Experimental study on the energy absorption characteristics of viscoelastic damping layers

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Abstract. This work aims to further promote the research and development of flexible damping technology for the seismic damage control of underground engineering structures. On the basis of the understanding of the application of viscoelastic damping theory to the field of earthquake resistance of bridge buildings, impact tests on different rock damping layer–concrete specimens are conducted using the improved split Hopkinson pressure bar test system to analyze the energy absorption characteristics of the viscoelastic damping layers. A comparative analysis of the test results is also performed to differentiate the laws of energy absorption of the viscoelastic damping layer structure using different damping layer materials (rubber and silicone) and different damping layer shapes (honeycomb, corrugated, and cylindrical). Given damping layers with the same material and structure, the energy absorption laws of the structures with different damping layer thicknesses are compared and analyzed. The optimal thickness of the damping layers is also discussed. Results show that the incident energy absorbed by the damping layers of different materials increases by more than 10\% relative to the control group (rock–concrete specimen). Such an increase indicates that the structures have superior energy absorption characteristics and that the rubber material can absorb more incident energy than the high-damping silicone as the damping layer. As for the damping layer shapes, the composite damping layer structure with a honeycomb shape achieves the best energy absorption among all structures. The comparison and analysis of the energy absorption effects when the damping layer thicknesses are 10, 20, and 25 mm reveal that a 20 mm-thick damping layer shows the best energy absorption effect. The current findings can provide theoretical foundation and data support for the application of composite damping layers to the seismic design of underground engineering structures.
1. Introduction

Under the background of the comprehensive promotion of the Belt and Road Initiative in this new era, the Qinghai–Tibet Plateau with rich natural resources has become the next main domain for national economic development. Therefore, the construction of tunnels and other basic strategies and lifeline projects in strong earthquake-prone areas presents a considerable challenge [1-2]. Grouting, densification, lengthening of anchor rods, strengthening of linings, and other rigid methods have long been used as earthquake resistance methods for tunnels in strong earthquake-prone areas at home and abroad [3]. However, a large number of tunnels have been damaged in recent years because of strong earthquakes, thereby leading to serious economic and property losses and threatening the safety of the country and the people. The existing seismic damage of tunnels has prompted the abandonment of traditional rigid aseismic methods in engineering. In recent years, flexible damping technology has emerged as a research hotspot in the study of seismic damage control of tunnel structures.

In flexible damping technology, damping layers are mainly set between linings and surrounding rocks to absorb the seismic energy transmitted by the latter; such layers are obtained through the plastic deformation of damping materials, such as polystyrene geofoam, plastic concrete, and foam concrete, so as to reduce the seismic damage of linings [8]. By conducting shaking table tests with damping layers, domestic scholars have proved that damping layers can effectively reduce the seismic response of acceleration in linings and the amount of energy transferred from surrounding rocks to the linings [9-10]. Hu Jun, Zhang Wenge, and Zhao Wusheng studied the damping mechanism and damping performance of the aforementioned damping materials by conducting experiments and numerical simulations [11-13]. However, current damping materials exhibit weak mechanical properties and strong plasticity. Moreover, damping layers are set only on the basis of the thickness factor and without consideration of the viscoelasticity of materials [5]. A viscoelastic damping structure (Figure 1) is a type of vibration isolation structure based on viscoelastic damping theory. Its principle is that vibration energy is converted into heat energy by the friction between the molecular chains of polymer damping materials so as to achieve vibration reduction [14-15]. Zeng Xiankui et al. conducted an orthogonal test on the influence of the composition ratio of rubber compounds in damping materials on damping performance and found that carbon black N330 exerts the greatest effect on the performance of damping materials [16]. Li Hao et al. performed a numerical calculation to analyze the seismic performance of an existing single span frame structure strengthened by rubber isolation and bulking-restrained braces (BRB) damping and found that both measures greatly improve the seismic capacity of such structures [17]. In the study of the earthquake resistance of bridge buildings, Zeng Zhibin developed practical shock absorption structures, such as shock absorption bearings and damping walls, on the basis of constrained damping theory [18]. Thompson and Ma Xueqiang studied the influence of a constrained damping structure set with a viscoelastic damping material on the vibration and noise reduction performance of rail transit [19-20]. Ai Zhen proposed a composite damping layer structure on the basis of the classical energy dissipation principle of free damping and constrained damping [21]. The displacement and strain energy formulas of the composite damping plate were established through the continuous relationship of the interlayer displacement and thin plate theory. Moreover, the differential formula of motion and the eigenvalue formula of vibration frequency were derived. The results of the study provide a theoretical basis for the application of the proposed structure to automobile vibration and noise reduction. However, no systematic and in-depth research has explored the earthquake resistance of underground tunnels despite the proposed aseismic design of composite damping layer structures [22].
To deeply and systematically evaluate the energy absorption characteristics of composite polymer damping structures, the current study investigates the energy absorption laws and effects of damping layers by using the improved split Hopkinson pressure bar (SHPB) test method under the same loading rate for different damping layer materials and structures. The materials and shapes of damping layers that achieve the best energy absorption effects are also proposed. Given the same damping layer material and shape, the optimal thickness ratio of damping and concrete layers is discussed by comparing the energy absorption laws of damping layers with different thicknesses.

