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THE LARGE TENSILE TESTS USING THE
EQUIVALENT ENERGY METHOD

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HEAVY SECTION STEEL TECHNOLOGY PROGRAM

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THE PREDICTION OF THE FRACTURE BEHAVIOR OF THE LARGE TENSILE TESTS USING THE EQUIVALENT ENERGY METHOD*

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Abstract

The equivalent energy method has been proposed as a procedure for relating flaw size, stress and temperature for ASTM A 533, grade B, class 1 steel. The initial application of the method has been applied to the 6-in.-thick flawed tensile specimen behavior which is being investigated by Southwest Research Institute. Prior to each test a calculation of the fracture behavior of the specimen has been performed. The data from compact tension specimens have been used as a basis for prediction. Since results from 6-in.-thick compact tension specimens were available only up to 75°F, reasonable extrapolations were necessary to perform the analyses.

The predicted results are compared with the experimental results. Considering the extrapolations necessary to make the predictions, it is shown that the comparison generally supports the potential of the equivalent energy method for making quantitative fracture analyses.)

Introduction

There are several methods of relating flaw size, temperature and fracture behavior (fracture stress, strain, energy, etc.) under investigation by the researchers of the Heavy Section Steel Technology (HSST) Program and by many other investigators throughout the world. The sophistication of the methods usually increases directly with the complexity of the problem and/or the economic and social impact should failures reoccur time and time again. The mammoth primary containment pressure vessels of

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commercial water reactor power plants are unique in that no catastrophic failure which might endanger the public must ever occur with the corollary that even a minor failure could precipitate the shutdown of a plant with resulting economic repercussions to the nuclear power industry and inconvenience and hardship on the power dependent public. In a real sense this is a major concern of the HSST Program. Indeed a primary objective of the HSST Program is to develop a technology capable of making quantitative assessments of the margins of safety which exist in nuclear reactor pressure vessels under inservice conditions. Since all vessels are assumed to contain flaws, discontinuities and/or inhomogeneities of some size (although perhaps small), the margins of safety in the presence of flaws, etc., however small and reasonably large, must be made amenable to quantitative calculations.

A presentation¹ was made at the 4th Annual Information Meeting of the HSST Program in which specific observations were made of the behavior of the larger specimens tests (drop weight, dynamic tear and compact tension) performed on the ASTM A 533 grade B class 1 steel plate from which, together with the equivalent forging grade ASTM A 508 class 2 steel, all the pressure vessels of the large commercial nuclear power plants in the United States are being fabricated. The general approach of that presentation was that increasing thickness degrades the fracture resistance throughout the temperature range from frangible through transitional and tough behavior. Thus however remote fracture might be in a thinner vessel it is less remote in a thicker vessel. Considerable discussion and some research have been devoted to this question during the intervening year. This paper, together with Papers 12² and 13 of this conference, represent a follow up of the prior discussion. Witt and Berggren,³ Witt and Mager,⁴ and Mager⁵ have added further information in this area of interest.

The general approach or method of analysis developed throughout Refs. 1 through 5 is called the equivalent energy method and is, in fact, a method of modeling. The basic assumptions are well accepted by the engineering community and the logic of the method is so constructed that areas of technical disagreement are non-existent. The applicability, generality and practicality are then the areas for evaluation. These however fall in the realm of engineering judgment.

In Paper 13 of this conference we see an application of the equivalent energy logic; however sufficient supporting data are not currently available to present the most convincing argument. In this paper an actual application of the equivalent energy method for predicting fracture is presented.

One of the major accomplishments of the HSST Program during the last 12 months has been the testing of eight more (for a total of ten) large cross section (18-in.-wide, 6-in.-thick) flawed tensile specimens. The tests were performed under subcontract by Southwest Research Institute and are reported in Paper 22 of this conference. Prior to each test one equivalent energy method or another was used to evaluate the general fracture behavior. The procedure used on each specimen is briefly summarized below. This is followed by a general evaluation of the success of the analyses.

