An Experimental Investigation into the Use of Buffered Particle Dampers

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SUMMARY:

This paper presents a systematic experimental investigation of the effects of buffered particle dampers attached to a multi-degree-of-freedom (MDOF) system under different dynamic loads (free vibration, random excitation as well as real onsite earthquake excitations). A series of shaking table tests of a three-storey steel frame with the buffered particle damper system are carried out to evaluate the performance. It is shown that buffered particle dampers have good performance in reducing the response of structures under dynamic loads, especially under random excitation case. It can effectively control the fundamental mode of the MDOF primary system; however, the control effect for higher modes is variable. It is also shown that, for a specific container geometry, a certain mass ratio leads to more efficient momentum transfer from the primary system to the particles with a better vibration attenuation effect, and that buffered particle dampers have better control effect than the conventional rigid ones. Properly designed buffered particle dampers can effectively reduce the response of lightly-damped MDOF primary system with a small weight penalty, under different dynamic loads.

Keywords: buffered particle damper; shaking table test; passive vibration control

1. INTRODUCTION

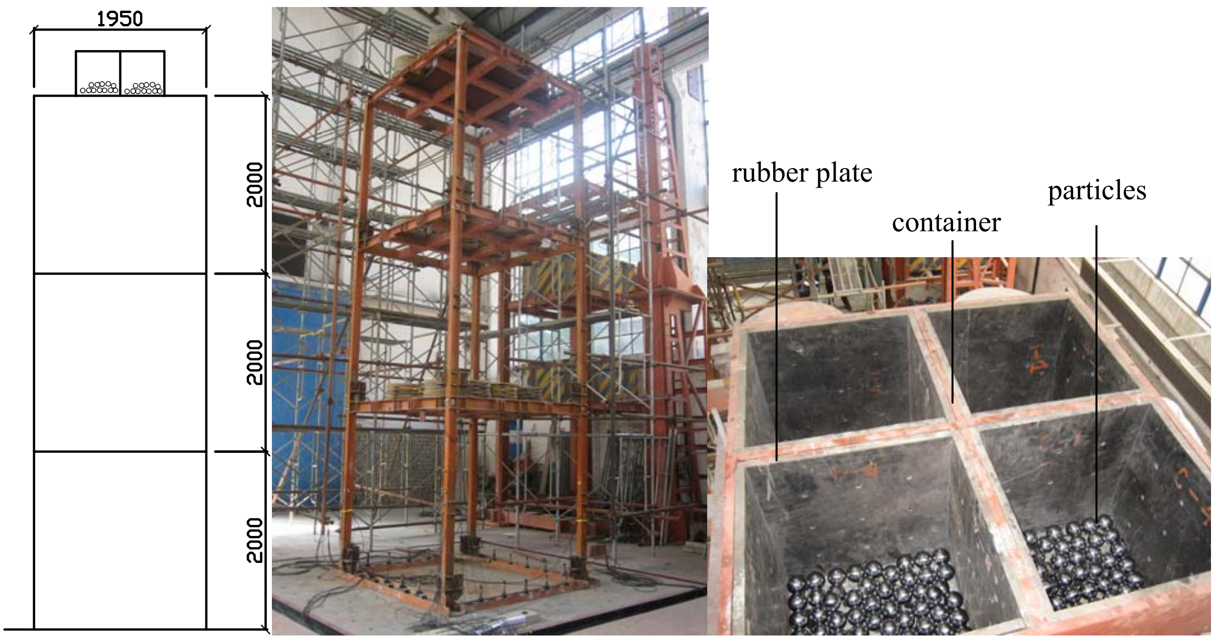
Among numerous structural control applications, passive energy dissipation devices, such as tuned mass dampers, are widely applied in controlling the dynamic response of structures due to their simplicity and lack of power requirements. One such possible passive system is a particle damper, which evolves from the single-particle impact damper (Masri, 1966), consisting of a container and freely moving particles (e.g., ball bearings, tungsten powders, etc.). The main damping mechanics are momentum transfer and energy dissipation during the impact between the particles and the primary system. Impact dampers will produce impulsive loads between the two coupled systems and will cause a high-level of noise during the impact process. Simultaneously, large contact forces will result in material deterioration and local deformation accompanying plastic collisions. To reduce these problems, some attempts have been made, by introducing the idea of multi-unit impact dampers (Masri, 1969, Bapat, 1985), bean-bag dampers (Popplewell, 1989), particle or granular impact dampers (Papalou, 1996, Araki, 1985, Lu, 2010). On the other hand, some researchers also incorporated buffer materials in the impact damper system to reduce the impact forces (Li, 2008).

Despite numerous analytical and experimental studies that have been conducted over the years into the various aspects of the motion of particle dampers, the understanding of the complex particle damping mechanism has still not been well developed, due to the system’s high nonlinearity and the complexity involving interactions among a large number of parameters under arbitrary dynamic excitations. It can be seen that most studies have investigated the performance on Single-Degree-of-Freedom (SDOF) systems, usually under the action of simple excitations such as sinusoidal loading. However, for most structures found in civil engineering, such as the case of a multi-storey building under dynamic loads, the structure cannot reasonably be approximated as a SDOF system, since the complex external loading and the damper impacts themselves are likely to excite more than just the fundamental mode of vibration. Moreover, most results have focused on conventional single-particle impact dampers or particle dampers; if the buffer material is introduced, the study is limited to the simple single-particle impact dampers. Additionally, experimental tests of buffered particle dampers attached to a large scale MDOF primary system are seldom investigated in the literature. Consequently, there is a need to carry out systematic tests of buffered particle dampers when operating with a MDOF system that is subjected to different dynamic loads.

