

α(°C)	(σ/σ_y)
0	0.85...1
-10	0.70...0.85
-20	0.60...0.70
-30	0.50...0.60
-40	0.40...0.50
-50	0.35...0.40
-60	0.30...0.35

25 is a safety term (°C) due to the scatter observed in the temperature corrections presented by Eqs (1) and (2).

For as welded structures, it is recommended that the evaluation of TK28 be carried out by selecting σ_y equal to the actual yield strength of material, e.g. 50 N/mm² higher than the minimum guaranteed yield strength, and $\alpha = 0$.

In the original document of M.Sanz, the results are presented in the form of diagrams for each yield strength level. They are easily obtained by the application of Eq. (3).

II.2. *The method based upon elasto-plastic fracture mechanics*

This method is based on the concepts introduced in the British document P.D.6493 : "Guidance on some methods for the derivation of acceptance levels for defects in fusion welded joints". It is a simplified and generalized version of this document. It was first proposed to the Sub-Commission by M. George (U.K.) in doc. IX-F-79-13. Since then, several modified drafts have been circulated.

The proposed method is quite straightforward in that by the use of proportionality constant, the Charpy V energy level required at the service temperature is calculated according to

$$CV = B.\sigma_y.e \qquad (4)$$

where :

CV is the Charpy V impact energy at the service temperature (j, 10 x 10 specimen),
σ_y is the yield strength of the steel (N/mm²),
e is the thickness (mm).

The proportionality constant B is evaluated from the "total" stress or strain on the member, including the design stress, multiplied if necessary by a stress concentration factor plus the residual stresses, multiplied by an appropriate safety factor. As a guide Fig. 3 was given.

The required Charpy V impact energy at the service temperature can be then transformed to the steel classes B,C,D, etc. with the help of a reference Charpy V transition curve provided in the document.

For the interested reader, this method can be briefly justified on one illustrative short example.

a. Assume a Flaw size equal to 20 >% of the thickness.

b. Assume a design stress of 0.67 yield to be multiplied by 1.2 for stress concentration (a value of 1.2 is considered sufficient because with an initial flaw size of 20% of the thickness, the magnification of the stress intensity factor at the crack tip will not be much higher). Add to the above result a stress value equal to yield in order to account for residual stresses. This gives a ratio of "total" effective strain (stress) to yield strain (strength) of about 1.80.

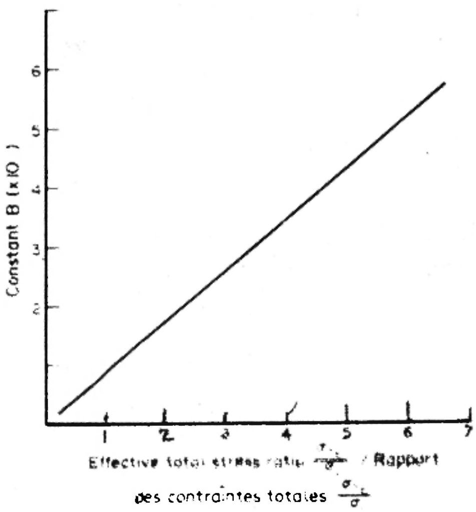


Fig. 3

c. Using the COD design curve, as provided for instance in PD6493, one finds a value of C equal to 0.10 leading to $\delta_{crit} \geq 1/C(\sigma_y/E).a$

where

a(mm) is the critical flaw size,

and to $\delta_{crit} > 10.(\sigma_y/E).0.2.c$

d. If one considers that 150 δ_{crit} (mm) is a reasonable experimental lower bound for CV(Joule) the above relationship reduces to

$$CV > (1.5).10^{-3}.\sigma_y c$$

III. Comparison of the methods

III.1. *General*

Figure 4 summarizes some of the most evident differences between these two methods.

1.1 The basic underlying fracture mechanics theories, linear elastic or elasto-plastic, are not the same. It is not considered to be the work of the Sub-Commission IX-F to define what are the areas of application and the limitations of these theories. This would be better done within Commission X and reference has already been given in the Background to two IIW published documents on this matter. Therefore, the work of the Sub-Commission was not concentrated on a choice between the methods on the basis of their theoretical background. A comparison of the suggested requirements resulting from the application of both methods in order to find possible general guidelines to be presented in the simplest fashion to the users has instead been undertaken.

1.2. This comparison could not be done straight forwardly because the first method suggests testing temperatures at which a fixed Charpy V impact energy should be obtained whilst the latter suggests requirements of the Charpy V impact energy to be obtained at the service temperature.

This results from the different types of correlation used in the two methods between the Charpy V properties and the fracture toughness measurements. The first method uses a correlation between temperatures at which fixed toughness levels are measured whilst the other uses the COD design curve and a lower bound of the COD values as a function of the Charpy V energy at fixed temperatures.

