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Design and Simulation of a Laser Measurement Technique in Split Hopkinson Pressure Bar Test

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Abstract

The Split Hopkinson Pressure Bar (SHPB) is a commonly used technique to measure the stress-strain behavior of materials at high strain rates. Using Utilizing the strain records signals recorded in the input and output bars, the average stress, -strain and strain rate in the sample can be calculatedis determined by the one-dimensional wave propagation equations of SHPB formulas based on the one-dimensional wave propagation theory. The accuracy of a SHPB test is based on this assumption as well as dynamic equilibrium. In this paperarticlework, the possibility feasibility of using a laser measuring system to obtain the dynamic properties of a wide range ofvarious materials using split Hopkinson pressure bar without strain gages is studied. In this method which is a non-contact one, the displacements of bar/sample interfaces are measured directly using a laser extensometer technique. After designing a proper set of optical elements, the operation of the method is evaluated using numerical simulation in ABAQUS/Explicit. Cast iron, aluminum and polypropylene samples, which represent the properties of hard to soft, respectively, were studied to evaluate the proposed measurement method for different materials. The comparison with other strain gage methods shows good agreement and lower fluctuation in stress-strain curves. Moreover, since the one-dimensional wave propagation is not used in this method, we show by numerical simulation that the proposed method can be used even with shorter pressure bars which can reduce the cost of manufacturing and maintaining the SHPB apparatus.

Nomenclature

ε_I	Incident strain pulse	ε_s	Sample strain
ε_R	Reflected strain pulse	h_s	Sample length
ε_T	Transmitted strain pulse	σ_s	Sample stress
c_b	Wave speed in the bars	ρ_b	Density of the bars
A_b	Cross sectional area of the bars	A_s	Cross sectional area of the sample
v_1, v_2	Interface velocity of input and output bars	u_1, u_2	Interface displacement of input and output bars

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1. Introduction

Determining high strain rate mechanical properties of materials is of great importance due to wide range of applications in automotive and defense industries as well as several high speed forming and fabrication methods [1, 2]. The Split Hopkinson Pressure Bar (SHPB) is an important method of obtaining such behaviors. SHPB was originally developed by Kolsky and has been widely used and modified to determine the dynamic properties of a variety of engineering materials such as metals, concrete, ceramics, and composites. The classical Hopkinson pressure test system draws stress-strain curves of materials by recording strain signals on the bars and wave propagation equations. However, if the specimen in a SHPB is a soft material, such as an elastomer, the mechanical impedance of the specimen is very small compared to that of a steel bar. Chen et al. [3–5] have proposed some ways to measure this weak signal in the output bar, such as using softer bars, hollow output bar, and measuring with piezo crystals. The results were satisfactory, although the piezo crystal calibration faces some challenges [6]. Chen et al. [7] use a laser gap gage to measure the deformation of the sample directly and monitor the low amplitude dynamic loading stresses on the sample with a pair oftwo piezoelectric transducers that which are embedded located in the bars. Gao et al. [8] proposed a digital image correlation (DIC) technique using successful ultra-fast camera (10^6fps) and image processing to measure strain in Hopkinson pressure bar test. In this measurement method an ultra-fast camera is installed on top of the sample, which is responsible for taking photos during the pressure test. The procedure is simple, by fixing the distance from the camera to the sample each pixel in the recorded images represents a certain amount of displacement. By obtaining the amount of sample displacement and having its initial length, the strain curve is obtained. The accuracy of the curve obtained in this method depends on two factors, the first factor is the frame per second of the camera. The amount of impact time varies for different samples; but on average, this time is about 150 microseconds according to the simulation results. For this purpose, if the camera has 10^6 frames per second, it can take 150 shots. The second factor is the resolution of the images, which shows the accuracy of the displacement measurement. In these cameras, this resolution decreases sharply by raising the imaging frame rate, which is the challenge of the DIC method. The results show that the strain obtained in this method of measurement does not have a high accuracy and requires the advancement of technology in the construction of ultra-fast cameras. Li and Ramesh [9] proposed a method for measuring the strain in the sample using Laser Occlusive Radius Detector (LORD), which measures the strain of the sample based on changes in the diameter of the test specimen and the Poisson's ratio of the material. They presented the results of strain changes in a Hopkinson tensile test on aluminum alloy (A359) samples. The results were satisfactory; however, the main disadvantage of this method is that it requires the Poisson's ratio of the sample. Nie et al. [10] proposed a laser extensometer measurement technique for strain measurement in split Hopkinson tension bar; this new technique allows researchers to test a wide range of materials in Hopkinson experiments. Other researchers then utilized this laser extensometer technique split Hopkinson pressure bar test. The results showed that this measurement method was in good agreement with the strain gage curves [11, 12]. Fu et al. [13] installed two shutters at the end of the bars to measure the velocity directly between the faces using a micro-displacement fiber interference system for each reflector. Using this method, both stress and strain of the sample were calculated with acceptable accuracy. Yang et al. [14] used a new laser measuring system to identify the properties of samples with a diameter of less than 2mm, this method is non-contact and can make the Kolsky bar applicable to characterizing the dynamic mechanical properties of materials under higher strain rates and smaller size conditions.

