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Article

Improving the Seismic Performance of Staircases in Building Structures with a Novel Isolator

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Abstract: A staircase provides the main escape way from a building in an emergency. Unfortunately, it may suffer severe damages or even collapse during an earthquake. For improving the seismic performance of staircases, this paper proposes an innovative staircase isolator with the features of lightweight, cost-effective and ease of construction and replacement, which is formed by suitable engineering plastic shims between rubber layers. A connection construction scheme is also proposed for the isolated staircase. Systematic performance tests have been carried out to characterize the isolator in terms of mechanic behavior and ultimate states. The test results show that mechanical properties of the proposed staircase isolator are excellent and suitable for staircase in building structure. In order to investigate the influence of staircase on building structural responses, time history analyses of a typical building structure without staircase (WS), with fixed staircase (FS) and with isolated staircase (IS) are conducted and compared within the environment of SAP2000. Results show that staircase isolation can effectively eliminate the diagonal bracing effect of staircase slab and make structural components uniformly stressed. When the novel isolator is employed for staircase in a building structure, there is no vulnerable position in staircase and the performance of staircase in building structure can be greatly enhanced.

Keywords: Seismic isolation; seismic performance of staircases; staircase isolation; engineering-plastics rubber isolator; rubber isolator

1 Introduction

A staircase plays an important role in daily life as the main way of vertical transport in the building structures. It is important and even the only vertical emergency escape access in fire, earthquake and other disasters [1]. It must be unblocked in the above emergency for providing egress of personnel. However, staircases suffered severe damages and even collapsed in past earthquakes [2,3]. In response to this, related provisions in *Code for Seismic Design of Buildings* (GB50011-2001) [4] have been revised for improving seismic performance of staircase after the 2008 Wenchuan earthquake in China. Numerical analyses and experimental studies carried out so far have focused on the seismic performance of staircase. Modal linear and nonlinear push-over analyses were conducted to investigate the seismic behavior of two types of staircases in a typical RC building [5]. Elastic and elasto-plastic analyses for 18 RC frame structures with and without staircases were conducted and results compared to study the influence of staircase on the structural seismic performance [6]. Shake table tests of prefabricated steel staircase were carried out to investigate the dynamic characteristics and seismic behavior of steel staircases in a full scale building [7]. Pseudo-static test was performed to assess the anticipated seismic performance of full size prefabricated steel staircase [8] and its corresponding finite element analysis was developed to study the seismic behavior of prefabricated steel staircase [9]. Possible causes for damage of staircase include that the earthquake action is not considered in its design process [5,6], and also that diagonal bracing of staircase slab makes the stairwell stiffer than the surrounding components [2,6,7]. The larger the stiffness of stairwell, the greater the earthquake action, and therefore staircase is prone to damage early during an earthquake.

Experimental studies and numerical analyses show that the connection between slab and landing is the vulnerable position [6–9] and suggestions about improving its seismic performance are put forward. One suggestion is to strengthen the connection [7,8], but the earthquake action will increase accordingly. Another suggestion is to use seismic isolation technology in staircase of a building structure [6]. Seismic isolation technology is an effective means to reduce structural and nonstructural damages during earthquake. It is widely accepted and used in the world [10]. Consequently it is reasonable to expect that seismic isolation technology can improve the seismic performance of staircase, which is often regarded as nonstructural member. In ensuring the proper seismic performance of the isolated structure, the behavior of the isolation bearing plays a key role. The conventional isolation bearings mainly concerned in actual implementations are the sliding and elastomeric bearings [11]. To obtain proper seismic isolation effects, novel isolation bearings and several variations and improvements to the traditional isolation bearings have been proposed. A nonlinear vibration isolator with a quasi-zero stiffness characteristic, consisting of a vertical linear spring and two nonlinear pre-stressed oblique springs, was developed by [12]. This novel nonlinear isolation system was proposed to isolate vibrations in vertical direction for building structure recently [13]. A sliding bearing with stiffness and damping properties dependent on the displacement amplitude was obtained by using multi-spherical sliding surfaces [14]. A sliding hydromagnetic bearing was developed by combining a sliding bearing with a magnet to introduce an alterable restoring force [15]. A negative stiffness device was proposed by complex mechanism combination to obtain excellent isolation effects during the seismic events [16]. However, a flat sliding bearing does not possess a restoring force and a curved sliding bearing will lift up and lower down the isolated structure. Newly proposed isolation bearings rarely undergo test of actual earthquake. The most widely used bearing in building structures is the steel laminated elastomeric bearing, consisting of alternating steel plates and rubber layers [17]. However, this type of isolator is relatively large, heavy, expensive and difficult to install [18–20], and therefore also not appropriate for staircase. In addition, the required compressive strength and maximum shear strain of staircase isolator are much lower than those of traditional isolators. Consequently, a special isolator needs to be developed for staircase in building. Therefore, the paper presents an innovative isolator for improving the seismic performance of staircases. A systematic experimental study on this staircase isolator is conducted to evaluate its mechanical properties. Furthermore, a typical building structure is designed and analyzed using SAP2000 finite element software to assess seismic performance of the staircase isolation at different seismic intensity levels.

2 Development of Innovative Staircase Isolator

In order to apply seismic isolation technology to staircases in buildings, the connection construction scheme shown in Fig. 1 is proposed for staircase. The upper end of the staircase slab is fixed, whereas

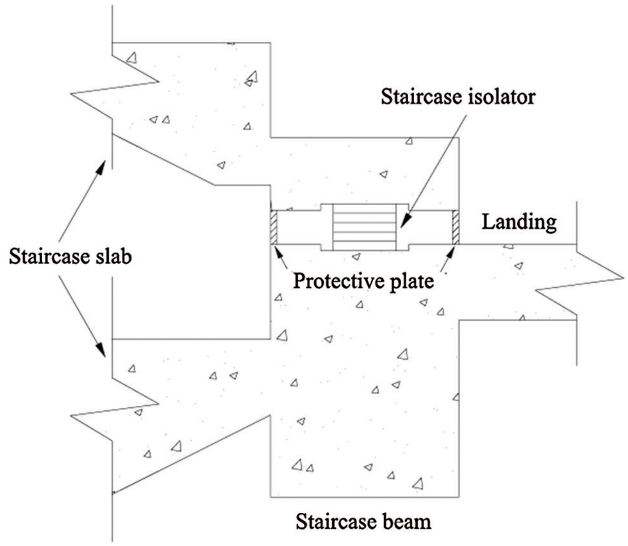

Figure 1: Illustration of staircase isolation

the lower end is connected with the staircase beam by means of the proposed innovative isolator, so as to eliminate the diagonal bracing effect of the slab. The staircase isolator is surrounded by protective plates to prevent from damage caused by natural or anthropic factors. The isolation system decouples the staircase from the main structure, making it works like a substructure under earthquake action [21]. The vertical loads of the isolator include the self-weight and live loads of the staircase slab. The required horizontal deformation of staircase isolator depends on the story drift of building structure. The differences in mechanical performance requirements and available installation space make staircase isolation quite different from traditional isolation [22].

