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Performance evaluation of suspended ceiling systems using shake table test

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Abstract. The national standard being used in Turkey for suspended ceiling systems (SCS) regulates material and dimensional properties but does not contain regulations regarding installation instructions which cause substandard applications of SCSs in practice. The lack of installation instructions would potentially affect the dynamic performance of these systems. Also, the vast majority of these systems are manufactured using substandard low-quality materials, and this will inevitably increase SCS related damages during earthquakes. The experimental work presented here focuses on the issue of dynamic performance of SCSs with different types of carrier systems (lay-on and clip-in systems), different weight conditions, and material-workmanship qualities. Moreover, the effects of auxiliary fastening elements, so called seismic perimeter clips, in improving the dynamic performance of SCSs were experimentally investigated. Results show that clip-in ceiling system performs better than lay-on system regardless of material and workmanship qualities. On the other hand, the quality aspect becomes the most important parameter in affecting the dynamic performance of lay-on type systems as opposed to tile weights and usage of perimeter clips. When high quality system is used, tile weight does not change the performance of lay-on system, however in poor quality system, tile weight becomes an important factor where heavier tiles considerably decrease the performance level. Perimeter clips marginally increase the dynamic performance of lay-on ceiling system, but it has no effect on the clip-in ceiling system under the shaking levels considered.

Keywords: suspended ceiling systems; shake table tests; performance characterization; non-structural elements; seismic perimeter clips

1. Introduction

Non-structural elements which are not considered as parts of buildings' structural system must still keep their integrity under earthquake action. Damage experienced in non-structural elements during an earthquake significantly affects the functionality of the building since staying operational after a damaging earthquake is very important for certain type of buildings (e.g.,

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hospital, emergency response buildings etc.). Poor performance of nonstructural components in past earthquakes has led to the evacuation of buildings, economic losses, and in extreme cases fatalities (Sharpe *et al*. 1973, Benuska 1990, Badillo 2003).

One of the most widely reported types of nonstructural damage in past earthquakes is the failure of suspended ceiling systems (Badillo 2003). This is due to widespread use of such systems in private/public buildings and hospitals. For this reason, performance of suspended ceiling systems during earthquakes requires special attention.

The relevant standard TS-EN 13964 in Turkey used for suspended ceiling systems (SCS) mostly deal with material and dimensional properties of the systems such as dimensions of constitutive parts, mechanical resistance of the material used during manufacturing, fire resistance, acoustic properties, durability, and heat insulation, as well as material testing methods to obtain these properties. However, this standard does not contain any information regarding installation instructions; instead the standard refers to the supplier specific instructions for installation. This leads to inconsistencies in installation of SCSs leading to substandard applications in practice which in turn directly affects the dynamic performance of these systems; therefore careful investigations and standardization of installation instructions are required. Although there is a standard for regulating manufacturing processes of SCSs in Turkey, still the vast majority of these systems are manufactured using substandard or code nonconforming low-quality materials. This problem combined with the lack of standard for installation further complicates the issue, and will inevitably increase the SCS related losses during earthquakes.

Past work on SCSs shows that numerical and/or analytical modeling studies on SCSs are difficult due to several reasons: complicated geometrical and connection details, system level uncertainties encountered once the whole system is assembled, nonlinear response once the system is forced beyond linear range, and extremely hard modeling challenges such as un-seating of supports and/or tiles. These difficulties hamper analytical modeling studies, and therefore leading researchers to mainly use experimental techniques to understand seismic performance of SCSs. Some of the past important experimental studies performed on SCSs are highlighted below.

One of the first shake table tests on SCS was conducted by ANCO Engineers in 1983 to assess the seismic performance of a 3.6 m×8.5 m suspended ceiling system with intermediate-duty runners and lay-in tiles. The major finding of the study was that the most frequent damage seen in SCS was around the perimeter at the intersection of the walls and the ceiling system where the primary and secondary runners buckled or unseated from the wall angle. The authors also observed that the inclusion of compression rods did not reduce the damage level in the system. Rihal and Granneman *et al*. (1984) subjected a 3.66 m×4.88 m suspended ceiling system to harmonic excitations. The major findings of the study were that vertical struts reduced the vertical motion of the ceiling systems, and sway-wires were useful in reducing the overall dynamic response of the system. Armstrong World Industries (ANCO 1993) performed a series of earthquake tests on a suspended ceiling system. The tests were performed on a 7.31 m×4.26 m ceiling system using earthquake motions representative of various seismic zones (ICBO 2000). The main result drawn from the experimental work was that the ceiling systems tested met the UBC design requirements for nonstructural components in critical facilities. In another study by Yao *et al*. (2000), a set of tests were performed to characterize the effects of installing sway-wires in SCSs. Tests showed that the installation of 45° sway-wires as recommended by the Ceiling and Interior System Contractors (CISCA 1992) did not lead to a significant reduction in the seismic vulnerability of ceiling systems. Badillo *et al*. (2007) has conducted a series of earthquake qualification tests and fragility work on suspended ceiling systems manufactured by Armstrong World Industries. These tests were unique in the sense that each ceiling system was subjected to a set of simultaneous horizontal and vertical ground excitations. Two different performance limit states were used for qualification purposes, namely loss of tiles and failure of the grid system.

