Advances in high strain rate material testing

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Abstract

In this contribution, attention is focused on new developments and possibilities for advanced material testing using split Hopkinson bar setups. The possibility to test non-common materials (such as small diameter steel cords), and to generate more dimensional stress states (e.g. in a three-point-bending configuration) is outlined. In both tests very low amplitude signals have to be captured. Because measurement devices have become much more sensitive in recent years, these signals can now be measured with sufficient accuracy. Moreover, the technical specifications of high-speed imaging devices have improved tremendously. A technique to extract the deformation of a Hopkinson specimen from high-speed streak camera images—using geometrical Moiré and phase shifting—will be presented. Other advances, made possible by the increased availability of numerical tools, are enhanced signal processing and/or data extraction techniques. Finally, a combined numerical/experimental method to exclude the influence of the specimen geometry on the stress-strain curves extracted from classical Hopkinson experiments is presented.
Keywords: high strain rate, split Hopkinson bar, Kolsky apparatus, deformation measurement, bending test, steel cord, optimization.

1 Introduction

Due to the increased importance of issues related to the safety of for instance passengers during a car crash, or to the protection of buildings prone to terrorist attacks, there is an ever-growing need for reliable experiments providing mechanical properties of materials in impact circumstances. As a consequence, the use of split Hopkinson bar (SHB) devices has increased tremendously in recent years. During a split Hopkinson tensile bar (SHTB) experiment, a small material sample is subjected to a uniaxial tensile load at a high rate of strain.

WIT Transactions on The Built Environment, Vol 87,
www.witpress.com, ISSN 1743-3509 (on-line)
doi:10.2495/SU060091

Within certain limits, the strain rate in the specimen can be adjusted. The main advantages of SHB experiments are that test execution is relatively simple, and that the interpretation of the obtained results is straightforward.

Recently, advances have been made in the capacities of SHB devices both to test non-common materials and to allow a more profound material characterization. These advances are triggered by ever better performing *measurement devices*. SHTB experiments on materials which, because of their strength or geometry, involve low stress levels, were not possible using the classical, elastic metallic bars. Indeed, the amplitude of the signals needed to calculate the stress in these specimens was too small to be recorded. However, due to the availability of measurement devices with enhanced sensitivity and accuracy, signals previously immeasurable can now be captured. Bending experiments based on the SHB principle also involve small amplitude signals. So, for some materials even these tests are now possible. Bending experiments provide information on the high strain rate behaviour of the materials complementary to the information obtained by conventional tensile or compression Hopkinson bar experiments. This information can be used to validate material models developed based on solely uniaxial experiments.

The technical specifications of *high-speed imaging devices*, more particularly the spatial resolution and maximum frame rate, also improved tremendously. In this contribution, a technique will be presented to obtain the strain distribution along the length of a SHTB specimen during an experiment using a high-speed streak camera. By applying this technique, the classical assumptions concerning the specimen deformation, on which the interpretation of Hopkinson experiments is based, could be verified.

The progress and availability of *numerical methods* such as finite element techniques creates new possibilities as well. In literature, numerous studies can be found dealing with numerical simulations of experiments. These simulations not only provide new insight in impact experiments, but also allow optimisation of existing test setups, specimen geometries and interpretation of the obtained results. Here, a combined experimental/numerical technique is presented, which aims at optimizing the obtained stress-strain curve.

2 Split Hopkinson bar experiments

2.1 Steel cord experiments

A schematic representation of the split Hopkinson tensile bar (SHTB) setup at Ghent University is given in Fig. 1. The setup consists of two long bars, an input bar and an output bar, between which a specimen is sandwiched. A tube-like impactor is put around the input bar and accelerated towards an anvil at the outer end of this input bar. Thus, a so-called "incident" tensile wave is generated, and propagates along the input bar towards the specimen. The incident wave interacts with the specimen, generating a reflected and a transmitted wave. The strain histories $\varepsilon_i(t), \varepsilon_r(t)$ and $\varepsilon_t(t)$ corresponding to respectively the incident, reflected and transmitted wave are usually measured by means of strain gages at well-chosen points on the Hopkinson bars.

