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A STUDY OF SEISMIC RESPONSES OF FRAMED STEEL STRUCTURE IN CASE OF SHANGHAI'S ARTIFICIAL EARTHQUAKE

HOVHANNES MESROPYAN, L. D. YANG*

Pe baza ingineriei aplicată practic, articolul studiază caracteristicile seismice ale unei construcții model cu trei etaje, realizată din oțel şi izolată cu izolatori de tip arc-cauciuc. Pentru simulare s-a folosit o masa de producere artificială a cutremurului prin zguduire. Masa de zguduire realizată de MTS Corporation este prevazută cu un sistem de control computerizat capabil să identifice parametrii dinamici ai modelului din oțel cu şi fără izolatori arc-cauciuc. Frecvența naturală, rata şi modul de amortizare, precum şi proprietățile structurale cum ar fi masa, rigiditatea şi matricea de amortizare au fost obținute prin măsurare. Pentru a evalua eficiența sistemului de izolare a fundației şi efectul miscărilor induse de cutremur au fost utilizate atât analize numerice cât şi testarea cu ajutorul mesei de zguduire, folosindu-se un model cu şi fără sistem de amortizare. Condițiile au simulat un cutremur artificial caracteristic oraşului Shanghai. Comparațiile arată că raspunsul modelului cu sistem de amortizare este mai atenuat decât în cazul sistemului cu fundație fixă, iar amortizarea creşte datorită utilizării sistemului de amortizare arc-cauciuc.

On background of the practical engineering, this article studies the seismic characteristics of a three-storey steel model isolated with Spring-Rubber (SR) isolators, using a shaking table. Shaking table of MTS Corporation, with computer control system was used to identify dynamic parameters of the Steel model with and without SR bearings. The natural frequencies, damping ratios and mode shapes as well as structural properties, namely, the mass, stiffness and damping matrices, were obtained. In order to evaluate the efficiency of the base isolation system and the effect of earthquake ground motions shake table testing of the model with and without the isolation system were carried out under Shanghai's Artificial earthquake. The comparison showed a reduced response of the model with isolated system compared to the one for the fixed-base model and also that the damping increased due to SR isolators.

Keywords: Spring-Rubber (SR) isolators; simulation, seismic responses

Introduction

For a few decades, the use of the base isolation technique has achieved significant success in reducing the structural damage to buildings from earthquake

* Ph.D, Post graduate student, Tongji University; Prof., Dept. of Geotechnical engineering, Tongji University, Shanghai, CHINA

attacks. Despite the existing overall effectiveness of base isolators, further study and development are required for improving the ways to protect structures and their contents against earthquakes.

In this paper base isolation through Spring-Rubber Isolators is the key solution as protecting mean for structures. Springs are designed and incorporated with rubber to improve isolation performance in vertical direction. Several cases (Kobe and Northridge earthquakes) confirmed that vertical factor of earthquakes have played vital role in destroying structures as in traditional way the vertical factor is ignored. This proposal is one of the first that suggests a vertical shock absorber that is backed up by experimental as well as analytical results which illustrate its functionality and performance in reducing the effect of vertical vibration on structure. Springs which are applied around rubber increase the horizontal dissipation and assist rubber to become flexible horizontally.

1. Base Isolation and SR Isolator as Smart Isolated System

Spring-Rubber bearings are considered as the baseline against which smart damping strategies are compared. The modeling approach for these two systems is described as in equation 1 below. The horizontal force required to induce the SR isolator into its post-yield phase can be expressed as the sum of three forces acting parallel:

$$f_{SRI} = Q_{Sb} + k_b x_b + c_b \dot{x}_b \quad (1)$$

where $Q_{Sb} = (1 - K_{yield} / k_{initial})Q_y =$ yield force of springs; $Q_y =$ yield force from both springs and the rubber stiffness, x_b is relative displacement, c_b, is damping coefficient, k_b is stiffness of isolator, $Kyield$ and $Kinitial$ are yielding and initial stiffness of springs.