2. Energy absorption principle of damping materials

After the plastic deformation of a ductile damping material, the deformed part loses its energy absorption ability when the material is compressed again by external force. In such a case, the material cannot easily achieve secondary energy absorption. Meanwhile, a viscoelastic polymer damping material is an irregular macromolecular chain polymer; the friction between its macromolecules is converted into heat energy that is then dissipated so as to achieve repeated energy absorption for the protection of tunnel support systems under the impact of earthquakes. In the stress–strain curve of a viscoelastic damping material illustrated in Figure 2, the area of hysteresis loop (OABD) represents the energy that dissipates when the material is impacted by an external force. The principle of energy dissipation is that in the process of compression (OAB), the molecular chains inside the material are compressed and squeezed together. Then, the action of the external force is converted into heat energy and internal energy by overcoming the friction and resistance between the macromolecules. In recovery deformation (BCD), the internal energy of the material is converted into the heat energy generated by overcoming the friction and resistance between the macromolecules. The process causes the internal molecular chain structure to stretch back. The energy produced by the impact of the external force is absorbed and then dissipates through heat dissipation.

![Figure 1. Diagram of viscoelastic damping layer structure](image1)

![Figure 2. Stress–strain curve of viscoelastic damping material and changes of molecular chain](image2)
3. Test system and calculation principle

3.1. Test equipment

The SHPB test system with a diameter of 100 mm from the Engineering Mechanics Test Center of Guangdong University of Technology is adopted as the test equipment (Figure 3). The length of the incident bar is 5,500 mm, the length of the transmission bar is 3,500 mm, the density of the bars is 7,740 kg/m$^3$, and the elastic modulus of the bars is 206 GPa. Thus, the propagation velocity of the stress wave in the rods is 5,158.97 m/s according to formula (1).

$$C_0 = \sqrt{\frac{E}{\rho}}$$ (1)

where $C_0$ is the propagation velocity of the stress wave in the rods, m/s; $E$ is the elastic modulus of the bars, Pa; and $\rho$ is the density of the bars, kg/m$^3$.

During the test, a conical bullet is used to impact the incident bar at a certain speed under the action of high-pressure gas so as to generate an inclined half-sine incident wave in the incident bar that balances the dynamic force [24]. Figure 4 illustrates a 1,000 mm-long conical bullet and its incident wave generated in the test system.

![Figure 3. Sketch of SHPB system](image)

**Figure 3.** Sketch of SHPB system

![Figure 4. Cone-shaped striker and incident wave](image)

**Figure 4.** Cone-shaped striker and incident wave
3.2. Energy calculation principle

The process of the stress wave generated by the bullet hitting the incident bar and propagating in the bars is recorded by a strain gauge installed on the incident and transmission bars (Figure 3). The SHPB test is based on two basic assumptions, namely, one-dimensional hypothesis (plane assumption) and assumption of uniformity. Under the one-dimensional hypothesis, the strain waveform at other points can be known through the strain gauge’s measuring points, that is, the strain waveform at the interface between the specimen and the incident bar or transmission bar can be obtained. Under the assumption of uniformity, the stress and strain fields in the specimen are uniform along the length of the specimen.

