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A STUDY ON COMBINED ISOLATION SYSTEM

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SUMMARY

Natural rubber bearing and sliding rubber bearing are both frequently used in seismic base isolation for mitigating structural response. Because of the vertical strength limit of rubber bearing and the unacceptably large displacement response at the top of isolators with sliding rubber bearings, a new kind of bearing, i.e. combined isolation system (CIS), is developed in the present paper. An experimental study on the dynamic characteristics of CIS, including horizontal stiffness, damping and their variation with frequency of lateral loading, vertical pressure and shear strain, is conducted. Experimental investigation indicates that CIS possess the advantages of sliding rubber bearing and common rubber bearing. Then a calculation model of CIS is derived from the analysis based on the experiment. Furthermore, a new isolator of CIS is designed for a practical structure reducing seismic response. Nonlinear seismic response analysis of the structure with CIS is performed. The comparison analysis shows that CIS can significantly mitigate the seismic response, not only base shear, but also story drifts of the structure with acceptable displacements of the isolator.

INTRODUCTION

Nowadays, structural integrity and safety are of utmost importance as the consequences of failure are devastating. Maintaining the structural integrity becomes particularly important when the structures are subjected to severe earthquakes and strong wind loading. Passive, active, semi-active and hybrid structural control strategies have been developed for alleviation of wind and seismic response of buildings and bridges. In order to develop the structural control concept into a workable technology, serious efforts have been undertaken to research and develop passive and active structural control devices, and today we have many such devices installed in a wide variety of structures. So far, the main structural protective systems can be divided into three groups according to the approaches followed to manage the energy associated with transient environmental events. The first group includes seismic isolation devices, the second passive energy dissipation devices and the last group semi-active and active control systems.

Because of their mechanical simplicity and no power requirements, passive control systems have been widely applied. Among others, seismic base isolation is an effective technique for reducing the seismic forces. Isolators provide the needed flexibility so as to shift the first mode natural frequency of isolated

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structure away from predominant frequency of the design earthquake motion, and then the structural earthquake action is minished [1]. In this paper, attention will be paid to seismic isolation devices.

A variety of isolation bearings have been developed for reducing structural seismic and wind-induced responses. Elastomeric bearings [2] and lead-rubber bearings [3, 4] have been used in structural and bridge engineering previously in 1970s, particularly in 1980s. Other new bearings are exploited afterwards, such as high damping rubber bearings [5, 6], friction pendulum bearings [7, 8], sliding bearings [9 to 11], high load multirotational (HLMR) bearings including pot, disc and spherical bearings [12], etc.

With regard to the earthquake, the insertion of a very flexible base isolation system is generally favorable. Laminated rubber bearings (LRB) and sliding rubber bearings (SRB) are most frequently utilized since they can provide suitable horizontal flexibility, but because of the vertical strength limit, too many bearings in isolation system should lead to great lateral stiffness. Otherwise, sliding rubber bearings possess high initial stiffness and very low post yielding stiffness, which would cause unacceptably large displacements of structures after sliding occurs and residual displacement after earthquake. So, in this paper, a so-called combined isolation system (CIS) composed of LRB and SRB is developed in order to satisfy serviceability under lower intensity earthquakes and wind loads, and response reduction under strong earthquakes. It is cheaper and can provide suitable initial stiffness, post yielding stiffness and damping for structural seismic mitigation.

EXPERIMENTAL TESTS ON BEARINGS

EXPERIMENTAL SCHEME

In order to attain the dynamic characteristics of rubber bearing, sliding rubber bearing and combined isolation system, pseudo-static tests on rubber bearing (shown in Fig.1) and on sliding rubber bearing (see Fig.2) are performed first, then experimental test on the combined bearing composed of the two formers is carried out. Test set-up is shown in Fig.3. Research contents include horizontal stiffness, damping and their variations with loading frequency, vertical pressure and shear strain. Vertical pressure loaded on the combined isolator is 600kN constantly and lateral load is shown in Fig.4. The frequencies of horizontal loading are 0.01Hz and 0.3Hz, respectively.