SR base isolation system is a new class of smart isolation, which is capable of reducing the horizontal and vertical seismic forces transmitted to the structure. Purposed system is easy to manufacture. It can be made very stiff in the vertical direction to take the vertical load and reduce the energy of vertical input of earthquake wave and be very flexible in the horizontal direction to isolate the horizontal vibrations. This kind of base isolation is very effective in reducing the high accelerations, or the high frequency motions. The main aim of this system is to shift the natural frequencies of structures to a lower value, to avoid structural resonance and collapse.

2. Test Program

The test program was conducted in The Key State Laboratory for Disaster Reduction of Tongji University, Shanghai, China from 17 to 27 October 2005.

SR isolator is shown in fig. 1. It was designed and fabricated using 6 helical springs assembled in pins on steel sheet platforms with the central high-dumping natural rubber. High-damping natural rubber bearings have two functions, flexibility and damping as an intrinsic property of the high-damping rubber itself, which consequently eliminate the need for a separate bearing and damping system.

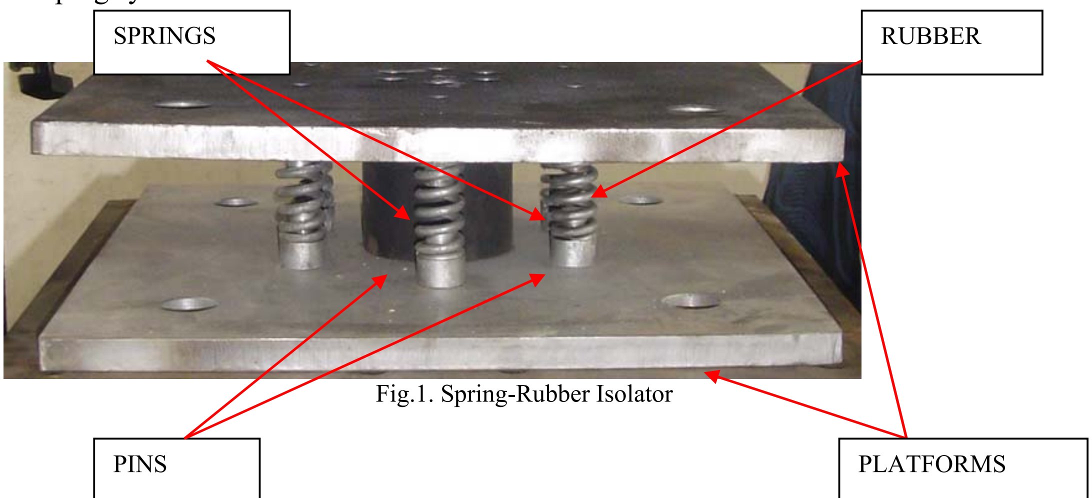


Fig.1. Spring-Rubber Isolator

The steel model is a prototype of 1:4 scaled building; it is a symmetric single-bay three storey steel frame (fig. 2). Steel frame consists of four columns from S-section (#S4X7.7) steel beams, connected at each floor by Steel channel (#C5x9) beams and crossbeams manufactured by welding two steel channels (C4x7.25). There are two ribs (Steel channel (#C5x9) beams) which are applied in a middle of each storey by Y direction only. This makes structure to be different by stiffness in X, Y directions. The Model will be installed on shaking table with lower stiffness in X direction (see figure 1 and the summary properties of model in table (1). To ensure that the test buildings were rigidly connected to the shaking table, the columns of each building were first welded to large steel beams, which were in turn tightly bolted with SR isolators.

