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Numerical Study of the Data Processing Methods in SHPB Experiments*

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Abstract: Accurate measurement of the stresses and velocities at the boundaries of a dynamically loaded specimen may be obtained using split Hopkinson pressure bars (SHPB). However, the determination of a representative stress-strain curve based on these measurements can be challenging. According to the principle of SHPB technique, there are three groups of formulae to process the experimental data, and all the formulas are sensitive to time shifting. Due to transient effects and the error of time shifting, the stress-strain curves lack consistency. In order to solve the problem of time shifting, we introduce the three-wave mutual-checking method based on the conservation of momentum and the corresponding data processing program. It is shown that a more reliable stress-strain curve could be obtained using this method. In order to prove the correctness of this curve, numerical simulations of the SHPB experiments were performed. The results show that by using this program, the same result can be obtained by either the three-wave method or the two-wave method, and what matters more is that this method can avoid the error of time shifting which the traditional method cannot.

Key words: finite elements; SHPB; three-wave mutual-checking method; data processing

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1 Introduction

SHPB has been widely used to test the properties of materials at high strain rates.[1-4] But there are some factors that affect the accuracy of the measurement. The main aspects that determine the accuracy of the measurement in SHPB experiment can be classified in five types. The first type is related to the SHPB basic assumptions.[5] The SHPB technique is based on two assumptions, namely, the assumption of one-dimensional stress wave propagation in bars and that of stress uniformity along the specimen thickness. The second type is related to the accuracy of the forces and the velocities at the specimen boundaries provided by the SHPB system. The third type is related to the interface friction between the specimen and the bars.[6-7] The fourth type is of weather the inertial response of the specimen could be neglected. The fifth type is how to process the data of the SHPB experiment.

The following factors affect the data processing. First, the three basic waves are measured at sections other than the bar-specimen interfaces. They have to be shifted from the strain gauges to the

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specimen faces. Waves change in their shapes (wave dispersion) on propagating along the bar. Second, the exact time shifting for the three waves has to be identified and the proper formulae have to be selected. When one SHPB experiment has been completed, the wave signals are recorded. Although there are some factors that may affect the accuracy of measurement, such as the errors due to stress equilibrium, inertia response and interface friction, the data processing method can be adopted to improve the final accuracy.

The influence of the time shifting is analyzed by numerical simulations and the results obtained from different processing methods are assessed. Furthermore a data processing program is developed, visually showing the three basic waves recorded and the corresponding stress-strain curves obtained by using the different processing methods, by adjusting the relative starting-times of those three basic waves.

2 SHPB Data Processing Methods

A typical SHPB set-up is sketched in Fig. 1.[8] It is composed of a long input bar and a long output bar with a short specimen sandwiched between them. The impact of the bullet at the free end of the input bar develops a compressive longitudinal incident wave $\varepsilon_i(t)$. Once it arrives at the bar specimen interface, a reflected wave $\varepsilon_r(t)$ is developed in the input bar, whereas a transmitted wave $\varepsilon_t(t)$ is developed in the output bar. The three basic waves are recorded by the strain gauges respectively in the input and output bars.

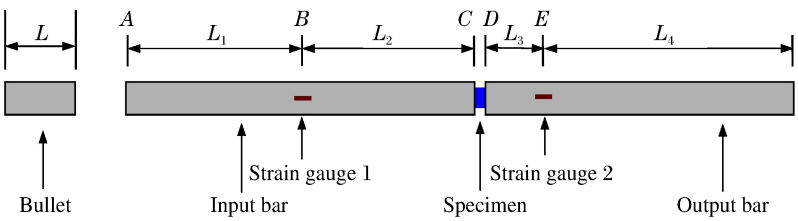

Fig. 1 The schematic diagram of a SHPB setup

During the numerical simulation experiments, the bars must remain elastic and should be long enough to avoid the overlapping from the incident and the reflected elastic waves. So the following assumptions are made:

(a) The wave propagation in the bars is well approximated by the one-dimensional wave propagation theory, implying that the radial-inertia and the friction effects of the specimen are all negligible.

(b) The stress and the strain in the specimens are uniformly distributed in the axial direction.

