Testing in Support of the Development of Accurate Numerical Simulations of Plastic Deformation and Failure

Amos Gilat[1], Jeremy D. Seidt[1]

[1]The Ohio State University
Department of Mechanical and Aerospace Engineering
Columbus OH, USA

1 Abstract

Testing in support of the development of materials models in numerical simulations consists of material characterization tests and validation tests. Testing at various strain rates, temperatures, and loading conditions is used for characterizing plastic deformation and failure of materials. The data from the tests is used for developing constitutive equations (material model) that are utilized in numerical codes that are used for simulations of practical applications. Emphasis in the present paper is on the significance of the Digital Image Correlation (DIC) method for measuring full-field deformations and the development of new tests. It includes the use of DIC in Split Hopkinson (Kolsky) Bar (SHB) tests (compression, tension and torsion), a special apparatus, consisting of a hydraulic actuator and a very long transmitter bar, for tests at intermediate strain rates (50 s^{-1} –200 s^{-1}), tensile tests with DIC at elevated temperatures (up to 850°C), and simultanious full-field deformation and temperature measurement in tensile tests at low and high strain rates. Many of these tests have been used during in the development of the deformation and failure model (MAT224) in LS-DYNA. The model is based on experimental determination of a failure surface that gives the equivalent plastic strain to failure as a function of stress triaxiality and the Lode parameter. In validation tests material specimens or components are subjected stress states that are different than the ones used for determining the material models. The tests are simulated and predictions of loads, deformation and failure are compared with measurements. Two examples of validation tests, the punch test and the spot weld test, are presented.

2 Background

Numerical simulation of the response of materials under applied loads has reached a level of maturity at which it can be used with confidence for design purposes. Numerical codes like LS-DYNA include many material models for deformation and failure (constitutive relations) that can be selected for specific applications. The various models require input parameters that are specific to the material that is being simulated. The accuracy of the simulations depends on the values of the input parameters which are determined from experimental data.

In general, testing in support of the development of accurate materials models can be divided into two groups. In one group are characterization tests that are used for the derivation of the parameters in the material models, and the other group are validation tests. When plastic deformation and failure are involved, the characterization tests consists of uniaxial stress state tests and combined stress state tests. The uniaxial stress tests consist of tension, compression and shear tests at various strain rates and temperatures. This data is used for obtaining the parameters of the plasticity model. The combined state of stress tests are used for calibrating the failure models. The objective is to conduct tests with various combination of stresses and measure the strain at failure. The results from these tests are used for verifying the plasticity models for the deformation, and for deriving the values of the parameters in the failure and damage models. The second group of tests are validation tests. These are well instrumented tests in which material specimens are loaded in a non-uniform combined state of stress that are different from the characterization tests. The validation tests can also include tests on small components (e.g. welded connection, channel crush beam). The validation tests are simulated numerically using the constitutive models for plasticity and failure that were developed based on the data from the characterization tests and the simulation results are compared with the experiments.

The present paper reviews testing configurations and techniques that have been developed recently for the purpose of providing accurate data for determining the parameters in material models for deformation and failure. Of special interest is MAT224 which is a relatively new deformation and failure model in LS-DYNA. The input requires stress strain curves from tests at different strain rates and temperatures and values of equivalent failure strain at various state of stress (various combinations of stress triaxiality and Lode parameter).

3 Uniaxial Stress Tests at Various Strain Rates and Temperatures

Uniaxial (tension, compression, shear) tests can be done at various strain rates and temperatures. At quasi-static strain rates between 10^{-4} s^{-1} and 1 s^{-1} tests are done using a hydraulic machine. At strain rates above 500 s^{-1} tests are done using the split Hopkinson bar (SHB) technique. A special machine was developed for testing in tension and compression at intermediate strain rates of 20 s^{-1} to 200 s^{-1}. The technique is a hybrid of a SHB and a hydraulic machine. A specimen that is placed between the end of a long bar and a hydraulic actuator is loaded by the hydraulic actuator, Fig. 1. As the specimen is loaded, a wave propagates to the end of the bar and reflects back. The force in the specimen is measured by strain gages that are placed on the bar and the strain in measured directly on the specimen with DIC. The actual setup is shown in Fig. 2.

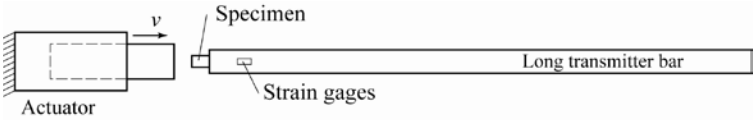


Fig.1: Schematic of the intermediate strain rate apparatus.

