MODELLING OF PLUGGING FAILURE IN STRUCTURAL IMPACT

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Summary Finite element analysis of plate perforation is performed using a thermoelastic-thermoviscoplastic constitutive model and two uncoupled damage-based fracture criteria with unilateral conditions. The models are applied in explicit finite element analysis of localized shear plugging of a 12 mm thick steel plate struck by a blunt projectile in the sub-ordinance velocity regime. The results show that if unilateral conditions are properly introduced, the failure criteria give similar results.

INTRODUCTION

Finite element analyses of plugging failure of steel plates are carried out using a thermoelastic-thermoviscoplastic constitutive model combined with two different uncoupled damage criteria with unilateral conditions. Fracture is assumed to occur at a critical damage and crack propagation is modelled with element erosion. In addition, two other erosion criteria based on temperature and element distortion are used to get rid of troublesome elements which hamper the accomplishment of the simulations. The material parameters are determined based on inverse modelling of various material tests. The constitutive relation and fracture criteria are applied in explicit finite element analysis of the perforation of 12 mm thick Weldox 700E steel plates struck by blunt projectiles in the sub-ordinance velocity regime. The importance of including unilateral conditions in the damage evolution rule is shown. If this is not properly done, strain localization into narrow adiabatic shear bands is not predicted, and an unphysical failure mode is predicted. It is further shown that when unilateral conditions are introduced, adiabatic shear banding is properly described. In addition, a cut-off to the fracture strain for high pressures is important to describe fracture within the adiabatic shear band in the first phase of the penetration process where the stress state is pressure dominated. The physical explanation for this cut-off could be shear dominated failure at low pressures. Since damage is suppressed at low pressures, large strains are reached leading to high temperatures by adiabatic heating. The result is that the material loses its shear strength, which in this study is modelled by element erosion when the temperature reaches 90% of the melting temperature. This also allows for getting rid of troublesome elements that are overly deformed and often lead to premature termination of the simulations. The strong mesh size sensitivity in the plugging problem is investigated, and the results indicate that the solution will converged at an element size comparable to the width of the localized shear band observed experimentally.

EXPERIMENTAL RESULTS

The influence of strength on the ballistic properties of 12 mm thick high-strength steel plates was studied by Dey et al. [1]. The plates were made of Weldox 460E, Weldox 700E and Weldox 900E, where the numbers indicate the nominal yield strength of the material. The plates, which had 500 mm in diameter, were struck by projectiles having various nose shapes. The diameter, mass and HRC hardness value of the projectiles were 20mm, 197g and 53 in all tests, and a compressed gas-gun was used to launch projectiles within the velocity range from 150 to 400 m/s. For blunt projectiles failure occurred by plugging (Figure 1), while for conical and ogival projectiles ductile hole-enlargement was the governing fracture mode. A metallurgical study revealed strongly localized shear bands only in the plates struck by blunt projectiles [2]. The width of the localized shear band was found to decrease with increasing strength, from more than 100 μm for Weldox 460E to about 10 μm for Weldox 700E and Weldox 900E. The reasons for the strong shear band localization are primarily thermal softening and microstructural changes caused by adiabatic heating and growth of damage under large plastic strains. In this paper, only Weldox 700E plates struck by blunt projectiles will be considered.

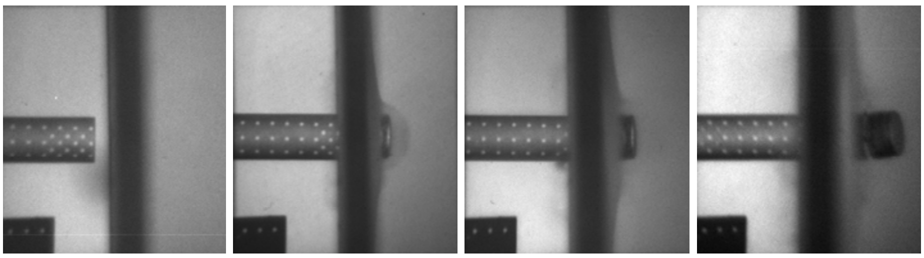

Figure 1*:* High-speed camera images showing perforation of a 12 mm thick Weldox 700E steel plates struck by a blunt projectile.

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NUMERICAL SIMULATIONS

Finite element analysis of the blunt projectile impact tests was carried out using the explicit solver of the non-linear FE code LS-DYNA. Four-node axisymmetric elements with one integration point and a stiffness-based hourglass control were used in all finite element models. Contact was modelled using an automatic 2D single-surface algorithm without friction. The constitutive relation was the modified Johnson-Cook model proposed in [4], while fracture was modelled either by continuum damage mechanics (CDM) or the Cockcroft-Latham (CL) criterion. The parameters of the models were determined based on inverse modelling of various material tests. A detailed description of the different models and the identification of material constants can be found in [3].

