Energy transfer rules and damage characteristics analysis of layered mortar specimen under low-velocity impact

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Abstract: The energy transfer rule and failure pattern of layered mortar specimen are helpful to analyze the seismic performance of layered structure. Split Hopkinson pressure bar equipment was used for one-dimensional impact tests of specimens with double fissures under low-velocity. Experimental results show that when the impact speed is lower than 5.26 m/s, the energy consumption of the layered mortar specimens with a parallel fracture spacing of 18 mm increases with the increase of the impact velocity. When the speed is increased from 5.26 m/s to 6.04 m/s, the energy consumption increases first and then decreases, and the impact velocity corresponding to the maximum value is determined by the physical and mechanical properties of the layered fracture of the specimen and the impact strength of the material. Within the low speed range of 3.38 m/s~5.26 m/s, damage variable presented an increase weak power function relationship with the increasing impact speed, meeting \( d = -10014.08e^{-0.32} + 0.83 \), and the damage value of the specimen was about 0.72. The results of this study provide a reference for the analysis of the dynamic characteristics of laminated cement mortar material in construction engineering.

1. Introduction
Layered masonry mortar will affect the dynamic behavior and seismic stability of buildings. Many scholars have done relevant research in recent years. Liu Hongyan analyzed the influence of joint geometric characteristics on dynamic failure characteristics of rock mass by the method of simulation of mortar materials and SHPB impact experiment[1, 2]. Wang Jianguo and Yang Yang studied the influence of joint dip Angle, joint thickness, joint filling material and strain rate on the dynamic mechanical properties of rock with the help of SHPB experimental device[3-6]. LIU Tingting analyzed the propagation characteristics of stress wave through the biparallel joint rock[7]. Yu Jin and Li Yexue studied the variation law of the stress wave passing through the rock joint surface and conducted energy analysis[8, 9].

To clarify energy transfer, energy dissipation law, strength characteristics and failure mode of layered mortar materials under dynamic load, the SHPB dynamic test device recommended by the international society of rock mechanics is adopted in this paper to carry out impact mechanical tests for layered cement mortar specimens at different velocity.
2. SHPB impact test design

2.1. Preparation of stratified mortar specimens
To study the dynamic properties of layered mortar material, the mortar specimens of this test is designed to three layer, select the intensity of the ratio of two kinds of material (physical and mechanical parameters of material such as table 1).

| Material                  | m₁ : m₂ : m₃ | Density (g.cm⁻³) | Compressive strength (MPa) | Elasticity modulus (GPa) | Poisson ratio (μ) | Cohesion (MPa) | Frictional angle (°) |
|---------------------------|--------------|------------------|---------------------------|--------------------------|------------------|----------------|----------------------|
| Cement mortar of A ratio  | 1 : 2 : 0.45 | 2.13             | 40.2                      | 32.8                     | 0.25             | 21.5           | 30.5                 |
| Cement mortar of B ratio  | 1 : 4 : 0.6  | 1.81             | 17.5                      | 21.1                     | 0.32             | 14.7           | 28.4                 |

In the middle interlayer of the composite specimen, cement mortar with B ratio is placed with a thickness of 18mm. Both sides are cement mortar with A ratio, with a thickness of 40mm. The finished stratified cement mortar specimens with spacing of 18mm are as shown in figure 1.

2.2. Dynamic impact test equipment
The study on energy transfer characteristics and failure modes of stratified mortar specimens under dynamic load was completed on SHPB[10]. The bullet and each bar were steel material with a diameter of 50mm, and a density of 7100kg/m³, a longitudinal wave velocity of 5060m/s, the length of the bullet was 0.6m, the length of the incident bar and transmission bar was 2m, and the absorber bar was 1m.