Table 1

Properties of Steel Model

Height	6 m
Length	1.95 m
Width	1.95 m
Storey Height	2 m
Columns	Steel S-section beam (S4x7.7)
Beams	Steel channel (C5x9)
Cross beams	Steel channel (C4x7.25)
Weight	1661 kg

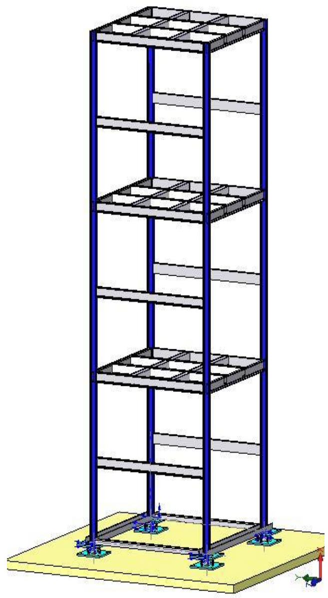


Fig.2. Structure of Steel Model

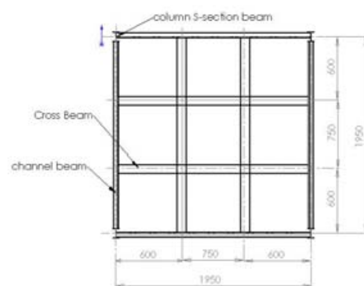


Fig. 3 Plane Section of steel structure

3. Shaking Table Devise and Experimental Arrangements

The experiments were carried out on a six degrees of freedom seismic simulator of the State Key Laboratory for Disaster Reduction in Civil Engineering at Tongji University in Shanghai, China.

Three types of data were desired to be obtained from the shaking table tests, and therefore three classes of instrumentation were installed: accelerometers, sensors of displacements and bending and axial strain gages.

In order to keep the test similar to that in the real conditions all parameters were scaled. Scaling was necessary to maintain the dynamic similitude between the model and the corresponding full-scale building, as well. The time axes for earthquake waveform was scaled to 1/4 of the original ones to achieve dynamic harmony of model and to increase the frequency of input waves to escape from resonance, and as well as to keep the first mode frequency of the model consistent with dominant frequency of the earthquake records. The modulus of elasticity, Young's modulus, (E) scale is set to 1 since the material (steel) is the same in both real structure and model. Additional steel masses are added on each floor 500 kg and total 1.5 tons to satisfy the similitude requirements, bringing the total dead load of the superstructure, including the base floor, to 32 KN. The setup of all sensors is shown in fig. 4. Total of 17 accelerometers, 8 displacement sensors and

