VIII International Conference on Computational Plasticity
COMPLAS VIII
E. Oñate and D. R. J. Owen (Eds)

EXPERIMENTAL CHARACTERISATION AND COMPUTATIONAL MODELLING OF FAST CRACK GROWTH IN HIGH STRENGTH STEEL SHEETS

Amber Walker, Li Wang, Ben Elliott, Arin Jumpasut and Nikica Petrinic

Impact Engineering Team, Solid Mechanics and Materials Engineering Group
Department of Engineering Science, University of Oxford, UK
e-mail: amber.walker@stcatz.ox.ac.uk, web page: www.eng.ox.ac.uk

Key words: Impact Engineering, High Strength Steel, Fast Crack Growth.

Summary. *This paper outlines the procedures for experimental characterisation of dynamic fracture in ductile materials and validation of computational tools for predictive numerical modelling of fast crack growth in pre-stressed high strength steel panels subjected to impact loading. The arguments for undertaking the proposed experiments are summarised, the experimental procedures are outlined and the modelling methodology is presented in view of inverse modelling of material parameters for the constitutive model. Comparison of experimental and numerical results within the purposely developed inverse modelling framework seeks to improve predictive modelling of damage evolution in dynamic ductile fracture process thus enabling accurate simulation of impact phenomena.*

1 INTRODUCTION

Good understanding of the common types of failure is vital to engineering design as it is essential to keep in check the parameters that limit load-carrying capacity thus ensuring structural integrity of the mechanical systems under consideration. Most research efforts involving material fracture are related to quasi-static loading conditions in which the inertia effect upon the development of the fracture process can be neglected. In these experiments the specimens and procedures for the ductile crack growth experiments have been standardised, e.g. compact tension specimen, side-grooved bending specimen, etc. [1]. This preponderance of static fracture in engineering applications accounts substantially for the fact that dynamic fracture problems have, historically, attracted less attention. However, an additional and obvious reason could be that dynamic fracture problems are analytically more complicated and experimentally more demanding than their quasi-static counterparts.

Most materials contain defects of one or many different types, such as fatigue cracks, corrosion, impurity inclusions or fabrication defects. If a pre-stressed structure made of such materials is quickly loaded, the strain energy is sufficient to accelerate a crack capable of growing in a catastrophic manner. This subject has been a main topic of interest to aerospace and automotive industries, because the recent advanced methodology in structure design and the introduction of new materials for these sectors demand better understanding of the fast crack propagation phenomenon. To investigate this dynamic behaviour of materials, a laboratory test was designed to reproduce the most significant features of the ductile fracture process in high strength steel supplied by an automotive manufacturer, with advanced high speed photography techniques and a bespoke program to process the films/images.

To simulate the experimental testing of fast crack propagation, the Bammann Damage model was employed in the commercial software LS-DYNA3D. The Bammann Damage model couples temperature dependent isotropic elasto-visco-plasticity and scalar damage mechanics, and the material's behaviour is described in a range of equations using some parameters, which can be obtained from simple experiments and numerical analyses. Implementation in the in-house software DEST allowed improvements to the model that account for non-symmetric tension/compression behaviour and introduce a length scale into the evolution of damage which virtually removes the mesh dependency of simulations.

Experimental results and the numerical models were compared primarily using the information on surface displacements obtained by tracking dots on the surface of the specimen. The data was extracted from a series of photographs by means of the in-house image analysis program. The simulation results were in good agreement with the experimental data. The developed integrated experimental-numerical approach to predictive modelling forms a broad basis for the study of dynamic failure in materials of relevance to many sectors of industry regarding to safety and design. This work aims to explain better how damage evolves under dynamic conditions and how current material characterisation and numerical modelling techniques for simulation of impact phenomena can be improved.

2 EXPERIMENTAL METHODOLOGY

2.1 Materials and Tensile Testing at Different Rates of Strain

The material used in this investigation was a high strength steel in a virgin state, supplied by a car manufacturer. Specimens of the same geometry were used in a series of uniaxial tensile tests at all loading rates in order to remove any geometric size effects thus enabling direct comparison of results obtained at distinct rates of strain. The specimen geometry is shown in *Figure 1.*

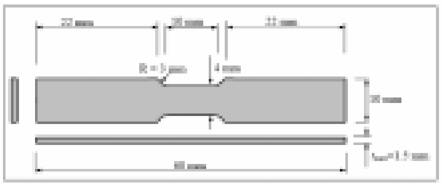

Figure 1. Flat parallel gauge steel tensile specimen

2.2 Fast Crack Propagation

The specimens for crack propagation under impact loading were designed to be of sufficient length and width to allow pre-loading with a stress approaching two thirds of the yield stress, and to achieve a steady crack propagation velocity (*Figure 2).*

The preload is applied to the specimen by means of two pneumatic cylinders with a capacity of 80 kN. A wedge-tipped impactor is used to open up the notch and thus initiate the crack. The impactor is driven against the specimen by a cylindrical rod – a projectile accelerated by a gas gun and running on nylon bushes within the gun barrel. Triggered by a strain gauge attached to the impactor, a digital camera provides high-speed photographs of the experiment. In order to take advantage of the recorded images, a grid of small black dots (spaced at 2mm) was printed on the central part (40mm wide) of the front surface of the specimen. In-house software was developed to process the images. The software is designed to track the motion of the dots over time in the x-y plane of the loaded panel. History of the positions of individual dots can then be compared to displacements of the corresponding particles within the finite element model (*Figure 3).*