Fig.2: Intermediate strain rate apparatus.

The bar is more than 40 m long which allows a test duration (until the reflected wave arrives at the strain gages that measure the force) of more than 0.016 s. At a strain rate of 20 s^{-1} it provides enough time for the specimen to deform to a strain of 0.3. Results from tensile testing of HHS at various strain rates are shown in Fig. 3.

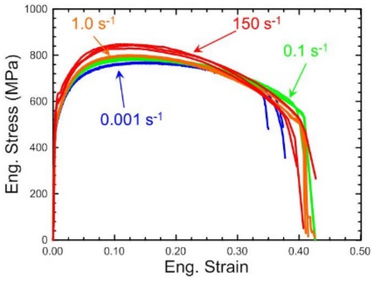
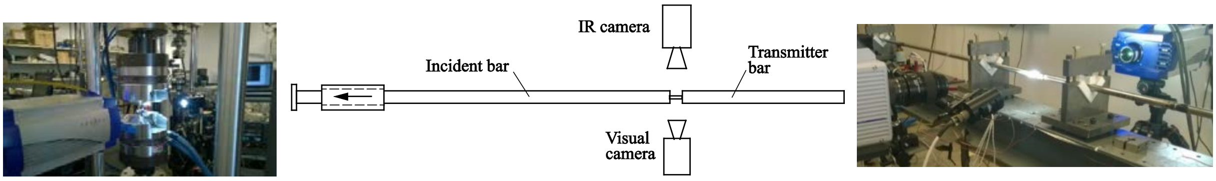


Fig.3: Tensile stress strain curves for HHS at different strain rates.

4 Simultaneous Full-Field Deformation and Temperature Measurements

A new experimental setup, in which full-field deformation and full-field temperature are measured simultaneously on the surface of a specimen during tensile tests at various strain rates has been recently developed. The setup consists of a flat thin specimen and visual cameras on one side of the specimen and a high speed IR camera on the other side. Tests at quasi-static stain rates are done using a servo-hydraulic load frame. Tests at high strain rates were done using a tensile Split Hopkinson (Kolsky) Bar (SHB) apparatus, Fig. 4. Example of DIC and IR images from a test with a specimen made of stainless steel at strain rate of 0.1 s^{-1} is shown in Fig. 5. The figure shows synchronized DIC processed images recorded by the visual camera and IR camera images at different times during a test. The figure show nearly uniform deformation and temperature rise at the early part of the test and localized deformation and heating during the necking. Quantitative data shows that in this test the maximum temperature in the necking area reaches 140°C. In tests at strain rates of 200 s^{-1} and 3,000 s^{-1} the maximum temperature exceeds 300°C. The data from this type of experiment can be used for a more accurate determination of material parameters in plasticity models.



(*a*) (*b*) (*c*)

Fig.4: Experimental setup with visual and IR cameras. (a) Servo-hydraulic load frame. (b) Tensile split Hopkinson bar, schematic. (c) Tensile split Hopkinson bar, photograph.

