Proceedings of the Tenth Pacific Conference on Earthquake Engineering
Building an Earthquake-Resilient Pacific
6-8 November 2015, Sydney, Australia

Performance Study of Seismic Bracing Assemblies of Suspended Ceiling Systems

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ABSTRACT: Many suspended ceilings were damaged in the past earthquakes due to the lack of proper installation. In 2011, an appendix was issued for the seismic installation of the suspended ceilings in the Taiwanese seismic design code for buildings. However, the construction of the lateral bracing assembly has always been a difficult problem. 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 just as the braced ceiling systems. Therefore, there is an increasing concern if the bracing assembly is necessary or not.

In order to understand the dynamic behaviour of the ceiling bracing assemblies, full scale shake table experiments were conducted in this study. Some ceiling specimens were subjected to unidirectional ground motions while others were subjected to a horizontal and a vertical ground motions acting together. Test results showed the bracing wire carried only a small portion of the inertial force, and the use of the bracing assembly may not improve the seismic response of the ceiling system, especially if the system was subjected to strong vertical excitation.

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 its occupants. In Taiwan, many cases of ceiling damage were observed in the 1999 Chi-Chi earthquake. The failure of the suspended ceilings became a significant hazard in hospitals and thus seriously halted the medical services (Loh, 1999).

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; Rihal et al., 1984; Reinhron, 2000; Badillo et al., 2007; Gilani et al., 2010, 2012).

In 2011, an appendix referring to ASTM E580-06 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 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 set up the bracing assembly.

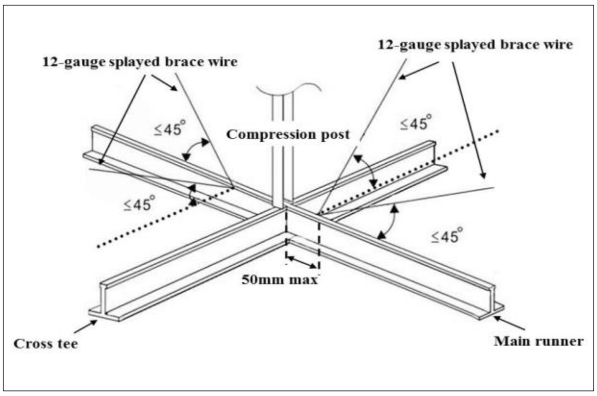

Figure 1. Details for the bracing assembly

Figure 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) mention that the use of the vertical strut did not reduce the dynamic responses of the ceiling systems, and Yao (2000) also observed limited effectiveness of the bracing assemblies. 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.

In addition to the previous discussions, some other researches have also shown 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, a concise description of the instrumentation and test processing procedure is presented, 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. Suspended ceiling specimens 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.

Figure 5 demonstrates the layout of the ceiling system which is symmetric in plan with dimension of 7.3m by 2.7m. 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. 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. All the ceiling systems were constructed using the JTB-Seismic Design exposed tee system manufactured by a Taiwanese qualified manufacturer (Yi Star Enterprise Corp.). The main runners and the cross tees were aligned in two configurations: 1) the main runners installed in the north-south direction (Figure 5-a), and 2) the main runners installed in the east-west direction (Figure 5-b).

