THE APPLICATION OF POST YIELD FRACTURE METHODOLOGY TO THE EVALUATION OF LARGE STRUCTURES

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SUMMARY

The objective of this work is to determine how to use small specimens test results to measure fracture toughness values for application to the evaluation of large structural components.

Linear elastic fracture mechanics concepts based on the crack tip stress intensity factor, K, have been extended into the post yield regime by the use of elastic-plastic characterizing parameters such as J integral and COD. One of the primary applications of this technology is the determination of fracture toughness values from small specimens tests taken primarily in the post yield regime which can be used to evaluate structures operating in an essentially linear elastic regime. The fracture toughness values may be either conservative or unconservative depending on the fracture mode; extreme care must be taken in interpretting these results.

In steels which exhibit a fracture mode transition the fracture behavior must be considered in three different ranges, a range of brittle cleavage fracture at low temperature, a transition range and a ductile fracture range at higher temperatures. In the brittle, low toughness range, fracture generally occurs in the linear elastic regime for most test specimens and there is little problem in developing toughness values from small specimens. In the transition range fracture toughness increases rapidly with increasing temperature and toughness values must often be determined from specimens in the post yield regime. Many studies have shown that toughness values determined from small specimens may be much higher than those determined from large specimens. Therefore, an attempt to use small specimen test results for the evaluation of large structures may be unconservative. This difference in toughness has often been attributed to loss of constraint in the small specimens. Results from this study show that loss of constraint is not necessarily the problem, rather this difference in toughness can be attributed to a statistical variation in material toughness. Large specimens incorporate a larger statistical sampling of toughness values. To determine toughness from small specimens a proper statistical sampling must be considered to evaluate the variability in toughness. Test results show that a lower bound toughness estimate from small specimen tests provides a conservative estimate of the toughness value for large structures.

In the ductile fracture range the toughness is relatively large and the opposite result is obtained. Fracture toughness measured at the initiation of the ductile fracture process on small specimens gives an overly conservative value. To properly assess the toughness of a large structure stable crack growth and stability criteria must be considered. Methods for predicting instability in the ductile fracture range have to be theoretically formulated. Work remains to experimentally verify these criteria. When properly applied a realistic value of fracture toughness for a large structure can be obtained from small specimen tests.

This work shows that fracture toughness values can be obtained from small specimen tests and applied to large structures. Care must be taken to properly categorize to range of fracture behavior so that the analysis is neither overly conservative or unconservative.

1. Fracture in the Transition Region

The fracture behavior in the transition region for steel alloys is shown schematically in Fig. 1. Fracture toughness values determined from small specimens, generally by post yield fracture methods; e.g., J_{Ic} [1], may show a lot of scatter but on the average are greater than equivalent fracture toughness values obtained from larger specimens. This difference in toughness has often be attributed to a loss in through thickness constraint for the smaller specimens. This explanation appears to have some experimental backing because the larger specimens often fail by a cleavage mechanism at low toughness while the smaller specimens fail by a ductile mechanism at high toughness. A loss of constraint argument; however, has some serious implications namely that small specimens cannot be used to determine the fracture toughness for large structural components in the transition region. The uncertainty about the use of small specimens can be taken into the beginning of the ductile, "upper shelf", fracture regime. Although small laboratory test specimens may indicate completely ductile fracture at a given test temperature, there is no guarantee that the structure, if it contains thick sections, would fracture in a ductile mode. If the loss of constraint explanation is correct, values of toughness in the transition region and the start of the ductile fracture regime cannot be accurately determined unless specimens containing the full structural thickness are tested.

A loss of constraint explanation of transition range fracture behavior can be questioned from two points. First, small specimens that are of a deeply cracked bend geometry have a considerable amount of constraint built into the geometry. Second, small specimens tested in the transition range do not uniformly show higher toughness than larger specimens. They generally show a considerable amount of scatter with some specimens exhibiting relatively low toughness and others showing very high toughness. The average for this scatter in the smaller specimens is higher than the toughness exhibited by the larger specimens.