The stress and strain rates can be determined by the three-wave method of the SHPB test, as shown in the following formulas:

\[
\sigma(t) = \frac{A_s}{2A_0} E (\varepsilon_T + \varepsilon_R + \varepsilon_I) \tag{2}
\]

\[
\varepsilon(t) = \frac{c_0}{L_s} \int_0^t (\varepsilon_T - \varepsilon_R - \varepsilon_I) \, dt \tag{3}
\]

\[
\dot{\varepsilon}(t) = \frac{c_0}{L_s} (\varepsilon_T - \varepsilon_R - \varepsilon_I) \tag{4}
\]

where \( \varepsilon_I \) and \( \varepsilon_R \) are the strains of the incident and reflected waves measured on the incident bar; \( \varepsilon_T \) is the strain of the transmission wave measured on the transmission bar; \( L_s \) is the length of the specimen, \( m; A_0 \) is the cross-sectional area of the bars, \( m^2; \) and \( A_s \) is the cross-sectional area of the specimen, \( m^2. \) The stress–strain relationship curve of the specimen at a certain strain rate can be deduced using the previous formulas (1–4).

The friction energy generated by the interface between the bar and the specimen and between the specimen and another specimen is assumed to be negligible during the test. Thus, according to the law of energy conservation, the energy absorbed by the specimen is defined as

\[
W_S(t) = W_I(t) - W_R(t) - W_T(t) \tag{5}
\]

where \( W_S(t) \) is the energy absorbed by the specimen, \( J; W_I(t), W_R(t), \) and \( W_T(t) \) are the energies carried by the incident, reflected, and transmitted waves, respectively, \( J. \)

These energies can be calculated by the following formulas:

\[
W_s(t) = \int_0^T A_x \sigma_x(t) C_0 \varepsilon_x(t) \, dt \tag{6}
\]

\[
\sigma_x(t) = E \varepsilon_x(t) \tag{7}
\]

where \( A_x \) is the cross-sectional area of the corresponding bars. As the bars have equal cross-sections, \( A_x = A_0, m^2. \sigma_x(t) \) denotes the stress time history of the incident, reflected, and transmitted waves, \( Pa; \) \( \varepsilon_x(t) \) is the strain time history of the incident, reflected, and transmitted waves.

The energies of the incident, reflected, and transmitted waves can be obtained by substituting formula (7) into formula (6) and then combining formulas (2–4), as shown in the following formulas:

\[
W_I(t) = E C_0 A_0 \int_0^t \varepsilon_I^2(t) \, dt \tag{8}
\]

\[
W_R(t) = E C_0 A_0 \int_0^t \varepsilon_R^2(t) \, dt \tag{9}
\]

\[
W_T(t) = E C_0 A_0 \int_0^t \varepsilon_T^2(t) \, dt \tag{10}
\]

The energy absorbed by the specimen during the test \( W_S(t) \) can be obtained from formula (5).

4. Samples and scheme

4.1. Sample preparation

As shown in Figure 5, the basalt samples taken from the Baihetan Hydropower Station were prepared into disk-shaped specimens with a diameter of 50 mm (\( \varphi \)) and thickness of 25 mm (\( d \)). According to the strength standard of C30 concrete, standard curing was also carried out for 28 days after manual pouring. The concrete samples were then prepared into specimens with the same size as the basalt specimens; the damping layer was made of rubber (black) and silicone (white) with two different damping ratios.
For the damping layer composed of the two materials, the sample diameter was 50 mm, and three shapes were designed: cylindrical, honeycomb, and corrugated (Figure 6). The cylindrical sample is a solid sample (Figure 6a). On the basis of the cylindrical sample, the honeycomb sample is obtained by cutting off seven holes with a radius of 5 mm according to the position shown in Figure 6 (b). The corrugated sample is obtained by cutting out three peaks and two troughs according to the size shown in Figure 6 (c).

Figure 5. Images of actual samples

4.2. Testing scheme

The cylindrical, corrugated, and honeycomb rubber and silicone samples with a 1:1 thickness ratio of 1:1 to the concrete samples were selected for the test to determine the influence of the different structural forms and materials of damping layers on the energy absorption effect of the composite...
structure. The specific test scheme is shown in Table 1. Each group of the test scheme was repeated thrice, and the average value of the final results was taken. In the test, a proper amount of Vaseline petroleum jelly was rubbed on the interfaces between the bars and the samples to reduce the energy loss caused by friction. The rock sample was placed on the side of the incident bar, and the concrete sample was placed on the side of the transmission bar. This setup is consistent with the propagation sequence of a seismic wave when it reaches a tunnel structure. The placement of the samples is shown in Figure 7.