2. EXPERIMENTAL SETUP AND PROCEDURE

2.1. Experimental Setup

The experimental model consisted of a three-storey steel frame as the primary structure and a buffered multi-unit particle damper on the top floor. Figure 1 shows the configuration of the model. The total masses from the first floor to the roof, including the frame self-weight during testing, were 1915 kg, 1915 kg, and 2124 kg, respectively. The natural frequencies of the primary system were f1 = 1.07 Hz, f2 = 3.2 Hz, and f3 = 4.8 Hz. The buffered multi-unit particle dampers were made of steel plates consisting of four rectangular containers, with the dimensions of length 0.49 m × width 0.49 m × height 0.5 m, in which the bottom and the walls around each container were covered by 20 mm thickness rubber plates. Hence, the net dimensions of each container were length 0.45 m × width 0.45 m × height 0.48 m. They were attached symmetrically with respect to the shaking direction. Learning from the experience of Saeki (Saeki, 2002), who did an experiment on a particle damper under harmonic excitation with 6mm diameter steel ball, and found that when the cavity length was around 60 mm, the vibration attenuation effect was the best; the diameter of steel ball bearing was chosen to be 50.8 mm. Considering real engineering projects, the mass ratio between the damper and the primary structure should be small, and based on the pre-test experience (to be introduced in section 3.1), a number of 63 steel ball bearings were put into each container, with the total mass of 135 kg, which was 2.25% of the primary system mass. The design procedure combined the realistic consideration and the preliminary optimization idea.



(a) (b) (c)

Figure 1. Configuration of frame model with buffered multi-unit particle dampers (unit: mm). (a) Elevation; (b) Photo of the experimental model; (c) Photo of the buffered particle dampers

2.2. Experimental Procedures

In order to evaluate the performance of the buffered particle damper system under different dynamic loads, both free vibration case in pre-test, random excitation case and real onsite earthquake ground motion cases in the shaking table test, were investigated. Free vibration pre-test was carried out by giving the top floor an initial displacement. The random excitation experiments were performed using a randomly generated base excitation with band limited frequency content between 0 Hz and 25 Hz to encompass the natural frequencies of the primary structure. For real onsite earthquake ground motions, four earthquake time histories of acceleration were selected, which were Kobe (1995, NS), El Centro (1940, NS), Wenchuan (2008, NS) (shown in Figure 2.) and Shanghai design code specified artificial earthquake accelerogram (SHW2, 1996). All time histories of acceleration were inputted in only one direction of the test model, and the time interval was 0.02s.

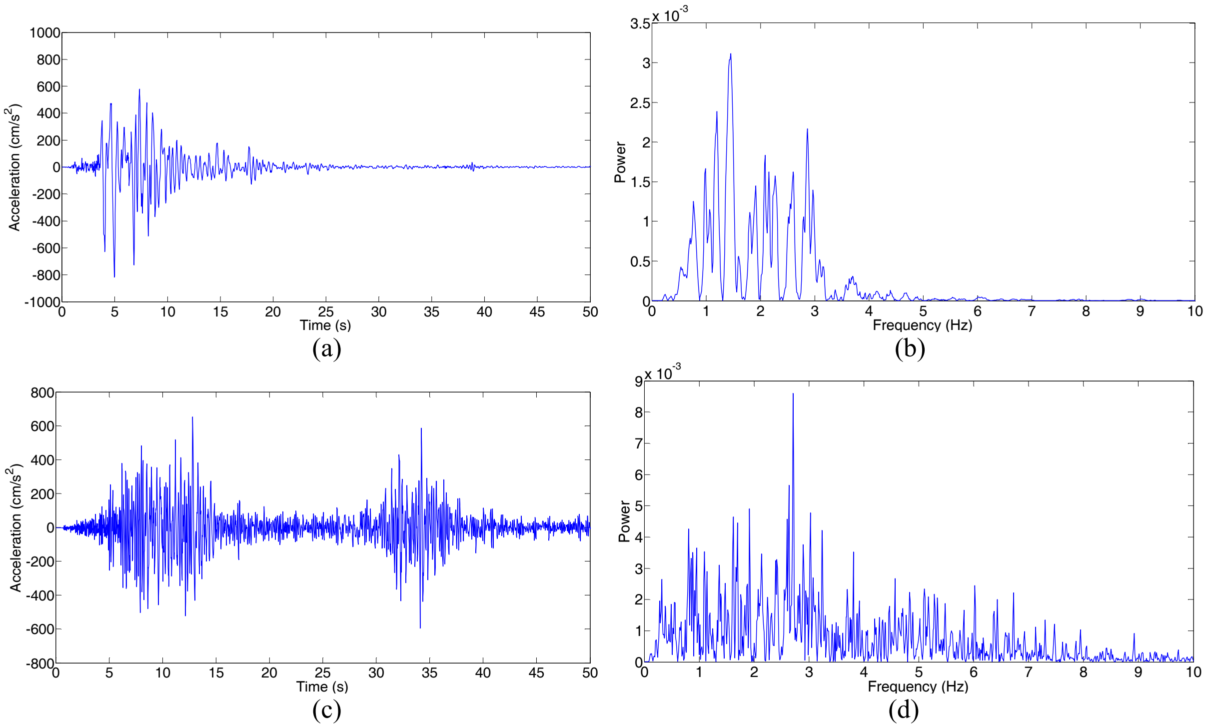


Figure 2. (a, c) Acceleration time history curves of (a) Kobe wave and (c) Wenchuan wave; (b, d) Corresponding Fast Fourier Transforms of (b) Kobe wave and (d) Wenchuan wave.

