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TESTING OF CEILING COMPONENTS UNDER EARTHQUAKES

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Abstract

The failure of suspended ceiling has been one of the most widely reported types of nonstructural damage in building structures. Suspended ceilings have been vulnerable to damage from earthquake, sustaining panel loss and grid failure in moderate earthquake, even in absence of major structural damage. Also, the seismic damage of suspended ceilings has given the largest economic loss and function loss to prohibit the building from remaining operational after an earthquake and it sometimes may endanger the life or safety of its occupants.

This study presents the vibration behavior and seismic capacity of typical suspended ceiling systems in Korea, M-bar system ceiling and T-bar system ceiling with the static tests and the dynamic tests. To investigate the capacity of suspended ceiling components, the static tests were performed in three stages; component level, joint level and module level. Shaking table tests were performed to investigate the dynamic behavior of the suspended ceilings with horizontal excitations using data of El-Centro earthquake and Mexico City earthquake. The dynamic performance, such as acceleration response, displacement response, deformation, natural period were evaluated in the experimental program.

Keywords: suspended ceiling; component test; M-bar systems; T-bar system; shaking table test

1. Introduction

Nonstructural components attached to the floors, roof, and walls of buildings are not parts of intended load-bearing structural system. Typical examples of nonstructural components include suspended ceilings, cladding systems, mechanical and electrical equipment, piping systems and access floors. In the past earthquakes, the failures of nonstructural components have been often observed and reported. There were widespread failures of ceiling systems and mechanical equipment in the 1971 San Fernando Earthquake [1], and failures in piping systems and signboards of hospital in the 1994 Northridge Earthquake [2]. The damage of nonstructural such as partitions fell and cladding system failed were also observed in 2006 Hawaii Earthquake [3], 2010 Chile earthquake [4], and 2011 off the Pacific coast of Tohoku Earthquake [5].

The failure of suspended ceiling has been one of the most widely reported types of nonstructural damage in building structures under earthquakes. Failures of ceilings can be summarized: falling of ceiling panels, buckling of ceiling grid members (bars and channels), failure of ceiling grid members, and damage near ceiling perimeter.

Suspended ceilings have been vulnerable to damage from earthquake, sustaining panel loss and grid failure in moderate earthquake, even in absence of major structural damage. Also, the damage of suspended ceilings gives the largest contribution to the economic loss due to an earthquake. Suspended ceiling are used in commercial and residential buildings, and damage to them can prohibit a building from remaining operational after an earthquake and, in some cases, may endanger the life or safety of its occupants. For these reasons, seismic design of suspended ceiling is essential. The seismic design of suspended ceilings is prescribed in Korean Building Code (KBC 2009) [6], but it is hard to trust owing to it came from International Building Code (IBC 2006) without any revising. Seismic design criteria for Korean ceiling system is needed. Before revising criteria for suspended ceilings, some of tests for ceilings should be conducted including the investigation of the capacity of the ceiling components and the dynamic response characteristics of ceilings.

In this study the seismic behavior of suspended ceilings in Korea is investigated. This study consists of static test of components and shaking table test. The first stage of study is to investigate the static capacity of ceiling components in three steps. The static tests were conducted at component level, joint level and module level. Then, the results were checked whether the capacity satisfies the quality certifications of the suspended ceiling. The second part is to investigate the dynamic response characteristics of ceilings by shaking table tests subjected to the past major earthquake data with appropriate scale factors. The acceleration response, displacement response and deformation response of components were recorded and analyzed. Thus the main objectives of the study are as follows;

1) To investigate the critical failure modes by static capacity of ceiling components and their major failure modes
2) To investigate the interaction between the suspended ceiling systems and the lateral stiffness of frames by investigation of dynamic response characteristics of total systems on shaking table.

2. Static Capacity of Components of Suspended Ceiling

Before we performed shaking table testing for ceilings, series of static tests for components of suspended ceilings was performed according to the British Standard in UK [7] which includes the certification procedure of ceiling qualification (Suspended ceilings – Requirements and test method (BS EN 13964:2014)). The specimen to be tested included those products as used for dynamic test. The test investigated the deflection and the admissible loading of the substructure components for critical structural chains of components.