![Figure 7. Actual image of impact test setup](image)

**Table 1.** Testing scheme involving shapes and materials of damping layers

| Materials | Groups | Shapes     | Thickness ratio |
|-----------|--------|------------|-----------------|
| Rubber    | AB1    | Cylindrical|                 |
|           | AB2    | Corrugated | 1:1             |
|           | AB3    | Honeycomb  |                 |
| Silicone  | AC1    | Cylindrical|                 |
|           | AC2    | Corrugated | 1:1             |
|           | AC3    | Honeycomb  |                 |
| Control Group | DZ  | /          | 1:1             |

According to the test results, the optimal structural form and material of the damping layers with the best energy absorption effect could be determined. The thickness ratio of the damping layer to the concrete sample with the best energy absorption effect was obtained following the test scheme in Table 2.

**Table 2.** Testing scheme involving thicknesses of damping layers

| Materials | Groups | Thickness ratio | Thickness/mm |
|-----------|--------|-----------------|--------------|
| The optimal structural form and material of above results | AD1    | 0.4:1           | 10           |
|           | AD2    | 0.8:1           | 20           |
|           | AD3    | 1:1             | 25           |

5. Results and discussion

According to the test scheme in Table 1, impact tests were carried out on each group of samples under the same load conditions. Figure 8 shows the shape of the samples after impact. In the control group of rock–concrete samples without a damping layer, the crushing degree was very serious after the impact of dynamic load, and a part of the concrete sample broke into powder particles. Under the action
of the damping layer, the samples in the experimental group maintained a relatively complete overall shape, thus indicating that the damping layer between the rock and the concrete absorbed and dissipated most of the energy under the impact of dynamic load. In addition, under the impact of dynamic load, the existence of the damping layer weakened the crushing degree of the rock and concrete samples and even maintained their shape without damage. Hence, only certain parts of the samples showed cracks. This result indicated that the composite damping layer structure was not affected by the transfer direction of the impact load. Even though the damping layer was in the “sandwich” position and was not the first to be impacted by the load, the contact between the damping layer and the concrete layer and that between the damping layer and the rock layer caused the tensile and compressive deformation of the damping layer. These phenomena made the damping layer absorb and dissipate the impact energy, thereby weakening the crushing degree of the concrete and rock samples.

5.1. Effect of different damping layer materials
The change curves of the incident energy, reflected energy, transmitted energy, and absorbed energy after the impact test were obtained according to the calculation principle described in Section 3.2. As the change trends of the experimental group were similar, only the results of the cylindrical rubber and silicone as the damping layer and those of the control group are listed herein (Figure 9).

The change trends of the energies were similar during the impact process. For the control group, the samples dissipated 40.42% of the incident energy, which acted on the rock and concrete samples and caused serious crushing (Figure 8 (d)). In the structure with a damping layer, the samples dissipated more than 50% of the incident energy. With the cylindrical silicone and cylindrical rubber as the
damping layers, the samples dissipated 54.35% and 55.31% of the incident energy, respectively. The rubber material obviously showed better energy absorption ability than the silicone material.

![Figure 9. Energies in SHPB rods under different damping layer materials](image)

The dissipative speed of energy changing with time in the impact process of the test structure is defined as the variation rate of the dissipative energy of the structure, as shown in formula (11). At the end of the test, the variation rates of the dissipative energy of the structures with the cylindrical rubber and silicone as the damping layers and that of the control group were calculated according to formula (11). The results are shown in Figure 10.

\[
\psi_s(t) = \int_0^T W_s(t) \, dt
\]  

(11)

where \(\psi_s(t)\) is the variation rate of the dissipative energy of the test structure and \(W_s(t)\) is the dissipative energy, J.

Figure 10 shows that the variation rates of the dissipative energy of the test structures present a “straw hat”-shaped distribution, that is, they increased rapidly at first to reach the peak, then decreased rapidly, and finally approached zero slowly until the end of the impact. The peak values of the variation rates of the dissipative energy of the structures with damping layers were significantly higher than that of the control group. Such result indicated that the damping layer greatly improved the energy absorption ability of the structure. Meanwhile, the peak values of the variation rates of the dissipative energy of the structure with rubber as the damping layer were greater than those of the structure with silicone as the
damping layer. Moreover, the variation rates of the former peaked earlier than the latter, thereby indicating that the energy absorption efficiency of the rubber material was better than that of the silicone material used in the test.