Among the reviewed works, only Fu et al. used laser measurement to calculate both stress and strain of a specific sample by measuring the velocity of the bar/sample interfaces. However, the method needs placing shutter between bar and sample which makes the implementation difficult. Moreover, samples with high and low stiffness were not tested which may affect the accuracy of the method. Therefore, in this paper, we intend to investigate numerically the possibility of measuring the dynamic properties of a wide range of materials using split Hopkinson pressure bar by measuring the displacements of bar/sample interfaces directly using a laser extensometer technique. In fact, we show that the stress-strain curve of the sample can be obtained using this method. Moreover, it is usual in all types of Hopkinson tests, i.e., pressure, tension and torsion, that the aspect ratio of bars are about 100 or more [2, 15]. However, since in laser measurement method stress and strain are obtained directly from the interfaces of the sample and the one-dimensional wave propagation is not used, the proposed method can be used even with shorter pressure bars (or lower aspect ratios).

The paper is organized planned as follows. In section 2 the design of a laser assisted SHPB setup as well as the methodology of numerical simulation and theoretical formulations are presented. Simulation results are discussed in section 3 and finally conclusions are drawn in section 4.

2. Materials and Methods

In this section, first the design of laser measurement system is proposed; then the numerical simulation of laser assisted split Hopkinson pressure bar test is explained.

2.1. Laser Assisted SHPB Test

A conventional SHPB test apparatus consists of a gas gun, a striker bar, an incident bar, a transmission bar and a measurement system. The gas gun launches the striker bar to impact the incident bar which sandwiches the specimen between the incident and transmitted bars. Due to the lower impedance mismatch betweenof the specimen and compared to pressure bars, a tensile pulse isthe reflected pulse into the incident bar is tensile while and a compressive pulse is transmitted into the transmission output bar. The strain gages measure the incident (ε_I), reflected (ε_R) and transmitted (ε_T) strain pulses as shown in Fig. 1. These strains are then used to compute the stress (σ_s), strain rate ($\dot{\varepsilon}_s$), and strain (ε_s) in the specimen as follows by assuming dynamic equilibrium ($\varepsilon_I + \varepsilon_R = \varepsilon_T$)

$$\sigma_s(t) = \frac{A_b E_b}{A_s}\varepsilon_T \tag{1}$$

$$\varepsilon_s(t) = \frac{-2c_b}{h_s}\int_0^t \varepsilon_R(t)dt \tag{2}$$

$$\dot{\varepsilon}_s(t) = \frac{-2c_b}{h_s}\varepsilon_R(t) \tag{3}$$

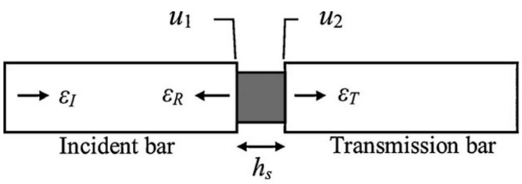


Fig. 1. Schematic of the wave propagation in Hopkinson pressure bars [16].

In the following we explain about the laser measurement system which can be used in SHPB test. Fig. 2 shows a schematic of this measurement system which is similar to the work done by Nie et al. [10] but is used here for compressive Hopkinson test. As it can be observed in Fig. 2, a red-light laser is directed toward a line generating Fresnel lens. Therefore a line laser beam is generated, and a portion of the line laser passes through the distance between input and output bars and over the sample. It should be noted that to use this measurement technique, the diameter of the sample must be smaller than the bar to meet the above-mentioned conditions which is the usual case of SHPB specimens. The passed beam is then divided into two parts to calculate the displacement history of the interfaces of the input and output bars with the specimen. This is done by a right-angle prism mirror and after the laser beam is split in two parts, two convex lenses collect the line laser at one point. The spot light is recorded by a photodiode, and an amplifier circuit is used to amplify the recorded voltage. Finally, the output voltage is recorded by an oscilloscope. Therefore, two voltage-time curves are stored by the oscilloscope by performing an impact test. Calibration coefficients are used to convert these curves into displacement curves. There is a linear relationship between voltage changes and displacement, which is obtained by measuring the voltage at specific displacements of this calibration coefficient. The equations that convert these bar displacement curves into stress-strain curves are explained in the following. To obtain the strain-time curve with the laser measurement system, we use Eq. (1) as below:

$$\varepsilon = \frac{u_1 - u_2}{h_s} \tag{4}$$

where σ_s is the sample stress, A_s is the cross-sectional area of the sample, and A_b is the cross-sectional area of the output bar. Using the mentioned equations, the laser measuring system can be used instead of strain gage measuring system as a complete non-contact measuring system which is able to plot the dynamic stress-strain curve of the material.

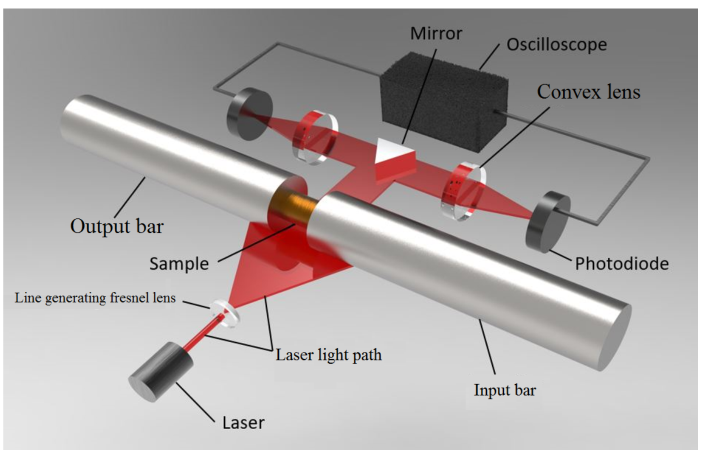


Fig. 2. A schematic of the splitting-beam laser extensometer measurement technique for Hopkinson bars.

where ε indicates the strain of the specimen, u_1 presents displacement of the input bar, u_2 is displacement of the output bar, and h_s is the initial length of the specimen. Moreover, we obtain the stress in the output bar (σ_b) by means of the velocity of the output bar (v_2), and the density (ρ_b) and wave propagation speed (c_b) of the bar as below:

$$\sigma_b = v_2 \rho_b c_b \tag{5}$$

It should be noted that the output bar velocity diagram is obtained by differentiation from the output bar displacement diagram with respect to time. According to the force equilibrium, the sample stress can be obtained as:

$$\sigma_b A_b = \sigma_s A_s \tag{6}$$

2.2. Numerical Simulation

In this study, the numerical simulation of the SHPB test is performed using the commercial finite element software ABAQUS/Explicit. The model consists of the striker bar, the incident bar, the specimen and the output bar. Due to the symmetry of the geometry, loads and boundary conditions, a two-dimensional axisymmetric model of the SHPB is developed using the solid 2-D element CAX4R where the longitudinal axis of the bars is taken as Y-axis. The impact velocity of the striker bar is taken as the initial condition and a surface-to-surface contact is defined between the bars and specimen interfaces.

For a clear comparison and evaluation of the capabilities of the laser measurement system, three different sample materials, i.e., cast iron, aluminum and polypropylene, which represent hard to soft materials respectively, have been used. Table 1 shows the properties of each of these specimen materials along with the materials used for the pressure bars. Nonlinear isotropic hardening plasticity was assumed for all the samples. The stress-plastic strain data were extracted from typical experimental data such as [17, 18]. In the simulations, for better comparison, three stress-strain curves of a specific sample obtained using different methods are compared with the "input curve" of the numerical model for the sample.

The first curve, called "laser", is the stress-strain curve obtained using Eqs. (4-6). In these equations, the strain is obtained directly using the difference between the displacement difference of the input and output bar interfaces divided by the length of the sample. Moreover, the stress is obtained from the velocity of the output bar interface.

The second curve is named "sample". To draw this curve, the stress and strain are obtained directly from an element of the surface of the sample. It is noted that uniformity of stress distribution is checked and one of the nodes at the middle of the sample has been used. Moreover, the mesh sensitivity analysis was performed and the mesh sizes were considered accordingly.