3. EXPERIMENTAL RESULTS

3.1. Free Vibration Pre-test

The free vibration pre-test is a preparation for the following shaking table tests, with the purpose to get a general idea of how buffered particle dampers work and how many particles should be attached. The pre-test was carried out by giving the top floor an initial displacement. The acceleration time histories at top floor of the test frame are shown in Figure 3, in which three different mass ratios (μ) of the buffered particle dampers are adopted. It can be seen that the acceleration time history in the mass ratio of 0.0225 case decays much faster than that in the cases of 0.015 and 0.03 mass ratios, which indicates that the former mass ratio results in better vibration attenuation effect, when using the damper dimensions discussed above. The reason is that, in the case of 0.015 mass ratio (42 steel ball bearings in each container), the particles need to take a relatively longer time for traveling from one wall of the container to the opposite wall after a collision, and relatively fewer impacts occur. While in the case of 0.03 mass ratio (84 steel ball bearings in each container), there is not enough space for particles to move freely in the container, and they cannot generate vigorous motion. Hence the momentum transfer from the primary system to the particles is smaller, and the vibration reduction effect is worse. Based on this experience, the mass ratio of 0.0225, which is 63 steel ball bearings in each container, was applied in the following shaking table dynamic tests.

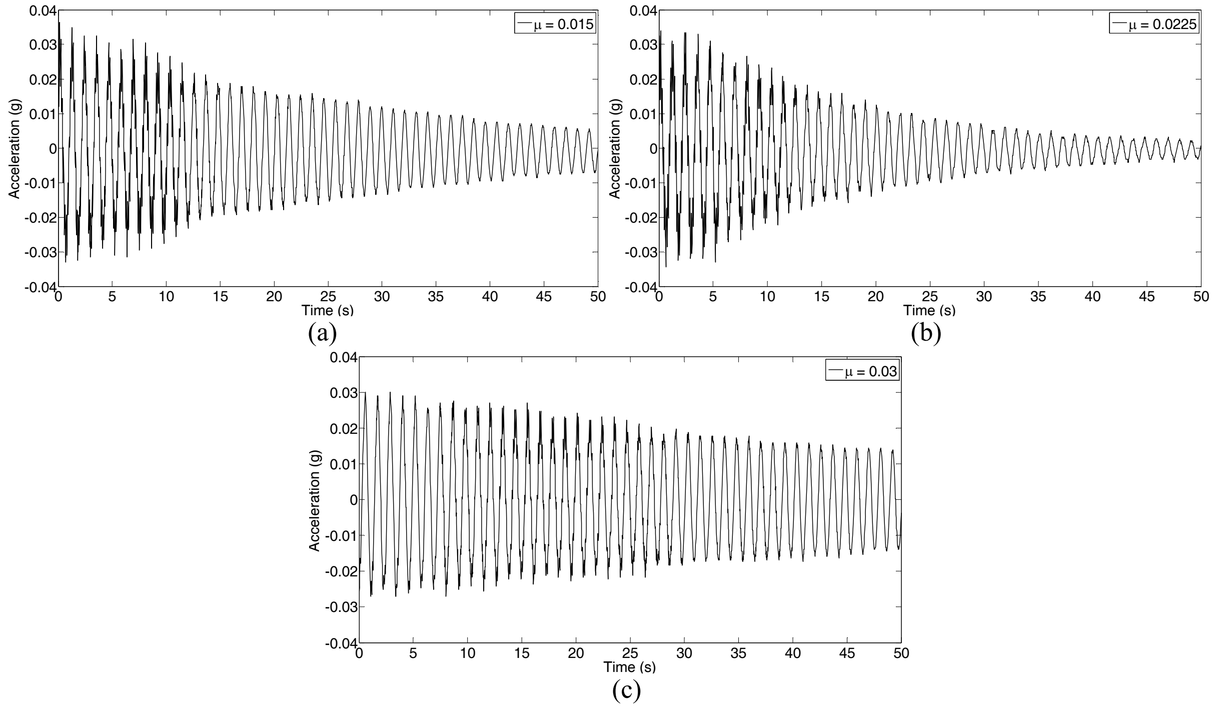


Figure 3. Acceleration time history at top floor of the primary system with different mass ratios. (a) μ=0.015; (b) μ=0.0225; and (c) μ=0.03.

3.2. Random Excitation Test

The random excitation experiments were performed using a randomly generated base excitation with band limited frequency content between 0 Hz and 25 Hz, to encompass the natural frequencies of the primary structure. Figure 4 shows the acceleration and displacement time histories at the roof level of the test frame. The response of the primary system with buffered particle dampers is much smaller than that without the damper during most time durations, except for the very beginning short time period. The reason is that particles need to take some time traveling to the wall of the container and induce collisions. Once significant momentum is imparted to the impact mass, the response begins to reduce.

