A Study of Seismic Strengthening Behavior for The Dry-wall With Mortar-filling System in Taiwan

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SUMMARY:
The partition walls with light-gauge steel framing are commonly used in Taiwan. In addition to the early dry-wall (DW) system, the dry-wall with mortar-filling (DMF) system has been developed in recent years in order to provide more soundproofing, safety from theft, and other purposes. Although the DMF is more appropriate for general living requirements, there are few studies about the seismic behavior of this system under earthquakes.
This paper investigates the seismic behavior of the DMF system and attempts to improve it by providing retrofit details via experiments. Full-scale specimens are constructed to represent the typical practice of DMF in Taiwan. The loading is applied by using an actuator and the failure mode of specimens are recorded during each drift level. Details are given about the damage of the specimens and the effect of the retrofit design.

Keywords: Partition wall, non-structural wall, dry-wall with mortar-filling system, story-drift,

1. INTRODUCTION

The partition walls in a building are important non-structural components, of which the functions may include partitioning the space, sound-proofing, preventing burglary and securing privacy. In 1980's, the dry-wall (DW) system was first introduced from the USA. This system has the advantage of lightweight structures, ensured quality, and accelerated construction. Due to these advantages, it was commonly used in the construction of commercial, hospital and residential buildings in which the traditional RC and brick partition walls are replaced. However, most of the users still think that partition walls should convey solidity when knocked, and that DW systems still have problems, such as inadequate strength to hang objects, poor soundproofing, and vulnerable to burglary. To satisfy the needs of the users in Taiwan, the dry-wall with light-weight mortar-filling (DMF) system was developed within the last decade. Taiwan is distinctive in using this technique.
Although the DMF system is more appropriate for general living requirements, the seismic behaviors and sturdiness of this system under earthquakes have not been extensively studied. Some post-earthquake survey reports in Taiwan revealed that the building structures could resist small to moderate seismic events without damage, but its DMF could have been easily damaged. Not only may Damages include the fracture of water pipes to cause flooding in a building, but they may also cause out-of-plane collapse and threaten lives.
This paper aims at the studying on the inter-story drift performances of the DMF system. The results will be analyzed and discussed for future design specifications in Taiwan.

2. THE DRY-WALL WITH MOTAR FILLING SYSTEM IN TAIWAN

The construction of DMF system assimilates the grouting formwork of RC walls and is a special technique developed due to the living habits of Taiwanese people. This system is similar to the DW system, since they only differ in interior materials; while the former is filled with lightweight mortar, the latter mainly uses insulation material such as TFRB or FR4.