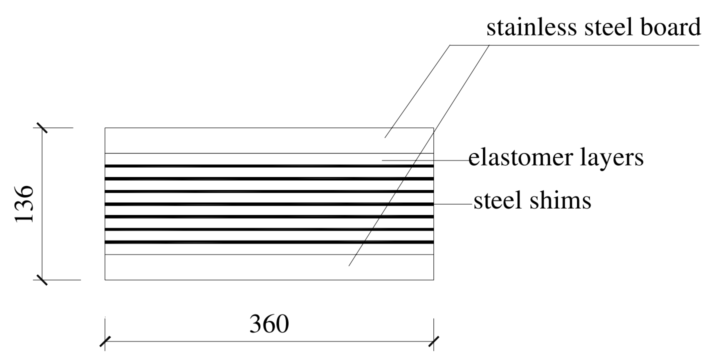


Fig.1 Cross section of LRB (sizes in mm)

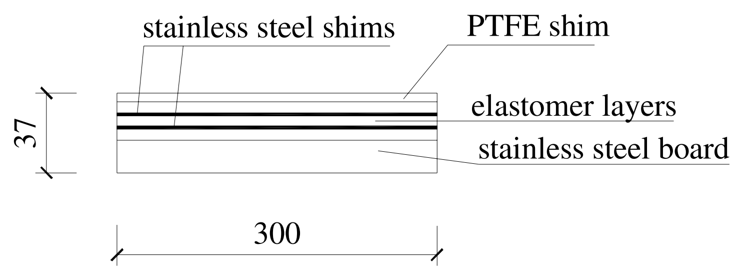


Fig.2 Cross section of SRB (sizes in mm)

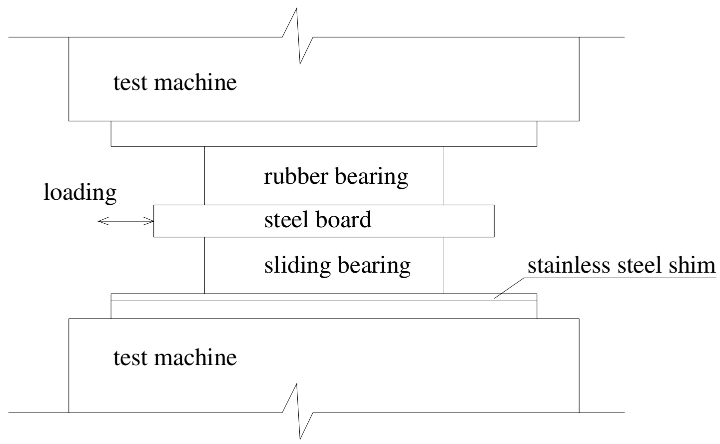


Fig.3 Sketch of test set-up

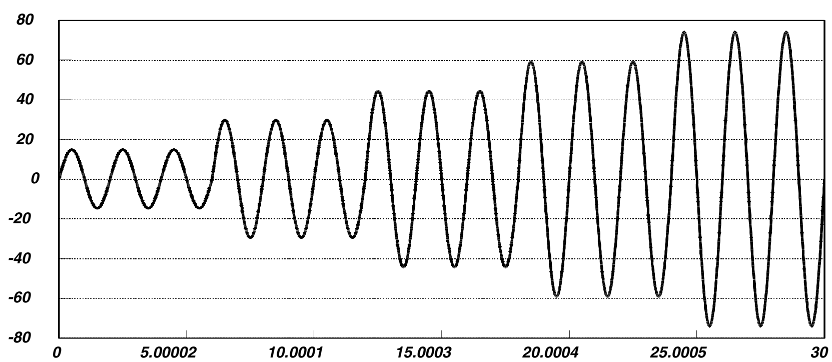
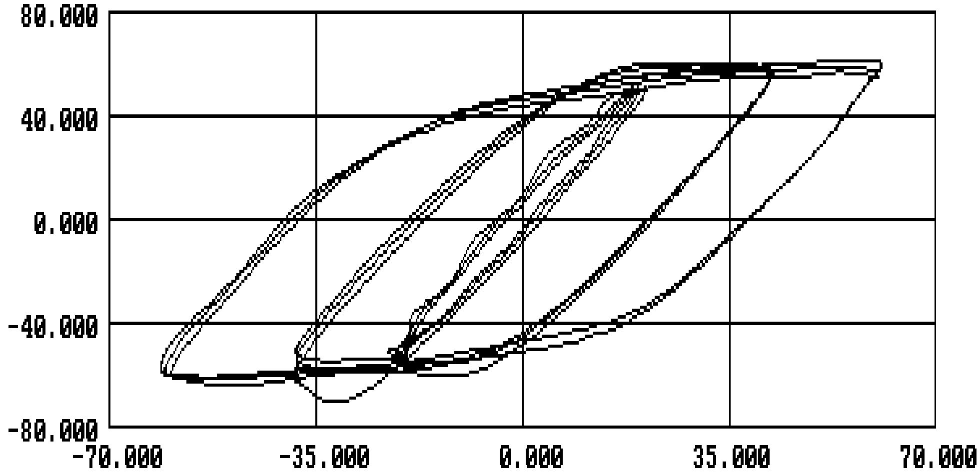