4 Strain Gages were arranged on model to measure their absolute responses in the *x*, *y*, and *z* directions.

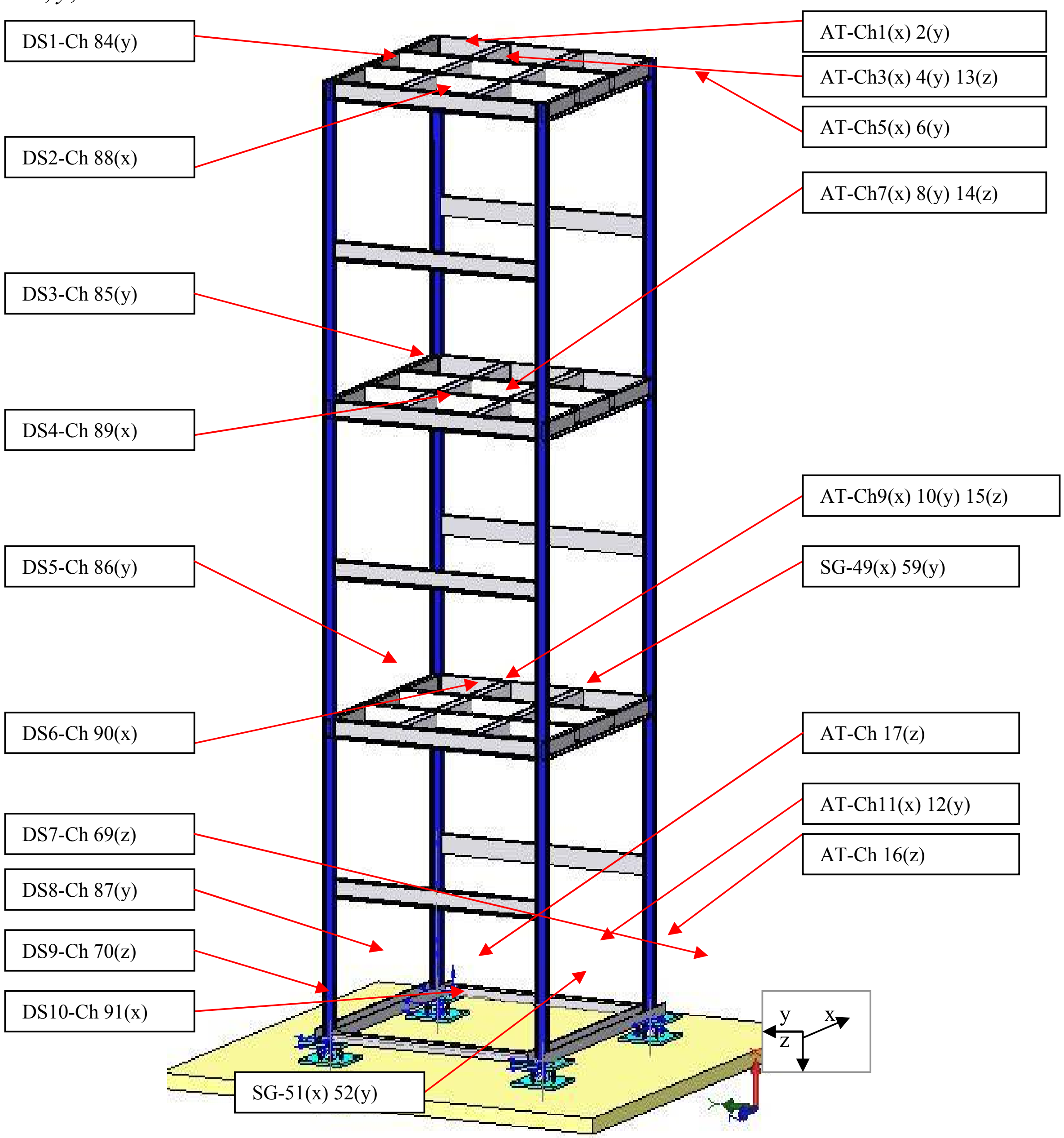


Fig. 4. Distribution of the sensors

**DS-Displacement Sensors; AT- Accelerometers; SG-Strain Gages; Ch -Channels

4. Experiments of Model

The experiments were performed by applying two directional horizontal motions (X, Y) and one vertical motion (Z). The test consists of two phases. Phase one is the test of Model with isolator, which includes three circle testing and, phase two is the test without isolator including two circles testing. In each circle motions are applied with increased acceleration step by step. Earthquake testing of the model have been conducted using Shanghai's artificial earthquake[†]. Acceleration time-history inputs (0.2g) of Shanghai artificial wave in three different directions are shown in Fig. 5 below.

