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COMPUTER SIMULATION OF THE CHARPY V-NOTCH TOUGHNESS TEST

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COMPUTER SIMULATION OF THE CHARPY V-NOTCH TOUGHNESS TEST*

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ABSTRACT

We have simulated the dynamic Charpy V-notch test on the computer. The calculational models (for A-533 Grade B class 1 steel) used both a rounded and a flat-tipped striker. We found that the notch stress/strain state was independent of the three-point loading type and was most strongly correlated with notch-opening displacement. The dynamic stress/strain state at the time of fracture initiation was obtained by comparing the calculated deformed shape with that obtained in interrupted Charpy V-notch tests where cracking had started. The calculation was also compared with stress/strain states calculated in other geometries at failure. We have also calculated the distribution and partition of specimen energy. Adiabatic heating and strain rate are discussed.

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Symbols

B	specimen thickness
C	elastic compliance
CVN	Charpy energy
E	Young's modulus
$\bar{\epsilon}^p$	equivalent plastic strain
$\dot{\epsilon}_{yy}$	strain rate
NDTT	nil ductility transition temperature
P	load
r	notch root radius
σ_m	mean stress
$\bar{\sigma}$	equivalent stress
σ_1	principal stress
σ_0	initial yield stress

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INTRODUCTION

The ASTM Type A Charpy V-notch specimen is the toughness diagnostic specimen most widely used in operating nuclear pressure vessels. This specimen, located near the inside wall of the reactor vessel, monitors the degradation in fracture toughness of the vessel during its service life. Reduction in toughness reduces the fracture safety level of the vessel, as a result of which the vessel may have to be operated at reduced power loads or be completely shutdown for in-situ thermal annealing.

The Charpy impact test has historically been used as a screening test for fracture prone materials. The specimens are small and inexpensive; the test is simple to perform and the data is easy to interpret. These data are the Charpy V-notch energy (CVN) required to fracture the specimen. However, the physics of the dynamic deformation process is extremely complex and only a small fraction of this Charpy energy is associated with the initiation of ductile fracture. The relationship of this toughness measure to more accepted measures of fracture toughness associated with fracture initiation is tenuous. Correlations between CVN and fracture toughness are empirical and no one correlation is useful over the entire transition range. Further, CVN is not useful in fracture analyses of specific vessel or specimen geometries.

The calculation reported here is part of a more extensive program on ductile fracture in pressure vessel steel (see Norris, et al, 1977). An objective of this program is a better understanding of the physics of the Charpy V-notch test leading to a better relationship between CVN and fracture toughness. All work is for SA-533 Grade B Class 1 nuclear pressure vessel steel at 100°C.

Our computer calculations show a distribution of plasticity in the specimen, at general yield, similar to that predicted by the slip-line

solutions; the plastic zones grow from the notch and the impact surface and merge as plastic hinges. These continue to spread to the specimen notch-side surface. Although the hinges have the same general shape as predicted by the slip-line solutions, they differ from a rigid, perfectly plastic material in that the slip lines become wide bands of plastic flow. Thus, while the general picture is similar to the slip-line field, the details of the dynamic stress/strain state are different.

We estimated the time of crack initiation by comparing the stress/strain state of the Charpy calculation with results of computer simulations of other test specimen geometries at failure. This estimate agrees with crack initiation times found in Charpy tests. Determination of the time of fracture allows us to calculate the energy required to initiate fracture and to relate it to measurements of fracture toughness appropriate for fracture initiation.

We found that fracture starts at about 230 μ s, well before the maximum load occurs in the instrumented test. The stress/strain field at the notch tip is essentially independent of striker tip shape and is most closely correlated with the notch opening displacement. This, in turn, is an accurate measure of the notch root strain. This strain, at failure, is 100%. The maximum stress occurs 1.6 notch radii below the notch surface and is $2.9 Y_0$. The maximum mean stress at this point is $2 Y_0$. The analysis provides information on the distribution and partition of kinetic and internal energy, and on adiabatic heating.