The third curve is called the "strain gage". To plot this curve, the classical Hopkinson pressure bar method is used. The stress wave in the middle of the input and output bars (the location of the strain gage in the practical test) is used, then the stress-strain curves are plotted using the one-dimensional wave propagation Eq. (4) to (6) which assume dynamic equilibrium. In practice, these assumptions may not be entirely true and can cause errors in the results.

To validate the laser measurement method, it is necessary that the displacement of the input and output bars interfaces with sample be equal at different points. For this purpose, we have considered three different points at the cross section of the bars. Fig. 3 shows these points, which are named as a (top bar cross section), b (middle bar cross section), and c (center bar cross section). The points mentioned above are similarly considered in the interface of both input and output bars. For brevity, only points of output bar are illustrated in Fig. 3. This validation is performed for all three sample materials. Fig. 4 shows an example of an input and output bar strain gage pulses for a cast iron sample in the simulation of bars with 2 meters length. The incident (ε_I), reflected (ε_R) and transmitted (ε_T) strain signals are clear and apart from each other.

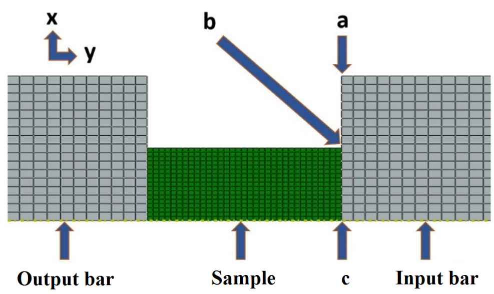


Fig. 3. Finite element model for Hopkinson pressure bar test, point a) Top of the bar cross section, point b) Middle of the bar cross section, and point c) Center of the bar cross section.

Table 1
Geometry and material properties of SHPB setup.

Name	L (mm)	D (mm)	E (GPa)	ρ (kg/m^3)	Yield stress (MPa)
Input bar	2000	20	192	7845	-
Output bar	2000	20	192	7845	-
CI sample	10	10	166	7845	293
Al sample	10	10	71.7	2800	350
PP sample	10	10	1.7	1050	20

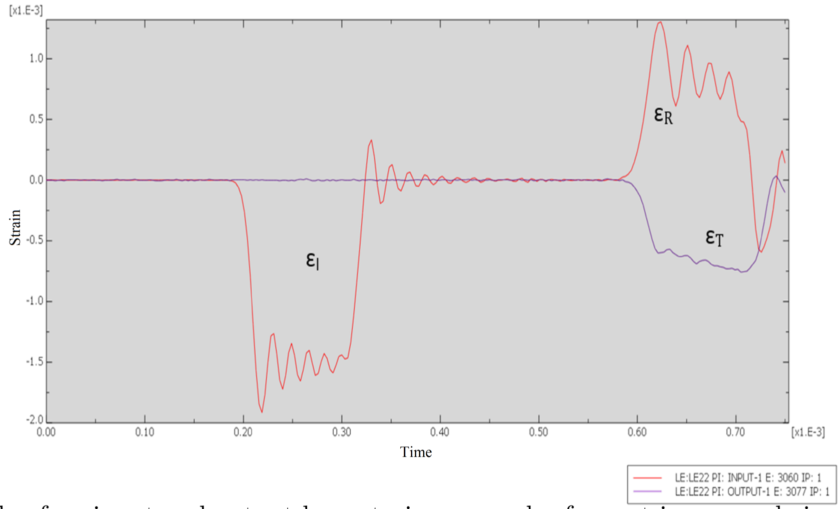


Fig. 4. An example of an input and output bars strain gage pulse for cast iron sample in a simulation.

3. Results and Discussion

In this section the numerical results are presented to prove that the designed measurement system is proper for testing samples with various mechanical properties. Moreover, we show that the method is applicable to SHPB setup with shorter pressure bars.

3.1. Effect of Specimen Mechanical Properties

Here the simulation results for three sample materials are compared. Fig. 5 show the results of this comparison for cast iron (CI), aluminum (Al) and polypropylene (PP) respectively. In each curve, the displacement diagrams of the input and output bars are illustrated for the three points mentioned in Fig. 3. Due to the length of the input bar and wave speed of steel bars, all the signals start at about 400μs. All three curves show excellent agreement, so it can be concluded that the displacement of the bars are equal at any point on the surface of the bar. It should be noted mentioned that as the sample becomes stiffer, as in Fig. 5c to Fig. 5a, there is a small amount of difference which is almost negligible. Therefore, in the laser measurement technique, measuring the displacement of any point on the cross section would be valid. Moreover, it can be concluded from the comparison of these three diagrams that the displacement of the output bar decreases with the softening of the sample. This may challenge the capability of the laser measuring system for testing soft materials. However, the focus of the laser beam and amplification of signals, as a non-contact system, can be adjusted from one test to another to overcome this issue.