Fig.4 Lateral load-time curve
(in mm and second respectively)

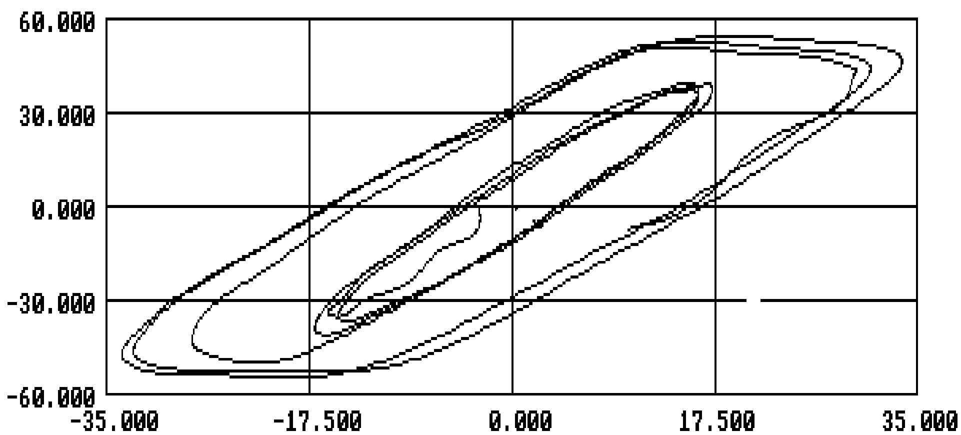
TEST RESULTS ANALYSIS

LATERAL STIFFNESS

Base isolator is the critical element of isolated building. Lateral stiffness of the isolator is one of the most important design parameters. The lateral load-shear strain hysteresis loops of the combined isolator are depicted in Fig.5 (a and b), where (a) is for load frequency of 0.01Hz and (b) 0.3Hz. From the hysteresis curves, we can find that the initial stiffness of combined isolator is high while the post yielding stiffness is very low but not zero. Comparison analysis of the test results shows that the initial stiffness, 2.78×10^6N/m, of the combined bearing is approximately equal to the superposition of stiffness, 2.10×10^6N/m and 0.63×10^6N/m of LRB and SRB, respectively. The second-stage stiffness of the combined bearing after sliding occurs is approximately equal to that of the rubber bearing.



(a) **Load frequency = 0.01Hz**



(b) **Load frequency = 0.3Hz**

Fig.5 Load-displacement hysteresis loops under shear
(in kN and mm respectively)

DAMPING

Another important behavior is energy dissipation for isolator to reduce structural seismic response. We can also find that the hysteresis loops in Fig.5 are fat and stable. It indicates that the combined bearing has excellent capacity of energy dissipation close to that of common lead-rubber bearing. According to the test results, damping ratio of the combined bearing reaches nearly 0.15.

ISOLATION APPLICATION

PRACTICAL ENGINEERING

The considered example structure for this analytical study is the No.1 building of Jianye City Garden-phase II in Zhengzhou, Henan province, China. It is a fifteen-story masonry apartment building with twelve split-level floors. The split-level dwelling building is 18.6m high with plane sizes of 18.3m×14.0m (see Fig.6). The maximum elevation difference of split-level floors is about 1.4m in height. Base isolation method is considered for the complex building while common seismic resistant methods could not satisfy the requirements.

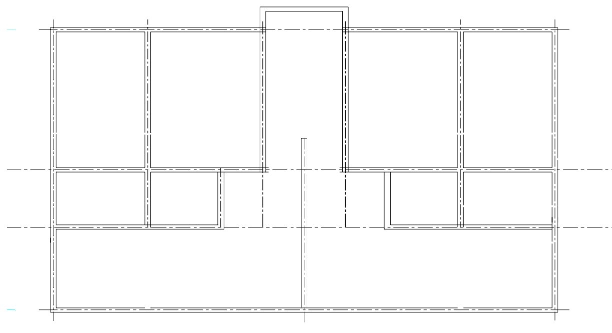


Fig.6 Plan of the building

MODEL ASSUMPTIONS

To highlight important characteristics of combined isolation system installed for base isolation and to make the problem manageable, some assumptions are necessary at present.