It is obvious that common circle or square rubber isolators are not suitable for staircase isolation. The mechanical properties required for the stiffening plates of the staircase isolator can be reduced compared to the traditional isolators. Considering requirements on mechanical performances of the isolator and restrictions on the use of space, a novel rectangle isolator for staircases was developed and is presented in this paper. The stiffening plate of staircase isolator is made of engineering plastic, with unsaturated polyester and xylem fiber. It can effectively restrain the lateral deformation of rubber and improve the mechanical behavior of the novel isolator compared with fiber or fiber cloth [23]. A certain number of connection slots are arranged on the upper and lower surfaces of the isolator to allow the entry of initial setting concrete. Therefore, steel connection plates are not required for staircase isolator. The installation and replacement process are thus very simple due to the new connection details.

Despite low weight, cost-effective, ease of installation and replacement compared to common isolators, due to the use of engineering plastic sheet instead of steel plate [20], the requirements of its vulcanization process are higher, and minimum values of the isolator shape factors need to be determined. After several trial products and process improvements, the temperature and pressure of vulcanization process are set at 138 ± 5°C and 9–10 MPa. Minimum values of the first and second shape factors of the staircase isolator are 5 and 2.5 respectively, according to theoretical analysis [20,24] and test of the trial products. Staircase isolator with stable performance is successfully obtained as shown in Fig. 2 using the vulcanization process proposed in this paper. Its shape factors and other geometry parameters are tabulated in Tab. 1.

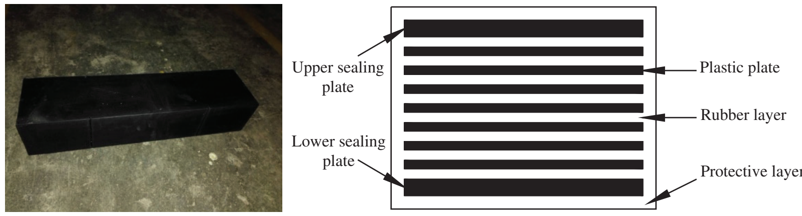

Figure 2: Illustration of staircase isolator

Table 1: Geometric parameters of staircase isolator

Plane dimension	Height	Top and bottom plate thickness	Protection rubber layer thickness	First shape factor (S_1)	Second shape factor (S_2)
400 × 100 mm	80 mm	10 mm	5 mm	7.31	3

3 Mechanical Properties of Staircase Isolator

As a special isolator, mechanical properties of the staircase isolator need to be fully obtained. Its mechanical performance is evaluated in the Cultivation Base for State Key Laboratory of Seismic Control and Structural Safety at Guangzhou University. A series of tests have been conducted by using the elastomeric bearing test system to determine its horizontal and vertical behavior. The test system is capable of testing an isolator subjected simultaneously to vertical loading and horizontal displacement. The maximum loads are 5000 kN and 2000 kN in the vertical and horizontal directions, respectively. The displacement capacity of the test rig is ±350 mm in the vertical direction and ±600 mm in the horizontal direction. The reference compressive stress σ_0 of staircase isolator is set to 1.5 MPa in this experiment, and the tested shear strain is set as ±20% (6 mm), ±50% (15 mm), ±100% (30 mm) according to the story drift ratio of typical building structure specified in the code [4] (i.e., 1/550, 1/250, 1/50).

3.1 Test in Vertical Direction

A vertical test is performed with the maximum and minimum vertical loads corresponding to vertical compressive stresses of $\sigma_0 \pm 30\%$. Four loading cycles with peak-to-peak values are performed, and the relationship between vertical force and displacement is shown in Fig. 3. The vertical compressive stiffness is calculated from the third hysteresis loop and its value is 109.17 kN/mm. In the ultimate vertical bearing capacity test, the vertical force is increased from zero until damage occurs. The isolator is damaged when the vertical force reaches 304.67 kN and its corresponding ultimate vertical bearing capacity is 8.68 MPa.

3.2 Test in Horizontal Direction

A set of horizontal tests for horizontal stiffness of the isolator are carried out. The constant vertical load σ_0 and fully reversed cycles of dynamic horizontal displacements are applied to the isolator in tests. The tests are repeated in four cycles when shear strain amplitude of γ is no more than ±100% (i.e., ±20%, ±50%, ±100%) and two cycles are repeated when shear strain amplitude of γ are ±150%, ±200% and ±250%. If the isolator is not damaged under the above load conditions, two cycles are repeated when shear strain amplitude of γ is ±300%.

The relationship between horizontal force and displacement is shown in Fig. 4. From the curves, it can be observed that the isolator behaves linearly when the shear strain is not greater than 200% of the total thickness of rubber layers. The horizontal stiffness of isolator is close to 0 when the shear strain is 250% and then become negative when the shear strain is 300%. The horizontal stiffness is calculated according

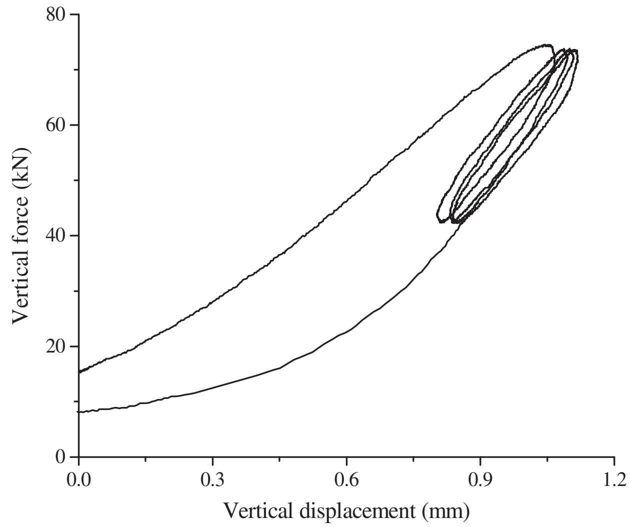

Figure 3: Relationship between vertical force and displacement of staircase isolator