2.1 Component test

The maximum flexural capacity have to be estimated to check whether the strength of ceiling bar and channels are satisfied for demand strength. As shown in Table 1 the capacity of M-bar, carrying bar and minor channel for the distributed load of ceiling boards are tested. The unit weight of textile, the length of M-bar, the equivalent uniformly distributed load and M-bar spacing were considered for testing. According to BS certification the demand of maximum bending moment and the strength allowance of ceiling components are satisfied.

Table 1- Data of bar and channel of ceilings

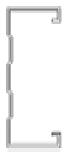
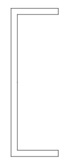
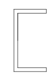
Direction	M-bar 50mmX25mmX0.5mm(t)	Carrying Channel 38mmX12mmX1.5mm(t)	Minor Channel 19mmX10mmX1.2mm(t)
X-1			
Y-1			
X-2			

Table 2-Results of bending tests

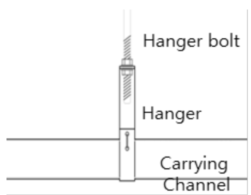
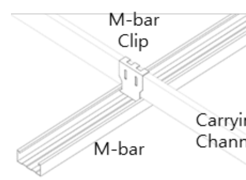
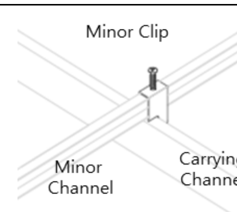
Components	Direction	Specimen No.	Max. load F_u (N)	Displacement at max. load, Δ (mm)
M-bar	X-1 (Positive)	1	355	9.8
		2	342	9.52
		3	333	9.77
		Average	**340**	**9.7**
	X-2 (Negative)	1	355	15.85
		2	363	20.17
		3	364	20.56
		Average	**360**	**18.86**
Carrying channel	Y-1	1	446	10.67
		2	381	12.02
		3	438	9
		Average	**420**	**10.56**
Minor channel	Y-1	1	246	16.02
		2	248	15.48
		3	253	17.18
		Average	**250**	**16.23**

2.2 Joint Test

Joints of ceiling frames are critical components to further develop the ceiling system collapse due to the consequence of failure. Joints have to be designed and fabricated to have enough strength and ductility capacity not to lead to the premature failure of ceiling system. Direct tensile test of hangers was conducted for each joint to check whether joint components were vulnerable or not to subsequent failure. There are three components of joining in M-bar system: hanger, M-bar clip and minor clip. Each component consists of the following sub-components.

J1: Hanger, Hanger bolt and Carrying channel
J2: M-bar Clip, M-bar and Carrying channel
J3: Minor Clip, Minor channel and Carrying channel

Table 3.-Test parameter of joint level

	J1	J2	J3
Specimens			
Sub-component	Hanger bolt, hanger, carrying channel	M-bar, M-bar clip, carrying channel	M-bar, Minor clip, carrying channel

LVDT (Linearly Variable Differential Transducer) and strain gauges were prepared to measure the displacement and deformation of ceiling components.

2.3 Module test

A 1.5m X 1.5m X 1.53m rectangular steel frame has been constructed in order to test the ceiling module systems. Each column was welded to thickness 30mm plate enough to stand the frame. On the top of frame, there are two beams with diameter 10mm holes, span 900mm. These holes enable to suspend ceiling module systems.Module level's specimen is 1200mm X 1200mm size. The hanger and hanger bolt's spans are 900mm. The four specimens were used to module level test. All of the specimens are M-bar system ceiling and heights of ceiling is 0.3m. Test parameters were minor channel's being and direction of loading. In M-bar system ceiling construction, the minor channel is installed space 3000mm, supporting to stand carrying channel. Loading was vertical load and loading range was all 600mm x 1200mm, the directions were x-direction and y-direction.

The four specimen ware tested. M 1-B and M 2-B (without minor channel) have the large maximum load, 1.8kN and 2.26kN compare to M1-A and M1-B (with minor channel), 1.65kN and 2.13kN. Also the load-deflection with transverse loading pad (M1-B and M2-B) showed the large maximum load compared to the case of logitudinal loading pad. In the module tests, the ceiling system failures were observed caused M-bar clip's failed.

The sequence of failure of M 2-B is as follows: 1) Carrying channel was bended; 2) Top of the M-bar clip was loosed; 3) Hanger was bended; 4) Carrying channel fell forward; 5) M-bar clip fell down; 6) Ceiling system failure. Two ceiling failures had different sequence of failure and failure modes. However, all the specimens failed when M-bar clips fell down. Each of ceiling component has enough ductility. However, the test specimens on joint level and module level showed brittle failure modes caused by the failure of M-bar clip. To improve such failure mode the detailing of M-bar clips is needed to find the alternative joint methods.