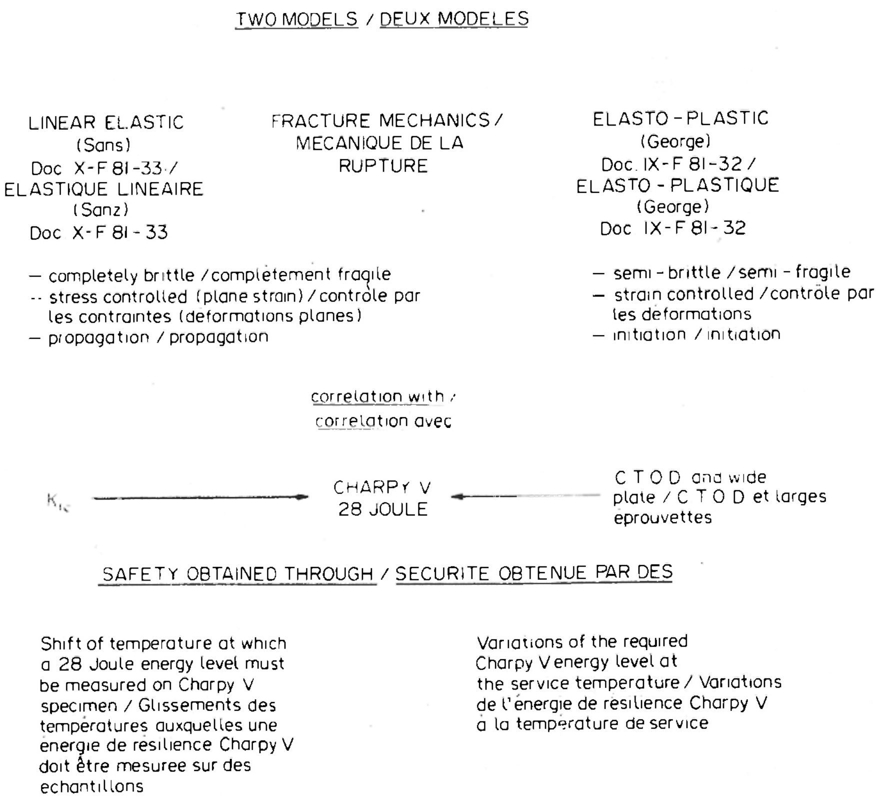
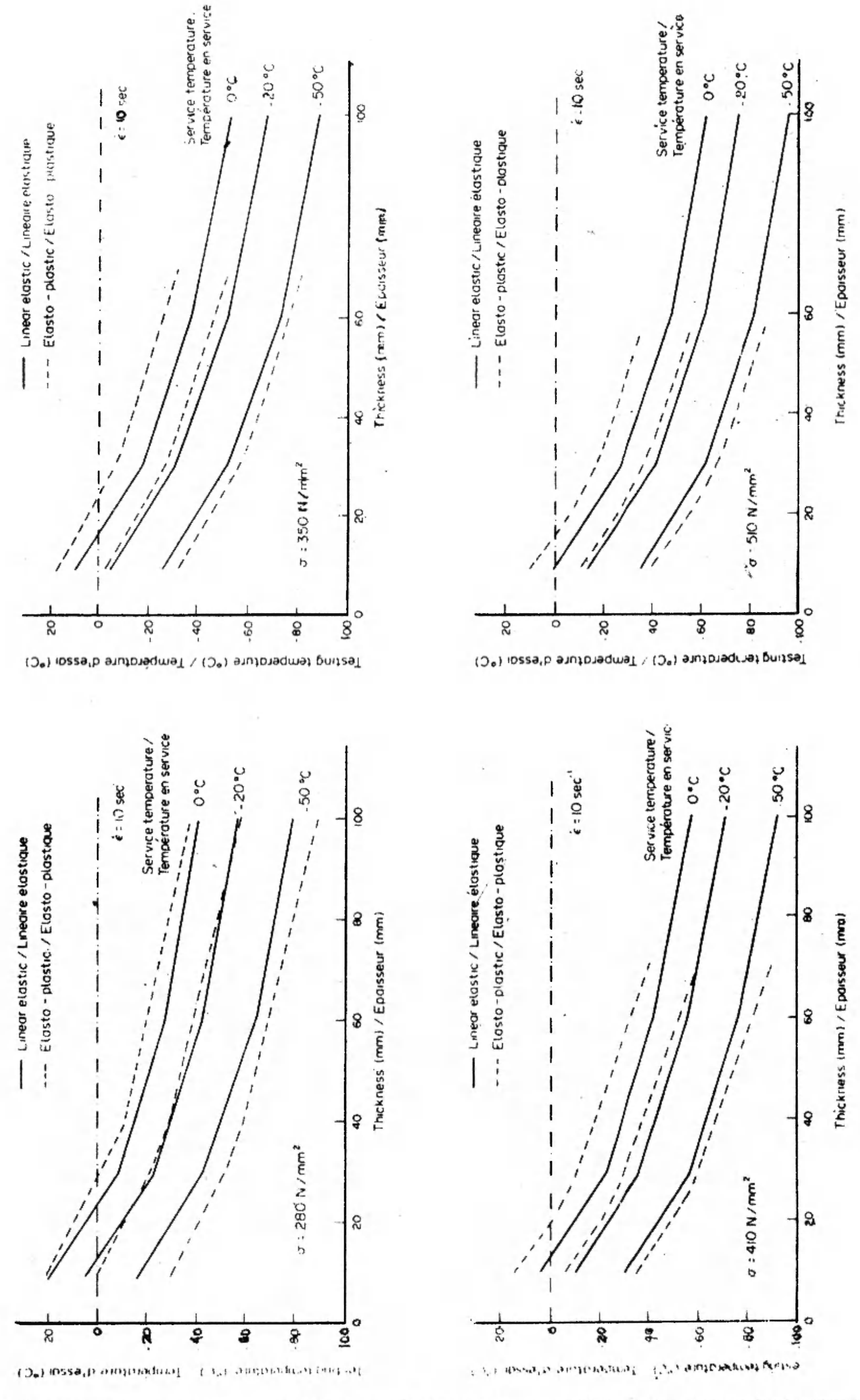


Fig. 4



Linear elastic / Lineaire elastique
Elasto - plastic / Elasto - plastique
ε̇ : 10 sec
Service temperature / Température en service
0 °C
-20 °C
-50 °C
σ : 280 N/mm²
σ : 350 N/mm²
σ : 410 N/mm²
σ : 510 N/mm²
Thickness (mm) / Epaisseur (mm)
Testing temperature (°C) / Temperature d'essai (°C)

Figs 5a to d

The comparison presented was nevertheless made possible through the use of the reference transition temperature curves given or implicitly assumed in each one of the methods.

1.3. The number of factors taken implicitly into account in each method is different (e.g. loading rate is considered in one but not in the other). Through the safety factors provided in both methods, they may however have been taken into consideration implicitly.

For this reason, the comparisons were performed first in the case of the most severe conditions; that is, as welded constructions with a high loading rate = 10 sec^{-1}.

1.4. The comparisons presented hereafter are presented as they were first done. No steps have been taken to select free constants so that a better agreement would be obtained. The exercise has been done by the strict application of the suggested methods without modifications to improve the agreement being the results.

III.2. Comparison of the suggested temperatures at which a 28 Joules Charpy V impact energy should be measured.