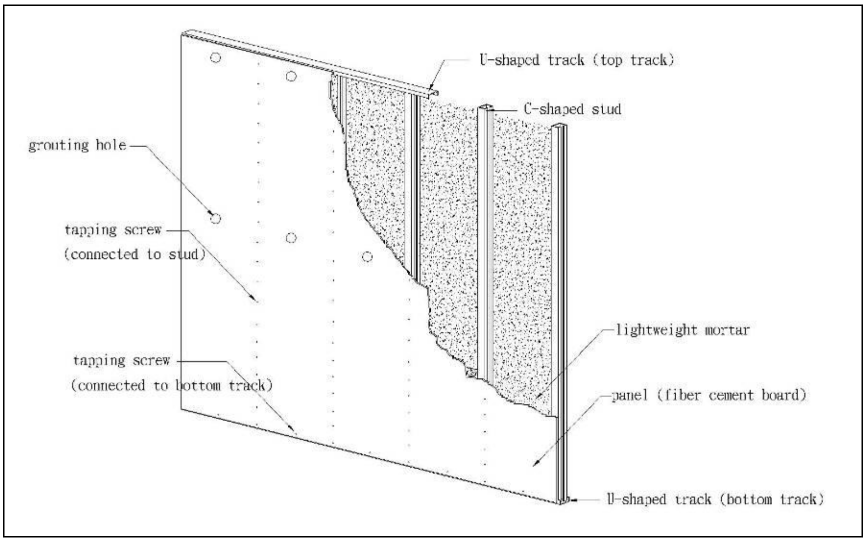


Figure 1. Typical construction of the DMF system

Figure 1 shows the typical DMF system in Taiwan. The DMF system consists of horizontally laid out U-shaped tracks and vertical C-shaped studs as its main frames. The U-shaped tracks act as the top and bottom tracks, and they are fixed on the structural components (slabs, beams) with powder-driven nails. The distance between each powder-driven nail is 60 cm. The nail holes are staggered and are not in-line. The studs are cut into an appropriate length according to the height of the wall and then are fit snug-tight in the U-shaped tracks. For the DMF systems, because of the heavy mass of the partition walls and the pressure during the process of grouting, the stud spaces are closer with a general distance between each stud ranging from 24-30 cm. If the end studs (see Figure 2.a) of the partition walls come into contact with the structural components (columns, shearwalls), they also have to be fixed on the structural components with powder-driven nails, like the U-shaped tracks. After the frame is installed, the surface panels (fiber cement boards) are then fastened to studs as well as the bottom track with tapping screws, whose spacing is 10 cm. There should be a 1- cm clearance kept between the panels and the structure members. At last, holes are dug on the surface panels and mortar enters from them. The lightweight mortar for grouting is composed of cement, sand and Styrofoam pellets, of which the percentage is 1:2:4.

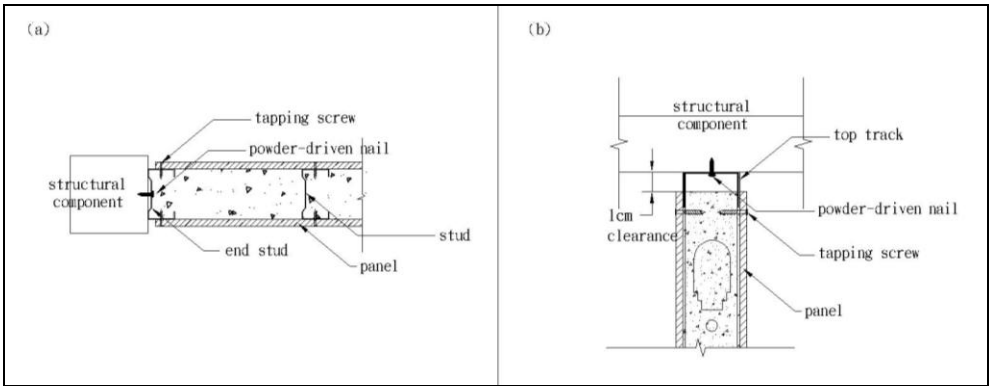


Figure 2. Details of the end stud (a) and the top track (b)

To prevent the DMF from carrying vertical dead loads from the upper structures, the studs should not be connected directly with the top track web and the distance between them is 1-1.5 cm. Similarly, there should be a 1 cm clearance between the mortar and the top track web during grouting (Figure 2.b).

The major characteristics of the DMF system are as follows:

1. Thickness and weight: The thickness of the DMF system is about 7.5-9 cm. The weight is 60~160kgf/m².
2. Construction: The construction goes fast, and on average a worker per day can accomplish 12 m² of the wall.
3. Fireproofing, moisture-proofing and sound-proofing: The fireproofing capacity can lasts for 1-2 hours, and the other two functions are also satisfactory.
4. Characteristics of object-hanging and the solid echo: As the walls are solid due to grouting, the characteristics of object-hanging and the solid echo are similar to those of RC walls.
5. Guard against theft: It works better than the DW system and this is one of the reasons why the DMF system is commonly used in residential buildings in recent years.