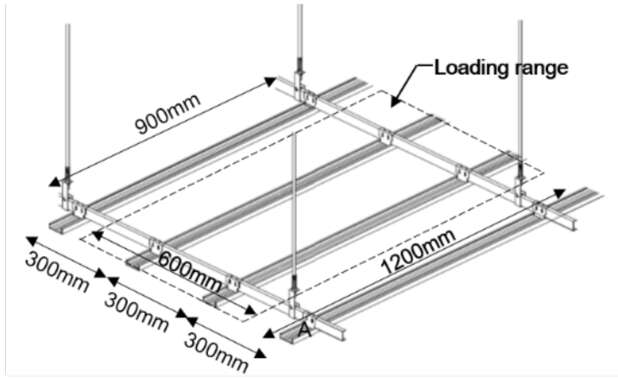


Fig. 1- M-bar system

3. Shaking Table Test

After the series of components tests were performed, the shaking table tests were prepared to investigate the dynamic behavior of suspended ceilings and the interrleationship between ceilings and supporting frames. The experiment program was planned with consideration of the natural period of supporting frame, the height of ceiling, the lateral displacement allowance by gap betweens ceiling and frames and type of ceilings (M-bar system ceiling and T-bar system ceiling).

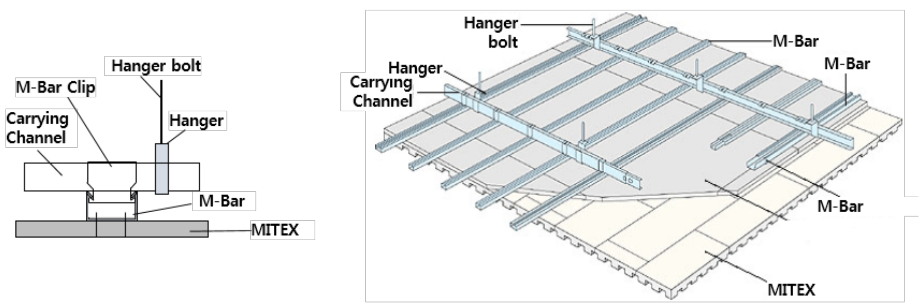


Fig. 2- M-bar system

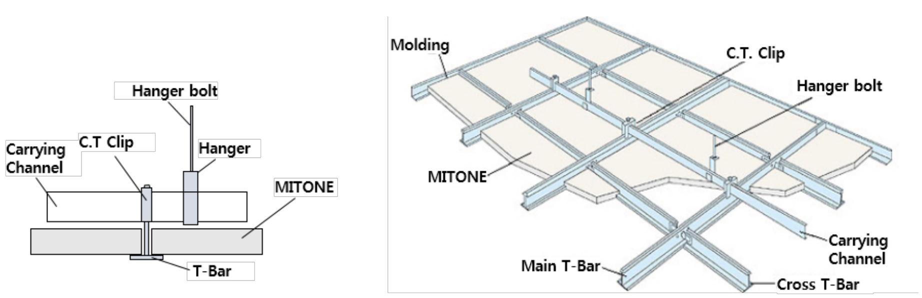


Fig. 3- T-bar system

The dynamic charateristics include acceleration response, displacement response, deformation of components, and natural periods of frames and total systems. The earthquake simulator in the KOCED [14] (Korea Construction Engineering Development) of Pusan University at Yang-san in Korea has three controlled degrees of freedom, the maximum payload of 300 KN and the working frequency range of 0 to 50 Hz. One of the simulators can move the horizontal axes up to 1g at nominal payload and the maximum displacment by ±300mm.

According to ICBO-AC156 code [8] "acceptance criteria for seismic qualification testing of nonstructural components", the required response spectrum, is obtained as a function of the design spectral response acceleration for short periods, S_{DS}, depending on the site soil condition and the maximum earthquake spectral acceleration for short period. In this series of experimental program, S_{DS} was chosen according to the site characteristics listed in KBC 2009 [6]: the S_{DS} of normal rock is 0.36 g and the S_{DS} of soft soil is 0.65g.

