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LOW-COST SEISMIC ISOLATION TECHNOLOGY FOR LOW-RISE RURAL BUILDINGS

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Abstract

This paper proposes an innovative low-cost isolator with lightweight and cost-effective features for use in low-rise residential buildings. The low-cost laminated isolator is formed by plastic shims with unsaturated polyester fiber reinforcement between rubber layers. Both types of low-cost isolators within the G4 rubber layers and G6 rubber layers have been designed and manufactured. Performance tests are systematically carried out to characterize the isolator in terms of mechanic behavior (e.g., compression, shear, and their relationship), dynamic properties (e.g., damping), and ultimate states. A connection construction scheme is put forward for low-rise rural buildings. This simple isolation technology provides scientific and technological support for popularizing seismic isolation technology in underdeveloped rural areas.

Keywords: seismic isolation technology; simple isolator; rural buildings; engineering plastic plate; connection construction

1. Introduction

The recent earthquakes in China, Haiti, and Nepal have emphasized the fact that the major loss of life in earthquakes happens when the events occurs in developing countries. Even during relatively moderate earthquakes in areas with poor housing conditions many people could be killed by the collapse of brittle heavy unreinforced masonry or poorly constructed concrete buildings. For example the Wenchuan and Yushu earthquakes in 2008 and 2010 caused, numerous people living in the rural areas to lose their lives. This is because many masonry and reinforced concrete buildings underperformed against these earthquakes and then collapsed. Thus, more attention should be paid to the residential buildings in undeveloped rural areas.

One of the solutions to seismic protection is the base isolation in which isolators are installed at the base of structure to limit ground motions transmitting to the structures [1]. Generally, the most widely used isolators are the steel laminated elastomeric bearings, consisting of steel shim plates between rubber layers. In this type of isolators, the steel shim plates provide a high stiffness in the vertical direction, while the rubber layers supply flexibility in the horizontal direction. However, this type of isolator is relatively large, heavy and expensive. In order to apply the advanced technology of seismic isolation in rural areas or in low-cost buildings, a study for reducing the cost and weight of isolators is required.

As suggested by Kelly [2] in 1999, substituting the steel shim plates by fiber reinforcement materials can create a high elastic stiffness, as well as address the shortcoming in the traditional laminated rubber isolators. This study showed that the fiber-reinforced isolators can create a reasonable tilting and vertical stiffness as steel-reinforced isolators with a similar dimension. In comparison, the fiber-reinforced isolators outperformed the steel-laminated rubber isolators by the lightweight and cost-effective features and convenience for construction.

Some researchers have carried out studies on the fiber-reinforced isolators. Kelly and Taldairov [3], Tsai and Kelly [4] investigated the theoretical approaches to analyzing the compressive stiffness and bending stiffness of the fiber-reinforced rectangular isolators. Ashkezaria et al. [5] and Khanlari et al. [6] designed and manufactured specimens of the fiber reinforced elastomeric seismic isolators, and then studied their dynamic and mechanical characteristics. Kanga et al. [7, 8] investigated the effect of hole and lead plug in FREI (fiber reinforced elastomeric isolator) where the reinforcing element-normally steel plates are replaced by a fiber reinforcement. Toopchi-Nezhad et al. [9, 10] presented a finite element model for the analysis of strip fiber reinforced elastomeric isolators (FREIs) that are subjected to any given combination of static vertical and lateral loads. However, as the out-of-plane stiffness of the fiber layers is very small in previous studies, it is a great challenge to obtain similar constraint on lateral deformation of rubber layer as the traditional rubber isolator would do [11, 12]. Otherwise, it would lead to a big drop on the vertical stiffness and isolator capacity. Another obstacle to overcome is that the ultimate deformation of this kind of novel isolator is so small that would make the fiber-reinforced isolator may fail under strong earthquakes. Therefore, the challenging goal is to design cost-effective seismic isolators by using fiber reinforcement engineering plastic sheet, and achieve ideal stable performance as the seismic isolators with steel plates.