The ground motion is assumed to occur in one horizontal direction so that the problem can be simplified as a two-dimensional problem without consideration of torsional effects. The superstructure is modeled as a linear multi-degree of freedom system where the mass is concentrated at each split-levels and the stiffness is provided by the walls in the corresponding direction. The mass of each degree is that of the corresponding floor together with half of the wall mass of the neighboring layers.

The base isolation system is composed of common rubber bearing and sliding rubber bearing. The idealized restoring force model of the combined system is shown in Fig.7. Then the calculation shearing model of the structure is derived as illustrated in Fig.8 schematically. Mass and stiffness of the model are listed in Tab.1.

Tab.1 Story mass and stiffness of model

Story	Mass（kg）	Horizontal stiffness（N/m）
Isolation story	2.04×10^5	$1.23\times10^8/1.27\times10^7$ (initial / yielding)
1	1.59×10^5	1.29×10^{10}
2	1.18×10^5	1.00×10^{10}
3	1.35×10^5	1.00×10^{10}
4	1.18×10^5	1.00×10^{10}
5	1.35×10^5	1.00×10^{10}
6	1.18×10^5	1.00×10^{10}
7	1.35×10^5	1.00×10^{10}
8	1.18×10^5	1.00×10^{10}

9	1.35×10^5	1.00×10^{10}
10	1.18×10^5	1.00×10^{10}
11	1.35×10^5	1.00×10^{10}
12	1.19×10^5	1.00×10^{10}
13	1.35×10^5	1.00×10^{10}
14	1.25×10^5	0.98×10^{10}

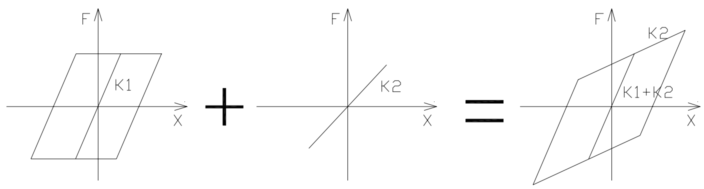


Fig.7 Bilinear hysteresis model of combined isolation system

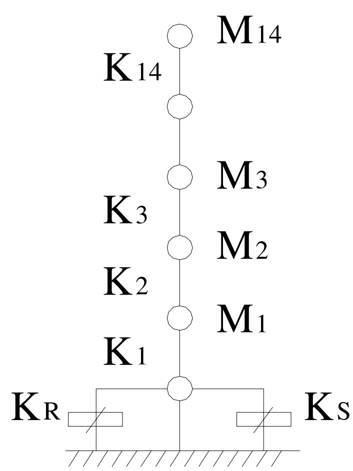


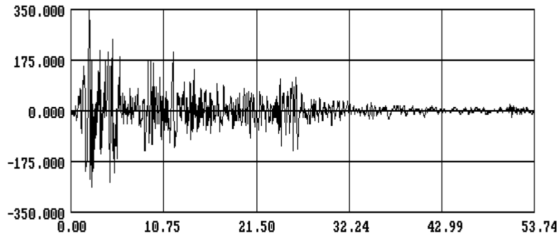
Fig.8 Model of dynamic analysis
(K_R: stiffness of rubber bearing; K_S: stiffness of sliding bearing)

SEISMIC ANALYSIS

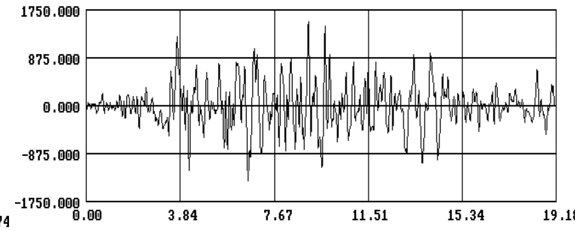
EATHQUAKE WAVES

Nonlinear seismic response of the base isolated structure excited by earthquake is conducted. Exciting earthquake waves selected are El Centro wave, Taft wave and an artificial wave, respectively. Each wave excites with peak ground acceleration (PGA) of 35gal, 100gal and 220gal, respectively. Earthquake acceleration waves are shown in Fig.9 (a, b and c).

