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Seismic Performance of Demountable Architectural Partitions without Top Restraints

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ABSTRACT

In this study, the partition wall systems of interest are demountable: comprised of rigid panels clipped on steel light gage framing, glazed panels and doors to create an office space. Their bottom railings are attached to carpeted floors with adhesive carpet fastening strips. Shake table tests were conducted to study the overall performance of these demountable architectural partitions (DAPs) and verify their seismic capacities. Two specimens, with the basic plan geometry of a C-shape 3m x 4m x 3m and a height of 2.6 m, were tested at the Structures Laboratory of the École Polytechnique de Montréal, Canada. The inputs are unidirectional and representing the simulated top floor responses of two office building models that match the seismic hazard in Montréal and Vancouver. For comparison, two top floor responses to the Taiwan Chi-Chi Earthquake were also selected as the input. The testing results indicate that with the installation of good workmanship and proper joint detailing, the DAPs can perform with no or only minor damage in over 1.0g Canadian design earthquake inputs. However, they would not likely resist the near fault seismic events such as Chi-Chi, with large peak floor acceleration up to 3.0g and displacement up to 115mm.

***KEYWORDS*:** Operational and Functional Components (OFC), Non-structural Components (NC), Demountable Partitions, Architectural Partitions, Carpet Fastening Strip, Shake Table Test

1 Introduction

During earthquakes, damage to operational and functional components (OFCs) in buildings not only causes great economical loss, but it may also lead to injury or death of building occupants (Yao, *et al.*, 2008; Soong, *et al.*, 2000). Consequently, several national codes, standards, and official documents have stressed on enhancing the design of OFC anchorage/restraint to improve their seismic security.(Foo, *et al.*, 2007; ASCE, 2006; CSA, 2006; Fierro, *et al.*, 1994; ICC, 2006). Light partition wall systems, a most common architectural component in office buildings, are therefore suggested to be braced to the structural system or floor slab above them. However, direct attachment to the structural system would prevent the partition units to be easily re-arranged. In order to retain flexibility in architectural floor arrangements and minimize damage to interior finishing, demountable architectural partitions (DAPs) are commonly used to create closed work areas in office buildings in North America. Such partition systems, as shown in Fig. 1, are complex arrangements of vertical panels with glass or veneers, doors, posts and railings with metallic clipping and screw connectors, and are typically installed in areas equipped with suspended ceilings. Instead of being inter-story drift sensitive like conventional drywall partitions (Lee, *et al.*, 2007), this kind of partition wall system is considered as motion/acceleration sensitive. Nevertheless, there is very little published research on the seismic behaviour of DAPs. Only one previous study performed shake table tests on a bookcase - dry partition wall system and concluded that overturning failure of the DAP with heavy bookcase might occur when no transverse wall restraint is provided (Filiatrault, *et al.*, 2004b). However, the emphasis of the study was rather on the response of the bookcase units, and it was concluded that free-standing bookcase units performed better than those anchored to the wall partition, due to the pounding between the tops of unanchored bookcases and partition walls preventing resonance from occurring. In order to obtain a better understanding of the behaviour of DAPs under earthquakes, this paper attempts to study the load paths and overall performance of DAPs installed without top restraints by performing shake table tests.

