Performance Report

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Nuclear Power Plant Life Extension Using Subsize Surveillance Specimens

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SUMMARY

Life extension of the existing light water reactors will require a comprehensive database on the effects of neutron irradiation on the embrittlement of pressure vessels. In order to assess the embrittlement, a large number of full size (5.5 x 1 x 1 cm) Standard Charpy (ASTM Standard E 23) surveillance specimens must be irradiated in limited reactor spaces. Such irradiations invariably introduce significant variations in temperature and neutron flux across the specimens. The use of subsize surveillance specimens is proposed to circumvent the difficulty. The choice of subsize surveillance specimens, however, necessitates the need for methodologies for the prediction of the upper shelf energy (USE) of full size Charpy V-notch specimens based on subsize data.

The empirical correlation methodologies published earlier for predicting the USE of full size Charpy specimens based on subsize test data appear to work satisfactorily for either highly ductile

materials (USE > 200 J) or relatively brittle materials (USE << 100 J). However, the USE of current reactor pressure vessel (RPV) materials of nuclear power plants generally decreases from about 150 J at the beginning of irradiations to less than 100 J at the end of operating life. A methodology is proposed here that works well in predicting the USE of full size specimens based on subsize data for RPV materials in both unirradiated and irradiated conditions. The methodology uses partitioning of the USE into two components, USE_i and USE_p. USE_i is the macro-crack initiation energy and is defined as the energy required to initiate a crack across the width at the notch-root of the Charpy specimen. USEp is the crack propagation energy of the macro-crack till complete fracture of the specimen occurs.

USEp of full size specimens is determined by a dynamic Finite Element Modeling technique and uses subsize precracked Charpy specimen test data, and the tensile behavior of material. USE_i is a small fraction (<20%) of the USE and is estimated based on the fractional decrease in the USE_i of subsize specimens due to irradiation.

1. Introduction

Subsize Charpy V-notch specimens have been proposed as a reasonable alternative to the ASTM standard full size Charpy specimens for the surveillance of nuclear reactor pressure vessels (RPV). The choice of subsize Charpy specimens would permit the placement of a sufficiently large number of specimens near the RPV for the purpose of monitoring its embrittlement throughout its lifetime. For example, if third size specimens were to be used, twenty seven specimens could be placed in the same volume as a single full size Charpy specimen. The choice of subsize specimens would not only increase the number of surveillance specimens that could be placed near the RPV, but it would also increase the uniformity of temperature and neutron fluence among the surveillance specimens. Furthermore, broken halves of irradiated full size specimens can be machined to fabricate subsize specimens which can be reinserted into the vessel for continued surveillance at higher fluences.

The choice of subsize surveillance specimens necessitates the need for the development of methodologies for the prediction of the upper shelf energy of full size Charpy V-notch specimens based on subsize data. Numerous investigations have been carried out in the past to develop such methodologies [1-18] .

These methodologies, however, are not applicable at all ductility levels of irradiated RPV materials. As the Upper Shelf Energy (USE) diminishes from a high value (~200J) to a low value (<100J), three different methodologies have been found to be successful in correlating the USE of full and subsize specimens in different regimes of ductility.

The simplest of these methodologies is applicable at high ductility levels (USE >200J). In this technique, normalized USE is defined as the ratio of the measured value and a normalization factor Bb^2 [1,2] or $(Bb)^{3/2}$ [3,4], often referred to as the fracture volume. The normalized values of USE are equal for full and subsize Charpy specimens [1-4,7]. It is important to note that the normalization factor is independent of the span and the notch geometry, including the notch angle, notch depth, and the notch root radius. It is believed that blunting of the crack tip during macro-crack initiation and crack propagation makes the effects of span and notch geometry on USE negligible for highly ductile materials.

A more complicated situation arises when the USE falls below 100J. RPVs during the latter half of their life are expected to attain such low values of USE. Kumar and co-workers [5,6,8-

10] have shown that the USE normalized by a factor equal to $(Bb^2)/(S^*K_t')$ is equal for full and subsize specimens. Here S is span and K_t' is a modified stress concentration factor. K_t' is equal to the product of the elastic stress concentration factor at the notch root (K_t), and the plastic constraint (Q) [19]. Q is equal to $(1+\pi/2-\theta/2)$, where θ is the notch angle in radians. It is to be noted that at the low value of USE the blunting of the crack tip is relatively small and the effects of span and the stress concentration factor on crack initiation and propagation are significant.

For reactor pressure vessel materials (USE~150 J), there does not appear to be a clear consensus on the choice of a single normalization factor. For some materials, the normalization factor of Louden et al. [7] works well. While for some other materials, the normalization factors used by Corwin et al. [1,2] and Lucas et al. [5,6] works well [8].

A methodology is proposed here that works well for pressure vessel materials in both unirradiated and irradiated conditions and uses partitioning of the USE into two components, USE_i and USE_p. USE_i is the macro-crack initiation energy and is defined as the energy required to initiate a crack across the width at the notch-root of the Charpy specimen. USEp is the crack propagation energy of the macro-crack till complete fracture of the specimen occurs.

USEp of full size specimens is determined by a dynamic Finite Element Modeling technique and uses subsize precracked and notched Charpy specimen test data, and the tensile behavior of material. USE_i is a small fraction (<20%) of the USE and is estimated based on the fractional decrease in the USE_i of subsize specimens due to irradiation.

The work presented was undertaken to elucidate the dependence of crack propagation energy in precracked specimens (USE_p) on ligament size, and to predict the USEp of full size specimens based on subsize data. Dynamic Finite Element Modeling (FEM) using a computer code ABAQUS Explicit of the fracture of full (1.000 x 1.000 x 5.400 cm), half (0.500 x 0.500 x 2.360 cm), medium (0.400 x 0.400 x 2.360 cm) and third size (0.333 x 0.333 x 2.360 cm) specimens was performed. USE_p determined by FEM was compared with the experimental data. Except for one isolated data point for a half size specimen, all experimental values agreed with the calculated values using FEM.

For the full size Charpy specimen, the span was 4.600 cm. This span was chosen so that the specimens could be tested in an existing machine. The span is larger than 4.0 cm as prescribed in the ASTM Standard E23 for full size specimens. However, it has been shown by FEM that the effect of a longer span would have little effect on the upper shelf energy.

For all subsize specimens, the span was 2.000 cm. In addition, one set of half size specimens (0.500 x 0.500 cm) with full length of 5.400 cm and full span of 4.600 cm were also examined. For all five specimen geometries, four different precrack depths i.e. 30%, 40%, 50%, and 60% of the full width (W) of the corresponding specimen were modeled. The experimental data for comparison were available for precrack depths that were 42%, 52% and 68% of W. A comparison was made between the experimental values and the best fit of the FEM data. A reasonable agreement was achieved in most cases. Having achieved confidence in the FEM analysis, the USEp of full size specimens were predicted based on subsize USEp data using FEM.

USEi of full size irradiated specimens was estimated to be equal to the unirradiated value reduced by a factor equal to the ratio of the subsize unirradiated and irradiated values. It is important to note that USEi is always less than 30% of USE. Therefore, a reasonable estimate of USEi serves well in predicting the crack initiation portion of USE.

2. Experimental procedure

The specimens used for the experimental data were machined from A533B HSST Plate 02 material in the L-T orientation. The material was obtained from Dr. R.K. Nanstad of Oak Ridge National Laboratory. The full size upper shelf energy of a standard Charpy V-notch specimen (ASTM Standard E23) is 152 J. The fatigue precracking and Charpy impact testing of the specimens were performed according to the procedures published by Kumar et al. earlier [15].

Dimensions for both full and subsize specimens are given in Fig. 1. Except for the span the full size specimen dimensions are in accordance with ASTM standard E23. The span for the full size specimens was set at 4.6 cm in the present study. While there are no standards available for subsize specimens, the dimensions used in this study for half and third size specimens are similar to those used in other investigations [1-10]. It is to be noted that the lengths of both half and third size specimens were equal to 2.36 cm. The span for both kinds of specimens was also equal and was set at 2.0 cm.