3. EXPERIMENTAL PROGRAM

Full-scale specimens of the DMF system were constructed in this study. Since the partition walls are considered displacement sensitive, the experimental loading steps were displacement controlled by an actuator. The specimens were tested with lateral cyclic loading, and the damage patterns were investigated and recorded during each drift level. This study included two groups of experiments. The first group was to study the seismic performances of the current practice in Taiwan. The second group experimented on retrofitted tests of partition walls to minimize the possibility of damage during earthquakes.

A steel test frame shown in Figure 3, composed of one 1000 ×450 mm H section steel (base) and three 400 ×200 mm H section steels served as beam and column, was built. The joints of the frame were designed as hinges. Inside the frame were 100 ×100 mm steel tubes, which represented the building structures and allowed the specimens to be constructed on the frame. The actuator was connected to the H section beam, and the cyclic loading was applied from the actuator through the frame to the specimens to simulate the partition walls under earthquakes.

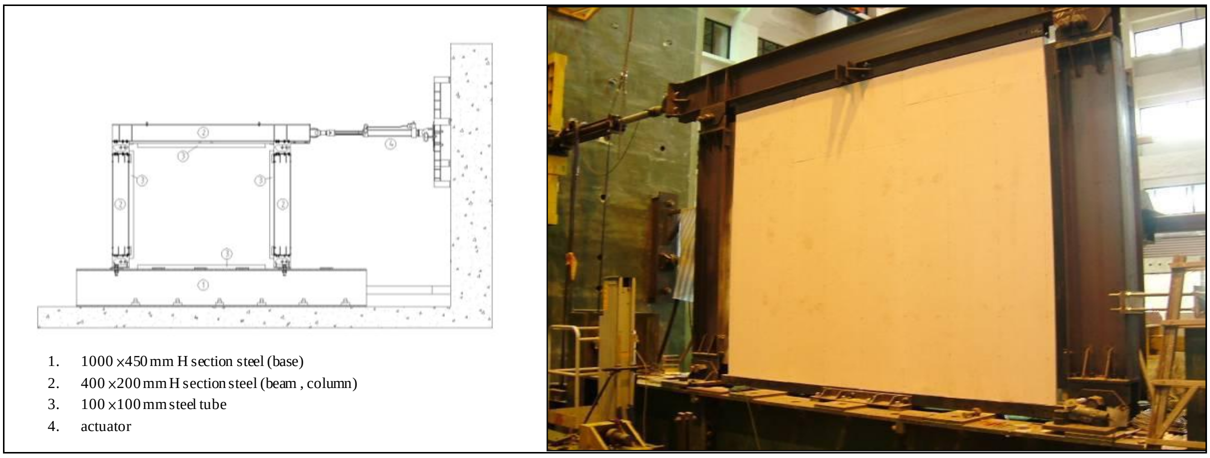


Figure 3. Details of the test frame

The specimens were tested by an experimental program (FEMA-461), which provided recommended resting, loading history, and documentation procedures for the investigation of the seismic performance of the partition walls. The actuator was displacement controlled with the velocity of 1.38mm/sec, and 12 different drift levels were tested in sequence (0.15％, 0.21％, 0.29％, 0.41％, 0.57％, 0.8％, 1.1％, 1.5％, 2.1％, 3.0％, 4.0％ and 5.0％). The damage conditions were recorded during each level until the specimens collapsed seriously or were about to overturn.

A total of eight specimens (W1, W2, …, W8) were tested in this study. Four single specimens were subjected to the in-plane direction loading and out-of-plane loading respectively, and the other 4 specimens were combinations of both in-plane and out-of-plane walls in T and L shape. The out-of-plane specimens were 2720 mm high and 1400 mm long, while the in-plane specimens were 2720 mm high and 3250 mm long. About the L shape and T shape specimens, the out-of-plane walls were 800 ×2720 mm for the former and 1500 ×2720 mm for the latter, and the in-plane walls were 800 ×2250 mm for both. The thickness of the walls was 77 mm including two 6 mm surface panels and the interior mortar. Each specimen had PVC water pipes inside it.

