—Technical Note —

THREE-WAVE MUTUAL-CHECKING METHOD FOR DATA PROCESSING OF SHPB EXPERIMENTS OF CONCRETE

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ABSTRACT

Two-wave methods and Three-wave method are conventional methods to process the SHPB experiment data. Due to the presence of transient waves in dynamic experiments, both the stress and strain fields within a specimen are seldom absolutely uniform. Different date processing methods lead to different results. In this paper, we have developed a program to compare the results getting from different methods. The difference of the strains corresponding to the ultimate stress can reach 20%. Which one is better? One material shouldn't have different constitutive. In order to solve the problem, we have developed Three-wave mutual-checking method, which is based on the conservation of the momentum of the whole system. This method provides a checking mechanism, so some human error can be avoided when process the same experiment data. By this method, different person can obtain the only credible stress-strain curve based on the same test data.

Keywords: SHPB, Three-wave mutual-checking method, Data processing, Concrete.

1. INTRODUCTION

Concrete have been widely used in civil engineering structures. To understand the dynamic response of structure, the analysis of concrete under high strain rate is often assessed by numerical simulations. However, the accuracy of the implemented constitutive model of concrete dominates the prediction accuracy of the numerical analysis. Up to date, the high-rate mechanical properties of the concrete have been widely investigated by Split Hopkinson Pressure Bar (SHPB) tests [1-4]. The main aspects that determine the accuracy of measurement in SHPB compression tests can be classified in three types [5]. The first type is related to the SHPB basic assumptions. The SHPB technique is based on two assumptions [6], namely, the assumption of one-dimensional stress wave propagation and the assumption of stress uniformity along the specimen thickness. The second type is related to the accuracy of the forces and velocities at the specimen boundaries provided by SHPB system. The third type is related to the interface friction between the specimen and bar.

When one SHPB experiment has been completed, the wave signals are recorded. Some aspects that affect the accuracy of measurement cannot be changed, such as stress equilibrium, lateral inertia and interface friction. But how to process the signals evidently affect the accuracy [7]. According to the principle of SHPB technique, the dynamic stress-strain curve of tested materials can be determined by the measured incident, reflected and transmitted strain history. Or due to the assumption of stress uniformity, it can be determined by any two of them. For convenience, the former is briefly called "Three-Wave Method" and the latter is called "Two-Wave Methods". The combination of incident and transmitted strain history is called "Two-Wave-1 Method" and the combination of incident and reflected strain history is called "Two-Wave-2 Method" [6].

Knowing that specimen equilibrium is never exactly achieved, the stress-strain curve getting from Three-Wave Method is different from the curves getting from Two-Wave Methods. How much is it? How to get the only credible result? In the following, we'll discuss it.

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2. EXPERIMENTAL APPROACH

A dynamic experiment is performed with a modified SHPB [8]. The schematic of it is shown in Fig. 1. Besides the standard components in a conventional SHPB (a gas gun, a striker, an incident bar, a transmitter bar, a momentum absorption device, and a data acquisition system), a pulse shaper at the impact end of the incident bar is employed in the modified SHPB (Fig. 1). The pulse shaping techniques were originally developed three decades age to produce a non-dispersive pulse. Nowadays, the employment of a well-designed pulse shaper enables to facilitate dynamic stress equilibrium and constant strain rate deformation in the specimen. The pulse shaping techniques are described in detail in the literatures [9-12].

In SHPB experiment, the specimen is sandwiched between the incident bar and the transmitter bar. The impact of the striker, which is launched by the compressed wave in the gas gun, on the end of the incident bar through the pulse shaper generates an elastic wave (incident wave), which propagates through the incident bar. When the incident stress wave travels to the bar/specimen interface, a part of the wave is reflected back into the incident bar as a reflected wave due to the mechanical impedance mismatch between the bars and specimen. The rest part of the wave is transmitted into the transmitter bar as a transmitted wave. The specimen is being compressed. Both incident and reflected waves are recorded by the strain gauges on the incident bar, and the transmitted wave is recorded by the strain gauges on the transmitter bar.

