Toughness Requirements for Welded Structures in the Arctic

Study shows the limitations of the Charpy test in verifying toughness requirements for Arctic structures

BY B. A. GRAVILLE AND W. R. TYSON

ABSTRACT. This paper presents some background work that was done during the development of steel toughness requirements for CSA (Preliminary) Standard S473, "Steel Structures, Part III of the Code for the Design, Construction, and Installation of Fixed Offshore Production Structures (Ref. 1)." This Standard covers welded offshore structures that could operate in the Arctic exposed to temperatures down to –50°C.

Introduction

In a limit states or load-resistance factor design approach to structures, the probability of ultimate limit states being reached must be acceptably low. Fracture is one of the possible ultimate limit states that must be considered, but despite considerable recent effort in probabilistic fracture mechanics, design against fracture is not currently based on explicitly determining fracture risk. Rather, an arbitrary fracture criterion is selected that tacitly reflects in a qualitative manner the level of acceptable fracture risk. For example, it may be considered reasonable that one ought to assume the presence of a given size crack residing in a given stress field at the lowest anticipated service temperature. The result of this approach is normally a minimum toughness requirement for the material and possibly for the weld metal and heat-affected zone also. This becomes part of the material specifications. Several levels of toughness may be specified depending on the criticality of the member.

There have been two main approaches to toughness requirements for critical applications. In North America, many specifications can be traced back to the early work by the U.S. Navy. The approach of its research assumes that fracture initiation may occur at local brittle regions (such as arc strikes, heat-affected zones of welds, and local mechanical damage) and that the toughness of the material must be adequate to prevent this crack from continued propagation. Since the initiating crack in the local brittle region (the "pop-in") is rapidly moving, it is the dynamic toughness of the surrounding (base) metal that controls continued propagation, regardless of the loading rate on the structure. Such a "brittle initiation" criterion may also be considered as a crack arrest criterion depending on whether the initiating crack is immediately arrested (pop-in arrest) or arrested after some distance (short or long crack arrest). This approach is summarized in the well-known Pellini fracture analysis diagram (Ref. 2) indexed to the nil ductility transition temperature (NDTT) as determined by drop-weight tests.

In Europe, the dominant philosophy emphasizes the prevention of fracture initiation. Weld metal and heat-affected zone properties are based on fracture mechanics criteria (such as critical crack tip opening displacement (CTOD), which are then correlated back to Charpy tests for practical use (Ref. 3). The CTOD tests are performed at the same temperature and strain rate and on the same thickness as for the real structure. The CTOD initiation approach, however, is not used directly to determine base metal toughness properties. These have been established from welded wide plate tests with notches in the HAZ (Ref. 4). They are, therefore, "brittle initiation" tests. Work many years ago showed that the results from such tests are compatible with the fracture analysis diagram and the NDTT (Ref. 5). Where large numbers of wide plate tests are carried out under quasi-static conditions with notches placed in local brittle regions such as the heat-affected zone, the lower bound of the load/temperature curve is very close to the base metal crack arrest curve as determined, for example, by Robertson tests and as indexed in the fracture analysis diagram by the NDTT — Fig. 1. Thus, the Charpy requirements for base metal in European standards for offshore structures derived from wide plate tests are not vastly different from those in API standards based on the fracture analysis diagram. The wide plate test approach has had the advantage of defining the effect of thickness, which has always been a problem in the fracture analysis diagram.

KEY WORDS

Temperature Shifts
Toughness Requirements
Offshore Structures
Arctic Structures
Crack Initiation
Crack Arrest
Fracture Analysis Diagram
CSA S473
NDTT/Fracture Analysis Diagram
Risk/Consequence Diagram

Risk/Consequences Diagram

Because CSA S473 applies to a wide variety of structures, including both tubular and caisson types, it is necessary to have a framework for selecting fracture criteria appropriate for each structure. This has been done by the introduction (Ref. 6) of the risk/consequences diagram (Fig. 2), which combines the risk, *i.e.*, probability of fracture initiation occurring, with the consequences of a

B. A. GRAVILLE is with Graville Associates, Inc., Georgetown, Ontario, Canada. W. R. TYSON is with CANMET, Ottawa, Ontario, Canada.

