Size Effect in the Split Hopkinson Pressure Bar Experiment

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Abstract. For many structures, their service environment is very strict, and the requirements for the impact resistance of materials are very high. Therefore, the dynamic testing method has important scientific significance and application value for practical engineering. Split Hopkinson pressure bar (SHPB) is one of the most common experimental methods for obtaining dynamic mechanical properties of materials. However, there is no uniform standard for the size of the bars and specimens used in the test. Theoretically, the size has little influence on the experimental results, but it has not been proved by experiments. This paper mainly studies the influence of device/specimen sizes of split Hopkinson pressure bar through experiments, it is demonstrated that the sizes of bars and specimen have little effect on experimental results.

1. Introduction

The dynamic testing method has important scientific significance and application value for practical engineering. The split Hopkinson pressure bar (SHPB for short) is one of the most popular experimental methods for investigating the dynamic behaviours of materials [1]. The experimental diagram is shown in Figure 1, a thin specimen disc is sandwiched between the incident bar and transmission bar. A compressive stress pulse is generated in the incident bar by the impact of a striker bar, and load the specimen disc, and meanwhile the reflected pulse and transmitted pulse are generated. A data collector is used to record the incident wave, reflected wave and transmitted wave generated during the experiment. The recorded incident pulse, reflected pulse and transmitted pulse are used to determine the strain rate, strain, and stress in the specimen by using one-dimensional stress pulse theory [2].

\begin{align*}
\dot{\varepsilon}(t) &= \frac{c_b}{l_s} (\varepsilon_i - \varepsilon_r - \varepsilon_t) \\
\varepsilon(t) &= \frac{c_b}{l_s} \int_0^t (\varepsilon_i - \varepsilon_r - \varepsilon_t) dt \\
\sigma(t) &= \frac{\varepsilon_bA_b}{2A_s} (\varepsilon_i + \varepsilon_r + \varepsilon_t)
\end{align*}

Where \(E, A, c, \) and \(l\) are Young modulus, cross-section area, stress pulse speed and specimen length, subscripts \(b\) and \(s\) stand for the bar and specimen, respectively; \(\varepsilon_i\), \(\varepsilon_r\) and \(\varepsilon_t\) are the incident pulse, reflected pulse and transmitted pulse, respectively.
The specimen length results in a non-equilibrium stress state during the initial loading period [3,4]. A criterion to determine the stress equilibrium within the specimen was suggested by Ravichandran and Subhash [5] and frequently cited. It was revealed that the stress equilibrium is associated with the reflecting times of stress waves in specimen [6,7]. Therefore, stress equilibrium time depends on the dimension and wave speed of the specimen [4,8]. The other factor is from three-dimension effect of stress wave propagating along elastic bars, as shown by Davies [9] in 1948. However, metal material tests are rarely corrected for dispersion, since the dispersion is considered insignificant. But no validated experiment has been conducted [10].

In the present work, the influence of specimen and bar sizes on the measurement accuracy of SHPB tests is researched. Hopkinson devices with different dimensions were employed to test copper alloy T2 specimens under a special strain rate to investigate the size effect.

2. Experimental Details

Experiments were conducted to investigate the size effect. The experiments were conducted on the SHPB apparatus of Fundamental Science on Aircraft Structural Mechanics and Strength Laboratory, Northwestern Polytechnical University.

In order to investigate the size effect, special experiments were performed using different bars (5 mm, 12.7 mm and 19 mm in diameter respectively). Cylindrical specimens with different dimensions were tested at a chosen strain rate.

First, the specimen size effect was experimentally studied. 12.7 mm-diameter bars were used. A diameter ratio is defined as n=d/D, where d and D are the diameters of the specimen and bars, respectively. Specimens with n=0.6, 0.5 and 0.4 are made to study the influence of specimen diameter. Meanwhile, for each n, specimens with length/diameter ratio of 0.5 and 1 were tested to study the influence of specimen size. All the specimens are tested at a chosen strain rate.