During the experiment, the pressure bars must remain elastic and should be long enough to avoid the overlapping from the elastic waves. In addition, the ends of the bars contacted with the specimen must remain flat and parallel throughout the dynamic loading.

In this study, the steel bars in the modified SHPB with pulse shaping technique have the same diameter of 75mm, and the length is shown in Fig. 1. The diameter of the concrete specimen is 75mm, and the length is 50mm. Then the following assumptions are made:

1. The wave propagation in the bars is well approximated by one-dimensional wave propagation theory.
2. The stress and strain in the specimens are uniformly distributed in the axial direction.
3. The radial-inertia and friction effects of the specimen are negligible.

Based on the first assumption, the strain rate, strain, and stress histories in the specimen can be calculated from the recorded bar-surface strain signals with the following equations, namely, Three-Wave Method.

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

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

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

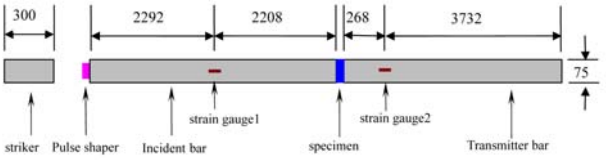


Fig. 1 The schematic diagram of a SHPB setup.

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 are initial cross-sectional area and length of the specimen, respectively. For the concrete experiments in this study, the diameter of the specimen and bars are the same.

When the specimen is in a state of uniform stress, we have

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

The Eqs. (1) ~ (3) can be simplified as:

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

$$\varepsilon(t)=\frac{2C}{l_0}\int_0^t\left(\varepsilon_i(t)-\varepsilon_t(t)\right)dt \tag{6}$$

(1) Two-Wave-1 Method, Using the incident and transmitted strain histories to calculate the stress-strain curve.

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

(2) Two-wave-2 Method, Using the incident and reflected strain histories to calculate the stress-strain curve.

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

$$\varepsilon(t)=-\frac{2C}{l_0}\int_0^t\left(\varepsilon_r(t)\right)dt \tag{9}$$

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

In order to achieve equilibrium, the pulse shaping technique is carefully designed to produce a relatively low rate of loading for satisfaction of dynamic stress equilibrium.

3. EXPERIMENTAL DATA PROCESSING

The origin wave profiles recorded by the strain gauges are given in Fig. 2. We shift the relative position of the three waves depending on the position of strain gauges and the wave speed.

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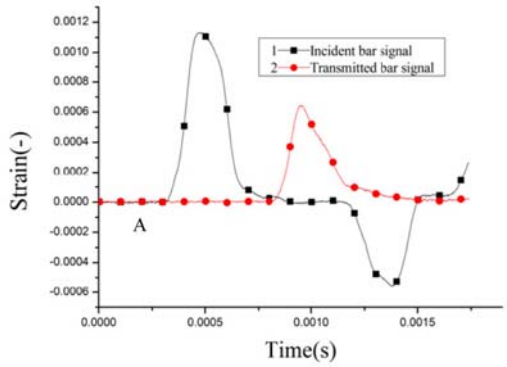


Fig. 2 Strain gauge signals obtained from incident and transmitted pressure bars when pulse shaper is applied.

Firstly we select a point A (Fig. 2) as the start point on the base line. The impulse width is approximate 500μs. So

$t_A \sim t_A + 500\mu s$ is the incident strain histories,

$t_A + \frac{2l_1}{C} \sim t_A + \frac{2l_1}{C} + 500\mu s$ is the reflect strain histories,

$t_A + \frac{l_1 + l_2}{C} + \frac{l_0}{C_0} \sim t_A + \frac{l_1 + l_2}{C} + \frac{l_0}{C_0} + 500\mu s$ is the transmitted strain histories.

t_A the start point of the integral.

l_1 the distance from the gauge to the specimen end face in the incident bar.

l_2 the distance from the gauge to the specimen end face in the transmitter bar.

l_0 the thickness of the specimen.

C_0 the wave speed of the specimen.

C the wave speed of the bar.

