VERTICAL MOTION EFFECTS ON SUSPENDED CEILINGS

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Abstract

Past earthquakes have shown widespread damage to the suspended ceilings. Despite their frequent use in Taiwan, many suspended ceilings experienced damage in earthquakes owing to the lacked proper seismic design or efficient installation. In 2011, Taiwan Building Code issued the seismic installation of the suspended ceiling systems which are similar to the ASTM E580-09. However, the construction of the lateral bracing assembly has always been a difficult challenge. Problems include slack installation or omission of the bracing wires due to obstructions result in uneven quality of the bracing system in-situ. In recent years, some researches have demonstrated that the lateral bracing assembly may not adequately resist the lateral force. The other researches have even shown that unbraced ceiling systems may perform well when providing both sufficient clearance and wide closure. Therefore, there is an increasing concern about the necessity of the bracing system.

In order to understand the dynamic behavior of bracing systems of the suspended ceilings, full scale shaking table experiments of suspended ceiling systems were conducted in this study. The first series of experiments on 5.7m × 2.7m ceiling systems looked into the seismic effects of the bracing assemblies. Some ceiling specimens were subjected to unidirectional ground motions while the others were subjected to a horizontal and a vertical ground motions acting together. The results clearly showed that the bracing wire bore only a small portion of the inertial force, and this situation became more obvious while the ceiling systems were subjected to vertical excitations. The second series of experiments on 5.7m × 2.7m ceiling systems compared the seismic performance of the braced and unbraced ceilings. The preliminary observations revealed that the use of the lateral bracing including compression post may not improve the seismic performance of the ceiling system. The unbraced ceiling systems performed well just as the braced ceiling systems when excited only by horizontal ground motions, and it performed better when the vertical ground motions were added to the ceiling systems.

Keywords: suspended ceilings, lateral bracing assembly, bracing wire, shaking table experiment, vertical motion

1. Introduction

Suspended ceiling systems are widely used in commercial and residential buildings. The past earthquakes have highlighted that losses resulting from damage to them can be significant. The ceiling collapse can make a building inoperable after an earthquake. In some cases, it may endanger the life safety of the occupants. In Taiwan, many cases of ceiling damage were observed in the 1999 Chi-Chi earthquake. The failure of the suspended ceilings became a serious hazard especially in hospitals and halted the medical services [1]. Patients were forced to stay outside and were cured carelessly.

The early suspended ceiling systems were easily damaged in earthquakes mainly due to the lack of proper seismic design or efficient installation guidelines. In order to evaluate and better understand the dynamic response of the ceiling systems, various experiments for suspended ceilings have been conducted for more than three decades to provide an effective seismic design (ANCO, 1983[2]; Rihal et al., 1984[3]; Reinhorn, 2000[4]; Badillo et al., 2007[5]; Yao, 2000[6]; Gilani et al., 2013[7]). In 2011, an appendix referring to ASTM E580-09[8] was issued in the Taiwanese building seismic design code. The appendix explicitly provides guidance for the seismic installation of the suspended ceiling systems. The main construction details include the use of the the fixtures at two fixed adjacent ends and the installation of the edge hanger wires which have proven advantageous in limiting the movement of the ceiling systems. In addition, the lateral bracing assemblies are required for all ceiling areas greater than $100m^2$. However, the construction of the bracing assembly has always been a difficult problem leading to uneven qualities of the suspended ceilings. Figure 1 shows a bracing assembly consisting of four wires splayed 90° from each other also at an angle not exceeding 45° from the ceiling plane and a vertical strut performing as a compression post. To satisfy the demand of the angle not exceeding 45°, sufficient space in the horizontal direction is necessary. However, the installation of the suspended ceilings has always been arranged after the construction of other overhead non-structural elements such as mechanical equipment and piping systems. For this reason, the lateral bracing members especially the splayed wires are frequently obstructed by equipment and consequently installed in bad construction. Figure 2 demonstrates a common situation of ceiling construction in Taiwan, and it is obvious that there is almost not enough space to install the bracing assembly.