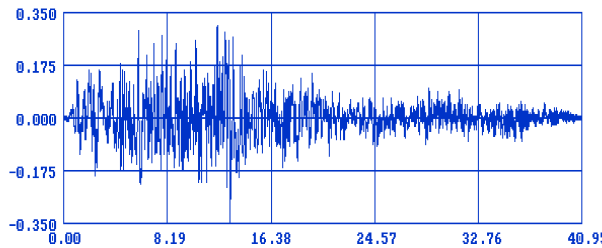
In calculation, the damping ratio of the upper structure and isolation layer are 0.05 and 0.15, respectively. Dynamic friction coefficient is approximately 0.08.



(a) **El Centro wave**
(acceleration in mm/sec^2)



(b) **Taft wave**
(acceleration in mm/sec^2)



(c) **Artificial wave**
(acceleration in m/sec^2)

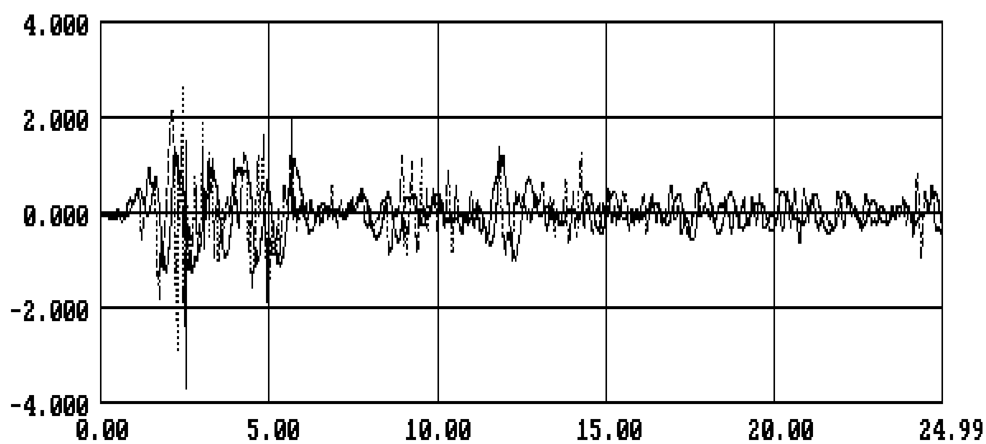
Fig.9 Acceleration time-history of waves

SEISMIC RESPONSES

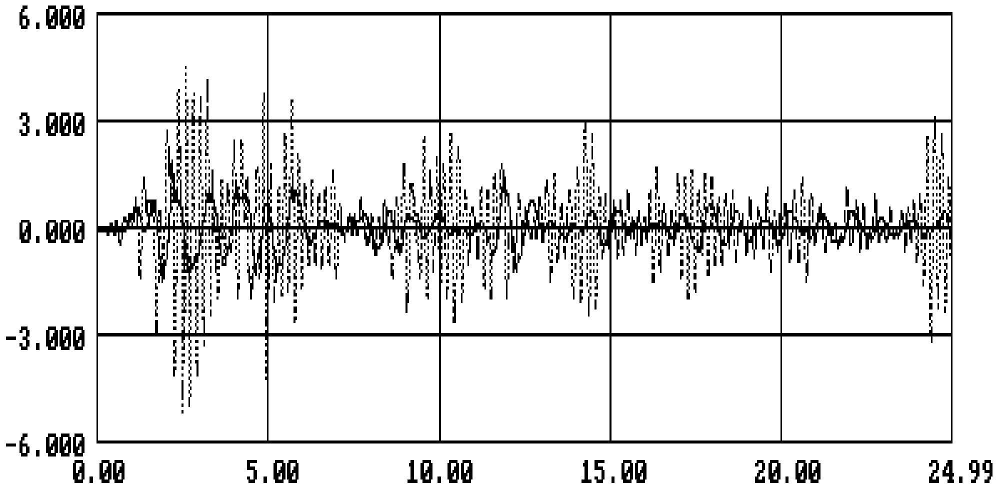
Displacement, velocity and acceleration as well as interlayer shear force responses of the structure with and without base isolation are calculated.

ACCELERATION RESPONSES

Acceleration time-histories of the first floor and the roof of the structure excited by El Centro wave with PGA of 220gal are shown in Fig.10(a and b), real line for base isolated and dash line for fixed-base structure, respectively. From Fig.10 we can find that, at each floor, the amplitudes of acceleration responses of the structure with base isolation is much lower than that of the structure with fixed base. The maximum acceleration response values of floors of the structure with base isolation and fixed base are listed in Tab.2 and depicted in Fig.11. The comparison shows that the acceleration response of the structure is significantly mitigated with base isolation.