![Figure 10.](image)

**Figure 10.** Variation rates of dissipative energy with different damping materials

### 5.2. Effect of different damping layer shapes

![Figure 11.](image)

**Figure 11.** Percentage of dissipative energy under different damping layer shapes

|                  | Silicone | Rubber | Average |
|------------------|----------|--------|---------|
| Cylindrical      | 54.35%   | 55.31% | 54.83%  |
| Corrugated       | 51.79%   | 52.59% | 52.19%  |
| Honeycomb        | **57.01%** | **58.31%** | **57.66%** |

**Table 3.** Mean values of the proportions of dissipative energy under different damping layer shapes

Figure 11 illustrates the dissipative energy of the structures with different damping layer forms under the condition of two different materials. The specific values of the ratio of dissipative energy to incident energy for every structure are shown in Table 3. The results showed that the honeycomb damping layer had the best energy absorption ability, followed by the cylindrical damping layer and corrugated damping layer. The structure with the honeycomb damping layer dissipated 57.66% of the
5.3. Effect of different damping layer thicknesses

On the basis of the results of the test scheme shown in Table 1 and the analysis of the influence of the damping layer material and shape on the energy absorption characteristics of the structures, impact tests were conducted following the test scheme shown in Table 2. The objective was to determine the influence of different damping layer thicknesses on the energy absorption characteristics of the structures. With the thickness of the concrete sample kept unchanged, the thickness ratios of the damping layer to the concrete layer were set to 0.4:1, 0.8:1, and 1:1. The proportion of dissipative energy after the impact tests for the cylindrical rubber damping structures under different damping layer thicknesses was obtained, and the results are shown in Figure 12. The energy absorption ability of the structure was the best, accounting for 61.16% of the incident energy, when the thickness ratio of the damping layer to the concrete layer was 0.8:1. The second-best results were obtained with the thickness ratios of 1:1 (accounted for 58.31% of the incident energy) and 0.4:1 (accounted for 54.28% of the incident energy). This outcome showed that the thickness of the damping layer had a nonlinear relationship with the energy absorption ability of the composite damping structure and that the idea that the thicker the damping layer is, the better the energy absorption ability of the structure did not hold true; such result is similar to the conclusion of Qiao Lan [22].

Figure 12. Proportion of dissipative energy under different damping layer thicknesses

6. Conclusion

Considering the viscoelastic properties of polymer damping materials, this study proposes a composite damping structure for use in the earthquake resistance of underground tunnel engineering structures. Through the improved SHPB test system, the influence of the material, form, and thickness of damping layers on the energy absorption ability of the structure is analyzed. The preliminary results are as follows:

(1) The control group structure without a damping layer shows serious breakage after dynamic load impact. In this group, the concrete sample partially breaks into powder particles. By contrast, the experimental group structures with damping layers can remain relatively intact or show undamaged
morphology. Relative to that for the control group structures, the incident energy absorbed by the different experimental groups increases by more than 10%, which indicates that the damping layer absorbs and dissipates most of the incident energy under the impact of dynamic load and that the viscoelastic damping layer structure has superior energy absorption ability.

(2) The energy absorption ability of the structure with rubber as the damping layer is better than that of the structure with silicone as the damping layer material. In addition, the energy absorption ability of the honeycomb damping structure is better than that of the cylindrical and corrugated damping structures. The energy absorption ability of the honeycomb rubber damping structure is the best and reaches 58.31%. The rock and concrete samples are not seriously broken after impact, and they even remain intact, thereby indicating that most of the energy dissipated by the structure is transformed into internal and heat energy by the rubber damping layer.

(3) The variation rates of the dissipative energy for all types of structures shows a “straw hat” distribution with time, that is, they increase rapidly at first to reach the peak, then decrease rapidly, and finally approach zero slowly until the end of impact. Meanwhile, the peak values of the variation rates of the dissipative energy of the structure with a damping layer are significantly greater than those of the control group structure. This result indicates that the damping layer greatly improves the energy absorption ability of the structure.

(4) When the thickness of the damping layer is 20 mm, the energy absorption ability of the viscoelastic damping structure is the best. The relationship between the thickness of the damping layer and the energy absorption ability of the composite damping structure is nonlinear; hence, the idea that the thicker the damping layer is, the better the energy absorption ability of the structure will be does not hold true.

(5) The test results and analysis show that when a honeycomb rubber material is selected as the damping layer, the viscoelastic damping structure achieves good energy absorption ability. Hence, the thickness of the damping layer should be selected reasonably. These conclusions provide theoretical and data support for the structural design of underground tunnel engineering structures with earthquake resistance.

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