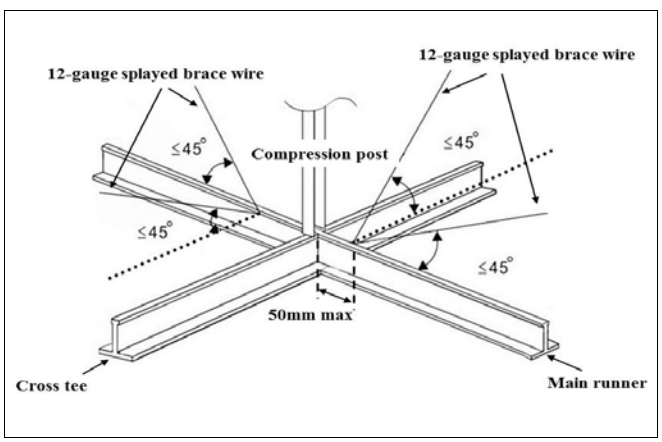

Fig. 1 – Details for the bracing assembly

Fig. 2 – Unfavorable installation condition

Although many researches have noted that the seismic performance of the ceiling systems is affected by the placement of the lateral bracing assemblies. In fact, the effectiveness of the bracing assembly has not been certainly verified. ANCO (1983) mentioned that the use of the vertical strut did not reduce the dynamic responses of the ceiling systems [2], and Yao (2000) also observed limited effectiveness of the bracing assemblies [9]. The experimental results have demonstrated that splayed wires, even with the compression post, may not adequately resist the lateral force due to the construction problems. In recent years, a series of full scale shake table tests performed at E-Defense in Japan have shown that the use of the lateral bracing assemblies also may not improve the seismic response of the ceilings, especially if the systems are subjected to strong vertical excitation. Moreover, the compression posts installed in the bracing assemblies even increase the damage to the suspended ceiling systems [10, 11].

In addition to the previous discussions, ASCE 7-10[12] has also demonstrated that unbraced ceiling systems may perform well only by providing both sufficient clearance and wide closure. Considering the difficulty in installation and the uncertain effect of the bracing assembly, the necessity of the bracing system becomes a discussed issue. This paper looks into the seismic performance of suspended ceilings with reference to Taiwanese building seismic design code and current construction practice. The main objectives of this study are to determine the effect of the bracing assembly and to identify the dynamic behaviour of the ceiling systems subjected to vertical excitations. In this paper, two series of ceiling experiments are presented. A concise description of the instrumentation and testing procedure is introduced, and the experimental results will be analyzed and discussed in detail.

2. Experimental setup

Experiments of suspended ceiling systems were performed using a shaking table at the National Center for Research on Earthquake Engineering (NCREE) in Taiwan. Both two series of ceiling experiments with different test configurations were installed in the 8m by 3m and 2m high steel frame as shown in Figure 3. The natural frequencies of the steel frame along the long side (denoted as X direction) and short side (denoted as Y direction) are 35Hz and 10Hz respectively. Considering the possibility of resonance effect of the steel frame in Y direction, ground excitations are performed only in X direction. Furthermore, the small H steels at the top of the frame are also reinforced (Figure 4) to avoid local mode effect. The natural frequency of the steel frame in vertical direction (Z) is approximately about 30Hz.

Fig. 3 – Elevation view of the steel frame

Fig. 4 – Top view of the steel frame

Figure 5 demonstrates the layout of the ceiling specimen with dimension of 5.7m by 2.7m in the first series of experiments. The lateral bracing assemblies were placed in the middle of the ceiling systems and were installed in two configurations. The compression posts were only installed in the A type system while all other details were identical in both configurations. The 24mm wall moldings were attached to the perimeter boundaries. At the west and south side, tapping screws were used to fix the ceiling grids to the wall moldings (Figure 6). Alternatively, at the east and north side the grid members were attached with 12mm clearance to the wall moldings that allowed the grid members to float freely (Figure 7). The grid systems were constructed to carry at least 80kgf in compression and in tension by using the exposed tee system (412 type) manufactured by a Taiwanese qualified manufacturer (CKM BUILDING MATERIAL CORP).

Mineral fiber tiles with a thickness of 6mm weighting 10kgf/m^2 were used in the experiments. The tiles were placed within the grid system, simply resting on the flange of each tee grid. Hanger wires hanging the main runners were placed at an interval of 1220mm (4 ft.), and the edge hanger wires were placed within 200mm (8 in) from the boundary. The wires were made of #12 gauge wires which looped through the holes in the grid members and connected to the steel frame above with connection devices and powder-driven nails. Figure 8 shows a common practice of the connection device widely used in Taiwan. The ceiling specimens were suspended 1m from the frame structure to the ceiling plane. In order to determine the effect of the bracing assembly, a load cell was installed on splayed wires as shown in Figure 9.