The history of the stress, the strain and the strain rate in the specimen are derived from the measured waves, using the following expressions [1]:

$$\sigma(t) = \frac{A_b E_b}{A_s} \varepsilon_t(t)$$
$$\varepsilon(t) = \frac{U_{ob} - U_{ib}}{L_s} = -\frac{2C_b}{L_s} \int_0^t \varepsilon_r(\tau)\, d\tau \qquad (1)$$
$$\dot{\varepsilon}(t) = \frac{V_{ob} - V_{ib}}{L_s} = -\frac{2C_b}{L_s} \varepsilon_r(t)$$

with

- L_s the gage length of the specimen
- E_b the modulus of elasticity of the Hopkinson bars
- C_b the propagation velocity of longitudinal waves in the Hopkinson bars
- A_s and A_b the cross section area of the specimen and of the Hopkinson bars
- U_{ib} and U_{ob} the displacements of the interface between the specimen and, respectively, the input bar and the output bar, and V_{ib} and V_{ob} the corresponding velocities

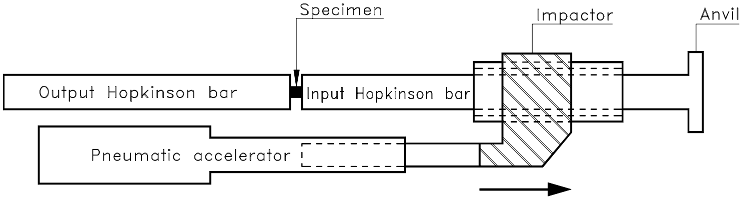

Figure 1: Experimental setup of a typical split Hopkinson tensile bar device.

If materials are tested which, because of their strength or geometry, involve low stress levels, the transmitted wave has a low amplitude. In some cases the corresponding strain history $\varepsilon_t(t)$ becomes immeasurable. Then, the use of low-stiffness materials such as polymers instead of metals for the Hopkinson bars can be a solution. However, since these bars exhibit *visco*-elastic behaviour, the main advantage of SHB-tests disappears: stress, strain and strain rate in the specimen can no longer be straightforwardly calculated from the *recorded* waves

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using Eqs. (1). Fortunately, in recent years more sensitive and accurate measurement devices are commercially available. Using a highly sensitive transient recorder, it is now feasible to test for example steel wires and cords with the conventional 25 mm diameter aluminium bars.

Fig. 2 represents a steel cord between the input and output Hopkinson bar after testing. The incident and reflected wave, measured on the input bar, and the rescaled transmitted strain wave, measured on the output bar, are also depicted. The maximum stress amplitude of the transmitted wave is less than 4 MPa. In Fig. 3 static and dynamic force-strain curves for the steel wire are represented. The dynamic curve is calculated from the recorded signals presented in Fig. 2a.

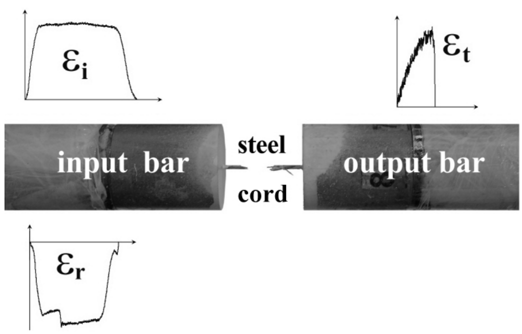

Figure 2: Broken steel cord between the input and output Hopkinson bar. The recorded incident, reflected and transmitted waves are also represented.