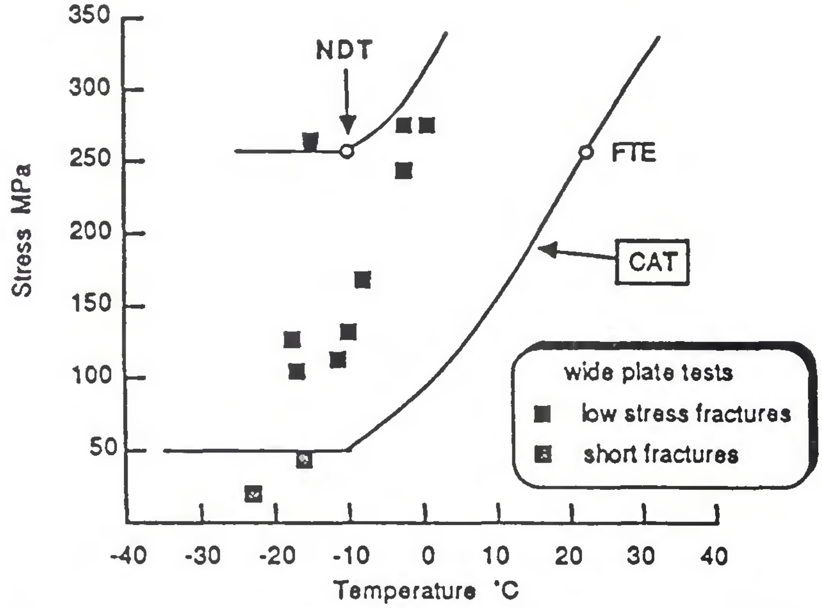

Fig. 1 — Wide plate data plotted on the fracture analysis diagram showing complete compatibility between the two approaches (Ref. 5).

fracture if it occurred. The major factor influencing risk is the stress, whereas, the consequences relate to the safety class of the structure and the redundancy of members. The consequences component represents, in a qualitative sense, the importance factor in limit states design. Although other standards introduce similar concepts (criticality, special steels), the separation of risk and consequences in a two-dimensional matrix provides a very flexible engineering tool for selecting appropriate fracture criteria. For example, in Box 9 of the S473 matrix with the highest risk of fracture initiation, the serious consequences require control of both fracture initiation in weld metal, heat-affected zone, and base metal, as well as crack arrest capabilities in the base metal. A full discussion of the matrix and the corresponding fracture toughness requirements in S473 have been presented elsewhere (Ref. 7).

The fracture toughness requirements for the base metal are based on the assumption of brittle initiation, and they use the NDTT, as determined by the drop weight test, as the prime index. As in other standards, various levels of crack arrest capability are set by applying a thickness-dependent temperature shift of the NDTT relative to the lowest toughness design temperature. This temperature shift approach, which is common in toughness specifications, has a weakness in that it assumes that toughness increases above the NDTT at the same rate for all materials. This may not be the case, and toughness tests carried out at temperatures remote from the service temperature may not correctly indicate fracture behavior at the service temperature. Nevertheless, the drop weight test has real structural significance at the NDTT, and correlations with large scale tests support the temperature shifts proposed for practical use in toughness specifications.

Consequences →

Risk of Fracture Initiation ↓

	Safety Class 2	Safety Class 1	
		Highly redundant	Limited redundancy
Compression	Box 1	Box 2	Box 3
Tension, no high stress concentrations	Box 4	Box 5	Box 6
Tension, high stress concentrations, hot spots	Box 7	Box 8	Box 9

Fig. 2 — The risk/consequence diagram.

Charpy Correlations

The majority of steel toughness specifications existing today use the Charpy V-notch (CVN) test. This test is relatively inexpensive, convenient, and has a long history of successful use. The Charpy test with its blunt notch does not, however, relate directly to fracture behavior, and CVN specifications have been determined in the past on the basis of empirical correlations. These correlations, however, were established on steels quite different from those now available for Arctic structures.