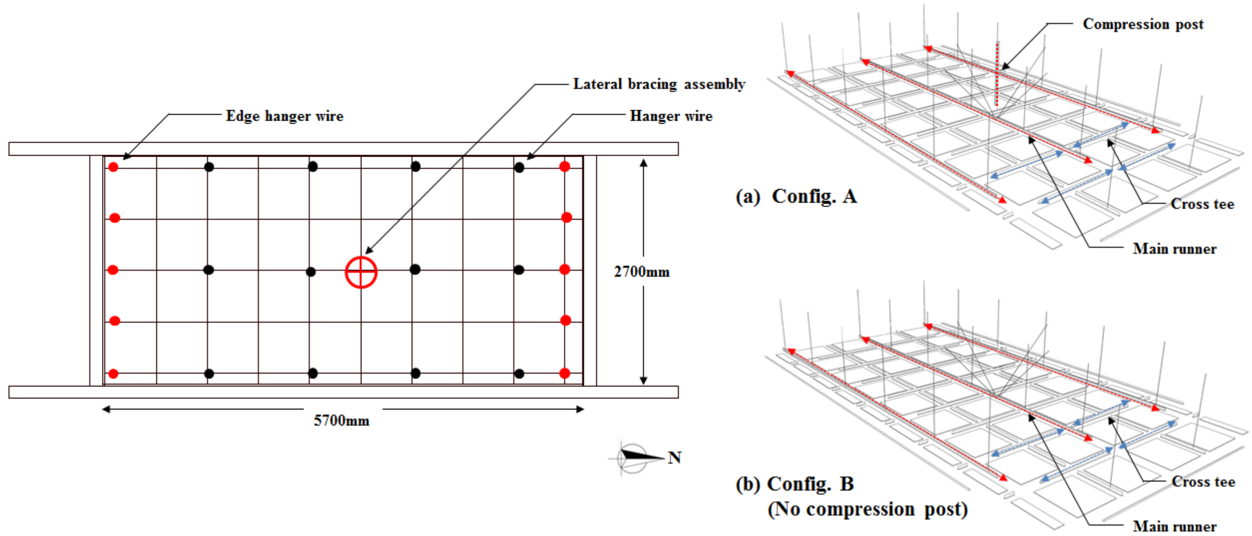

Fig. 5 – Overall view of the ceiling system in the first series of experiments

Fig. 6 – Installation of the fixed end

Fig. 7 – Installation of the free end

Fig. 8 – Hanger wires and connection devices

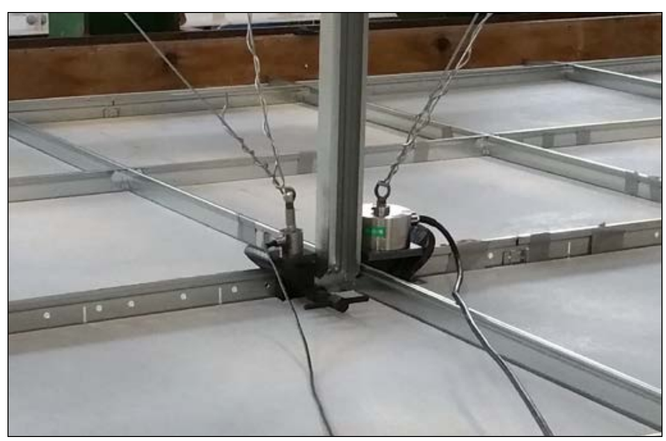

Fig. 9 – Installation of the load cell

Figure 10 displays the layout of the ceiling system in the second series of experiments. The specimen is symmetric in plan with dimension of 7.3m by 2.7m. Most of the construction details were the same as the specimens in the first series of experiments. The ceiling grids were constructed using the JTB-Seismic Design exposed tee system manufactured by another Taiwanese manufacturer (YI STAR ENTERPRISE CORP.) The grid systems were also qualified to carry a load of not less than 80kgf in compression and in tension. The main runners and the cross tees were aligned in two configurations: 1) the main runners installed in the north-south direction (Figure 10-a), and 2) the main runners installed in the east-west direction (Figure 10-b).