An alternative model based on sampling size was proposed to explain the difference in toughness between small and large specimens [2]. This model suggested that toughness varied from point to point in a given heat of material and that the fracture toughness value for any test specimen was controlled by the point of lowest toughness along the crack front. Larger specimens would exhibit lower toughness on the average simply because they sampled a larger range of material toughness values than the smaller specimens do. This is shown schematically in Fig. 2. The long crack front of the large specimen samples a wide range of toughness values and is more likely to contain a point of low toughness. Smaller specimens sample a correspondingly smaller range of toughness, however, when a large number of small specimens are tested some will exhibit low toughness and other high toughness resulting in the large amount of scatter observed. This behavior is illustrated in Fig. 3 for an ASTM A471 NiCrMoV rotor steel tested at three temperatures in the transition region of this steel [3]. With increasing test temperature the small specimen fracture toughness values show an increasing amount of scatter. Although the average toughness for the small specimens is much higher than the lower bound for the larger specimens, the lowest values for the small specimens fall very near the large specimen lower bound. These results would indicate that the smaller specimens do not have less constraint than the larger specimens, rather they sample a smaller range of toughness values. When large numbers of specimens are tested some show low toughness corresponding to the low toughness point in the larger specimen while other do not contain a low toughness point.

One of the larger specimens tested at 325°K shows a much higher toughness than the lower bound values. If this specimen had toughness controlled by constraint, it should fall near the lower bound. A more suitable explanation is given by the sampling size model. At this temperature there are a smaller number of low toughness points and the specimen did not contain one.

An additional illustration for this model is given in Fig. 4 for an A533B, Class 1 steel where small specimen fracture toughness values are compared with a valid K_{Ic} value (ASTM method E399) obtained from a large specimen (240 mm thick) at a single test temperature 253°K [4]. As the specimen size is reduced, the amount of scatter increases, and the average toughness is higher than the K_{Ic} value, however, the lowest toughness values for the smaller specimens are lower than the large specimen K_{Ic} value. Again for this behavior the sampling size model offers a better explanation of the results than the loss of constraint model.

The sampling size model suggests that small specimen toughness results can be used to predict the fracture potential of large structural components. The small specimens do not always overestimate the toughness of the large structure; rather a proper number of specimens is needed to adequately test the statistical variability in fracture toughness. Extremal statistics can be applied to the scatter in toughness for the small specimens to determine a lower bound which adequately predicts the toughness for the large structure [3].

2. Ductile Fracture Behavior

While fracture toughness values determined from small specimens in the transition region appear overestimate the toughness for a large structure, the opposite may occur in the ductile fracture regime. Fracture toughness determined from an initiation criterion such as J_{Ic} [5] may underestimate the fracture potential of a large structure. This is illustrated in Fig. 5 for ASTM A471 steel where fracture toughness determined by J_{Ic} on the upper shelf is considerably lower than the equivalent toughness determined by valid K_{Ic} values (ASTM method E399) [6]. An explanation for this behavior is shown schematically in Fig. 6. K_{Ic} values determined by E399 are taken at 2% crack extension. If the material shows an increasing resistance to crack growth as determined on a crack growth resistance curve, R curve, and the K_{Ic} specimen is fairly large, then a toughness value taken at 2% crack growth could be considerably larger than the equivalent value taken at the initiation of crack growth. An R curve for the ASTM A471 steel, Fig. 7, shows an increasing resistance to ductile fracture with ductile crack extension and a toughness value taken at 2% crack extension for the large K_{Ic} specimens ($\Delta a \approx 4$ mm) could be more than twice as large as the J_{Ic} value ($\Delta a \approx 0$).

To adequately evaluate the fracture potential of a large structure from small specimen test results a criterion other than crack initiation must be used. A model based on ductile instability has been developed by Paris, et al. [7] using an elastic-plastic R-curve approach [8]. The material resistance to fracture is taken from the slope of the R curve and is labeled T_{MATL}. A fracture driving force labeled T_{APPL} is calculated for the structure when $T_{MATL} > T_{APPL}$ the structure is safe from a ductile fracture instability.

J_{Ic} is a material property, however, the point of ductile instability is not but is a function of many parameters, the material toughness (R curve slope) and tensile properties and the structural geometry and loading stiffness. J_{Ic} is relatively easy to determine experimentally [5] and often represents a high enough toughness to guarantee that a structure is safe from ductile fracture. When the J_{Ic} is too conservative in the ductile regime, a ductile instability criterion can be used to evaluate the material toughness at levels above J_{Ic}. Although a fracture methodology based on a ductile instability criterion needs further experimental verification, [9] this approach offers a way to use small specimen toughness results to predict the fracture potential of a large structure in the ductile fracture region.

3. Conclusions

Small specimens can be used to experimentally determine fracture toughness for the evaluation of large structural components. For steel alloys which exhibit a fracture mode transition with increasing temperature the the application of small specimen toughness results must be made relative to three ranges of fracture behavior.