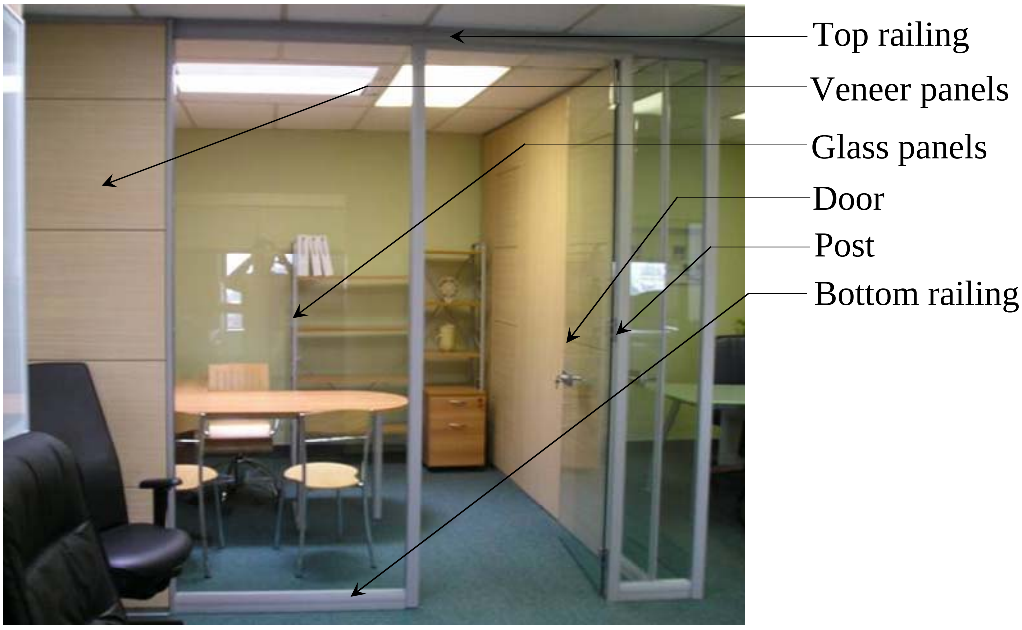


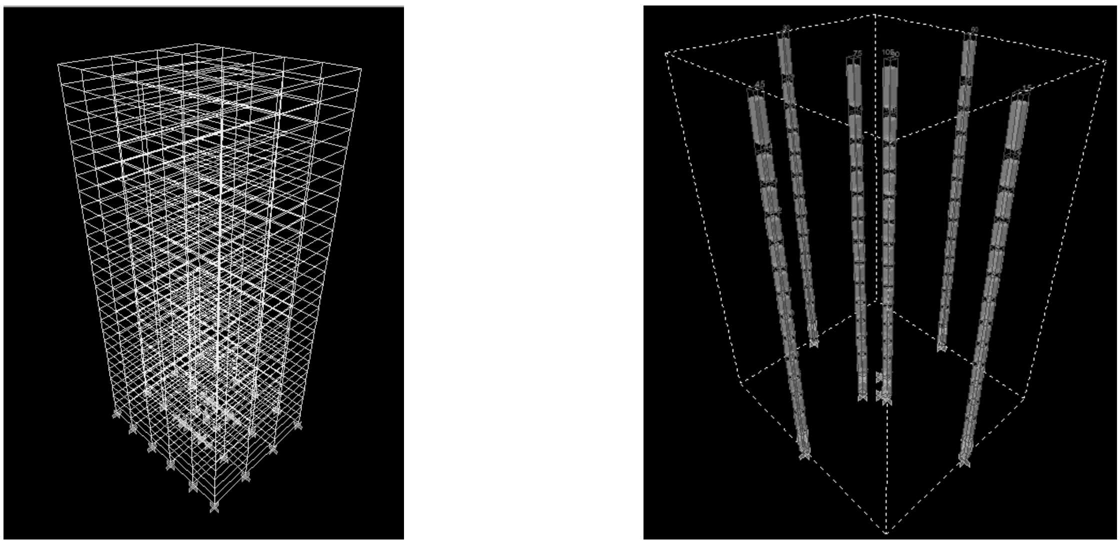
Figure 1 A typical work unit area delimited by a DAP system

The DAPs tested in this study are attached to carpeted floors with adhesive carpet fastening strips under a bottom railing while no mechanical restraint is provided to the ceiling above them. Two specimens are tested with the basic plan geometry of a C-shape 3m x 4m x 3m and a height of 2.6 m, which is typical of a practical single work unit area. The objectives of the tests are to study the seismic load paths and overall performance of the DAPs unrestrained at the top and verify their seismic capacities for use in office buildings. The shake table tests were conducted at the Structures Laboratory of the École Polytechnique de Montréal, Canada. Excitation inputs are unidirectional, perpendicular to the long side of the specimens: they were mainly the simulated top floor responses of two Montréal office building models (in SAP2000) (Computers and Structures, Inc., 2002) to base accelerograms that match the seismic hazard in Montréal and Vancouver, as prescribed by the uniform hazard design spectra of the 2005 National Building Code of Canada (NBCC) (Atkinson and Beresnev, 1998). For comparison, two top floor responses to the 1999 Chi-Chi Earthquake in Taiwan were also selected as input. The results presented include the seismic capacity and the failure modes of the DAPs and, in conclusion, the authors present some recommendations to improve the seismic performance of the DAPs.

2 Simulation of the Floor Input Seismic Events

Numerical models of two Montréal existing reinforced concrete shear wall (RCSW) buildings of 27-storey (Building I) and 14-storey (Building II) in height are simulated in SAP2000, as shown in Fig. 2.

In both models, the joints at the same floor elevation level are constrained to move together to simulate rigid floor diaphragms. The floor masses are lumped at the center of mass of each level. For Building I, all columns and beams have been simulated in the model, while only eight equivalent stick elements of side walls, columns and center core have been modeled in Building II. Although two different approaches were used to establish the models, they have been verified by the results obtained from ambient vibration tests (AVT) (Gilles and McClure, 2008). Table 1 shows the agreement between the SAP2000 analytical and AVT results, confirming the reliability of the two simulation models.