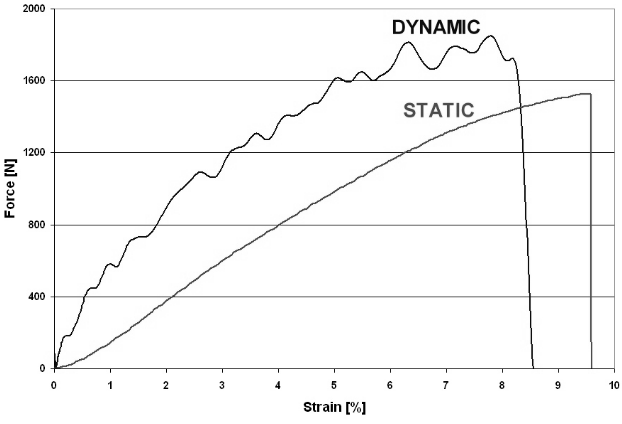

Figure 3: Static and dynamic force-strain curves for the steel cord.

2.2 Bending experiments

The principle of Hopkinson testing can also be used for high strain rate bending. Here, the specimen is a small bar or—in case of sheet materials—a strip, as can be seen in Fig. 4.

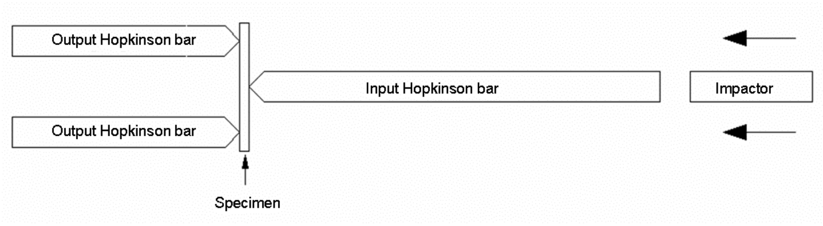

Figure 4: Experimental setup of a split Hopkinson bar bending device.

Instead of one output bar, as is the case for tensile and compressive experiments, now two parallel output bars are used. The ends of these bars support the specimen placed in a three point bending configuration. One end of the input bar is in contact with the middle of the specimen. At the other end of the input bar a compressive wave is generated. This wave travels towards the specimen, and bends it. The incident and reflected waves are recorded by strain gages on the input bar. From these waves, the history of the bending force and displacement of the middle of the specimen can be calculated using formulas similar to Eqs. (1). The waves transmitted to the output bars are also measured.

From these waves the history of the forces exerted on the supports and the corresponding displacements can be calculated. The amplitude of the wave transmitted to the output bar is in most cases very small, even for high strength materials. Consequently, these experiments are not possible without the new-generation, highly sensitive measurement devices.

The relative importance of shear stresses to normal bending stresses can be adjusted by varying the span of the specimen. Numerical simulations of bending experiments have shown that due to wave propagation phenomena the resulting stress and strain distribution in the specimen is quite complex. Results of bending experiments can be used to validate material models developed on the basis of uniaxial SHTB-experiments.

3 Advanced measurement and data extraction techniques

3.1 Measurement of the specimen deformation

A combined optical/numerical technique is developed to measure the time evolution of the strain distribution along the length of the specimen. In this paper, only a brief description of the measurement principle is given; more details can be found in [2]. An extension and optimization of the technique is presented in [3].

The experimental setup is presented in Figure 5. A line grid (3 lines/mm) is attached to the specimen; the lines are perpendicular to the axis of the specimen. The image of the line grid is projected on a photographic film, which is laid inside the drum of a rotating-drum streak camera. During an experiment, the drum of the camera rotates at a constant speed, and the image of the deforming line grid is projected onto the moving film. Thus, the evolution of the specimen deformation is recorded on the film.

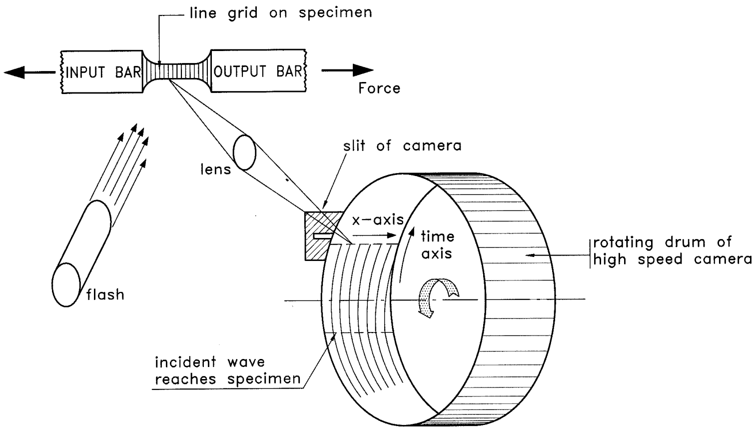

Figure 5: Schematic representation of the setup used for the deformation measurement.