We put the start point of strain histories together, just like the Fig. 3. The curve 2 is the summation of the incident strain histories and reflected strain histories, which reflects the stress level on the left side of concrete specimen. The curve 3 reflects the stress level on the right side of the specimen. If the stress uniformity assumption is satisfied completely, the curve 2 and curve 3 should be identical. Unfortunately, they are not the same. They have displayed the asymmetry stress.

Figure 4 illustrates the stress-strain relations of the concrete specimen through the waves given in Fig. 3. Two-Wave Methods and Three-Wave Method lead to different results, especially the strain corresponding to the ultimate stress. The difference is approximate 20%. Based on SHPB theory, all the three stress-stain relations are correct, but the error is so much. One specimen should not have two stress-stain relations. The error primarily comes from the values of l_0, l_1, l_2, C_0, C and the assumption of stress uniformity.

In the system of SHPB, when the striker strike the incident bar,

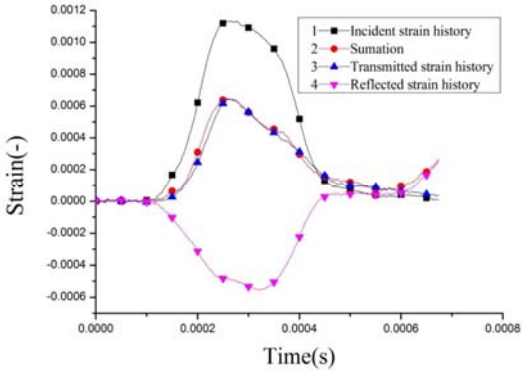


Fig. 3 Incident, transmitted and reflected strain histories at the boundary of the specimen.

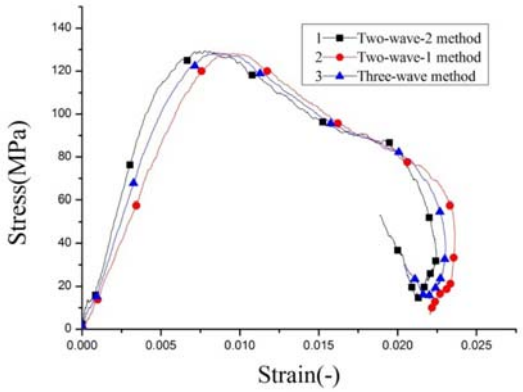


Fig. 4 The stress-strain curves got from the waves in Fig. 3 by three methods.

$$\sigma = E\varepsilon \tag{11}$$

$$\sigma = \rho C v / 2 \tag{12}$$

where σ is the stress of the bar, ε is the strain history of the bar, ρ is the density of the bar, C is the wave speed of the bar, and v is the velocity of the striker. So

$$v = 2E\varepsilon / \rho C \tag{13}$$

The momentum of the incident bar is the product of the mass of the propagation part and the particle velocity. So the momentum of the incident bar is

$$\int_{t_1}^{t_2} \rho CA \cdot \frac{2E\varepsilon}{\rho C} dt = \int_{t_1}^{t_2} 2AE\varepsilon \cdot dt = 2AE \int_{t_1}^{t_2} \varepsilon \cdot dt \tag{14}$$

where A is the area of the bar, t_1 is the start point of the strain history and t_2 is the end point of the strain history.

From the equation we can get a conclusion that the momentum of the incident bar and the area of the strain history have linear correlation.

After the striker strike the incident bar, the momentum of the SHPB system is conservation, so the area of the transmitted strain history equal the summation of reflected and incident strain history. At the boundary of the specimen, the transmitted strain history should equal the summation of reflected and incident strain history at any time, if we ignore the effect of the specimen. But from Fig. 3 we can't judge it.

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We change the relative position of the three waves, till we can judge the momentum of the system is conservation at any time. Just like Fig. 5. The curve 2 and curve 3 are approximately identical. Of course the figure doesn't reflect the stress uniformity. Now we calculate three new stress-strain curves based on the current position relation of Fig. 5, using Two-wave methods and Three-wave method. The result is put in the Fig. 6. All the method's results are approximately the same. The stress-stain curve getting from Three-wave method is the average of Two-Wave Methods, so it's used as the only stress-strain relation of the concrete specimen.