McCormick *et al*. (2008) carried out a full scale experimental work for investigating the combined system behavior of gypsum board partition walls and traditional and seismically designed suspended ceilings. Experimental results show that both ceiling types performed well with a difference that seismically designed ceiling had larger capacity than the traditional ceiling. The study by Gilani *et al*. (2010) gives a comprehensive summary of some of the experimental work carried out on SCS systems for performance evaluation, SCS components and installation requirements, and as well as performance of suspended ceilings in recent earthquakes. One of the major conclusions of the paper is that suspended ceiling components installed per code performed well. A recent shake table test conducted by Magliulo *et al*. (2012) on two types of SCS systems, namely single and double frame ceilings, showed that these systems experienced no damage at all shaking intensity levels indicating very low fragility. Possible reasons behind this high performance are investigated in the paper. Ecchevarria *et al*. (2012) has carried out a study on the analytical modeling of suspended ceiling systems where analytical models of SCS with and without bracings have been developed. A comparative study has been carried out; but it is noted that the model has some limitations such as inability to capture progressive collapse of ceiling systems. Wen-Chun *et al*. (2013) has conducted a series of full scale tests investigating the global seismic performance of a coupled system composed of partition walls and suspended ceilings. One of the main outcomes of the study was that in the case of non-seismic installations, the whole system would collapse suddenly when the excitation hits the capacity threshold. Soroushian *et al*. (2015a, 2015b) published two companion articles on the evaluation of seismic capacity of suspended ceiling components, namely ceiling wires, interaction between ceiling panels and sprinkler heads, and grid connections. The first of the two articles presents the test results conducted on these components for axial, shear and bending capacity characterizations, and corresponding fragility curves, and the second article uses these experimental results to develop component level analytical models for improving modeling capabilities in order to fill the gap between complexity of actual ceiling systems and over-simplified analytical models.

Due to aforementioned modeling challenges, an experimental approach is chosen also in this study for characterizing the seismic performance of SCSs. The experimental work presented here mainly focuses on the specific issue of experimental characterization of the dynamic performance of suspended ceiling systems used in Turkey with different types and qualities (standard and substandard) as well as the effects of installation differences seen in practice. From this perspective following issues are studied: (i) general dynamic response of suspended ceiling systems (lay-on and clip-in) assembled using different structural elements (i.e., exposed T24 runners and clip-in keels), (ii) effects of different quality (i.e., code conforming and non-conforming) suspended ceiling materials on the dynamic performance of these systems, (iii) effects of tiles with different weights (steel and gypsum), and (iv) effect of an installation improvement so called seismic perimeter clips. Although the study focuses on the problems related to a specific country (Turkey), still the observations and recommendations made herein will shed light to other countries with similar problems, and therefore the results are invaluable for many other countries which do not explicitly regulate the installation of SCSs by specific codes.

Fig. 1 General view of the shake table used for the tests

2. Experimental facility, test setup and details of test specimens

2.1 Earthquake simulator

The dynamic tests were performed using the shake table system available at the Structural Engineering Laboratory of Dokuz Eylul University as shown in Fig. 1. The system is developed specifically for the purpose of studying earthquake performance of non-structural systems. It is a uni-axial system guided on two rails with wheels which also prevent rocking motion. The system is capable of producing periodic wave forms with different frequencies and amplitudes, as well as producing sine sweeps with simultaneously increasing amplitudes. It should be noted that the simulator is not a servo-hydraulic system, instead it is a mechanical system composed of a crank-shaft assembly connected to an electrical engine producing circular motion with different frequencies. This circular motion is then converted to translational motion with a shaft connected to the platform. One end of the shaft is connected to a steel disk where the engine is connected, and the other end is connected to the moving platform where the SCSs are mounted.

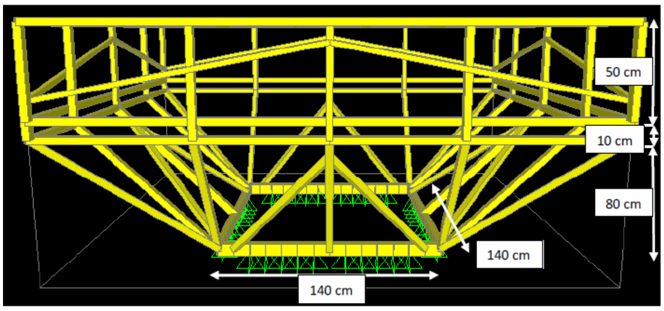
The stroke and frequency of the periodic motion are set by a control software at the beginning of each test. The controller in the system is not a feedback type controller; in other words once the motion starts off, there is no way to alter the motion of the platform using a feedback signal (e.g., displacement). Although the system is an open-loop system, due to the mechanical nature of the table, extensive commissioning tests showed that different test frequencies and stroke values were accurately reproduced even at the maximum payload conditions (~4000 N). On the negative side, due to its mechanical nature, the table is not able to produce random earthquake type waveforms. Regarding the signal fidelity of the table, it can be said that the target frequency could almost perfectly be reproduced; but the target amplitude was slightly distorted due to superposition of the odd harmonics of the target frequency on the main harmonic signal.

Other properties of the simulator are platform size = 140 cm×140 cm, maximum rigid payload capacity=4000 N, max. acceleration=±2.0 g at 3 Hz (where g is the acceleration of gravity), max. stroke=±125 mm at 0.3 Hz (max. acceleration at 0.3 Hz is 0.045 g), frequency range of operation= 0.3 Hz-3.0 Hz. Later in the paper the performance envelope for the simulator is provided. Notice that as the frequency of operation decreases, table displacement increases but simultaneously table acceleration decreases, and as the frequency of operation increases table acceleration increases but simultaneously table displacement decreases.

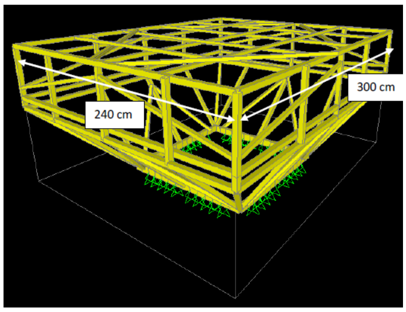
It should be emphasized that the highest operational frequency of the table is 3 Hz. This puts a cap on the maximum acceleration level that can be reached by the table platform. The frequency upper limit, in turn, puts a limit on the inertial force levels that can be attained on the SCSs. If higher frequencies could be reproduced on the table, higher force levels could be obtained which may lead to different SCS performances at these higher frequencies; therefore the results presented in this study must be viewed within the frequency range of interest (i.e., between 0.3 Hz-3 Hz).

