MECHANICAL ASPECTS OF THE CHARPY IMPACT TEST

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A comparative experimental and FEM study has been performed, in order to investigate dynamic and constraint aspects of the Charpy test. Testing of standard V-notch Charpy specimens was performed under dynamic and static loading conditions. 2-D plane strain and 3-D models were used in numerical analysis. In order to incorporate strain-rate effects, an elastic-viscoplastic constitutive equation has been applied, based on actual test data obtained for a low-alloy structural steel. Fully dynamic analysis clearly indicated inertial effects. Modal analysis enabled the identification of the origin of the oscillations on the load-displacement curve as beam vibration of the specimen resulting from interaction with the elastic striker.

INTRODUCTION

The instrumented Charpy impact test is largely applied in industry, due to the fact that it is easy to conduct and results can be obtained quickly and with little cost. Yet it seems that among some users there is still some uncertainty about the origin of the oscillations occurring on the load vs. displacement records. Furthermore, some doubt exists concerning the actual state of constraint in this rather small type of specimen. The study of inertial effects is of some interest in the cleavage fracture domain, since failure will occur after a relatively short loading time, thus possibly not allowing for oscillations to dampen out quickly enough. This study is performed, in parallel with a comparative study by Tahar, Piques and Forget (1), as a first step in the framework of a common research programme devoted to modelling of the Charpy test based on a "local" criterion for cleavage fracture.

EXPERIMENTAL PROCEDURE

The material used for the investigation was taken from a nozzle cut-out of a nuclear pressure vessel made of A 508 Cl.3 steel. This is a 0.16 C 1.3 Mn 0.7 Ni 0.5 Mo

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structural steel used for heavy forged components in nuclear industry. Heat treatment includes 2 austenitisations followed by water quenching and tempering, and final stress relief.

Parameter Identification of the Constitutive Equations

Static tensile tests ($\dot{\varepsilon}$ = 4.10^{-4} s^{-1}) have been conducted at temperatures ranging from -196 °C up to room temperature. A Lüders strain of about 1% was found. Since the development of Lüders bands is considered to be a characteristic of tensile testing conditions, and not an intrinsic characteristic of the material *per se*, an extrapolation of the strain-hardening part of the stress-strain curve to zero plastic strain was performed, in order to receive the "true" material response. Thus a new yield limit was defined (see figure 1). This procedure, which is based on dislocation movement considerations, has already been documented in literature, for instance, amongst others, by Lindley (2).

Since the material just below the notch root of a Charpy specimen exhibits high strain rate during deformation, it was necessary to investigate the strain-rate sensitivity of the material. Compressive testing at an approximate strain rate of 1000 s^{-1} was performed on a Hopkinson bar device. Additionally, quasistatic (4.10^{-3} s^{-1}) and intermediate strain rate (1 s^{-1}) compressive tests were performed on an INSTRON hydraulic testing machine, at temperatures between -150°C and +100°C. Only the plastic deformation up to 5 % was considered, in order to obtain the material law under virtually "isothermal" conditions. These tests allowed to numerically identify the parameters for the elastic-viscoplastic material law in additive formulation proposed by ABAQUS FEM software.

Impact Testing

Charpy tests on three different standard instrumented impact pendulum devices have been conducted, at a nominal impact velocity of 5 ms^{-1} and temperatures ranging from -90°C to room temperature. Instrumentation consisted of measuring striker displacement and force. Additionally, a few tests on specimens equipped with strain gauges have been undertaken, in order to study the nature of the apparent oscillations on the load-displacement record.

Static Testing

Static testing of standard Charpy specimens was performed on an INSTRON hydraulic testing machine. Both striker and supports had been machined according to Charpy testing standards. A crosshead speed of 0,25 mm.min^{-1} was imposed. Instrumentation also included a clip gauge to measure the notch opening, and potential drop and temperature recording devices. Temperatures between -150°C and -30°C were studied.