Figure 3. Elevation view of the steel frame

Figure 4. Top view of the steel frame

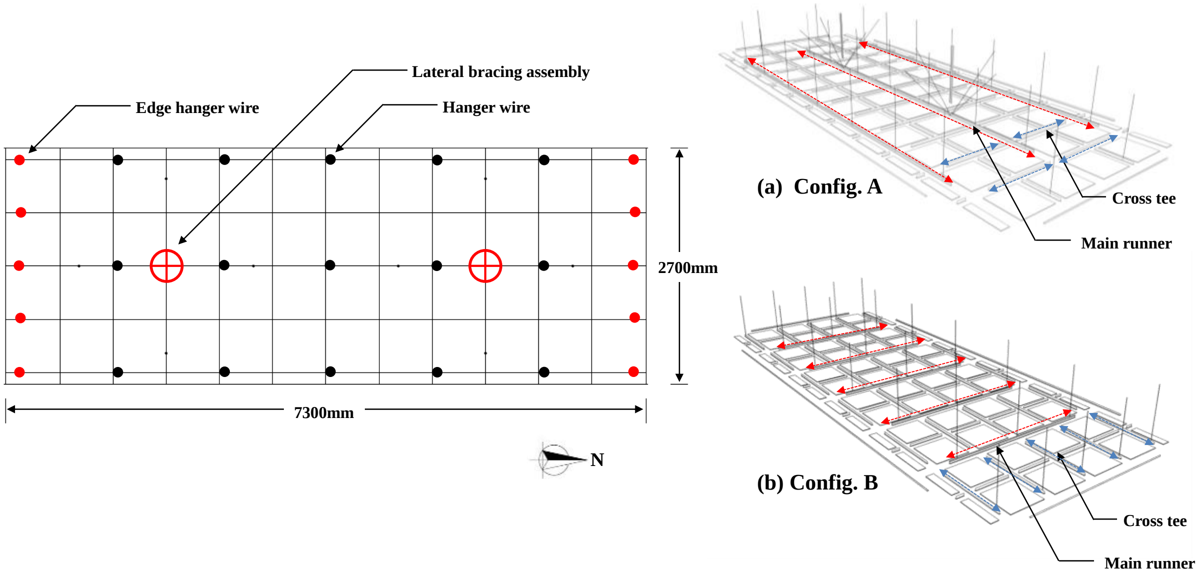

Figure 5. Overall view of the ceiling system

Figure 6. Hanger wires and connection devices

Figure 7. Installation of the load cell

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 12gauge 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 6 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. To compare the behaviour 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. In order to determine the effect of the bracing assembly, a load cell was installed on splayed wires as shown in Figure 7.

Table 1. Description of ceiling specimens

Test Group	Specimen	Config.	Bracing Assembly	Input Direction	Comment
1	C1	A	No	X	-
	C2	A	No	X+Z	-
	C3	B	No	X	-
	C4	B	No	X+Z	-
2	C5	A	Yes	X	Connection joint reinforced
	C6	A	Yes	X+Z	Connection joint reinforced
3	C7	A	Yes	X	Connection joint reinforced no compression post
	C8	A	Yes	X+Z	Connection joint reinforced no compression post

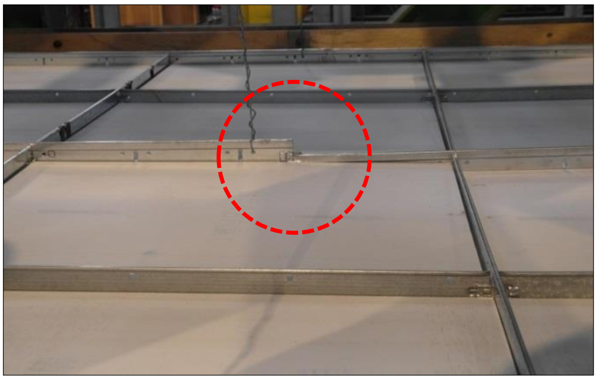

Figure 8. Detachment of the main runner joint

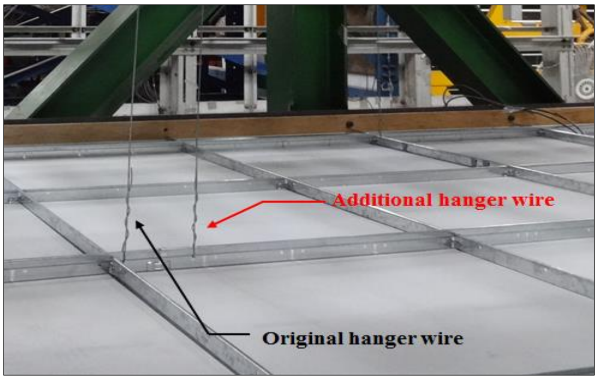

Figure 9. Installation of the additional hanger wire

Table 1 summarizes the ceiling configurations. The ceiling specimens are divided into three groups in accordance with the installation of the bracing assemblies while all other details are identical. One thing is particularly worth mentioning, a certain connection joint of the main runner in the A type detached (Figure 8) 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 9 (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.

3 EXCITATION PROTOCOL

To evaluate the dynamic behaviour of the suspended ceiling systems subjected to earthquake induced excitation, the 1999 Chi-Chi Earthquake record considered most representative in Taiwan 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 floor motion on the test steel frame. According to the Taiwanese building seismic design code the maximum level of S_{DS} = 1.14g, 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).

4 EXPERIMENTAL OBSERVATIONS

During 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. In Table 2, a summary of damage observations occurred at different excitation levels is given.

Table 2. Damage Observations of ceiling specimens

	C1	C2	C3	C4	C5	C6	C7	C8
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

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 10. 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 not observed fallen over the course of the experiments. The largest damage was generated in C6 specimen that the ceiling was completely collapsed (Figure 11). Some of the failure patterns will be discussed in the following text.

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 12. 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 pop rivet 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 (Figure13). 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 paper, 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 14). 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 15). 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 C6. In order to study whether the failure of hanger wire was caused by construction problem, the specimen C5 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.