1. At low temperatures toughness is low and small specimens often give linear elastic valid K_{Ic} toughness results (ASTM Method E399).

2. As the temperature is increased and the transition region is approached, the level of toughness increases markedly. In this range the toughness values determined from small specimens often greatly overestimate the toughness of larger specimens or structures and extreme care must be taken to properly evaluate the small specimen results. A model based on sampling size suggests that small specimen toughness can be used to evaluate large structures if a sufficient number of specimens are tested to adequate sample the statistical variability in material toughness. Extremal statistics applied to these results gives an appropriate value of toughness for application to the large structural components.

3. In the purely ductile "upper shelf" fracture range toughness determined by an initiation cirterion such as J_{Ic} may underestimate the true fracture potential of a large structure. A fracture methodology based on R curves and ductile instability can be used to assess the fracture potential of large structures above J_{Ic}.

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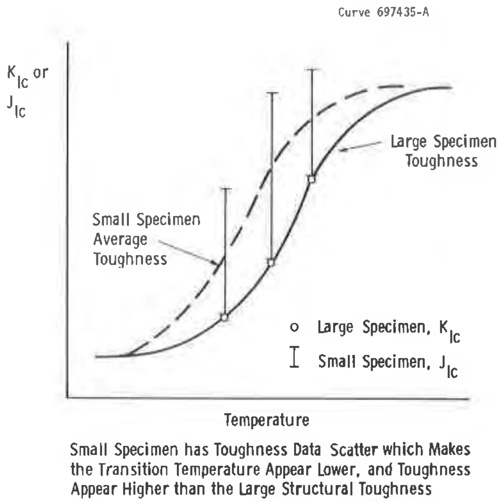

Fig. 1 — Small specimen fracture toughness data in the transition region

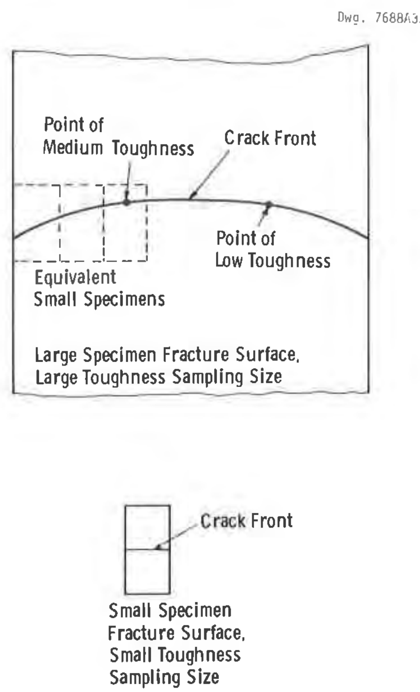

Fig. 2 — Schematic showing the difference in fracture toughness sampling size between large and small specimens

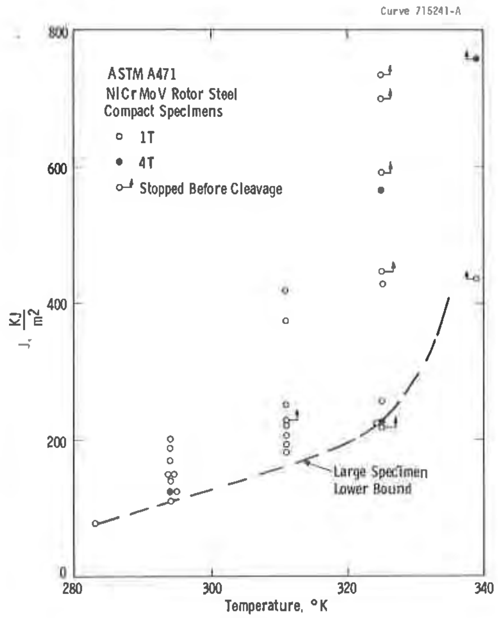

Fig. 3 — Fracture toughness (J) for cleavage versus temperature for an ASTM A471 steel