NUMERICAL ANALYSIS

Mesh. 2-D and 3-D FE meshes have been generated by means of I-DEAS software. In 2-D up to 2300 4-noded, and in 3-D 8700 8-noded linear isoparametric elements with reduced integration have been used. Due to symmetry, only half (2-D) or one quarter (3-D) of the specimen needs to be modelled. The 3-D mesh consists of 10 layers of elements in the thickness direction, with decreasing node distance towards the outer surface. A fine mesh is used for modelling contact surfaces and notch section of the specimen. Rigid surface contact elements have been used to model striker and supports. A coefficient of friction of 0,1 was assumed. Loading of the specimen is modelled by imposing a fixed displacement (for static testing simulation) or velocity (for dynamic testing simulation) to the striker. In fully dynamic analysis, impact velocity is imposed upon the rigid striker contact surface via a spring element, thus simulating machine compliance. A mixed 2-D/3-D element approach using constraint equations for the 3-D part had to be given up, since it was found that the 3-D part would need to be very large in order to yield a correct solution.

Analysis. The ABAQUS 5.4 finite element analysis program with implicit integration scheme has been used. Finite strains have been accounted for, thus allowing the description of local stress and strain fields in the heavily deformed notch region of the Charpy specimen. Calculations of impacted specimens included the following features : 5 ms^{-1} striker velocity imposed ; elastic-viscoplastic material behaviour ; quasistatic or fully dynamic (including inertia terms ; 2-D only) solution procedure. Fully adiabatic conditions have been considered, thus not allowing any transfer of the heat generated by plastic deformation, since the characteristic heat diffusion time is considered to be about one order of magnitude longer than the duration of an impact test. Any numerical simulation has been terminated after a displacement of the striker of 2 mm, since testing showed that, in the temperature regime under investigation, failure of the specimen occurs within this range.

RESULTS AND DISCUSSION

In order to validate the numerical models, experimental and numerical global response results (load-displacement) are compared in figures 2 and 3. In the simulation of static testing, a "stick-slip" effect appears, which seems an artefact due to the contact algorithm, since it does not appear on experimental curves, but does so on results of calculation even assuming no friction. No ductile damage has been taken into account, which is supposed to develop after a deflection in the order of 0.5 mm, according to the observation of the potential drop signal. Consequently, a slight overestimation of the numerically obtained global response curve for larger displacements arises. In conclusion, the 3-D modelling seems rather reliable. The global dynamic response of the specimen largely overestimates the reaction force. This is due to the 2-D plane strain hypothesis applied for dynamic calculations, since 3-D calculation in fully dynamic conditions would be extremely costly.

Modal analysis enabled the identification of the origin of the oscillations as beam vibration of the specimen resulting from interaction with the "elastic" striker, phenomenon which has already been specified through different mass-spring analyses and beam solutions, e.g. by Sahraoui and Gillaizeau (3). It was found that amplitude and frequency of the apparent oscillations on the load-displacement record are greatly influenced by the stiffness of the experimental device (i.e. machine compliance).

The evolution of the longitudinal strain rate in the first element close to the notch root is plotted in figure 4. It shows strong fluctuations for the dynamic analysis, but influence of these fluctuations on strain hardening is considered to be negligible, in comparison to the general level. The apparent strain rate is lower for 3-D analysis, due to the coarser mesh used. The evolution of stresses was found to exhibit negligeable oscillations. The distribution of the longitudinal tensile stress along the ligament in the centre plane of the specimen is plotted in figure 5. It is compared for deflections of 0.5 and 2 mm, and for fully static (elastic-plastic material behaviour) and dynamic (elastic-viscoplastic material behaviour) testing conditions. Stresses obtained in dynamic testing are much higher, due to strain rate hardening. In figure 6 it is shown that, for a considered temperature of -90°C, the longitudinal tensile stress in plane strain 2-D analysis closely follows the solution obtained in the centre plane of the 3-D model.