BACKGROUND

The first slip-line solutions for a rigid, perfectly plastic material in three- and four-point bending were found by Green (1953) and Green and Hundy (1955). Their experiments with partially deformed specimens (sectioned and

etched to color the regions of plastic flow) showed remarkable similarity to their calculated plastic strain field solutions, which assumed a sharp V notch. The three-point bending solution for the sharp V-notch specimen was extended to a specimen with a finite root radius by Alexander and Komoly (1962). Their solutions assumed yielding was localized in plastic hinges around the minimum cross section.

Ewing (1968) showed that this is true only if the notches are sufficiently deep. He showed that the Type A specimen had insufficient notch depth for localized yielding, and that the plastic flow would spread away from the minimum cross section to the notch side surface. He then determined the slip-line field for a flat-tipped indenter and obtained the general yield load, i.e., the indenter force consistent with the assumed slip-line field. This general yield load, which may be related to the yield stress of the material, can be obtained from instrumented Charpy V-notch tests, and has been used to estimate the dynamic yield strength of the material. General yield is a calculated state for which a consistent set of external loads and internal stresses are calculated.

It is questionable whether these perfectly plastic, slip-line solutions can be applied to work-hardening materials. Our numerical work-hardening solutions show that the plastic flow is distributed in wide bands centered approximately on the slip lines. At general yield the strain in these bands ranges from 35% at the notch to 1% at the point of the hinge farthest from the specimen symmetry axis. Maximum stresses develop well inside the notch plastic region and do not develop at the elastic-plastic interface. The load-shear yield stress relation that Ewing and Green and Hunn found is inaccurate in view of the varied work-hardening conditions in the plastic hinges at general yield. Further, since crack initiation in a ductile material is associated with large geometry changes, the initial geometry slip-line

solutions fail to satisfy the boundary conditions in the deformed state. The slip-line solution does not track the changing stress state with the deformation.

Computer solutions have contributed to the understanding of notched bending. Griffiths and Owen (1971) used a finite-element, elastic-plastic, small deformation program to calculate a static Charpy bar in pure bending. Their calculation used the Type A notch, but assumed a notch depth of 4.23 mm, a minimum cross section of 8.47 mm, and a support span of 38.1 mm (compared to the Type A dimensions of 2, 8, and 40 mm, respectively). Their zone size at the notch radius (r) was about $r/4$.

Their calculations, made on 3% silicon steel, showed that: notch surface strain is constant over a distance of 1.2 times the root radius, stress intensification at progressively larger loads differs significantly from that predicted by the slip-line field solutions, and local fracture stress is independent of temperature for fractures preceding general yield. Their calculations considered only a notch strain up to about 8%, corresponding to general yield for this material.

COMPUTER MODEL

Figure 1 shows the meshes for the simulations. We modeled only one-half of the striker and one-half of the specimen. The calculation used 1360 zones in the specimen and 200 zones in the striker. Sixty zones were used across the minimum cross section. The geometry is plane strain. A boundary support point at $x = 0$, $y = 20$ mm allows a vertical (y) velocity, but not a horizontal (x) velocity. The striker was given an initial velocity of 4.91 m/s (16.1 ft/s), corresponding to a typical 1.22-m (4-ft) striker drop height. The mass of the three zones on the back end was increased to give one-half of the

striker a total mass of 13.6 kg (30 lb). The initial energy in the calculation (using one-half of the striker and specimen) was 163 J (120 ft-lb).

We simulated SA-533 Grade B Class 1 steel at 100°C. The properties were obtained from standard tests on a nuclear pressure vessel nozzle knockout (heat CDB) described by Marston, et al. (1975). Their data showed a yield strength of 441 MPa (64,000 psi), ultimate strength of 602 MPa (87,300 psi), 26% elongation, and 65% reduction in area. The transverse, uppershell Charpy toughness is 136 J (100 ft-lb). The computer simulations used a Young's modulus of 211 GPa (30×10^6 psi), Poisson's ratio of 0.29 and a yield stress of 458 MPa (66,400 psi). The flow law (see Fig. 2) assumed isotropic hardening with an effective stress-equivalent plastic strain curve obtained by correcting smooth tensile data (Norris, et al., 1977). No damping was used in the simulation.