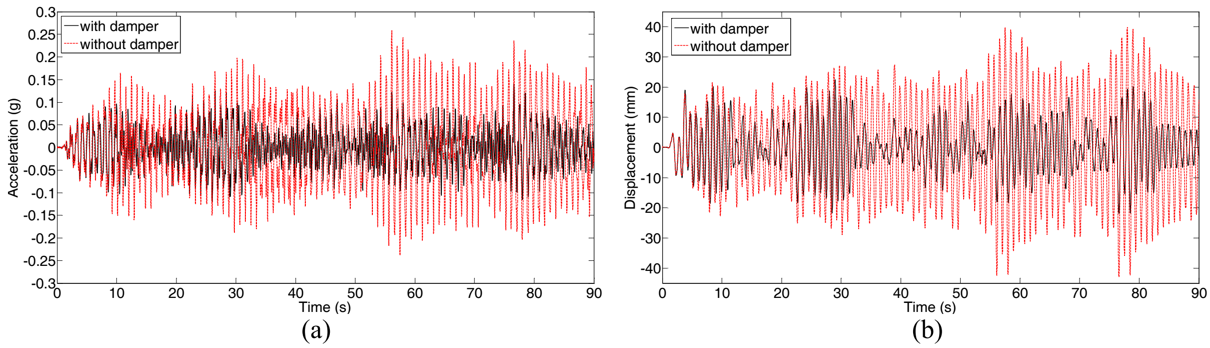


Figure 4. Response time history at top floor of the primary system under random excitation. (a) Acceleration; and (b) Displacement.

Figure 5 shows the corresponding power spectral density (PSD) of the acceleration response at different floors, in which the PSD is plotted in a logarithmic form for better comparison. There is a clear vibration attenuation effect of the buffered particle damper for each storey at the first mode of vibration; however, the vibration control effect upon the higher modes is minor. The reason may lie in the location of the damper, which is on the top floor, in the region of the largest displacement for the first mode, not the largest displacement for the second or the third mode. However, considering the response contribution of the first mode is much greater than the higher modes, the damper had better to be placed on the top floor. The same phenomena is also demonstrated in Li's experiments (Li, 2006b).

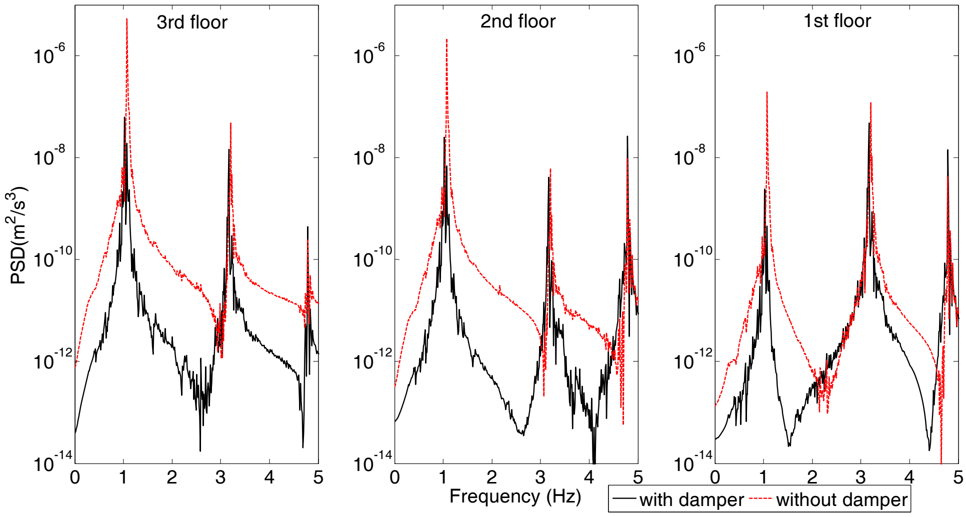


Figure 5. Power spectral density of the primary system acceleration response under random excitation.

3.3. Onsite Earthquake Excitation Test

The real onsite earthquake excitation tests were carried out by using four typical earthquake records. Table 1 shows the system response of the test frame under different earthquake ground motions, including the maximum displacement responses (X_3) and their root mean square (r.m.s) value (σ_3), and the maximum acceleration responses (A_3) at the roof of the test frame. The r.m.s of displacement is an index to the vibration energy.

Table 1. System response of the test frame under 0.1g onsite earthquake excitation

Seismic input	Kobe			El Centro		
	X_3(mm)	σ_3 (mm)	A_3 (g)	X_3(mm)	σ_3 (mm)	A_3 (g)
Test frame with dampers	63.104	11.748	0.335	49.255	11.438	0.281
Test frame without dampers	73.984	19.882	0.398	53.936	18.095	0.311
Reduction effect (%)	14.7	40.9	15.8	8.7	36.8	9.6

Table 1. System response of the test frame under 0.1g onsite earthquake excitation (Cont.)

Seismic input	Wenchuan			SHW2		
	X_3(mm)	σ_3 (mm)	A_3 (g)	X_3(mm)	σ_3 (mm)	A_3 (g)
Test frame with dampers	40.723	10.292	0.307	88.953	22.169	0.451
Test frame without dampers	47.435	12.47	0.345	118.393	29.656	0.586
Reduction effect (%)	14.1	17.5	11.0	24.9	25.2	23.0

$RE = (R_0 - R) / R_0$, where RE is the reduction effect, R_0 is the response of system without dampers, and R is the response of system with dampers.