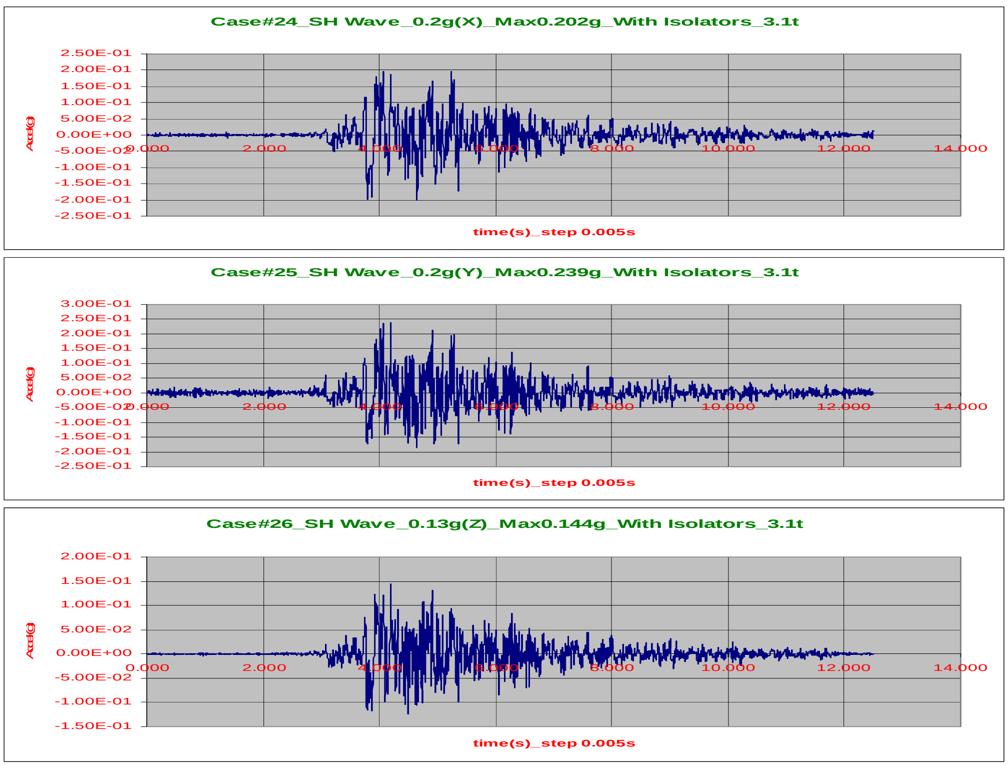


Fig. 5 Input of Shanghai's Artificial Earthquake

Earthquake wave is input by gradually increasing the magnitude by three circles: inputs with 0.1g magnitude in X, Y direction and 0.065g in Z direction; inputs with 0.2g magnitude in X, Y direction and 0.13g in Z direction; inputs with

[†] Shanghai earthquake wave is artificial wave designed for testing buildings especially in Shanghai, the time history acceleration has aggressive behavior and the vibration endures quite long compare with other earthquakes. Region-Central Asia; Country-P.R. China; Epicenter-Downtown of Shanghai; Peak Acceleration-0.2g; Duration-39s.

0.4g magnitude in X, Y direction and 0.26g in Z direction. In the beginning and after each circle the White Noise (0.07g) motion was used for scanning and restoring the dynamic characteristic of the model.

5. Test Results

Dynamic Responses

To identify the natural frequencies and modal damping ratios of the model with and without isolators, a 0.07 g white noise ground motion was input into the shaking table. The recorded acceleration responses were then processed to obtain the transfer functions, which are shown in the tables 2; 3; 4; 5; 6; 7 below.

Table 2

Dynamic Responses of Model with Isolators in X direction

Mode Number	Frequency *f* (Hz)	Damping Rate ξ	Amplitude of transform function			
			1st level	2nd level	3rd level	4th level
1st	**1.17**	**0.085**	**1.5**	**5.70**	**9.76**	**12.59**
2nd	**4.10**	**0.024**	**2.51**	**13.71**	**6.70**	**9.34**
3rd	**6.45**	**0.014**	**1.63**	**10.25**	**12.79**	**4.55**
4th	**11.72**	**-**	**12.25**	**2.00**	**0.47**	**0.51**

Table 3

Dynamic Responses of Model without Isolators in X

Mode Number	Frequency *f* (Hz)	Damping Rate ξ	Amplitude of transform function			
			1st level	2nd level	3rd level	4th level
1st	**1.56**	**0.064**	**1.5**	**12.99**	**25.21**	**32.29**
2nd	**4.30**	**0.022**	**-**	**13.50**	**7.04**	**9.85**
3rd	**6.64**	**0.014**	**-**	**4.84**	**5.91**	**1.82**

Comparing dynamic responses in X direction of model with and without SR isolators (listed in tables above) the following could be concluded:

1. The1st mode frequency is reduced 25%.
2. The 1st mode damping rate is increased by 24%.
3. The increase of the values of transform function from 1st level to 4th is about 6 times for isolated model, and about 22 times for fixed base model.