This paper develops an innovative low-cost isolator which consists of laminated rubber and plastic sheets with unsaturated polyester fiber reinforcement between the rubber layers. First, the plastic sheets used in this innovative isolator are introduced, and the overall design of this isolator is described. Both types of low-cost isolators within G4 rubber layers and G6 rubber layers have been designed and manufactured. Subsequently, performance of the innovative isolator is experimentally evaluated to characterize mechanic behaviors (e.g., compression, shear, and their relationship), dynamic properties (e.g., damping), and ultimate states. A connection construction scheme is put forward for low-rise rural buildings.

2. Design of innovative low-cost isolator

The low-cost isolator proposed in this paper consists of laminated rubber and plastic sheets with unsaturated polyester fiber reinforcement between the rubber layers, resulting in a lightweight, cost-effective isolator for use in low-rise residential buildings. One of the key features of this innovative isolator is the fabrication cost which is less than 10% of a steel-laminated rubber isolator. This feature offers an opportunity for a wide use of this type of isolator in the undeveloped rural areas provided that its seismic performance is comparable to the steel-laminated rubber isolators.

2.1 Mechanical property of the engineering plastic

The engineering plastic is a kind of composite material, made up of the unsaturated polyester and glass fiber cloth. To investigate the characteristics of the unsaturated polyester fiber reinforcement engineering plastic plate, two kinds of tests have been carried out, and the results are summarized in Tables 1.

From Table 1, the bending and tensile test results show that the mechanical properties of engineering plastic plate meet the requirements as a replacing stiffening material for rubber isolator. It provids the option that the conventional steel plate in an isolator can be replaced with the engineering plastic plate.

Table 1 – The unsaturated polyester engineering plastic plate tensile and bending test report

No.	**Tensile**			**Bending**	
	Modulus /MPa	**Strength /MPa**	**Elongation at break /%**	**Modulus /MPa**	**Strength /MPa**
1	17126.86	302.61	2.39	13080.08	460.16
2	18045.53	304.44	2.38	12709.24	468.18
3	16576.54	292.44	2.35	12351.18	492.64
4	17931.35	316.57	2.41	10889.42	428.77
The average	17420.07	304.02	2.38	12257.48	462.44
Dispersion coefficient	0.0399	0.0325	0.0105	0.0783	0.0570

2.2 Manufacturing of the novel simple isolator

A prototype isolator is developed in accordance to the design for use in a low-rise masonry building, which is typically seen in the rural areas. This novel simple isolator provides economical vertical stiffness, enough horizontal flexibility, and is small in size and lightweight.

Fig. 1 shows a designed square simple isolator based on the modulus of brick masonry. The pads of the isolator are 240mm long, 240mm wide and 111mm high, and consist of eleven 3mm fiber reinforcement engineering plastic laminates bonded to twelve 4mm layers of rubber. The top and bottom plates (fiber reinforcement engineering plastic) are 8mm thick. The G4 rubber layer or high damping G6 rubber layer is used to the rubber sheet in the isolator.

Fig. 1 – Illustration of a simple isolator

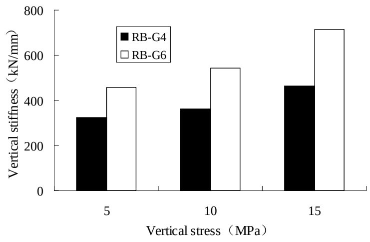

Fig. 2 – The comparison of vertical stiffness

3. Performance evaluation of the simple isolator

Performance of the innovative low-cost isolator is evaluated in the Cultivation Base for State Key Laboratory of Seismic Control and Structural Safety at Guangzhou University.

A series of tests are conducted by the Elastomeric Bearing Test Machine to determine the horizontal and vertical behaviors (i.e., stiffness, hysteresis, etc.), corresponding damping, frequency dependence, and ultimate state (i.e., shear strain and strength, maximum vertical strength, etc.). The testing machine is capable of testing an isolator concurrently subjected to vertical and horizontal loadings. In the vertical direction, the maximum compressive load is 10000kN, and the total displacement is 350mm. In the horizontal direction, the maximum compressive load is ±500kN, and the total displacement is 200mm.