It can be seen that: (1) the frame with buffered particle dampers has smaller response compared with that of the frame without dampers. (2) The vibration reduction effect of the r.m.s of displacement is much better than that of the peak displacement, in which the former is 17.5% - 40.9%, and the latter is 8.7% - 24.9%. This means that buffered particle dampers can help the primary system to dissipate a lot of input earthquake energy, and the displacement can be effectively reduced as well. (3) The vibration reduction effect is different under different seismic ground motions. In the experiment, the system under Wenchuan excitation resulted in the worst reduction effect. The reason may lie in the frequency content of the input earthquake excitations. Figure 2 shows the excitation of Kobe wave and Wenchuan wave in the time domain and frequency domain, respectively. One can see that the main frequency of Kobe wave is around 1.4 Hz, which is near the fundamental frequency of the primary system (1.07 Hz), while that of Wenchuan wave is around 2.7 Hz. Another reason may be that the displacement response of the frame under Wenchuan wave is smaller than that under other inputs, which leads to milder movements for particles in the container. There are fewer collisions between the particles and the primary system, and the buffered particle dampers dissipate less input energy. Consequently, the system generated the worst reduction effect under Wenchuan wave. (4) The vibration reduction effect for the r.m.s displacement response under the random excitation test, which is discussed in Section 3.2, is about 55%. It is larger than the corresponding value in all onsite earthquake excitation input cases. This means that the performance of buffered particle damper system under stationary random excitation is much better than that under real earthquake excitations. It is also further evidence that the reduction effect of buffered particle damper is influenced by the characteristics of the input excitations.

The time histories of the responses of the test frame with buffered particle dampers are also much smaller than those of the uncontrolled frame. Figure 6 shows the displacement time history at the roof level of the test frame, in which a solid line represents the response of the frame with a damper, and the dotted line shows the response of the uncontrolled frame. From Figure 6, one can see that the buffered particle dampers system not only reduces the maximum response of the displacement, but also makes the whole time history attenuate quickly, so that the response during most of the time period is reduced. This is also additional evidence that the r.m.s of the displacement reduction effect is better than the maximum displacement reduction effect. Another interesting phenomenon in Figure 6 is similar to that in Figure 4, which is that the responses of the controlled and uncontrolled system are the same at the very beginning time period, after a while, the curve of the controlled frame begins to decay quickly. This is also a similar phenomenon encountered in the operation of Tuned Mass Dampers. The vibration reduction effect is not good at the very beginning and becomes better as time goes by. The reason is that (as in the previous tests discussed above) it takes some time for the particles to impact the wall of the container. After certain impacts, the buffered particle damper system starts to dissipate the input energy by momentum transfer.