Table 4

Dynamic Responses of Model with Isolators in Y direction

Mode Number	Frequency *f* (Hz)	Damping Rate ξ	Amplitude of transform function			
			1st level	2nd level	3rd level	4th level
1st	**1.56**	**0.064**	**1.02**	**3.12**	**5.18**	**7.00**
2nd	**8.01**	**0.024**	**4.66**	**6.39**	**2.49**	**3.40**
3rd	**15.04**	**0.020**	**6.14**	**1.84**	**4.09**	**2.74**
4th	**19.92**	**0.010**	**2.35**	**4.23**	**4.28**	**0.65**

Table 5

Dynamic Responses of Model without Isolators in Y

Mode Number	Frequency *f* (Hz)	Damping Rate ξ	Amplitude of transform function			
			1st level	2nd level	3rd level	4th level
1st	**3.13**	**0.030**	**1.02**	**5.24**	**8.37**	**10.35**
2nd	**4.10**	**0.024**	**-**	**0.97**	**2.00**	**2.86**
3rd	**11.33**	**0.017**	**-**	**7.50**	**3.49**	**5.70**
4th	**19.14**	**0.010**	**-**	**2.62**	**3.35**	**1.11**

Comparing dynamic responses in Y direction of model with and without SR isolators (listed in tables above) the following could be concluded:

1. The frequencies in first two modes are reduced about 50%.
2. The first mode damping rate is increased by 46%.
3. The increase of the values of transform function from 1st level to 4th is about 7 times for isolated model, and about 10 times for fixed base model.

Table 6

Dynamic Responses of Model with Isolators in Z direction

Mode Number	Frequency *f* (Hz)	Damping Rate ξ	Amplitude of transform function			
			1st level	2nd level	3rd level	4th level
1st	**8.01**	**0.061**	**7.65**	**7.81**	**7.9**	**7.85**
2nd	**12.89**	**-**	**2.11**	**1.03**	**1.04**	**1.30**

Table 7

Dynamic Responses of Model without Isolators in Y direction

Mode Number	Frequency *f* (Hz)	Damping Rate ξ	Amplitude of transform function			
			1st level	2nd level	3rd level	4th level
1st	**21.09**	**0.014**	**-**	**4.19**	**4.41**	**12.73**
2nd	**24.22**	**-**	**-**	**14.35**	**7.32**	**-**

Comparing dynamic responses in Z direction of model with and without SR isolators (listed in tables) above the following could be concluded:

1. The frequencies are reduced about 62%.
2. The first mode damping rate is increased by 77%.
3. The increase of the values of transform function from 1st level to 4th is about unchanged for isolated model, but for fixed base model the increase is 3 times from 2nd level to 4^{th}.

Acceleration Responses

Absolute acceleration responses of Model with and without SR isolators measured and recorded by accelerometers are shown in figure 6. No damage was found on steel model, these results showed that the relationship between accelerations was in the elastic range. For almost all inputs the acceleration responses of model with SR isolators are attenuated compared with fix base model. As already was stated above the earthquake hysteresis behavior on model are different, which highlight the variousness of reduced responses.