We simulated the impact of rounded striker tip to see if the results differed from a flat-tip simulation. The computer program allowed the gap between the rounded striker and the specimen to close as the specimen deformed; it also allowed interface slip. The flat-tipped striker/specimen interface was modeled with a rigid connection. The data from this latter calculation are reported below.

The HEMP computer program was used for the calculations (Wilkins, 1969).

CALCULATED STRESS/STRAIN STATE

We have calculated the deformation caused by the rounded-tip striker for 100 μ s and the flat-tip striker for 400 μ s. Figure 3 compares specimen deformation at three different times for both striker tips. The plastic flow originates at the point where the tip of the rounded striker hits the specimen.

For the flat-tip striker, flow originates at the corner areas of high shear strain. The specimen has a large elastic region between the notch and impact surface.

The contours of equivalent plastic strain (Fig. 3) show that there are differences between the strain fields of the calculations made with the rounded tip and those made with the flat tip, even at the notch. Differences at the notch are associated more with differences in the two mesh sizes than with a real difference in the stress/strain state at the notch. Profiles of stress and strain plotted across the ligament for both calculations are in agreement near the notch root. While the general stress state differs for the two calculations, the stress/strain states at the notch are similar.

Another calculation, using pressure to drive the specimen, was compared with the flat-tip striker calculation after 230 μ s. This calculation used the same mesh size as the flat-tip calculations. Here, for the same notch-opening displacement, we found the notch stress/strain state differed by only a few percent. Therefore, we have concluded that the notch stress/strain state is not sensitive to the driving force model.

At 35 μ s, the growing plastic hinge segments of the flat-tip calculation join at a point in the specimen originally 4 mm from the notch root and 3 mm above the center plane of the specimen. The time history of equivalent plastic strain at this point is shown in Fig. 4a; at 100 μ s, the strain reaches 1%. The spatial distribution of plastic strain at 100 μ s is shown in Fig. 4b. The notch strain at this time is 35%. This happens at about the time instrumented striker experiments show a sharp reduction in the slope of the load-vs-time record. This is referred to in the instrumented Charpy literature as general yield and corresponds to the general yield of the slip-line solutions.

An elastic finite-element program was used to obtain the natural frequencies of the plane-strain Charpy V-notch specimen and the displacement

required for yielding to start in the notch. The calculation used 730 zones, with 60 zones across the 8-mm ligament. Fewer zones were used away from the notch. The displacement needed for notch yielding to start is 0.0611 mm at a load of 5.55 kN (1248 lb). The nondimensional compliance ECB is 23.22. The dynamic elastic-plastic calculation shows an equivalent plastic strain of 1.5% at the notch for this displacement. The periods of the first three vibrational modes of the specimen were calculated to be 84.1, 23.5, and 20.8 μ s. These calculations all assumed that the specimen was free to rotate and translate on the support.

Figure 5 shows the distribution of principal stress, mean stress, and equivalent plastic strain at the notch. The figure compares the states at 230 and 330 μ s, the interval over which fracture is thought to occur. The stress and mean stress appear to be relatively stationary with time; the strain varies strongly with time as the notch opens.

CHARPY CRACK INITIATION

We have estimated the time of crack initiation* by calculating and comparing the stress/strain states at the notch and with the same states in other calculated geometries where fracture initiation time is known. Next, we compared the estimated time with the crack initiation times of deformed Charpy specimens from interrupted dynamic tests. Based on these comparisons, we estimated that fracture starts at the notch surface between 230 and 340 μ s for

* We defined a crack as a new surface (disregarding blunting) greater than approximately 0.25 by 0.25 mm.

a 4.9 m/s impact velocity. Instrumented Charpy data shows that the maximum load for this material, at 100°C and 4.9 m/s impact velocity, occurs at about 700 μ s.

The specimens obtained from the interrupted tests were heat tinted, cooled in liquid nitrogen, and broken to expose the fracture surface. These surfaces were inspected at 30 $\times$ magnification to locate the specimen that had the least amount of deflection, but still exhibited cracking. The procedure is not precise; the crack initiation is camouflaged by the blunting that occurs in this tough steel.