Fracture Analyses of the Large Flawed Tensile Tests

In this section we shall review the methods used to predict the fracture behavior of the flawed tensile specimens. It is perhaps well to recall when the tests were initiated that the equivalent energy approach had not been developed. While the interpretation of the calculated results has changed somewhat, the basic approach has essentially remained intact. The general description of each of the ten specimens tested are given in Table 1. For more specific details reference should be made to Paper 22 of this conference. The analyses and experimental results for each specimen are discussed below.

Speciman No. 1. This test was performed at a time when the equivalent energy approach was in its infancy. The test temperature of about 220°F was chosen mainly because methods of obtaining sharp flaws in such large specimens had not been successful and it was generally agreed that at sufficiently high temperatures the flaw sharpness would not be an overriding factor in the fracture behavior. The high temperature test also offered an opportunity to make a specific technical evaluation. Prior to the test the author had participated in an analysis which eventually resulted in Ref. 3. Based on this analysis, one could expect a significant

Table 1. Specimen Conditions, Test Parameters and Test Conditions for the Ten Flawed Tensile Specimens

Specimen No.	Plate No.	Orientation	Gage Section Location ^a (in.)	Machined Flaw Depth x Flaw Length, (in.)	Flaw Location ^d (in.)	Method of Crack Sharpening	Final Flaw Depth x Flaw Length, (in.)	Test Temperature (°F)
1	03	Longitudinal	3-9	2.38 x 6 ^b	3	Stress corrosion	2.38 x 6	220
2	03	Longitudinal	3-9	2.38 x 6 ^b	3	None	2.38 x 6	220
3	01	Longitudinal	~1-7	2 x 8 ^c	~7	3 point bending	2.1 x 8.1	50
4	01	Longitudinal	~1-7	2 x 8 ^c	~1	3 point bending	2.1 x 8.1	100
5	01	Longitudinal	~1-7	2 x 8 ^c	~1	Local fatigue	2.5 x 8.4	75
6	01	Longitudinal	~1-7	3 x 9 ^c	~7	Local fatigue	3.38 x 9.3	100
7	03	Longitudinal	3-9	2 x 8 ^c	3	Local fatigue	2.4 x 8.3	100
8	03	Transverse	3-9	2 x 8 ^c	3	Local fatigue	2.4 x 8.4	100
9	03	Transverse	3-9	2 x 8 ^c	3	Local fatigue	2.38 x 8.4	220
10	03	Transverse	3-9	2 x 8 ^c	3	Local fatigue	2.4 x 8.4	130

^aLocation through thickness of 12-in.-thick plate

^bSemielliptical

^cSemicircular

^dDepth below original 12-in.-thick plate surface of surface of specimen in which the machined flaw was originated

thickness or flaw size effect between similar large and small specimens at all temperatures including the very tough behavior usually described as upper shelf behavior. The test temperature chosen was such that it should demonstrate the existence of the thickness effect for tough behavior. Only two quantities were considered necessary to perform an equivalent energy analysis at the time of the first test. One was the appropriate load deflection (load-strain, stress-strain, etc.) curve from a flawed model. The second was the size effect in energy absorbing capacity between model and prototype. Neither of these were available. However, a size effect between a 1-in.-thick and a 6-in.-thick dynamic tear specimen of 2.75 was chosen based on the results eventually published as Ref. 3 (see Fig. 4 of Paper 13 of this conference for the curve actually used). The best load-deflection curve that was available was one obtained from a gross strain specimen with a rectangular cross section of 1.82 in. by 0.83 in. thick.⁶ Based on the thickness the width would have had to have been 2.5 in. to have modeled the cross section of the prototype specimen (18 in. by 6 in. thick). The gage length was 9.5 in. compared to 3.3 in. for a model. The actual crack was 0.75 in. long by 0.29 in. deep as compared to 0.83 in. long and 0.33 in. deep for a model. The gage section contained two such cracks. Since the size effect (later to be called volumetric energy ratio) was based on the total energy to fracture dynamic tear test specimens the complete load-deflection curve of the model was used. The results from the analysis led at a prediction of 7,600,000 lb required to fracture the specimen. The critical maximum load on the 6-in. specimen was not measured directly because of yielding which occurred in the calibration region. A maximum load of between 7 and 7.5 million pounds is known to have been reached. Had the energy to maximum load on the selected model been used the prediction would have been well within this interval.