Half of the specimens of each size were fatigue-precracked according to the procedure described below. Both notched-only and precracked specimens were irradiated to 0.5 x 10^{19} n/cm^2 (E>1 MeV) at 290 °C in the University of Virginia Research Reactor irradiation facility.

2.1. Precracking

Precracked specimens were prepared by loading the notched specimens in a three point bend arrangement and subjecting them to an oscillating load (15 Hz) in a closed loop hydraulic system. The minimum and maximum loads for the oscillations were determined in advance according to ASTM standard E399 modified for miniature specimens. The maximum loads at the start of the precracking were approximately 550 kg, 180 kg, and 60 kg for full, half, and third size specimens, respectively. The load was reduced every time the crack progressed approximately 250 microns. The minimum loads were maintained at one-tenth of the maximum load during the precracking process. To precrack to the desired lengths it took approximately 100,000 cycles for full size and approximately 30,000 cycles for half and third size specimens. In every case the remaining ligament size of precracked specimens was half the width of the notched specimen.

2.2. Charpy impact testing

All the specimens were tested in the same instrumented drop tower utilizing an anvil with two test locations for the two specimen lengths and a moveable striker. Note that the half size and third size specimens have the same length. Data from each test were recorded on a digital oscilloscope and transferred to an IBM PC AT for storage and analysis.

Two load cells (4,500 kg for full-size and 1,600 kg for subsize) were used to increase the sensitivity over the lower load ranges that were relevant to the subsize specimens. Both load cells were calibrated to ensure that their response was linear over the desired range.

The impact velocity of the crosshead (V_o) was measured for each specimen by attaching a flag of known dimension to the crosshead positioned so that the flag passed an infrared sensor just prior to impact, causing a change in voltage during interruption by the flag. The duration of this change was measured on the oscilloscope and the velocity calculated. V_o was determined as the average of at least 5 calibration runs, conducted periodically throughout during testing. The energy integrated from the load-time curve during testing and the initial kinetic energy of the crosshead are used to calculate the energy absorbed by the specimen during fracture. The procedure is illustrated in the next section.

Temperature control for all specimens was accomplished in a conditioning chamber where elevated temperatures (50 °C - 350 °C) were attained with a heated stream of argon or helium. Temperature control was achieved by adjusting the rate of gas flow into the conditioning chamber. Independent temperature calibrations were performed for each specimen size; two to four thermocouples were attached at various locations along the length of the specimen to quantify the variability in temperature. Each specimen was kept at the test temperature for a sufficient amount of time prior to testing to ensure temperature stabilization. Low temperatures (-150 °C - 0 °C) were achieved by chilling the specimens by cold nitrogen gas to a temperature about 50 °C below the desired temperature. The specimen was then allowed to warm up to the desired temperature in the enclosed testing area.

Specimen placement was achieved by pneumatically driven pistons that moved the specimen from its initial position, into the conditioning chamber, and out of the chamber onto a positioning arm. A stepping motor was used to rotate the arm, dropping the specimen into the appropriate position on the anvil for testing. The elapsed time between the exit of the sample from the conditioning chamber and the impact was 1 - 2 seconds.

3. Determination of actual absorbed energy in Charpy impact tests

The relationship between the apparent absorbed energy, E_a, and the actual absorbed energy, E, in a drop tower Charpy impact test is given as [12]:

$$E = E_a(1 - E_a/4E_0)$$

where E_a is the energy obtained from the load-time curve $\{= V_0 \int_0^T P(t)\,dt\}$, P(t) is the load at time t, T is the duration of the test, V_0 is the velocity at impact, and

$E_0 = \frac{1}{2} m V_o^2$, m is the mass of the cross-head.

4. Fracture model development

The crack propagation energy (USE_i) was determined by modeling fracture in precracked Charpy specimens. All modeling of the Charpy specimens and impact test was conducted using a dynamic explicit-integration finite element code, ABAQUS Explicit, from the HKS corporation [20]. Two HP 9000-715/75 workstations were used to run the code. Depending on specimen geometry and mesh refinement, a typical simulation of the Charpy impact test could take from 3 to 40 hours of CPU time.

4.1. Explicit dynamic analysis using ABAQUS

ABAQUS Explicit uses a dynamic analysis procedure which implements an explicit integration rule with the use of diagonal mass matrices [20]. The equations of motion are integrated using the explicit central difference integration rule:

$$\dot{J}^{i+\frac{1}{2}} = \dot{J}^{i-\frac{1}{2}} + \frac{\Delta t^{i+1} + \Delta t^{i}}{2} \ddot{J}^{i}$$

$$J^{i+1} = J^{i} + \Delta t^{i+1} \dot{J}^{i+\frac{1}{2}}$$

The superscript (i) refers to the increment number. The central difference integration is explicit in that the kinematic state may be advanced using known values of $\dot{J}^{-1/2}$ and $\ddot{J}$ from the previous increment. In order to increase computational efficiency, ABAQUS uses diagonal element mass matrices. The accelerations at the beginning of the increment may be computed by:

$$\ddot{J} = M^{-1} \times (F^{i} - I^{i})$$

Where ***M*** is the diagonal lumped mass matrix, ***F*** is the applied load vector, and ***I*** is the internal force vector. The code integrates through time using many small stable time increments. The time incrementation scheme in ABAQUS is fully automatic and requires no user intervention. The use of small increments (directed by the stability limit) is advantageous in that it allows the solution to proceed without iterations and without requiring tangent stiffness matrices. The explicit procedure is ideally suited for analyzing high speed dynamic events like those found in Charpy impact testing.

Assuming that the stable time increment does not change drastically during the analysis, the cost in CPU time for an explicit dynamic analysis is related to the size of the mesh in the following manner:

$$\text{Cost} \propto N \frac{T}{\Delta t}$$

Where N is the total number of elements in the mesh, T is the duration of the event, and t is the stable time increment size. The stable time increment decreases exponentially with decreasing element size. Therefore, the total CPU cost usually increases linearly with the number of elements in the model, and exponentially with the refinement of the mesh.

4.2. ABAQUS failure model

ABAQUS Explicit contains an elastic-plastic material model which allows the modeling of crack growth by deleting elements from the mesh. ABAQUS treats crack initiation and growth by calculating a space-averaged strain and then deleting elements in the mesh when any element reaches an input defined plastic failure strain (ε_f^{pl}). In order for this deletion of elements to produce stable results, the stress state of the damaged element must be reduced to zero by the time of failure. ABAQUS accomplishes this by applying a damage level to the material prior to failure. This damage parameter is used to degrade the stress state as well as the elastic moduli. The damage value of any element is zero until the strain in the element exceeds a user defined offset failure strain (ε_0^{pl}). The damage in an element can range from zero (no damage) to one (failed) and is calculated from the equivalent plastic strain as follows:

$$\text{DAMAGE} = D = \frac{\varepsilon^{pl} - \varepsilon_0^{pl}}{\varepsilon_f^{pl} - \varepsilon_0^{pl}}$$

At each increment, the equivalent plastic strain (ε^{pl}) is obtained and damage is assessed using the above equation. Damage may not be removed from an element; and when the damage reaches a value of one, the element is deleted from the mesh and a crack is formed or extended.

4.3. User defined material model

When modeling Charpy impact tests using the ABAQUS material failure model, a fundamental problem with the crack propagation is observed [21]. ABAQUS only determines the magnitude of plastic strain in an element relative to the failure criterion. This allows cracks to initiate and propagate under tensile or compressive constraints with identical failure criterion. In order to correct this problem, a user defined Fortran subroutine is used to model the material constituent equations and hence model failure. This routine is called by ABAQUS instead of the normal material model. The routine uses the same mechanism for modeling crack initiation and propagation as the ABAQUS model with the exception of when the damage factor is incremented. A deviatoric stress given by

$$\sigma_{mean} = \frac{1}{3}(\sigma_{11} + \sigma_{22} + \sigma_{33})$$

is used to determine if an element is under tensile or compressive loading. If the value of σ_{mean} is positive then damage is allowed to increase in that increment. If σ_{mean} is negative or zero then no further damage can result.