3. SHPB impact test design

3.1. Preparation of stratified mortar specimens
The energy equation of incident wave, reflection wave and transmission wave is as follows[11]:

\[ E_i = A \rho_0 C_0 \int_0^T \varepsilon_i^2(t_l) dt_l \]  \hspace{1cm} (1)

\[ E_r = A \rho_0 C_0 \int_0^T \varepsilon_r^2(t_l) dt_l \]  \hspace{1cm} (2)

\[ E_t = A \rho_0 C_0 \int_0^T \varepsilon_t^2(t_l) dt_l \]  \hspace{1cm} (3)

\[ E_o = E_i - E_r - E_t \]  \hspace{1cm} (4)

Where,  \( E_i \),  \( E_r \),  \( E_t \),  \( E_o \) are energy of incident wave, reflected wave, transmitted wave and dissipated energy;  \( A \),  \( \rho_0 \),  \( C_0 \) are the cross-sectional area, material density and elastic longitudinal wave velocity of the incident bar and transmission bar;  \( \varepsilon_i(t_l) \),  \( \varepsilon_r(t_l) \),  \( \varepsilon_t(t_l) \) are the strain time-history curve of incident, reflected and transmitted waves.

3.2. Wave curves at different impact velocities
The specimens in this group are impacted at four different velocities of 3.38m/s, 4.81m/s, 5.26m/s and 6.04m/s, and the strain time-history curves of each specimen are shown in figure 2. The measured
waveforms under different impact velocities are different significantly. It can be seen from the $\varepsilon - t$ curve that the amplitude of strain waveform increases gradually with the increase of the impact velocity of the bullet. When the impact velocity increases from 3.38m/s to 5.26m/s, the transmission is amplitude gradually increased. However, when the impact velocity is 6.04m/s, the transmission wave amplitude decreases instead and the reflection is amplitude increased obviously. This is because when the impact velocity is less than 6.04m/s, the dynamic strength of the mortar specimen has reached its maximum. When the impact velocity is 6.04m/s, the fracture in the specimen increases during wave propagation, the transmission of the wave is blocked and the reflection of the wave is increased.

![Fig 2. Strain-time curves under different impact velocity](image)

3.3. Energy transfer characteristic

After dynamic loading was completed on the SHPB device, calculated and averaged multiple groups of the energy ratio of reflection $E_{R}/E_{i}$, transmission $E_{T}/E_{i}$ and dissipation $E_{D}/E_{i}$. The calculation results are shown in table 2. Calculate the total absorption energy density $u$, total dissipation energy density $e_{p}$ and damage variables $d$ of each specimen from equations (5) to (7) [12, 13]. The results were listed in table 2.

\[
\begin{align*}
\sigma d\varepsilon &= u \quad (5) \\
\frac{e_p}{V} &= \frac{E_D}{E_i} \quad (6) \\
\frac{d}{u} &= \frac{e_p}{u} \quad (7)
\end{align*}
\]

| NO. | $v$/m.s$^{-1}$ | $E_i$/J | $E_R$/J | $E_T$/J | $E_D$/J | $E_D/E_i$ | $u$/kJ.m$^{-3}$ | $e_p$/kJ.m$^{-3}$ | $d$ |
|-----|---------------|---------|---------|---------|---------|-----------|----------------|-------------------|-----|
| J2  | 3.348         | 55.78   | 33.25   | 12.11   | 0.233   | 134.43    | 61.71         | 0.46              |
| J1  | 3.571         | 65.15   | 30.93   | 14.22   | 0.307   | 111.69    | 74.09         | 0.66              |
| J8  | 3.662         | 68.53   | 32.76   | 14.53   | 0.310   | 108.37    | 81.38         | 0.75              |
| J3  | 4.812         | 118.35  | 47.26   | 26.01   | 0.381   | 284.80    | 229.71        | 0.81              |
| J4  | 4.969         | 136.71  | 55.21   | 28.87   | 0.385   | 330.02    | 268.18        | 0.81              |
| J6  | 5.258         | 159.96  | 52.26   | 39.65   | 0.425   | 402.06    | 346.75        | 0.86              |
| J7  | 5.540         | 157.29  | 53.93   | 23.33   | 0.388   | 374.42    | 310.98        | 0.83              |
| J5  | 6.038         | 193.46  | 124.19  | 4.30    | 0.336   | 414.13    | 331.06        | 0.81              |