Both W1 and W2 specimens followed the typical DMF system construction practices in Taiwan, and W1 specimen was tested out-of plane while W2 was tested in-plane. The tracks and the end studs were fixed to the steel tubes and the other studs were installed with approximately 30 cm spacing. The panels were fastened to all studs and the bottom track, and a 1 cm clearance was left between the panels and the steel tubes. W3 and W4 specimens were combinations of two perpendicular walls, and the types of W3 and W4 were T shape wall and L shape wall. Figure 4 showed the details of the connections.

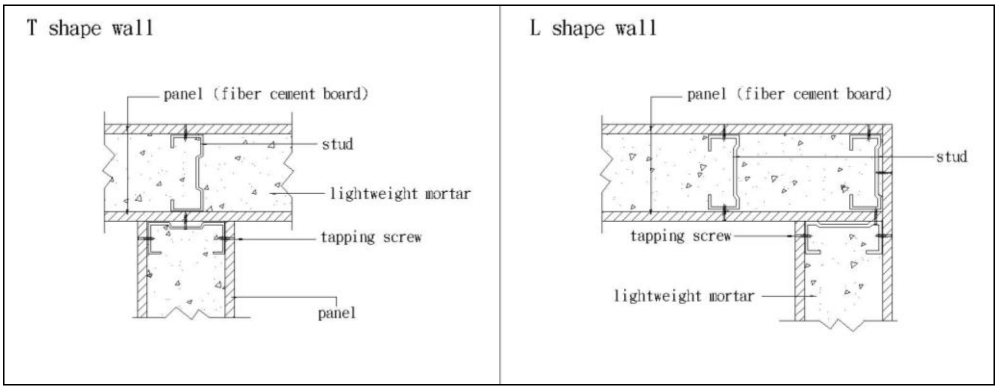


Figure 4. Detailed connections of the T shape wall and the L shape wall

W5 and W6 specimens were the comparison groups with W2, and they were also subjected to in-plane loading. W5 was similar to W2 but changed the distance between each powder-driven nail from 60 cm to 30 cm. The end studs in W2 specimen were fastened both to the steel tubes and the panels; nevertheless, the end studs in W6 were only fastened to the steel tubes. Additional studs shown in Figure 5 were installed near the end studs and the panels were fastened on them. Between the end stud and the additional stud TFRB was filled in order to satisfy the fireproofing capacity. In addition, the panels and the bottom track were fixed together in W2 but separated in W6, and a PVC water pipe was wrapped by ceramic fiber carton in W6 specimen (see Figure 6).

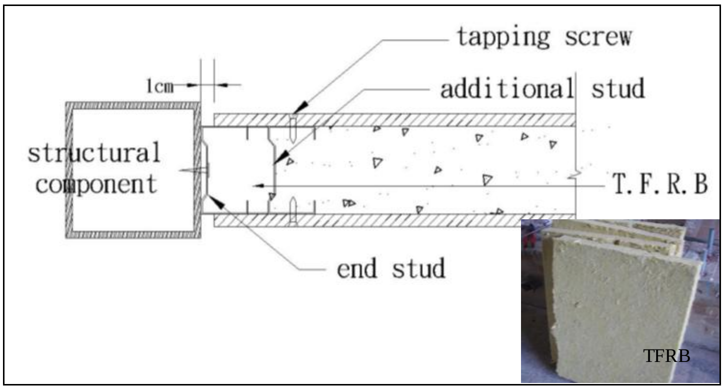


Figure 5. Details of the W6 specimen

Figure 6. Water pipe wrapped by ceramic fiber carton

W7 and W8 specimens were T shape walls and the construction was similar to W6. In comparison with W3 specimen, which had panels of the in-plane wall directly connected to the out-of-plane wall, a 1cm spacing was left in W7 and W8 specimens (see Figure 7). W8 was almost the same as W7 but an additional stopper was placed at the top junction of the two perpendicular walls, shown in Figure 8.