2.2 Test frame and sensor layout

A steel test frame with a plan dimension of 3.0 m×2.4 m was designed and manufactured to test the suspended ceiling systems. The purpose of the test frame was to provide realistic boundary conditions for the ceiling systems to be tested. Finite element model of the test frame is shown in Fig. 2. The test frame was designed as rigid as possible in order to minimize the dynamic interaction that may take place between the table platform and the test frame. In other words, dynamic amplification from the shake table platform level to the test frame level where the ceiling system to be attached must be avoided. Analysis results showed that the frequency of the first fundamental longitudinal vibrational mode (along the degree-of-freedom of the platform) was around 12 Hz which was sufficiently larger than the highest operational frequency of the simulator (i.e., 3 Hz) to avoid excessive amplification. Fig. 3 shows the steel test frame mounted on the shake table. In the figure, three different levels are indicated. The different suspended ceiling



(a) Front view



(b) Perspective view

Fig. 2 Finite element model of the steel test frame

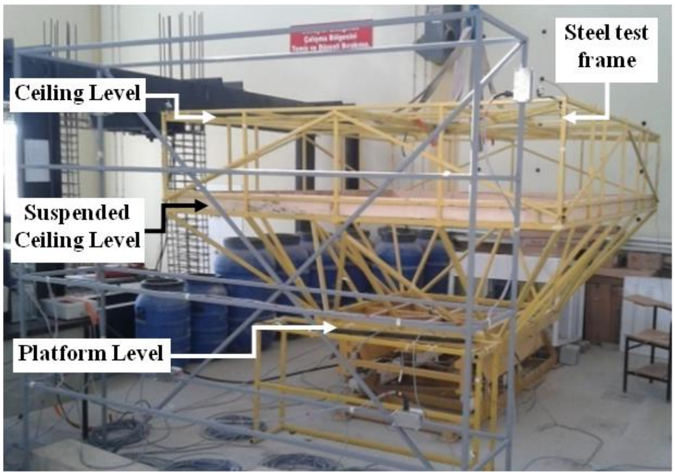
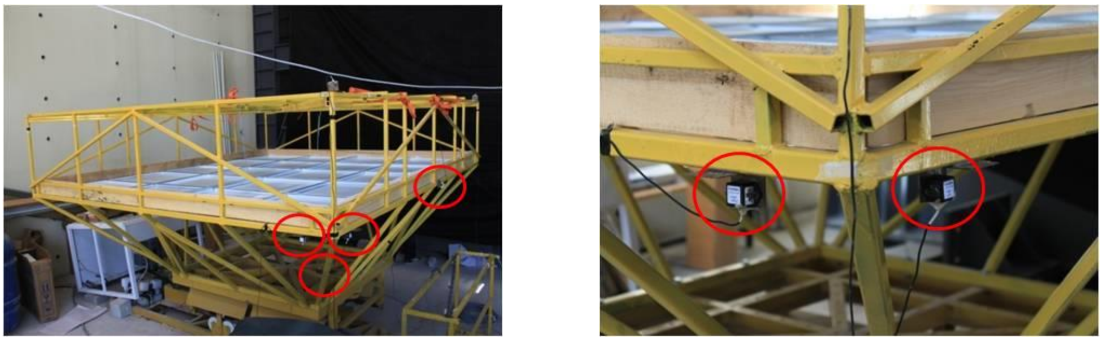
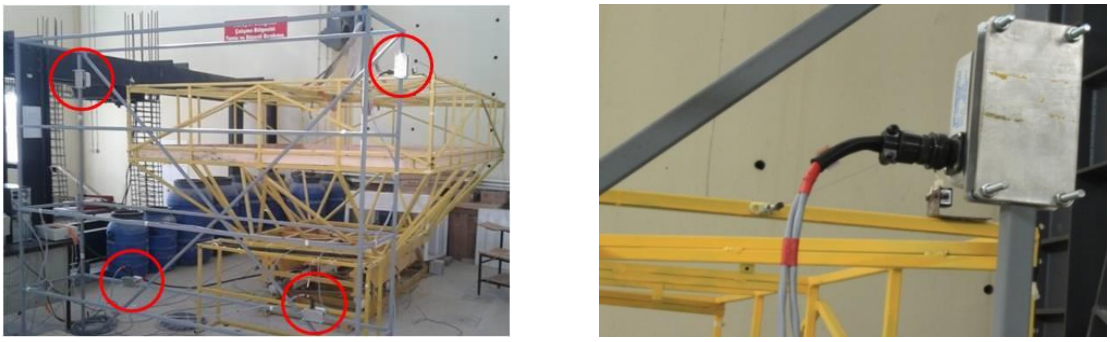


Fig. 3 Steel test frame mounted on the shake table



(a) Overall view (b) Close-up view

Fig. 4 Locations of the accelerometers



(a) Overall view (b) Close-up view

Fig. 5 Locations of the string-pots

systems were mounted at the level designated as “suspended ceiling level”. The ceiling systems were suspended by suspension wires from the level designated as “ceiling level”.

Accelerometers and displacement transducers were used to monitor responses of the simulator platform, test frame, and ceiling systems. Fig. 4 shows the locations of the accelerometers on the platform and the test frame. Total of four uni-axial accelerometers with ±4 g range were used to record the acceleration of the platform along the longitudinal degree-of-freedom (dof), and the suspended ceiling level along longitudinal, transversal and torsional dofs.