To determine whether the CVN test could be used as a substitute for the drop weight test in S473, a survey (Ref. 8) was conducted to explore correlations between the two test methods. Data were collected from the literature for steels where both the NDTT and Charpy transition data were provided. The data showed that the CVN energy at the NDTT varied over a considerable range from a few joules to almost 350 J. There was no relation between this energy and the yield strength of the material — Fig. 3. Increasing the required CVN energy with increasing yield strength has been a common practice in many standards, but these results show that this practice does not ensure a consistent fracture behavior. The range of CVN energies specified for yield strengths up to 400 MPa (58 ksi) (typically, numerically equal to $\sigma_y/10$) is very small compared to the range of energies observed at the NDTT for many steels.

Examination of the data showed that the energy absorbed at the NDTT increased as the carbon and sulfur level of the steel decreased, and this is to be expected since the cleaner steels require greater energy to initiate fracture from the blunt notch of a CVN specimen. As a rough guide, the absorbed energy at the NDTT could be related to 10S + C — Fig. 4. It is noted there is a rapid rise in the Charpy energy as 10S + C decreases below 0.25% and this figure is a rough dividing line between the "old" and "new" types of steels. This is not to imply that only sulfur and carbon influence the CVN energy at the NDTT; it is merely a simple way of characterizing the steels studied.

The same behavior can be shown in another manner by plotting the temperature shift between the 40-J Charpy transition temperature and the NDTT as a function of the sulfur and carbon content — Fig. 5. With low-sulfur and low-carbon steels, an NDTT up to 80°C (144°F) above the 40-J Charpy transition temperature has been observed. For these steels, therefore, the Charpy transition temperature could be well below the NDTT of the steel, and a 40-J CVN toughness criterion would not provide any significant resistance to brittle initiation.

For the older steels with 10S + C >0.25%, there is a good correlation between the 40-J Charpy transition temperature and the NDTT — Fig. 6. For the modern cleaner steels, no such relation exists — Fig. 7. Neither is the relation improved very much by using a fracture appearance transition temperature instead of energy transition temperature.

The increase in Charpy energy at the NDTT with reduced carbon and sulfur is not dependent upon any particular steel processing route, although many of the low-carbon low-sulfur steels in the database were produced by TMCP methods. The same behavior is observed with normalized steels where the carbon and sulfur is sufficiently low. This effect of cleanliness overrides any effect due to yield strength, and it is interesting to note that at the time when higher Charpy energies for higher yield strength materials were being promoted (Ref. 9) some of the steels being studied at the time were clean, vacuum degassed materials. It is possible that apparent yield strength effects observed at that time were in fact the cleanliness effect.

The implications of these observations were clear for the development of

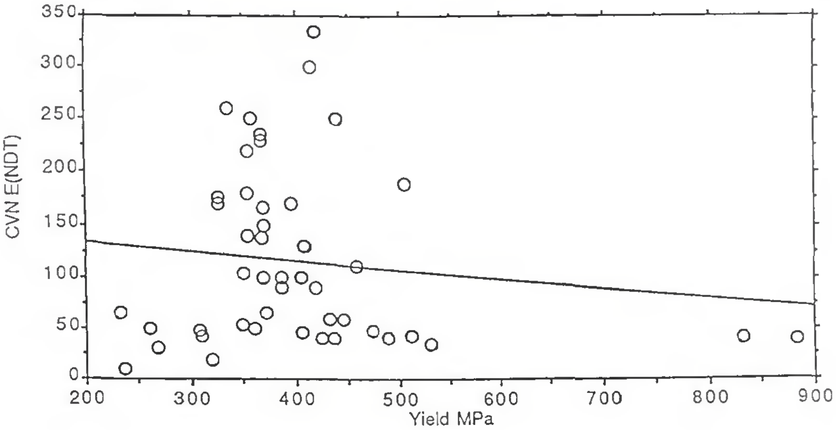

Fig. 3 — CVN energy at the NDTT plotted against yield strength.