Based on the first assumption, the strain rate, the strain, and the stress histories in the specimen can be calculated from the recorded bar-surface strain signals with the following equations, namely:[9]

(1) Three waves method (Kolsky, 1949)

$$\dot{\varepsilon}(t)=\frac{C}{l_0}(\varepsilon_i-\varepsilon_r-\varepsilon_t) \tag{1}$$

$$\varepsilon(t)=\frac{C}{l_0}\int_0^t(\varepsilon_i-\varepsilon_r-\varepsilon_t)\,\mathrm{d}t \tag{2}$$

$$\sigma(t)=\frac{A}{2A_0}E(\varepsilon_i+\varepsilon_r+\varepsilon_t) \tag{3}$$

Where ε_i, ε_r and ε_t are incident, reflected, and transmitted strain histories, respectively; A is the cross-sectional area

of the bars; E and C are Young's modulus and elastic wave speed in the bar material, respectively; A_0 and l_0 stand for the initial cross-sectional area and the length of the specimen, respectively.

When the second assumption is satisfied, namely the specimen is in a state of uniform stress, we have

$$E[\varepsilon_i(t)+\varepsilon_r(t)]=E\varepsilon_t(t) \tag{4}$$

The Eqs. (1)-(3) can be simplified either to Eqs. (5)-(7) or to Eqs. (8)-(10), as follows.

(2) Two-wave-1 method, using the incident and transmitted waves to calculate the stress-strain curve

$$\sigma(t)=\frac{A}{A_0}E\varepsilon_t(t) \tag{5}$$

$$\varepsilon(t)=\frac{2C}{l_0}\int_0^t[\varepsilon_i(t)-\varepsilon_t(t)]\mathrm{d}t \tag{6}$$

$$\dot{\varepsilon}(t)=\frac{2C}{l_0}[\varepsilon_i(t)-\varepsilon_t(t)] \tag{7}$$

(3) Two-wave-2 method, using the incident and reflected waves to calculate the stress-strain curve

$$\sigma(t)=\frac{A}{A_0}E[\varepsilon_i(t)+\varepsilon_r(t)] \tag{8}$$

$$\varepsilon(t)=-\frac{2C}{l_0}\int_0^t[\varepsilon_r(t)]\mathrm{d}t \tag{9}$$

$$\dot{\varepsilon}(t)=-\frac{2C}{l_0}\varepsilon_r(t) \tag{10}$$

Theoretically, when the above two basic assumptions are satisfied, the results obtained by the three-wave method and the two-wave method should be consistent. However, it is not the case in practice, particularly depending on the time-shifting technique. In the following, we will discuss this problem through the numerical simulation experiment.

(4) Three-wave mutual-checking method

The three-wave mutual-checking method (3W-MC-M) was proposed by Shang *et al*.[10] It is based on the original three waves method, while a time-shifting method is introduced to correctly adjust the relative starting-time position of the basic waves. In fact, an arbitrarily adjusting of the relative position of the three waves may cause a new error. In the 3W-MC-M the time-shifting is based on the following two characteristics, so that the error decreases and the material constitutive behavior obtained is more credible.

According to momentum conservation, the difference of transmitted and incident waves should be equal to the reflective wave. So when we process the data, we can adjust the relative position of basic waves till this character is satisfied. In this way, we can avoid the time shifting error.

According to the basic assumptions of the SHPB experiment, two waves method and three waves method should provide a consistent stress-strain curve. We adjust the relative position of basic waves till the stress-strain curves calculated from different methods are as identical as possible.

Those two characteristics are equivalent. They will be satisfied simultaneously, when the time shifting is accurate. In the following, we will analyse the curves obtained from different methods through numerical simulation experiments.

3 Finite Element Simulations of SHPB Experiment on Steel

To ensure a reasonable uniformity of the stress within the specimen, the length of the specimen should be much smaller than that the of stress wave. Steel is usually regarded as a homogeneous

isotropic material, so the thickness of the specimen can be small. The assumption of the stress uniformity is satisfied better than e. g. concrete-like materials. Theoretically, the stress-strain curves obtained from the above-mentioned different method are approximately the same.

In this study, the technology of pulse shaping is used. The conventional split Hopkinson pressure bar apparatus is modified by shaping the incident wave so that the specimen is in a dynamic stress equilibrium and has a nearly constant strain rate over most of the test duration. [11-12]

3.1 Numerical Model

The calculations are performed using the general-purpose finite element code Abaqus/Explicit version 6.10 with element type CAX4R(axis symmetric element, reduced integration). Parameters of the bar: Young's modulus $E=210$ GPa, Poisson's ratio $\gamma=0.3$, Diameter $D_b=14$ mm, Density $\rho=7\,850$ kg/m^3. The position of strain gauge can be confirmed through Fig. 1. $L_1=0.75$ m, $L_2=0.75$ m, $L_3=0.33$ m. These parameters can confirm the time shifting, and separate the incident, transmitted and reflected waves.