Actually, we have introduced the checking mechanism. Firstly we shift the relative position of the three waves till we can judge the momentum of the system is conservation. Then calculate the stress-strain curves using Two-wave methods and Three-wave method. Accept the Three-wave method's result as the only result. This method is called Three-wave mutual-checking method [13]. Due to the checking mechanism, some error coming from the values of l_0, l_1, l_2, C_0, C can be avoided. So any one can get the only credibly result from the same experiment data.

Three-wave mutual-checking method is inspired by the processing of experimental data obtained from the concrete compression tests. However, it can be used for SHPB data processing of concrete-like materials and metals. But this method isn't suitable for soft materials. The reason is that the transmitted strain history of the soft material is too little.

Figure 7 is an example that the relative positions of the waves are shifted incorrectly. If there is no the checking mechanism, any method can get a stress-stain relation, just like Fig. 8. And any of the results may be looking good. We don't know which one is better, and the difference is so much. So they are not creditable. By the Three-wave mutual-checking method, we can avoid it.

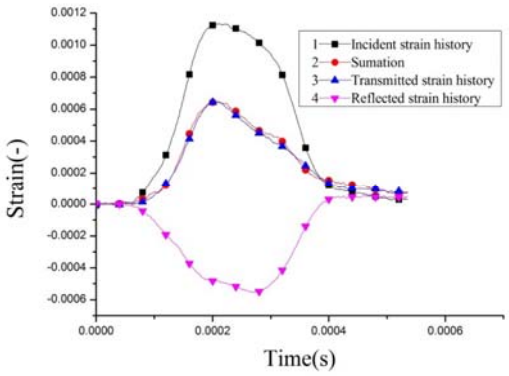


Fig. 5 The wave relative positions which have been shifted.

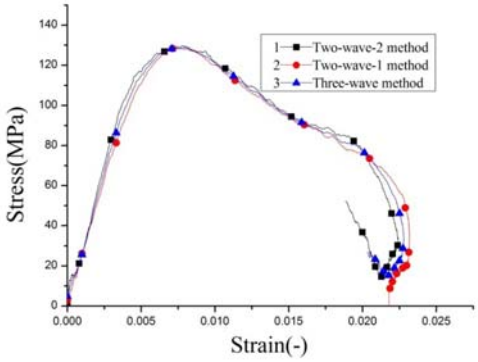


Fig. 6 The stress-strain curves got from the strain history in Fig5 by three methods.

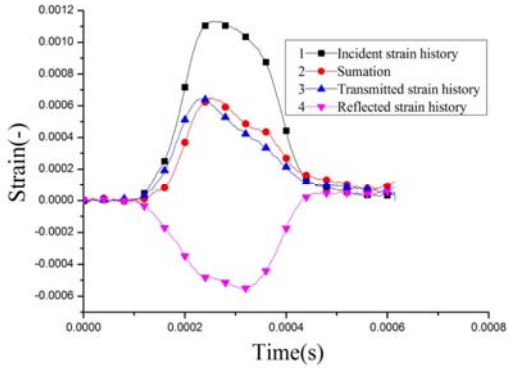


Fig. 7 The wave relative positions which have been shifted incorrectly.

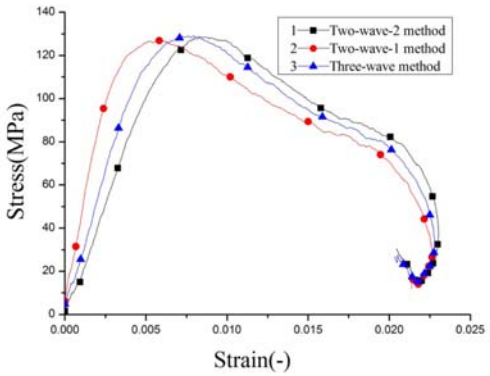


Fig. 8 The stress-strain curves got from the strain history in Fig. 7 by three methods.