This user defined material failure model accurately models the fracture of a Charpy specimen under impact. The model has been tested and benchmarked against the ABAQUS Von Mises plasticity material model [21].

4.4. Benchmarking

In order to obtain confidence in both, the elastic response of the user defined material failure model, and the ABAQUS finite element model which included initial and boundary conditions, a simple, low-velocity bar impact was modeled. Because an analytical solution for the maximum deflection in a simple bar is easily obtained, comparison of analytical and ABAQUS results would allow benchmarking of the model.

The analytical solution for a full size un-notched specimen under 3-point elastic impact loading was developed using a conservation of energy approach. If gravitational forces on the striker and bar are neglected, the kinetic energy of the striker prior to impact can be related to the strain energy stored in the elastically bent specimen. The maximum Center Load-Line Displacement (CLLD) of the bar can be given as a function of striker velocity. From small-displacement elastic theory, the displacement as a function of static load is given by:

$$\Delta = \frac{PL^3}{48EI}$$

Where E is Young's modulus of the material and I is the moment of inertia of the specimen. The energy balance equation is written as:

$$U_k = U_e$$

$$\frac{1}{2}mv^2 = \frac{1}{2}P\Delta_{max}$$

The above two equations are combined to give the maximum CLLD as a function of striker velocity.

$$\Delta_{max} = \sqrt{\frac{mv^2L^3}{48EI}}$$

The maximum displacement is linear with respect to striker velocity. The only assumptions used are that inertial effects in the bar are neglected, the striker is modeled as a rigid body, and the striker remains in contact with the specimen until maximum deflection is reached.

To simulate the elastic impact of a full size specimen, the striker was given a mass of 1 kg. The impact velocity of a rigid striker was varied from 10 cm/s to 150 cm/s and modeled using ABAQUS. A comparison of the results of maximum CLLD vs. striker impact velocity with the analytical elastic solution is given in Fig. 2. When the impact velocity reaches around 70 cm/s, the maximum stress in the bar at maximum CLLD exceeds the yield limit, thus moving into the plastic deformation regime. Before reaching this point, ABAQUS results agree with the elastic solution. As would be expected, the ABAQUS results diverge from the elastic solution as the impact velocity is increased beyond 70 cm/s.

4.5. Charpy impact modeling

A dynamic finite element model of the Charpy impact test in which fracture initiation and propagation to complete failure was performed. Both 2D half-symmetry and 3D quarter-symmetry models of the striker, pre-cracked Charpy specimens, and anvil were constructed using the codes IDEAS-SDRC and ABAQUS. Models for full (1.000 x 1.000 x 5.400 cm), half (0.500 x 0.500 x 2.360 cm), half-2xL (0.500 x 0.500 x 5.400 cm), medium (0.400 x 0.400 x 2.360 cm), and third (0.333 x 0.333 x 2.360 cm) size specimens have been made for several USE materials. A study of finite element mesh schemes and coarseness was used to develop a stable and reliable model of the Charpy impact test [21]. The striker and anvils were modeled using rigid bodies. An illustration of the mesh for a full size specimen is given in Fig. 3. An area (or volume for 3D) around the crack plane has been refined as well as an area around the anvils. In order to save computing cost, the elements in the extremities of the specimen were left relatively coarse. The effect on USE of not refining the entire specimen is negligible. It was found that if the Charpy impact was modeled using conventional impact energies (around 200J), the computational time was excessive. In order to speed up the simulation and therefore save CPU time, a high energy impact on the order of 80,000 J was used. Fig. 4 illustrates the effect of increasing the impact energy on the USE of a third size, medium USE specimen. It can be seen that with a difference of only 8.5% in USE, a savings of 69 hours of CPU time on an HP9000-715/75 can be made.

The material properties for A533B HSST Plate 02 were obtained from the EPRI report (NP-933) Nuclear Pressure Vessel Steel Data Base [22]. Ramberg-Osgood constants for a true stress-strain curve were obtained from Haggag [23]. An initial bi-linear stress-strain relation for A533B with a failure strain of around 30% was made. This 30% failure strain was chosen with the knowledge that the local failure strain would be higher than the EPRI 2 in. gauge length failure strain (~24%). The offset failure strain was then chosen at 10% less than the failure strain. It was found that the model becomes unstable if the difference between offset and failure strain is less than 5%. The USE of a full size specimen (precracked to 40% width) calculated by ABAQUS was compared to the corresponding experimental value of 35.5 J. The failure and offset strains were then shifted to calibrate the ABAQUS model with experimental data. It was found that the failure strain needed to be increased to 50%. This calibrated medium USE material stress-strain curve is shown in Fig. 5.

Fig. 6 shows the upper shelf energy (USE_p) of full size precracked Charpy specimens as a function of ligament size. The ABAQUS FEM material stress-strain curve was calibrated at a ligament size of 0.4 cm. USE_p for three more ligament sizes (0.5, 0.6 and 0.7 cm) were then calculated using ABAQUS. A curve of the form mb^n was fit through the four data points. m and n are fitting parameters and b is the ligament size. The value of m and n were 202.0 and 1.90 for the best fit, with a correlation factor of 0.9992. It is worth noting that the value of n is quite close to 2. Fig. 6 also shows the experimental data of USE_p measurements of full size specimens with ligament sizes equal to 0.40, 0.48, and 0.64 cm. The scatter in the experimental data around the mean value is shown by a vertical band. The experimental data are in excellent agreement with the best fit curve.

Fig. 7 shows the calculated and experimental data for USE_p of half size specimens (0.500 x 0.500 x 2.360 cm). The best fit curve through the calculated data for USE_p of specimens with ligament sizes of 0.21, 0.26, 0.30, and 0.34 cm is represented by the form 57.0 $b^{1.55}$. The first two experimental data points (b = 0.21 and 0.26 cm) are in reasonable agreement but the third experimental data is substantially away from the curve. Additional experiments and ABAQUS calculations are in progress to ascertain the reasons for this discrepancy. The discrepancy is particularly puzzling since the ABAQUS calculations and experimental data are in excellent agreement for half size-2xL specimens (0.500 x 0.500 x 5.400 cm), as shown in Fig. 8.

Fig. 9 shows the dependence of the USE_p of third size (0.333 x 0.333 x 2.360 cm) specimens on ligament size. The computed values can be best fit by the expression 44.8 $b^{1.66}$. The ligament size dependence of USE_p of third size specimens increased slightly from that of the half size specimens. The experimental values are consistently lower than the calculated data by about 5%.

From the foregoing analysis, it is quite clear that the ligament size dependence of full size and subsize specimens is not the same. The dependence increases from a value of approximately 1.6 for subsize to 1.9 for the full size specimens.

The good agreement between the calculated and experimental data makes it possible to predict the crack propagation energy (USEp) of full size specimen based on subsize data.

4.6 Macro-crack initiation energy

The macro-crack initiation energy (USEi) is the energy required to initiate a macro-crack through the thickness of the specimen at the notch-root of the Charpy specimens. USEi is normally a small fraction (<30%) of USE. Due to the impracticality of fabricating Charpy specimens with shallow fatigue precracks (20% width) with flat vertical faces, particularly for third and half size specimens, all irradiated specimens were precracked to 50% of the specimen width. (Unlike unirradiated specimens, if the fracture surface of a tested Charpy specimen is found to be wavy it would mean a loss of the specimen and no replacement of the irradiated specimen could be obtained without waiting for at least another year and with a prohibitive cost.) Both USEp and USEi for irradiated specimens, therefore, had to be estimated from the absorbed energy of specimens precracked to 50% of the width.