Fig. 6 represents a typical picture, recorded with this Moiré technique. Each horizontal line represents the line grid at one moment during the experiment. At the top of the picture, corresponding with times before the start of the loading, the lines do not change in width. Once the incident wave reaches the specimen, and the specimen is subjected to the tensile load, the lines are stretched. The more to the bottom of the picture, the larger the distance between the lines becomes. At a certain moment a crack starts in the middle of the specimen. Afterwards, one part of the specimen (the part to the right of the figure, corresponding with the side of the input bar) moves away from the other part. The duration of the experiment, from the start of the loading to the nucleation of the crack, is about 0.75 ms. At the moment of cracking, the mean strain in the specimen was slightly lower than 50 %.

A numerical technique, based on a combination of digital geometric Moiré and phase shifting, was developed to calculate the displacements and strains along the axis of the specimen during the entire experiment from the recorded picture. A detailed description of the processing algorithm can be found in [3]. The strain is calculated as the space derivative of the displacement field.

However, since the displacement profiles are subject to noise, calculating the strain is not straightforward [4]. The strain in a certain point is therefore calculated as the mean slope of the displacement curve in an interval around the considered point. Intervals of 1 mm are found to give good results: on the one hand the accuracy of the obtained strains is sufficiently high, and on the other hand the oscillations are kept within reasonable limits. Fig. 7 represents the strain along the axis of the specimen at different moments in time. Between two consecutive curves a time interval of 50 μs is considered; the central zone of the specimen, where the cross-section is constant, is situated between the vertical lines.

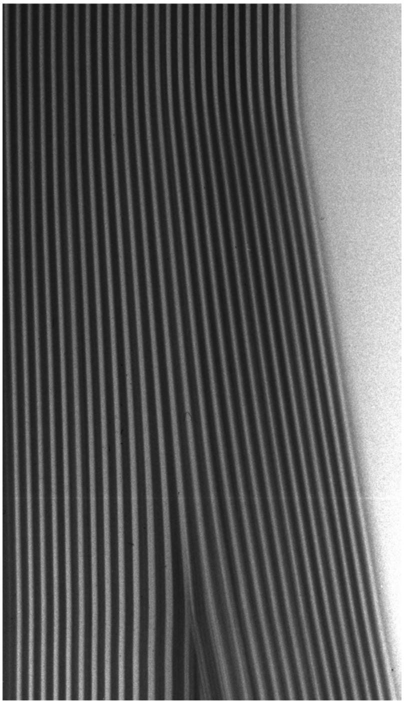

Figure 6: Recorded image of a line grating on a specimen by the streak camera during a SHTB experiment.

The technique yields the true distribution of the deformation along the length of the specimen. Classical assumptions concerning the specimen deformation can thus be verified. The technique was used to study the influence of the specimen deformation on the observed high strain rate behaviour.

3.2 Optimized stress-strain curve calculation

From experiments, it is clear that the influence of the specimen geometry, or more general of the experimental setup, on the observed behaviour cannot be neglected: the stress-strain curve extracted from the recorded signals during a SHTB experiments using Eqs. (1) is highly specimen geometry dependent [5]. The observed mechanical behaviour is a combination of *structural* and *material* response. Inconsistencies between the assumed and real specimen behaviour account for these differences. Evidently, it is of utmost importance that the obtained stress and strain histories are an accurate representation of the real stress and strain in the material in a zone around the centre of the specimen where the assumed homogeneous, uniaxial stress and strain field is obtained.