In figure 7 the temperature distribution in the notch root region due to adiabatic heating in dynamic testing can be seen, for a deflection of 0.5 mm, and an initial temperature of -90°C (2-D plane strain analysis). It can be stated that the temperature elevation is already quite important, but confined to a very small zone. Figure 8 shows an energy balance analysis of a dynamic impact test performed at -90°C : It can be seen that, after two oscillations, kinetic energy is rather low, in comparison to total energy ; this means that, if the specimen fails after the time taken for two oscillations, the energy measured on the dial, and the energy obtained by integrating the force-displacement signal is nearly entirely consumed by deformation and fracture of the specimen ; so a static evaluation procedure can be applied. The "classical" 3τ criterion for validity of Charpy impact tests (e.g., see Server (4)) requires that fracture does not occur before 3 oscillations. It could be considered too conservative, if the second apparent oscillation reaches "full" level before failure of the specimen.

CONCLUSIONS

It has been shown that numerical modelling of the Charpy impact tests yields quite reasonable results. Fully dynamic analysis can well explain apparent oscillations on experimentally obtained load-displacement records. Inertial fluctuations of stresses in the notch region dampen out quickly due to plasticity. Local stresses in 2-D plane strain analysis were found to follow those in the center plane of the specimen in 3-D analysis. It can be concluded that, for a temperature of -90°C considered, a 2-D plane strain quasistatic evaluation procedure can be employed, in order to apply a local cleavage fracture criterion.

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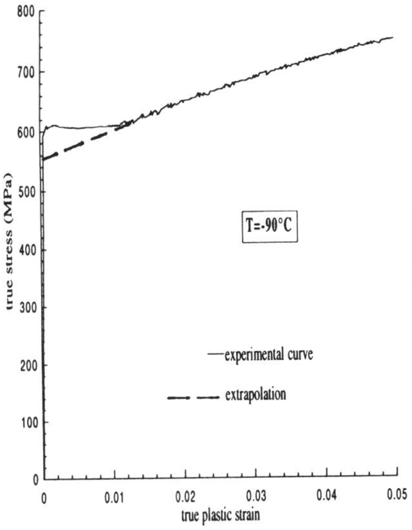