4.7 Prediction of the full size upper shelf energy

The full size upper shelf energy of irradiated specimens can be predicted by adding the USEp and USEi values. USEp is predicted using the finite element analysis based on subsize test data by a procedure similar to the one described in Section 4.5, except that the calibration point now is the crack propagation energy of the precracked subsize specimen.
The unirradiated USE of the full, half, and third-size specimens in both notched-only and precracked (50% width) conditions are given Table 1. The corresponding irradiated data (0.5 x 10^{19} n/cm^2, E>1MeV) are shown in the Table 2. Measured value of the crack propagation energy (precracked to 50% width, ligament size = 0.166 cm) of the third-size irradiated specimen is 2.05 J. The USEp of the third-size specimen (ligament size = 0.282 cm) using FEM is determined to be 4.94

J. Furthermore, using FEM the calculated value of the USEp of full-size irradiated specimen is 122.2 J.

The USEi of the irradiated full-size specimen is estimated by a reduction of the full-size unirradiated USEi by a factor equal to the ratio of the USEi of unirradiated (2.67 J) and irradiated third-size specimens (2.46 J). Since the USEi of full-size unirradiated specimen is 19.8 J the irradiated value of full-size USEi is 18.2 J.

Adding the values of USEp and USEi gives 140.4 J as the value of irradiated full-size USE. This compares well with the measured value of 133.4 J.

<u>Application of FEM technique to other test data</u>

The above technique of determining the USE was applied to another irradiated material, Weld 72 W with good success. Fig. 10 shows that USE of both full and half size irradiated precracked specimens, as calculated by FEM using third size test data, are in good agreement with the experimental data.

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TABLE 1: Upper Shelf Energy (USE)
A533B HSST Plate 02D
(Non-Irradiated)

	FULL SIZE		HALF SIZE		THIRD SIZE	
	NOTCHED	**PRECRACKED**	**NOTCHED**	**PRECRACKED**	**NOTCHED**	**PRECRACKED**
SPECIMEN ID	N37-N50, N73 (15 tested)	N24-N35 (10 tested)	N43-N54, N83-N84 (16 tested)	N29-N42 (14 tested)	N14, N50-N64, N95-N97 (20 tested)	N33-N49 (17 tested)
TEMPERATURE RANGE	64-300°C	200-300°C	150-255°C	177-256°C	22-200°C	64-235°C
USE (J)	155.0	56.0	28.0	8.0	8.0	2.0

TABLE 2: Upper Shelf Energy (USE)
A533B HSST Plate 02D
(Irradiated – 0.5 x 10**19 n/cm**2, E>1MeV)

	FULL SIZE		HALF SIZE		THIRD SIZE	
	NOTCHED	**PRECRACKED**	**NOTCHED**	**PRECRACKED**	**NOTCHED**	**PRECRACKED**
SPECIMEN ID	N51 141°C N52 220°C N54 252°C N56 190°C (4 tested)	N03 239°C N06 278°C N08 318°C N07 191°C (4 tested)	N62 219°C N65 N/A N68 171°C N67 270°C	N02 246°C N09 211°C N05 164°C N13 299°C	N66 166°C N67 66°C N70 112°C N77 N/A	N11 159°C N16 125°C N08 200°C N04 244°C
USE (J)	133.0	49.0	26.0	8.0	8.0	2.0

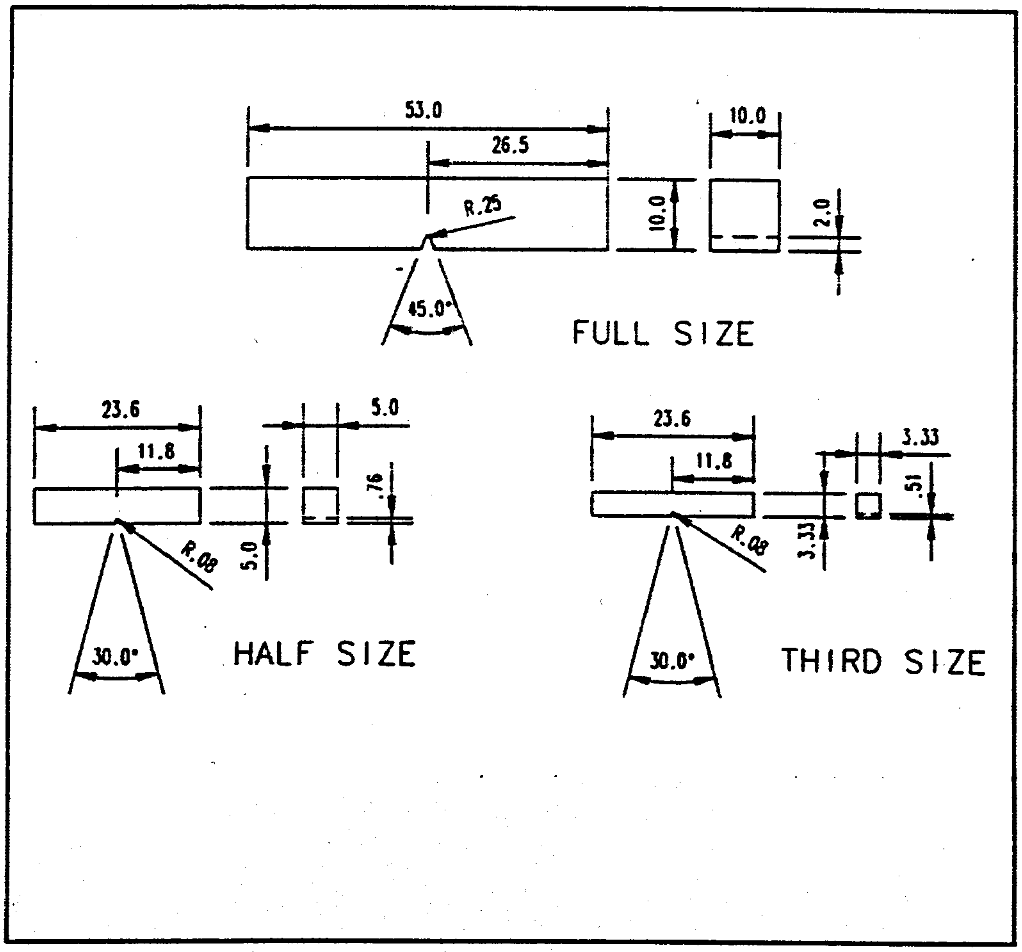

Figure 1. Specimen dimensions (millimeters).