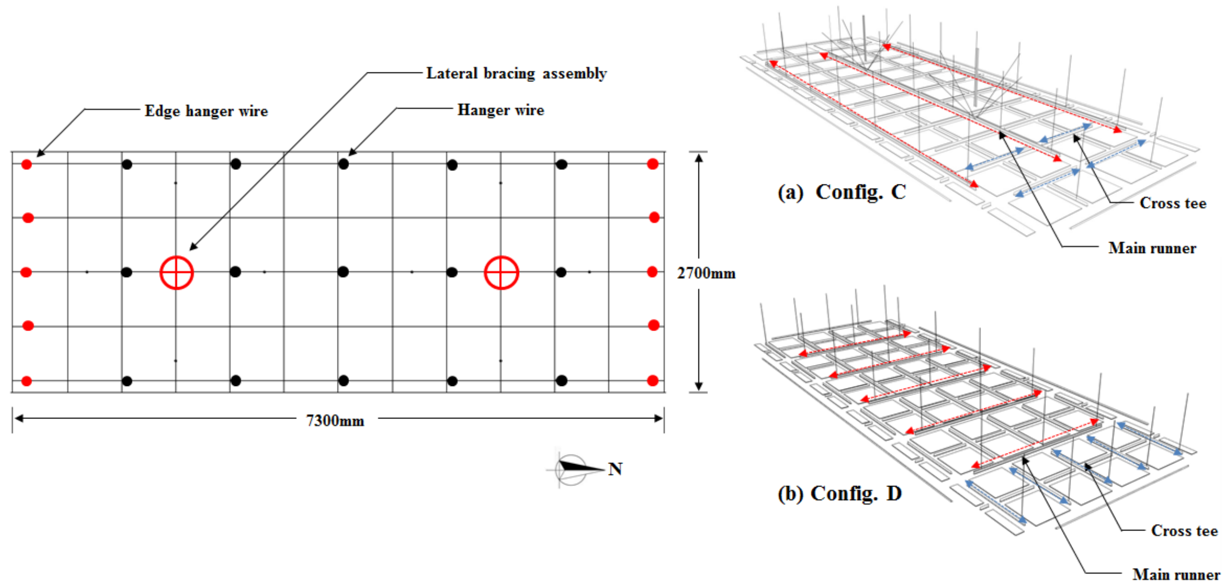

Fig. 10 – Overall view of the ceiling system in the second series of experiments

To compare the behavior of braced and unbraced ceiling system, two lateral bracing assemblies were installed in some ceiling specimens although the entire ceiling areas were much smaller than 100m^2.The lateral bracing assemblies were placed 1840mm from the boundary and the distance between two bracing assemblies was 3660mm. Moreover, the bracing assemblies were installed only in the A type configurations since the spacing regulations mentioned above were not applicable in the B type configurations.

Table 1 –Description of ceiling specimens

Test Series	Specimen	Config.	Bracing Assembly	Input Direction	Comment
1	C1	A	Yes	X	-
	C2	A	Yes	X+Z	-
	C3	B	Yes	X	no compression post
	C4	B	Yes	X+Z	no compression post
2	C5	C	No	X	-
	C6	C	No	X+Z	-
	C7	D	No	X	-
	C8	D	No	X+Z	-
	C9	C	Yes	X	Connection joint reinforced
	C10	C	Yes	X+Z	Connection joint reinforced
	C11	C	Yes	X	Connection joint reinforced no compression post
	C12	C	Yes	X+Z	Connection joint reinforced no compression post

Table 1 summarizes the ceiling configurations in accordance with the installation of the bracing assemblies. A total of twelve specimens (C1, C2, …, C12) were tested in this study. One thing is particularly worth mentioning, a certain connection joint of the main runner in the C type detached (Figure 11) every time when excited by vertical excitations, and this unexpected failure happened not only in one specimen. Therefore, an additional hanger wire shown in Figure 12 (denoted as "Connection joint reinforced" in Table 1) was installed when the specimen was reconstructed. The reason of this problem will be further discussed in the following section.