Also, longitudinal displacements of the test frame at the ceiling and platform levels were followed by four string-pots with ±1000 mm stroke range (Fig. 5). Displacements measured by the string-pots were mainly used to cross-check accelerations reached on the platform and on the ceiling levels. Also, they were useful in assessing the flexibility of the test frame (which should have been very stiff) by calculating inter-story drift occurring between the platform and the ceiling levels. Other than these purposes, they were not directly used for response interpretations, for that purpose acceleration responses were exclusively used. Dynamic data was recorded by a 24-bit 16-channel dynamic data acquisition system.

2.3 Suspended ceiling systems

In general suspended ceiling systems are composed of following components: (i) grid system which is composed of main- and cross-runners, (ii) wall mouldings (L-type and C-type profiles), (iii) suspension wires, and (iv) tiles; there are also some auxiliary elements to wedge or connect these components together. Within the scope of the experimental study, dynamic response of T24 and Clip-in grid systems were studied under two different material qualities (i.e., high and low) and also under high and low workmanship qualities. Here by high quality material, it is meant that manufacturing of the ceiling components comply with national standards (manufactured locally and approved by the national standard institute), and by low quality material, it is meant that manufacturing does not comply with national standards (components imported from eastern markets without any further check by the national standard institute).

Quantifying high and low workmanship, and including it as a test parameter was a challenging task; but based on the carefully made field observations and personal communications with the assembly workers, the authors have concluded that it is an important parameter that does affect the system performance considerably, and hence must be included as a parameter. One of the most important workmanship defects observed was the distance between the screws used to fix wall mouldings to walls/beams. In a high quality workmanship conditions, the distances is between 30 to 40 cm whereas in a low quality conditions the distance is between 60 to 80 cm (about twice as large). Therefore for the high quality system this distance was set to 30 cm whereas in the low quality system it was set to 60 cm. Another workmanship defect was loose connections between individual grid components; this problem was more pronounced in one of the suspension grid types (i.e., T24) used in the study. This defect is introduced in the low quality system by the assembly worker under close guidance of the authors. The assembly worker was kept the same connection defect throughout the entire test program to ensure that the same defect level was maintained. It should be noted that the same assembly worker worked during the entire test program in order to keep the workmanship skill the same.

2.3.1 T24 suspension grid systems

T24 type suspension grid is used with lay-on tile systems (Fig. 6). In the lay-on system, a grid system is formed by two different grid component, namely main and cross runners. The main

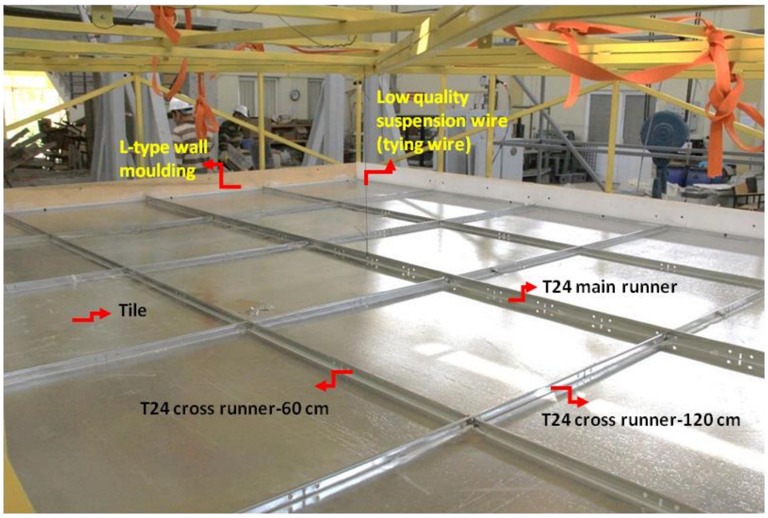


Fig. 6 A typical suspended ceiling system with T24 suspension grid (low quality setup)

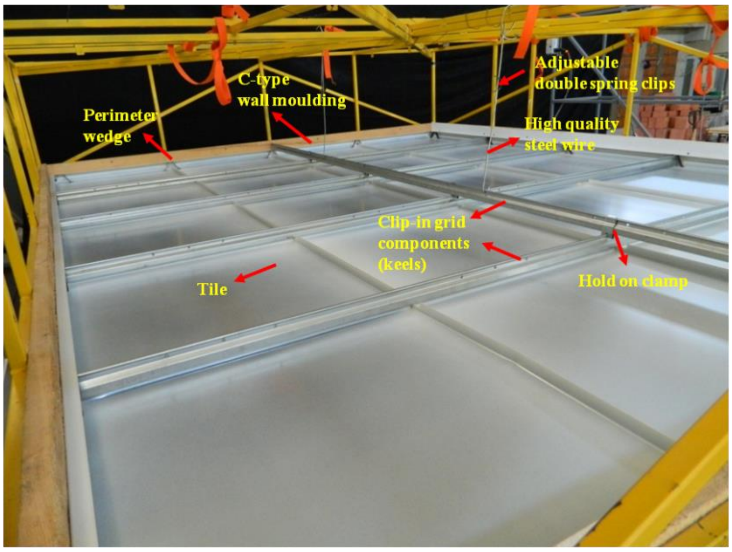


Fig. 7 A typical suspended ceiling system with clip-in grid system (high-quality setup)

runners are used in one-direction placed parallel to each other at intervals of 120 cm. Cross runners have two different lengths of 60 cm and 120 cm. 60 cm cross runners are used in the direction of main runner, and 120 cm cross runners are used perpendicular to the main runner forming a grid system. At the perimeters, runners are placed on the L-type wall mouldings as shown in Fig. 6. Dimensions of L-type mouldings are 20×20×2 mm.