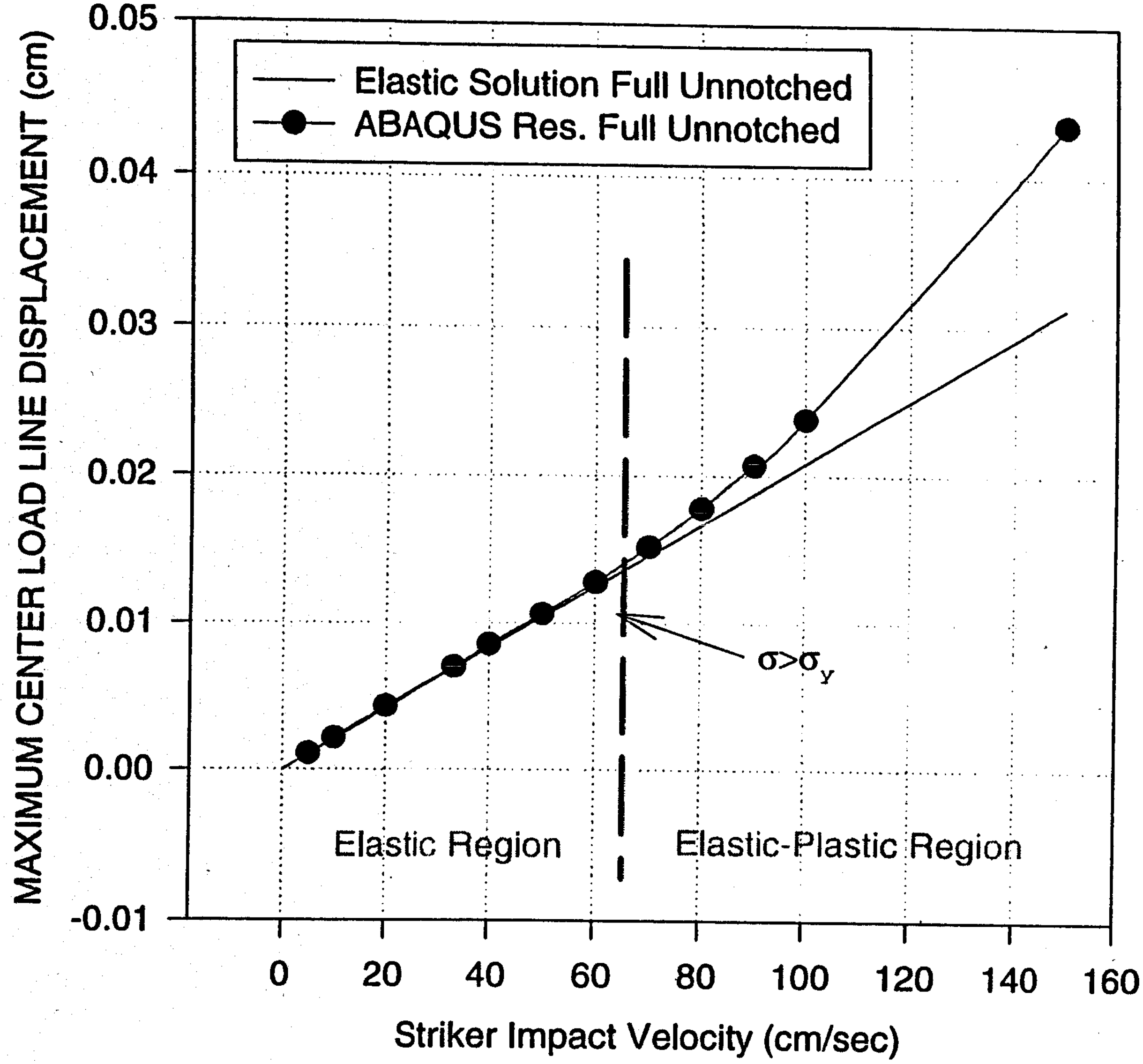

Fig. 2. ANALYTICAL MAX. LOAD-LINE DISPLACEMENT UNDER IMPACT vs. ABAQUS RESULTS

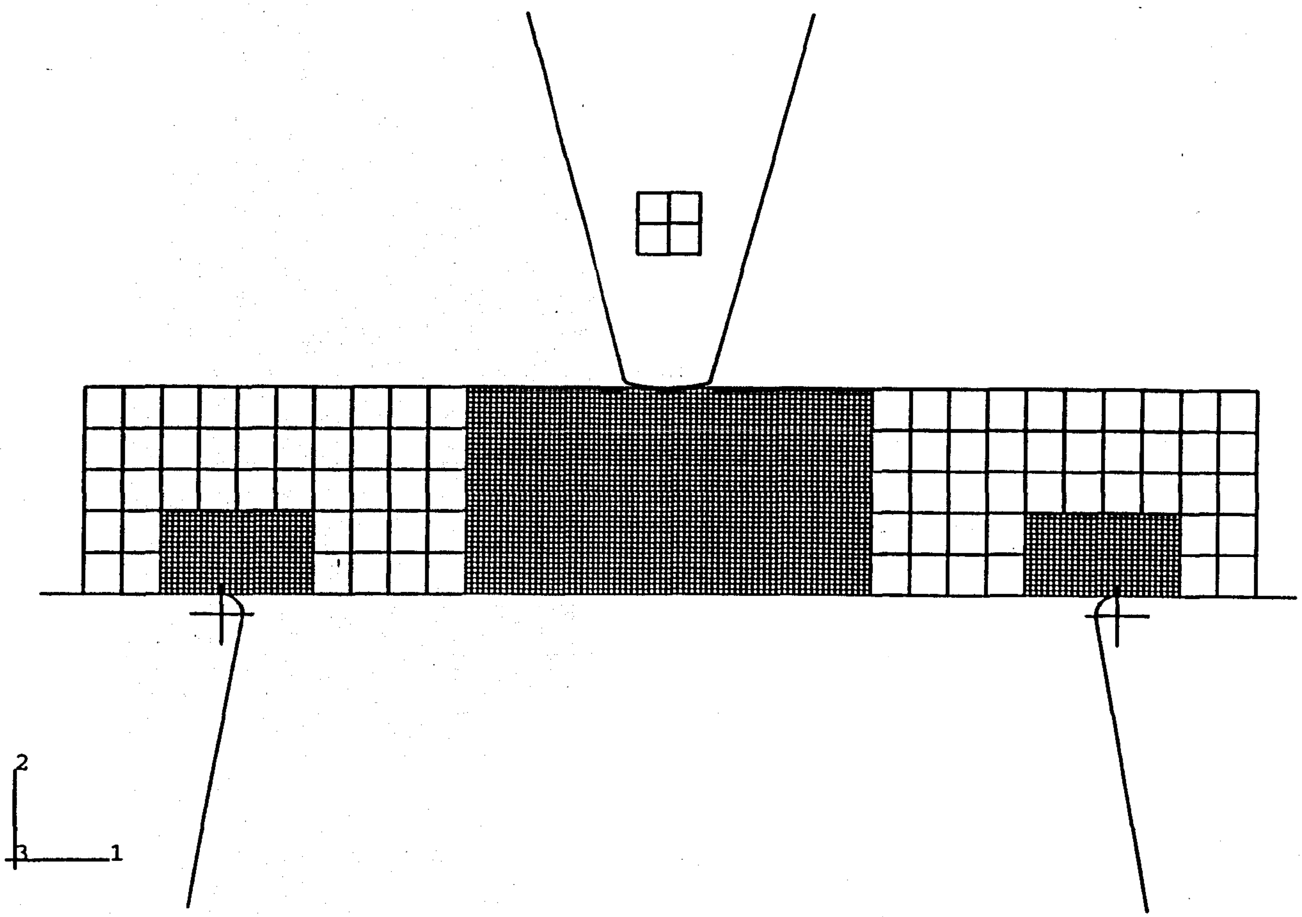

Fig. 3. 2D Finite Element Mesh

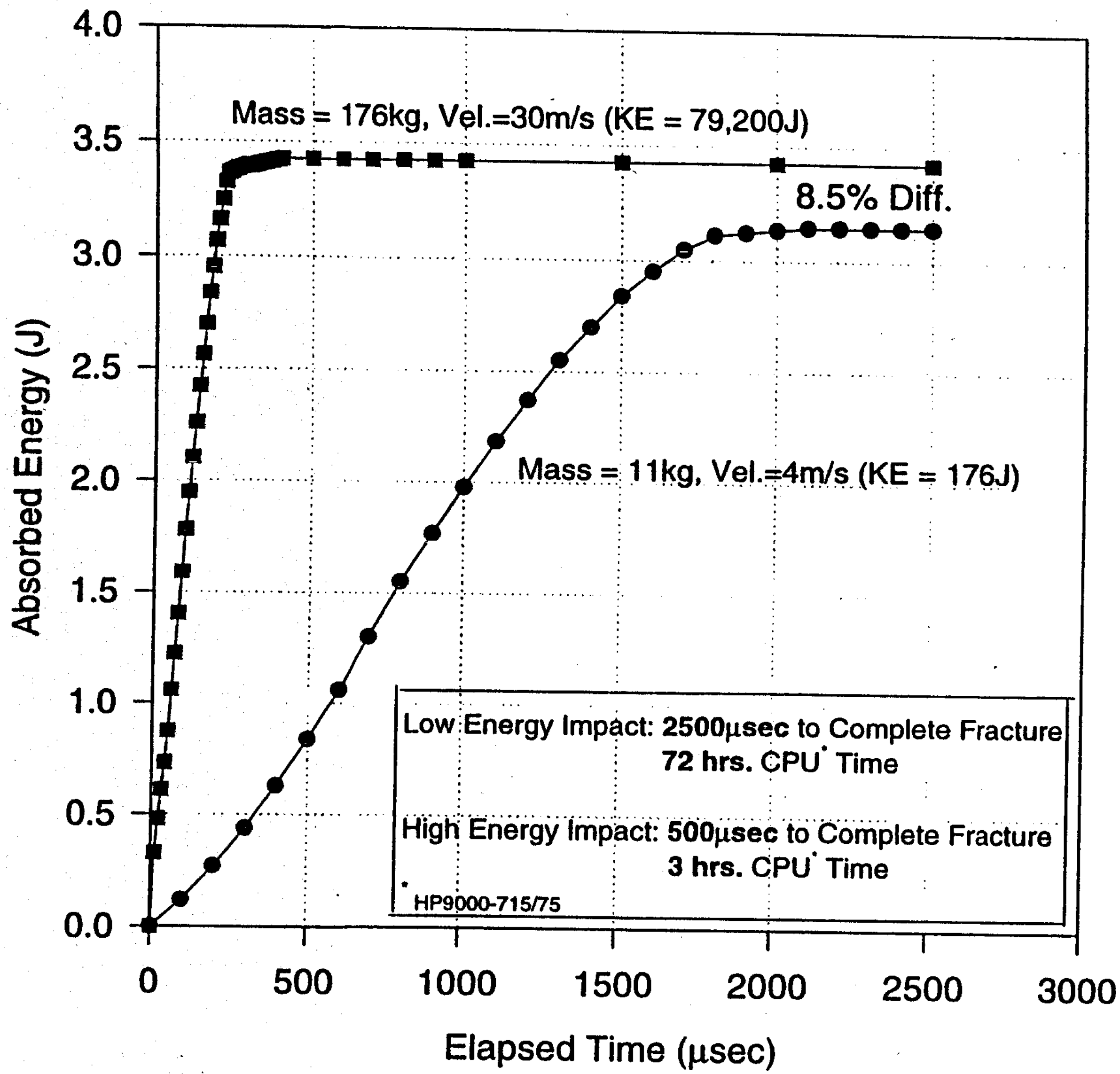