The excitations in this study were generated by simulating the data of past two major earthquakes: one is El-Centro earthquake, and the other one is Mexico City earthquake. El-Centro earthquake represents the characteristics of short period excitation with the peak acceleration of 0.34g. Meanwhile, Mexico-city earthquake represents the typical earthquake of long period with the peak acceleration of 0.01g. To investigate the effect of long period earthquake, Mexico City earthquake was chosen. The excitation was generated for the level of moderate seismicity as S_{DS} =0.36g and the level of high seismicity as S_{DS} =3g. The S_{DS} of 0.36g corresponds to El-Centro earthquake of 30 % scale down, and the S_{DS} of 0.65g corresponds to El-Centro earthquake of 50 % scale down. S_{DS} =3g corresponds to El-Centro earthquake of 300 % scale up. Thus the excitation level is decided 30% to 300% on El-Centro earthquake and 30% to 120% on Mexico City earthquake.

3-1 Strong frame with ceilings

A 3.5m x 3.5m rectangular steel frame has been built to install the ceiling systems to the upper beams. The frame was made laterally braced. Four channels were welded along upper beams and had holes for suspension of ceiling at intervals 900mm. The total weight of the test frame is 19.2kN.

The test frame was fixed to the shaking table platform using 48mm diameter bolts. A rectangular steel plate whose dimensions are 800 x 800 mm and 30mm thick constitutes the basement where test frame columns are welded. (**Fig. 2**) The test frame was designed with reference to the previous reported experimental programs of suspended ceilings. [9][10]

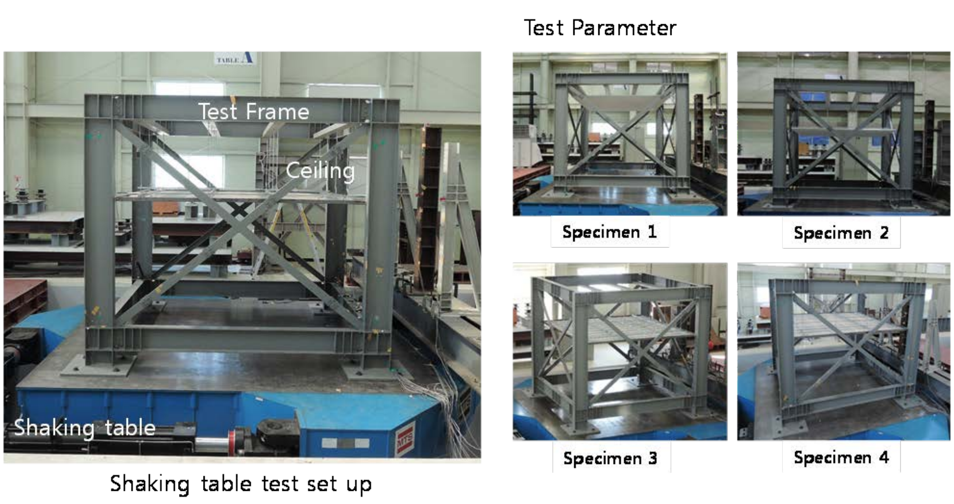


Fig. 4 - Setup for shaking table test

Three parameters studied in this investigation, which influence the excitation of suspended ceilings include: the height of suspended ceilings. The two different heights of suspended ceilings, 0.3m (short height) and 1.0m (normal height), were performed to experiments. The other two parameters are as follow:

- Lateral-displacement control: Using square-shape steel pipe, the lateral displacement of ceiling was controlled. The effect of wall can be simulated by installing square-shape steel pipes around the top of frames. The experiment can find characteristic of the natural free vibration of ceilings were observed without the blocking of walls.
- Type of suspended ceilings: M-bar ceiling system and T-bar ceiling system. M-bar ceiling system and T-bar ceiling system are mostly used in Korea. One of main differences between two ceiling systems is how to attach ceiling boards to bars. In M-bar system, ceiling boards and M-bar are connected by screws (**Fig 4-8**). In T-bar system, ceiling boards are lay on the T-bar without any connections.(**Fig 4-9**)

Table 5-Test parameters

Specimens	Type of ceilings	Height of ceilings	Lateral-displacement control	Ceiling area	Type of Frames
1	M-bar system	0.3 m	X	3 m X 3 m	Rigid Frame
2	M-bar system	1 m	X		Rigid Frame
3	M-bar system	1 m	O	3.325 m X 3.316 m	Rigid Frame
3A					Added mass (Acc. excitation)
4	T-bar system	1 m	O		Rigid Frame

Specimen 3A, M-bar ceiling system with walls (1 m) and added mass (12 ton), was set on the shaking table. The test results is compared with those of specimen 3, M-bar ceiling system with walls (1 m) to Specimen 3A. Before the shaking test, the random white noise excitation were applied to evaluate natural frequencies.