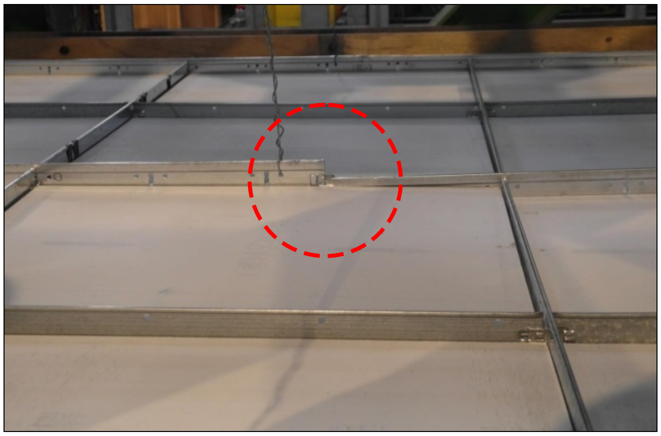

Fig. 11 – Detachment of the main runner joint

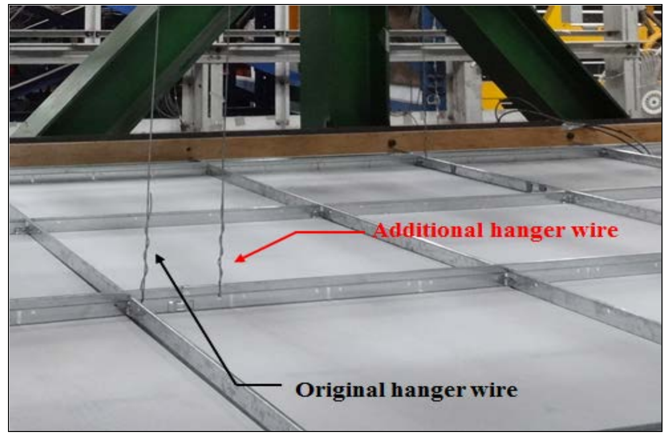

Fig. 12 – Installation of the additional hanger wire

3. Excitation protocol

In order to evaluate the effect of the bracing assemblies, sine waves were performed in the first series of experiments. Four different horizontal acceleration (0.4g, 0.6g, 0.8g and 1g) levels were tested in sequence (denoted as sin-H400, sin-H600, sin-H800 and sin-H1000). Specimens C1 and C3 were subjected to unidirectional ground motions while C2 and C4 were subjected to a horizontal and a vertical ground motions acting together. The vertical ground motions were performed as 2/3 of the horizontal ground motions (denoted as sin-V267, sin-V400, sin-V533 and sin-V667).

To determine the seismic performance of the braced and unbraced ceiling systems, real earthquake records were performed in the second series of experiments. In comparison with all the other Taiwan earthquake records, the 1999 Chi-Chi Earthquake was considered most representative and was chosen as the test ground motion. The earthquake record was modified following the AC156 (ICC-ES, 2010) parameters in order to simulate the roof motion on the test steel frame. According to the Taiwanese building seismic design code the maximum level of S_{DS} = 1.136g, and the corresponding parameters of $A_{RIG\text{-}H}$=1.36g, $A_{FLX\text{-}H}$=1.82g, $A_{RIG\text{-}V}$=0.30g, and $A_{FLX\text{-}V}$=0.76g were considered as the target spectrums for the horizontal and vertical excitations (denoted as H1300 and V300). To take account of the floor amplification effect in vertical direction, another vertical excitation three times proportional to the V300 was performed (denoted as V900). Moreover, considering the vertical motions might be larger than the horizontal motions in near-fault earthquakes, a strong vertical excitation with same scale as H1300 was applied in the experiments (denoted as V1300). In this series of the experiments, the ceiling specimens were subjected to the constant excitation (H1300) in horizontal direction while subjected to incremental excitations (V300, V900, and V1300) in vertical direction.

4. Experimental observations

In Table 2, a summary of damage observations at different excitation levels is given. Over the course of the first series experiments, the ceilings specimens were undamaged while the magnitude of horizontal ground motion was less than 1g. Only some tapping screws were found dislodged and some perimeter connection failed at the stage of sin-H1000.

In the second series of experiments, almost no damage to the ceiling specimens was observed in response to unidirectional ground excitations while only a few tapping screws were dislodged as shown in Figure 13. The result revealed that the seismic ceiling systems used in Taiwan certainly had good resistance to horizontal forces. Concerning the experiments with vertical excitations, some of the perimeter connections and cross tee latches failed but the grid members especially the main runners always remained intact. Without losing the support of the tee grids, the tiles were stayed inside the grids over the course of the experiments. The largest damage was generated in C10 specimen that the ceiling was completely collapsed (Figure 14). Some of the failure patterns will be discussed in the following text.

Table 2 – Damage Observations of ceiling specimens

Series 1	C1	C2	C3	C4
sin-H400	No damage		No damage	
sin-H600	No damage		No damage	
sin-H800	No damage		No damage	
sin-H1000	■		■	
sin-H400 V267		No damage		No damage
sin-H600 V400		No damage		No damage
sin-H800 V533		No damage		No damage
sin-H1000 V667		■□		■□

Series 2	C5	C6	C7	C8	C9	C10	C11	C12
H1300	■		■		■		■	
H1300 V300		■		■		■		■
H1300 V900		□		□		□		□
H1300 V1300		□▲		□▲		□△●		□▲

	Damage Definition
■	Dislodged tapping screw
□	Damaged perimeter connection
▲	Damaged latches of cross tee
△	Failed hanger wire
●	Complete failure

Fig. 13 – Dislodged tapping screw

Fig. 14 – Collapse of the ceiling system

4.1 Tapping screw failure

The horizontal inertial force generated by the mass and the response acceleration of the ceiling induces axial force in the grid members. This force accumulates and becomes greater near the perimeter support than in the middle and is transferred to connection of tapping screws. However, as the tapping screws are installed regardless of the ceiling mass or the intensity of the input excitation, damage to tapping screws is always the first failure pattern observed during the experiments.