(a) **First floor**



(b) **Roof**

Fig.10 Time-history of acceleration

(acceleration in m/sec^2)

Tab.2 Comparison of acceleration (in m/sec^2)

Layer	Base isolation	Fixed base
1	1.33	3.67
2	1.33	4.48
3	1.36	3.80
4	1.39	4.23
5	1.42	3.95
6	1.45	3.66
7	1.48	3.65
8	1.51	3.42
9	1.55	3.65
10	1.57	3.84
11	1.61	4.35
12	1.63	4.71
13	1.65	4.98
14	1.67	5.17

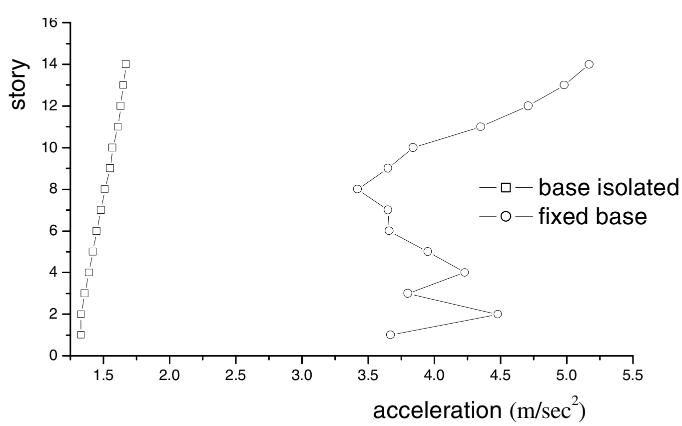
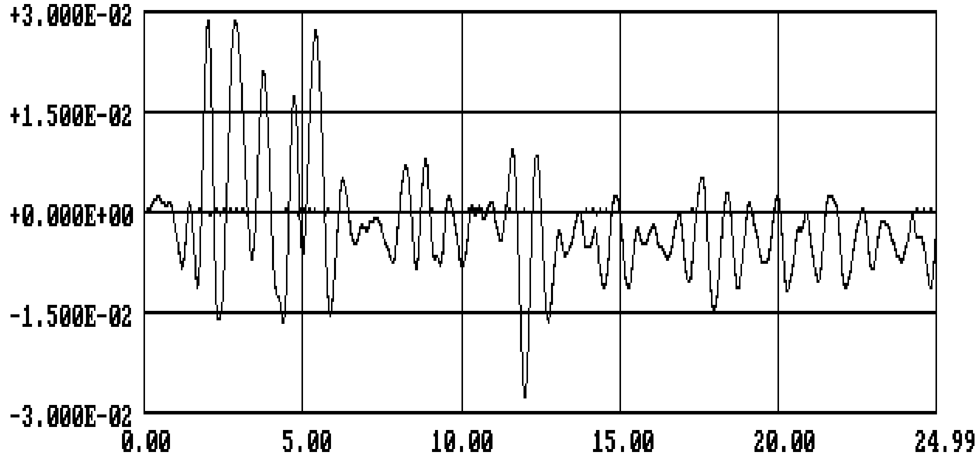


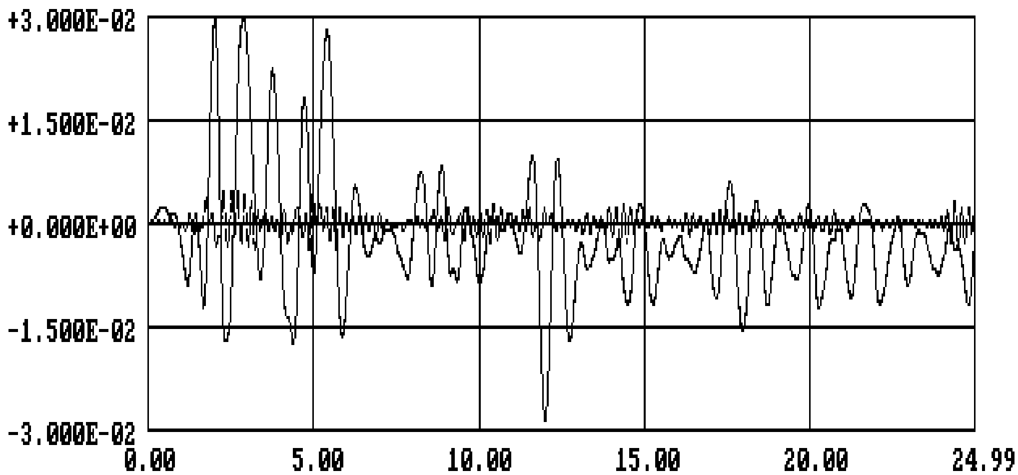
Fig.11 Comparison of the maximum accelerations