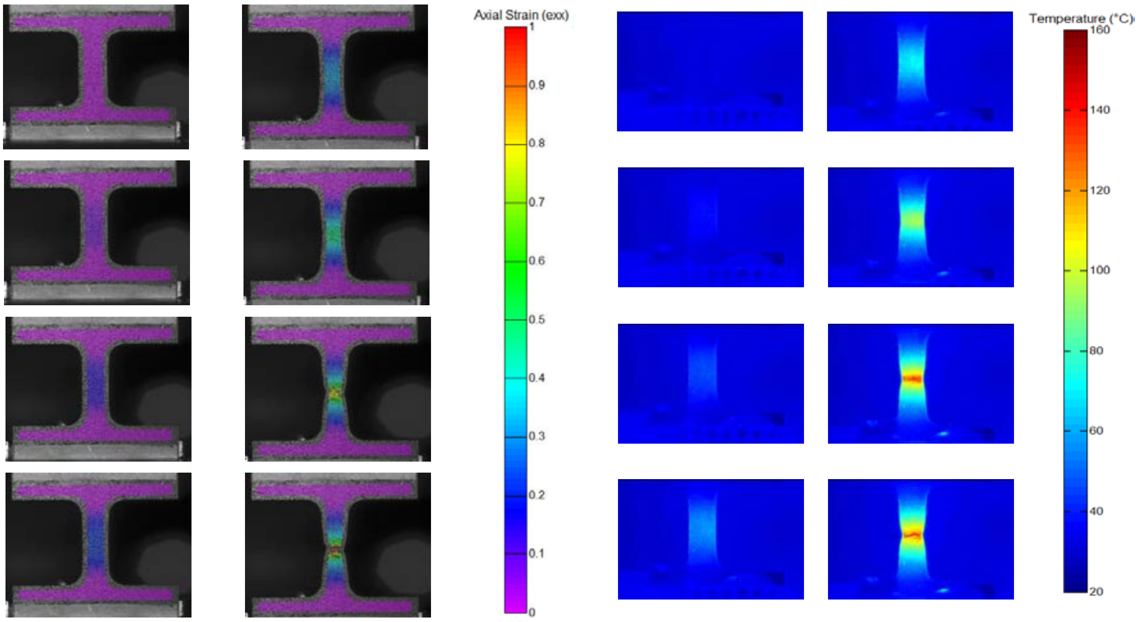


Fig.5: DIC (left) and IR (right) images recorded during a 0.1 s-1 strain rate tensile test.

5 Data for Determining Failure Surface

Data for determining the failure surface is obtained from tests in which the material is subjected to a combined state of stress. Examples are tension tests of notched flat and notched round (axisymmetric) specimens with different notch dimensions, plane strain tension experiments with smooth and notched specimens with different notch sizes, and biaxial tension-torsion and compression-torsion tests. Digital Image Correlation (DIC) is used in all the tests for a direct measurement of the deformation (full field) on the surface of the specimens. The force and DIC data together with numerical simulation of the experiments is used for determining the state of stress (triaxiality and Lode parameter) and deformation in the specimens throughout the test and at the instant of fracture. For example, a comparison between DIC experimental data and numerical simulation is shown in Fig. 6. DIC data from tensile testing of flat-notched-specimens with different notch sizes is shown in Fig. 7.

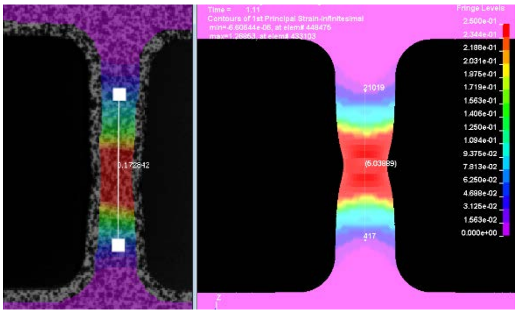


Fig.6: DIC data and numerical simulation of a tensile test.

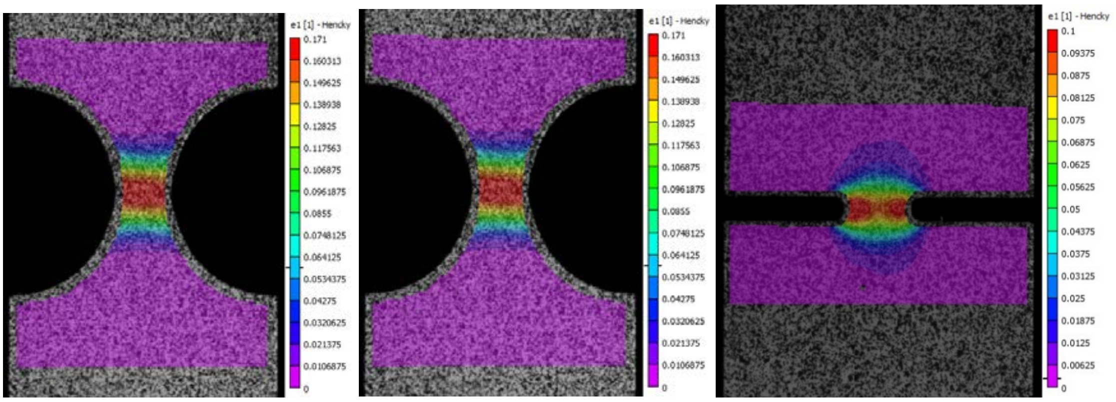


Fig.7: DIC data from tensile testing of flat-notched-specimens.

6 Static and Dynamic Punch Test

The punch test in which a punch is pushed into a plate can be used as a validation test for plasticity and failure models. By using punches of different geometry and plates with different thicknesses different state of stress and failure modes (petaling, spalling, plugging) can be formed. The test provides the history of the load, and by using DIC also the history of the deformation at the back side of the plate and details of the failure. The test can be done quasi-statically using a hydraulic frame or dynamically using the compression SHB apparatus. A setup of the dynamic punch test is shown in Fig. 8. DIC images and specimens tested are shown in Fig. 9.