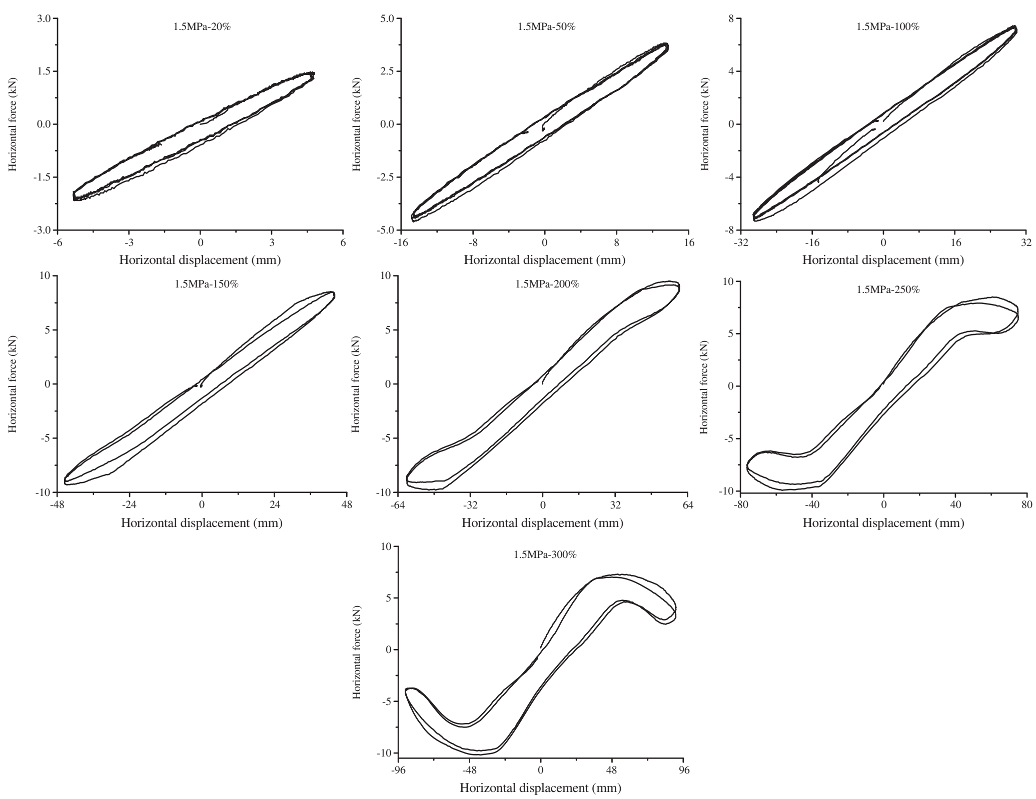

Figure 4: Relationship between horizontal force and displacement of staircase isolator

to data from the third hysteresis loop ($\gamma \leq 100\%$) or the second hysteresis loop ($\gamma > 100\%$). Relationship between horizontal stiffness and shear strain is shown in Fig. 5. It can be seen that the horizontal stiffness decreases linearly when shear strain is not greater than 200%, especially in the range between 50% and 200%. The horizontal stiffness is very close when the shear strain is between 200% and 300%. Equivalent viscous damping ratio of isolator is the ratio between hysteresis energy and strain energy [26].

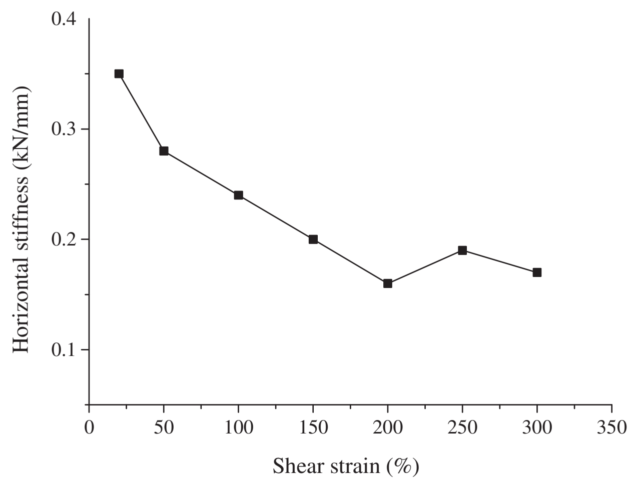

Figure 5: Relationship between horizontal stiffness and shear strain

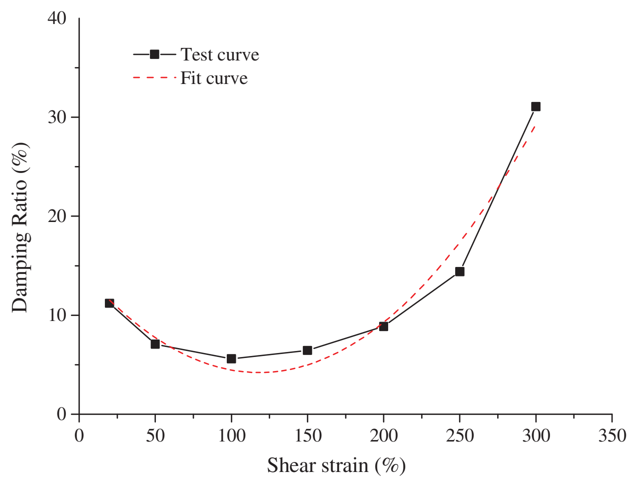

Figure 6: Relationship between equivalent viscous damping ratio and shear strain

Fig. 6 shows the relationship between equivalent viscous damping ratio and shear strain. From the non-linear fit, it is found that the equivalent viscous damping ratio has an approximately parabolic variation. The above results show that the ultimate horizontal deformation capacity of the isolator is 250%.

3.3 Pressure Dependency of Staircase Isolator

The pressure dependency of horizontal stiffness of isolator test is conducted under the pressure of 1.5 MPa, 3 MPa and 5 MPa, respectively. The relationship between horizontal force and displacement at different pressures is shown in Fig. 7. The hysteresis loops are clearly wider under the pressure of 5 MPa, and resemble those of high damping isolators, especially under the shear strain of 100%. The horizontal stiffness of isolator is calculated from the third hysteresis loop and it decreases almost linearly with increasing shear strain and pressure as shown in Fig. 8. The relationship between equivalent viscous damping ratio and shear strain under different pressures is shown in Fig. 9. Its consistent variation trend is increased with the increase of pressure and decreased with the increase of shear strain under the pressure of 1.5 MPa and 3 MPa. On the other hand, the equivalent viscous damping ratio increased with the increase in shear strain under pressure of 5 MPa. This is mainly due to a very high vertical load, which approaches the vertical load bearing capacity of the isolator.