Table 6- Natural period of specimen

Natural Period (sec)				
Specimen	1	2	3	4
Ceiling	0.23	1.01	0.03	0.03
Frame	0.03			

The maximum recorded values of acceleration on the ceilings and on the test frame roof were drawn and compared to the maximum acceleration recorded at the base of the shaking table. On the ceiling, there were 4 accelerometers to record the acceleration. Accelerometers of A1 to A3 were installed in the edge of ceiling, and A4 was installed in the center of the ceiling.

In these tests, the displacements of ceilings and frame were recorded using LVDTs. For the displacement of ceilings of Specimen 3 and Specimen 4 the maximum displacement were very small with comparison of the Specimen 1 and Specimen 2 under both El-Centro and Mexico City excitations. The maximum displacement values of the ceilings are listed in Table 7**.**

Table 7- Maximum displacement at ceilings

Displacement(mm)		Ceiling				
		1	2	3	3A	4
El-Centro	30%	4.82	46.36	2.27	16.76	2.03
	50%	5.74	76.56	2.66	29.04	2.22
	70%	5.86	108.86	2.90	38.08	2.95
	100%	23.90	162.58	3.22	-	4.18
	120%	33.43	193.71	4.05	-	5.36
	150%	42.00	235.90	4.33	-	6.17
	200%	48.25	-	5.34	-	7.40
	250%	58.95	-	7.05	-	10.43
	300%	118.47	-	8.76	-	12.71
Mexico-city	30%	3.51	10.24	3.43	36.70	1.47
	50%	3.88	15.01	4.50	60.58	3.29
	70%	3.94	19.42	4.87	77.51	5.32
	100%	4.39	28.82	5.14	-	7.12
	120%	4.32	36.35	5.76	-	7.62

In this series of test, the strain gauges detected the largest strain on the hanger and hanger bolt among ceiling components (Hanger, Hanger bolt, M-bar, Carrying channel, M-bar clip, Minor channel, and Minor clip). It is interpreted that stress concentration were developed on the hanger and hanger bolt. In the test for El-Centro 150% excitation, the minor clip showed larger deformation than the other El-Centro excitation (30% to 120%).

3-2 Flexible frame with ceilings

Three M-bar systems and one T-bar system was tested using the earthquake simulator from KOCED used as for the strong frame test. Six Accelerometers (added 1 accelerometer was installed on the top of beam) and four LVDT and strain gauges were set to monitor the response of the test frame and suspended ceilings. The frames were subjected in the horizontal excitation (x-direction). The El-Centro and Mexico City earthquakes were applied in the x-direction of frame by varying the excitation level to 30%, 50% and 70%.

Table 8- Natural Period (sec) of specimen

Specimens	Type of ceilings	Height of ceilings	Lateral-displacement control	Type of Frames
1	M-bar system	0.3m	X	Flexible Frame
2	M-bar system	1m	X	Flexible Frame
3	**M-bar system**	**1m**	**O**	Flexible Frame

3A				**Added mass (Acc. excitation)**
4	T-bar system	1m	O	Flexible Frame

Table 9- Natural Frequency and Natural Period of specimen 3 and 3-A

	Specimen 3		Specimen 3-A	
	Frame	Ceiling	Frame	Ceiling
Natural Frequency(Hz)	35.79	32.07	1.99	1.99
Natural Period(sec)	0.03	0.03	0.5	0.5

The natural period of ceiling in Specimen 3 was measured as 0.03 Hz and that in Specimen 3A as 0.5 Hz. Also, the natural period of frame was similar to the ceiling, both Specimen 3 and Specimen 3A. The natural period of Specimen 3A was longer than that of Specimen 3 due to the lateral stiffness reduction in Specimen 3 by adding mass on the top and removing the bracings of frame.