Figure 1 Extrapolation technique used for redefining the yield limit

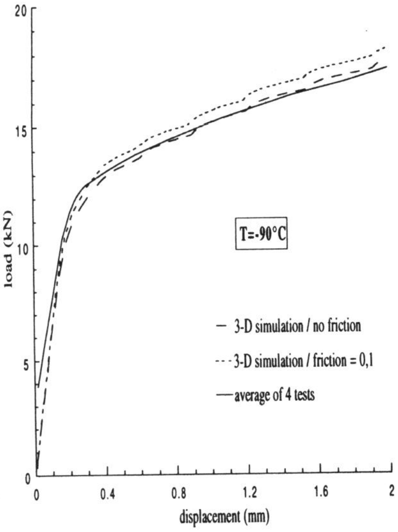

Figure 2 "Static" experimental and numerical global response

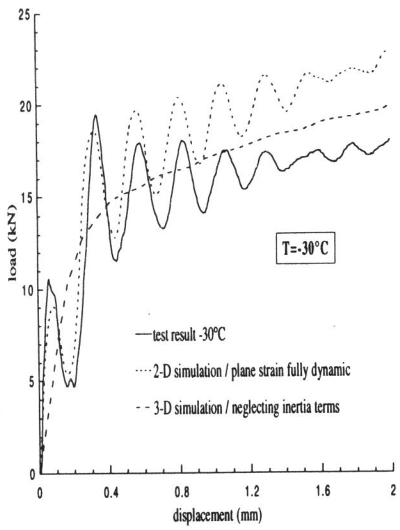

Figure 3 "Dynamic" experimental and numerical global response

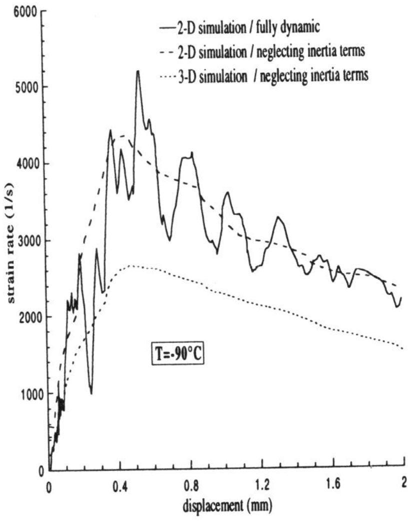

Figure 4 Longitudinal strain rate in the notch root element

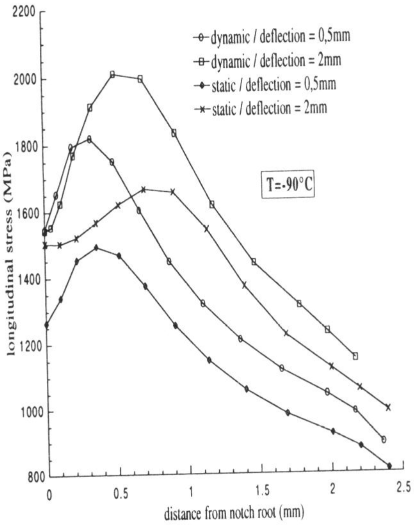

Figure 5 Longitudinal tensile stress : 3-D analysis / center plane

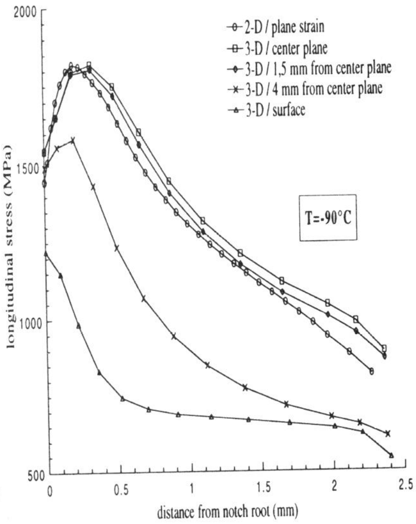

Figure 6 Longitudinal tensile stress : different plane sections and 2-D

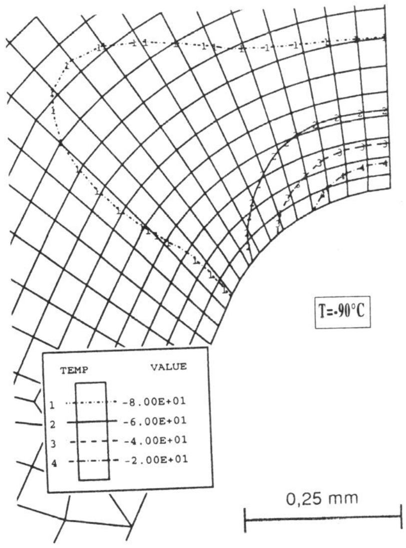

Figure 7 Temperature ahead of the notch after a deflection of 0.5 mm

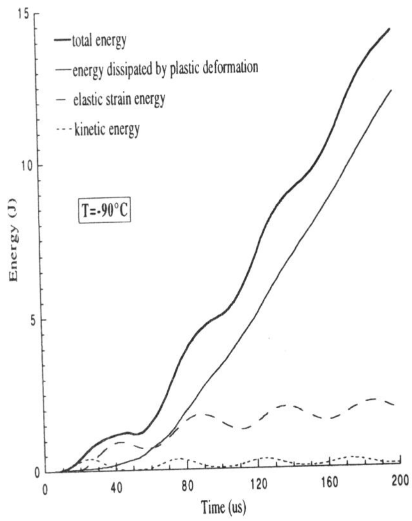

Figure 8 Energy balance for 2-D fully dynamic analysis