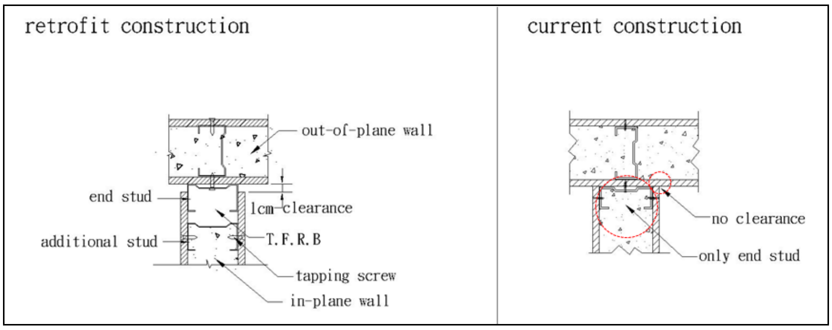


Figure 7. Retrofit construction in T shape wall

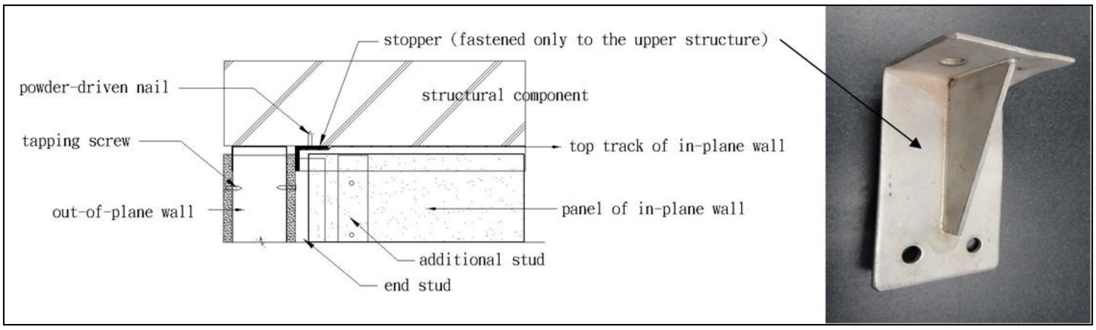
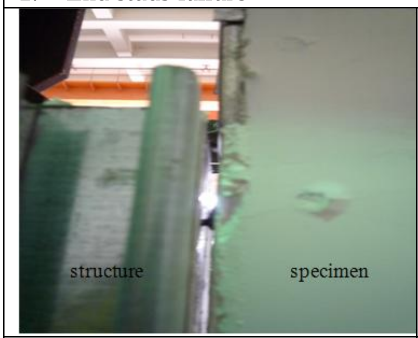
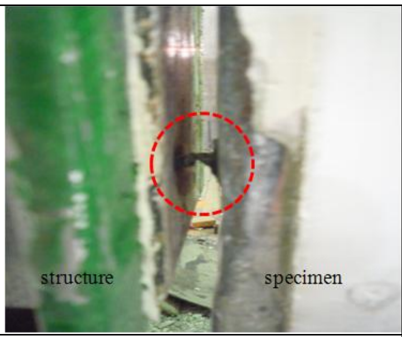
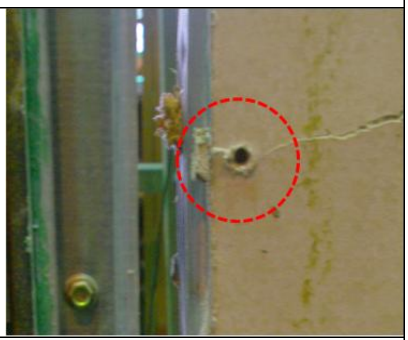


