HIGH RATE DEFORMATION BEHAVIOUR DURING EXPLOSION LOADING OF STEEL

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For the failure prediction of dynamically loaded structures, experiments will be performed to investigate the materials failure behaviour under high rate loading. This research is carried out in conjunction with the TNO-Prins Maurits Laboratory, a defence research organisation. Results will be used for improvement of naval frigates. Several experiments have been done at low strain rates to determine the materials plastic behaviour. New experiments at high strain rates will reveal the materials strain rate sensitivity. Plastic strains are being measured by high speed film technique and subsequent analysis of the images.

INTRODUCTION

During the past ten years research was carried out on the structural response of naval ship compartments on dynamic loading caused by internal explosion of a warhead. This research has led to a new project at the Delft University of Technology, named: Prediction of the Failure Behaviour of Dynamically Loaded Structures by Local Fracture Criteria. This project aims at an improvement of modelling techniques for the failure prediction of welded (ship) structures under dynamic loading. Finite element calculations will be used to simulate the onset of rupture in the loaded ship panel. For this purpose the finite element code Abaqus will be used. Several failure models will be implemented and results will show the ability for accurate failure prediction in dynamic loading cases. After selection of an accurate model, this model will be verified on experimental results of several geometry's of tensile specimen. Final validation of the model will be done using test data from experiments on structural parts.

EXPERIMENTAL SETUP

For the investigation of the material behaviour at high strain rates, an experimental setup has been build. This setup consists of a high rate loading machine along with a load

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measuring device and applications for strain measurement. A schematic view of the test setup is shown in figure 1. In the following sections each component of this setup will be highlighted and some practical problems discussed.

High Rate Loading Machine

A servohydraulic high rate single shot testing machine (ESH 1855, 50kN) has been upgraded with a new digital controller (Dartec 9600 series). Speeds can be achieved of about 9m/s in tension and compression. High rate loading is applied in this way to achieve loading rates similar to explosion loading of a ship panel. To start the experiment at the proper rate, a "lost motion device", see figure 2, is being applied for freely accelerating the actuator of the machine without the specimen being loaded. This device has been derived from an example at the Imperial College, London.

Load Measurement

Load measurement has been done first with a standard loadcell, which came with the machine. However, to get more accurate results, a piezoelectric loadcell has been applied which has been mounted on the standard loadcell. In this setup, the appearance of a low-frequency distortion was measured on the piezocell signal. To gain more insight in this phenomenon, the setup has been considered to act like a mass-spring system. Mass and stiffness results in a undercritically damped oscillating mechanical system. An example of the measured response from the piezoloadcell during a high-speed tensile test is given in figure 4 (tensile force is given in negative direction). It is seen from this figure that also a high frequency oscillation is apparent in the loadsignal, which results from the resonance of the piezotransducer itself (loadcell ringing). For appropriate measurement of the dynamic load, numerical filtering of the piezosignal will be done.

In addition, a dynamic measurement of the load will be done using a dynamometer, in which the force is computed from the elastic deformation of a larger area section in the tensile specimen. This elastic deformation is being measured using a strain gage. An adequate DC-amplifier has been build to improve the signal response of the Wheatstone bridge. This amplifier has sufficient bandwidth (100 kHz), and uses a differential input to eliminate signal noise from the electrical circuit. The risetime is sufficiently short to follow the rise in the load signal in the elastic region of deformation of the specimen.

Strain Measurement

An experimental technique for plastic strain measurement is being applied using a high-speed drum camera (Cordin Model 350 Drum Camera). From the frames taken by this camera, the diameter reduction and necking phenomenon will be studied. In the chapter on derivation of the materials flow behaviour from optical measurements, this issue will be highlighted.

The drum camera operates at a maximum framing rate of 35,000 frames per second. Main advantage of this camera is the high accuracy and relatively large area of the frame (10 x 7.5 mm). In this setup, an objective lens is being used from Rodenstock, type: Rogonar-S, 1:4.5, f=150mm. This lens gives 1:1 optics at a distance of 60 cm from the mounting thread to the object; a round tensile bar of 5 mm diameter. The film type used is Kodak Tmax 400 BW (TMY 5053) which gives satisfactorily results. In combination with the camera, a manual camera controller is being applied (Model 441 Camera Controller) from which the drum speed in revolutions per second can be measured. The light source used is a Model 659 Light Source from the Cordin company, which gives a constant illumination level for an adjustable time period, varying between 0.5 and 11 milliseconds. For longer periods an alternative light source will be used. The time interval (Ti) for the sequence of frames is being derived from the measured drum speed and the number of frames per drum revolution. Exposure time of each frame is 6.63% of the interframing time Ti , and can be altered by changing internal stops of the camera, resulting in either a half or a double exposure time.