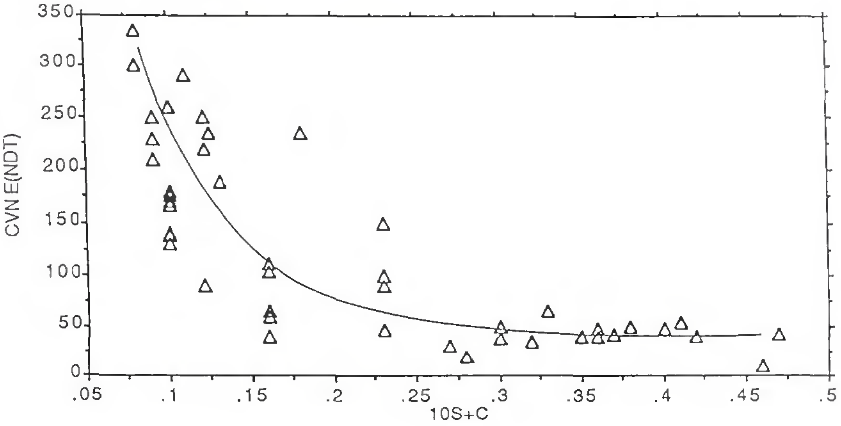

Fig. 4 — CVN energy at the NDTT as a function of the sulfur and carbon content.

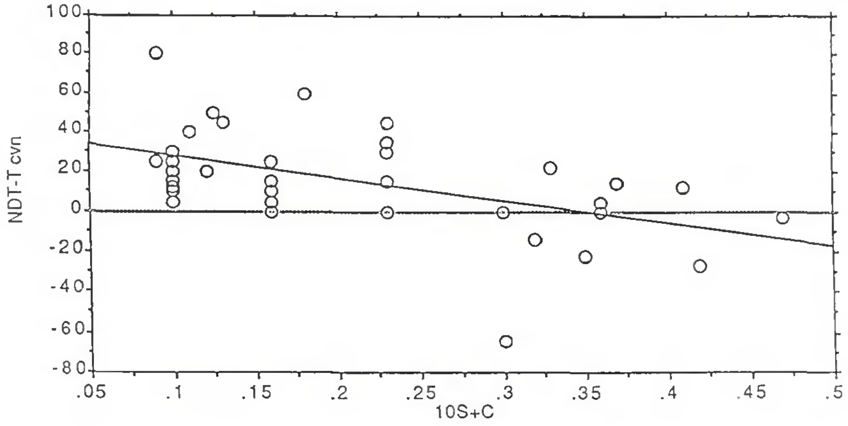

Fig. 5 — Difference between the NDT temperature and CVN transition temperature plotted against a function of the carbon and sulfur content.

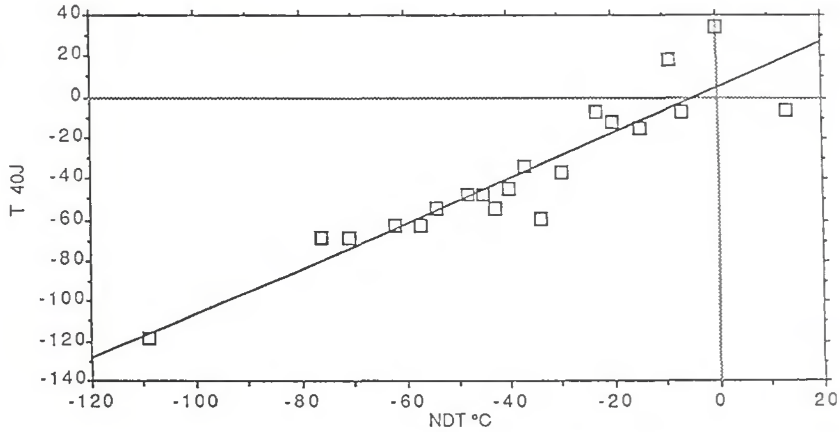

Fig. 6 — Plot of CVN 40-J transition temperature against the NDTT for "old" steels with 10S + C >0.25%.