(a) Building I, 27-storey height (b) Building II, 14-storey height

Figure 2 Building models in SAP2000

Table 1 Fundamental periods comparison between the AVT and SAP2000 analytical results

Building	**T_{AVT} (s)**		**$T_{SAP2000}$ (s)**	
	Mode 1	**Mode 2**	**Mode 1**	**Mode 2**
I	2.17	1.98	2.17	1.99
II	0.71	0.68	0.71	0.68

Several seismic events compatible with the uniform hazard spectra of NBCC 2005 (Atkinson and Beresnev, 1998) were selected as the input to the building models in SAP2000, and their top floor peak acceleration responses are listed in Table 2 as the Target Peak values. These values show that with the same exceedance probability in 50 years, the western Canadian (Vancouver) seismic events have higher intensity than eastern Canadian (Montréal). Besides, the floor acceleration responses of Building II are larger than those of Building I under the same excitation level, because the taller Building I has a longer fundamental period. However, comparing their FFT spectra, as shown in Fig. 3, Building I has more abundant frequency components than Building II, and the responses of the same building to different seismic events have similar distribution of frequencies. Moreover, it is worthy of note that Building I floor responses show a peak at the frequency component of 4.8Hz, which is close to the natural frequency of the specimens tested in this study. This leads to a larger acceleration amplification of the DAP specimens when subjected to the floor input of Building I, as will be shown in the experimental study section.

Table 2 Seismic events input to the shake table

Seismic event	Target Peak Floor Acceleration (g)	Achieved Peak in Shake Table Testing (g)	
		DAP	DAPR
I_M10%_E70_300*	0.11	0.15	NA
II_M10%_E70_200	0.26	0.35	NA
I_V10%_W72_100	0.35	0.33	0.33
II_ChiChi_T76_50	0.40	0.62	0.60
II_V10%_W60_50	0.55	NA	0.90
I_M2%_E70_100	0.53	NA	0.69
I_V2%_W72_70	0.67	NA	0.74
II_M2%_E70_70	0.74	NA	1.23
II_V2%_W65_50	1.04	NA	1.45
I_ChiChi_T76_15	1.38	NA	3.19

*Notes to Table 2:

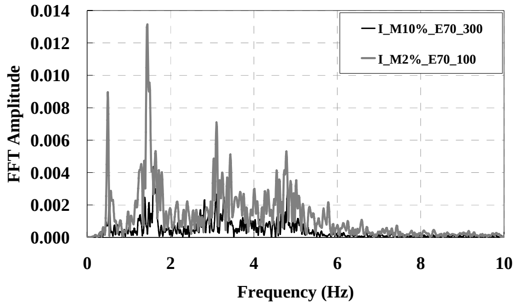
I_M10%_E70_300: Top floor acceleration response of Building I under Eastern earthquake input with magnitude 7.0 at 300 km from the epicenter.

I and II indicate top floor response of Building I and Building II, respectively.

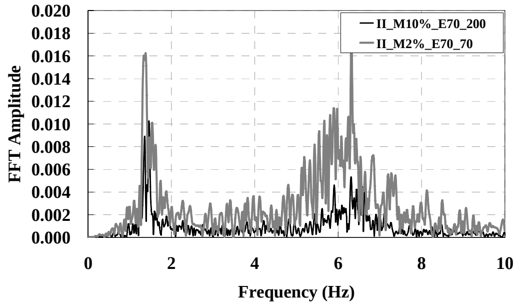
M: Seismic event in Montréal; V: Seismic event in Vancouver

%: Percentage probability of exceedance in 50 years

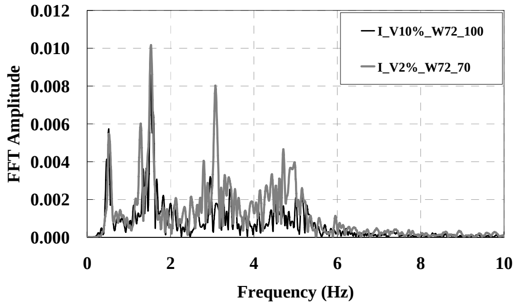
NA: Not available



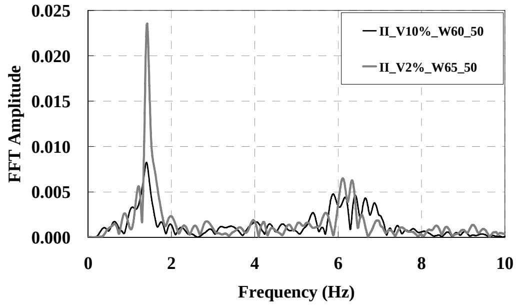
(a) Building I responses to Montréal seismic events