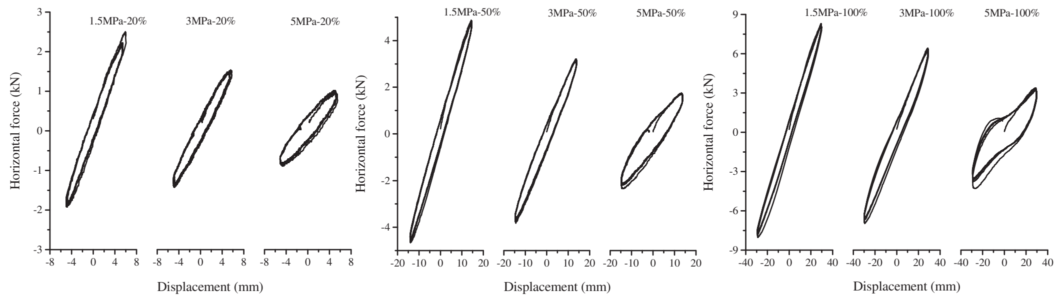

Figure 7: Relationship between horizontal force and displacement of staircase isolator at different pressure

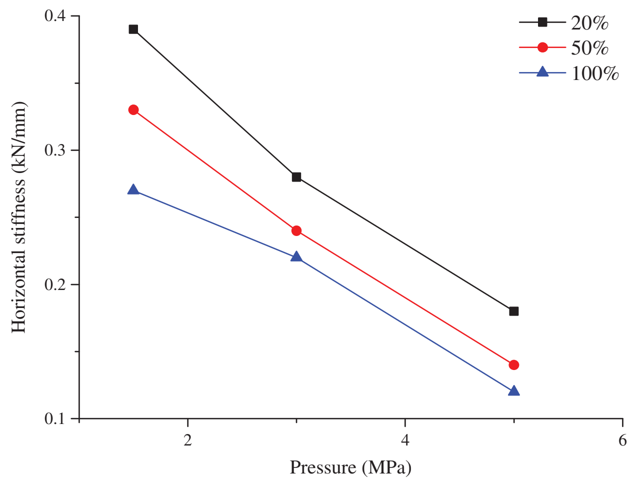

Figure 8: Relationship between horizontal stiffness and shear strain at different pressure

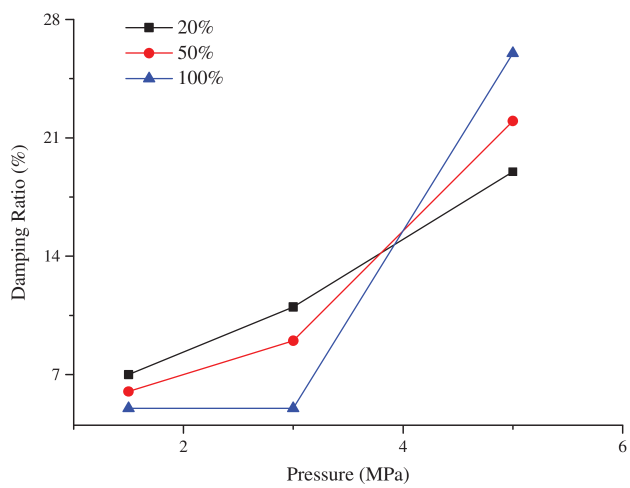

Figure 9: Relationship between equivalent damping and shear strain at different pressure

3.4 Temperature Dependency of Staircase Isolator

The test for temperature dependency of horizontal stiffness is conducted under temperature of −20°C, −10°C, 0°C, 23°C, 40°C, respectively. All the test steps are carried out in accordance with the ISO 22762-1 specifications [25]. The values of horizontal stiffness and equivalent viscous damping ratio are calculated from the third hysteresis loop and then normalized with respect to corresponding value at 23°C. The relationship between horizontal stiffness change ratio and temperature in different shear strain is shown in Fig. 10. The maximum variation of stiffness is 26%, obtained at the temperature of −20°C and shear strain of 20%, whereas the stiffness variation between 0°C and 40°C is negligible (within 5%). The non-linear fit of the data trend is carried out using the method proposed in ISO 22762-3 [27]:

$$K_h = \left(1.045 - 0.004T + 8.193 \times 10^{-5}T^2 - 3.682 \times 10^{-7}T^3\right)K_{h23}$$

where T is the test temperature and K_{h23} is the horizontal stiffness of the isolator at 23°C. The predicted horizontal stiffness values are in good agreement with test results, with a maximum relative error less than 10%. The relationship between change of equivalent viscous damping ratio and temperature at different shear strain is shown in Fig. 11. The maximum variation of damping ratio is 62%, obtained at 0°C with shear strain of 20%. The equivalent viscous damping ratio of isolator is more sensitive to temperature variations than the horizontal stiffness. However, all the previous variations meet the requirements of the European standard EN15129 [28].

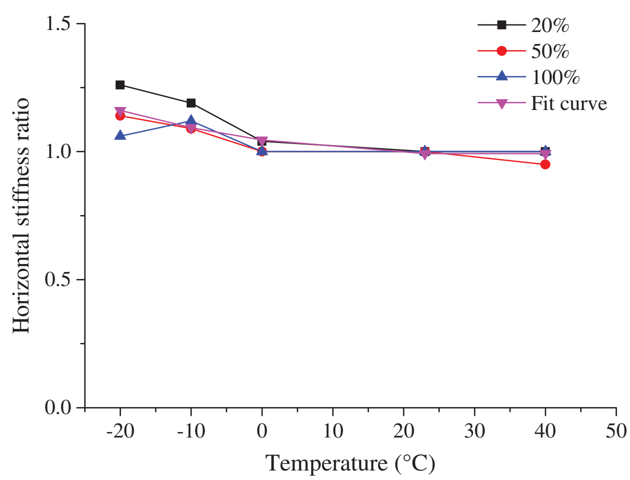

Figure 10: Variation of horizontal stiffness on temperature at different shear strain