4.2 Perimeter connection failure

The primary damage in perimeter connections is the unseating of the ceiling grids from the wall molding as shown in Figure 15. Since 50mm wall molding is barely used in Taiwan therefore only 24mm wall molding was applied in the experiments. This failure can possibly due to the insufficient seat length of the wall molding at the unfixed sides or the failure of tapping screws at the fixed sides. As the unseating grid members move back toward the perimeter boundary, the grids hit the wall molding to cause the observed damage (Figure16). In some cases the failure of perimeter connection result in grid members and tiles falling from the ceiling, which particularly occurred around the connections of cross tees and wall moldings. In this study, an additional test (B type configuration) without the wall moldings was conducted to evaluate the performance of the ceiling in a severe condition. The grid members of the ceiling were still intact in the shape of rectangle after the test and no falling tiles were observed (Figure 17). The result demonstrates the edge hanger wires can effectively prevent the grid members and tiles from falling.

4.3 Hanger wire failure

The attachment connecting the hanger wire and the frame structure failed during extreme vertical excitation (Figure 18). The failure of one hanger wire resulted in missing vertical supporting and uneven loading distribution of the ceiling grids, which led to a progressive failure of other hanger wires and caused a chaotic global collapse of the ceiling system. In all experiments, failure of hanger wires only occurred in the braced ceiling specimen C10. In order to study whether the failure of hanger wire was caused by construction problem, the specimen C9 was reused with vertical ground motions after the unidirectional excitation test was finished. The result showed similar damage patterns including failure of hanger wires and serious collapse of the ceiling.

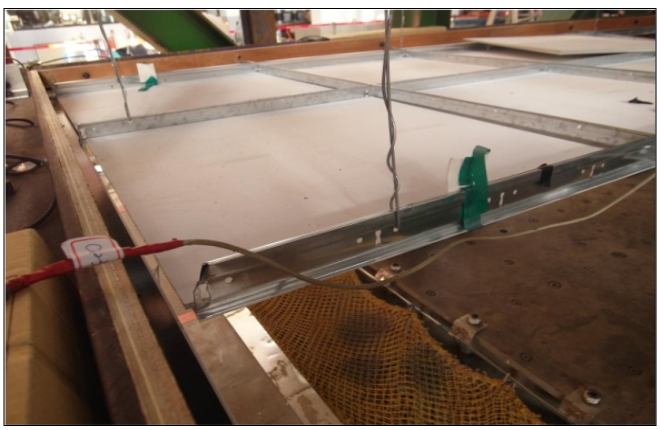

Fig. 15 – Unseating of grid members

Fig. 16 – Failure of perimeter connection

Fig. 17 – Specimen without wall moldings   Fig. 18 – Failure of hanger wire

4.4 Connection joint of main runner failure

The damage to the connection joint of the main runner is an unexpected failure during experiments. The 7.3m main runner of the C type consisting of three pieces of grid members and has two connection joints along the grids, one of the joints shown in Figure 19-a failed frequently at low amplitude vertical excitation. Studying the locations of these two connection joints, the damaged joint is placed closely beside a hanger wire while the undamaged one is placed at the middle of two hanger wires (Figure 19-b). Displacement incompatibility on both sides of the connection joint is considered the most possible reason of the failure condition. When the grid members sustain downward loading inclusive of the excitation and the impact force from tiles, the grid on the left side of the joint is directly restrained by the hanger wire but the grid on the right side vibrates obviously. To prevent the displacement incompatibility between the connection joints, an additional hanger wire is installed beside the joint as shown in Figure 19-c, which has proven effective since no failure is observed after reinforcing.

