A method of incident pulse shaping for SHPB

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Abstract

The split Hopkinson pressure bar (SHPB) testing method has been widely used to obtain dynamic compression properties of solid materials. In the experiment, the state of dynamic stress equilibrium and deforming at a nearly constant strain rate over most of the test duration should be achieved. Therefore, pulse shaping techniques are usually needed. A new method for SHPB incident pulse shaping is proposed in this paper. The material vacuum cement of which the strength can be ignored is used as the pulse shaper. The experimental results show that a satisfactory shaping effect can be obtained in a wide application scope with this method. The numerical simulation analysis indicates that the shaping function of vacuum cement is mainly due to the radial inertial effect in the high speed deformation process of the material.
Keywords: SHPB, pulse shaper, vacuum cement, granite.

1 Introduction

Split Hopkinson pressure bar (SHPB) has become a commonly accepted test method for strain rates in the range of 10^2–10^4 s^{-1} and has been used to test various engineering materials such as metals, ceramics, rocks, concrete, composite materials, polymers and foam, etc.

A typical SHPB setup is composed of long input and output bars with a short specimen placed between them. The impact of a striker at the free end of the input bar develops a compressive longitudinal incident wave. Once this wave reaches the bar–specimen interface, a part of it reflects back to the input bar, while another part goes through the specimen and develops the transmitted wave in the output bar. Usually, the shape of the striker is a rod made of the same material and with the same diameter as the bars. The incident wave raised by the impact is an approximately flat-topped trapezoidal stress pulse with amplitude proportionate to the impact velocity, and with duration proportionate to the

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length of the striker. The shape of the pulse could not be adjusted, and there is a significant high-frequency oscillation with the incident curve which may affect the test accuracy. Particularly, for some kind of the brittle materials, the specimen may experience considerable damage before it reaches the state of uniform deformation. In order to reduce the dispersion effects in wave propagation, to ensure the stress balance and deformation uniformity during the experimental process, and achieve constant strain rate loading, the shaping technology for SHB has been developed.

Pulse shaping technique has been discussed and developed over the past four decades. Duffy *et al*. [1] were probably the first researchers to use pulse shapers to smooth pulses. Their pulse smoother is a short length of tubing with a narrow neck made of 1100-0 aluminium so that it deforms plastically during the passage of the pulse. It reduces the magnitude of the higher-frequency components and smoothens the pulse of torsional split Hopkinson bar experiment. The method of changing the shape of the striker bar was also used to modify the shape of the incident wave in SHPB [2, 3]. The method of pulse shaping by plastic deformation is also applied to SHPB by Frantz *et al*. [4] in 1984. A thin disc was attached to the impact face of the input bar, the plastic deformation of the disc causes an increase in the rise-time and changes the shape of the stress pulse. Many kinds of materials, such as copper [5], brass [6], rubber [7], and others have been chosen as the thin disc shaper. Frew *et al.* [5, 8] have developed an analytical model to predict the effects of this kind of shaper with varying geometry, the length and striking velocity of the striker bar.

In the dynamic compressive experiments for granite, we found that vacuum cement, a material of which the strength is negligible, was effective in modification of the incident wave shape and time during for SHPB.

2 Experimental results

Vacuum cement is an industrial product made of purified petroleum grease and mountain clay with high viscosity, high asphalt content. It is a kind of black sludge with stable characteristics, which has good plasticity, and it is not easy to get dry in the air. Vacuum cement is often used for the temporary sealing of vacuum equipment.

A photo of a SHPB system and the end face of the input bar placed with vacuum cement shaper is given in figure 1. The strength of vacuum cement is