3.1 Vertical test

In order to investigate the vertical stiffness of the novel simple isolator, a vertical test is performed. There were four cycles of loading with peak-to-peak values. Some bearings were tested to obtain vertical stiffness under various maximum values of vertical loads. The vertical stiffness is computed using a linear regression method on the linear portion of the hysteresis loops. In the third hysteresis loop, the vertical stiffness of RB-G4 isolator under 5 MPa, 10 MPa and 15 MPa is calculated to be 322.97kN/mm, 361.53kN/mm and 464.45kN/mm, respectively. And the vertical stiffness of RB-G6 isolator under 5 MPa, 10 MPa and 15 MPa is calculated to be 457.28kN/mm, 543.89kN/mm and 713.12kN/mm, respectively. The comparison of vertical stiffness between RB-G4 isolator and RB-G6 isolator is shown in Fig. 2. The results indicate that the vertical stiffness of RB-G6 isolator is higher than that of RB-G4 isolator. This increase is equal to 41.59%, 50.44% and 53.54% under 5MPa, 10MPa and 15MPa, respectively. The ultimate stress of the RB-G4 and RB-G6 isolator is 79.84 MPa and 82.44 MPa, respectively. The vertical test result shows that the novel isolator has sufficient vertical stiffness.

3.2 Horizontal test

To investigate the horizontal characteristic of the novel simple isolator, a set of tests on horizontal stiffness of the simple isolator under various compression levels and shear strains are carried out.

Horizontal tests are performed on isolators by applying a constant vertical load and fully reversed cycles of dynamic horizontal displacements. The horizontal tests are performed on the isolator specimens with shear strain amplitude of ±100%, vertical compressive stress of 5MPa. The tests are repeated in four cycles. The horizontal loads have been applied at frequency of 0.05Hz. By carrying out the horizontal tests, the shear force-displacement loops are obtained, shown in Fig. 3. According to the third hysteresis loop, the horizontal stiffness of the RB-G4 and RB-G6 isolator is calculated to be 0.4614kN/mm, 0.5494kN/mm, respectively.

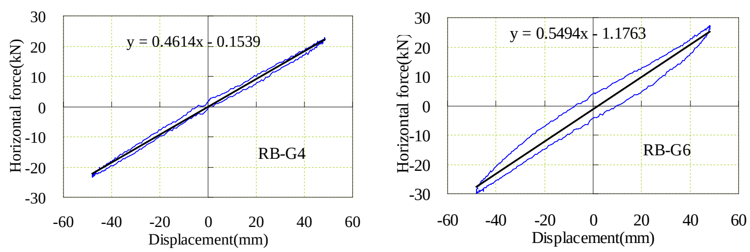

Fig. 3 – Horizontal force-displacement of the RB-G4 and RB-G6 isolator

Under different vertical compressive stress of 5MPa, 7.5MPa, 10MPa, 12.5MPa, 15MPa, the horizontal tests are conducted on the isolator with shear strain amplitude of ±100%. The two type isolator of the relativity between horizontal force and displacement of isolator is shown in Fig. 4 and the relativity between horizontal stiffness and vertical stress of isolator is shown in Fig. 5, respectively. It is shown that the horizontal stiffness of the isolator is decreases with the vertical stress increasing.

Under different shear strain amplitudes of ±100%, ±200%, ±250%, ±300%, the horizontal tests are performed on the isolator with vertical compressive stress of 5MPa. The relativity between horizontal force and displacement of two type isolators under 5MPa is shown in Fig. 6. According to the hysteresis loops, the relativity between horizontal stiffness and shear strain of isolator is shown in Fig. 7. The results show that, under the same vertical stress, the horizontal stiffness of the isolator has decreased with the shear strain increasing. The relativity between horizontal stiffness and shear strain of isolator shows nonlinear behavior.

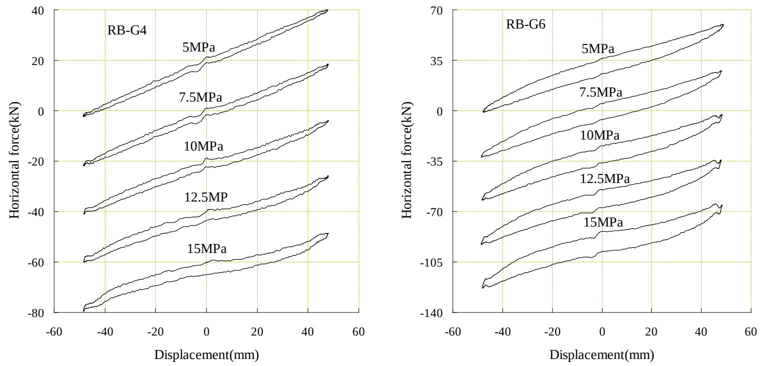

Fig. 4 – Relativity between horizontal force and displacement of RB-G4 and RB-G6 isolator under 100%