2.3.2 Clip-in suspension grid systems

Clip-in keels are used with clip-in ceiling systems, and a single type of grid component is used for that purpose (Fig. 7). In this system, grid components at the top are placed at intervals of 120 cm in one direction, and the ones at the bottom are placed at intervals of 60 cm in the direction perpendicular to the top ones. As shown in Fig. 7, grid components in both directions are connected to each other with *hold on clamps*. Opposite two sides of each tile is restrained by the grid at the bottom. At the perimeters, runners are placed on C-type wall moldings. Perimeter wedges (auxiliary elements) are used for tightly pressing the free sides of tiles on the mouldings. Dimensions of C-type mouldings are 20×40×2 mm.

2.3.3 Suspension wires

Suspension wires with two different material qualities were used; namely low quality 2 mm thick tying wires (Fig. 6) which is very commonly used in practice, and high quality 4 mm thick galvanized steel wires (Fig. 7). High quality wires were used with the high quality grid system, and low quality wires were used with the low quality grid system. Also in high-quality grid systems, adjustable double spring clips for adjusting the length of suspension wires were used (Fig. 7) whereas in low-quality systems wires were just twisted in the shape of a hook to suspend the grid as very frequently done in real life applications.

2.3.4 Tiles

Three different types of tiles were used for the experimental program. For T24 suspension grid,

Table 1 Properties of the tiles used for the suspended ceiling systems

Grid System	Tile type	Material Quality	Tile Size [mm]	Weight [N/tile]
T24	Gypsum	Low	595×595×8	21.78
		High		25.21
T24	Steel	Low	595×595×2	5.59
		High		15.01
Clip-in	Steel	Low		6.48
		High		16.78

(a) For lay-on grid system (b) For clip-in grid system

Fig. 8 Seismic perimeter clips

steel and gypsum tiles and for clip-in grid system only steel tiles were used which is the only option for the clip-in system. For both ceiling systems, total of 20 tiles were used in each installation. Dimensions and unit weights of steel and gypsum tiles, both low and high quality cases are given in Table 1. Notice that gypsum tiles are heavier in terms of unit weight than the steel tiles, therefore will attract larger inertia forces during seismic events.

2.3.5 Seismic perimeter clips

Perimeter clips shown in Figs. 8(a)-(b) are for T24 and clip-in grid systems, respectively. Although being optional elements, they are used for securely fastening the main runners to the wall mouldings as opposed to no fasting (i.e., main runners were just sitting on the mouldings). These clips are developed by a local manufacturer, and are intended to improve the earthquake performance of the suspended ceiling systems; but have never been tested under dynamic action. Therefore, effects of the seismic perimeter clips in improving the earthquake performance of SCSs must be examined.

Based on the aforementioned information, four distinct variables are considered important for the seismic performance of SCSs, which are: (i) effects of different grid components (T24 runners vs. clip-in keels), (ii) effects of material quality and workmanship (details regarding this parameter are explained above), (iii) effects of different tile weights (steel vs. gypsum), and (iv) effect of perimeter clips. The test matrix given in Table 2 was prepared considering these variables, and the corresponding ceiling system configurations were tested under dynamic action. In the following

Table 2 Test configurations for different suspended ceiling systems

Conf.	Material and Workmanship	Grid Component	Tile Type	Tile Material	Suspension Wire Type	Perimeter Clips
1	High quality	T24	Lay-on	Gypsum	Thick	No
2	Low quality	T24	Lay-on	Gypsum	Thin	No
3	High quality	T24	Lay-on	Gypsum	Thick	Yes
4	High quality	T24	Lay-on	Steel	Thick	No
5	Low quality	T24	Lay-on	Steel	Thin	No
6	High quality	T24	Lay-on	Steel	Thick	Yes
7	High quality	Clip-in keels	Clip-in	Steel	Thick	No
8	Low quality	Clip-in keels	Clip-in	Steel	Thin	No
9	High quality	Clip-in keels	Clip-in	Steel	Thick	Yes

paragraphs, high quality system will refer to both high material and workmanship quality, whereas low quality system will refer to both low material and workmanship quality.

3. Test protocol

Test (loading) protocol used to determine the seismic performance of suspended ceiling systems was established by taking into account certain aspects of seismic loading protocols provided in two different codes, namely Istanbul Highrise Buildings Code (2008) - IHBC, and Acceptance Criteria for Seismic Certification by Shake-Table Testing of Non-Structural Components (AC156).

The loading protocol specified in IHBC is considered simple to be used directly for testing SCSs without introducing any changes. The protocol specified in IHBC requires a full scale non-structural component and/or system to be tested in two discrete frequencies (0.4 Hz and 0.8 Hz) with gradually increasing amplitudes. Maximum amplitude level to be gradually reached is specified indirectly by inter-story drift level of 2.5% of the height of the unit tested. The code requires that at each amplitude level, four full cycles of motion at each frequency and amplitude must be reproduced on the shake table. The test protocol mainly targets displacement sensitive non-structural elements, and therefore it is anticipated that the specified protocol would not be appropriate to test acceleration sensitive systems such as suspended ceilings, and that it would be necessary to reproduce higher inertial forces. On the other hand, due to the working principles and operational limits of the available shake table, the loading protocol described in AC-156 could not be strictly followed either. The main reason for this is that the shake table cannot reproduce nonstationary broad-band random excitation which is a prerequisite of AC-156. This excitation must be synthesized from a required response spectrum developed for a particular ground spectral acceleration factor (S_{DS}) which varies per specific geographical location and site soil condition.

A different testing protocol had to be followed in this study due to above mentioned reasons. This protocol was developed by making use of different aspects of both codes mentioned above wherever it was possible and appropriate. It should be underlined here that if AC156 could have been strictly followed, some of the results obtained would have been different. The details regarding the test protocol used are provided in the following paragraphs.