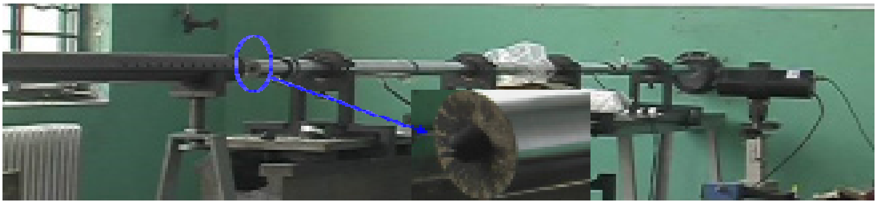
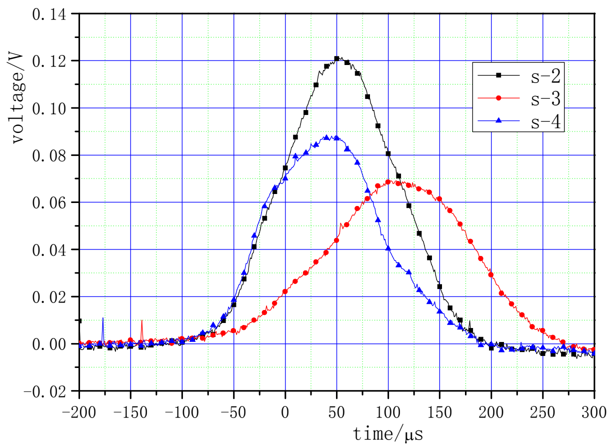


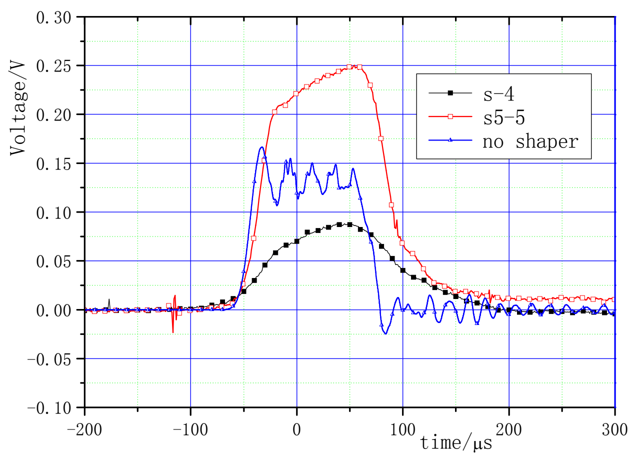
Figure 1: SHPB system and vacuum cement shaper.

negligible, so that the slight difference in shape has no effect on the incident wave. The diameter of the bars made of high strength steel is 50mm, with the elastic modulus of 200GPa, a density of 7800 Kg/m^3, and elastic wave velocity of 5100m/s. The length of strike rod is 300mm.

In the experiment, an amount of vacuum cement was kneaded into a sphere. The diameter of the sphere is measured to determine the material amount to be used, and then it is placed at the centre of the front end surface of the input bar, and compressed it into a hemi-sphere shaper.



(a)



(b)

Figure 2: Pulse curves in several shaping cases.

Table 1: Experimental condition for several shaping cases.

Exp. Num.	s-2	s-3	s-4	s-5
diameter (mm)	14	14	10	10
velocity ($m \cdot s^{-1}$)	15	11	11	28

Table 1 and Figure 2 show the shaped incident wave curves for the cases of two vacuum cement diameters and three impact velocities. The wave curve without shaping is given in Figure 2(b) as well for comparison purpose. From the figures it can be seen that, the incident pulse of the SHPB is significantly modified by the vacuum cement shaper. Compared to the case without any pulse shaping technique applied, with the shaper, the duration and rising time of the pulse are longer, and the waveform is significantly smoothened. With the same shaper diameter, the amplitude of the incident curve increases with the impact velocity. It is also noted that the duration of the curve decreases and the shape of the waveform changes gradually.

Combining the adjustment of the impact velocity and the diameter of the vacuum cement, different shaping results such as sinusoid, slow-rise trapezoid can be obtained to meet the needs of the constant strain rate SHPB experiments for rock class brittle materials or for ductile materials.

3 Numerical simulation

The experimental phenomena was analysed with finite element numerical simulation further in this section. The process of the pulse shaping was simulated with a two-dimensional axisymmetric numerical model using the software LS-DYNA. The geometry model and the element mesh are shown in figure 3. The model includes the impact bar, the input bar and vacuum cement shaper.

Elastic material model is adopted to describe the impact bar and the input bar in the numerical simulation with the material parameters of steel. The vacuum cement shaper is described by the elastic-plastic model. The yield stress is chose as 0.1MPa, which is less than one-thousandth of the stress in bars in the experiments. The material parameters are shown in Table 2.