Another way to measure the strain is provided by the use of strain gages. The strain gage will only represent the first 5% strain, because of its limited range of application. The signal from this gage, which will be mounted on the gage length of the specimen, will be conditioned in a similar way as the strain gage signal for the dynamic load measurement. More accurate strain measurement will be obtained from this gage in comparison with the camera frames for small strains.

Triggering

Synchronisation of data acquired from several measuring devices will be done by the use of triggerpulses to start sequentially these devices. Schematically a time event chart is given in figure 3, the trigger pulse comes up at an adjustable level of the actuator displacement. Before the test starts, the camera shutter will be opened manually; daylight exposure is negligible for it's relatively low intensity and short exposure time of each frame.

DERIVATION OF THE MATERIAL'S FLOW BEHAVIOUR

For the characterisation of the material's flow and fracture behaviour, the data from the optical and strain gage measurements will be used. From these measurements the actual stress in the specimen can be obtained, as well as the flow stress of the material. Standard methods are being used to convert the engineering strain into true (logarithmic) strain. The strain is being calculated from the optical data according to equation 1.

$$\varepsilon_{true} = 2\ln\left(D_0 / d\right) \qquad \text{Eq. (1)}$$

The corresponding flow stress in the material relates to the actual stress in axial direction of the specimen in a way stated by von Mises. This flow stress can be found from measurement of the shape of the neck using Brigman's relation, reference (1), to correct for multiaxial stress components. A digital image processing technique will be used to obtain data on the radius of the neck, for this purpose the film has to be transferred to digital format using a high resolution 35 mm automated film scanner.

Because of slight anisotropy in thickness direction of the rolled plate material, the initially round cross section of the specimen develops to an oval shape at continuing strain. From measurements at low strain rates the plastic strain ratio r (strain in thickness direction of the plate divided by strain in longitudinal plate direction) has been obtained and will be used to calculate diameter reduction in perpendicular measuring direction when only one diameter is being measured at high strain rates.

LOW STRAIN RATE RESULTS

Using the procedure mentioned above, some results were obtained from low rate tensile tests; high rate tests will take place in the near future. Digital images were taken with two cameras (Jai monochrome CCD camera) in mutually perpendicular directions and analysed with application software (TimWin). Results are shown in figure 5. In this figure two more correction methods have been applied which lead to different results, see reference (2). From these low strain rate results, the materials strain rate dependence has been evaluated at the maximum tensile stress. A slight increase of the maximum (and yield-) stress has been observed, the tendency for the fracture strain is not quite visible in this low strain rate regime, higher rates has to be applied to make this clear. Applied strain rates vary from 1 e-4 to 6 e-2 per second in the uniform strain range.

Ductile failure of each specimen has been observed and expected failure behaviour at room temperature is ductile for the strain rate regime up to 150 per second. Several different geometry's of tensile specimen will be tested in the near future as to reveal the materials dependence on stress triaxiality. These tests will be reproduced at high strain rates.

CONCLUSIONS

High rate testing in tension of steel implies several phenomena to be accounted for. First, no vibrations should disturb the mechanical behaviour to be measured, resonance of the system should be avoided or accounted for in subsequent data analysis (filtering). Second, the impact loading of the specimen will introduce stress waves of which notice should be made when analysing load data from strain gage measurements on the elastic region of the specimen. Third, the signal amplification should occur at sufficient speed to avoid signal attenuation caused by low bandwidth of the amplifier.

The material shows slight anisotropy and rate dependent behaviour. No evident influence on the fracture strain has been measured at low strain rates.

ACKNOWLEDGEMENT

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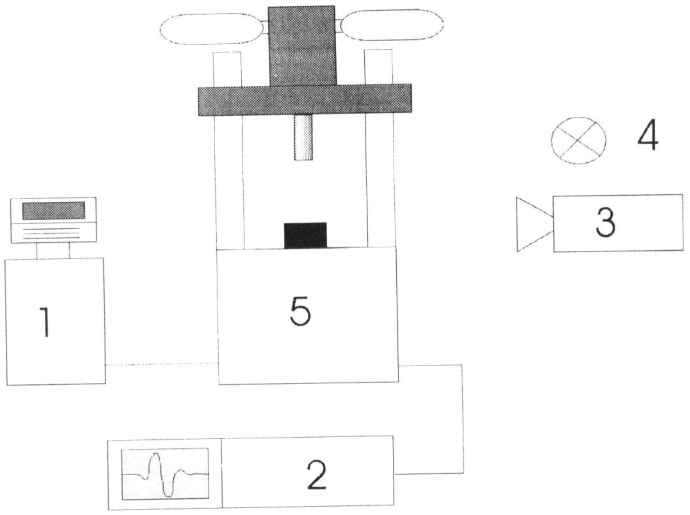
(2) Bakker, A., "Numerical Methods in Fracture Mechanics", Proc. of 5th int. conf. Edited by A.R. Luxmoore and D.R.J. Owen, Pineridge Press, U.K., 1990.