Specimen No. 2. This specimen was also tested at about 220°F for the same reason as Specimen No. 1 and to obtain a better definition of the actual maximum load. Prior to this test a 1-in.-thick model of the specimen was tested. During the interim it was decided that in making equivalent energy type calculations only the energy to maximum load in

the model should be used. The same size effects data were used in the analysis of this specimen as the first specimen. However, bounding values of the size effect (2.3 to 3.1) were used for a thickness of 6 in. (see Fig. 4 of Paper 13) to calculate bounds on the maximum load to be obtained during the large specimen test. A load-deflection curve of an unflawed 1-in.-thick model had also been obtained. Analyses were made using both the flawed and unflawed curves. The analyses and results are outlined in Paper 12 of this conference. Only the results are repeated here. By using the load-deflection curve for the flawed model, a maximum load to fracture the prototype specimen of between 7,425,000 and 7,650,000 lb was predicted. Results from using the unflawed model curve were 7,400,000 to 7,600,000 lb. The actual maximum load to fracture was 7,550,000 lb. This test together with that of the first specimen confirmed the existence of a significant size effect as discussed in Ref. 3.

One conclusion from this analysis was that it is preferable to use the load-deflection curve of the unflawed model. This is consistent with fracture mechanics in that a nominal stress (load) in the region of the flaw but with the flaw not present is calculated. Also this avoids having to make the assumption that model and prototype behave the same to maximum normalized load even though possibly the flaws in one or the other or both have grown somewhat and similitude can really no longer be claimed.

Specimen No. 3. This was the first test performed on a large flawed tensile specimen at other than shelf temperature. The flaw was sharpened by three point bending and was grown in depth about 0.1 in. (as measured after the test). The flaw shape here was changed from that of the two prior tests. It was machined as a semicircular crack, 8 in. long and 2 in. deep.

Since K_{Ic} was known at 50°F (about $140,000 \text{ psi}\sqrt{\text{in.}}$, see Ref. 7), this temperature was chosen for the test. The equation

$$K_{Icd} = C \sigma_f \sqrt{\pi a_d \cdot s_{d,f}} \quad (1)$$

with $d = 1$ was used to make the calculation where $K_{Ic1} = 140,000 \text{ psi}\sqrt{\text{in.}}$, $C = 0.60$, and $s_{d,f} = 6$. This gave a stress at maximum load of 67,500 psi. (Note: As discussed in Paper 12 of this conference, σ_f is really not the

stress but defines the proper energy under the real load-deflection curve where the linear portion of the curve is extrapolated up to the calculated stress.) It was then concluded that between 0.2 and 0.3% strain should be obtained in the gross section at maximum load.

It is perhaps well to call attention here to the fact that this specimen as well as Specimen Nos. 4, 5, and 6 were obtained from the bottom ingot end of HSST Plate 01. In this region the proportional limits of stress-strain specimens had been found to be quite low with yield stresses as low as 52,000 psi (see page 56 of Ref. 6). With this in mind it was concluded prior to the test that adequate prediction of the load might be difficult but fair accuracy for the strain should be obtained. Also as noted in Table 1, the surfaces of Specimen Nos. 3, 4, 5, and 6 were no more than about 1.25 in. from the original surface of the 12-in.-thick plate. As shown by both Berggren⁸ and Loss,⁹ material at a depth of about 1 in. begins to differ significantly in energy absorbing capacity from center material at a temperature above 50°F.