Table 2: Material parameters in the simulation.

Material	Density /$kg \cdot m^{-3}$	Elastic modulus /GPa	Poisson's ratio	Yield stress /MPa	Tangent modulus /MPa
Steel	7800	210	0.3	-	-
Vacuum cement	1200	2.1	0.3	0.1	0.1

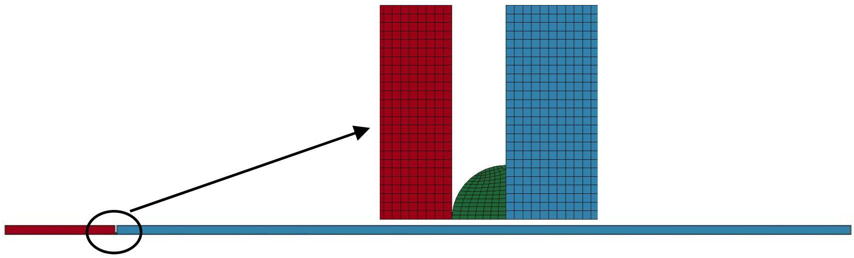


Figure 3: Geometry model in the simulation.

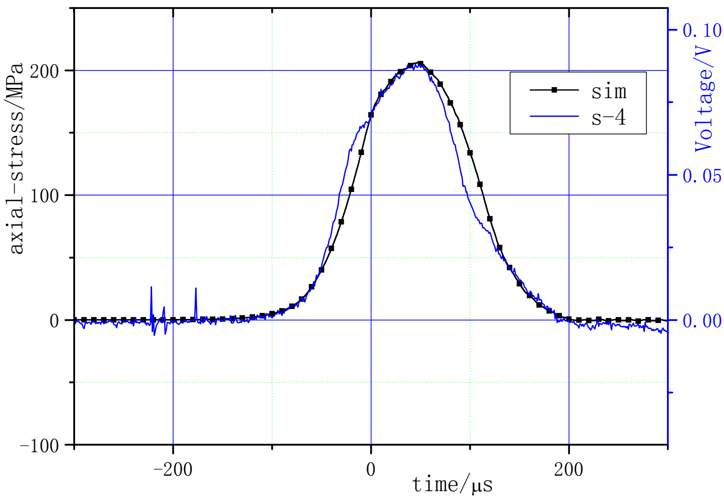


Figure 4: Comparison of simulation waveform with experiment result.

Figure 4 shows the comparison of numerical simulation and experimental test curves. It can be seen that the numerical simulation result agrees well with the test result, indicating the reliability of the material model used for the vacuum cement shaper.

Figure 5 shows the contact force between the bars and the shaper, and figure 6 shows the deformation images at several typical time instants during the impact process. The time 0 μs is defined as the beginning of interaction between the cement shaper and the impact bar. The amplitude of the curve begins to increase apparently after impact of about 450 μs, and at about 630 μs, the load reaches its maximum value, and drops to zero at about 800 μs after impact. Combined with the images from Figure 6, it can be seen that at time of 400 μs, large deformation has occurred to the shaper whereas the contact force is negligible at the same time instant as shown in figure 5. At the time point of 500 μs, the compression value of the shaper is more than 80% while the

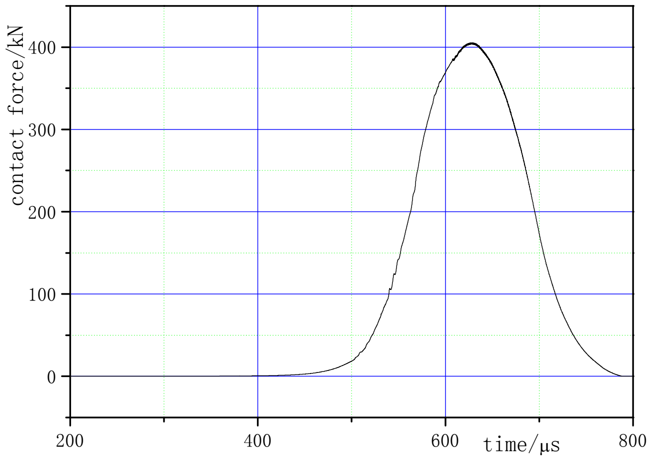
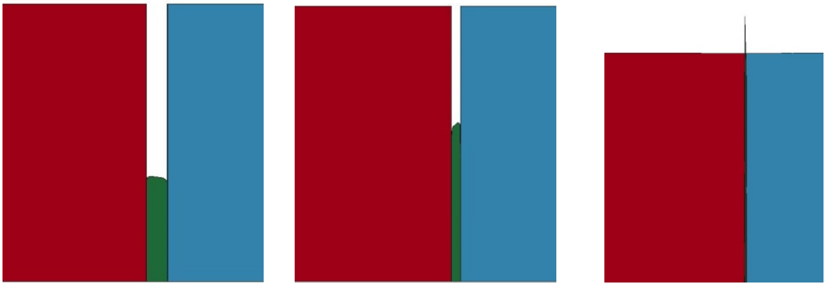