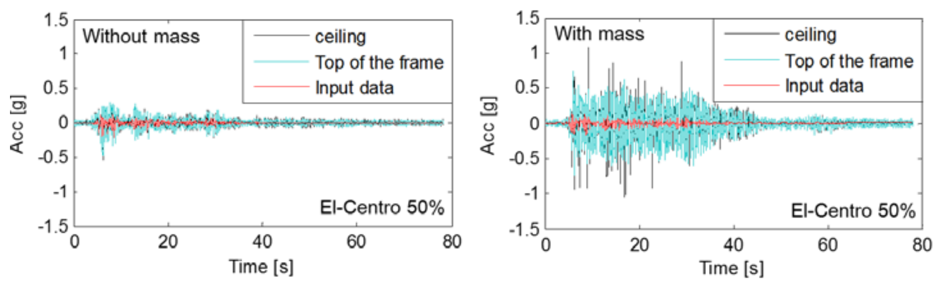


Fig.5 - Response acceleration of 3 and 3A (El-Centro 50%)

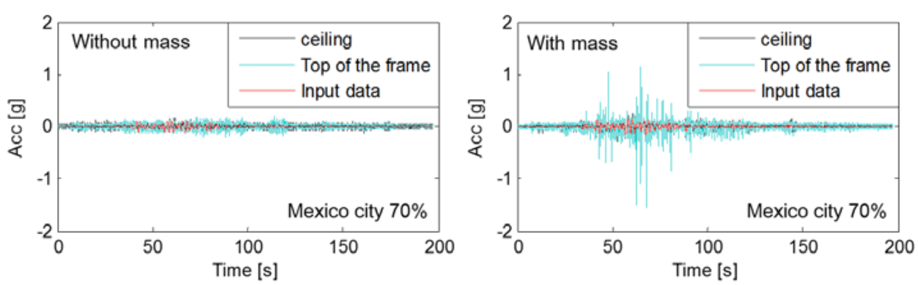


Fig. 6 - Response acceleration of 3 and 3A (Mexico City 30%)

For Specimen 3 and Specimen 3A in El-Centro excitation, Specimen 3A showed the acceleration amplification of top of the frame and ceiling. The maximum acceleration of Specimen 3A was recorded as 1.71g and 2.89g for the scale factors 30% and 50%. The resulting accelerations showed 5 times larger than the maximum acceleration of Specimen 3.

For Specimen 3 and Specimen 3A in Mexico City excitation, they have no significant difference in the acceleration at the top of the frame and the ceiling. For Mexico City 70% excitation, the acceleration response of top of the frame and the ceiling of Specimen 3A showed 5 time larger amplification than those of Specimen 3. The maximum displacement of the ceilings of 4 specimens under two excitations are listed in Table 10.

Table 10-Maximum displacement (mm) on the specimen (Ceiling),

Displacement(mm)		Ceiling				
		1	2	**3**	**3A**	4
El-Centro	30%	4.82	46.36	**2.27**	**16.76**	2.03
	50%	5.74	76.56	**2.66**	**29.04**	2.22
	70%	5.86	108.86	**2.90**	**38.08**	2.95
	100%	23.90	162.58	**3.22**	**-**	4.18
	120%	33.43	193.71	**4.05**	**-**	5.36
	150%	42.00	235.90	**4.33**	**-**	6.17
	200%	48.25	-	**5.34**	**-**	7.40
	250%	58.95	-	**7.05**	**-**	10.43
	300%	118.47	-	**8.76**	**-**	12.71
Mexico-city	30%	3.51	10.24	**3.43**	**36.70**	1.47
	50%	3.88	15.01	**4.50**	**60.58**	3.29
	70%	3.94	19.42	**4.87**	**77.51**	5.32
	100%	4.39	28.82	**5.14**	**-**	7.12
	120%	4.32	36.35	**5.76**	**-**	7.62

4. Discussion

Simple analysis models for suspended ceilings are suggested by hanging pendulums with fixed and simple boundaries to compared with the experimental results. Two models gave the lower and upper bounds for the maximum displacement. By varying the lateral stiffness of the cantilever model we found reasonable values between two bounds. Table 10 shows that the approximate stiffness between 50 % and 70 % are close to the experimental maximum displacements.