Fig. 4. Comparison of Low and High Energy Impact for 3D Third Size Medium USE Specimen (Precracked 50% W)

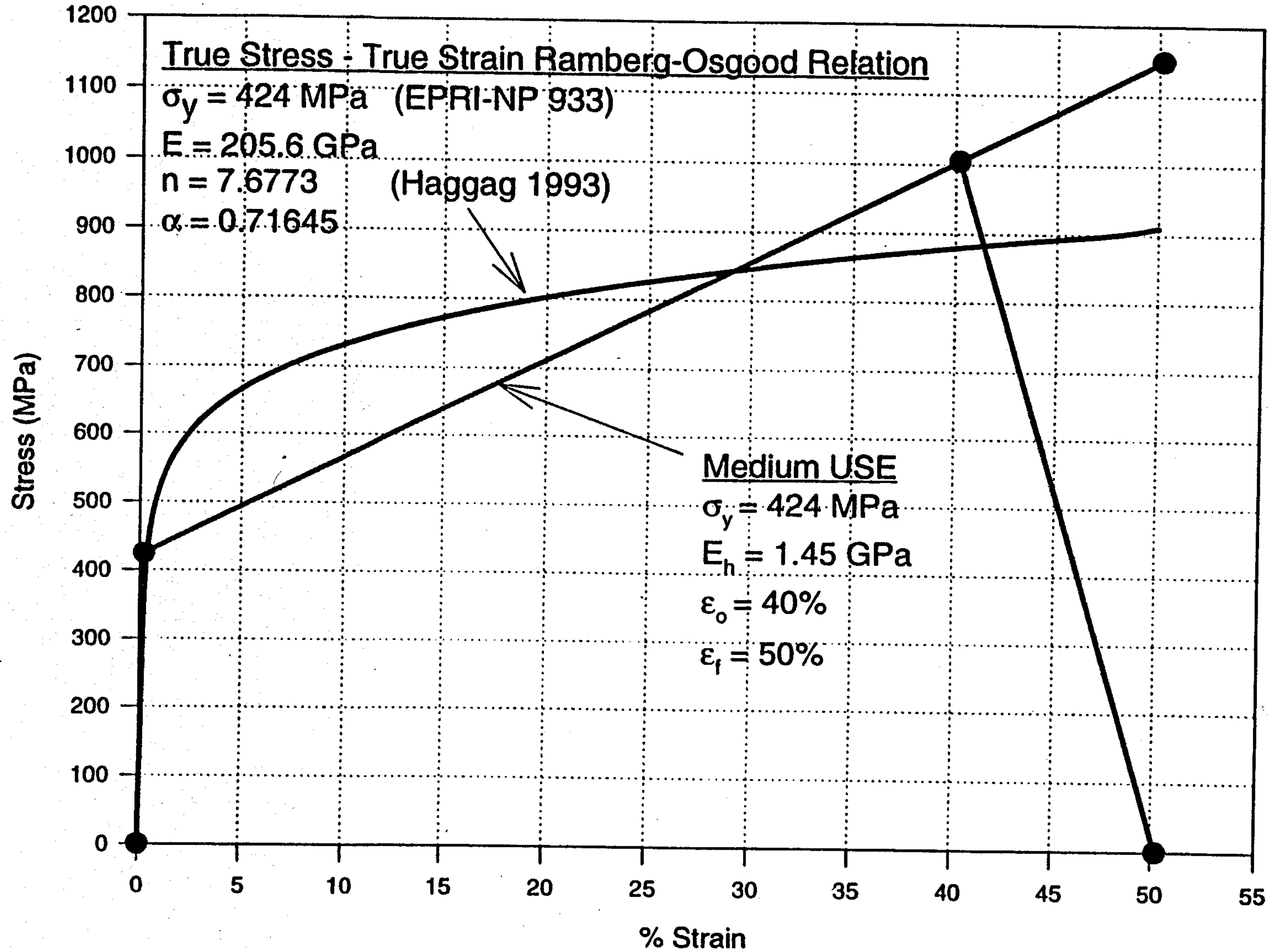

Fig. 5. Stress-Strain Curve of Medium USE for A533B Plate 02 Steel Used in ABAQUS