Figure 5: Contact force between the bars and the shaper.



(a) 400 μs (b) 500 μs (c) 630 μs

Figure 6: Deformation images of shaper during the impact.

corresponding loading value is only five per cent of the maximum contact force; when the force reaches its maximum value at 630 μs, it is found that the shaper has been compressed into a thin sheet with a diameter exceeding that of the bars. These results also indicate that slight change in the initial shape of the shaper has no effect on the waveform shape. The stress pulse curve after shaping is mainly affected by interaction condition of the bars and the deformed shaper. As observed in the experiment, there is only a thin layer of vacuum cement remained between the impact and the incident bar after experiment. Most of the vacuum cement has splashed away. Since a very low material strength was adopted in the numerical simulation, the improvement of the capacity of carrying loading of the shaper is caused by the multi-axial stress state of the cement material caused by the high-speed deformation caused by the impact.

4 A case of application [9]

Granite material contains of different particle size of quartz, mica, plagioclase, hornblende and other components, it is a heterogeneous mixture of a variety of minerals and it is a brittle material with very small fracture strain. For brittle materials in SHPB tests, if the incident stress wave is too steep, i.e. the stress rising time is too small, fracture of the material may be occurred before the stress equilibrium in the specimen is reached. When testing these materials, therefore, square wave loading, normally used in the metal testing, cannot be used. The vacuum cement shaper is adopted to test on the dynamic compressive material behaviour for granite. The specimen is sandwiched between the two pressure bars as shown in figure 7. Strain gages were pasted on the bars 1000mm away from the specimen ends. The shaped incident wave is not only very smooth, but also has a quite good reproducibility. The experimental results are given in Figure 8. It can be seen that the incident wave smoothed by the shaper

Figure 7: Installation of the granite specimen.

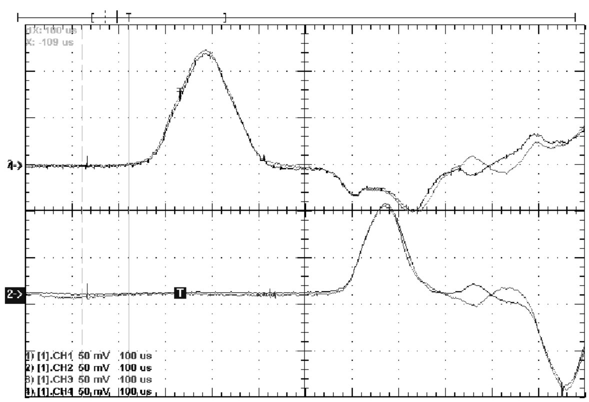


Figure 8: Typical measure curves.

has a shape of half-sine formation, and the rising edge of the wave is more than 100μs. The rising edge of transmission wave is also more than 100 μs, which can fully guarantee the uniformity of the specimen. The plateau of the Reflected wave in the loading process indicates that the specimen loading strain rate is almost constant before the specimen failure.

5 Summary

An SHPB incident pulse shaping method is proposed in this paper. Satisfactory shaping effect is obtained by placing hemispherical vacuum cement on the incident end of the incident pressure bar. This method not only can be used in brittle materials SHPB experiment for an expected slow rise wave and nearly constant strain rate, it also can be used in testing the ductile materials in SHPB experiment as a high frequency filter.

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