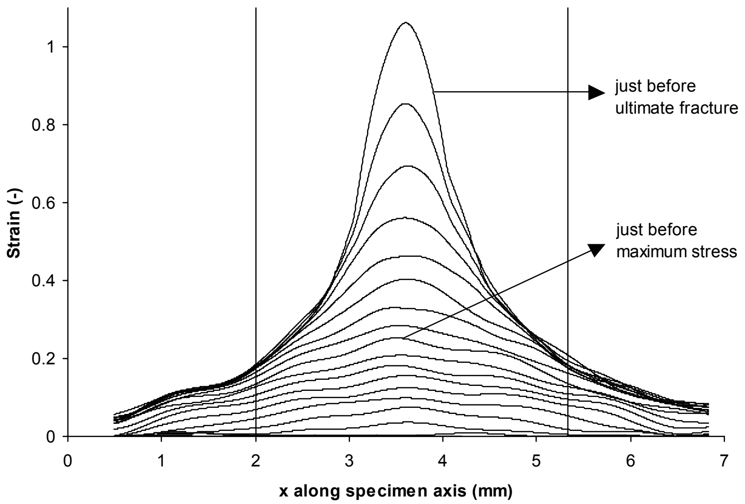

Figure 7: Strain along the axis of a Hopkinson specimen at different moments in time.

In order to obtain a stress-strain curve that represents the actual material behaviour, a combined experimental/numerical technique is developed. The SHTB setup is modelled using the finite element code Abaqus. The model comprises the test specimen and parts of both Hopkinson bars long enough to have no interference of reflected stress waves with the specimen during the time period of interest. To correctly take into account inertia and wave propagation phenomena, the interaction of a real wave with the specimen is modelled. The incident wave recorded during an experiment is applied as a tensile load at the free end of the input bar.

Using the finite element model presented above, the alternative procedure for the interpretation of the test results consists of the following steps (Fig. 8):

1. the material behaviour of the specimen is modelled in Abaqus by entering tabulated data corresponding to the stress-strain relationship extracted from the experiment (using Eqs. (1)),

2. the SHTB-experiment is simulated,
3. from the simulation results a stress-strain curve is calculated corresponding to the experimentally established curve, i.e. the stress is the stress in the centre of the specimen, and the strain is obtained by dividing the relative displacement of the specimen ends by the gage length,
4. the numerical stress-strain curve is compared with the experimental curve. When the agreement is insufficient, step 2 and 3 have to be repeated using an improved stress-strain curve for the specimen material behaviour.

Note that with this technique, no assumptions have to be made on the specimen behaviour. Here, the optimization is used for a SHTB-experiment; however, without changes it can also be used for compressive experiments and, with some adaptations, for bending experiments.

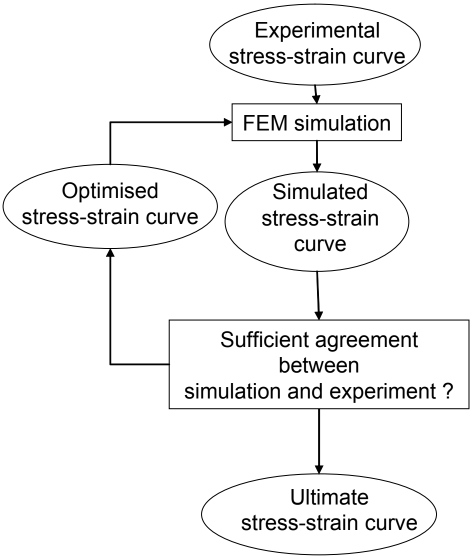

Figure 8: Schematic representation of the procedure used to optimize the stress-strain curve extracted from a SHTB experiment.

4 Conclusions

In this contribution, some recent advances in the practice of material testing based on the Hopkinson principle are presented. These advances have been made possible by the availability of more sensitive and accurate measurement devices and high-speed imaging tools. The increased access to *numerical methods* such as finite element techniques creates even more new possibilities.

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