Figure 8. Details at the top junction of two walls in W8 specimen

4. EXPERIMENTAL PROGRAM

Some typical damage patterns of the current DMF system have been revealed in the first group of the experiments. Failure happened mainly on the end studs, bottom tracks, panels, the water piping and the junction of the two walls. Since the end studs were directly fastened to the structures with powder-driven nails, the inter-story drift from the structures was firstly transferred to the interfaces and then to the specimens. Therefore the initial visible damage to the specimens was the separation of the end studs from the structure components. The end studs were also fastened to the panels with tapping screws, and the screws were embedded next. With increasing drift levels, the specimens were uplifted and the bottom tracks were pulled out from the structures. Slight panel damage appeared generally at the top corners and the damage progressed throughout testing. For T shape and L shape specimens, the connections between the two walls were easily damaged and the fracture of the water pipe was observed in all specimens at large drifts. Table 1 listed the typical damage patterns observed from the experiments.

Table 1. The typical damage patterns observed from the experiments.

1. End studs failure		
		
Separation between the end studs and the structure components.	Most of the nail heads were pulled out from the end studs and the nails were also damaged.	Screws fastened to the panels were embedded.

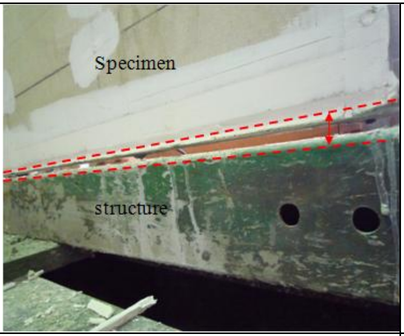
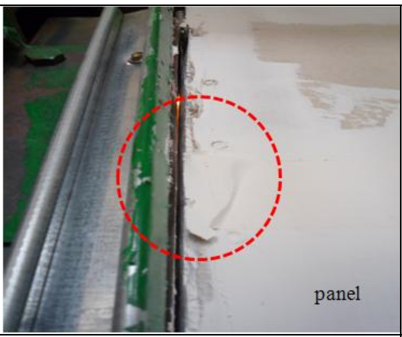
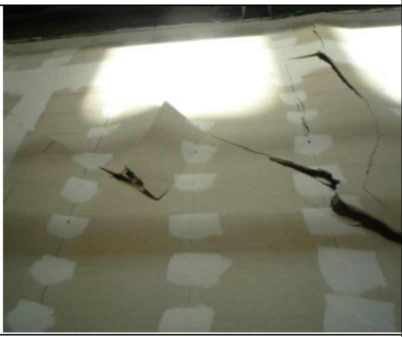
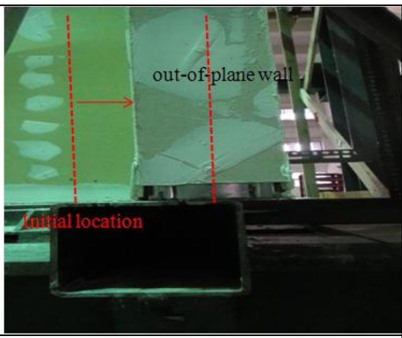
2. Bottom tracks failure		
		
The specimens were uplifted from the structures.	Most of the fasteners were threaded through the bottom tracks.	Some nails were directly pulled out from the structures.
3. Panels failure		4. Water pipe failure
		
Local cracking of the panels.	Widespread collapse of the panels.	Shear failure of the water pipe.
5. Junction failure of the two walls		
		
Separation at the junction of the two walls.	The fasteners of the bottom tracks were all damaged and the out-of-plane walls moved.	The top track flanges were bended and the out-of-plane walls leaned.