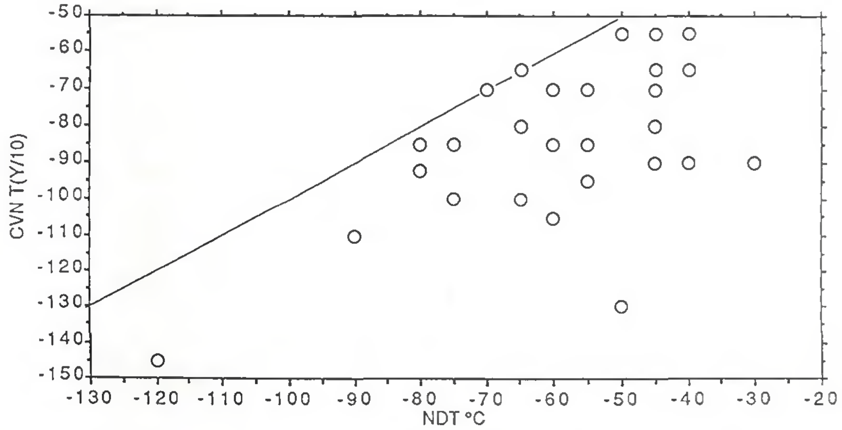

Fig. 7 — Plot of CVN $\sigma_y/10$ transition temperature against the NDTT for "new" steels with 10S + C <0.25%.

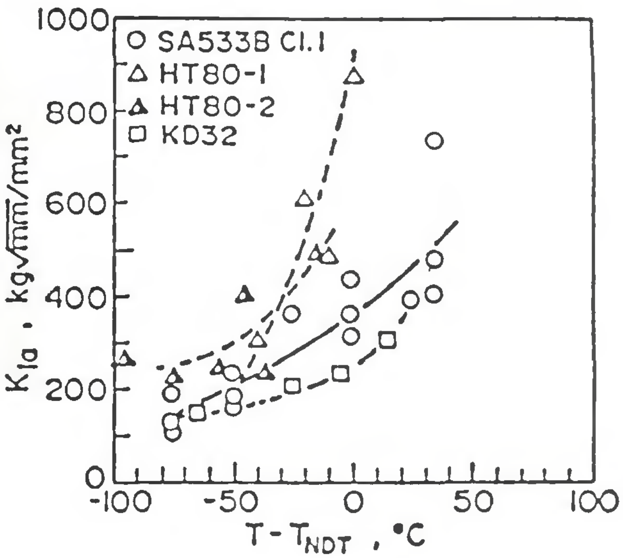

Fig. 8 — Data from Nakano and Tanaka (Ref. 11) showing poor correlation between crack arrest toughness and NDTT.

S473 in that Charpy tests could not be relied upon in the standard to provide assurance of any given level of fracture behavior. In fact, the steels that show the biggest shift between CVN temperature and NDTT are the very steels most likely to be used in Arctic applications. It is also clear that the problem could not be solved by setting alternative Charpy energies since in some steels the energy at the NDTT was beyond the capacity of Charpy testing machines. The standard has therefore adopted the drop weight test as the default test for material toughness testing. CVN tests continue to play a useful quality control role, for example, in identifying center-plate segregation, which would not be apparent in a drop weight test that evaluates surface properties. The implication of the results is also clear for existing toughness specifications that use the Charpy test (including those based on wide plate data from older steels) when applied to modern steels. Fortunately, the modern steels are generally very tough and often exceed Charpy specifications by a considerable margin. Nevertheless, it is clearly undesirable to be relying on this margin to achieve the desired fracture behavior.