2.1. For the method based upon linear elastic fracture mechanics theory, this temperature TK28 (°C) has been calculated according to Eq. (3) with :

- o. service temperature T_s equal to 0, -20 and -50°C,
- o yield strengths equal to 280, 350, 410 and 510 N/mm², assumed to be the actual yield strength of the base steel,
- o thickness ranging from 10 to 110 mm,
- o a loading rate equal 10sec^{-1} (that is the highest suggested and in accordance with the original recommendation of the authors), and
- o for as welded structures (that is with $\alpha = 0$).

2.2. For the method based upon the elasto-plastic fracture mechanics theory, the suggested requirement for the Charpy V impact energy at the service temperature was first calculated according to Eq. (4) with a selected value of the proportionality constant $B = 3.5 \times 10^{-3}$. This value of B corresponds according to Fig. 3 to a ratio of the "total" stress to yield strength of about 4; this value of the ratio can be interpreted as resulting for instance from the value of the stress indicated in the short example given in 2.2 multiplied by a safety factor of about 2.3. The results were then converted into a temperature TK28' at which a 28 Joules Charpy V energy should be measured with the help of the reference transition temperature curve provided in the original proposal by M. George. This curve was extrapolated linearly up to 100 Joules.

2.3 The results of this comparison exercise are shown in Figs 5a to d.

III.3. Comparison of the suggested Charpy V impact energy required at the service temperature

3.1. For the method based on elasto-plastic theory, these suggested requirements are directly obtained through Eq. (4). The same assumptions as under III-2.2 have made. Equation (4) implies that for given service conditions and safety, the Charpy V impact energy should increase linearly with base steel yield strength and plate thickness. Moreover it is also proportional to the ratio of the "total" to yield stress.

3.2. For the evaluation of the suggested requirements of the Charpy V impact energy at the service temperature according to the method based on linear elastic theory, a little more work is needed since it is desired to use only approximations and assumptions already used within the actual framework of the method.

In this method, a K_{1c} versus temperature transition curve is introduced. It is used to correct the testing temperature TK28 according to yield strength: term $\beta(\sigma_y)$. The analytical approximation of this curve, as it is suggested by the author is the following:

$$K_{1c} = 25 + 75\exp(\Delta T/60)$$

where :

- o K_{1c} is expressed in $MPa\sqrt{m}$,
- o ΔT is the temperature difference between the temperature at which K_{1c} has a given value and the temperature at which K_{1c} is equal to 100 $MPa\sqrt{m}$(°C).

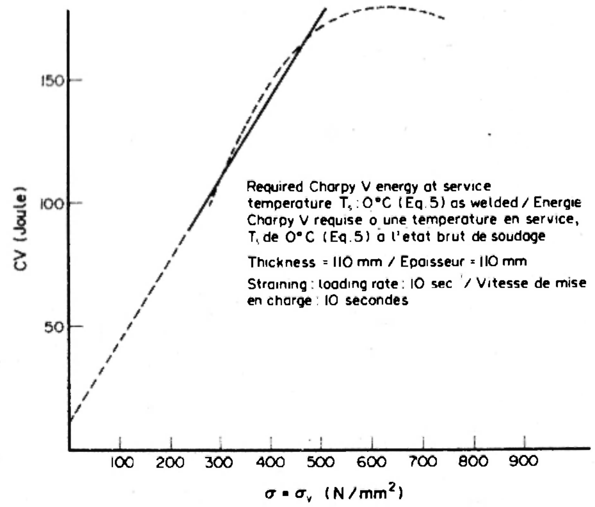


Fig. 6

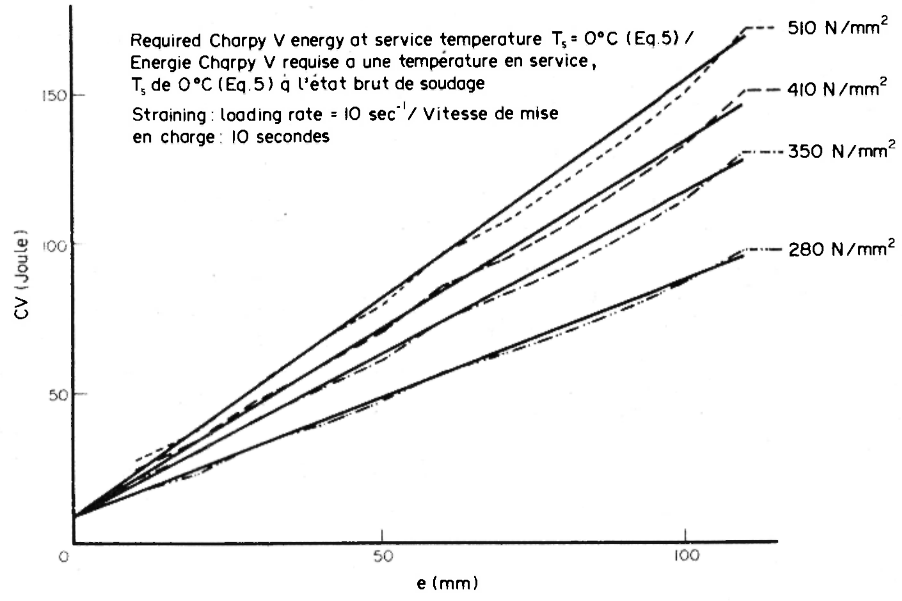


Fig. 7

The same authors have also shown, based upon their own experimental data and other data available in the literature which they used to establish their proposed method, that the Charpy V impact energy can be estimated from K_{1c} and vice versa through the relationship :

$$CV = (K_{1c}/19)^2$$

provided a shift in testing temperature is taken into account. This shift in temperature must be such that the temperature at which the 28 Joules Charpy V energy level is measured is made equal to the temperature at which K_{1c} is equal to 100 MPa$\sqrt{m}$. It is expressed by Eq. (1) at the basis of the method based on linear elastic fracture mechanics. The Charpy V energy at any temperature, and also at the service temperature, can therefore be estimated through the relationship:

$$CV=[1/19\{25+75exp(T_s-TK28)/60]^2 \qquad (5)$$

where T_s - TK28 = 1/1.4(0.4T_s + ΔT_e + ΔT_v + $\beta(\sigma_y)$ + $\alpha(\sigma/\sigma_y)$ + 25).