4 Seismic Response Analysis of Building Structure with Isolated Staircase

In order to systematically investigate the influence of staircase isolation on building structure and staircase elements, the typical frame structure shown in Fig. 12 is designed for different seismic fortification intensity levels. The frame can be designed as a six-story structure in the case of design PGA of 0.40 g and it has eight stories in other cases according to Chinese design code. Each story of the frame structure is 3.6 m high and slab thickness is 100 mm. The other structural information is shown in Tab. 2 and the plan of structure is shown in Fig. 13. The optimal position of stairwells is taken in the design process referred from [29] and the detail drawing of staircase is shown in Fig. 14. Staircase slab thickness is 120 mm and the cross sections of staircase column and beam are 300 × 300 mm and 200 × 400 mm, respectively. The structural site characteristics period is chosen to be 0.40 s. All the concrete strength grade of the structure is C30. Three types of frame structure models including the bare frame without

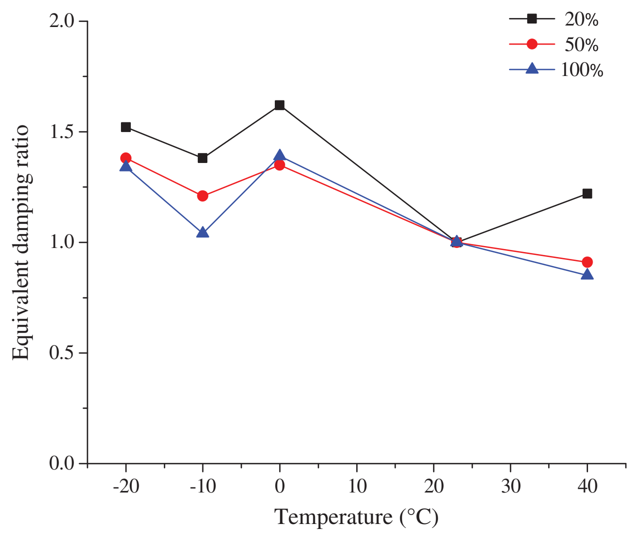

Figure 11: Variation of equivalent damping ratio on temperature at different shear strain

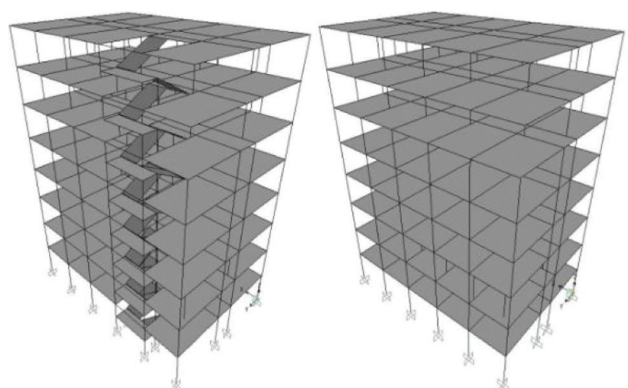

Figure 12: Structure model

Table 2: Structural information

Design	A	B	C	D	E	F
Seismic precautionary intensity level	6	7	7	8	8	9
PGA (g)	0.05	0.10	0.15	0.20	0.30	0.40
Column (mm)	400 × 450	450 × 450	500 × 500	600 × 600	600 × 600	750 × 750
Horizontal beam (mm)	200 × 400	200 × 450	200 × 450	250 × 550	300 × 650	450 × 800
Longitudinal beam (mm)	200 × 400	200 × 400	200 × 400	250 × 500	300 × 500	400 × 800

staircases (WS), with fixed staircases (FS) and with isolated staircases (IS), are established for different seismic precautionary intensity levels and analyzed using SAP2000. Columns and beams are simulated with bar elements and slabs are modeled using thin shell element. Uniform dead and live loads on structural components are calculated and shown in Tab. 3. Five load combinations are adopted in this analysis, based on dead load, live load and earthquake action. The effect of wind load on the structure is

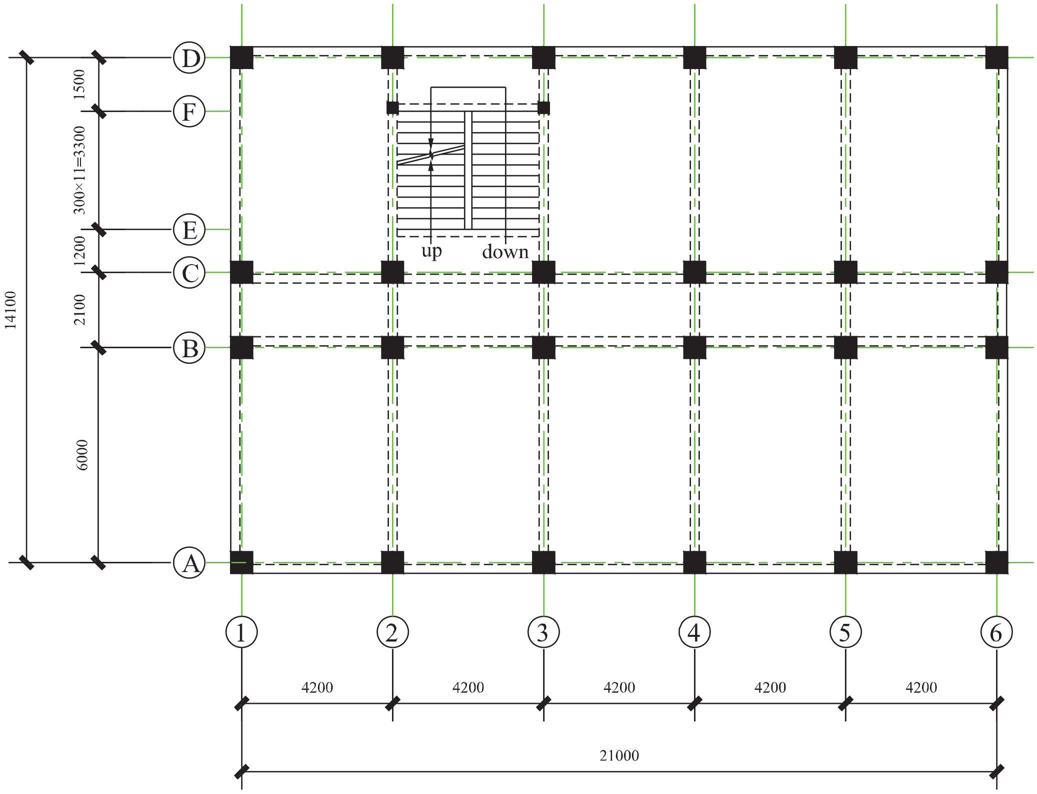

Figure 13: Structure plan view

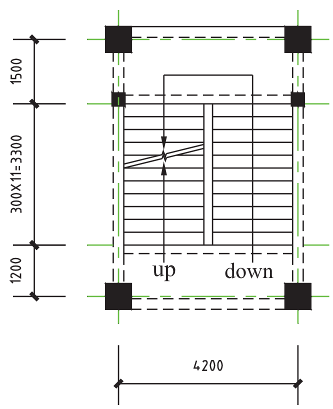

Figure 14: Staircase plan view

Table 3: The loads on structural elements

Element	Beam	Slab	Hallway slab	Staircase slab
Dead load	7 kN/m	5 kN/m^2	5 kN/m^2	7 kN/m^2
Live load	–	2 kN/m^2	2.5 kN/m^2	3.5 kN/m^2

not considered. Staircase isolators are simulated by the Rubber Isolator element in model IS. Based on the experimental results, the equivalent viscous damping ratio of isolator is taken as 4% and its vertical and horizontal stiffness are taken as 100 kN/mm and 0.2 kN/mm, respectively.