4. RELIABILITY ANALYSIS

We have introduced the Three-wave mutual-checking method for data processing in SHPB test. In the following, we will demonstrate that this method is reliable by numerical simulation.

4.1 Methodology of Reconstituted

In order to study various effects in SHPB test, it is necessary to develop a reliable methodology to simulate the test. Bertholf and Karnes [14] proposed a method to estimate the accuracy of SHPB test, where a quasi-static stress-strain relation is used to represent a strain-rate-independent model. The specimen and SHPB pressure bars are numerically simulated at a structural problem. Stress, strain and strain rate in the specimen are obtained from SHPB formulas, listed by Eqs. (1) ~ (10), based on the numerical strain outputs from the locations of the strain gauge stations on the incident and transmitter bars. The obtained stress-strain curve is

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called the "reconstituted" stress-strain curve. The accuracy of SHPB test can be estimated by comparing the numerically "reconstituted" stress-strain relation from a numerical SHPB test with the input quasi-static stress-strain relation.

4.2 Simulation Model

The goal of the simulation of SHPB test is to examine the accuracy of the Three-wave mutual-checking method. 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 = 210GPa, Poisson's Ratio γ = 0.3, Diameter D = 75mm, Density ρ = 7850kg/m^3. The position of strain gauge can be confirmed through Fig. 9. L_1 = 3m, L_2 = 1m, L_3 = 0.75m. These parameters can confirm the time shifting, and separate the incident, transmitted and reflected strain history.

All boundaries are free, and contact constrains are imposed to prevent from interpenetration of the system components, *e.g.*, incident pressure bar, transmitter pressure bar, and specimen. In order to avoid the friction coefficients affect DIF (dynamic increase factor), we set friction coefficient $\mu = 0$.

The specimen adopt the diameter Ds = 60mm, the length a = 26mm, and Poisson's Ratio γ = 0.25. The density of the specimen is 2700kg/m^3. The constitutive model adopts the linear Drucker-Prager model (ABAQUS theory manual version 6.10). The parameters are as follows: angle of friction is 40, flow stress ratio is 1 and dilation angle is 40. The stress-stain relation of the specimen is the input curve, which is plot in Fig. 10.

The numerical experimentation adopts the sine pulse shape which is depicted in Fig. 11. The value of the loading amplitude is 100MPa.

4.3 Result and Disscution

The strain history of points B and E in Fig. 9 are plotted in Fig. 12.

We align the starting point of each of the basic waves by Three-wave mutual-checking method. Then, we get Fig. 13.

In Fig. 13, the curve 1 is incident strain history, curve 2 is the summation of incident and reflected strain history, curve 3 is the transmitted strain history, and curve 4 is the reflected strain history. In Fig. 14, the curves *B*, *C*, and *D* are the stress-strain relations calculated from the strain history in Fig. 13 by Two-wave-1 method, Two-wave-2 method and Three-wave method, respectively. Curve A is the input stress-strain curve.

In Fig. 13, curve 2 and curve 3 are approximately the same. This character reflects the momentum conservation. In Fig. 14, the curves of A, B, C and D are about identical. A is the input stress-strain. B, C and D are the "reconstituted" stress-strain from the numerical SHPB test. The results prove that Three-wave mutual-checking method is a reliable method.

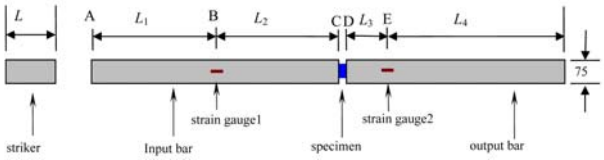


Fig. 9 The schematic diagram of a SHPB setup.