Three different demand levels were used to assess the seismic performance of the SCS systems. Since a particular earthquake hazard of a region in Turkey wanted to be studied, these demand levels were taken from a national earthquake code called the Earthquake Code for Coastal and Port Structures, Railroads and Airports (DHL, 2007). The region considered was a specific location in the city of Izmir which is the third largest city lying on the western coast of Turkey. The earthquake levels considered were D1, D2 and D3 with 50%, 10%, and 2% probability of exceedance in 50 years, respectively. Main reason for defining three distinct levels is to be able to assess the performance of different SCSs in different demand levels. Required acceleration response spectrums for these three different levels were calculated using the equation given in AC-156 using the particular seismicity of a location in Izmir. For this purpose the following equation is used

$$A_{Flex} = S_{DS} \times \left(1 + 2 \times \frac{z}{h}\right) \tag{1}$$

where *z/h* is the height factor ratio accounting for where the SCS system is mounted within the building. This value ranges between 0 and 1 where the value zero is used when SCS is at grade level, and the value unity is used when SCS is at the roof level. In this study, this ratio is taken as unity. Ground spectral acceleration factor S_{DS} is defined above and can be calculated as follows

$$S_{DS} = \frac{2}{3} \times F_a \times S_s \tag{2}$$

where F_a is short period soil coefficient, and S_s is short period spectral acceleration. S_s value is chosen for a specific location in Izmir, and F_a value is chosen by assuming that the soil type is type E which is a soil with equivalent shear wave velocity of 180 m/s and less (corresponding to a very unfavorable soil condition). S_S values used for D1, D2, and D3 level earthquakes are 0.6 g, 1.5 g, and 2.0 g, respectively. Based on the parameters given above and AC-156 specifications, required response spectrums were calculated, and are shown in Fig. 9.

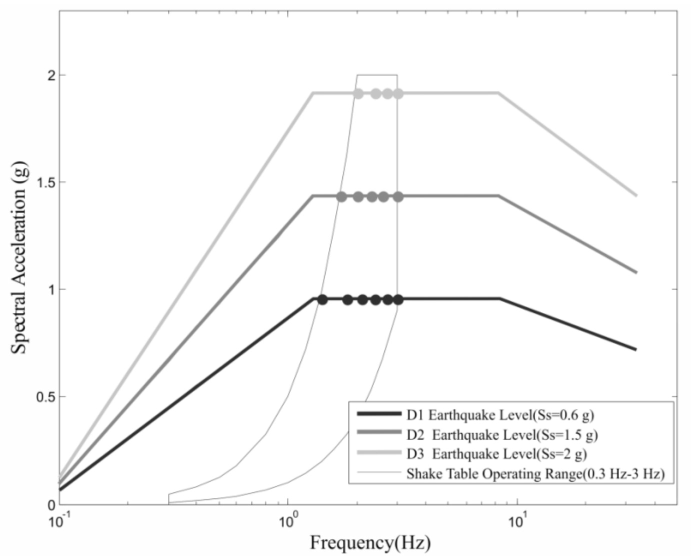


Fig. 9 Acceleration response spectrum plots corresponding to D1, D2 and D3 earthquakes, and the simulator’s performance envelope (operation range)

In Fig. 9, the performance envelope of the shake table is also shown. It is clear that the existing shake table is not capable of operating in the entire range of the response spectrum, and also is not capable of reproducing random broad-band excitation. Therefore, only some spectral acceleration-frequency pairs in harmonic form had to be used for performance evaluation tests (shown as dots in the figure). These pairs were chosen in such a way that they would exert maximum earthquake demand (i.e., in the plateau region) on the suspended ceilings. SCSs are acceleration sensitive nonstructural elements, therefore maximum spectral acceleration values at different frequencies were used to assess their seismic performances.

It should be reminded here that the shake table used is a mechanical system involving a crank-shaft mechanism. There is an eccentricity of approximately 120 mm on the disk where the shaft is connected; therefore the minimum displacement that the table could reproduce is ~120 mm (i.e., in other words the table cannot reproduce displacements smaller than 120 mm due this eccentricity). This in turn puts a lower bound on the acceleration levels that can be reproduced on the table which is 0.045g at 0.3 Hz.

4. Observations and evaluation of test results

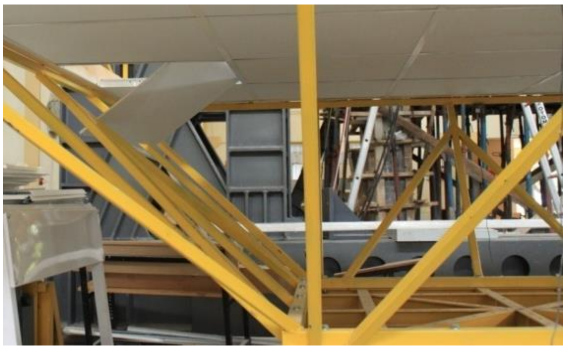
The loading protocol described above was applied separately in two different lateral directions. In order to do that once the tests for one direction were completed, the test frame was detached from the platform and rotated 90 degrees, and the tests for the other direction were performed. After each dynamic test, tiles and grid components were thoroughly investigated, and damaged components (e.g., broken latches of cross tees, chipped tiles, etc.) were replaced with the undamaged ones prior to the next test. Therefore each dynamic test, which had different intensity, was performed on ceiling systems of undamaged conditions. The installation of the ceiling system as well as replacement of broken parts were all done similar as in market applications by an experienced suspended ceiling assembly worker. The number of cycles to be reproduced for a particular test frequency was decided by the recommendation given in IHBC where it is recommended that for each test frequency *four* cycles need to be applied.