The test results for the gross section strain varied from 0.25 to 0.305% strain. Abrupt fracture occurred at a load of 5,300,000 lb. The gross section stress was slightly less than minimum yield stress.

Specimen No. 4. This specimen was similar to Specimen No. 3 except it was tested at 100°F. Equation (1) was used to make the calculation together with the volumetric ratio energy data given in Paper 12 of this conference (see Fig. 5 of that paper). Because of the apparent material variation giving variations in yield stress behavior, a load was not predicted. However a strain of about 0.5% in the gross section was predicted.

The results from the test were surprising. The maximum load attained on the specimen was 7,500,000 lb with a gross section strain of over 3%. In other words it behaved like Specimen Nos. 1 and 2 which were tested at a 120°F higher temperature. The fracture surface, while giving the appearance of other than cleavage for the most part, exhibited shear lips of significant size only in the regions where the flaw reached the surface. The prediction was low by around a factor of six in energy. The reason for this discrepancy is discussed in more detail in the next section.

Specimen No. 5. The test temperature of this specimen was chosen at 75°F so as to investigate further the transition behavior. This is the first specimen in which the flaw was sharpened by local fatigue as described in Paper No. 21 of this conference (the flaw was grown about 0.5 in. in depth as revealed after the test). The prediction, somewhat cautiously made, was that fracture should occur between 0.2 and 0.3% strain. Indeed such was the case with the gross section strain being about 0.2% strain for three gross section gages and 0.33% strain for a fourth.

Specimen No. 6. This specimen was selected to initiate a flaw size study, the flaw being prior to fatiguing 9 in. long by 3 in. deep. The machined flaw was also sharpened by local fatigue to about 0.4 in. additional depth as measured after the test. The test temperature was 100°F. The strain predicted for maximum load was between 0.4 and 0.6%. Fracture occurred at a surprisingly low load (4,700,000 lb). The gross section strain varied between 0.3 and 0.6%.

Specimen No. 7. On the basis of test results alone it was difficult to explain the very tough behavior of Specimen No. 4. It was then decided to test this specimen at 100°F. The flaw machined to 8 in. long and 2 in. deep was grown about 0.4 in. by local fatigue. The same prediction as made for Specimen No. 4 was applied to Specimen No. 7; that is a gross section strain of about 0.5% was predicted. Flat fast fracture occurred at a load of 7,100,000 lb. The gross section strain varied between 0.58 and 0.87% strain. The prediction was somewhat low; however, as observed in Fig. 5 of Paper 12 of this conference no prior 6-in.-thick specimens had been tested at 100°F before Specimen Nos. 4, 6, and 7.

Specimen No. 8. This was the first of the 6-in.-thick flawed transverse tensile specimens. Since Specimen No. 8 was from the same plate and the same general region as Specimen No. 7, the obvious test temperature was 100°F. No prior transverse specimens had been tested near the temperature except the standard tensile, dynamic tear, and Charpy impact specimens. The impact specimen energies indicated a definitely lower energy absorbing capacity for transverse orientation. No prediction was attempted but it was expected that this specimen would fail at a lower maximum load and gross section strain than Specimen No. 7. Such was the case. The

specimen failed at a load of 6,800,000 lb with a gross section strain of from 0.37 to 0.45%. The fracture surface was flat and identical to that of Specimen No. 7.