1= controller; 2=oscilloscope; 3=drum camera; 4=flash light; 5=high rate tensile machine

Figure 1. Schematic view of test setup for high strain rates

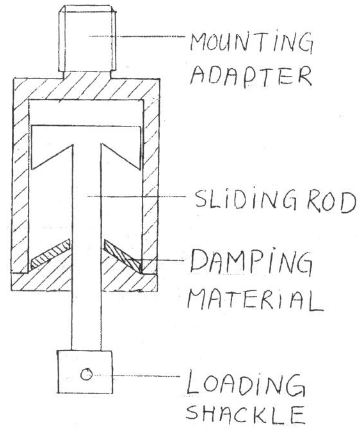


Figure 2. Lost Motion Device

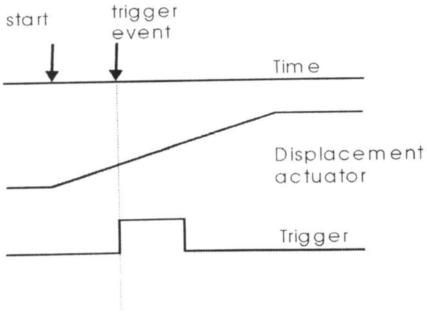


Figure 3. Time scheme for triggering

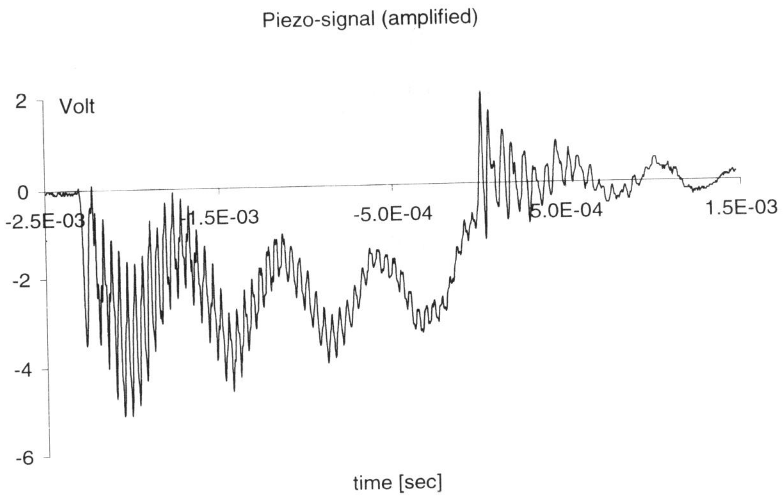


Figure 4. Measured signal from piezotransducer during a tensile test

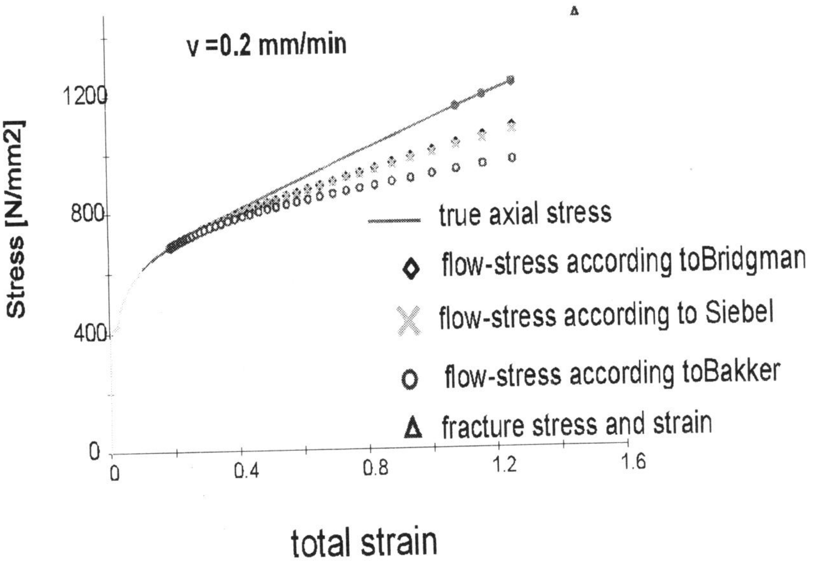


Figure 5. Corrected axial stress to flow stress