In the next step, we compare the recorded strain. All curves are plotted in the time interval of 0 to 750 microseconds, this time interval of the simulation is considered in the software from the beginning of the impact wave in the input bar. It is noted that Eqs. (1-6) calculate engineering strains and stresses. For better comparison, real stresses and real strains are calculated from engineering ones and are compared with the direct measurement of sample stress-strain curves as well as input stress-strain curves. Fig. 6a-c show strain-time curves for cast iron, aluminum and polypropylene samples. As can be seen from the curves, both the laser method and the strain gage method show good agreement with the strain that is obtained directly from the sample. The deformation begins at about 400μs, reaches the maximum value almost linearly and then elastically unloads.

Finally, material true stress-strain curves are plotted using different measurement methods and are compared with input stress-strain curves. In this regard, engineering stresses are calculated using Eq. (1) for strain gage measurement and using Eqs. (5) and (6) for laser measurement and then converted to true stresses. Fig. 7a-c show the true stress-strain curves of cast iron, aluminum and polypropylene, respectively. All measurement systems show good agreement with the sample curve. Specifically, comparing the strain gage method with laser measurement method, we can express that laser measurement is more accurate and has lower oscillations. The oscillation of strain gage method is mainly due to the assumption of dynamic equilibrium and 1D wave propagation which is not fulfilled in the test. Fig. 7c shows fluctuations in the strain gage measurement system for the polypropylene sample which is due to low impedance and low stress of this sample. The results of Fig. 7c show that as the sample softens, the oscillations of the strain gage curve increases and the accuracy of the results decreases. Moreover, the accuracy of strain gage and laser measurement decrease from cast iron to polypropylene samples since dynamic equilibrium is not satisfied completely for soft materials especially in the early stages of loading in the elastic region.

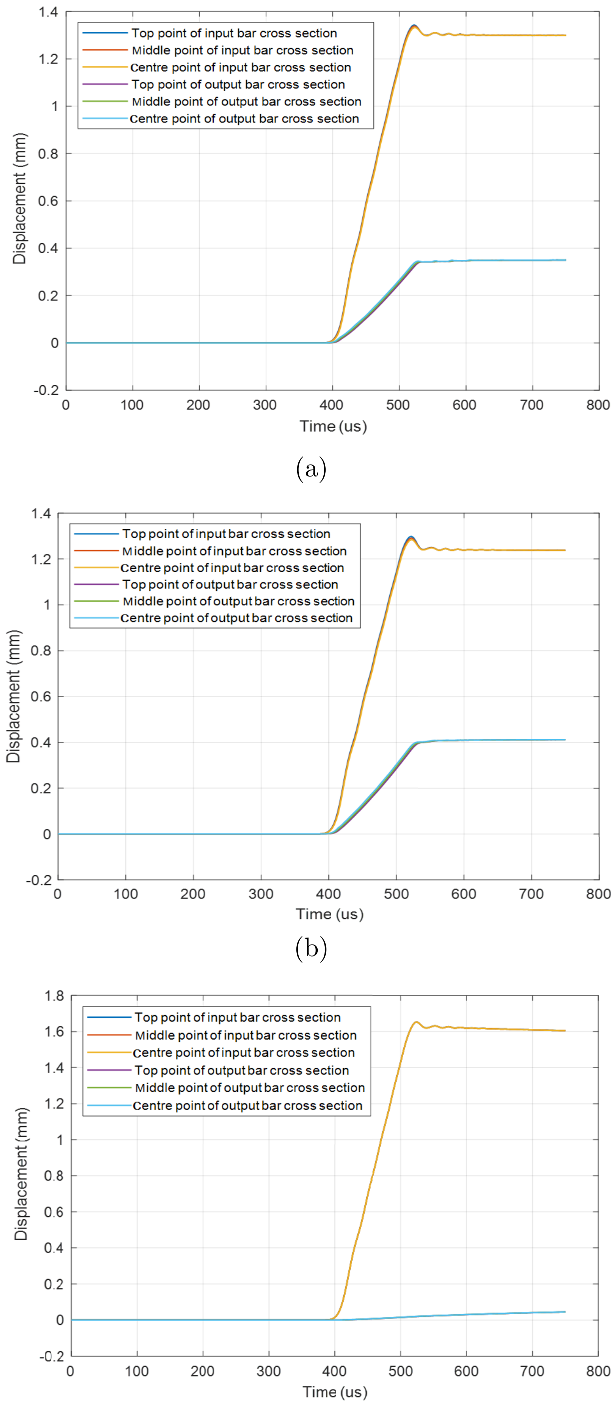


Fig. 5. Displacement of input and output bars: a) Curves for cast iron sample, b) Curves for Al sample, and c) Curves for PP sample.