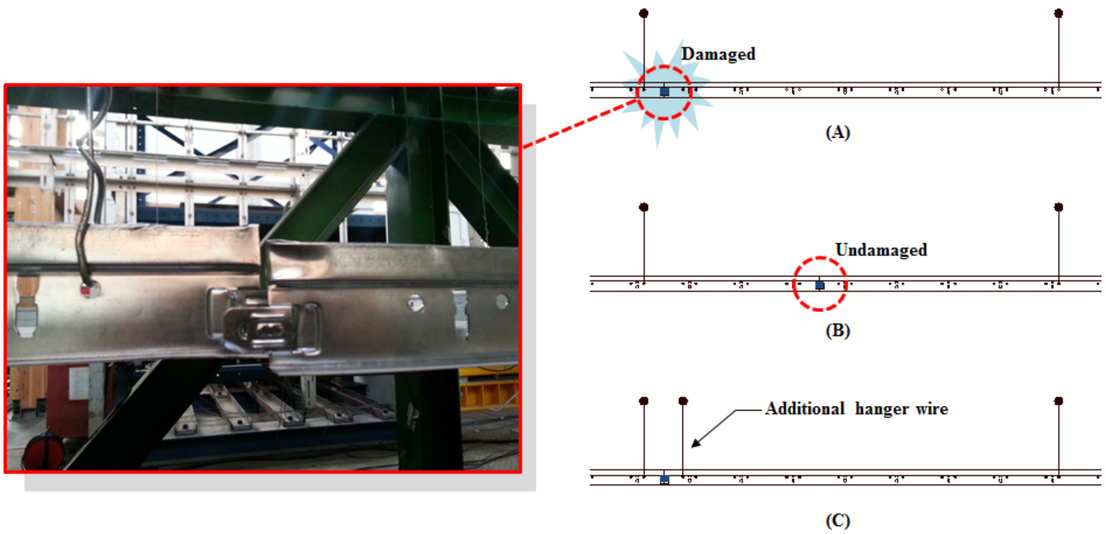

Fig. 19 –Damage to the connection joint of the main runner

5. Experimental analysis

The first series of experiments looked into the seismic effects of the bracing assemblies. Table 3 recorded the response accelerations of the ceiling systems (PA) and the loads carried by the bracing wires during every different excitation levels.

Table 3 – Response accelerations of the ceiling systems and the loads carried by the bracing wires

	C1		C3			C2		C4	
	PA	Load	PA	Load		PA	Load	PA	Load
sin-H400	0.49g	2.4kgf	1.13g	7.4kgf	sin-H400 V267	0.72g	3.8kgf	1.73g	12.5kgf
sin-H600	0.68g	3.9kgf	1.72g	13.2kgf	sin-H600 V400	1.25g	6.4kgf	2.82g	21.7kgf
sin-H800	1.0g	5.4kgf	2.46g	19.2kgf	sin-H800 V533	1.82g	8.5kgf	4.37g	31.2kgf
sin-	1.57g	10.2kgf	3.67g	31.7kgf	sin-	2.78g	15.8kgf	5.76g	48.3kgf

H1000					H1000 V667				

Take C1 at the stage sin-H800 for example, the maximum horizontal response acceleration of the ceiling specimen is 1.0g (Figure 20). Since the self-weight of the ceiling system is about 165kgf, the horizontal inertial force can be simply assumed as 165kgf. The load cell installed on the ceiling specimen help to measure the tensile force of the splayed wire and the maximum value is 5.4kgf (Figure 21). The result shows the bracing wire only sustains 3% of the horizontal inertial force.

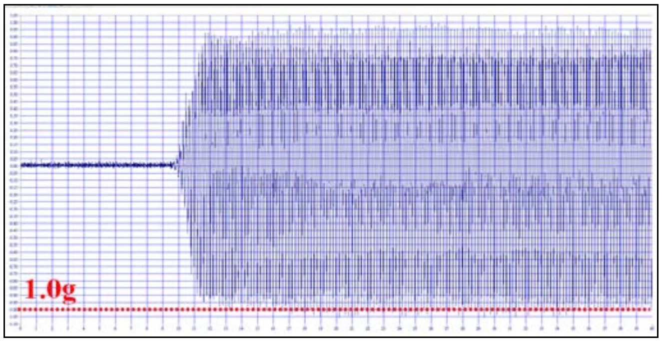

Fig. 20 – Response acceleration of the ceiling

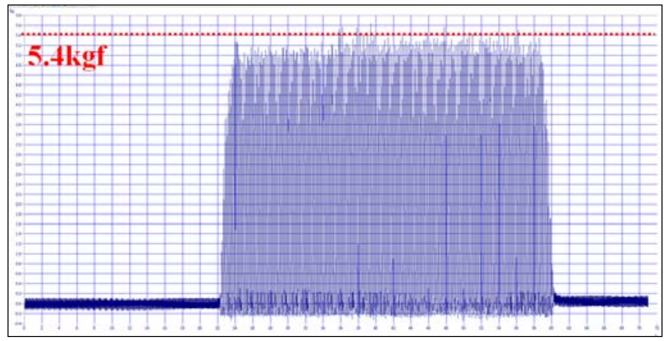

Fig. 21 – Tensile force of the splayed wire

Table 4 – Percentage of the horizontal inertial force sustained by the bracing wires

	C1	C3		C2	C4
sin-H400	2.9%	3.9%	sin-H400 V267	3.1%	4.3%
sin-H600	3.5%	4.6%	sin-H600 V400	3.1%	4.7%
sin-H800	3.3%	4.7%	sin-H800 V533	2.8%	4.3%
sin-H1000	3.9%	5.2%	sin-H1000 V667	3.4%	5.1%

Table 4 calculates the percentage of the horizontal inertial force sustained by the bracing wires. It is obvious that the bracing wire of the bracing assembly carries only a small portion of the lateral inertial force. From Table 3, the response acceleration of the ceiling system increases while the vertical excitation is applied to the ceiling. However, the effectiveness of the bracing wire is not obvious but reduced. This is because that the bracing wire buckled easily when suffering upward excitation and therefore loses its resistance to the lateral force. This observation points to an important message; that is, the installation of the lateral bracing assembly may not improve the seismic response of the ceiling system especially if the system is subjected to vertical excitation.