The results are shown in Table 1. The final specimen displacement was assumed to be equal to the prescribed striker displacement. The times associated with this deformation were determined by dividing these displacements by an impact velocity* of 4.9 m/s. The data show that, at 100°C, evidence of macroscopic fracture initiation is seen at about 340 μ s. This is well before the maximum load from an instrumented Charpy test.

Four additional specimens were deformed at 93°C (200°F) in the interrupted tests. These unbroken specimens were cut across the notch along the long axis and polished and inspected. The first crack occurred at a deformation between 1.63 and 2.16 mm. A study of the surface (see Fig. 6) suggested that the crack started at the notch surface and grew inward. These data show that the crack started between 332 and 440 μ s.

The time history of calculated equivalent plastic strain in five zones below the Charpy notch is shown in Fig. 7a. Blunting of the notch root radius results in intense straining and a high strain gradient. We have extrapolated

* The experiments were conducted at an impact velocity of 0.91 m/s (3 ft/s).

the zone-centered, equivalent plastic strain to the notch surface. The time history of stress normal to the notch is shown in Fig. 7b for four zones below the notch.

Estimated time of crack initiation may be obtained by comparing the calculated Charpy stress/strain state with known stress/strain states at failure. Simulations of tests on this material in four other geometries are discussed by Norris, et. al. (1977). These include two circumferentially notched round tension specimens and a smooth tension specimen. Failure in the smooth tensile specimen occurs at about an equivalent plastic strain of 100%, shown by the horizontal dashed line in Fig. 7a. It is seen that, based on strain alone, the specimen cracks between 230 and 290 μ s. The smooth-tension test simulation indicates failure at an axial stress of 1.28 GPa. This stress is not reached in the Charpy surface zone until much later; the surface stress normal to the notch at 400 μ s is about 1.1 GPa. The increase of this stress with time from 100 μ s to 400 μ s is small, but strain at 400 μ s has increased to about 150%. The surface stress at 230 μ s is about 0.95 GPa.

Profiles in Fig. 8 compare the stress perpendicular to the notch, the mean stress, and the equivalent plastic strain below the notch for the Charpy calculation and the notched and smooth tension simulations at corresponding times of fracture initiation.

ENERGY

The energy in a small process zone near the notch root at 230 μ s is only 12% of the energy in the specimen. At this time the local root temperature has risen over 150°C. Kinetic energy equals internal energy at 20 μ s.

The distribution of internal energy near the notch is shown in Fig. 9. These energy contours were converted to temperature contours using a specific

heat of 0.106 cal/g-°C. A small volume of material at the root of the notch experiences a temperature rise in excess of 150°C. The material in a process zone of about two root radii has a temperature rise greater than 50°C. The temperature rise of this material is of the same order as the transition temperature range. NDT for A533 is about -18°C and uppershell is 93°C. Since this dynamic test is nearly adiabatic,* this temperature rise should result in a considerable enhancement of toughness in the transition region, a result that is not obtained dynamically. For ductile rupture associated with high straining, the crack originates in the hottest material.

The notch energy at 230 μ s is only 12% of the total energy in the specimen. This number was obtained by editing the energy near the notch root in a process zone 1.3 mm deep and 2.6 mm perpendicular to the notch. Notch radius is 0.25 mm. Most of the energy is distributed away from the notch (i.e., in the plastic hinges, at the support, and below the striker), where it has little effect on fracture toughness. The internal energy in the specimen at 230 μ s is 13.95 J (10.31 ft-lb).

The partition of energy in the specimen is shown in Fig. 10. The dashed horizontal line in the figure is the specimen kinetic energy, assuming a notch velocity of 4.9 m/s and rotation around the anvil support. The calculation simulated a 27.3-kg (60-lb) striker impacting the specimen at 4.9 m/s. At 17 μ s, specimen kinetic energy is 2.4 times greater than internal energy, but they become equal at 20 μ s. At 100 μ s, corresponding to general yield, kinetic energy is 3.5% of the energy in the specimen. At 230 μ s, the ratio is 1.2%. The specimen contains only 4.3% of initial energy at this time and only 10.3% of the 136 J (100 ft-lb) of CVN energy required for complete fracture.

