Determination of high strain rate properties of metals using the virtual fields method

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Abstract. Due to the recent advances in ultra-high speed imaging it is now possible to combine full-field measurements with inverse techniques such as the virtual fields method to identify material properties at high strain rates. In this work an experimental technique to identify the elasto-plastic material properties of metals is presented. An ultra-high speed camera and the grid method are used to obtain time-resolved full-field deformation data as impact induced stress waves propagate in the metal samples. Using the virtual fields method two different types of virtual fields, stress gauge and sensitivity based, are compared. It was found that the sensitivity-based virtual fields improve the accuracy of the identification in the presence of noise.

Introduction

An understanding of the high strain rate properties of materials are essential for modelling phenomena such as aircraft/car crashes or bombing scenarios. For the models to be successful, it is crucial that the material parameters input in these complex finite element models are accurate. Characterisation of high strain rate properties of materials have been studied for decades using the split Hopkinson pressure bar (SHPB) as the standard testing tool. Nevertheless, the method suffers from several drawbacks and often its applicability is limited by the assumptions made for the SHPB [1], most notably the assumption of dynamic equilibrium. Recently, ultra-high speed cameras have progressed to the point that a stress wave traveling through material can be imaged. By employing full-field measurement methods such as grid method [2], it is possible to measure time-resolved displacements during high strain-rate tests. This approach enables the strain field over the entire surface of the specimen to be measured instead of the relying on point measurements and the assumption of homogeneity commonly employed for the SHPB. As a result a new generation high strain rate tests have been proposed.

The virtual fields method

In order to extract material properties from the full-field data, the virtual fields method (VFM) was employed [3]. In general, it relies on the principal of virtual work and enforces the dynamic equilibrium in the region of interest. Mathematically the VFM can be formulated as:

$$-\int_V \sigma : \varepsilon^* dV + \int_{\partial V} \boldsymbol{T}.\boldsymbol{u}^* dS = \int_V \rho \boldsymbol{a}.\boldsymbol{u}^* dV \tag{1}$$

where σ is the stress tensor, $\boldsymbol{T}$ is the traction applied on the boundary of the body ∂V, $\boldsymbol{a}$ is the acceleration, V is the volume of the body, $\boldsymbol{u}^*$ are the virtual displacements, and ε^* are the virtual fields (spatial derivatives of $\boldsymbol{u}^*$). The virtual displacements can be any function that is continuous and differentiable, thus there are infinite valid fields. The choice of virtual fields (VF) has a crucial impact on the quality of identified material parameters, as they act as spatial and temporal filters on the data. It is therefore necessary to select ones leading to accurate extraction. Currently, the standard procedure of selecting virtual fields in the case of dynamic testing is to use the so-called stress gauge approach. It enables the average stress for any given vertical cross section to be calculated from the average acceleration measured over a portion of the region of interest [4]. Although it is capable of reconstructing average stress-strain relationship, it is not optimal for localized deformation, e.g. in the case of plasticity where only a small sub-section of the material deforms plastically (and contains information on those parameters).

Sensitivity-based virtual fields. Recently, a new approach for generating high quality virtual fields for non-linear problems has been published, and was applied to a static test performed on a metal specimen [5]. These sensitivity-based virtual fields are constructed such that the virtual fields 'look like' the maps of stress sensitivity to the sought parameters, leading to a separate virtual fields for each of the parameters. These virtual fields highlight areas in the test, both in space and time, containing information about each parameter. Since they focus on areas rich in information, they improve the identification compared to the standard approach relying on average values. The sensitivity-based virtual fields can be directly translated to the dynamic testing. The main advantage is that they adapt dynamically to the data, which is essential in the case of the direct impact test where the region of the sample that has yielded changes over time.

Experimental protocol

In this work, two different metals, AL 6082 and 316L steel, were subjected to inertial impact tests. A white rubber paint was sprayed on each sample and then a black regular grid with a spacing of 0.9 mm was printed on the sample surface. Using the gas gun facilities in the Testing and Structures Research Laboratory, projectile was fired from a gas gun at 50 m/s. Light gates at the end of the gas gun were used to trigger the flash and a make trigger was used to start the camera. A Shimadzu HPV-X camera (400 x 250 px) was used to record 128 images of the impacted sample at 5 Mfps. The grid method with correction [2] was used to obtain the time-resolved displacement field from the collected images. After the displacement data was temporally smoothed, the acceleration was calculated by double differentiating the displacement. The displacement was then spatially smoothed and the strains were calculated by taking spatial derivatives.

Results and discussion

For comparison, quasi-static tests were performed on aluminium and steel tensile samples cut from the same sheet as the impact samples. Since the response of AL6082 is known to be strain-rate independent up to strain rates of 10^3, it was anticipated that the identified material properties for impact test would be similar to those identified from the quasi-static tests. Conversely, since the mechanical response of 316L is strain-rate sensitive the properties identified from the impact test was expected to be significantly higher. For the quasi-static and high strain rate identification, both the aluminium and the steel were assumed to obey a linear hardening model.

Table 1 shows the values identified for the yield stress and hardening modulus for the aluminium and steel specimens from quasi-static tests and impact tests using the stress-gauge virtual fields. The identification using the sensitivity-based virtual fields is on-going. In addition, to better quantify the difference in performance between the stress gauge and sensitivity-based virtual fields an image deformation procedure to simulate the experimental chain is also in progress.

Table 1: Identified plastic properties for AL 6082- T6 and 316 L

	Aluminium 6082 – T6		Steel 316 L	
	Yield stress	Hardening modulus	Yield stress	Hardening modulus
Quasi-static	272 ± 1 MPa	1.04 ± 0.04 GPa	301 ± 14 MPa	2.03 ± .22 GPa
Stress gauge	293 ± 24 MPa	1.92 ± 1.18 GPa	452 ± 13 MPa	4.72 ± 1.5 GPa

Conclusions

In this work, the elasto-plastic properties of aluminium and steel were identified using the stress gauge virtual fields. The identification with the sensitivity based virtual fields is underway and preliminary results on the aluminium samples indicate that both methods are capable of identifying the plastic properties. Further study, using image deformation, is required to determine which of the virtual fields more robustly identifies the parameters in the presence of noise.

References

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