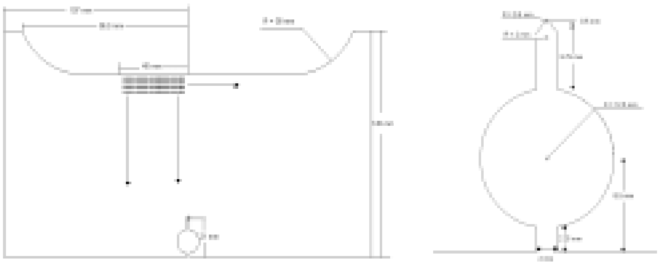

Figure 2. Steel specimen schematic

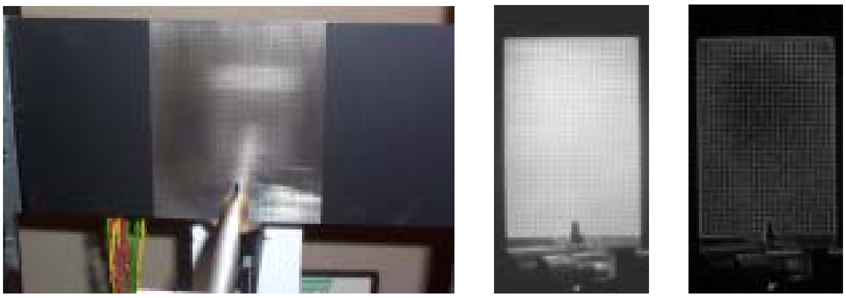

Figure 3. Progression from experiment to high-speed photograph to analysed image

3 NUMERICAL MODELLING

3.1 Materials and Tensile Testing at Different Rates of Strain

Initially, in the simulations of fast crack growth in steel panels, the original Bammann Damage model, developed by Sandia National Laboratory, was used in this investigation. This model couples the temperature dependent isotropic elasto-visco-plasticity and scalar damage mechanics, and has been used to analyse different types of loading conditions for various materials and has proved general enough to solve useful engineering problems that were previously difficult to solve [2]. Internal state variables are used to model the deviatoric plastic flow in a hardening-minus-recovery format, and damage is measured as a scalar internal variable closely following the Cocks-Ashby model of damage evolution [3].

3.2 Calibration of the Material Parameters from Simple Tensile Tests

The material parameters were determined from the tensile testing results at different rates of strain, e.g. yielding parameters, hardening parameters, etc. while ignoring temperature dependency of the parameters, since all experiments were conducted at room temperature. The calibration of the material parameters in the constitutive model was carried out by comparing the simulation results with the experimental data. This optimisation process was done using in-house software DEST. The inverse modelling approach explicitly tries to match the outcomes of laboratory experiments and numerical simulations. The virtue of a given set of parameters is described by the use of an objective function, which measures the difference between experimental results and the corresponding numerical results. The problem of finding the optimal parameters may then be cast as an inverse problem, where the objective function is to be minimised.

3.3 Fast Crack Growth Simulation

A finite element model of the fast crack specimen was created in MSC-Patran using 8-node brick elements. Element size ranged from 0.5 mm around the crack path to nearly 2 mm at the outer edges of the specimen. The analysis was carried out in two stages using the explicit solver LS-DYNA3D. The first stage represents the quasi-static pre-load by the pneumatic cylinders and the second simulates the impact by the wedge projectile and rapid propagation of the fracture through the panel width. Element failure was based upon the level of damage in each element, the load carrying capacity of which was lost when the threshold value was reached. *Figure 4* illustrates this process.

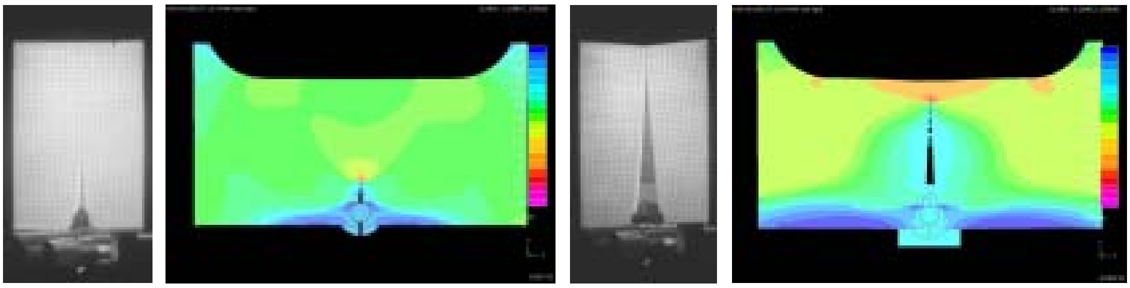

Figure 4. Photographs of crack growth during experiment compared with LS-DYNA3D simulations

4 CONCLUSIONS

Results of the adopted numerical modelling procedures show good agreement with data extracted from the experiments by means of high-speed photography. The material parameters determined from the inverse modelling of uniaxial tensile tests provided an accurate description of the material's behaviour. Further improvements are being investigated by means of inverse modelling of the dynamic ductile crack growth test, as the results from these experiments provide better information on the evolution of damage preceding ductile fracture in metals for automotive applications.

REFERENCES

[1] BS 7448 : Part 1 : 1991, *Method for determination of* K_{1c}*, critical CTOD and critical J values of metallic materials.*

[2] Bamman, D.J., Chiesa, M.L., Horstemeyer, M.F., and L.I. Weingarten, Failure in Ductile Materials Using the Finite Element Method, in: *Structural Crashworthiness and Failure,* (N. Jones and T. Weirzbicki, Editors), Elsevier Applied Science, pp. 1-54, 1993.

[3] Petrinic,N., Wang,L., Elliott,B.C.F.: *An Approach to Predictive Modelling of Failure in Metals Subjected to Impact Loading*; Proceedings of the 7th International Conference on Computational Plasticity COMPLAS2003; Barcelona; 2003.