Davies and Hunter showed that the slenderness ratio plays opposite roles on axial and lateral inertia effects and an optimal slenderness ratio exists[13]

$$\lambda=\frac{L_s}{D_s}=\frac{1}{2}\sqrt{3\gamma_s} \tag{11}$$

So the steel specimen adopt the following parameters: length $L_s=3.8$ mm, diameter $D_s=8$ mm, Poisson's ratio $\gamma_s=0.3$. And the Johnson-Cook model (Eq. (12)) is used here, in which $A=626$ MPa, $B=3.614\times10^9$, $n=0.82$, $C=0.0268$, $\dot{\varepsilon}_0=5\times10^{-4}$ s^{-1}.

$$\sigma_y=(A+B\varepsilon_p^n)\left(1+C\ln\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right) \tag{12}$$

In order to avoid the effect of friction, we set the friction coefficient of the bar/specimen interface $\mu=0$. All boundaries are free. Loading consisted of hitting the input bar with a pressure pulse[14] are plotted in Fig. 2.

3.2 Results and Discussion

During the analysis special attention was focused on the development of the data processing methods. The strain histories of points B and E in Fig. 1 are regarded as that of the strain Gauges 1 and 2 which are plotted in Fig. 3. Curve 1 is the strain history of point B, and curve 2 that of point E.

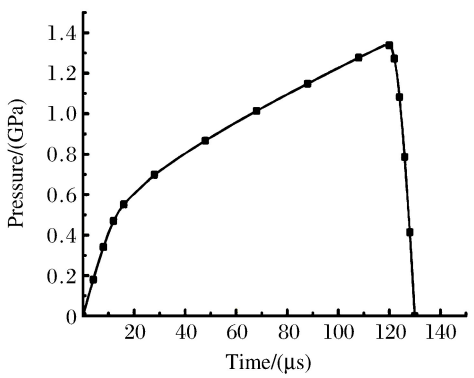

Fig. 2 Loading pressure pulse

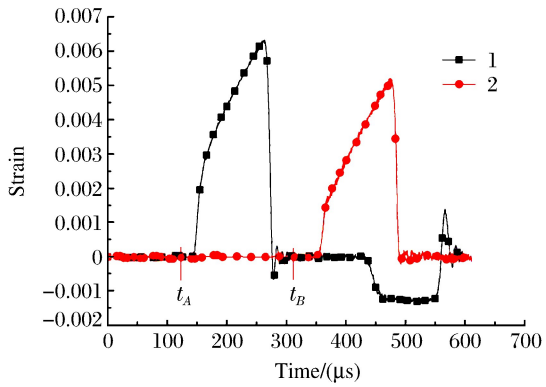

Fig. 3 Strain histories of points B and E in a numerical SHPB test

The strain rate, strain and stress histories of the material under investigation are calculated with Eqs. (1)-(10). However, the reflected and transmitted signals are measured at different locations on

the bars, or equivalently at different time. Note that Eqs. (1)-(10) are deduced for the waves at the specimen/bar interfaces. The measured waves thus must be synchronized, which turns out to be critical in data processing.

In principle, the waves measured at the strain gauge locations should be shifted to the specimen/bar interfaces before the equations are applied. There are two issues in practical experiments associated with the shift. One is the wave dispersion associated with the transverse inertia effects of waves propagating along an actual 3-D rod; and the other is the determination of the starting point of each of the waves for proper synchronization. Wave dispersions should be either experimentally eliminated or numerically corrected, which is not discussed here. We assume the duration of the incident, reflected and transmitted wave are the same, and select the duration of t_A-t_B in Fig. 3 as the basic duration of the incident wave. So

The history of reflected wave is

$$t_A + 2L_2/c_b \sim t_B + 2L_2/c_b \tag{13}$$

The history of the transmitted wave is

$$t_A + (L_2 + L_3)/c_b + L_s/c_s \sim t_B + (L_2 + L_3)/c_b + L_s/c_s \tag{14}$$

Where L_2 and L_3 are the distances from the strain gauge locations on the incident and the transmission bars to the bar/specimen interfaces, respectively (Fig. 1); L_s is the length of specimen; c_b is the stress wave speed in the bars; c_s is the stress wave speed in the specimen material, which often needs to be estimated.[15] So some artificial errors exist. In fact, when we do SHPB experiment, the errors of distance and wave speed exist objectively. How to avoid the errors? Three-wave mutual-checking method needn't use the Eq. (13) and (14), so these errors can be avoided. In the following, we first introduce the process of three-wave mutual-checking method, and then prove its validity.