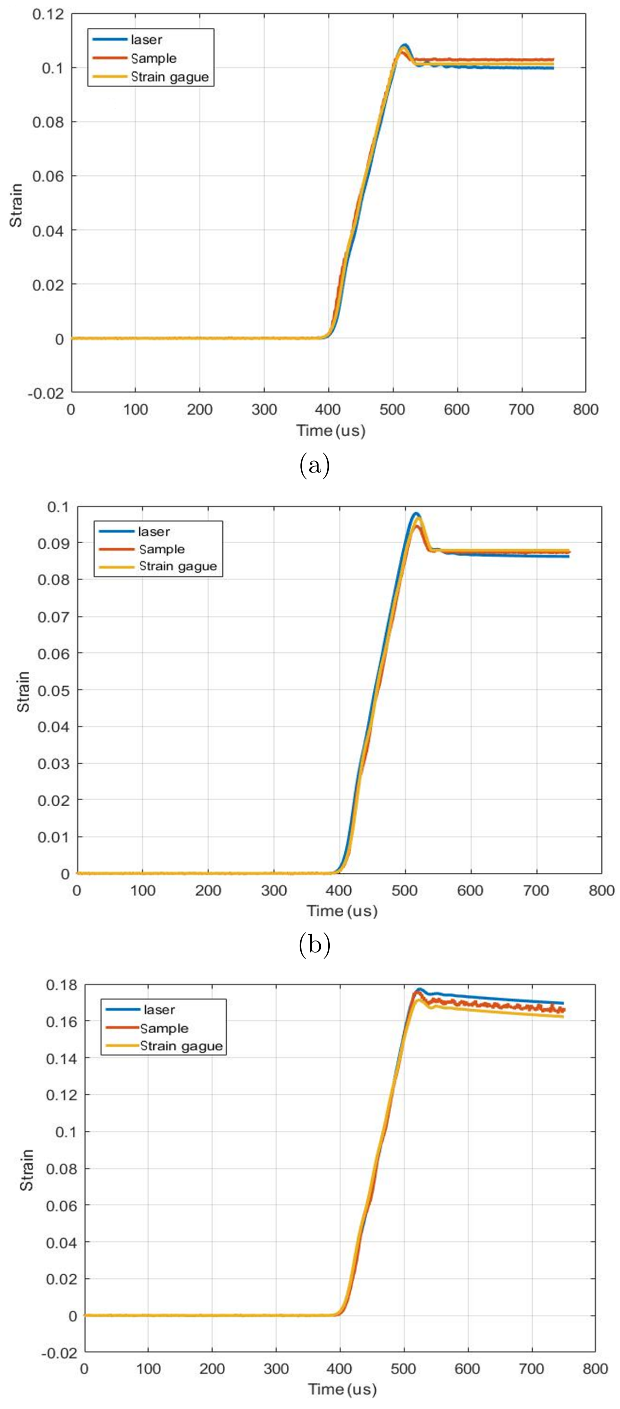
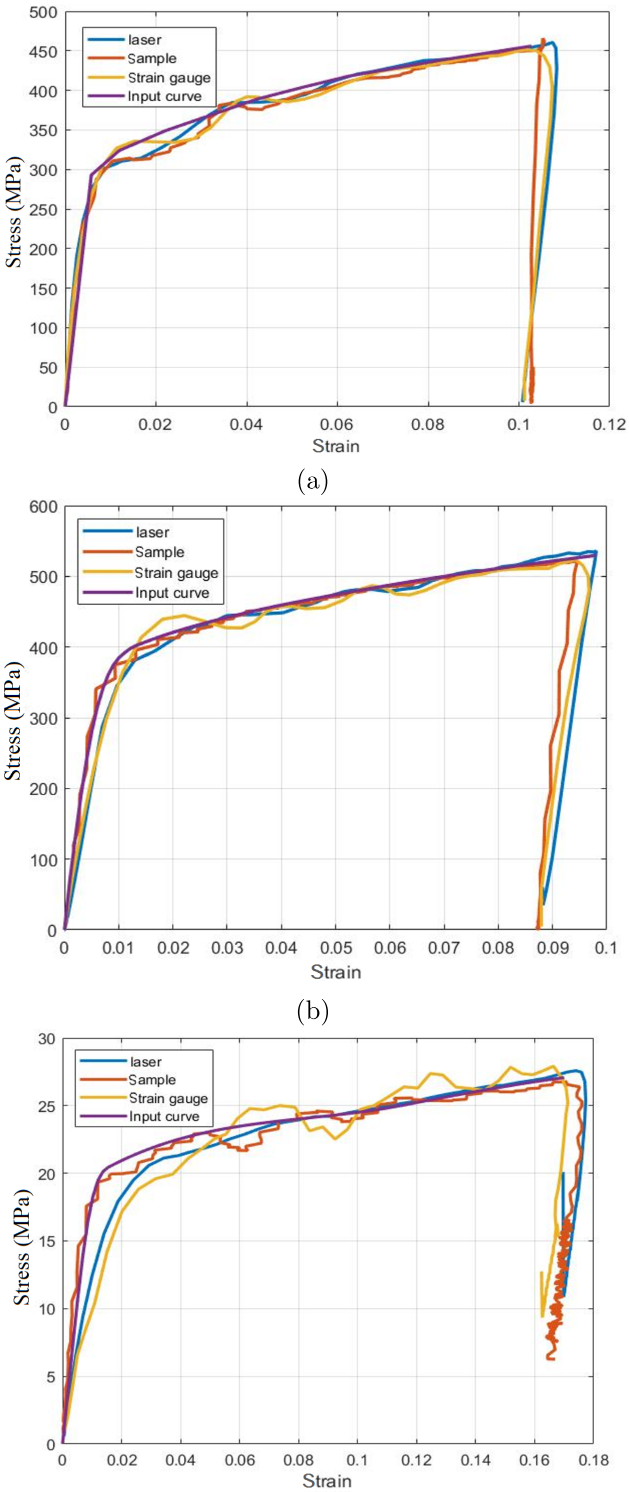