Specimen No. 9. The test temperature chosen for this transverse specimen was 220°F. It was practically identical with Specimen No. 8. Again no transverse specimen in comparable thickness had been tested near the selected test temperature. However it had been pointed out some 18 months before that the transverse dynamic tear data on 6-in.-thick class 2 plate tested at shelf temperature (see Ref. 9) appeared to exhibit a considerably greater size effect than the longitudinal data on the HSST 12-in.-thick class 1 plate. Since Specimen Nos. 1 and 2 were also from Plate 03, one would expect this specimen to behave similar to them but exhibit lower maximum load and gross section strain. Using only the ratio of longitudinal to transverse impact data from 1-in.-thick dynamic tear specimens tested at around 200°F to calculate a minimum transverse size effect for 6-in.-thickness of about 3.7, the author applied the same technique as that applied to Specimen Nos. 1 and 2. The analysis indicated a gross section strain of less than 2% and a load of less than 7,300,000 should be forthcoming in the actual test. The maximum load reached was 6,685,000 lb with a gross section strain of between 0.92 and 1.13%. The fracture surface exhibited large shear lips but not as large as Specimen Nos. 1 and 2. Most surprising in the test was the gross section strain. However the behavior was consistent with the transverse behavior for the dynamic tear specimens as noted above. The volumetric energy ratio for this specimen when compared with a 1-in.-thick model (not yet tested) will probably be between 4 and 5.

Specimen No. 10. This specimen was identical with Specimen Nos. 8 and 9. It presented an especially interesting challenge since Specimen No. 9 was fractured at 7:50 pm one evening and the test temperature for Specimen No. 10 had to be chosen before 6 am the next morning.

Interesting data for an analysis were on hand. Specimen No. 8 failed in flat fracture at 100°F with a gross section strain of less than 0.5% and a load of 6,800,000 lb. Specimen No. 9 failed in shear fracture at 220°F with a gross section strain of about 1% and a load of 6,685,000 lb.

It was decided to select a temperature on the basis that a gross section strain of 0.75% was desired. The following analysis was performed. By using the load deflection curve for Specimen No. 9 and the longitudinal load deflection curve for the 1-in.-thick model specimen performed prior to the test of Specimen No. 2, a volumetric energy ratio of 10.05 was found. Using the longitudinal to transverse energy ratio for the 1-in.-thick dynamic tear specimen of 1.33, a volumetric energy ratio of 7.5 was determined necessary to give the 0.75% strain. Next the curve shown in Fig. 11 was established using Fig. 15 of Ref. 3 as a guide. A size effect of 7.5 occurs at about 130°F and this was selected as the test temperature. The maximum load to fracture was predicted to be between 6,550,000 and 6,650,000 lb. The actual maximum load to fracture was 6,650,000 lb. Readings were made at this load three times (after each reading the load had dropped at least by 50,000 lb). The gross section strains on the first reading were between 0.62 and 0.69%, on the second, between 0.69 and 0.76% and on the third, between 0.75 and 0.83%. A fourth attempt to reach the maximum load was unsuccessful. The specimen exhibited a somewhat tough behavior with shear lips appearing on the edges of the crack near the surface. Failure occurred well after maximum load was reached. It is interesting to note that longitudinal Specimen No. 7 tested at 100°F failed in flat fracture at about the same strain as this specimen and at a higher load.

Evaluation of the Predictions

As noted previously it is not the objective of this paper to evaluate the significance of the large tensile tests but rather to evaluate the method of predicting the fracture behavior of the specimens per se. We must bear in mind that in general the only volumetric energy ratio data available to perform the analyses described in the previous section have been either from compact tension specimens or dynamic tear specimens. In a sense then the comparison bears directly on the applicability of the equivalent energy method. In particular it assesses the tentative conclusion reached in Paper 12 of this conference that the volumetric energy ratios depends substantially on thickness and temperature and to a much

Fig. 1. Results of Analysis for Selecting Test Temperature on Transverse Tensile Specimen No. 10.

less degree on geometry and method of loading. Another way to state the proposition is to ask if fracture, as a function of nominal stress (load), temperature, and flaw size can, in general, be expressed by Equation (1) with the two independent parameters C and $s_{d,f}$. The parameter $s_{d,f}$ accounts for thickness effects alone. C accounts for the geometry (flaw size and shape, etc.) and loading conditions and is the same quantity as used in linear elastic fracture mechanics.