Second, the bar size effect was also experimentally studied. 12.7 mm-diameter, 19 mm-diameter and 5 mm-diameter bars were used. The tested specimen dimensions for all the bars were n=0.6 and m=1. The specimens were all tested at a chosen strain rate.

The bar diameters D and specimen dimension factor n and m corresponding to each issue are listed in Table 1.

| Specimen sizes effect | D (mm) | n    | m    | Bar sizes effect | D (mm) | n    | m    |
|-----------------------|--------|------|------|-----------------|--------|------|------|
| D (mm)                |        |      |      |                 |        |      |      |
| 0.6                   | 0.5    | 5    |      |                 | 0.6    | 1    |
| 0.5                   | 0.5    | 12.7 | 0.6  |                 | 1      |
| 0.4                   | 0.5    | 19   |      |                 | 1      |

Table 1. The dimensions of bars and specimens corresponding to each issue
3. Results and Discussion

Several stress-strain curves of each specimen dimension at a strain rate of 3800 s\(^{-1}\) are obtained using a 12.7 mm-diameter bar. Curves for each specimen dimension are averaged to eliminate the influence of random factors.

For the convenience of comparison, the averaged stress versus strain and the average variances of stress values versus strains are plotted in Figure 2(a). It can be seen that good agreement can be achieved in the plastic phase. Therefore, the influence of the size of bar and specimen can be ignored for ductile metals in traditional SHPB tests.

However, distinct difference of the initial yield phase can be observed. For shorter specimens (\(m=0.5\)), the initial yield phase is more relaxative, while it is sharper for slender ones (\(m=1\)). The reason may be that the stress equilibrium is influenced by the specimen length-diameter ratio. In the initial yield phase, the plastic wave is dominant. Since plastic waves travel more slowly than elastic waves, thinner specimens trend to reach stress equilibrium sooner than slender ones.

The results of the bar size effect are shown in Figure 2(b). The stress-strain curves are obtained at a strain rate of 1200s\(^{-1}\). The curves have good consistency in the plastic phase, but exhibit large differences in the elastic phase. According to reference [10], the indentation effect of the sample will affect the accuracy of the measurement in the elastic phase of the stress-strain curve, and the degree of the indentation effect is different for different bar and sample sizes, which leads to the difference in the elastic section.

In sum, both the bar and specimen sizes have a significant effect on the elastic phase, but negligible effect on the plastic phase.

The stress equilibrium analysis is also conducted by comparing the relative difference between the stress-strain curves obtained by the one-wave and two-wave methods. The equilibrium factor is defined as[4]

\[
K = \frac{|\sigma_1(\varepsilon) - \sigma_2(\varepsilon)|}{(\sigma_1(\varepsilon) + \sigma_2(\varepsilon))/2}
\]  

where \(\sigma_1(\varepsilon)\) and \(\sigma_2(\varepsilon)\) are the stress obtained from the one-wave and two-wave method, respectively. As suggested by Ravichandran & Subhash[5], when \(k\leq0.05\), the specimen is regarded as being in stress equilibrium. The k-strain plots of the obtained curves are shown in Figure 3. Obviously, specimens reach equilibrium stress in the plastic stage.
4. Conclusion
The interface contact and its influence on the obtained stress-strain curves in the SHPB experiment was analysed both numerically and experimentally, and the size effect was investigated by SHPB experiments for pure copper. Based on the experimental and numerical results the following conclusions can be reached: For general SHPB tests on ductile metals, the size effect is not notable. The stress-strain curves obtained from different specimen sizes are consistent in the plastic phase. The same is true for different bar sizes.

5. Acknowledgments
This work was supported by the China Postdoctoral Science Fund (2019M653785) and the Basic Research and Strategic Reserve Technology Research Fund of China National Petroleum Corporation (2019D-5008 (2019Z-01)).

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