Four performance levels are considered to characterize the seismic performance of suspended ceiling systems: (1) Immediate Occupancy-1 (IO-1), (2) Immediate Occupancy-2 (IO-2); (3) Life Safety (LS); (4) Collapse Prevention (CP)/Collapse Level (CL). The performance levels are defined quantitatively by the number of damaged ceiling components which are described in Table 3 as percentage of damage in various ceiling subcomponents. First three limit states (IO-1, IO-2, and LS) account for the number (or percentage) of tiles dislocated or fell from the grid systems, and the 4th limit state (CP/CL) is associated with substantial structural damage in the grid system. Total of 270 dynamic tests were performed in two separate directions. In the following paragraphs, damage observations from some of these tests of configuration 2 (Table 2) are given. Damage observations from other configurations are not shown for the sake of conciseness; but the results from these tests are reflected in the results and general conclusions.

Damage shown in Fig. 10(a) occurred in the suspended ceiling system of configuration 2 at 2.4 Hz in D2 level excitation (1.44 g). It shows clearly that structural damage has not occurred in the system at this excitation level; only one tile was dislocated. This damage and hence the corresponding performance level is characterized as Immediate Occupancy-1 (IO-1). Damage shown in Fig. 10(b) occurred in the suspended ceiling system of configuration 2 at 2.1 Hz in D2 level excitation (1.44 g). It shows a low-level crushing at some of the mouldings. This damage and

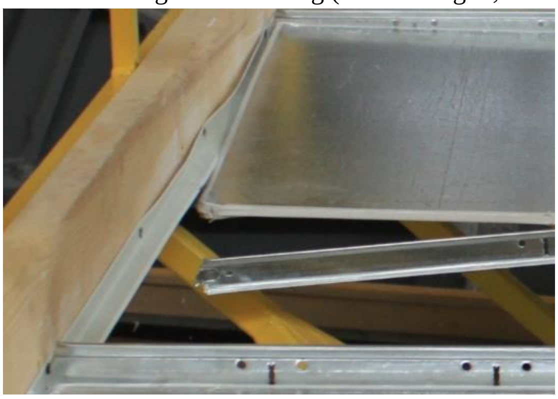
Table 3 Performance levels and corresponding damage types

Performance levels	Damage type
Immediate occupancy-1 (IO-1)	No damage or dislocation or rocking of a single tile
Immediate occupancy-2 (IO-2)	Dislocation/falling of 10% or less number of tiles, and low-level crushing at wall mouldings (L-type or C-type)
Life safety (LS)	Dislocation/falling of 33% or less number of tiles, unseating of one or more cross runner from wall mouldings, mid-level crushing at mouldings
Collapse prevention (CP)/Collapse level (CL)	High-level crushing/flattening of wall mouldings, dislocation and buckling of one or more cross runners



(a) Dislocation of a single tile (from config. 2, see Table 3)

(b) Low-level crushing of a moulding (from config. 2, see Table 2)



(c) Mid-level crushing at a moulding and unseating of one cross runner from the moulding (see Table 2)

Fig. 10 Damage or partial collapse in configuration 2

(a) Overall view

(b) Detailed view

Fig. 11 Complete collapse in configuration 2

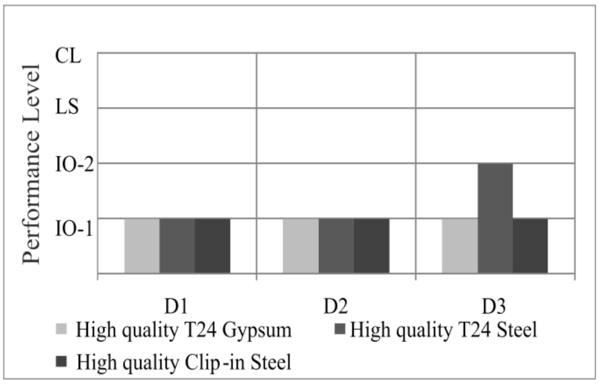
hence the corresponding performance level is characterized as Immediate occupancy-2 (IO-2).

Damage shown in Fig. 10(c) occurred in the suspended ceiling system of configuration 2 at 2.4 Hz in D3 level excitation (1.92 g). It shows a mid-level crushing in a moulding (not a widespread crushing damage), and unseating of one cross runner from the moulding. This damage and hence the corresponding performance level is characterized as Life Safety (LS) performance level.

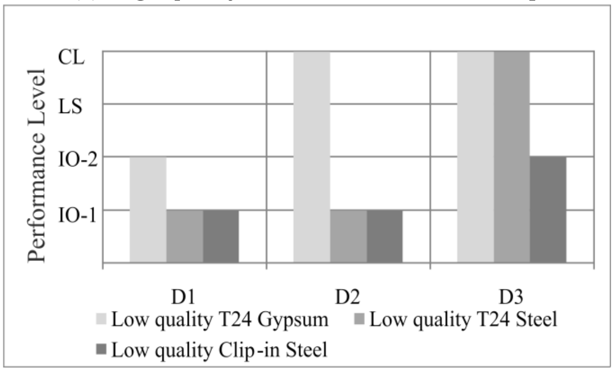
Damage shown in Fig. 11 occurred in the suspended ceiling system of configuration 2 at 2.7 Hz in D3 level excitation (1.92 g). It shows a damage state where complete collapse has occurred. This damage and hence the corresponding performance level is characterized as Collapse prevention (CP)/Collapse level (CL).

Figs. 12-15 show the performance levels of suspended ceiling systems with different configurations. In these figures, *x*-axis is the dynamic excitation level, and the *y*-axis is the performance levels described as in Table 3. It can be seen from Fig. 12(a) that in the case of high-quality materials and workmanship, T24 suspension system with steel tiles exhibit a slightly poorer performance than the other configurations (i.e., T24 suspension system with gypsum tiles and clip-in suspension system with steel tiles) under D3 demand level; but it can be said that at all excitation levels, high quality suspended ceiling systems perform at IO-1 and -2 performance levels. On the other hand, in the case of low-quality material and workmanship conditions as shown in Fig. 12(b), T24 suspension system with steel and gypsum tiles exhibit poorer performance than the clip-in suspension system with steel tiles. It should be noted that in some of these cases, the ceiling systems went through complete destruction (CL level performance). Therefore, it can be said that for the case of high quality material, both T24 type lay-on and clip-in systems perform similar with a slightly better performance of clip-in system. In the case of low quality material, the clip-in ceiling system shows a noticeable better performance compare to the low quality T24 lay-on system.