the relation curve of incident energy, reflection energy and transmission energy changes with impact velocity of specimens are shown in figure 3. It can be seen that the incident energy and reflection energy both tend to increase with the increase of impact velocity, but the rate of increase is different. However, the transmitted energy increases first and then decreases. In the figure, when the impact velocity is greater than 5.26m/s, the transmission energy begins to decline. This is when in this impact
velocity, the dynamic strength of the specimen has reached the peak, and the velocity increases again. The specimen begins to break, the void increases, the medium transmitting energy is no longer in close contact, and the transmission energy decreases.

\[ E_I = 12.59v^2 + 4.07v - 30.61 \]

\[ E_R = 29.81v^2 - 241.15v + 512.85 \]

\[ E_D = 12.59v^2 + 4.07v - 30.61 \]

Fig 3. Energy variable change with different impact velocity

The fitting curve of energy dissipation value with impact velocity, and presents a weak power function increase with impact velocity are shown in figure 4. However, considering the incident energy is also increased at the same time, the energy dissipation ratio is used for illustration, as shown in figure 5. It can be seen that, when the impact velocity is less than 5.26 m/s, the energy consumption ratio basically increases with the increase of impact velocity; when the speed is greater than 5.26 m/s, the energy consumption ratio decreases. The data jitter in the figure may be due to the discrete influence of the specimen material itself on energy transmission.

\[ n = -0.05v^2 + 0.53v - 0.91 \]

\[ R^2 = 0.944 \]

\[ R^2 = 0.905 \]

Fig 4. Dissipated energy vs. impact velocity  
Fig 5. Dissipation rate vs. impact velocity

4. Damage and failure mode analysis

The variation law of damage variable with impact velocity is shown in figure 6. Within the impact velocity range selected by the experiment, damage variable increases with the increase of impact velocity and also presents a weak power function relationship.
Fig 6. Damage variable vs. impact velocity

Fitting data points:

\[
\begin{align*}
\d &= -10014.08e^{-y^{0.32}} + 0.83 \\
R^2 &= 0.94876 \\
v &\in [3.27, 5.33]
\end{align*}
\]

(8)

Where, \(d\) is damage variable, \(R\) is the correlation coefficient of polynomial fitting. The larger the impact velocity, the higher the damage variable value, and the more serious the damage and breakage of corresponding joint specimens, as shown in figure 7. Layered mortar specimens in this group were damaged when \(d\) was about 0.72.

![Specimens after impact](image)

(a). \(v=3.27\) m/s  (b). \(v=3.58\) m/s  (c). \(v=3.66\) m/s  (d). \(v=4.81\) m/s

(e). \(v=5.00\) m/s  (f). \(v=5.33\) m/s  (g). \(v=5.54\) m/s  (h). \(v=6.04\) m/s

Fig 7. Specimens after impact

5. Conclusion
The following dynamic characteristics of layered mortar specimens with double cracks were obtained through SHPB dynamic experiment in this paper:

1. When the impact velocity is less than 5.26 m/s, the energy consumption ratio of layered mortar specimens with a gap spacing of 18mm increases as the impact velocity increases; when the velocity is greater than 5.26 m/s and increases to 6.04 m/s, the energy consumption ratio decreases.

2. When the impact velocity is a value between 5.26 m/s and 6.04 m/s, the energy consumption ratio reaches the maximum value, which corresponds to the peak strength of the impact in the low-speed range of the test. This critical velocity value is determined by the physical and mechanical properties of the layered crack and the impact strength of the material.

3. When the impact velocity increases from 3.38 m/s to 5.26 m/s, the damage variable increases
with the impact velocity in a weak power function, and satisfies \( d = -10014.08e^{-0.32v_{de}} + 0.83 \). The damage value of the specimen at the time of failure is about 0.72.

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