We select the starting point t_A and end point t_B of the incident wave (Fig. 3). The start points of the transmitted and reflected waves can be selected arbitrarily. The duration of the three waves is assumed as the same, so the end points of the transmitted and reflected waves can be calculated through t_A and t_B. Then we synchronize the signals, just like Fig. 4(a).

The basic waves are plotted in Fig. 4(a), where curve 1 is the incident wave, curve 2 the transmitted wave, curve 3 the reflected wave, and curve 4 the difference of the transmitted wave and the incident wave.

Fig. 4(b) shows the stress-strain relation obtained from the waves and the relative position in Fig. 4(a). Curves A, B and C are the stress-strain relations calculated from two-wave method 1, two-wave method 2, and three waves method.

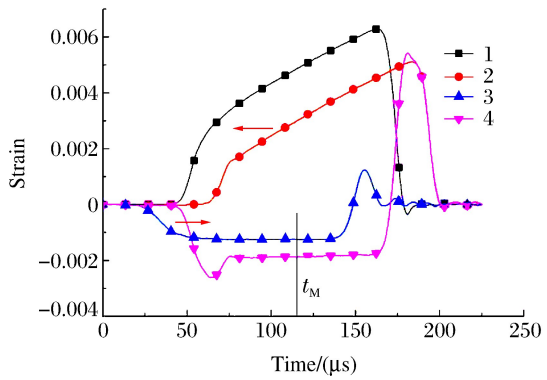

Fig. 4(a)　The waves and their relative positions

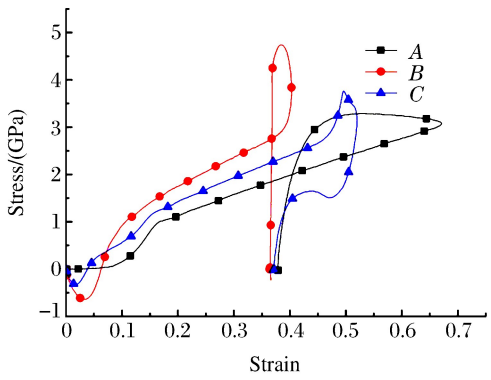

Fig. 4(b)　The stress-strain curves obtained from Fig. 4(a)

Obviously, those results are incorrect, because firstly the momentum is not conservative, for example, at the time of t_M (Fig. 4(a)). Secondly, the stress-strain curves calculated from different methods are not consistent (Fig. 4(b)). So we need to adjust the relative positions of the basic waves.

Then we shift the transmitted wave and the reflected wave (change their starting points), and obtain the Fig. 5, where curve 1 is the incident wave, curve 2 is the transmitted wave, curve 3 is the reflected wave, curve 4 is the difference of the transmitted wave and the incident wave. In Fig. 5(b), the curves A, B and C are the stress-strain relations calculated from the two-wave method 1, the two-wave method 2 and the three waves method respectively. It seems that the results are still not satisfactory too, since the stress-strain curves determined from the different methods are not consistent. But it looks better than the results in Fig. 4.

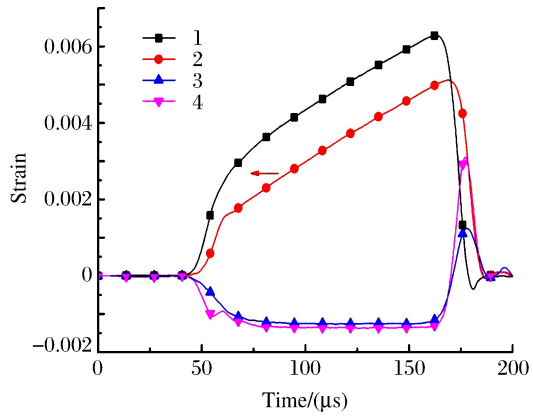

Fig. 5(a) The waves and their relative positions

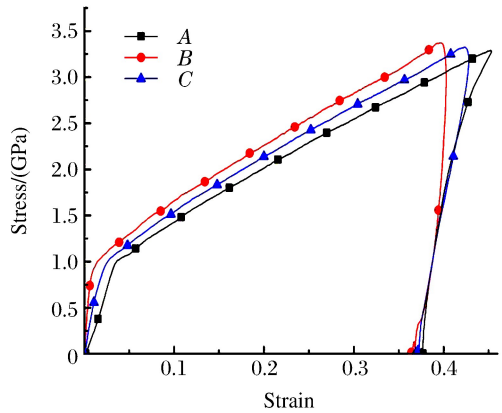

Fig. 5(b) The stress-strain curves obtained from Fig. 5(a)

We further adjust the relative positions of the basic waves. Then we obtain the Fig. 6. The legends in Fig. 6 are the same as in Fig. 5.

