DYNAMIC CRACK INITIATION IN 3PB DUCTILE STEEL SPECIMENS

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Experiments and numerical simulations have been performed on dynamically loaded 3PB ductile steel specimens. The experiments have been carried out in the test facility at the Division of Solid Mechanics at Lund Institute of Technology. The calculations were performed by using FEM. The experimental set-up, as seen from above, is shown in Fig. 1. The experiments have been made at impact velocities of about 15, 30, and 45 m/sec and 320 x 75 x 18 mm quarter notch specimens were used. In contrast to most of the 3PB experiments presented in the literature, the specimen was struck at its ends instead of at the midpoint. To achieve this a U-shaped hammer was used. Experiments have been made at impact velocities of up to 45 m/sec, which is about three times the velocity that can be reached in a drop weight tower test facility.

Material. The material used is pronounced ductile at static loading. The chemical composition from the test protocol for the Mn-alloyed, normalized steel (Swedish notation SIS2134) is: 0.14% C; 0.30 Si; 1.41 Mn; 0.014 P; 0.011 S; 0.045 Al; 0.030 Nb; 0.008 V; 0.005 N; 0.004 Mo; 0.009 Cu; 0.02 Cr, 0.04% Ni. Charpy V impact test at –20°C: average 223 Nm. The yield stress is 377 MPa and the ultimate stress is 540 MPa.

Measurements. High speed photography with a frame rate of 100,000 frames per second was used for overall recording of the event and for detailed measurement of crack initiation and Crack Mouth Opening Displacements (CMOD). A force transducer is incorporated in the mid-support. The time for impact was detected by the strain gauge placed close to one of the end points where the hammer hits the specimen. CMOD was measured from the high speed photos by means of a microscope.

Force Recordings and Bouncing Phase. When the specimen is hit by the hammer, it is first bounced away from the mid-support. The "bouncing time" was detected by the mid support force recording and it was 160 µsec for 15 m/sec and 190 µsec for 45 m/sec.

High Speed Photos. Two series from experiments run at 15 m/sec and 45 m/sec will be discussed. All time values presented have an accuracy within 10 µsec and are given from impact, detected by the end strain gauge. From the 15 m/sec series three courses of events will be pointed out:

1. Incipient crack surface separation is seen 50 µsec after impact.
2. The plastic deformation in front of the crack outlined by the shadow from the edge of the depression caused by plastic deformation in front of the crack tip is first seen 170 µsec after impact. Thereafter the plastic zone becomes enlarged.
3. The crack starts to grow slowly and no clear crack initiation is found in this series. Asymmetric plastic deformation in front of the crack tip appears: it is first seen 565 µsec after impact. Crack growth, also asymmetric and visible on the specimen surface is first seen 835 µsec after impact.

The experiments run at 45 m/sec display a partly different pattern. The courses of events obtained from the high speed photos show the following:

1. Incipient crack surface separation is seen 50 µsec after impact.
2. The shadow indicating plastic deformation is first seen 100 µsec after impact.
3. Starting 190 µsec after impact, the plastic deformation shows a narrow ditch as compared to the more shallow depression of the experiment performed at 15 m/sec. This ditch reveals crack growth in the interior of the specimen. Asymmetric plastic region and visible crack growth are obtained at 170 µsec and 220 µsec respectively. Crack arrest is obtained and a ditch revealing a second brittle central crack is developed 800 µsec after impact.

Determination of the instant when the crack starts growing is, quite obviously, a very delicate matter. The crack starts to grow in the specimen interior, and it can grow for quite a while before it reaches the specimen surfaces. Apart from direct observation of crack growth visible on the specimen surfaces, one has, in principle, two possibilities. One is to draw conclusions...
from the development of necking in front of the crack. Whereas a shallow plastic region can appear without interior crack growth, necking appears to be clearly associated with such growth, except, of course, when crack growth occurs through necking over the entire specimen thickness, as would be the case for very thin specimens. It also seems to be safe to assume that when necking is first observed, interior crack growth has been going on for a while. The other possible conclusion concerning onset of crack growth is to study CMOD which can be fairly accurately determined from the high speed photos. Comparison with numerical simulations assuming no crack growth could then possibly reveal the onset of crack growth earlier than the observation of necking.

The time for crack initiation obtained from the photos will in the following be referred to as the “necking” and the “visible crack growth” times, denoted by $t_{\text{ncg}}$ and $t_{\text{vsg}}$ respectively.

**Crack Morphology.** The fracture from the 15 m/sec experiment displays a ductile surface. With the exception of a small triangular area with its base along the original crack front, 45 degree shear fracture is obtained through the specimen.

At 30 m/sec and 45 m/sec partial, brittle fractures are obtained characterized by a central part with pronounced crystalline surface and ductile 45 degree shear lips at the sides. For both 30 m/sec and 45 m/sec, crack arrest occurs about halfway through the specimen. The brittle part is oriented basically in the continuation of the crack plane.

**Numerical Simulation.** The numerical simulations were made using the commercial finite element code ABAQUS. The material was modelled as an isotropic elastic-plastic hardening von Mises material. No rate depending material property was included. The mesh used is shown in Fig. 2. Due to symmetry, only half of the specimen was modelled. Two-dimensional eight node plane stress elements were chosen. The mesh is concentrated near the crack tip where also the eight node elements are degenerated into 6-node triangular elements.

In order to model a possible loss of contact at the load point and at the mid support, gap elements with one degree of freedom were introduced, see Fig. 2.

The two impact heads are rigidly connected to the U-shaped hammer, i.e. the distance between them is constant. Forces parallel to the specimen front side will therefore be introduced due to friction and mechanical interlocking between the, close to the impact point, more or less plastically deformed specimen and the impact heads. The numerical simulations have therefore been made with two different boundary conditions at the load point in order to cover the two possible extremes: no friction at all and complete mechanical locking. One set of calculations was thus made with roller boundary condition and a second set was made where no motion parallel to the specimen front side was allowed.

**Comparison between Experiments and Numerical Simulations.** The experimentally and numerically obtained values for termination of the bouncing phase at the three different impact velocities are given in Table 1. Two sets of values are presented from the numerical simulations according to the two sets of boundary conditions used.