This last formula was used to carry out the comparison in the case of service temperature equal to 0°C in the same hypothetical cases of application as under II.2.

3.3 The results of this comparison are presented in Figs 6 and 7 from which it is seen that the implicitly assumed value of the Charpy V impact energy resulting from the required TK28 testing temperature is very nearly equivalent to

$$CV = 10 + 3.10^{-3}.\sigma_y.e.$$

This result is obtained for as welded constructions and a loading rate equal to 10 sec^{-1}. It is a relationship very similar to Eq.(4) from the method based upon elasto-plastic fracture mechanics theory. A linear increase of the implicitly required Charpy V level at the service temperature with thickness is well verified (see Fig. 7). The linear relationship with steel yield

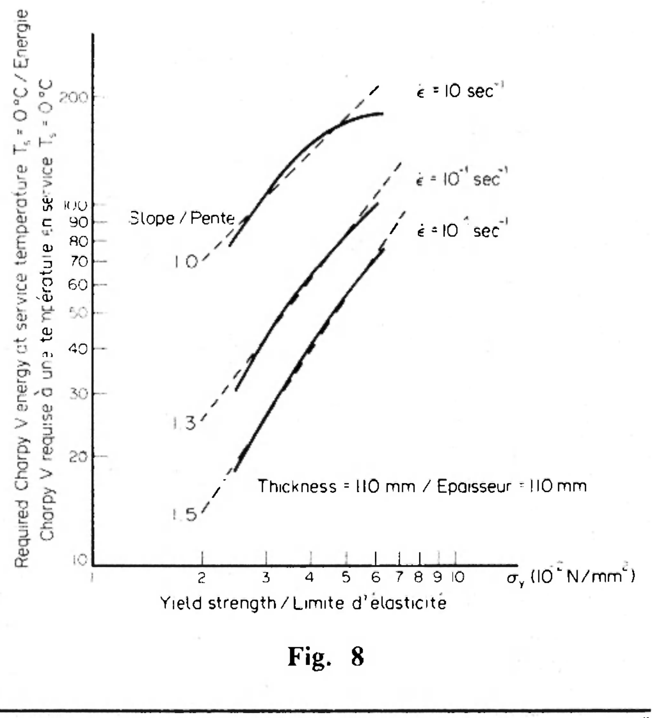


Fig. 8

strength is however an approximation not to be extended to higher strength steels which were never included in the scope of the first proposal by M. George (see fig. 6).

3.4. The same exercise has been repeated for other loading rates: 10^{-1} and 10^{-4} sec^{-1} and for stress relieved constructions. These results are presented in Figs 8 and 9.

It is observed that the implicitly required Charpy V energy at the service temperature according to the method based upon linear elastic theory varies linearly with the ratio of the design to yield stress (see Fig. 9). At the intermediate and lower loading rates, the required Charpy V energy level at the service temperature increases however more than linearly with steel strength: power law 1.3 or 1.5 (see Fig. 8).

III.4. *Comparison of the effect of thickness on the suggested requirements for the selection of steels - assumed initial flaw size*

4.1. Figure 10 summarizes the suggested shifts in testing temperature for a 28 Charpy V energy. Also included in the figure are shifts proportional to the square root of the thickness as found in Japanese documents.

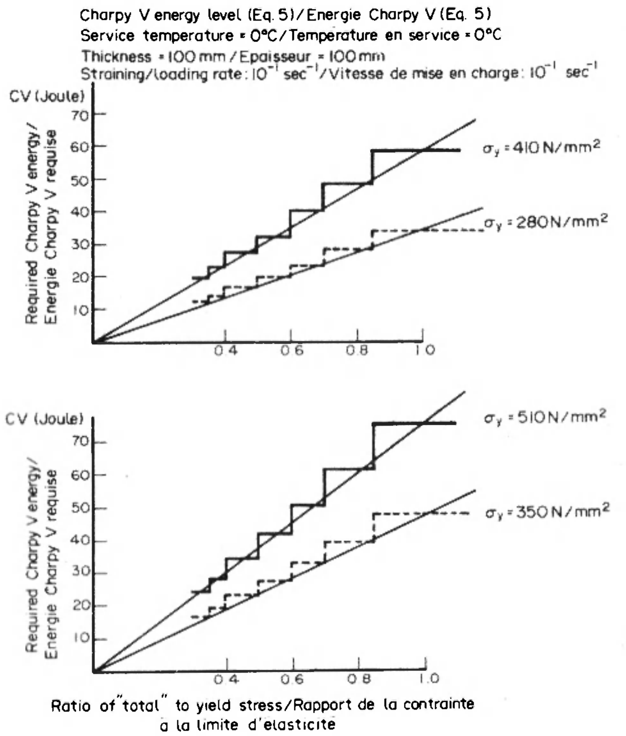


Fig. 9

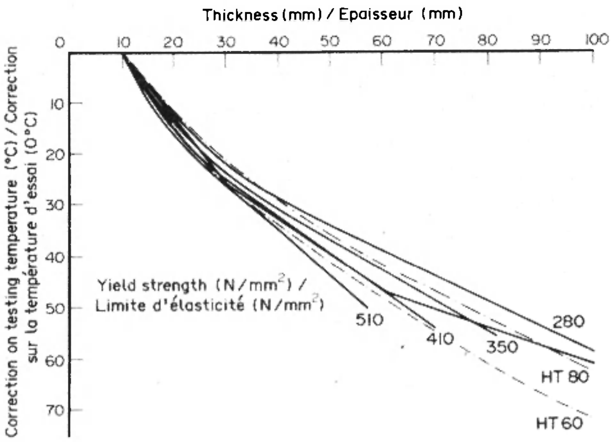


Fig. 10

The results from the method based on linear elastic fracture mechanics are directly obtained from differences in the term $\Delta T_{.}/1.4$ in Eq. (3).