Both the modal analysis and time history analysis are carried out in order to investigate the influence of staircase and staircase isolation on seismic performance of structure. A set of seven ground motions consistent with the code of seismic influence coefficient curve [4] in the statistical sense at seismic fortification intensity levels are selected from PEER (Pacific Earthquake Engineering Research Center) and are shown in Fig. 15. The periods of first six natural modes are shown in Fig. 16 for all the models, and the reduction of periods is shown in Tab. 4. It can be seen that including staircase in a model will significantly reduce its periods in most cases, the smaller the structural stiffness, the greater the period decrease, but use of staircase isolation will slightly reduce the structural period.

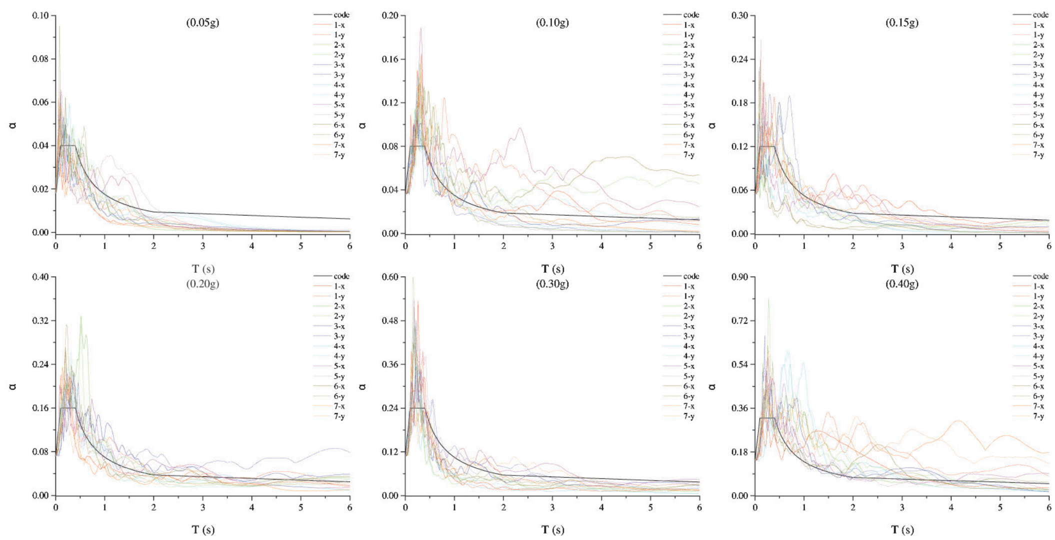

Figure 15: Selected ground motions

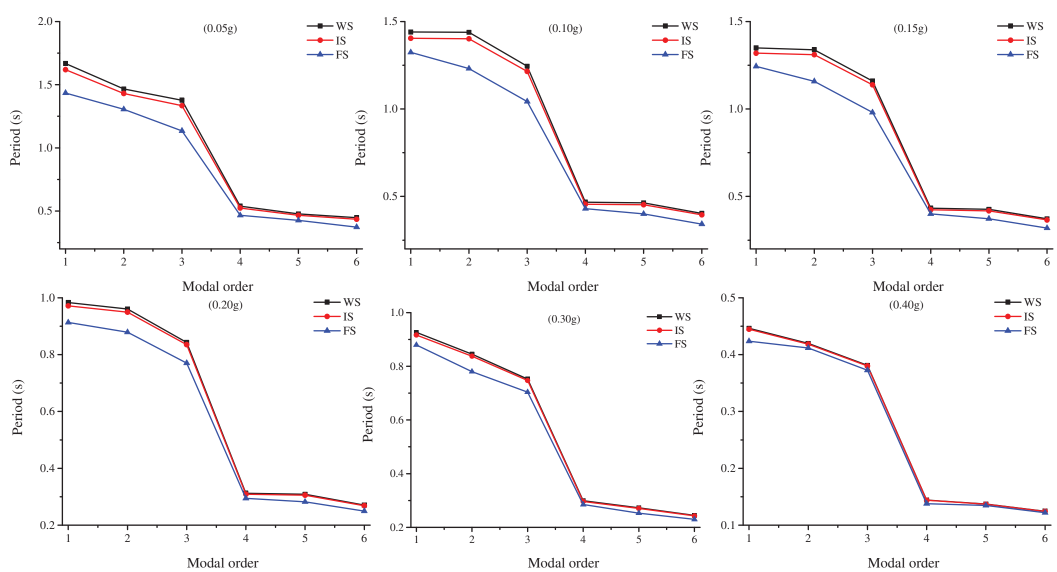

Figure 16: Periods of structural models

Table 4: The decrease of structural periods

Design	Period decrease of FS/WS	Period decrease of IS/WS
A	10.75%–17.59%	2.38%–3.10%
B	7.98%–16.21%	2.21%–2.57%
C	7.59%–15.51%	1.74%–2.26%
D	5.79%–8.64%	0.83%–1.21%
E	4.79%–7.71%	0.73%–1.65%
F	1.81%–5.08%	0.22%–0.36%

The comparison of structural dynamic characteristics illustrates the impact of staircase and staircase isolation on structure, and the results show that staircase isolation can significantly reduce the impact of staircase on structural dynamic characteristics. The maximum story drift ratio as shown in Fig. 17 is obtained from the process of maximum value of joints' displacement in analysis conditions. The story drift ratio of model WS is almost the same as model IS at every seismic precautionary intensity level. Compared with models WS and IS, the story drift ratio of model FS is larger in X direction and smaller in Y direction in most cases. This phenomenon is mainly due to the fact that staircase aggravated the torsional effect of the structure in overall analysis. However, staircase isolation is a good choice to eliminate this effect as the above results show.