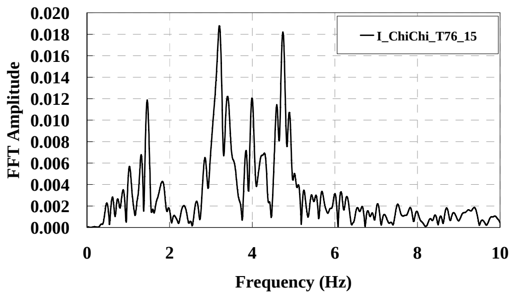
(b) Building II responses to Montréal seismic events



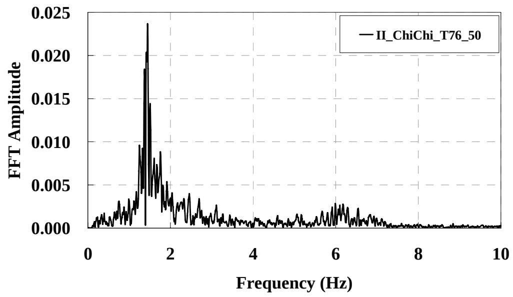
(c) Building I responses to Vancouver seismic events



(d) Building II responses to Vancouver seismic events



(e) Building I responses to ChiChi earthquake



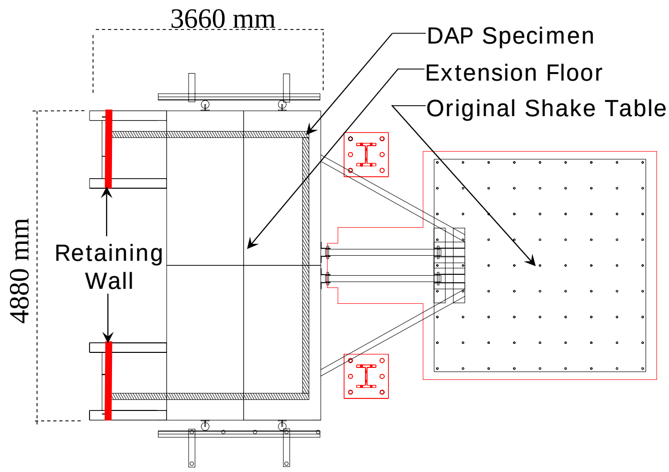
(f) Building II responses to ChiChi earthquake

Figure 3 The acceleration FFT spectra of the top floor responses of two building models to the seismic events in different areas

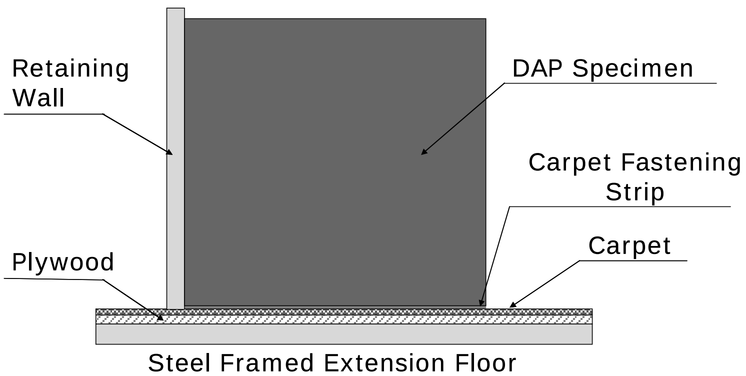
3 The Experimental Study

3.1 Testing setup

The tests were performed using the 3.4m x 3.4m uni-directional shake table of the Structures Laboratory of the École Polytechnique de Montréal, Canada. The peak-to-peak stroke of the shake table is 300 mm, and its operating frequency range is up to 50Hz. The capacity of the specimen payload and driving actuator is 135kN and 250kN, respectively. Due to the table dimension limitation, a 4880mm x 3660mm steel framed extension floor was constructed to carry the 3m x 4m x 3m DAP specimens, as shown in Fig. 4(a). In practical applications, the DAPs are usually installed with attachment to the existing drywall partitions or to the structural walls (masonry or concrete). Therefore two 0.85m wide x 2.75 m high retaining wall strips were built on the extension floor to restrain the side panels of the DAP specimens. Their plan and lateral views are shown in Figs. 4(a) and 4(b), respectively.