Table 2 showed the earlier stage of different damage patterns in the first group of experiments. From the results, damage to the W1 specimen was very limited and the specimen remained almost intact. This condition revealed that the out-of-plane loading was harmless to the partition walls. Compared with W1, obvious and severe damage occurred in the W2 specimen, which was subjected to the in-plane loading. The first failure sign at a drift ratio of 0.8% resulted in separation of the end studs from the structure components. Subsequently, separation zone increased throughout the testing and isolated the DMF from the structures. At a drift ratio of 1.5%, separation spread apparently along the interfaces and most of the nail heads were pulled out from the end studs. Other than the stud separation, screw embedding was observed at a drift ratio of 1.5%, and the screws were pulled into the fiber cement boards. However, this failure mode was not severe and could be repaired with mud and paint. Failure of the track fasteners occurred only at the bottom. In comparison with the top track, the bottom track was attached to the surface panel but the top track wasn't. While the loading made the specimen rotate and slide, the powder-driven nails at the bottom track were engaged in uplift and shear. The fastener failure appeared to have occurred in two primary modes: the fasteners were threaded through the bottom track and, less frequently, they were tilted. These failure modes were observed at a drift ratio of 1.5%.

The 1 cm clearance between the panels and the structure components was lost as testing progressed. Subsequently, at large drifts the panels came into contact with the structures and were under compression and shear. The panels sustained localized cracking at the top corners of the walls at a drift ratio of 1.1%, and widespread collapse appeared at a drift ratio of 2.1%. At the same drift level, the water piping experienced shear failure.

For W3 and W4 specimens, the damage progression of the in-plane walls resembled that in W2. But another significant failure occurred at the out-of-plane walls. As the specimens were cycled back and forth, the interaction between in-plane and out-of-plane walls was damaged most severely at the connections. In addition to the separation appeared at the junction, the top track flanges were bended and no longer restrict the out-of-plane walls. The separation was visible at a drift ratio of 0.8% and was totally separated at a 1.5% drift ratio. At a drift ratio of 3.0%, the out-of-plane walls leaned seriously and the testing stopped in fear of collapse.

Table 2. Damage progression of W1, W2, W3 and W4 specimens

Specimen		W1	W2	W3	W4
Damage pattern		inter-story drift ratio			
End Studs failure	Visible separation appeared between the end studs and the structure components.	none	0.8%	0.8%	0.8%
	Some nail heads were pulled out from the end studs.	none	1.1%	1.1%	1.1%
	The screws fastened the panels and the end studs embedded.	none	1.5%	1.1%	1.5%
	Most of the nail heads were pulled out from the end studs and the separation spread apparently.	none	1.5%	1.5%	1.5%
Bottom tracks failure	Visible separation appeared between the bottom tracks and the structure components.	none	1.1%	1.1%	1.1%
	Some fasteners of the bottom tracks were tilted and were threaded through the bottom tracks.	none	1.5%	1.5%	1.5%
	Most of the fasteners were threaded through the bottom tracks and the walls slid.	none	2.1%	2.1%	2.1%
Panels failure	Local cracking of the panels.	none	1.1%	1.5%	1.5%
	Widespread collapse of the panels.	none	2.1%	3.0%	3.0%
Water pipe failure	Shear failure of the water pipe.	none	2.1%	2.1%	3.0%
Junction failure	Visible separation appeared at the junction of the two walls. .	none	none	0.8%	0.8%
	The separation spread widely throughout the junction.	none	none	1.5%	1.5%
	Both the top and the bottom tracks were damaged and the out-of-plane walls started to move.	none	none	1.5%	1.5%
	Severe damage to the top track flanges and the walls leaned seriously.	none	none	3.0%	3.0%

Table 3 showed the results of W5 and W6 specimens. An intention of strengthening the shear resistance was applied in W5. From the results, it seemed that increasing the number of powder-driven nails had only small contribution to the water piping. The other damage patterns of W5 were observed at the same drift levels as that of W2. The retrofit construction in W6 specimen intended to reduce the connection between the partition walls and the structure components. The end studs and the bottom tracks fastened to the structures were not attached to the specimen. Despite the end stud flanges were squeezed by the additional studs at a drift ratio of 1.5%, damage to the fasteners was very limited. As the results, the bottom track remained intact and the shear failure of the water piping was finally appeared at a 4.0% drift ratio. Besides, widespread fall-off of cracked panels occurred at a very large drift ratio of 5% .