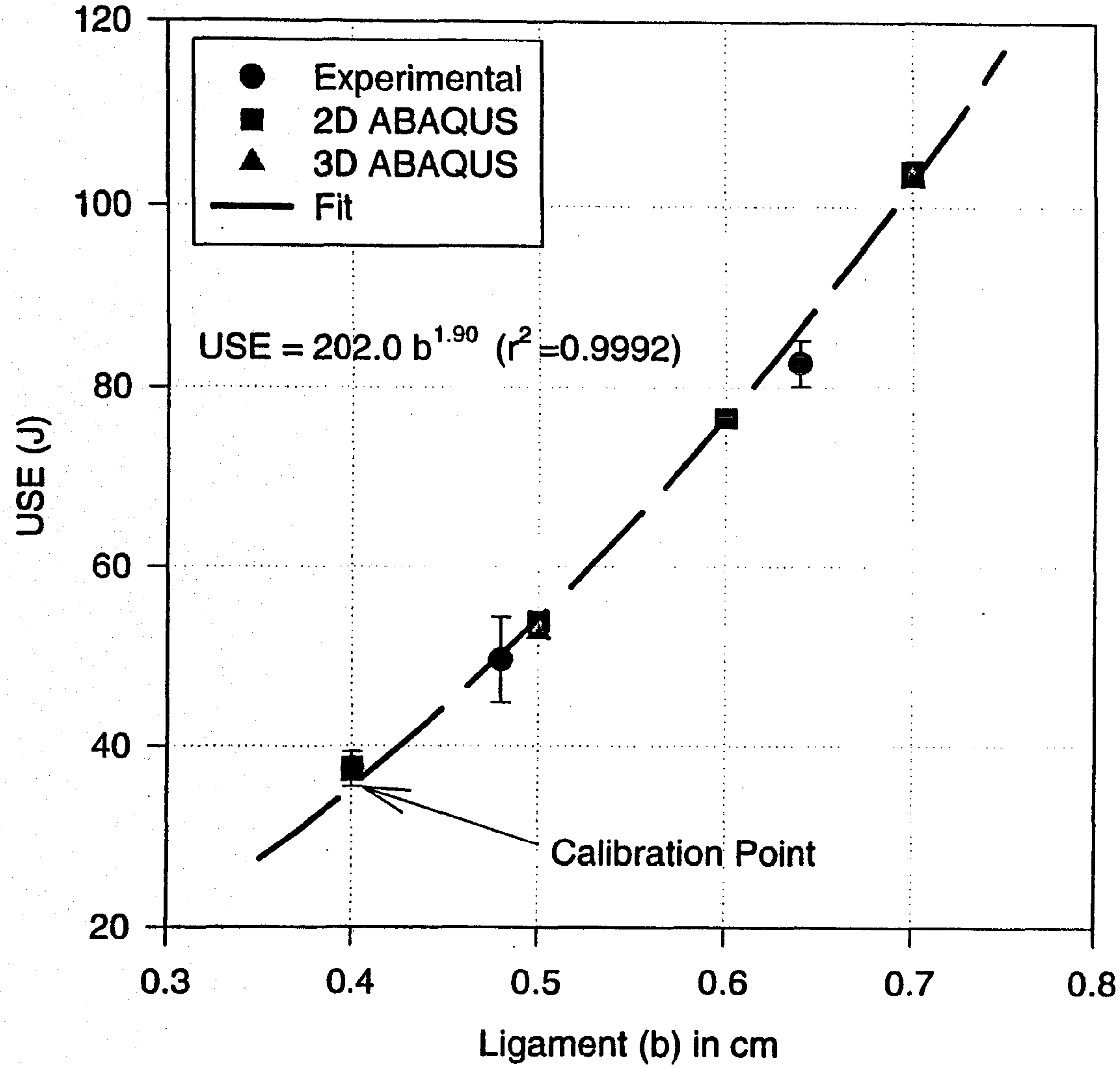

Fig. 6. USE vs. Ligament Size (b) for Full Size Medium USE Material

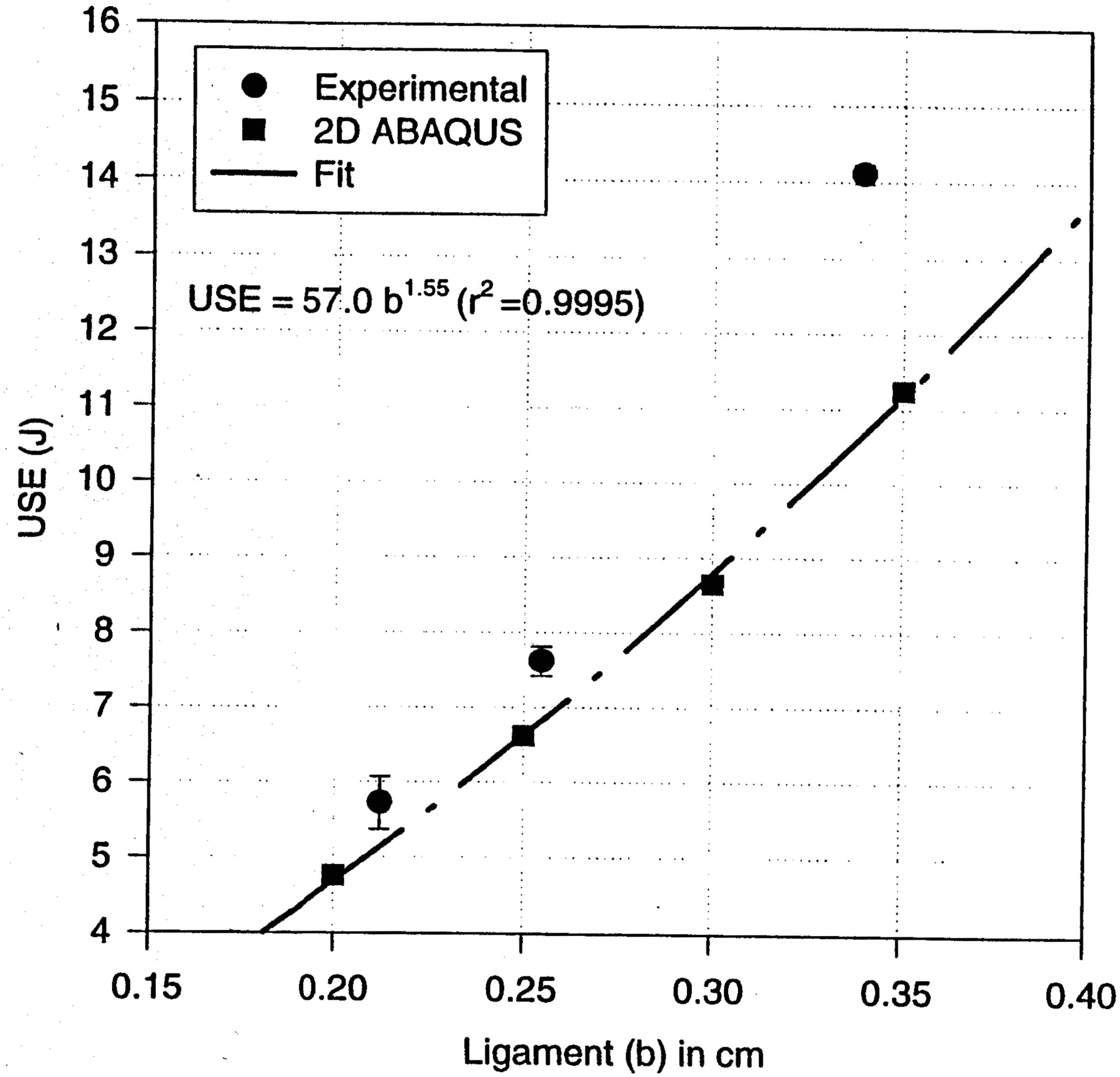

Fig. 7. USE vs. Ligament Size (b) for Half Size Medium USE Material

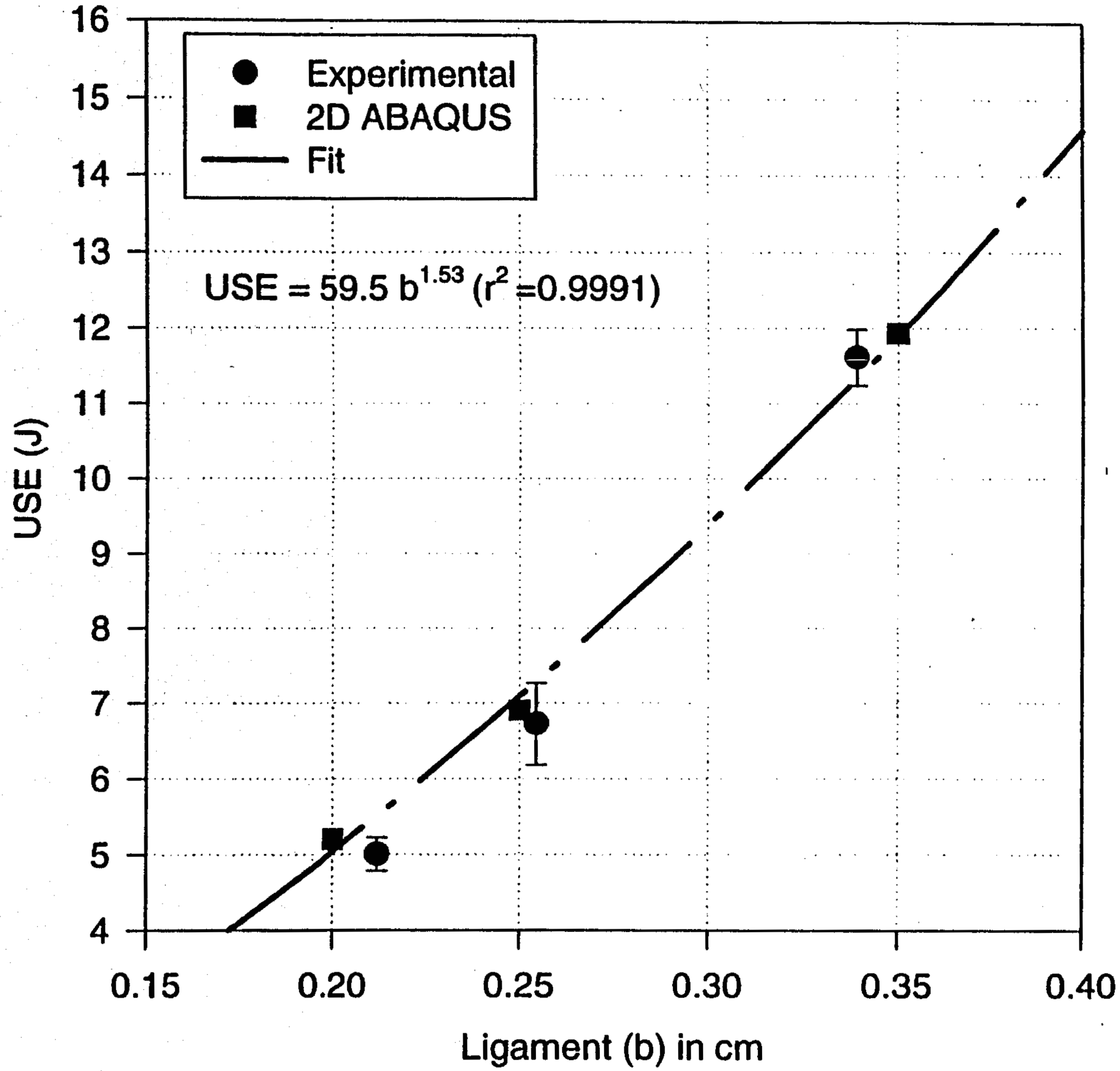

Fig. 8.USE vs. Ligament Size (b) for 2xL Half Size Medium USE Material