(a) Plan view

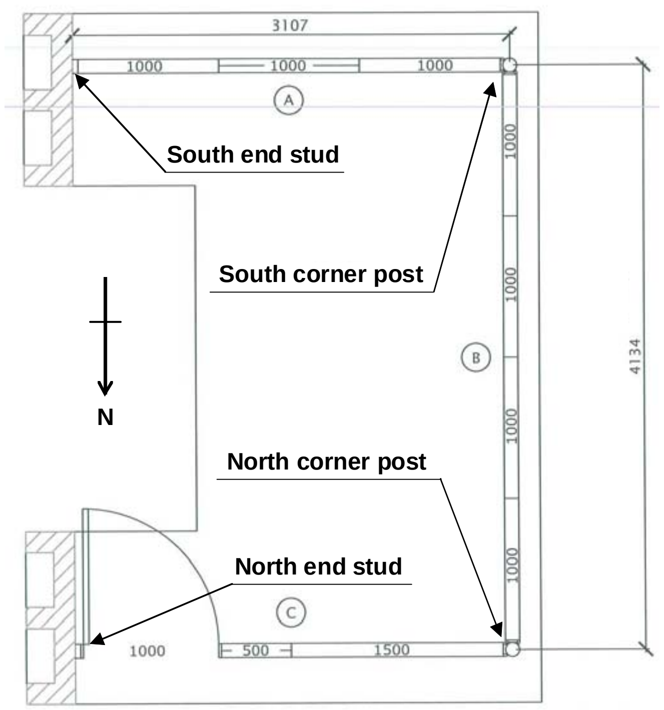


(b) Lateral view

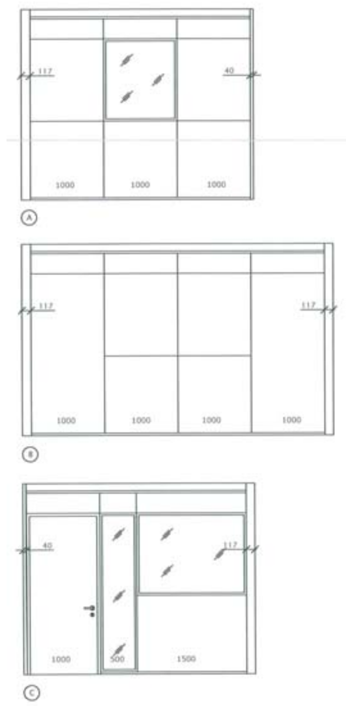
Figure 4 Shake table testing setup of the DAP specimen

3.2 Tested Specimens

Two specimens, DAP and DAPR, were built in a C-shape 3m x 4m x 3m plan and a height of 2.6 m; these dimensions represent a typical single work unit area. Their layouts are identical in plan and elevation views, as shown in Fig. 5, and Fig. 6 shows the picture of the installed DAP specimen. The joint details of specimens DAP and DAPR differ to compare the effectiveness of some joint reinforcements for seismic loadings. Fig. 7 shows the joint reinforcements installed in the DAPR specimen. Fig. 7(a) shows the toggle bolts used to fasten the end stud to the retaining wall. Figs. 7(b) and 7(c) show the stud brackets to integrate the studs with the top and bottom railings, thus providing continuity of the side wall framework and improving the robustness of the DAP structure.



(a) Plan view



(b) Elevation

Figure 5 DAP test specimen (A and C are defined as the side walls, and B is the front wall)

Figure 6　Installed DAP specimen

(a) Toggle bolts　(b) Top stud bracket　(c) Bottom stud bracket

Figure 7　Joint reinforcement details in DAPR

The special features of the two specimens tested are summarized in Table 3, where DAP and DAPR identify the specimens before and after joint reinforcement, respectively. The door of the specimen was located at the north side wall, as shown in Fig. 5(a) and Fig. 6, and the stud brackets were to fasten the studs of the side wall frames to the bottom and top railings. The most different features of the two specimens are the attachment mode of the end studs to the retaining walls: for DAP, two-sided tape strips were applied along the entire length of the studs, while three toggle bolts were installed at the bottom, mid-height, and top of the end-stud/retaining wall joint for DAPR.

Table 3 Features of the DAP test specimens

Specimen	Door at side wall	Two-sided tape	Toggle bolts	Stud brackets
DAP	Y	Y	N	N
DAPR	Y	N	Y	Y

Note:

Y: the specimen is constructed with the feature.

N: the specimen is constructed without the feature.

3.3 Instrumentation

The instrumentation used in the tests is shown schematically in Fig. 8. For the extension floor, four accelerometers and one displacement meter were used to measure the motions of the floor as well as the retaining walls in the main shaking direction. For the DAP specimens, five accelerometers and five displacement meters were used to measure the motion parallel to the input excitation, and two displacement meters were used to measure the motion of the front wall perpendicular to the shaking direction. The arrows shown in Fig. 8 indicate the measuring direction of the instrumentation sensors.