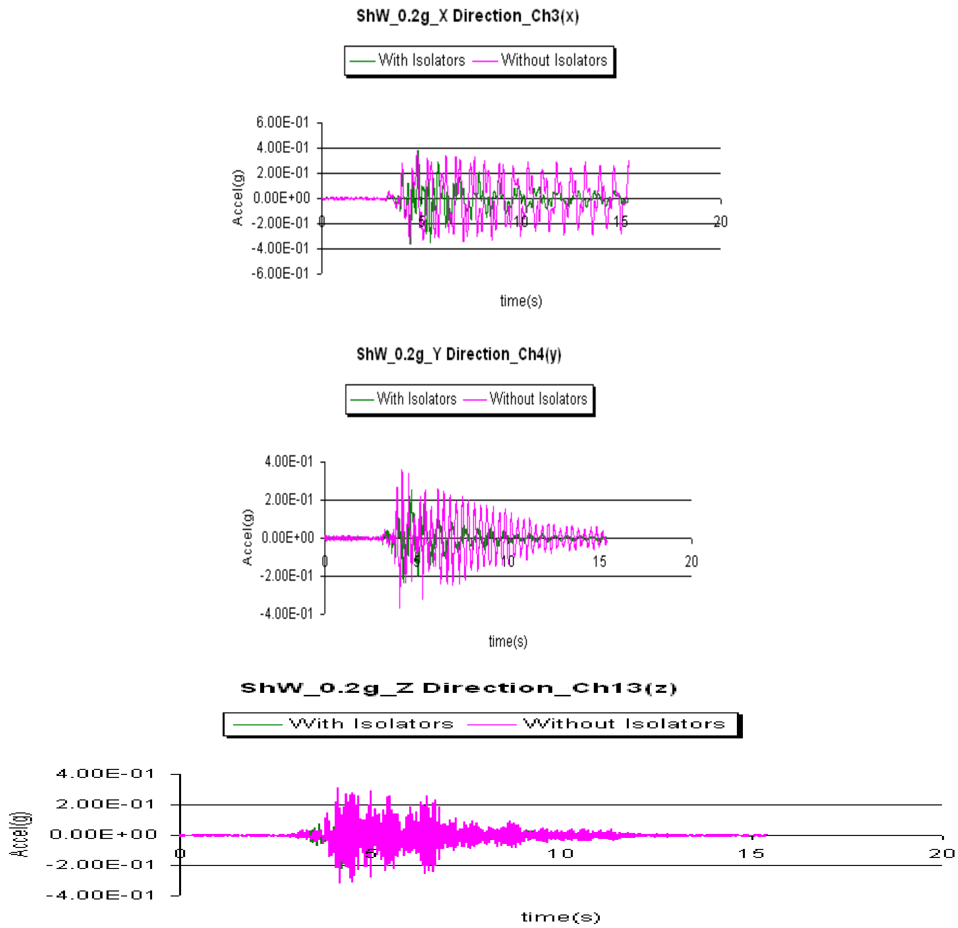


Fig. 6 Time History of Response Accelerations

Displacement Responses

Absolute displacement responses of Model with and without SR isolators measured and recorded by accelerometers are shown in figure 7. Displacement responses are proving the reasonable increase of the displacements of isolated model up to 10 percent which is the difference between displacement responses of model with and without isolators.

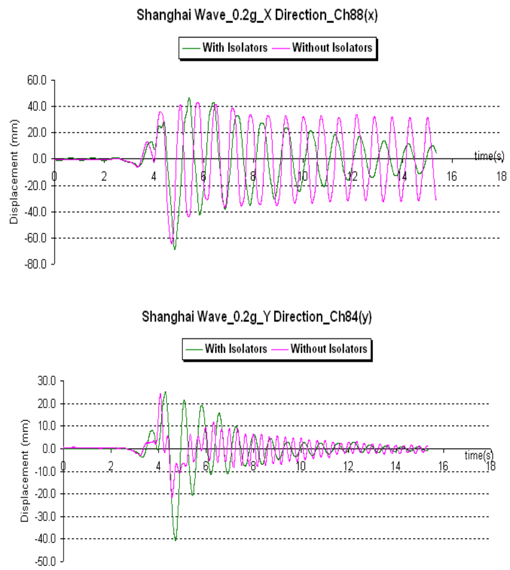
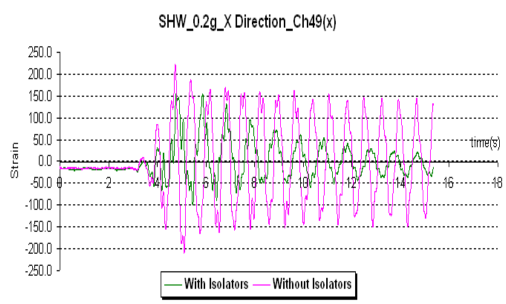