Fig. 6. Comparison of strain recorded: a) Curves for cast iron sample, b) Curves for Al sample, and c) Curves for PP sample.

As the simulation results show, the laser measuring system is able to measure the stress and strain of various materials, both soft and hard, in the Hopkinson impact test. The accuracy of the method was evaluated using numerical simulation of the test. This measurement is completely non-contact and is far from one-dimensional wave propagation assumptions which are not always met.

3.2. *Effect of Pressure Bar Length*

The conventional SHPB measuring system is based on the theory of one-dimensional wave propagation, which is why the design of the Hopkinson device uses bars of small diameter and long length to minimize measurement errors [2, 15]. Moreover, in order to extract the reflected signal correctly from the signal recorded by strain gages of input bar, strain gages should be mounted at the middle of the bars. According to the wave propagation analysis, the incident pulse duration (Δt) is a linear function of striker bar length (L).



(a)

(b)

(c)

Fig. 7. Comparison of stress-strain recorded: a) Curves for cast iron sample, b) Curves for Al sample, and c) Curves for PP sample.

$$\Delta t = \frac{2L}{c_b} \tag{7}$$

and the length of the input bar should be at least twice as the striker bar. If pulse shaper is used, the pulse duration increases and the pressure bar length should be increased further [19].

It is both difficult and costly to construct steel bars with high-precision of straightness and alignment with each other. On the other hand, maintaining bars in these conditions is also a difficult task to achieve and over time, with multiple impact tests, alignment and straightness may degrade. Moreover, the strain gage debonding from the bars is another common problem of this measuring system due to impact force.

To solve these issues, the laser measurement system can even change the design of the Hopkinson device; as the Eqs. (4-6) do not rely on one-dimensional wave propagation assumption and the measurements are performed at the interfaces with the sample. Therefore utilizing shorter pressure bars may be possible.

Here we show the simulation results for 0.5 meter input and output bars and compare with previous results obtained by 2-meter-long pressure bars. The other parameters of the device, including the material of the bars, are all the same as before and have not changed. The results are presented for a sample of aluminum with the length of 10mm and the diameter of 10mm. Fig. 8 shows the displacement diagram for the input and output bars. Fig. 9 shows the strain-time diagram for the aluminum sample and Fig. 10 shows the stress-strain diagram.