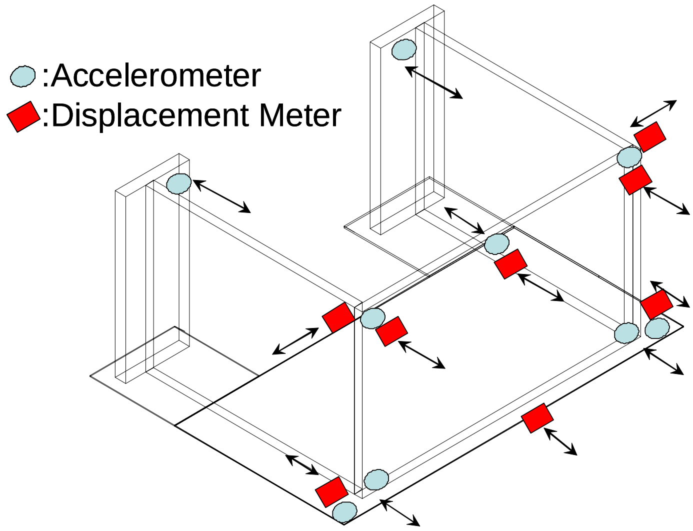
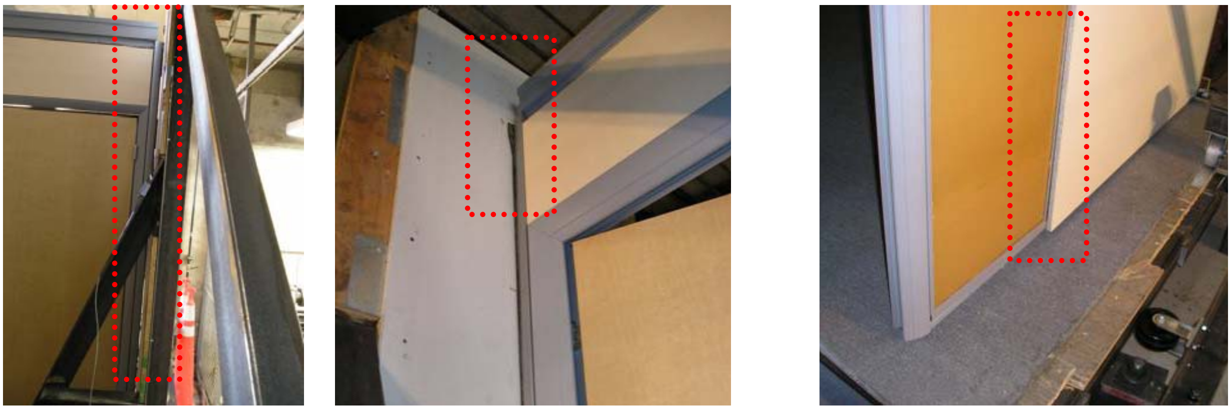


Figure 8 The testing instrumentation

3.4 Test results

3.4.1 Specimen DAP

After the installation of the specimen, small gaps were observed between the end stud and the retaining wall of the north side, as shown in Fig. 9(a). It reflected that in practical situations, the two-sided tape strips would not be seismically secure since normal construction tolerances make it difficult to provide continuous contact between the end stud and the retaining wall. By performing a free vibration test before any seismic input was applied, the initial natural frequency of the specimen in the shaking direction was found to be 4.0 Hz. At the I_V10%_W72_100 input level (the shake table achieved 0.33g), the specimen showed slight damage. The end stud detached from the retaining wall and a panel on the north side wall moved slightly, as shown in Figs. 9(b) and 9(c), respectively. However, the whole DAP system remained functional. The front wall showed no damage. After repair, the test kept proceeding. At II_ChiChi_T76_50 input level (the shake table achieved 0.62g), the specimen collapsed, as shown in Fig. 9(d). The end studs completely detached from the retaining walls and the panels showed large inclinations, while the studs of the side walls came off the top and the bottom railings, as shown in Figs. 9(e) and 9(f), leading to the collapse of the specimen and the end of this testing series. However, no sliding of the bottom railing with carpet fastening strips has been observed.



(a) (b) (c)

(d) (e) (f)

Figure 9 Views of tested specimen DAP

From this test series, we concluded that the seismic capacity of the DAP specimen was less than 0.62g of floor acceleration input. Considering its unsafe failure modes, some joint reinforcements, as aforementioned in Fig. 7, have been provided to increase the fastening strength of the end studs to the horizontal railings and the robustness of the entire wall frame structure.

3.4.2 Specimen DAPR

Before proceeding with the shake table tests, the natural frequency of the DAPR specimen in the shaking direction was measured at 4.5Hz (DAP was at 4.0 Hz), showing the effectiveness of the joint reinforcements provided in improving the stiffness of the specimen. Consequently, as shown in Fig. 10(a), no major damage to DAPR was observed after being subjected to the selected Canadian floor seismic events in Table 2, from I_V10%_W72_100 to II_V2%_W65_50, with maximum floor peak acceleration up to 1.45g. The specimen remained functional during the test and only some minor damage, such as the toggle bolts loosening or failures of some screws were observed. The specimen eventually collapsed, as shown in Fig. 10(b), when the input level went up to 3.19g, generated by the near fault event of I_ChiChi_T76_15. During this test input, damage occurred in the front wall, as shown in Fig. 10(c), while the framework of side walls remained visually undamaged. From the test results, it is concluded that the DAPR system can maintain its functionality during Canadian design earthquakes when joint reinforcements are provided to ensure framing continuity; however, it might not resist strong near-fault earthquakes.