Direct calculations may be made. In Table 2 we have the basis for performing the fracture calculations. The volumetric energy ratio data ($s_{1,6}$) is taken directly from Fig. 5 of Paper 12 of this conference. The

Table 2. Parameters for Calculating
Energy to Maximum Load
 K_{Ic1} at 220°F: 280,000 psi $\sqrt{\text{in.}}$
 C : 0.64

Temperature (°F)	a_1 (in.)	$s_{1,6}$
50	0.36	40
75	0.42	28
100 (A)	0.35	18
100 (B)	0.56	18
100 (C)	0.40	18
220	0.39	2.35 to 3.1.

shape factor C was calculated from the unnotched load deflection curve of a 1-in.-thick model tested at 200°F (see Fig. 4 of Paper 12 of this conference). The value of C given is probably sufficiently accurate for all the flaw depths and shapes except the large flaw which was 3.4 in deep. Since it is not known where on the unnotched load-deflection curve of the model such a flawed specimen would reach maximum load, the same value of C was used for the large flaw as for the smaller ones. One could speculate that on a 1-in. model the net section always reaches ultimate load and then establish maximum load points on the unnotched load-deflection curve for each flaw configuration. Randall's data⁶ supports this procedure but C 's determined in such a manner were not available for this paper.

Using the parameters given in Table 2 we see in Table 3 a comparison for calculated energies with the experimentally determined energies. A plot of the results is given in Fig. 2. The calculated and experimental energies are seen to compare quite well with two exceptions, both occurring at 100°F. The experimental results marked C from Specimen No. 7 are somewhat higher than calculated. The implication here is that the volumetric energy ratio of 18 is probably in error. As mentioned previously no prior specimens of thickness 6 in. or greater had been tested at 100°F except a 12-in.-thick dynamic tear specimen. The energy from that one test is the basis for the interpreted value in Fig. 5 of Paper 12 of this conference. However, Witt and Berggren³ found that this 12-in.-thick specimen alone exhibited a measured energy of at least 25% lower than calculated by their proposed energy model. A volumetric energy ratio of about 10 would give the average experimental energy for Specimen No. 7. A 6-in.-thick longitudinal compact tension specimen is scheduled for testing in the near future and should help resolve this difference.

It is not expected that the discrepancy in the predicted and experimental results of Specimen No. 4 [denoted by (A) in Fig. 2] will be satisfactorily resolved. There are several possible reasons for the discrepancy. First one surface of the specimen was within 1.25 in. of the original surface of the 12-in.-thick plate and the machined flaw was placed in the specimens from that side. As shown by Berggren⁸ and Loss⁹ (see Fig. 7 of Ref. 9) material 1 in. from the surface has around 50% more energy absorbing capacity at 100°F than center material. In fact 100°F is near shelf behavior at 1 in. from the surface.

One may ask why single out Specimen No. 4 for the anomaly when Specimen Nos. 3, 5, and 6 were practically identical. Specimen Nos. 3 and 6 had their flaws machined from the side opposite that of Specimen No. 4. Thus the whole flaw resided in center material. Specimen No. 5, while having its flaw on the same side as Specimen 4, was tested at 75°F where the difference in energies for material 1 in. in from the surface and center material is smaller and almost within the data scatter. One could well anticipate (and as verified by the results from Specimen No. 7) that had the flaw been on the other side of Specimen No. 4, flat fracture would have been obtained.

Table 3. Comparison of Calculated and Experimental Energies

Specimen No.	Test Temperature (°F)	a_1 (in.)	$a_{1,6}$	Calculated		Experimental Results, E^a (in.-lb/in. ³)	
				σ_6 (psi)	E^a (in.-lb/in. ³)	Average	Range
3	50	0.355	40	67,500	82.3	79	53-101
5	75	0.416	28	75,000	101.5	76	56-128
4	100 (A)	0.35	18	101,000	183	1140	
6	100 (B)	0.563	18	80,000	116.5	118	78-240
7	100 (C)	0.40	18	92,400	143	260	150-295
2	215	0.396	2.3-3.1	234,000-269,000	960-1260	1150	

^aEnergy to maximum load under the unnotched and normalized load-deflection curve.