Crack Arrest

The chief difficulty of using a temperature shift approach relative to the NDTT is determining the rate at which the toughness increases with temperature above the NDTT for each thickness. In the original fracture analysis diagram, the lower bound of the stress temperature transition curve, the crack arrest curve, was established from Robertson tests. This curve shifted to higher temperatures with increasing thickness. But this method of establishing the curve was clearly expensive and led to an alternate method (Ref. 2). A standardized crack arrest curve for each thickness was established as a straight line between a lower limit, determined by the limit of plane strain capacity, and an upper limit, which was a yield criterion. The position of these end points relative to the NDTT was established through a fracture mechanics argument. For low temperature applications where the dynamic yield strength is increased, the curves are shifted to lower temperatures relative to the NDTT (Ref. 10).

In order to explore the relation among various crack arrest and dynamic toughness measurements and the NDTT, a survey (Ref. 10) was made of data in the literature, and some of the results are summarized here. Some researchers have found no correlation between crack arrest toughness and the NDTT. For example, Nakano's and Tanaka's data (Ref.

11) are shown in Fig. 8. However, the drop weight test can be interpreted in fracture mechanics terms, and a number of researchers (Refs. 12, 13) have shown that the dynamic fracture toughness at the NDTT is of the order of

$$K_{Id} \sim 0.075\sigma_{yd} \qquad \left(MPa\sqrt{m}, MPa\right)$$

The dynamic yield strength depends on the (static) room temperature yield strength σ_{RT} and the temperature $T_{(°K)}$ and can be given by the following expression, which is based on an empirical analysis of Rolfe's and Shoemaker's data (Ref. 10):

$$\left(\sigma_y\right)_{T,d} = \sigma_{RT} + \frac{1850 - \sigma_{RT}}{T_{(°K)} \times 16.1 \times 10^{-3}} - 157$$

Using this expression for dynamic yield strength, the crack arrest data of Nagano and Tanaka has been normalized with respect to dynamic yield strength, and a reasonable correlation with NDTT is established — Fig. 9. Note that when plane strain conditions are maintained this relation holds for a very wide temperature range below and above the NDTT. Similarly, dynamic fracture toughness data, K_{Id}, normalized in the same way relates well to the NDTT — Fig. 10. Again, note the very wide range of temperatures over which this relation holds. The crack arrest toughness K_{Ia} values in Fig. 9 are somewhat higher than the K_{Id} values in Fig. 10.

K_{ca} values determined from a variety of tests such as double tension tests and Esso tests were also treated in the same manner. For a given steel, the curve for K_{ca} tests is much steeper than for K_{Id} or for K_{Ia} because plane strain conditions are not maintained — Fig. 11. It is the loss of plane strain constraint above the NDTT that results in the rapid rise of apparent toughness. These results show that a single logarithmic expression for toughness cannot be expected to apply to a very wide range of temperature above and below the NDTT. It was also apparent from the data that the slope and position of these curves varied widely and no pattern could be found. All the crack arrest measurements are plotted in Fig. 12, which shows some considerable scatter, although far less than when plotted against the Charpy 40-J transition temperature. These data have been useful in providing some confirmation that the S473 requirements offer a reasonable assurance of crack arrest.

Conclusion

Background work during the development of toughness requirements for CSA S473 showed that a "brittle initiation"