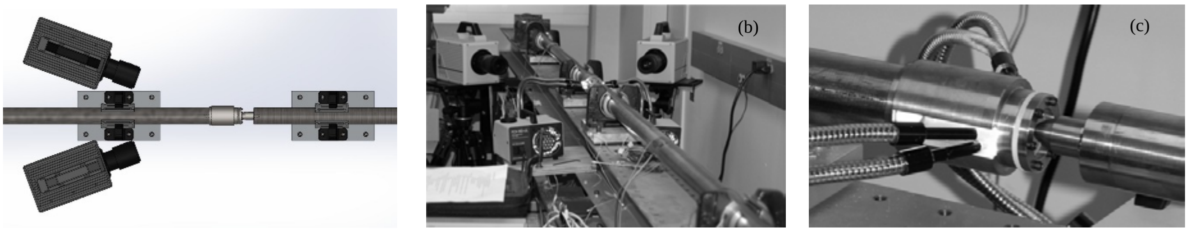


Fig.8: Dynamic punch test.

Fig.9: DIC images and specimens tested in the dynamic punch test.

7 Spot Weld Test

Spot weld joint test is an example of a validation test for plasticity and failure models of a component. A set up for such test where two DIC systems are used for measuring the deformations on different surfaces of the component is shown in Fig. 10. The experiment provides the history of the applied force and deformation throughout the test. Example of DIC data is shown in Fig. 11. The figures on the left and in the center show how the relative displacement between any two points can be measured, and the figure on the right shows a processed DIC frame with the strain during the test. A comparison of the measured force and deformation with the ones obtained from numerical simulation can be used to validate or possibly modify the material models in the numerical code.

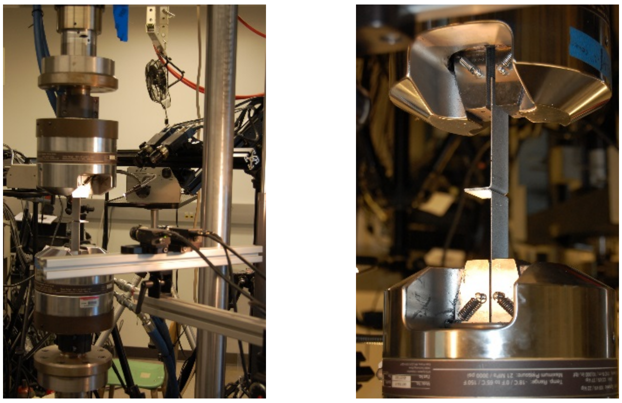


Fig.10: Experimental set up of a spot weld test.

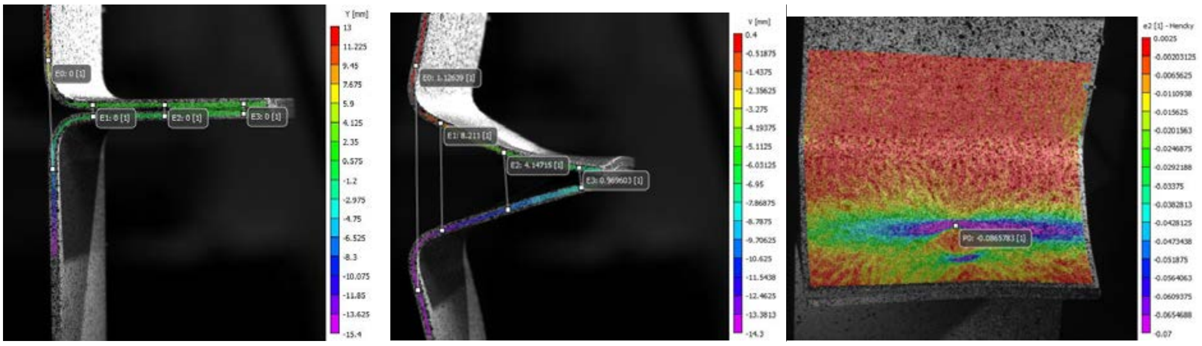


Fig.11: DIC data from a spot weld test.

8 Summary

The development of DIC and its integration into material and components testing have improved significantly the ability to develop more accurate materials models for plastic deformation and failure. Full-field DIC measurement of displacement and strains on the surface of a material specimen or a structural component can now be directly compared with finite element simulations. This is especially important in situations where the deformations are not uniform. Together with measurements of the applied loads the experimental data can be used to validate and improve the simulations.

Acknowledgements

The development of many of the testing techniques presented was supported by the U.S.A. Federal Aviation Administration, Grants No. 06-G-004 and 11-G-003. The authors are grateful to Mr. Bill Emmerling, Dr. Chip Queitzsch, and Mr. Don Altobelli of the FAA. The development of the intermediate strain rate test was supported by NASA, Grant No. NNX08AB50A.