Table 11- Maximum displacement [mm] on ceilings compared with analysis value and experimental value

	Maximum displacement (mm)					
Stiffness factor for Model 1	Model 1	30%	50%	70%	Model 2	Experimental data
	3.09	2.16	1.55	0.93	0.19	
30%	21	24	27	47	49	37
50%	38	41	47	76	79	64
70%	56	57	69	108	112	94
100%	80	82	100	158	165	139

120%	97	97	120	192	205	163

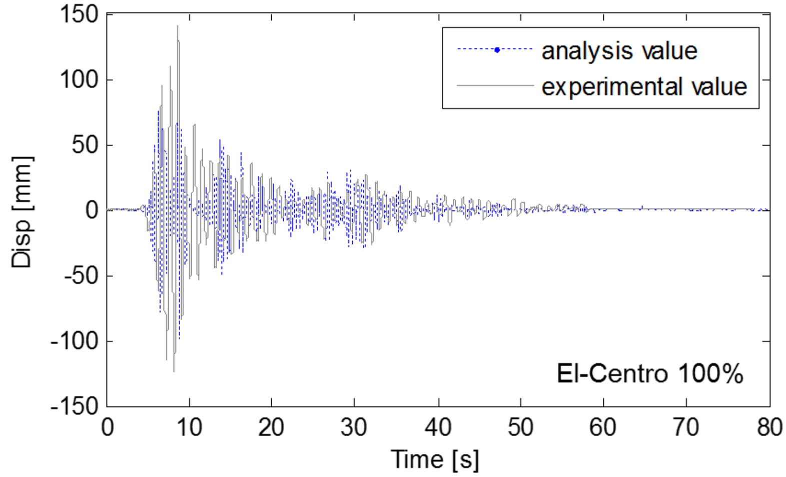


Fig. 7- Displacement of ceilings compared with analysis value and experimental value on El-Centro 100%

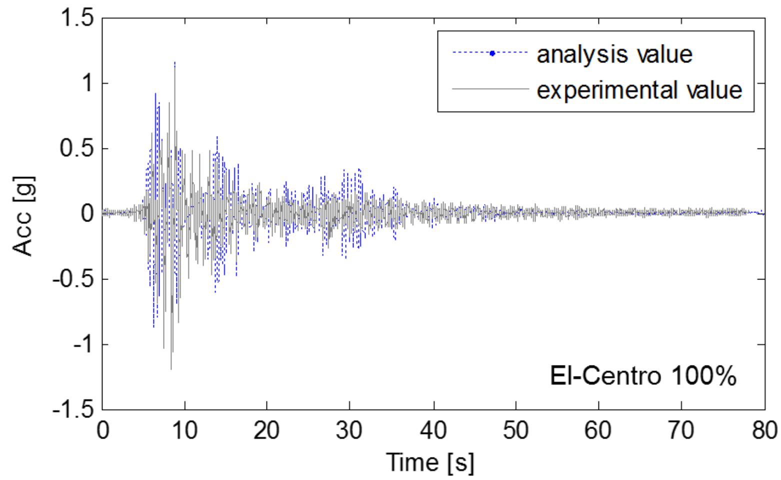


Fig. 8 - Acceleration of ceilings compared with analysis value and experimental value on El-Centro 100%

5. Conclusion

This study has shown both the static tests and dynamic tests for seismic design of suspended ceiling system as one of the nonstructural component. The ceiling components tests at each of three levels were performed to check the satisfactory requirement for capacity. Also the failure mode of components at three levels and the main cause of ceiling system were observed. Then, the seismic tests of the ceiling systems were performed to investigate the dynamic characteristics in simulated earthquake excitations. The dynamic performances including acceleration response, displacement response, deformation, natural period were evaluated.

Through the experiments, the results represents that the components of ceiling have fully ductility and enough bending rigidity satisfactory for the standard. At joint level, the connecting components evaluated in the tests satisfy the requirement in the standard. However, M-bar clip, one of the joint member, showing brittle failure of ceiling system is needed to be improved to prevent consequent brittle failure of ceiling systems. At module level, the deflection of the bars and channels were stiff enough below the limit by the standard. Also, major failure modes of ceiling systems and failure subsequences were identified depending given parameters. The major ceiling system failures were caused by the failure of clip of M-bar systems.

Through the shaking table testing for frames of different lateral stiffness with two ceiling systems, the dynamic characteristics of suspended ceilings on the top of frames were observed. Their acceleration response, displacement response and deformation response were measured. Under El-Centro excitation (short period), the magnitudes of acceleration, displacement and deformation increase as the excitation level increase. However, the dynamic response under Mexico City excitation (long period) showed no significant change as for El-Centro excitation. There was no ceiling system failure in the tests up to 1-g ground acceleration level but the minor damages such as the drop of the minor-clips, the damage of edge of ceiling boards were observed.

6. Acknowledgements

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