As can be seen, the curve 3 and curve 4 in Fig. 6(a) are now approximately the same. This characteristic reflects the momentum conservation. Correspondingly, the curves A, B and C are almost consistent. So the stress-strain curves, shown in Fig. 6(b), satisfactorily reflect the constitutive behavior of the specimen.

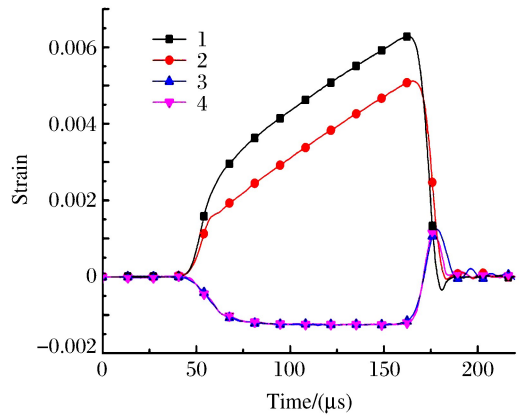

Fig. 6(a) The waves and their relative positions

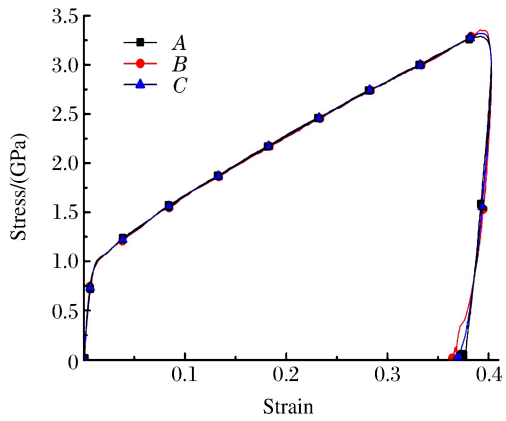

Fig. 6(b) The stress-strain curves obtained from Fig. 6(a)

The comparisons of the stress-strain curves obtained from different methods are shown in Fig. 7, where the curves A, B and C are the same as the stress-strain curves plotted in Fig. 6(b), the curve D is calculated from the finite element, the curve E is obtained from the Johnson-Cook model (Eq. (12)), taking the strain rate as $3.7\times10^{3}\ \mathrm{s}^{-1}$. All the curves are almost consistent with each other, which proves that the stress-strain curves obtained by the three-wave mutual-checking method are reliable.

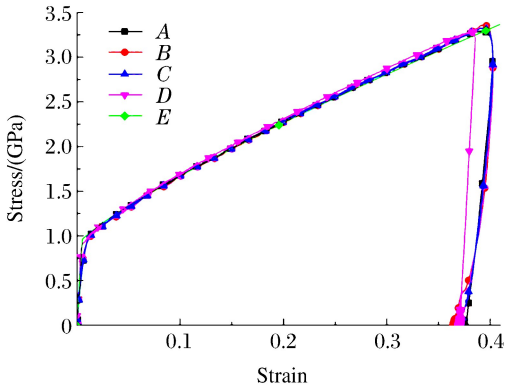

Fig. 7　Comparison of stress-strain curves

4　Conclusions

(1) Numerical simulations show that the two waves method and the three waves method are equivalent for small specimens, if the assumption of dynamic stress equilibrium in specimen can be satisfied, and thus the result is reliable.

(2) For homogeneous isotopic materials, such as steel, copper etc., the three-wave mutual-checking method can avoid the error due to time shifting.

(3) The three-wave mutual-checking method is established by satisfying two characters, namely: first, the momentum conservation; and second, all the curves obtained from different method are consistent with each other.

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基于数值模拟的SHPB实验数据处理方法

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摘要:在分离式霍普金森压杆(SHPB)实验中,可以精确测得加载试件边界上的应力和速度。然而,基于这些测量结果得到一条精确的应力应变曲线有一定难度。根据SHPB实验技术的原理,有3组公式可以处理实验数据,并且3组公式都对波头的选择敏感。由于波动效应的影响以及选择波头的误差,3种方法得到的应力-应变曲线缺乏一致性。为了解决正确对齐波头的问题,编写了三波耦合法的数据处理程序。该方法基于动量守恒,可以得到更可靠的应力-应变曲线。为了证明该方法的正确性,进行SHPB的数值模拟实验。结果显示,利用这种方法可以得到唯一的应力-应变曲线。这种方法可以避免对齐波头时的误差,而传统的两波法或三波法则不能。

关键词:有限单元法;分离式霍普金森压杆;三波耦合法;数据处理

中图分类号:O347.4 **文献标识码**:A

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