Fig. 7 Time History of Response Displacements

Responses of Strain gages

The bending responses are expressed through strain with measurement 10^{-6} and are shown in figure 8. The strains obtained from critical sections of the model justify the necessity of isolators, up to 40 percent reduced strains with their relative stresses confirming the safety factor of collapsing or damaging the model



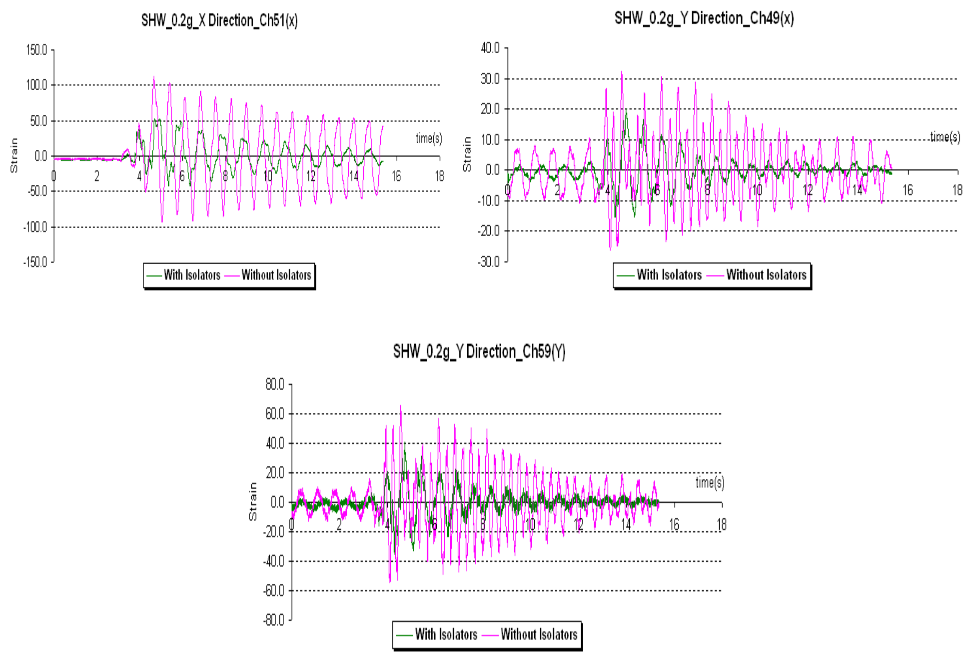


Fig. 8 Strain responses of Model with and without SR Isolators

Conclusion

In conclusion, one may say that the series of shaking table tests of Isolated Model performed was successful. The results of the performed studies have shown that effective seismic isolation through SR isolators are reasonable and can be implemented as real isolation system for buildings. Based on the experimental results obtained from shaking table tests in case of Shanghai's artificial wave the following general conclusions have been drawn:

1. Base isolation is a very effective way to reduce the seismic response of a structure; particularly floor acceleration; the period and damping; base shear, and displacement. This research effort has provided the necessary technical information to justify the use of SR isolators.
2. The isolator's effects are influenced by the property of earthquake. Tests have shown that isolators that perform well in one earthquake excitation are not suitable for another due to the unpredictable properties of an earthquake so the practical decision may be a complex process.
3. It is evident that the vertical component of a strong ground motion can be effectively attenuated by SR Isolators and it can guarantee structures from many damaging earthquake attacks whose vertical component is significantly high.

4. Series of shaking table tests of isolated model was successful. Shaking table test is very effective for researching seismic responses of structures with base isolation.

5. In cases of buildings which might not have been seismically designed, or it might have been seismically designed but to lower seismic level, such isolated systems with SR drawn from this study can be used to retrofit those buildings and improve their seismic reliability. Development of retrofit systems was shown to be very effective in providing life safety by preventing collapse and in minimizing the extent of damage.

6. The results of the survey and their correlation with experimental data are significant and provide a large amount of information that can be useful in understanding the performance of SR isolators and in developing further techniques for isolating this type of buildings. The documentation of this study of such seismic performance and testing of such SR isolators set techniques can be useful for further researches. This research is still at its early stage and is open to further studies and research.

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