* The characteristic thermal diffusion time is about 1 ms.

Estimates of CVN kinetic energy corrections may be obtained from Fig. 10. It is obvious that corrections must be made for fractures that occur before 100 μ s and that meaningful data for fractures that occur before 20 μ s are not possible at this impact velocity. Because of the periodicity of kinetic energy, more of a correction may be required as time increases. For example, no correction is required at 35 μ s, but at 55 μ s, 27% of the total specimen energy is kinetic. The kinetic energy is a spurious measure of fracture toughness and should be removed in evaluating toughness. The damping of the kinetic energy in this simulation relies entirely on the energy lost in plastic deformation. We have included no viscous damping in the calculation.

STRAIN RATE

The average strain rate at the notch is about 3000 s^{-1} for the 4.91 m/s impact velocity. Wilshaw (1966) reports a range of 2000 to 5000 s^{-1} . Our strain-rate calculations show considerable oscillations for the first 120 μ s of impact, with a peak rate of 6700 s^{-1} . Strain rate vs time is shown in Fig. 11a for the zone closest to the notch root.

The stress/strain curve for these calculations was obtained experimentally at a strain rate of approximately seven orders-of-magnitude lower than the maximum calculated notch strain rate. To determine the effect of the high rate on the flow-stress curve, we made high-rate tensile tests. The results gave us the stress/strain relationship at a rate of 3400 s^{-1} . We found that ultimate strength increased 13% in the A533 steel due to the high rate.

These tests used a split Hopkinson bar in tension (Hauser, 1966). Three specimens were tested at a strain rate of 3400 s^{-1} , and one quasi-statically at a crosshead rate of 1.3 mm/min (0.05 in./min) (see Fig. 11b). All tests were made at 20°C. LLL Standard T-2 Tab-2 tensile specimens were used. The overall

specimen length of 38.1 mm included the enlarged threaded ends. The center-section diameter was 4.06 mm for a length of 9.53 mm. It is doubtful that the small increase in ultimate strength can account for the reduction in toughness seen in the dynamic Charpy test in the presence of the adiabatic heating.

STRIKER RESPONSE

Striker force vs time is shown in Fig. 12. Two of these curves compare the average calculated cross-section force from a single zone at the striker midsection (the normal strain-gauge location) with the force obtained by integrating the axial stress over the tip of the striker. A third curve is instrumented Charpy experimental data at this striker velocity and temperature.

The oscillations are associated with the complex wave interactions between the specimen and the striker. The fundamental period of the elastic specimen is 84.1 μ s.* The specimen leaves the striker at about 25 μ s. Analysis of the velocity fields of the striker and the specimen clearly shows the interactive wave effects that result in separation. Specimen kinetic energy has reached a maximum at 17 μ s. The high amplitude of the calculated striker oscillations results from a lack of damping in the simulation that is probably present in the actual test. The magnitude of the oscillations appears to have little effect on the plastic deformation history of the specimen, as may be seen by the linear relationship between energy and time in Fig. 10.

The axial stress distribution across the striker is shown in Fig. 13 at 60 and 70 μ s. The distribution is shown at the striker tip and at a point 16 mm behind the tip, corresponding to the instrumented Charpy strain-gauge

* Support friction lowers this period to 58.4 μ s.

location. There is considerable variation across the tip, but at the striker midsection the stress is uniform.

To interpret these results for the striker, we must weigh the relation between the striker model in the computer and the real structure. The actual striker is a small cantilever plate that impacts the specimen on the plate edge. The plate mass is negligible compared to the massive open-bottomed steel box on which it is mounted. Our striker model uses only the cross-section dimensions of the striker, with rear-end density increased to model the box mass. The agreement of experimental data with the calculation shown in Fig. 12 suggests the model may be adequate.