DISPLACEMENT RESPONSES

Absolute displacement responses of the first floor and the roof of the structure excited by El Centro wave with PGA of 220gal are shown in Fig.12(a and b), respectively. It is noted that the absolute displacements of upper floors of the structure with isolation are approximately 10 times that of the corresponding floors of the structure without isolation. On the other hand, the absolute displacements of the floors close to each other with little difference, because the upper structure vibrates as a rigid body. Comparison of maximum absolute displacements of the structures with and without base isolation is depicted in Fig.13. It indicates that the absolute displacements of the structure with base isolation are much larger than with fixed base, however, the relative story displacements of base isolated structure are much less than that of fixed-base structure except isolation layer, where story drifts are concentrated. So the earthquake action can be obviously reduced.



(a) **First floor**



(b) **Roof**

Fig.12 Time-history of displacement

(displacement in m)

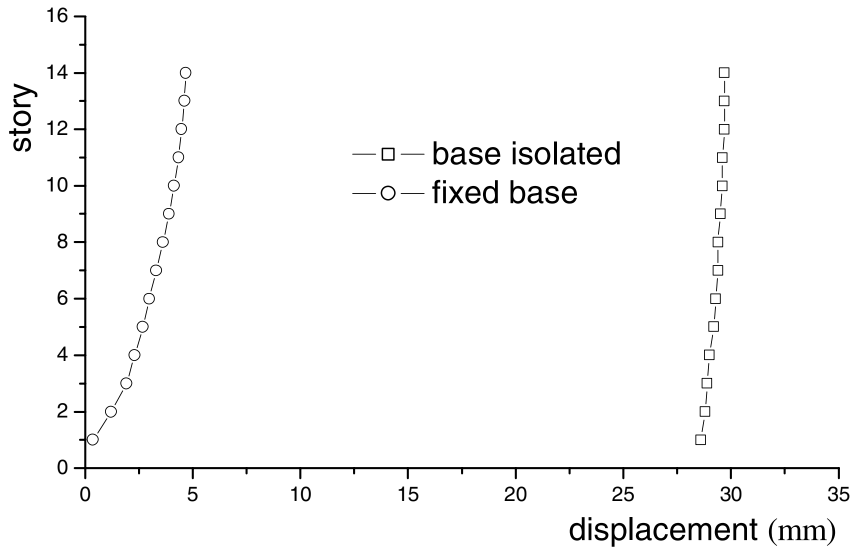


Fig.13 Comparison of story drifts

STORY DRIFT AND SHEAR FORCE

The maximum story drifts and shear forces of the structure, with base isolation or with fixed base, excited by earthquakes with PGA of 220gal are listed in Tab.3. Also, the story drifts are depicted in Fig.14.

Though the drifts of isolation layer are large (acceptably), the drifts of upper layers are very little. The story drifts of fixed-base structure are much large, which may cause walls crack. Furthermore, the story shear forces of the structure with base isolation are only 30 percent of the corresponding story shear forces with fixed base. It shows obviously that the combined isolator can significantly mitigate structural seismic responses.