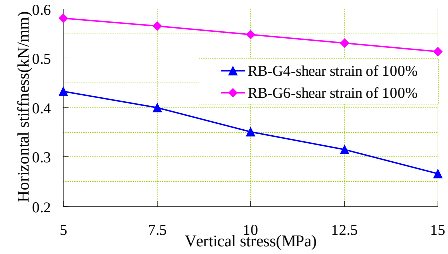

Fig. 5 – Relativity between horizontal stiffness and vertical stress of isolator

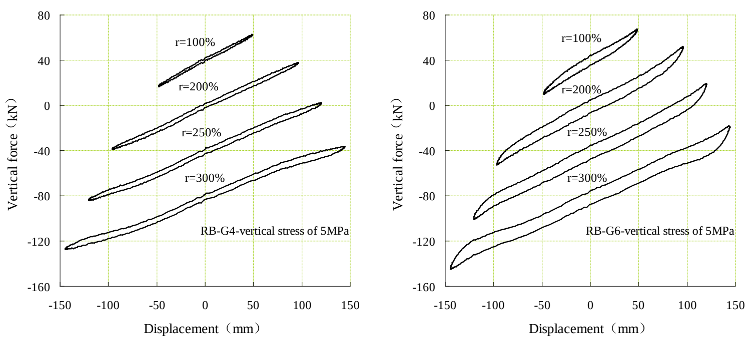

Fig. 6 – Relativity between horizontal force and displacement of RB-G4 and RB-G6 isolator under 5MPa

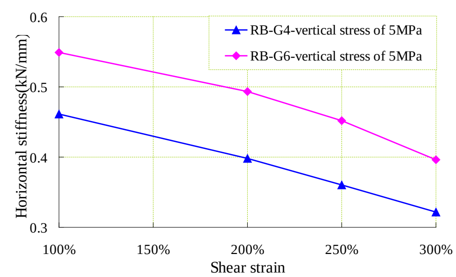

Fig. 7 – Relativity between horizontal stiffness and shear strain of isolator

3.3 Damping characteristics

The equivalent viscous damping of the simple isolator is one of the most important characteristics to be determined from the horizontal dynamic tests. This property can be checked with the plots of horizontal shear force-horizontal displacement. This force-displacement relationship shows hysteretic behavior. The size of the area enclosed by the hysteretic loop on the imposed strain level is a measure of hysteretic properties. The equivalent viscous damping is computed by measuring the energy dissipated in each cycle (ΔW), which is the area enclosed by the hysteresis loop. The formula to compute h_{eq} is

$$h_{eq} = \frac{2\Delta W}{\pi K_h (X_{\max} - X_{\min})^2} \tag{1}$$

Where K_h is the effective horizontal stiffness, and $X_{\max}$ and $X_{\min}$ are the maximum positive and negative shear displacements, respectively.

Form the combined compression and shear test, the equivalent viscous damping of the simple isolator is obtained from Eq. (1). Under different vertical compressive stress of 5MPa, 7.5MPa, 10MPa, 12.5MPa, 15MPa, and with the same shear strain amplitude of ±100%, the relativity between equivalent damping and vertical stress of two type isolators is shown in Fig. 8. The results also show that, under the same shear strain, with the vertical stress increasing, the equivalent damping of the two isolators has increased.

Under different shear strain amplitudes of ±100%, ±200%, ±250%, ±300%, the relativity between equivalent damping and shear strain of two type isolators under 5MPa is shown in Fig. 9. It is observed that the equivalent damping of the RB-G4 isolator is increased with the shear strain increasing, but the equivalent damping of the RB-G6 isolator is decreased with the shear strain increasing. According to the analysis for the equivalent damping of the isolator, one can conclude that the RB-G6 isolator is a kind of high damping isolator, whose equivalent damping basically is greater than 8%. This is relativity to the high damping G6 rubber layers in the isolator.