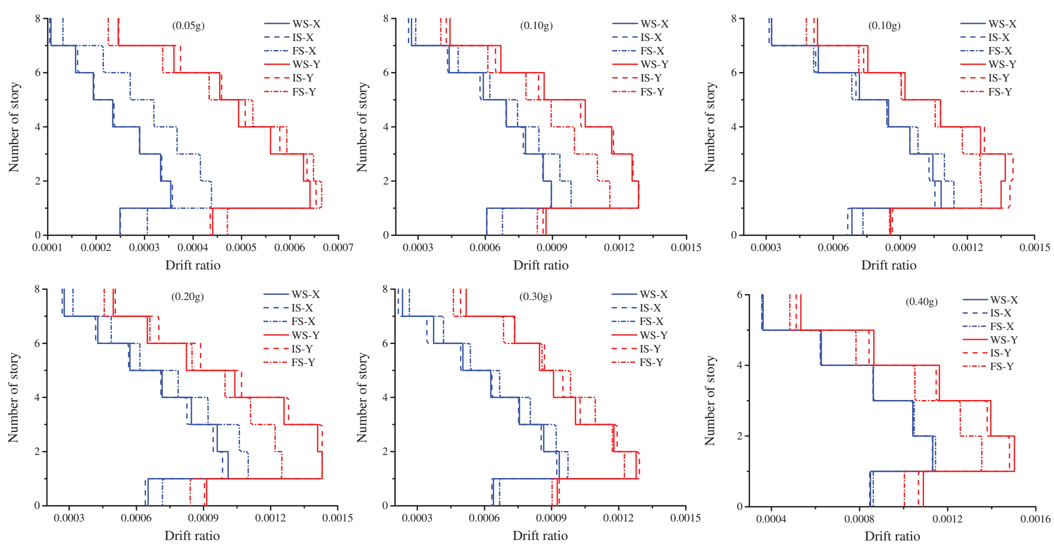

Figure 17: Results of story drift ratio for different designs

The maximum internal forces of staircase elements of models FS and IS in time history analysis are shown in Figs. 18–20. They are used to investigate the impact of staircase isolation on staircase elements. In Fig. 20, S11 and S22 represent the normal stress components in 1 axis (width direction of the slab) and 2 axis (length direction of the slab), and S12 represents the shear stress. The staircase elements are arranged in the order from left to right and from bottom to top. On the first floor, staircase beams and slabs in upstairs direction are numbered 1-1 and 1-2, and staircase columns located on 2 and 3 axes are numbered 1-1 and 1-2. The remaining floor elements are also numbered by following this rule.

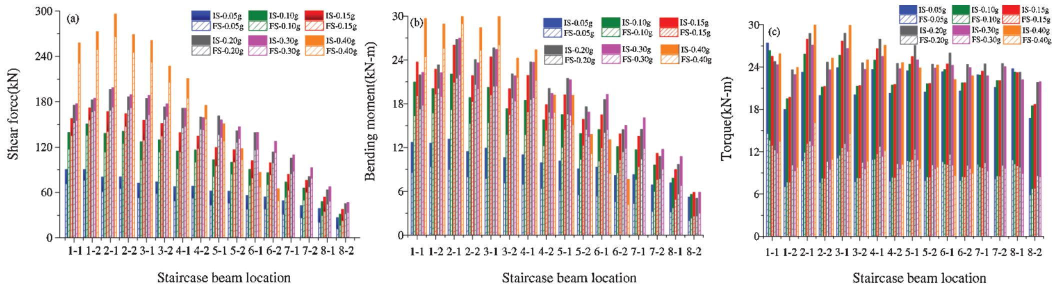

Figure 18: Mean values of staircase beam internal forces. (a) Shear force; (b) Bending moment; (c) Torque

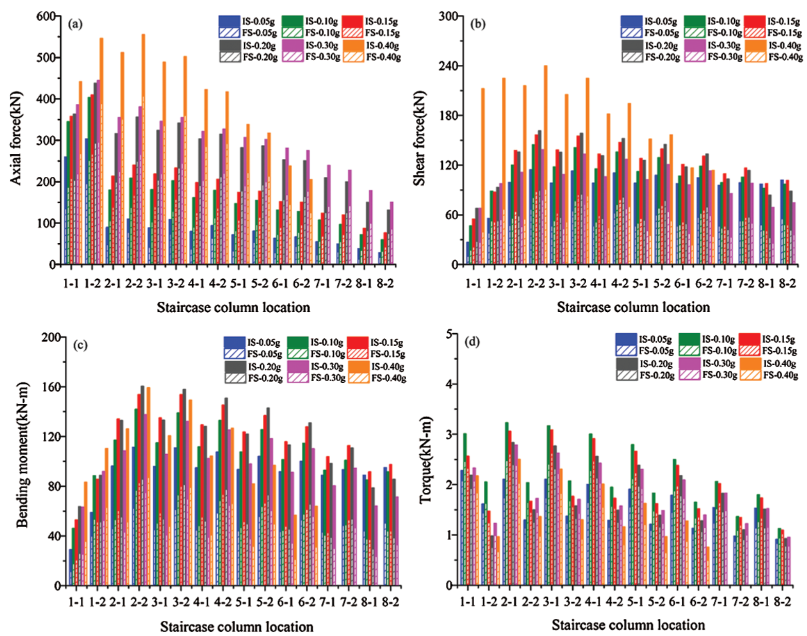

Figure 19: Mean values of staircase column internal forces. (a) Axial force; (b) Shear force; (c) Bending moment; (d) Torque

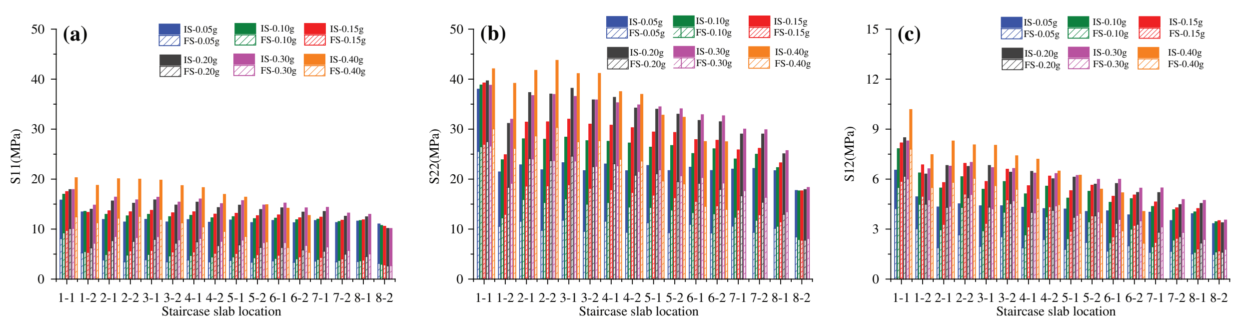

Figure 20: Mean values of staircase slab internal forces. (a) S11; (b) S22; (c) S12