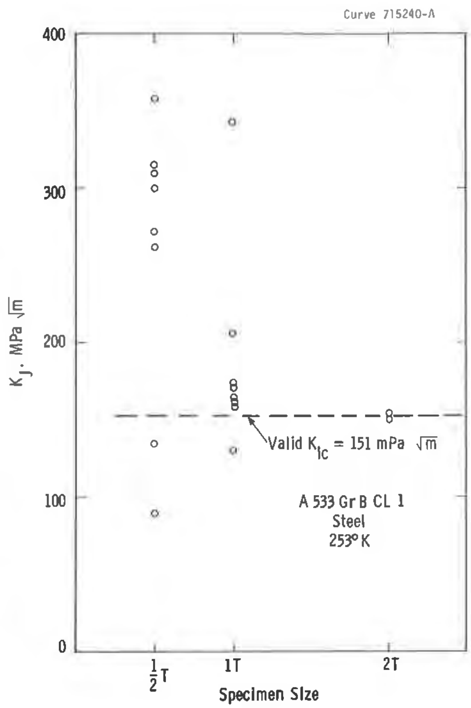

Fig. 4 — K for fracture calculated from J versus specimen size, A533B, Cl 1 steel Ref. (4)

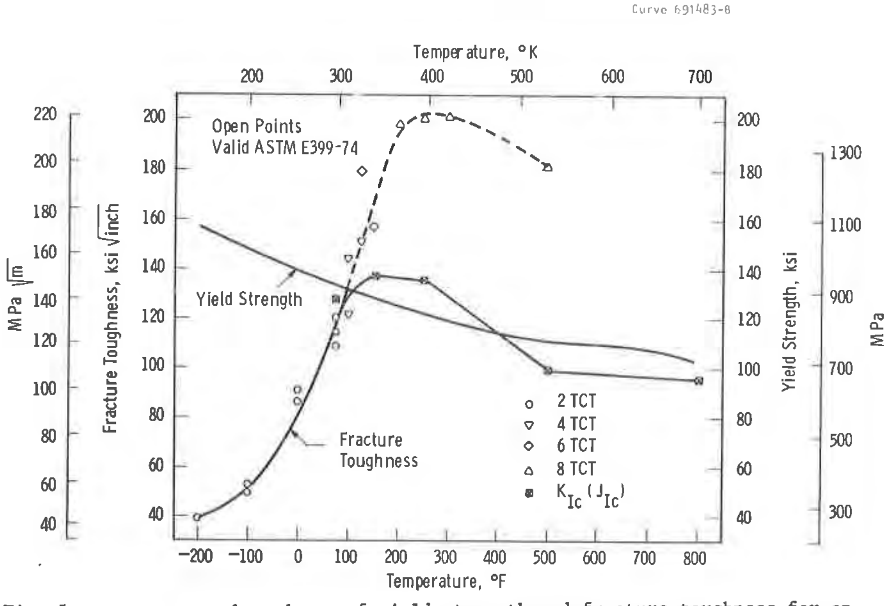

Fig. 5 — Temperature dependence of yield strength and fracture toughness for an ASTM A471 NiCrMoV rotor steel

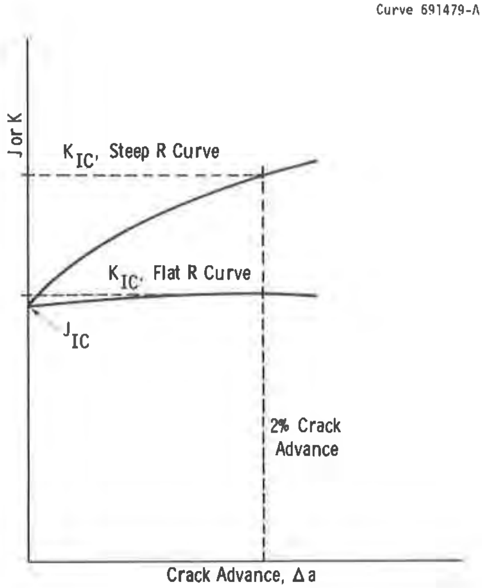

Fig. 6 — Schematic of R curve showing the differences between the J_{Ic} and K_{Ic} measurement points

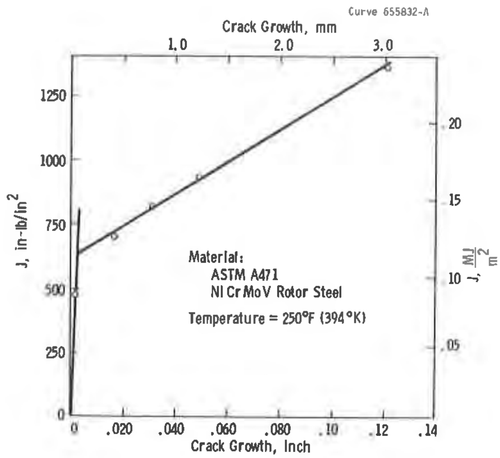

Fig. 7 — J resistance curves for an ASTM A471 NiCrMoV rotor steel at 250°F (394°K)