(a) (b) (c)

Figure 10 Views of tested specimen DAPR

4 Discussion

Since the non-reinforced DAP specimen could sustain only the first four inputs listed in Table 2, it was found inadequate, and the following discussion pertains only to the response of DAPR. In this test series, the accelerations at the top of the front wall were amplified more when subjected to the Building I floor seismic events than subjected to the Building II floor events, as shown in Fig. 11. This is explained by the frequency coincidence between the 4.5Hz fundamental frequency of the DAPR specimen and the frequency content of the inputs of Building I at approximately 4.8Hz. Comparing the measured horizontal displacements of the front wall in Fig. 12, it is seen that the Building I inputs also caused larger displacements than did Building II inputs. The displacements of the north corner were larger than the south corner, which was caused by the loosening of the toggle bolts on the north end studs during the test.

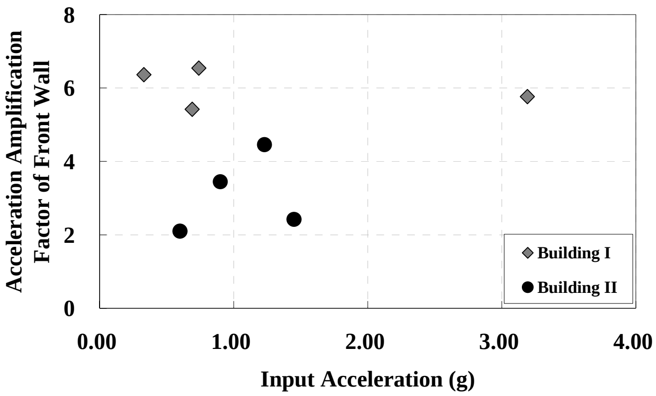
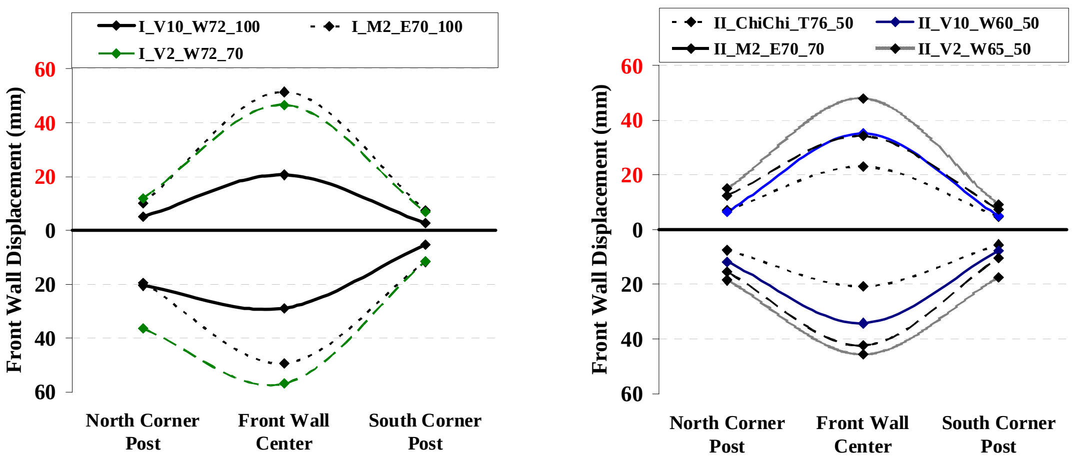


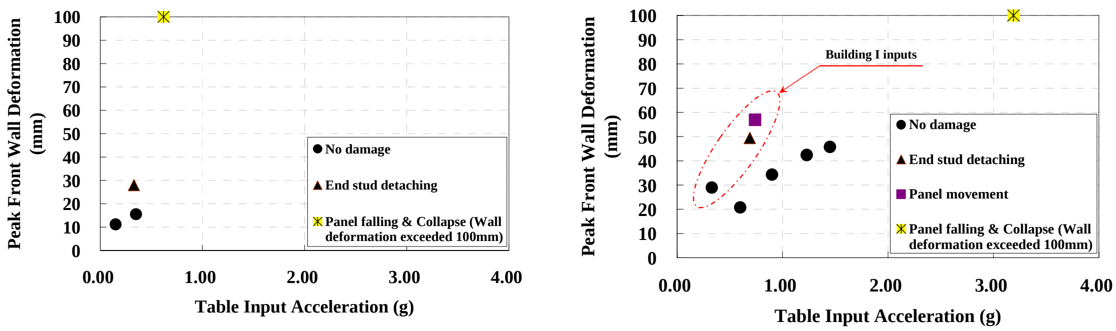
Figure 11 A comparison of the response acceleration amplifications of DAPR specimen under excitations from different floor responses