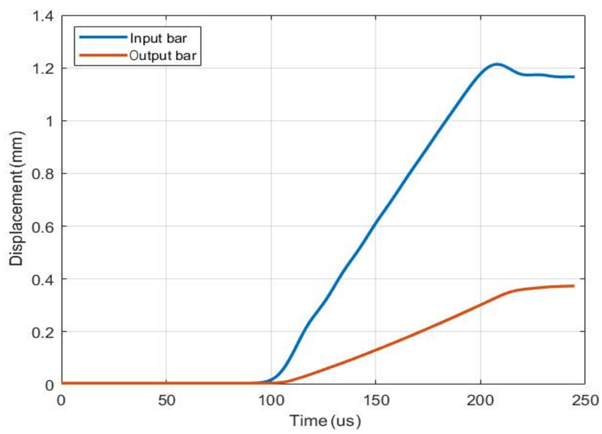


Fig. 8. Displacement of input and output bars for Al sample with 0.5 meter bars.

Another issue that should be mentioned here is the problem of interference of incident and reflected strain waves. In 2-meter bars, the strain gage is installed in the middle of the bar, which is a long distance from the end of the bar; the reflected wave does not interfere with the incident wave. However, in 0.5 meter pressure bars, a short distance from the end of the bar causes the strain wave to interfere. As the results show, this interference of the waves causes the strain and stress to fall faster (Figs. 9 and 10). On the other hand, the lack of one-dimensional wave propagation has increased the error so that the elastic unloading part of strain gage measurement in Fig. 10 is incorrect. However, the laser measurement system was able to track the stress and strain of the sample well and with high accuracy.

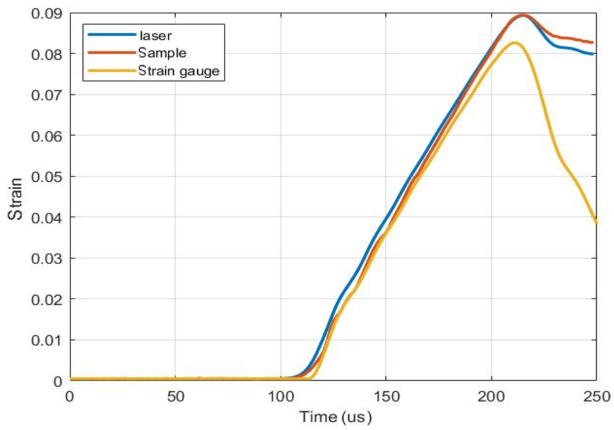


Fig. 9. Comparison of strain recorded for Al sample with 0.5 meter pressure bars.

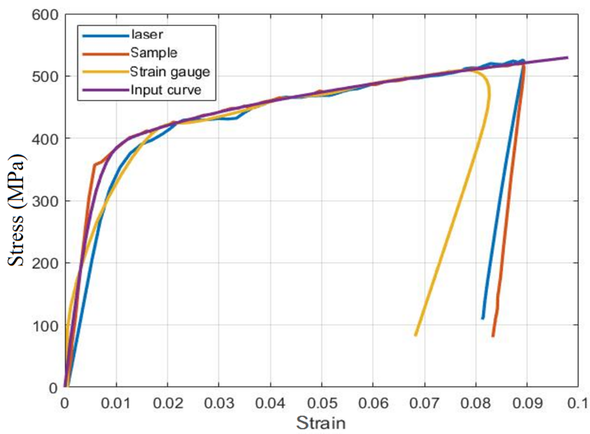


Fig. 10. Comparison of stress-strain curves for Al sample with 0.5 meter pressure bars.

4. Conclusions

In this work, numerical simulation of split Hopkinson pressure bar test was performed and the conventional strain gage measurement technique was compared with the designed laser measurement technique. The main finding conclusions are as below:

1. Equations in classical measurement system are associated with assumptions such as dynamic equilibrium and one-dimensional wave propagation. But in reality, these assumptions do not fulfill completely and may lead to inaccurate results.
2. The relationships of the laser measurement system are far from these assumptions, and the non-contact nature of this system prevents it from many systematic errors.
3. The simulation results show that the laser measuring system is able to measure the dynamic properties of a wide range of materials, both soft and hard, in the split Hopkinson pressure test.
4. The non-contact laser measuring system proposed in this work can change the design of the Hopkinson device and significantly reduce the length of the bars, which greatly reduces the cost of manufacturing and maintaining the Hopkinson impact test devices.
5. Therefore, the laser measuring system can be considered a good alternative to the classical measuring system in Hopkinson pressure test.
6. While the simulation of this measurement system is essential before construction, the implementation of the method and verification of the findings related to this work should be performed which is aimed by the authors in the near future.

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