The results from the method based on elasto-plastic fracture mechanics were obtained during the computations made for the comparison presented under III.2. The fact that the shifts of testing temperatures according to thickness vary with steel yield strength is a consequence of the shape of the reference transition temperature curve independent of yield strength whilst the required Charpy V energy is proportional to the yield strength.

4.2. Since fracture mechanics principles underly the methods under consideration, an initial flaw size was at least assumed at some step.

As already mentioned, an initial flaw size equal to a fixed fraction of the thickness was assumed in the method based upon elasto-plastic fracture mechanics. In the short example presented at the end of paragraph II.2, this fraction was equal to twenty percent.

In the other method, an initial plane through thickness defect of length 28 mm was selected. In order to guarantee that plane strain conditions are met so that the fracture is completely brittle, the criterion of the ASTM standard for K_{1c} measurement was applied, leading to a thickness of 100 mm. For heavier thickness, it is therefore considered that no further adjustment of the testing temperature TK28 is needed. The correction of the testing temperature TK28 for lower thicknesses was established on the basis of experimental data. As shown in the original paper of M. Sanz, one may calculate that the corresponding initial flaw size varies almost linearly from 110 mm down to 10 mm thickness. The results presented in Fig. 7 where the required Charpy V impact energy varies nearly linearly with thickness is another presentation of this linear relationship between thickness and initial flaw size. It is worth noting that since the correction of the testing temperature as a function of the thickness ΔT_e was introduced on the basis of experimental results, the subsequent calculations provide an experimental basis to confirm the validity of the choice of an initial flaw size equal to a fixed fraction of the thickness.

Similar guidance for the choice of an initial flaw size in also given in the code ASME III appendix G.

IV. Discussion

IV.1. *Field of application*

The methods presented give only general guidance on the selection of steel grades for welded constructions with regard to the risk of brittle fracture. Other failure modes which could be relevant for a particular application are not taken into consideration.

It must be emphasized that, in any case, the final choice of a steel grade is the responsibility of the fabricator, designer or other responsible agent.

It must be noted that no recommendations are given on the required levels of heat affected zone toughness. It is therefore implicitly assumed that the heat affected zone properties are not a controlling factor of weld performance. In consequence weld procedures should be qualified.

This general guidance in its simple form should not be used for fitness for purpose analysis. The exact significance of the initial flaw size introduced in the methods considered cannot be judged without taking into account all of the other factors and the implicitly built-in safety factors. Criteria and other specifications otherwise imposed on weld inspection, acceptance of weld defects and type of joints, should therefore be strictly respected.

In addition, these guidelines can only be valid where all measures commensurate with good welding practice have been taken.

IV.2. *Criteria used*

The suggested Charpy V requirements according to the two methods are of different nature. A testing temperature at which a fixed 28 Joules Charpy V energy should be measured, different from the service temperature, is suggested in the method based upon linear elastic fracture mechanics. A minimum Charpy V impact energy level at the service temperature is suggested in the other. This is a consequence of the different types of correlations used in the two methods to relate measurements from fracture mechanics tests and Charpy V properties. The choice of one type of requirement rather than the other appears perhaps more as a matter of philosophy and best engineering judgment. One factor to be considered would be the shape and location of the transition temperature curve.

As a hint, it may be noted that in the ASME code III appendix G, giving also guidance for the selection of steel grades based upon linear elastic fracture mechanics, the suggested requirement is given in terms of a sufficiently low RT-NDT with respect to service temperature. The procedure for determining the RT-NDT includes however two types of test: drop weight to measure the NDT and Charpy V at least 15°C higher than NDT to verify that the Charpy V impact energy is higher than 68 Joules and the lateral expansion greater than 0.9 mm. Reference is also sometimes made to the fracture appearance transition temperature (FATT).

In any case, confidence is gained by observing that the comparison between the requirements suggested by the two methods leads finally to similar results. Therefore, even though the fundamental difficulty of the choice between the type of requirement is not resolved, it does not appear to have great practical consequences provided that new steels with very different transition behaviors are not used. Even in this case, the simultaneous application of both types of requirement could provide sufficient safety.

IV.3. *Scope*

The scope of the method is restricted to structural steels. M. George recommended that this guidance be restricted to service temperatures above -40°C for thicknesses up to 75 mm and to above -50°C for thicknesses up to 40 mm. In the original document of M. Sanz service temperatures above -50°C are taken into consideration for all thicknesses up to 110 mm.

A lower thickness should be also defined, e.g. 10 mm.

M. Sanz extends the application of the method based upon linear elastic theory to steel with yield strength ranging from 235 N/mm^2 to 690 N/mm^2.M. George agreed to restrict his proposal to steels with yield strength lower than 450 N/mm^2.

A better agreement between both methods is however found for a limited range of yield strengths. It could therefore be appropriate to restrict the scope of the guidelines to steels with limited yield strengths. More experimental data and practical experience should be obtained on higher strength steels. To carry out a full fracture mechanics analysis for these can be recommended and would be probably economically justified.

IV.4. *Compatibility of the methods*

A good agreement is found on the adjustment of Charpy V requirements with plate thickness. It turns out that they are consistent with the assumption of an initial flaw size equal to a fixed fraction of the thickness.

The shifts in testing temperatures according to the method based on linear elastic fracture mechanics for different ratios of the design to yield stress are nearly equivalent to requiring Charpy V energy level at the service temperature proportional to the ratio of the "total" to yield stress/strain.

The same agreement between the variation of requirements with yield strength of the base steel according to each method is also found, at least at high loading rate.

The two methods are therefore found compatible if their scope is restricted to steels with limited yield strength. It remains however that there are some practical differences; the most important are outlined in the following paragraph.

IV.5. *Areas for future research*

5.1. The application of linear elastic fracture mechanics theory leads to equations of the form $K_{1c}+\sigma\sqrt{\pi a}$. To obtain requirements in terms of Charpy V energy, correlations between K_{1c} and CV are needed. Most of these are of the form $CV + (K_{1c})^2$, so that one would normally expect that the required Charpy V energy would increase with the square of the stress. This leads however to requirements generally considered as excessively stringent for high strength steels. A similar theoretical relationship would also be expected from COD type of analysis at low stress levels. In this case, the two theories are equivalent.