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Fig. 2. Comparison of Test Results from Flawed Tensile Specimens with Predictions Using Equivalent Energy Method.

The few thousand pounds per square inch difference in yield and ultimate stresses between material 1 in. in from the surface and center material in Specimen No. 4 could also be a significant factor in the behavior under discussion. If the effect was minimal then one would expect that the results from a longitudinal specimen tested at say 130°F (as was the transverse Specimen No. 10) would duplicate the behavior for Specimen No. 4, thus indicating a very rapid transition in this temperature interval.

The difference in flaw preparation could account for some or all of the apparent anomalous behavior of Specimen No. 4. The flaw in Specimen No. 4 was grown by fatigue in three point bending and was very minimal (about 0.1 in.) in growth at maximum depth. The same could be said for Specimen No. 3. In Specimen Nos. 5, 6, and 7 the flaw was grown between 0.4 and 0.5 in. at maximum depth by local fatigue. Here again it is difficult to say definitely what the effect would be except to remark that insufficient flaw sharpness usually leads to tougher behavior.

A remark about the behavior of the specimens prior to maximum load may give further insight. By direct observation on some specimens the tips of the flaws on the surface of the specimen always grow (open up) about 1/8 to 1/4 in. If the growth is straight, flat fracture is imminent; if however the growth terminates in a dimple, tough behavior with mixed or shear mode fracture follows. This indicates that where observations were made the flat fractures obtained from the tests are not the propagating type so much as their being driven by the load. In fact Specimen No. 6 which contained the large flaw and was tested at 100°F exhibited a pop-in. The specimen actually sustained a load of about 4,500,000 lb but with the flaw increased in maximum depth to 4.25 in. The fracture was still flat.

In Table 3 one observes a considerable variation in the experimental energies. This invariably results from the gross section gage behaviors as maximum load is approached. Often strain from a single gross section gage lags or leads the strain from the remaining three gross section gages as yielding (nonlinearity) occurs. The ranges in Table 3 result from all the functioning gross section gages. As an example the factor of about two in energy for Specimen No. 7 really reflects a difference in strain

to maximum load of from 0.58 to 0.87% strain. In this sense it is perhaps well to note that, by assuming one had in hand the actual load-deflection curve or at least knew the yield load on the specimen, the maximum load to fracture is well approximated by the calculated energies in all instances except one. The exception of course is the analysis of Specimen No. 4. The accuracy probably increases as toughness increases.

Conclusions

The object of this paper has been to compare in so far as possible an analysis of fracture behavior of the flawed tensile specimens with the experimental results. A combination of lack of pertinent data together with different flaw sizes and property variations has made the task somewhat difficult. Essentially it has been shown that the volumetric energy ratio curves from compact tension specimens, where data are available, compares with a similar curve for the large flawed tensile specimens. Data at 100°F and above is lacking for both the longitudinal and transverse orientation however. It is therefore somewhat speculative to say at this time that the satisfactory comparison shown is conclusive.

The accuracies with what the predictions have foretold the specimens' behaviors are certainly more than fortuitous and demonstrate a practical understanding of thick section fracture behavior. It is perhaps well to note that it is the generality of the equivalent energy method that is being explored and not really the method itself. If the volumetric energy ratio curve for compact tension specimens should prove to coincide with the corresponding curve for the tensile specimens or at least not be unduly conservative, then the practical application of the equivalent energy method is well on the way to being established. If in addition the volumetric energy ratio curves for 1-in.-thick compact tension specimens, 1/6 scale model tensile specimens and 1-in.-thick pressure vessels should all coincide, one may generalize the applicability of this method to pressure vessels in a very practical way. Whether such generality is possible or conservative will be forthcoming from tests which are scheduled for performance within the next six months.

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