Element erosion by an element-kill algorithm was used in the simulations to remove elements. The damage criterion causes element erosion when $D \geq D_c$. To get rid of elements with hardly any load-carrying capacity left, elements were also removed when $T_c \geq 0.9T_m$, i.e. at a critical temperature T_c close to the melting point of the material. The result is that a cut-off is introduced for the fracture strain at high pressures where damage is suppressed. This cut-off, which is only activated at very large strains and high pressures, is independent of the stress triaxiality and the Lode parameter but depends slightly on the strain rate. To avoid overly distorted elements which reduce the time step and could cause error termination, elements with aspect ratio less than 0.02 were deleted. The aspect ratio is defined as the ratio between the short and long diagonal, and is thus a measure of the shear deformation of the element. Both the critical temperature and the critical aspect ratio were determined not to disturb the crack prediction significantly.

A main observation from the simulations is that simple damage criteria with unilateral conditions and a cut-off value for the fracture strain at high pressures are able to predict shear localization and plugging failure. Figure 2 demonstrates the crack propagation and fracture process during perforation using the CL fracture criterion and 800 elements over the target thickness. The impact velocity was 220m/s, while the residual velocity was estimated to 125m/s. The extreme localization in the problem is clearly seen, and the plastic strain in the narrow shear band is well above 1.5. Even though much refined, only one row of elements was eroded along the major part of the crack path. It is also found that the failure criterion based on continuum damage mechanics and the Cockcroft-Latham failure criterion give similar results.

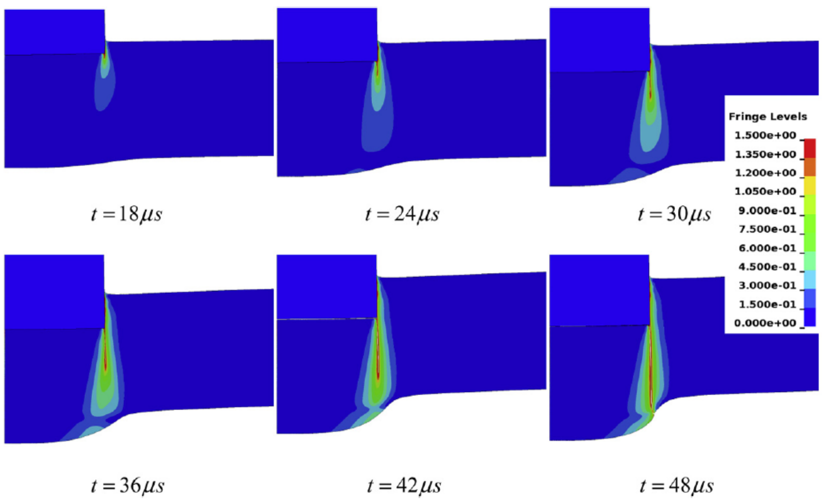

Figure 2: Strain localization (plotted as fringes of the equivalent plastic strain) and crack propagation using the Cockcroft-Latham (CL) criterion and 800 elements over the target thickness giving an element size of 15 μm ($v_i = 220$ m/s , $v_r = 125$ m/s).

CONCLUSIONS

The main conclusion from this study is that simple damage criteria with unilateral conditions and a cut-off value for the fracture strain at high pressures are able to predict shear localization and plugging failure. If unilateral conditions are not properly introduced in the damage evolution rule, strain localization into narrow adiabatic shear bands is not predicted, and an unphysical failure mode is predicted. It has also been shown that for this particular problem, the CDM criterion with unilateral conditions and the CL criterion give similar results.

References

[1] Dey S., Børvik T., Hopperstad O.S., Leinum J.R., Langseth M.: The effect of target strength on the perforation of steel plates using three different projectile nose shapes. *Int. J. Impact Eng.* **30**:1005-1038, 2004.

[2] Solberg J.K., Leinum J.R., Embury J.D., Dey S., Børvik T., Hopperstad OS.: Localised shear banding in Weldox steel plates impacted by projectiles. *Mech. Mater.* **39**:865-880, 2007.

[3] Kane A., Børvik T., Berstad T., Hopperstad O.S.: Failure criteria with unilateral conditions for simulation of plate perforation. *Eur. J. Mech. A-Solid* **30**:468-476, 2011.

[4] Børvik T., Hopperstad O.S., Berstad T., Langseth M.: A computational model of viscoplasticity and ductile damage for impact and penetration. *Eur. J. Mech. A-Solid* 2001;20: 685-712.