In the method based upon elasto-plastic fracture mechanics, a linear relationship is obtained between the required Charpy V energy and the stress by considering only the part of the COD design curve at high ratio of "total" to yield strains and by using a lower bound type of correlation between COD and Charpy V energy not including the steel yield strength.

In the method based upon linear elastic fracture mechanics theory, the proportionality between the implicitly suggested Charpy V impact energy at the service temperature and the stress is mainly due to the correction term ΔT_v for the loading rate. For the intermediate and lower loading rates a power law with an exponent of the yield strength a little higher than one but definitely lower than two would probably give a fit (Fig.8). It must however be realized that in the method based on elasto-plastic theory one would also obtain such a power law when using a more accurate value for B directly derived from the COD design curve at ratios of "total" to yield strains lower than about 1.5.

Is it an effect of the arbitrary nature of the correlations between K_{1c} or COD values, or more directly wide plate tests results, and Charpy V energy, if it can be found or, is it due to the higher strain rate sensitivity of lower strength steels?

At the present time, it may only be tentatively stated that a linear relationship (or with a stress exponent lower than two) between the required Charpy V energy at the service temperature and yield strength might be taken as a simple guideline for an easy first selection of the base material. It may also be finally noted that a linear increase of the Charpy V energy level with steel yield strength is already included in some of the more recent steel specifications and standards.

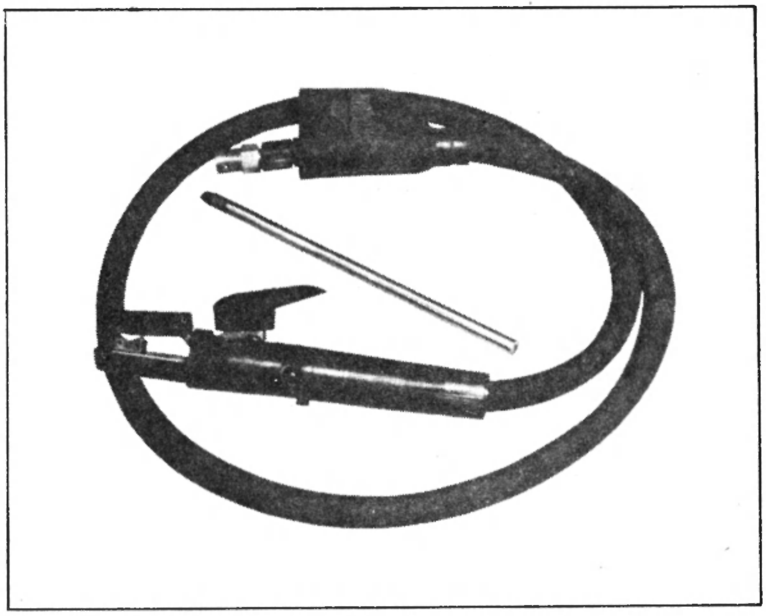
5.2. The strict application of the method based upon linear elastic fracture mechanics leads to apparently paradoxical suggested requirements, an example of which is given below. If for a welded construction with service temperature of 0°C, the base material has to be tested for 28 Joules Charpy V energy at -20°C. It would be required to test the steel at -56°C if the service temperature is lowered to -50°C. The difference between the suggested testing temperature and the service temperature decreases when lowering the service temperature. The physics behind this less severe requirement in terms of Charpy V properties when the service temperature becomes lower are not clearly understood. This is the second most important practical difference between the two methods and is clearly apparent in Figs 5a to d. It has however been verified that the other conclusions reached on the type of variations of Charpy requirements with thickness, yield strength or ratio of design to yield strength, presented in Fig 6 to 9 at a service temperature of 0°C, are not changed at lower service temperatures.

metal arc

GOUGING TORCH

• WELDING HOLDER • CABLE CONNECTOR • EARTH CLAMP

metal arc GOUGING TORCH WITH 360° FREE REVOLING CABLE



Metal Arc Torches are used to Gouge, Chamfer, Groove, Cut, Bevel,Flush off all metals including Aluminium, Copper, Brass, Magnesium, Alloys, Steel, Stainless Steel, Cast Iron and is used by major foundries, shipyards, penstock/pipe and all structural fabricators, chemical & petroleum complexes.

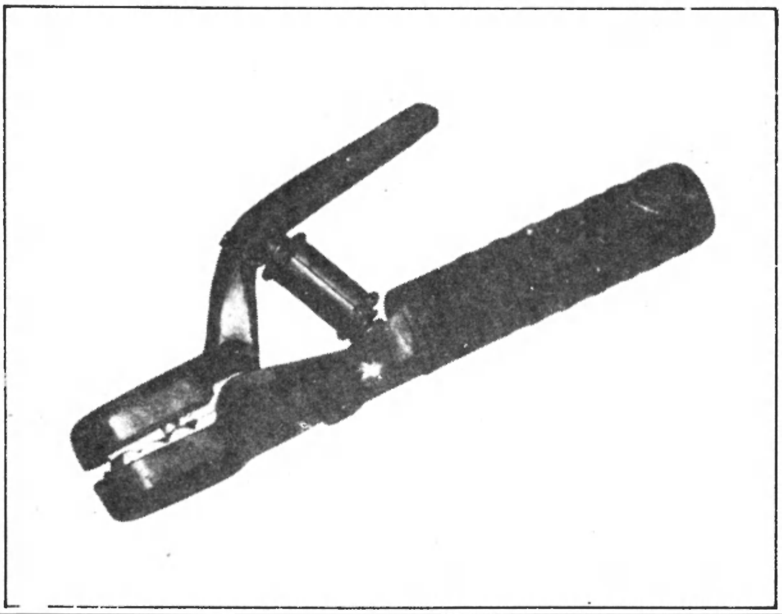
Gouging Torches are available in 3 models,M-1 for Standard Duty (for 3-8 mm Ø), M-2 for Heavy Duty (6-13 mm Ø) and Super Heavy Duty (8-19 mm Ø) Gouging Carbons.