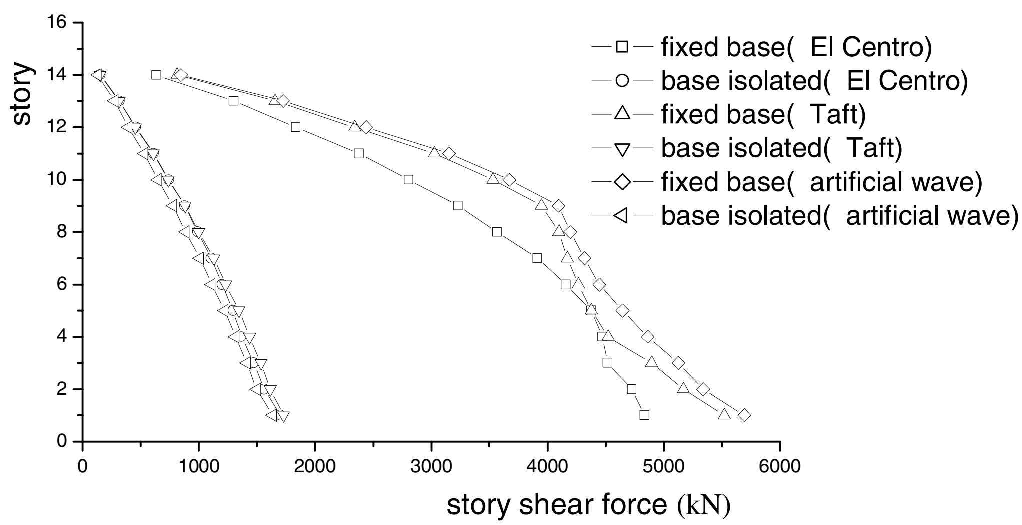


Fig.14 Comparison of story shear forces

Tab.3 Comparisons of story drifts and shear forces (with fixed base / with base isolated)

Story	Maximum storey drift (mm)			Maximum story shear force (kN)		
	El Centro	Taft	Artificial wave	El Centro	Taft	Artificial wave
Isolation layer	--/28.5	--/31.3	--/26.6	--/1891.0	--/1992.4	--/1831.3
1	0.38/0.13	0.62/0.13	0.65/0.13	4834.9/1703.3	5522.7/1728.4	5692.9/1637.6
2	0.85/0.16	2.19/0.16	1.15/0.15	4725.4/1564.9	5169.2/1615.9	5340.8/1498.9
3	0.71/0.15	1.27/0.15	1.31/0.14	4517.9/1472.4	4897.1/1535.0	5128.1/1414.6
4	0.46/0.14	1.20/0.14	1.12/0.13	4473.0/1369.4	4521.8/1437.0	4863.3/1313.9
5	0.47/0.13	0.67/0.13	0.84/0.12	4376.4/1295.7	4377.0/1344.7	4645.7/1221.5
6	0.42/0.12	0.49/0.12	0.61/0.11	4159.5/1201.1	4269.1/1232.4	4445.2/1109.9
7	0.39/0.11	0.54/0.11	0.63/0.10	3911.4/1106.6	4171.3/1128.2	4317.7/1007.4
8	0.36/0.10	0.41/0.10	0.43/0.09	3567.4/990.0	4100.7/1000.4	4197.0/887.3
9	0.32/0.09	0.40/0.09	0.41/0.08	3231.8/879.4	3950.2/881.4	4095.4/777.6
10	0.28/0.07	0.35/0.07	0.37/0.07	2806.9/741.6	3532.0/738.4	3672.2/647.5
11	0.24/0.06	0.30/0.06	0.32/0.05	2379.0/612.8	3028.4/609.1	3152.7/530.4
12	0.18/0.05	0.23/0.05	0.24/0.04	1835.6/458.1	2341.0/454.9	2437.9/394.1
13	0.13/0.03	0.17/0.03	0.17/0.03	1299.2/318.0	1657.1/314.6	1724.5/271.8
14	0.06/0.02	0.08/0.02	0.09/0.01	636.86/154.0	813.9/152.0	846.0/131.1

CONCLUSIONS

In this paper, a new alternative of base isolation system composed of common rubber bearing and sliding rubber bearing is invented for structural seismic mitigation. Experimental research on dynamic behaviors of the combined isolation system and seismic response analysis of a practical structure with the isolation system are carried out. Story drifts, acceleration and shear force responses of structure with the aforementioned base isolation and with fixed base are compared. Findings of the present study are:

1. The combined isolation system possesses suitable initial and post yielding horizontal stiffness. The initial stiffness is provided by stiffness of rubber bearing and sliding rubber bearing. The post yielding stiffness is provided by stiffness of rubber bearing and friction of sliding bearing. Structure with CIS can sustain serviceability under wind loads and low intensity earthquake.
2. In case of strong intensity earthquake, sliding rubber bearing in CIS would slide and then lateral stiffness of isolation layer decreased. Flexible isolation then reduces the earthquake action on the structure.
3. CIS has excellent capacity of energy dissipation due to frictional sliding. Dynamic friction coefficient and damping ration of the isolation system is approximately 0.08 and 0.15, respectively.
4. Under strong intensity earthquake, structural responses of interstory drifts and shear forces can be reduced by 60-70% without large displacement and residual deformation of the isolator

compared to that of structure with fixed base.

5. The combined isolator is cheaper than whole laminated rubber bearings installed in a structure.

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