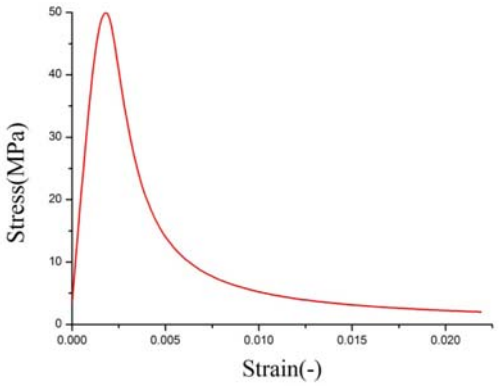


Fig. 10 The stress-strain relation of the specimen, which is the input curve.

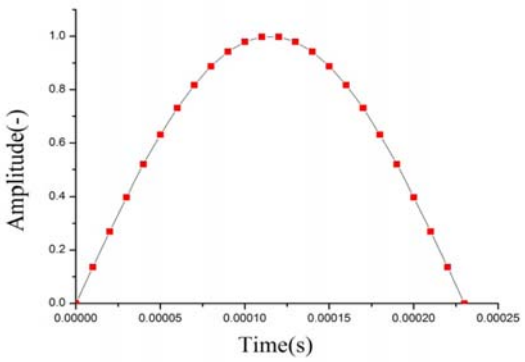


Fig. 11 Loading pressure amplitude.

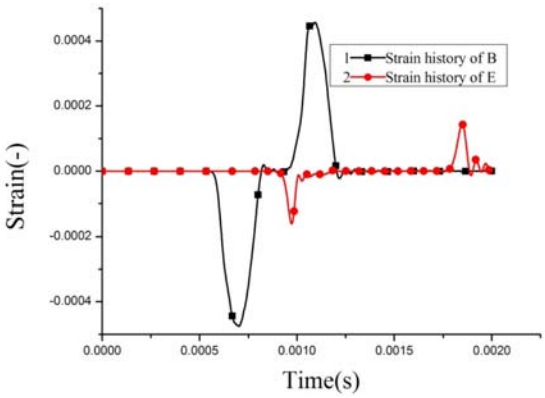


Fig. 12 Strain histories of points *B* and *E* in the numerical experimentation.

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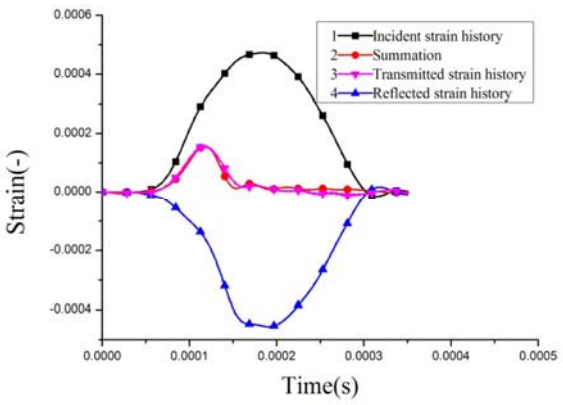


Fig. 13 Shifting the strain history by Three-wave mutual-checking method.

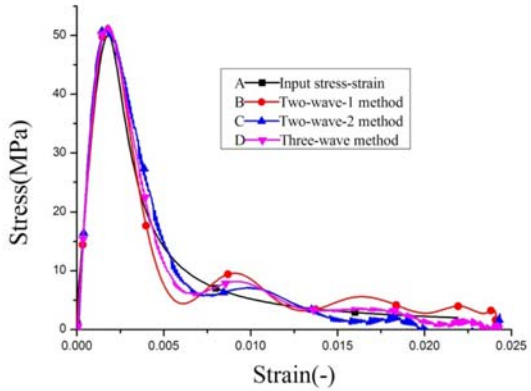


Fig. 14 The comparison between the input and the "reconstituted" stress-strain curves.

5. CONCLUSIONS

1. Based on the conservation of momentum, we have developed Three-wave mutual-checking method.
2. "Three-wave mutual-checking method" doesn't need the following parameters, wave speed and the distance between the strain gauge and bar/specimen interface. In the experiment, the Measurement Error is inevitable. The less parameter needed, the more accurate the result is. So this method is more accurate.
3. Numerical simulation shows that the result obtained by Three-wave mutual-checking method is accurate and reliable.

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