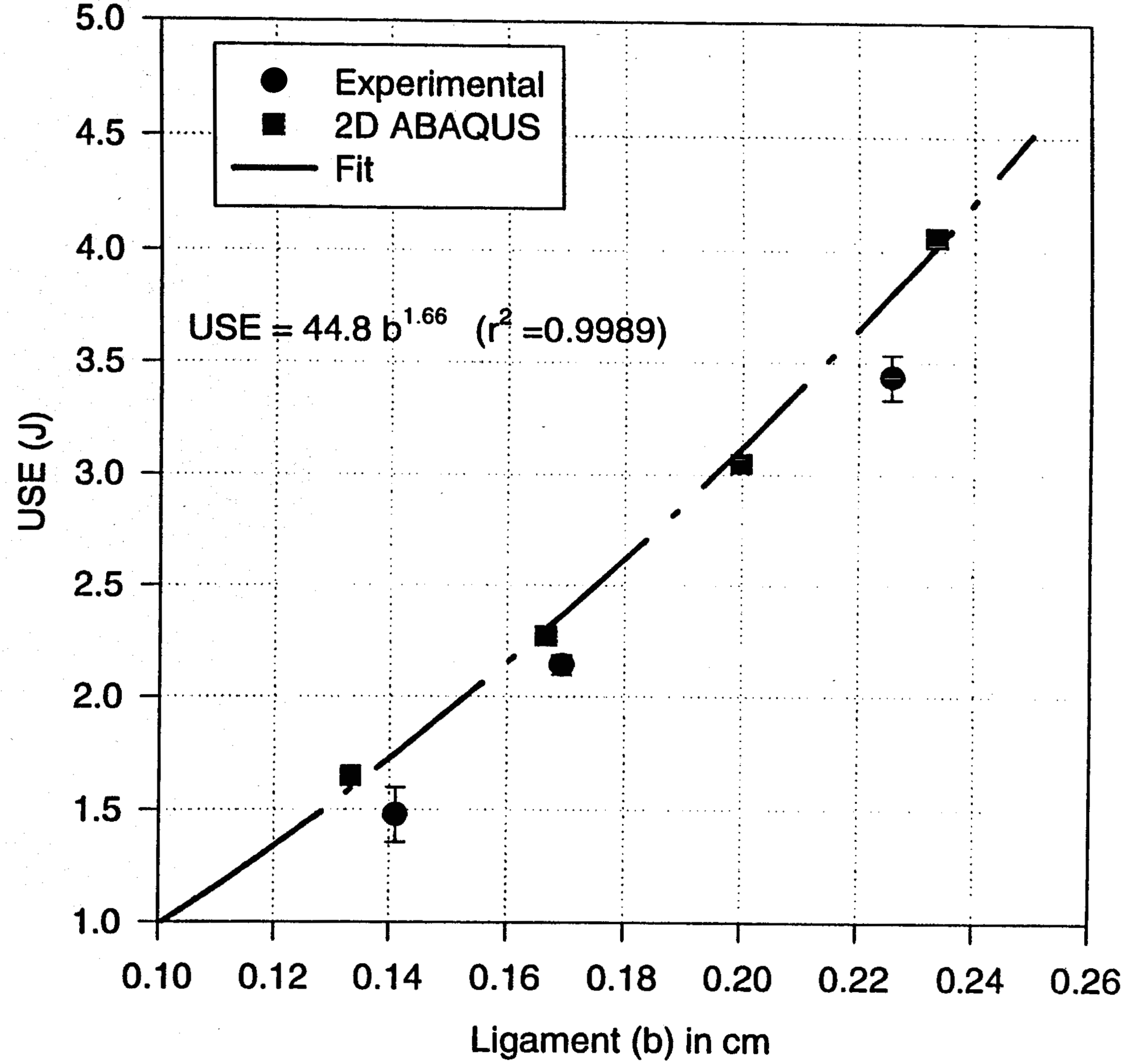

Fig. 9. USE vs. Ligament Size (b) for Third Size Medium USE Material

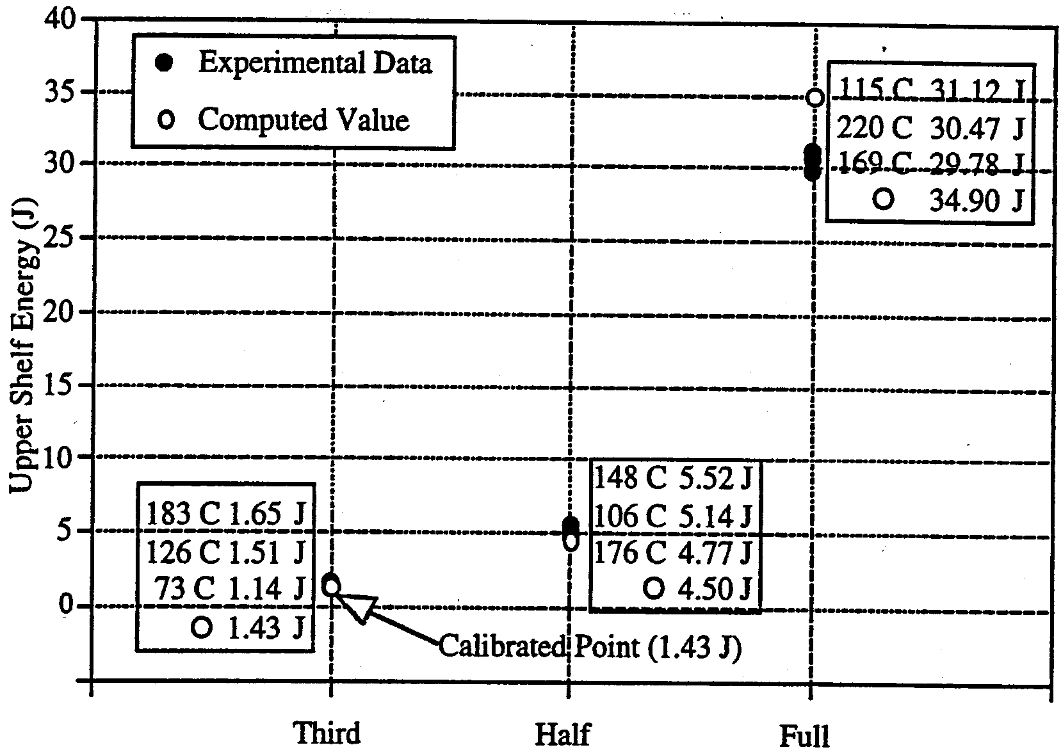

Fig. 10–*Full Size Upper Shelf Energy Predicted from Sub-Size Data For Irradiated* (1.0×10^{19} n/cm^2, E>1.0 MeV) *72W Weld Metal (2D Plane Strain Model)*