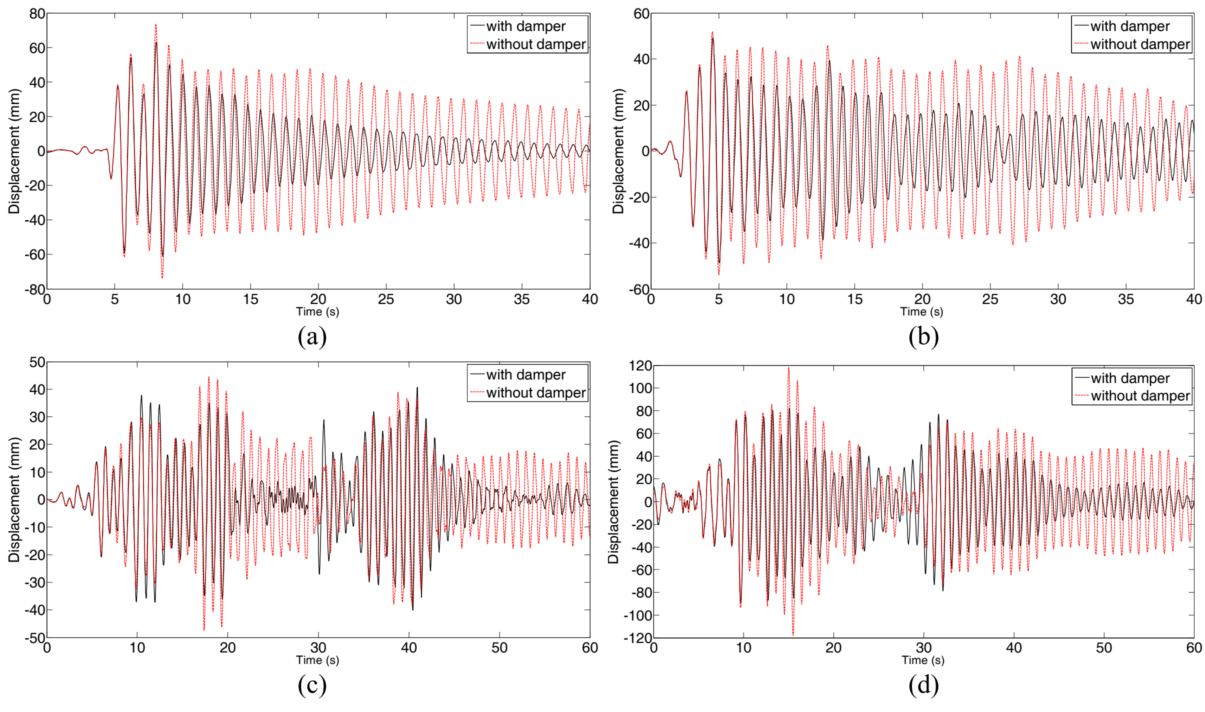
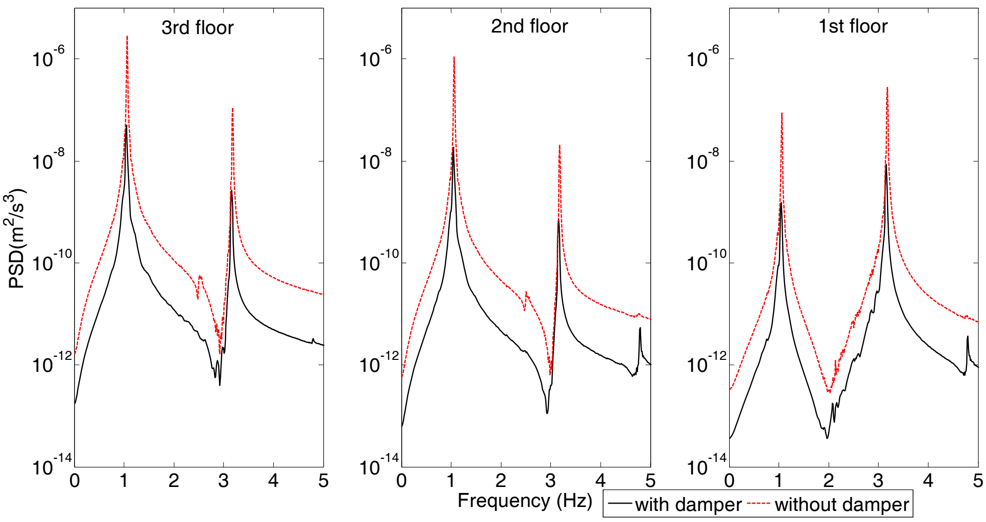
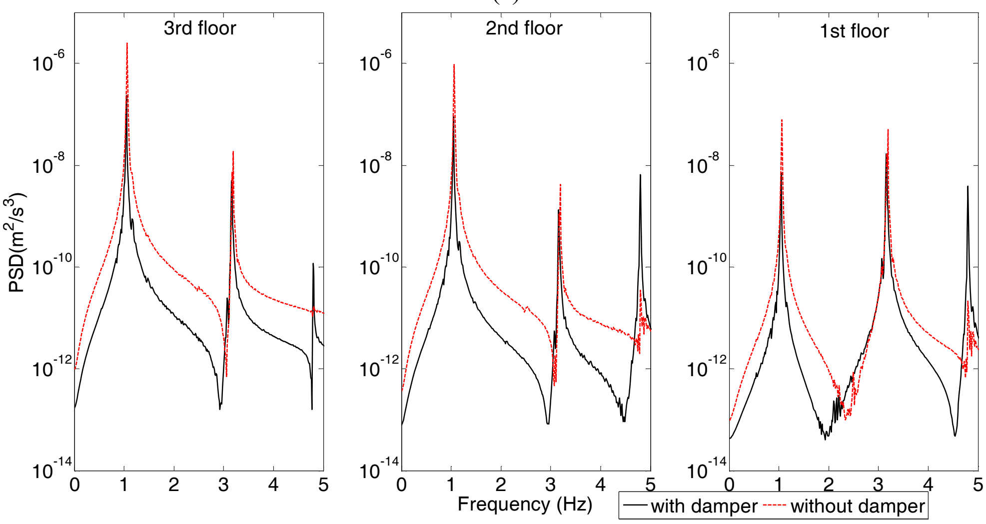


Figure 6. Displacement time history at roof level of the test frame under onsite earthquake excitation. (a) Kobe wave; (b) El Centro wave; (c) Wenchuan wave; and (d) SHW2 wave.

The corresponding power spectral density (PSD) of the acceleration response at different floors is shown in Figure 7, in which the PSD is plotted in a logarithmic form for better comparison. There is a clear vibration attenuation effect of the buffered particle damper for each storey at the first mode of vibration; however, for the second mode, the vibration control effect is not as good as the first mode, while for the third mode, the control effect depends on the earthquake inputs. The reduction of the third mode is obvious under Kobe wave input case, while the response of the third mode is enlarged under El Centro wave input case. This phenomenon indicates that the buffered particle damper system can effectively control the fundamental mode of the primary system; however, for the higher mode, the control effect cannot be guaranteed, for a specific damper configuration. Of course, it should be kept in mind that the contribution of the higher modes becomes progressively smaller, as to mode index increases. Another interesting phenomenon which can be found both in Figure 5 and in Figure 7 is that the off-resonance parts of the PSDs are always significantly lower for the with-damper case. This means that particle dampers can reduce the vibration of the primary system not only at the resonance parts, but also at the off-resonance parts, and that they can have a beneficial vibration attenuation effect over a wide frequency range. Many researchers have confirmed this advantage of the particle damping (Saeki, 2002, Xu, 2005, Panossian, 1991).



(a)



(b)

Figure 7. Power spectral density of the primary system acceleration response under onsite earthquake excitation. (a) Kobe wave; and (b) El Centro wave.