PROCESS DESCRIPTION

The process involves (a) The striking of an ARC between the metal workpiece and the carbon electrode. (b) Melting by the ARC, and (c) Removal of the molten metal with compressed air jets, flowing parallel to the electrode from the torch.

SPECIAL FEATURES:

* For high conductivity of current, copper is used end to end.
* Heat resistant insulators (for longer life of the torch)
* Triple swivel head air nozzels (for better metal removal rate)
* High tension lever allowing firm grip of the electrode (prevents arcing)
* Insulated dual purpose monocable for compressed air and electrical current.
* 360° Free revolving movement between torch and monocable (resulting in less wrist stress for welder and better fatigue free working)

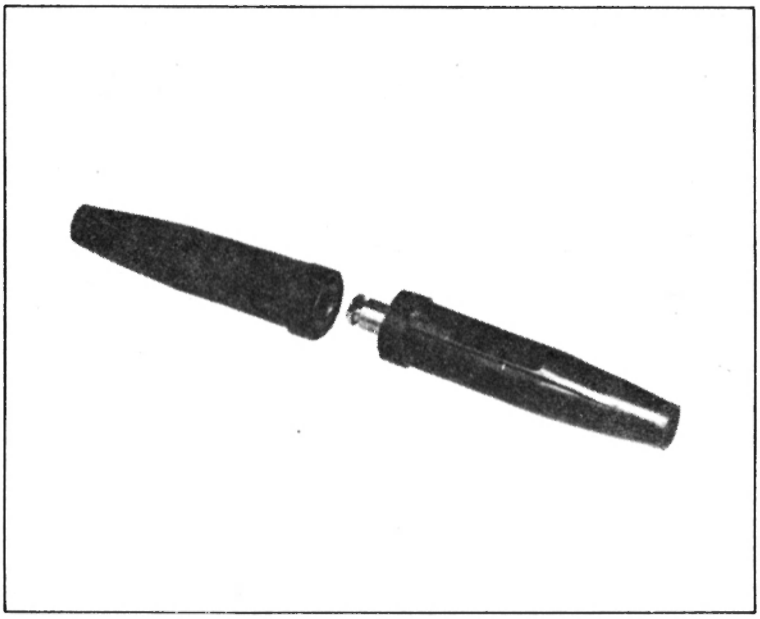


metal arc WELDING HOLDER WH-I

* For heavy duty manual arc welding.
* For current rating upto 600 Amps.
* Suitable for electrode dia up to 8mm.
* Open mouth jaw type.
* 100% fully insulated.
* Light weight and easy to handle.

SPECIAL FEATURES:

* Main body is made out of one piece brass alloy resulting in better current transmission, special design features ensure low heat and long life.
* Hood covers and handle are made out of special heat and arc resistant compounds to protect the welding holder from arc damage.
* For quick connection/disconnection of cable/holder, handle can be removed by one recessed allen screw.
* For better cable connection 3 allen screws provided with D shape grip plate

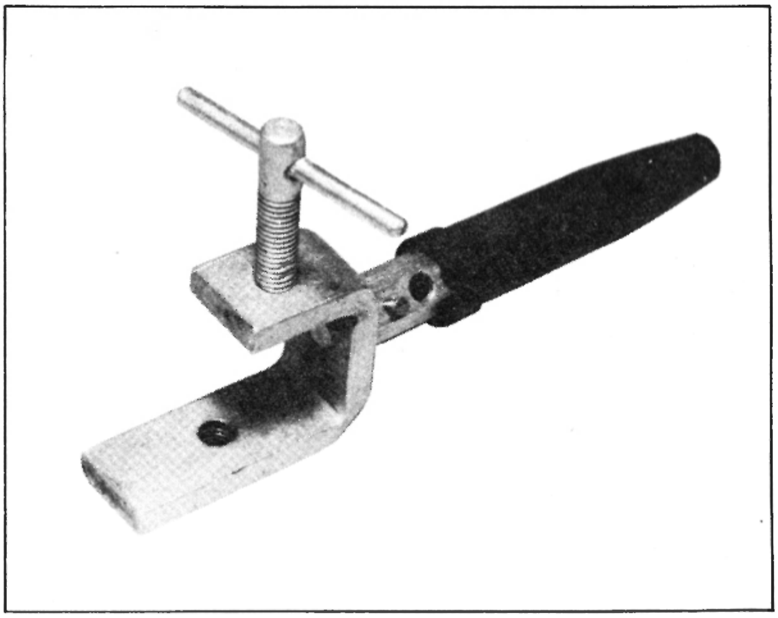


metal arc CABLE CONNECTORS 600 AMPS

SPECIAL FEATURES:

* Heavy duty cable connector suitable for high capacity usage and efficient operation to perform at nominal voltage drop and at high duty cycles.
* Interlocking parts made of high conductivity brass machined for close tolerance and perfect fit.
* The male and female ends of the connector have quick locking arrangement for positive engage/ disengage by 180° twist.
* Tension adjustments made easily on the split male plug with a screw driver.
* Better and quick cable connection at each end by alien screws and D shape grip plate.
* Fully insulated with special heat resistant rubber covers for safe operation under normal working conditions.

metal arc EARTH CLAMP 600 AMPS



SPECIAL FEATURES:

* For current rating upto 600 Amps.
* Robust construction from M.S. Section duly plated for longer life.
* Manual clamping effected through a screw ensuring full contact.
* Cable is fixed quickly and efficiently by two alien screws.
* Optional insulator cover available for cable connection.

ESTD. 1887

R.J. Wood & Co. Private Limited

REGD. OFFICE: STATE BANK BUILDING, CHANDNI CHOWK, DELHI-110006, INDIA
TEL.: (91-11) 2928044 & 2928045 • TELEX: 031-66271 WOOD IN
BOMBAY OFFICE: 506, SHARDA CHAMBERS, 15 NEW MARINE LINES, BOMBAY-400 020 INDIA

The origin of this difference between the two methods is probably to be sought in the correlation expressed in Eq. (1) where TK_{1c} is found more temperature sensitive than TK28. The authors stated moreover in the original document that they had theoretical reasons to believe that the slope of the correlation between TK_{1c} and TK28 would be close to 1 instead of 1.4. Clearly, as already mentioned, the effect of loading and straining rate on the ductile-to brittle transition behaviour remains an important area for future research.