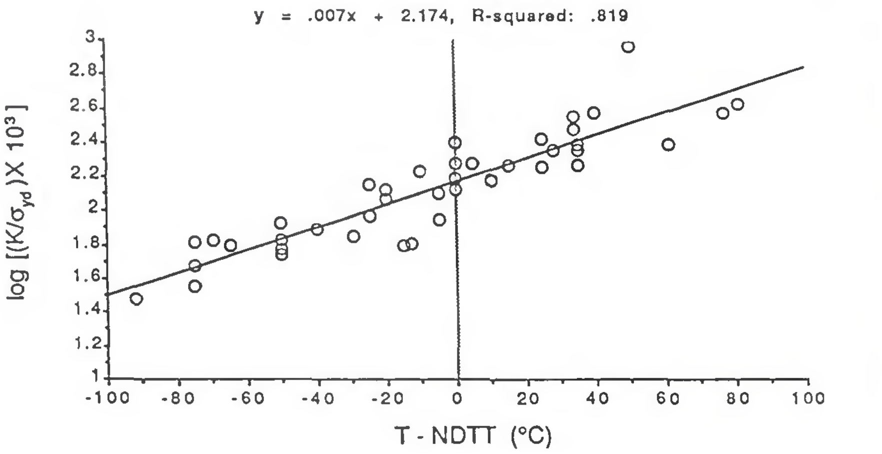

Fig. 9 — Nakano's and Tanaka's data plotted in logarithmic form with the toughness normalized with respect to the dynamic yield strength.

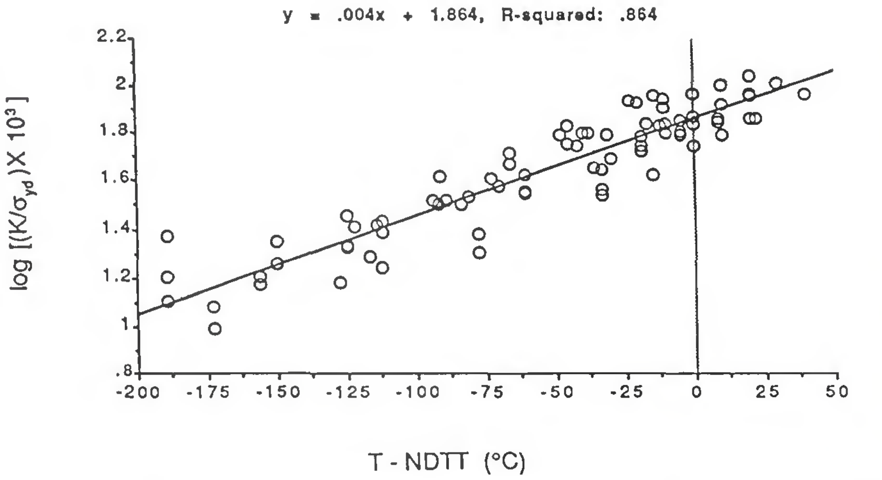

Fig. 10 — Dynamic toughness K_{Id} data in normalized form as a function of temperature relative to the NDTT.

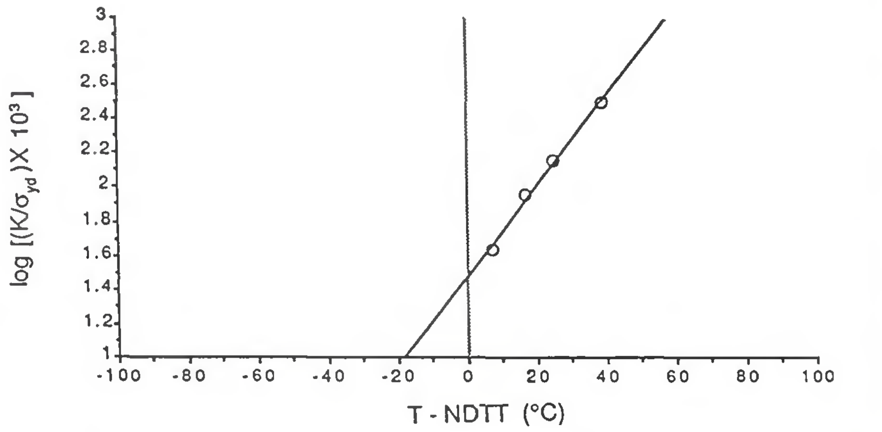

Fig. 11 — Normalized crack arrest toughness (K_{ca}) plotted against relative NDTT for a single steel.