(a) Responses to Building I input (b) Responses to Building II input

Figure 12 Response displacements of DAPR front wall

Fig. 13 shows a schematic plot of the damage severity of the specimens during the tests with different inputs. The effectiveness of the joint reinforcement in increasing the seismic resistance of the DAP system is obvious. The failure mode sequence started with the end stud detaching from the retaining wall, followed by panel rocking and out-of-plane movement, then the panel falling, and finally either the side wall or the front wall collapse, leading to the complete failure of the specimen. Moreover, from Fig. 13(b), it is seen that the Building I inputs caused lager front wall deformation, leading to more obvious damage to the DAPR specimen than did the Building II inputs. Again, it is explained by the coincidence between the frequency content of the Building I inputs and the fundamental frequency of the DAP specimen. Hence, it revealed that the frequency component of the input wave also plays an important role in affecting the performance of the DAP specimen, due to the resonance may occur. Overall, it was observed that the DAPR retained its functionality during the shaking events corresponding to Canadian design earthquakes, and it didn't collapse until subjected to the I_ChiChi_T76_15 near-fault floor seismic events.



(a) Specimen DAP (b) Specimen DAPR

Figure 13 The damage severity of the specimens during the tests with different inputs

5 Conclusions

In this study, two demountable architectural partition specimens unrestrained at the top were constructed and tested on a shake table extension floor. Several Canadian design earthquakes, matching the NBCC 2005 seismic hazard in Montréal and Vancouver, were considered as the inputs representing the east and west Canadian seismic events, respectively. Two records from the 1999 ChiChi Earthquake in Taiwan, including one near-fault event, were also considered. In the experimental study, the input excitation was parallel to the side walls, and no additional mass was attached to the specimens; i.e., they carried only their self-weight. The retaining walls on the testing platform proved capable to restrain the partition wall specimens until the specimen collapse. After the test series have been completed, the analysis of the results has yielded the following main findings:

(1) The collapse seismic capacity of the DAP specimens tested in this study was 1.45g and 0.33g with and without joint reinforcement, respectively.
(2) No visible sliding of the bottom railings with the carpet fastening strips has occurred during the tests.
(3) The failure mode sequence of the DAP system is the end stud detaching from the retaining wall first, followed by rocking and panel movement, then the panel falling, and finally either the side wall or the front wall collapse, leading to the complete failure of the specimen.
(4) The partition wall system without top restraint can perform well in moderate to large Canadian design earthquakes provided the installation and the joint details are of good workmanship. However, it would not likely resist severe near-fault seismic events.

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拆卸式輕隔間牆之受震行為研究

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摘 要

本研究主要以足尺之振動台試驗來探討可拆卸式輕隔間牆(DAP)之受震行為。DAP 在北美地區被廣泛地應用於辦公室空間，因其具有可拆卸式特性，故能在不破壞室內裝修之前提下，滿足辦公室因功能變更而變動隔間的需求，並且可以重複被使用。DAP 之結構系統類似常見之輕隔間牆，主要由 C 型冷軋鋼構成，藉由調整面板裝修材、玻璃以及門板之幾何配置，可圍封成各種用途之辦公室空間。特別的是，其底部僅藉由地毯粘黏貼條(魔鬼粘)與地毯固定，而頂部則無束制，故具有容易拆卸且重複使用之特性。研究過程利用位於 École Polytechnique de Montréal 結構實驗室之振動台，並參考一般辦公室空間尺寸，規劃兩組 3m x 4m x 3m ㄇ型平面、高 2.6 m 之 DAP 試體，探討其耐震能力及地震力傳遞路徑。輸入地震波為：參考 2005 年加拿大耐震建築規範(NBCC2005)，選取數筆模擬加國東、西兩岸震區之地震資料以及兩筆取自台灣 921 集集地震之震波，並將其輸入兩棟建築物之 SAP2000 模型中(分別為 14 層樓及 27 層樓)，得到樓板加速度反應後，單向輸入振動台，進行測試。試驗結果顯示，藉由適當之接頭細部補強以及確實施工，DAP 試體可承受超過 1.0g 之加拿大設計樓板震波，而不發生破壞。然而，由於取自 921 集集地震之近域樓板震波同時具有大加速度(3.0g)且大位移(115mm)之特性，造成 DAP 試體在此類具有高破壞力震波之作用下，於試驗中發生嚴重破壞並傾倒毀損。因此，在近斷層強震區，並不建議採用類似 DAP 系統之輕隔間牆。

關鍵字：建築功能性設施，非結構物，活動式隔間牆，可拆卸式隔間牆，輕隔間牆，地毯粘黏貼條，魔鬼粘