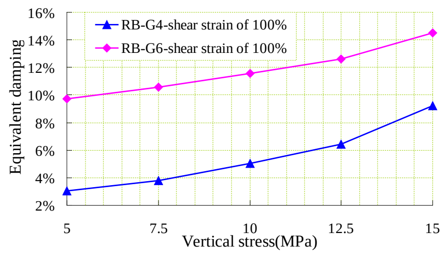

Fig. 8 – Relativity between equivalent damping and vertical stress of isolator

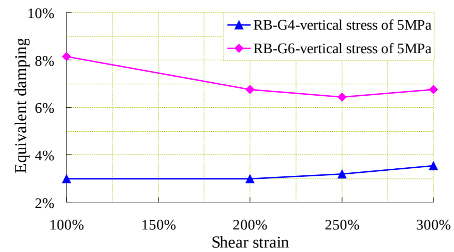

Fig. 9 –Relativity between equivalent damping and shear strain of isolator under 5MPa

3.4 Frequency dependence

To investigate the effect of the horizontal stiffness under the different frequency of the horizontal loading of the novel simple isolator, a set of tests on horizontal stiffness of the two type isolators under various loading frequency are carried out.

Under different loading frequency of 0.05Hz, 0.2Hz, 0.5Hz, 0.7Hz, the horizontal tests are conducted on the two isolators with shear strain amplitude of ±100% under vertical stress of 5MPa. The relativity between horizontal stiffness and loading frequency of isolator is shown in Fig. 10. It is observed that the horizontal stiffness of the isolator is increased with the loading frequency increasing, reach the top value, then it decreased with the loading frequency increasing, and the ratio of the increased and decreased is slightly.

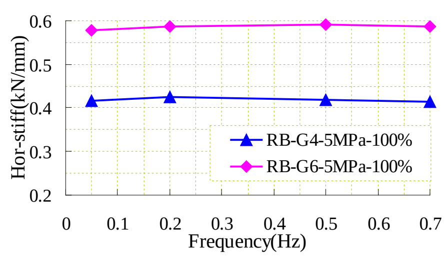

Fig. 10 –Relativity between horizontal stiffness and loading frequency

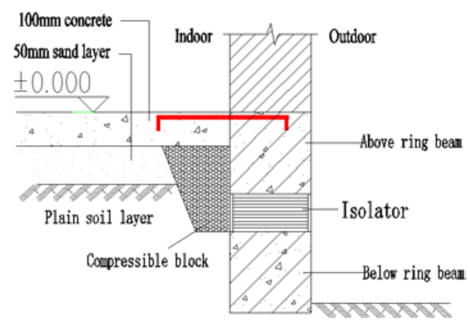

Fig. 11 – Connection construction of the isolation story

4. Connection construction

İn order to apply the low-cost seismic isolation based on the new novel isolator, a connection construction scheme is put forward for low-rise rural building, as shown in Fig. 11. From the Fig. 11, the new novel isolator install between the above ring beam and below ring beam, and a compressible block is set in one side to allow the motion of the isolator under earthquake. The indoor ground consisting of 100mm concrete layer, 50mm sand layer and plain soil layer.

5. Conclusions

This paper proposes an innovative simple isolator, which replaces steel plates of the traditional steel reinforced elastomeric isolator with unsaturated polyester fiber reinforcement engineering plastic plates. The design and manufacturing of seismic isolator reinforced with engineering plastic have been carried out. The following conclusions can be drawn from the experimental results.

1. Bending test and tensile test of the engineering plastic plate demonstrate that it has high possibility to replace steel reinforcements in isolators.

2. From the systematical experiment of the innovative simple isolator, the novel isolators have stability mechanical properties, it has sufficient vertical stiffness and horizontal stiffness.

3. The RB-G6 simple isolator is a kind of high damping isolator, whose equivalent damping level is basically greater than 8%. The horizontal stiffness has a stable frequency dependence for the two isolators.

4. A connection construction scheme is put forward for low-rise rural building, this novel simple isolator is of theoretical and practical significances and has good application prospect in the near future.

6. Acknowledgements

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