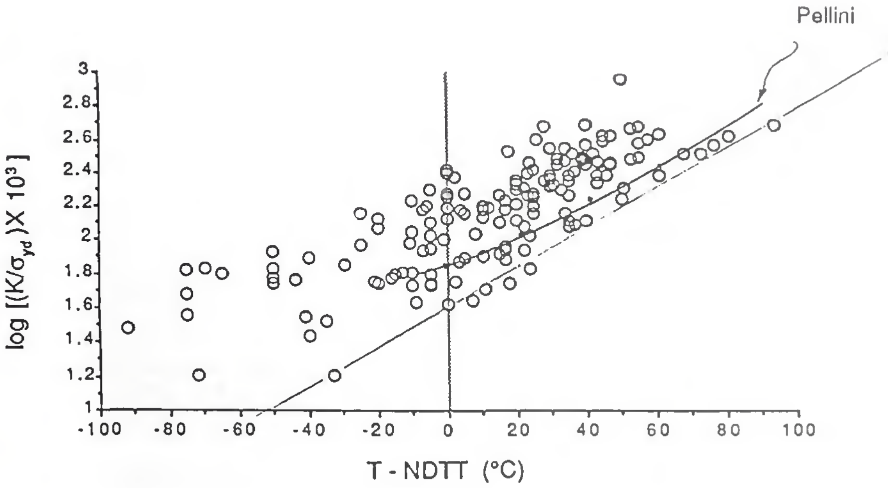

Fig. 12 — Crack arrest toughness normalized with respect to dynamic yield strength plotted against relative NDTT.

criterion has been the most widely used in developing toughness specifications. Both the welded wide plate approach used in Europe and the fracture analysis diagram method used in North America use this criterion and lead to similar toughness requirements for the base metal. Because Charpy correlations previously used cannot be relied upon for modern clean steels, toughness in CSA S473 is specified in terms of the nil-ductility transition temperature (NDTT) as determined by the drop weight test. Review of published crack arrest data shows that the use of temperature shifts relative to the NDTT provides a reasonable assurance of crack arrest.

Acknowledgment

Part of the funding for this project was provided through the Canada Center for Mineral and Metallurgical Technology (Panel for Energy Research and Development).

References

1. CSA Preliminary Standard S473-M1989. 1989. Steel Structures, Part III of the Code for the Design, Construction, and Installation of Fixed Offshore Production Structures. Canadian Standards Association.

2. Pellini, W. S. 1983. Guidelines for fracture-safe and fatigue-reliable design of steel structures. The Welding Institute, Abbington, England.

3. Pisarski, H. G., and Harrison, I. D. 1985. Fracture toughness considerations for offshore structures in U.K. waters. Proc. conf. Welding for Challenging Environments, Toronto, Canada, Pergamon, pp. 131–144.

4. Pisarski, H. G., and Harrison, I. D. 1986. Fracture toughness considerations for offshore structures. *Metal Construction* 18(12): 748–753.

5. Pellini, W. S. 1979. Principles of Structural integrity technology. Office of Naval Research, Arlington, Va.,

6. Toughness requirements for offshore steel structures used in an Arctic environment. 1987. Report to Canada Oil and Gas Lands Administration.

7. Tyson, W. R., and Braid, J. E. M. 1990. Fracture toughness considerations for Arctic and cold marine structures. Proc. Conf. on Metallurgy, Welding, and Qualification of Microalloyed (HSLA) Steel Weldments, Houston, Tex.

8. Graville, B. A. 1988. Correlations between Charpy properties and the nil-ductility transition temperature. Project I-1 of the CSA verification program for the Offshore Structures Code.

9. Gross, J. M. 1970. Effect of strength and thickness on notch ductility. ASTM STP 466, pp. 21–52.

10. Graville, B. A. 1989. Crack arrest requirements for Arctic structures. Report to CANMET.

11. Nakano, Y., and Tanaka, M. 1982. Crack arrest toughness of structural steels evaluated by compact test. Trans. Iron and Steel Institute of Japan 22:147–153.

12. Irwin, G. R., Krafft, J. M., Paris, P.C., and Wells, A. A. 1967. Basic aspects of crack growth and fracture. NRL Report 6598. Washington, D.C., (82p).

13. Tyson, W., and Harbec, J. 1984. Dynamic toughness: fracture mechanics interpretation of the drop-weight (NDT) test. International Journal of Fracture 25:133–141.