Figure 8 shows the normalized maximum displacement at every floor of the test frame under different seismic inputs. The displacement is normalized by dividing the response of the first floor of the uncontrolled frame. One can see that each floor of the frame can achieve vibration attenuation; however, the attenuation effect for the top floor is generally better than the other floors. The reason may lie in the position of the buffered particle damper. The motion at the roof is more vigorous than the other two floors, resulting in violent movements and impacts between the particles and the container.

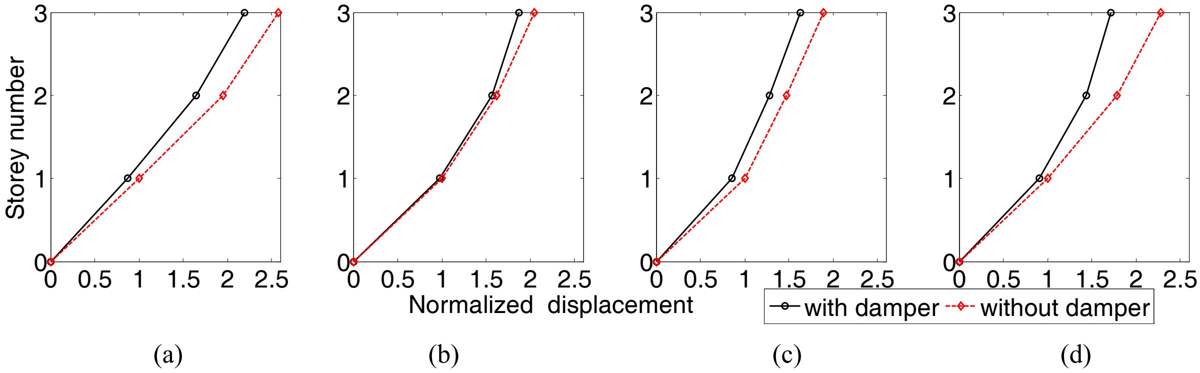


Figure 8. Maximum displacement at every floor of the test frame. (a) Kobe wave; (b) El Centro wave; (c) Wenchuan wave; and (d) SHW2 wave.

3.4. Performance Comparison

During the experimental test, the performance of particle damper with / without buffered material was also investigated. Table 2 compares the vibration reduction effect for the top floor of the test frame between the buffered particle damper case and the conventional rigid particle damper case. Figure 9 shows sections of the acceleration and displacement time histories at the roof level of the test frame under different dynamic loads. It is seen that the damper can achieve better performance provided that the buffered material is attached inside the container walls, especially for the random excitation input case. However, it should also be noted that the buffered particle damper does not manifest a lot of higher efficiency than the conventional particle damper. This is related to the property of the buffer material. Li (Li, 2006a) preliminary investigated the relationship between different buffer material and the performance of buffered impact damper (single particle in single container, with no interaction between particles), and found that the effective reduction of the vibration response depended not only on the magnitude of the contact force but also upon the contact time. Consequently, softer buffer material with higher coefficient of restitution may lead to more enhanced performance of buffered particle damper compared to the conventional rigid one.

Table 2. Vibration reduction effect (%) comparison of particle damper with / without buffer under dynamic loads

Seismic input	Random	Kobe			El Centro		
	σ_3	X_3	σ_3	A_3	X_3	σ_3	A_3
Buffered particle damper	54.9	14.7	40.9	15.8	8.7	36.8	9.6
Rigid particle damper	45.9	9.8	35.1	8.1	8.5	38.9	4.7
Improvement	9	4.9	5.8	7.7	0.2	-2.1	4.9

Table 2. Vibration reduction effect (%) comparison of particle damper with / without buffer under dynamic loads (Cont.)

Seismic input	Wenchuan			SHW2		
	X_3	σ_3	A_3	X_3	σ_3	A_3
Buffered particle damper	14.1	17.5	11.0	24.9	25.2	23
Rigid particle damper	7.2	11.8	7.6	18.5	21.6	19.2
Improvement	6.9	5.7	3.4	6.4	3.6	3.8