Internal forces of staircase beams are presented in Fig. 18. It can be observed that as compared with model FS, almost all results for shear force and bending moment in model IS are attenuated significantly. The torque is different from the other force components. As shown in Fig. 18c, it may increase at some positions and decrease at the other positions, but all the changes are relatively low. The above comparison results show that staircase isolation is effective in reducing shear force and bending moment of staircase beams, but has no significant impact on torque.

The results of internal forces of staircase column are shown in Fig. 19. It can be seen that compared with model FS almost all axial force and torque of model IS are reduced significantly. The trends of shear force and bending moment are different from other forces. They increased at the positions whose second number is 1 (i.e., 1-1, 2-1…) and decreased at the other positions. The magnitudes of the change from the first floor to the sixth floor are moderate and small for the rest. The above comparison results show that staircase isolation has a positive effect on the reduction of axial force and torque of staircase column, and its impact on the shear force and bending moment of staircase column is small.

Internal forces of staircase slab are shown in Fig. 20. As compared with model FS almost all normal stress in axis 2 and shear stress of model IS are reduced considerably. The trend of normal stress in axis 1 is different from other internal forces as shown in Fig. 20. It increased from the fifth floor to eighth floor and then decreased from the first floor to fourth floor, but all these changes are moderate compared with S22 and S12. It should be noted that the internal forces of staircase slabs at the lower floors play a controllable role in its design process. The above comparison results show that staircase isolation has a beneficial impact on the internal forces of staircase slab, especially for its S22 and S12.

The internal forces of staircase elements of model IS are fairly uniform compared with model FS as shown in Figs. 18–20 at different seismic fortification intensity level. The dispersion coefficient of internal forces of staircase elements is shown in Fig. 21. It is a good illustration of the impact of staircase isolation on its elements, which means that all staircase elements of model IS are stressed uniformly under earthquake action and also there is no vulnerable position in staircase. The internal forces of staircase elements of model FS changes greatly at every seismic fortification intensity levels. It is clear that the first and the second floors of staircase in model FS are prone to early damage during earthquake.

The design bending moment of staircase slab by the traditional method is 16.29 kN·m and its ratio of analysis value to design value is shown in Tab. 5. It can be observed that staircase slab designed using tradition method is not safe for model FS, but it has about 20% safety margins for model IS.

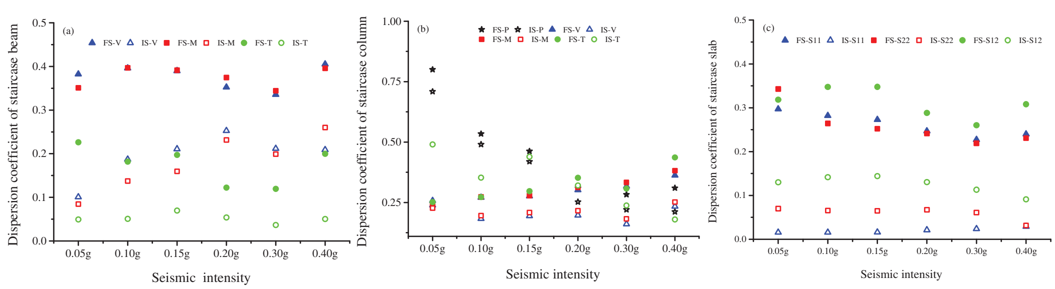

Figure 21: Dispersion coefficient of internal forces of staircase elements. (a) Beam; (b) Column; (c) Slab

Table 5: Ratios of the analysis value to design value of slab internal force S22

Design	Model FS	Model IS
A	156.72%	78.29%
B	162.58%	80.90%
C	165.55%	81.25%
D	169.21%	83.58%
E	163.58%	82.86%
F	186.40%	83.63%

Table 6: Maximum responses in staircase isolators

Model	Compressive stress (MPa)	Tensile stress (MPa)	Displacement (mm)
A	1.20	0.03	1.99
B	1.18	0.05	3.28
C	1.17	0.06	3.59
D	1.13	0.07	3.02
E	1.12	0.13	3.25
F	1.11	0.14	3.75

Results for the response of staircase isolators in the above analysis conditions are summarized in Tab. 6. The values of maximum compressive stress, tensile stress and displacement are 1.20 MPa, 0.14 MPa, and 3.75 mm in all analysis conditions. From the test results, the isolators under the above pressure and deformation remain linearly elastic, and staircase function well under strong ground motion.

5 Conclusions

1. A novel staircase isolator is developed by replacing the steel plate in the traditional isolator with suitable engineering plastic sheets in this paper. The vulcanization process and shape factor requirements of the new stiffening plates are obtained. Its connection details are optimized for a certain number of connection slots arranged on the surfaces of the isolator to allow the entry of initial setting concrete. Therefore, the novel staircase isolator has the advantages of low weight, cost-effective and ease to install and replace.
2. The ultimate vertical load bearing resistance and horizontal deformation capacity of the isolator are 8.68 MPa and 250%, respectively. Its vertical stiffness is 109.17 kN/mm and horizontal stiffness under 20% shear strain is 0.35 kN/mm. The horizontal stiffness of the isolator decreases with increasing shear strain and pressure. Instead, its equivalent viscous damping ratio increases with increasing pressure, and shows an almost parabolic growth as the shear strain increases.
3. Staircase isolation can effectively reduce the influence of staircase on the building dynamic characteristics and story drift during an earthquake. This effect increases as the stiffness of the structure decreases. The isolated staircase can be considered as a load during the structural design process using the conventional method and the internal forces of their elements have a safety margin of about 20%.
4. The isolated staircase elements are uniformly stressed and their internal forces are reduced at lower floors, especially at the first and second floors. There is no particularly vulnerable position in the isolated staircase. The staircase isolator remains in the range of linear elastic state under all analysis conditions according to its experimental results. Therefore, it can significantly improve the seismic performance of the staircase, ensuring its usability during the seismic event.

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