RESULTS

- The calculations show the general plasticity features of the slip-line field solutions.
- Fracture initiates at about 40% of the maximum load time of the instrumented standard Charpy V-notch test.
- There is no theoretical basis for applying the three-point (or four-point) load/dynamic-yield stress relation of rigid-plastic slip-line theory to this material.
- A process zone contains less than 12% of the specimen energy at fracture.
- Specimen energy at fracture initiation is only 10% of measured CVN.
- Specimen internal energy becomes equal to kinetic energy at 20 μ s. At 100 μ s, KE is less than 4% of IE.
- Notch adiabatic heating raises the notch temperature more than 150°C at time of fracture.
- Notch average strain rate is about 3000 s^{-1} . Ultimate strength of this material is increased 13% at 3400 s^{-1} .

- The notch stress/strain state is essentially independent of three-point loading method, but the state correlates well with the notch-opening displacement.

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Table 1. Crack initiation in A533 B, Class 1 Charpy V-Notch specimens.

Temperature, °C(°F)	Displacement,* mm	Time,† µs
28 (82)	0.762-1.12	155-230
79 (175)	1.12-1.63	230-334
177 (350)	1.63-1.80	334-369

* Striker displacement below specimen initial impact surface.

† Based on a constant 4.91 m/s impact velocity.

Figure Captions

Fig. 1. Zoning for Charpy V-notch computer simulations: (a) Flat-tip striker, (b) Zoning detail for round-tip striker; (c) Zoning detail for flat-tip striker.

Fig. 2. Effective stress-equivalent plastic strain curve used for the computer simulations.

Fig. 3. Equivalent plastic strain distribution for round-tip (left) and flat-tip (right) striker at three times. Contour levels are 1 = 10%, 2 = 1.0%, 3 = 0.1%.

Fig. 4. Plastic hinge growth from the notch and the impact surface: (a) $\frac{P}{E}$ vs time at the location where the plastic zones merge; (b) $\frac{P}{E}$ contour levels at general yield, $t = 100 \mu s$.

Fig. 5. Stress (GPa) and strain contours at 230 μs (left) and 330 μs (right): (a) Principal stress; (b) Mean stress; (c) Equivalent plastic strain.

Fig. 6. Polished middle cross section of a Charpy V-notch specimen at 100°C. The specimen is from an interrupted dynamic test: (a) Notch root, 125 $\times$; (b) Magnified notch root, 650 $\times$; (c) Magnified view of fracture damage at base of notch for a specimen with greater interrupted deformation. Circular depressions are MnS inclusion sites.

Fig. 7. Strain and stress time histories for zones below the notch: (a) Equivalent plastic strain — zone 1 is immediately below notch; (b) Principal stress σ_1 vs time. Initial notch zone size is 0.133 mm.

Fig. 8. Stress and strain distribution at failure in four specimen geometries. The origin for distance is taken at the notch root for the notched specimens and at the symmetry axis for the smooth tension specimen.

Fig. 9. Temperature distribution at Charpy notch at 230 μs , °C.

Fig. 10. Calculated Charpy V-notch specimen energy partition. Initial striker energy is 325 J (240 ft-lb). The dashed line is the rigid body striker KE, assuming the notch root moves relative to the support at 4.91 m/s (16 ft/s).

Fig. 11. Strain-rate behavior: (a) Calculated strain rate in the Charpy V-notch specimen at the notch root; (b) Comparison of Hopkinson tensile bar data at $\dot{\epsilon} = 3400 \text{ s}^{-1}$ with static data.

Fig. 12. Comparison of calculated striker force with instrumented standard Charpy data: (a) Specimen 2430, $T = 100^\circ\text{C}$; (b) Calculated data from striker tip and strain gauge location; (c) Superposition of calculated and experimental data.

Fig. 13. Stress distribution across striker at impact end and at strain-gauge location.

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Norris - Fig. 1

Norris - Fig. 2

Norris - Fig. 3

Norris - Fig. 4

Norris - Fig. 5

a

b

c

Norris - Fig. 7

Norris - Fig. 8

Norris - Fig. 9

NORRIS - Fig. 10

Norris - Fig. 11

Norris - Fig. 12

Norris - Fig. 13