5.3. The exact amount of relaxation of the Charpy V requirements after stress relief when compared to the requirements for as welded constructions should be further investigated.

An increase of the "total" stress (or strain) by an amount equal to yield strength (or strain) in the method based on elasto-plastic fracture mechanics in order to account for residual stresses may appear arbitrary.

On the other hand, in the method based on linear elastic fracture mechanics, the initial suggestion is to consider that the stress to be taken into consideration is the actual yield strength, it corresponds to a shift of the testing temperature of about 15°C, independent of thickness.

It seems that there are few quantitative experimental data on the mechanical effect of stress relief heat treatment of weldments on the ductile-to-brittle transition behaviour of welded structures. This should be further documented.

V. Concluding comments

V.1. *Steel classification*

It appears that, whatever the basis of the guidelines for a brittle fracture safe design of welded constructions, the steel eventually selected will be characterized by its Charpy V impact energy absorption. In other words, the Charpy test, used as a quality control test, is accepted worldwide and should be retained as such in the future.

Unfortunately the impact energy absorption also reflects the yield strength of the steel which makes its use for higher strength steel less reliable. The use of the lateral expansion would seem to be more correct but finds only limited application. Also, it may perhaps be necessary that the modern high purity steels (for which still no internationally agreed specification exists) should exceed the usual impact requirements. It has been reasoned that the impact specimens should exhibit not less than 50% fibrous shear.

V.2. *Relationship between steel classification and steel selection*

When a welded structure is designed, it is made to meet the requirements of the guidelines and a construction code. The steel to be used shall also meet the requirements and since it is still to be purchased only the (minimum) specified values are known. The actual strength and toughness of the steel cannot play a role in the design because the testing is merely a quality control done on samples taken as per specification.

It is stressed that carrying out impact tests on a sample of a given steel does not make it into a low temperature steel. Likewise, results of impact testing that go beyond the minimum impact strength of a low temperature steel do not upgrade it to a better material group. The obvious reason is that the steelmaker guarantees only the properties of the grade ordered.

V.3. *The presence of weldments*

Welds constitute areas where the ductility may be inferior to that of the parent metal and where defects may exist. Hence care must be taken that the quality control of the weld zone receives appropriate attention. The welding procedure shall be properly qualified with due regard to the weld heat input, post-weld heat treatment and the occurrence of defects.

For each steel grade, there exist a minimum and a maximum allowable heat input. The maximum allowable heat input should be related to thickness.

It should also not be overlooked that it is usually assumed that the weld metal and the heat affected zone have yield strengths at least equal to that of the base material.

V.4. *Post-weld heat treatment (stress relief)*

The fracture mechanics approach takes the influence of post-weld heat treatment as a reduction of residual stresses in the weldment. The metallurgical changes resulting from the heat treatment are disregarded, unless extensive impact testing of the heat affected zone is carried out. It is however, well known and wide plate tests have shown that post weld heat treatments do substantially improve the resistance to brittle fracture of welded constructions of some steels, but may impair it in some others.

V.5. *What the guidelines should define*

Guidelines for a brittle fracture safe design of welded construction should cover three essential parts:

a. Definition of the most unfavorable combination of temperature and stresses that may prevail. Experience has taught that the assessment of lower design temperature is the most difficult aspect in material selection for low temperatures. It requires detailed study of all possibilities for low temperature to occur and the stresses that could coincide. The consequences of possible misoperations and the desirability of installing safety devices to counteract or prevent these must be taken into consideration.

b. Definition of the demarcation of the various steels vis-a vis their field of application, i.e. materials selection graph showing the relationship between steel class (strength and toughness), wall thickness, lower design temperature in the as welded or stress relieved conditions.

c. Definition of the quality control measures to make sure that:

- o the steel used is equal to the steel selected.
- o the toughness in the weld zone is not unduly impaired.
- o there are no defects of unacceptable size.

Sub-commission IX-F has concentrated its work on the second part. The first and last parts are obviously complementary but fall outside its terms of reference. As a consequence all of the quantitative values presented in the text or the figures should be taken as the results of the comparative exercise undertaken and not as tentative recommendations which should refer to

- o the method of definition of the most unfavorable combination of temperature and stress that may prevail
- o the quality control measures
- o the type of constructions.

V.6. *Conclusion*

A choice between either of the methods should not be made on the merit of the theory alone. Therefore, any synthesis should be made using also the data available in existing rules for particular constructions: pressure vessels, naval and offshore constructions, bridges, etc. In other applications, after an initial selection according to the guidelines provided by these methods, it may be possible to improve the overall economics by using or referring to suitable complementary tests of fracture mechanics.

In view of the points of agreement from the comparison exercise carried out so far, it is considered that it should be possible to formulate approximate general guidelines for the brittle fracture safe design of welded constructions based upon Charpy V requirements. In order to avoid their misuse, their field of application should be very carefully outlined.

In the absence of more experimental data resulting from further research and of a more extensive practical experience, the proposed following restricted scope for a document summarizing these guidelines is considered as realistic:

- o thickness ranging from 10 to 100 mm,
- o yield strengths up to 420 N/mm^2,
- o steels Charpy V tested down to -50°C,
- o as-welded and stress relieved.

Prof. Dr. D.R.G. Achar, National Metallurgist - 1989

Proceeding to West Germany on a research assignment.

Prof. Dr. D.R.G. Achar, Head, Metal Joining Laboratory, IIT - Madras, is proceeding to West Germany for two years on a research assignment on Underwater Welding Technology.

During the period, he may be contacted at the following address :

Institute For Materials Research
GKSS - Forschungs zentrum Geesthacht GmbH.
D - 2054 Geesthacht, Max Planck Strasse,
Federal Republic of Germany,
Tel : 04152 - 87 - 2611