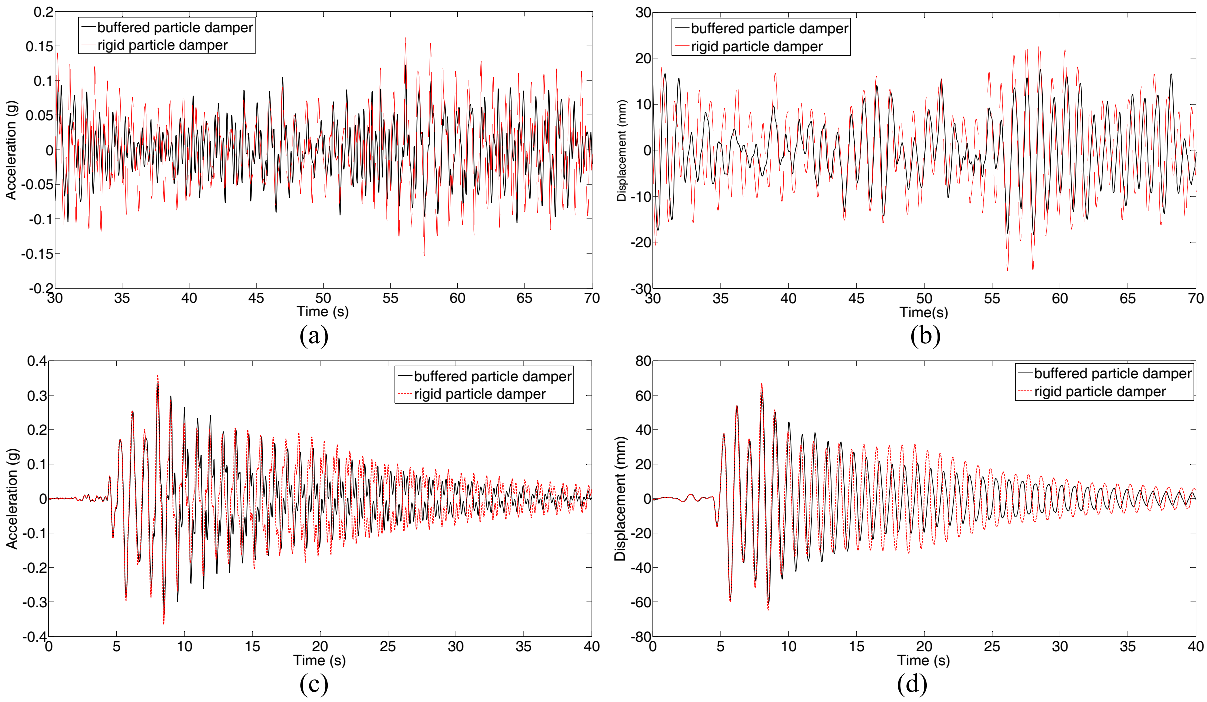


Figure 9. Comparison of response time histories at roof level of the test frame between buffered particle damper case and conventional rigid ones. The upper line (a, b) is under random excitation input, while the lower line (c, d) is under Kobe onsite seismic ground motion. (a, c) acceleration response; and (b, d) displacement response.

4. CONCLUSIONS

Although many researchers have presented the results of many experiments of particle dampers (including single unit impact dampers), the particle damper with buffer material is seldom investigated, especially for MDOF primary systems.

This paper investigated the performance of buffered particle dampers used for controlling the vibrations of MDOF structures under dynamic loads. It is found that, for a specific container geometry, a suitable mass ratio of particles results in more efficient momentum transfer from the primary system to the particles with better vibration attenuation effect, and that a buffered particle damper system has good performance in reducing the response of structures, both under random excitation and under onsite earthquake excitations, whereby the performance under random excitation is better. The reduced response includes acceleration, displacement, and r.m.s of the displacement, in which the r.m.s response reduction effect is the best. The buffered particle damper can effectively control the fundamental mode of the MDOF primary system; however, the control effect for higher modes is variable. From the shaking table test, it is also shown that the buffered particle damper has a better control effect compared to the conventional rigid ones. However, the precise reason for enhanced control effect needs further studied. It is found that properly designed buffered particle dampers can effectively attenuate the response of lightly-damped MDOF primary systems with a small weight penalty, under different dynamic loads (free vibration, random excitation, as well as real onsite earthquake excitations).

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REFERENCES

Araki, Y., Yuhki, Y., Yokomichi, I., Jinnouchi, Y. (1985) Impact damper with granular materials. *Bulletin of JSME,* **28:240,** 1121-1217.

Bapat, C. N., Sankar, S. (1985) Multiunit impact damper - reexamined. *Journal of Sound and Vibration,* **103:4,** 457-469.

Li, K., Darby, A.P. (2006a) An experimental investigation into the use of a buffered impact damper. *Journal of Sound and Vibration,* **291,** 844-860.

Li, K., Darby, A.P. (2006b) Experiments on the effect of an impact damper on a multiple-degree-of-freedom system. *Journal of Vibration and Control,* **12:5,** 445-464.

Li, K., Darby, A.P. (2008) A buffered impact damper for multi-degree-of-freedom structural control. *Earthquake Engineering & Structural Dynamics,* **37,** 1491-1510.

Lu, Z., Lu, X.L., Masri, S.F. (2010) Studies of the performance of particle dampers under dynamic loads. *Journal of Sound and Vibration,* **329:26,** 5415-5433.

Masri, S. F. (1969) Analytical and experimental studies of multiple-unit impact dampers. *Journal of the Acoustical Society of America,* **45:5,** 1111-1117.

Masri, S. F., Caughey, T.K. (1966) On the stability of the impact damper. *Journal of Applied Mechanics,* **33,** 586-592.

Panossian, H. V. (1991) Non-obstructive particle damping performance under compaction forces. *Machinery Dynamics and Element Vibrations,* **36,** 17-20.

Papalou, A., Masri, S.F. (1996) Performance of particle dampers under random excitation. *Journal of Vibration and Acoustics-Transactions of the ASME,* **118:4,** 614-621.

Popplewell, N., Semercigil, S. E. (1989) Performance of the bean bag impact damper for a sinusoidal external force. *Journal of Sound and Vibration,* **133:2,** 193-223.

Saeki, M. (2002) Impact damping with granular materials in a horizontally vibrating system. *Journal of Sound and Vibration,* **251:1,** 153-161.

Xu, Z. W., Wang, M.Y., Chen, T.N. (2005) Particle damping for passive vibration suppression: numerical modelling and experimental investigation. *Journal of Sound and Vibration,* **279:3-5,** 1097-1120.