Figure 10. Dislodged tapping screw

Figure 11. Collapse of the ceiling system

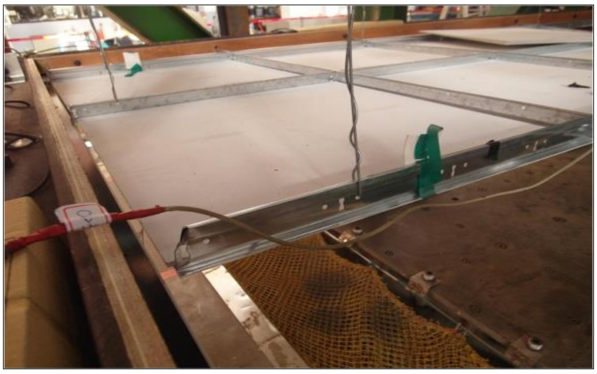

Figure 12. Unseating of grid members

Figure 13. Failure of perimeter connection

Figure 14. Specimen without wall moldings

Figure 15. 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 A type consisting of three pieces of grid members and has two connection joints along the grids, one of the joints shown in Figure 16-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 16-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 16-c, which has proven effective since no failure is observed after reinforcing.

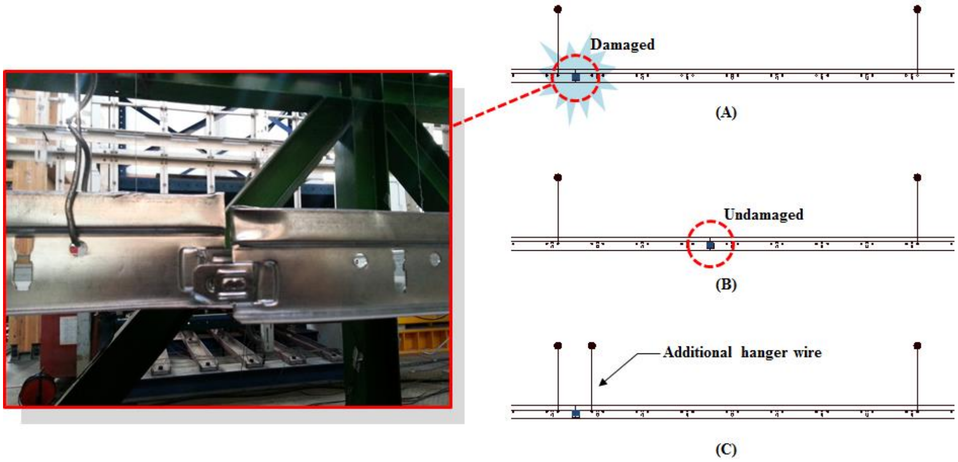

Figure 16. Damage to the connection joint of the main runner

5 EXPERIMENTAL ANALYSIS

This paper aims at evaluating the seismic capacity of the lateral bracing assembly, and the experiment results demonstrate that both braced and unbraced ceiling system perform well when undergoing horizontal motions. During the experiment C5, 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 17). The result shows the bracing wire only sustains 3% of the horizontal inertial force.

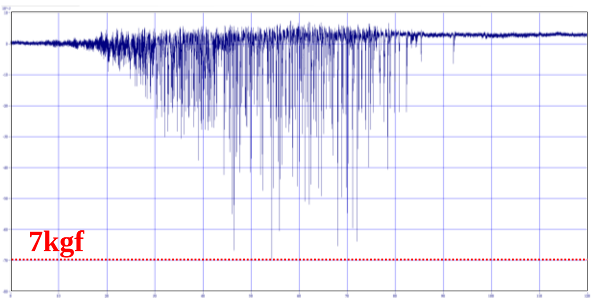

Figure 17. Tensile force of the splayed wire

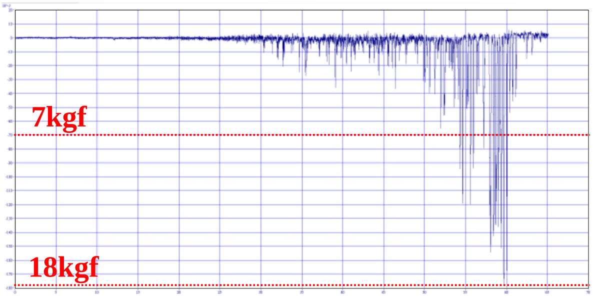

Figure 18. Tensile force of the splayed wire

In the first stage of the experiment C6 (H1300, V300), the tensile force sustained by bracing wire is lower than 7kgf as the vertical excitation is applied to the ceiling,. 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. Damage to perimeter connections occurred in the sequent stages of experiment C6 and it makes the ceiling become a system without edge retrains. In comparison with the result of C5, the splayed wire of C6 sustained more tensile force. However, the maximum tensile force measured before the ceiling collapsed is 18kgf (Figure 18), 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.

Experiments C7 and C8 are the comparison groups with C5and C6. 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.

6 CONCLUSION

According to the test result, the splayed wire of the bracing assembly carries only a small portion of the lateral inertial force and most of the inertial force is still acted on the ceiling members. 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.

7 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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