The testing results of W7 and W8 specimens were shown in Table 4. In comparison with the results of W3 specimen, many problems had been improved in W7 except the raked out-of-plane walls. This problem was due to the impact from the in-plane wall with increasing imposed drift. In order to solve this problem, a stopper was installed in W8 specimen at the top junction of two perpendicular walls.

The stopper provided its own stiffness to resist the impact and therefore the out-of-plane wall was leaned slightly at a 3.0% drift ratio. Furthermore, the same degree of slope like W3 specimen occurred at a drift ratio of 5.0%.

Table 3. Damage progression of W2, W5, and W6 specimens

Specimen		W2	W5	W6
Damage pattern		inter-story drift ratio		
End Studs failure	Visible separation appeared between the end studs and the structure components.	0.8%	0.8%	none
	Some nail heads were pulled out from the end studs.	1.1%	1.1%	none
	The screws fastened the panels and the end studs embedded.	1.5%	1.1%	none
	Most of the nail heads were pulled out from the end studs and the separation spread apparently.	1.5%	1.5%	none
	The end stud flanges were squeezed by the additional studs	none	none	1.5%
Bottom tracks failure	Visible separation appeared between the bottom tracks and the structure components.	1.1%	1.1%	none
	Some fasteners of the bottom tracks were tilted and were threaded through the bottom tracks.	1.5%	1.5%	none
	Most of the fasteners were threaded through the bottom tracks and the walls slid.	2.1%	2.1%	none
Panels failure	Local cracking of the panels.	1.1%	1.1%	2.1%
	Widespread collapse of the panels.	2.1%	2.1%	5.0%
Water pipe failure	Shear failure of the water pipe.	2.1%	3.0%	4.0%

Table 4. Damage progression of W3, W7, and W8 specimens

Specimen		W3	W5	W6
Damage pattern		inter-story drift ratio		
End Studs failure	Visible separation appeared between the end studs and the structure components.	0.8%	none	none
	Some nail heads were pulled out from the end studs.	1.1%	none	none
	The screws fastened the panels and the end studs embedded.	1.1%	none	none
	Most of the nail heads were pulled out from the end studs and the separation spread apparently.	1.5%	none	none
	The end stud flanges were squeezed by the additional studs	none	1.5%	1.5%
Bottom tracks failure	Visible separation appeared between the bottom tracks and the structure components.	1.1%	none	none
	Some fasteners of the bottom tracks were tilted and were threaded through the bottom tracks.	1.5%	none	none
	Most of the fasteners were threaded through the bottom tracks and the walls slid.	2.1%	none	none
Panels failure	Local cracking of the panels.	1.5%	2.1%	2.1%
	Widespread collapse of the panels.	3.0%	4.0%	5.0%
Water pipe failure	Shear failure of the water pipe.	2.1%	4.0%	4.0%
Junction failure	Visible separation appeared at the junction of the two walls.	0.8%	2.1%	2.1%
	The separation spread widely throughout the junction.	1.5%	2.1%	2.1%
	Both the top and the bottom tracks were damaged and the out-of-plane walls started to move.	1.5%	2.1%	3.0%
	Severe damage to the top track flanges and the walls leaned seriously.	3.0%	3.%	5.%

5. CONCLUSION

According to the testing result, the rotational behavior seems to be the major problem of the current DMF system and causes the fasteners to be pulled out easily. This is because the partition walls are tightly connected to the structural components, therefore the partition walls suffer easily as soon as the structures behave. A retrofit construction is applied in this study which reduces the connection between the partition walls and the structural components, and the results have significantly improved with the retrofit details. The retrofit construction has made the partition walls slide rather than rotate and delayed the deformation and the damage of the walls and the water piping against the story-drift. Most important of all, the boundary conditions of the walls remain intact, and efficiently prevent the partition walls from overturning.
The DMF system is commonly used in recent years, however, this system is directly developed from the DW system and the proper construction of it has not been studied seriously. This study attempts to find out an adequate construction of the DMF system and ensures people against accidents during earthquakes.

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