During the experiment C9 in the second series, the maximum horizontal acceleration is approximately 2.0g and generates 420kgf of the horizontal inertial force as the self-weight of the ceiling system is about 210kgf. The load cell installed on the ceiling specimen help to measure the tensile force of the splayed wire and the maximum value is 7kgf (Figure 22). The result also demonstrates the bracing wire only sustains 3% of the horizontal inertial force. At the last stage of the experiment C10 (H1300, V1300), damage to perimeter connections occurred and it makes the ceiling become a system without edge retrains. In comparison with the result of C9, the splayed wire of C10 sustained more tensile force. However, the maximum tensile force measured before the ceiling collapsed is 18kgf (Figure 23), which indicates that the bracing wire still sustains less than 10% of the horizontal inertial force. The ineffectiveness of the bracing wire is considered mainly a result from the slack wire effect. Although the wire is installed tightly before the tests, it becomes slacker as experiments progressed. Therefore, the slack wire allows some lateral movement before it effectively restrains the ceiling. However, the clearance is only 12mm between the ceiling grid and the boundary, which makes the wire difficult to perform ideally before the ceiling impact the boundary.

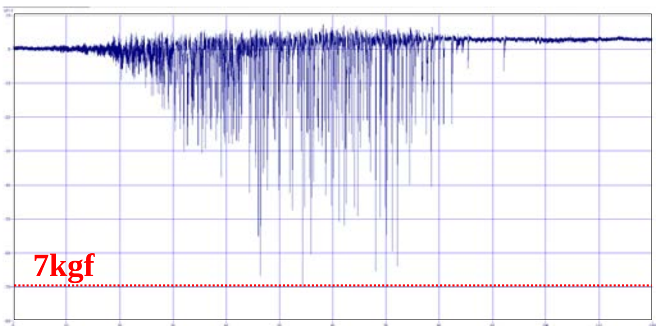

Fig. 22 – Tensile force of the splayed wire

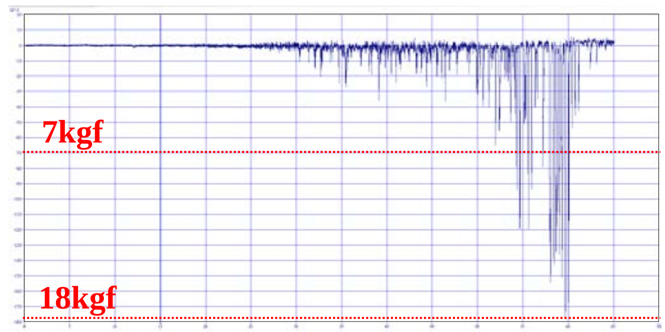

Fig. 23 – Tensile force of the splayed wire

Experiments C11 and C12 are the comparison groups with C9 and C10. Without the use of compression post, the splayed wire sustains more tensile force. However, it is still a small portion to the lateral inertial force. In addition, the vertical displacement at the center of the ceiling is measured during the test. It is found that whether the compression post is installed or not, the displacement is almost the same. This result shows the ineffectiveness of the compression post in limiting the vertical movement of the ceiling system.

5. Conclusion

According to the test result, the splayed wire of the bracing assembly carries only a small portion of the lateral inertial force and this situation became more pronounced while the ceiling systems are subjected to vertical excitations. Therefore, most of the inertial force is still acted on the horizontal ceiling members whether the bracing wires are installed or not. However, it is hard to say that the bracing wire is unnecessary since the ceiling specimen in this paper is not large enough to represent a common situation. Assuming a large suspended ceiling separated into several floating parts under an earthquake, it is believed that the bracing wire can help restrain the excess movement of the ceiling and reduce the possibility of further damage.

The original function of the compression post is to resist the vertical force induced by the bracing wire. Since the bracing wire sustains little force and the compression post also cannot provide resistance in limiting the vertical movement, the installation of the compression post can possibly be exempted from the bracing assembly.

From the previous discussion, some connections of the grid members show vulnerability to vertical excitation. Damage to the connection joint of the main runner is a special observation in this paper. A convenient retrofit construction is applied which efficiently prevent the failure from the strong vertical excitation.

6. Acknowledgements

This study was supported by the National Science Council, Taiwan (NSC 102-2221-E-006-225-MY3). The authors are grateful to this support.

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