There are several reasons why T24 suspension grid is more sensitive to material and workmanship qualities than clip-in grid system: (i) T24 grid system is formed with many junction points where short runners meet and form a grid system. In other words, instead of using uninterrupted several long runners resulting in fewer junction points, shorter runners forming many junction points are used; this nature of T24 systems results in a grid system with many vulnerable points. On the contrary, for the clip-in grid system several long runners (keels) are used resulting in fewer junction points. This results in a grid system with less vulnerable load-carrying nature. (ii) T24 grid system has end-clips at each end of the runners whereas clip-in systems do not possess end-clips. End-clips must be manufactured with a type of alloy having higher strength allowing force to be transferred in a better way among different runners. (iii) Clip-in system instead has very sturdy hold-on clamps avoiding vulnerable junction points and a better force

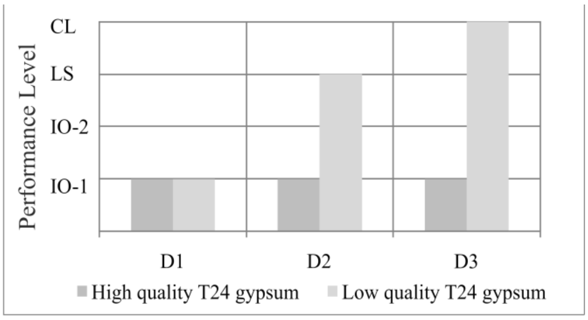


(a) High quality materials and workmanship

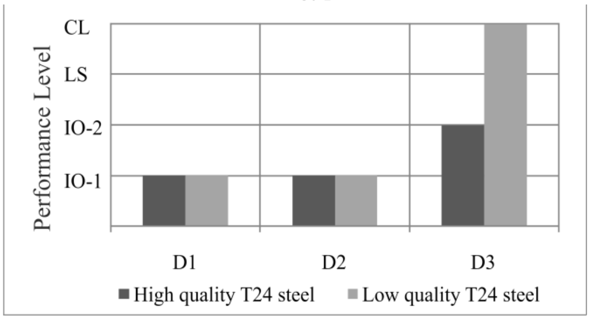


(b) Low quality materials and workmanship

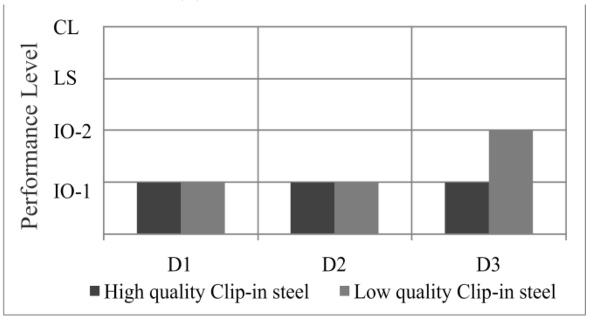
Fig. 12 Performance levels of different suspended ceiling systems with different configurations



(a) T24 with gypsum tiles



(b) T24 with steel tiles

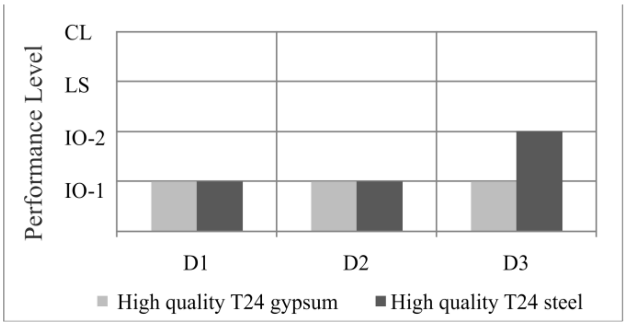


(c) Clip-in with steel tiles

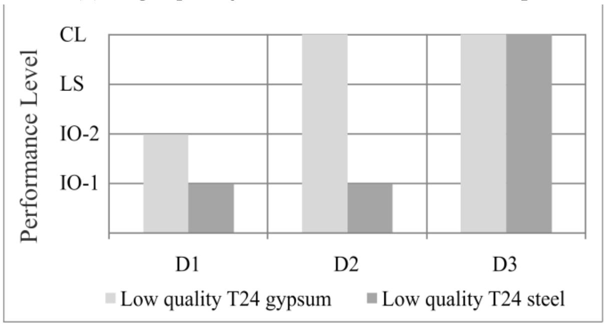
Fig. 13 Effect of material and workmanship qualities and tile weight on the performance of SCSs

transfer mechanism among different keels. (iv) T24 suspension grid can be used with heavier gypsum tiles whereas clip-in system does not have the gypsum tile option. Since these systems are acceleration sensitive, heavier tiles attract larger inertial forces putting higher load demand on the T24 grid system. Finally, (v) profiles used for clip-in system has larger cross-sectional areas than the profiles used for T24 system making them more resistive even under low quality material and workmanship conditions.

Figs. 13(a)-(b) show the effects of low/high material and workmanship qualities on the performance of lay-on type suspended ceiling systems (T24 suspension grid) with different tile conditions. It is very clear from the figures that material and workmanship quality affects the performance considerably with a worse performance characteristics as the tile type gets heavier (i.e., gypsum tiles). Fig. 13(c) shows the performance of clip-in grid system constructed with high and low quality material and workmanship conditions; it is clear that both for low and high quality



(a) High quality material and workmanship



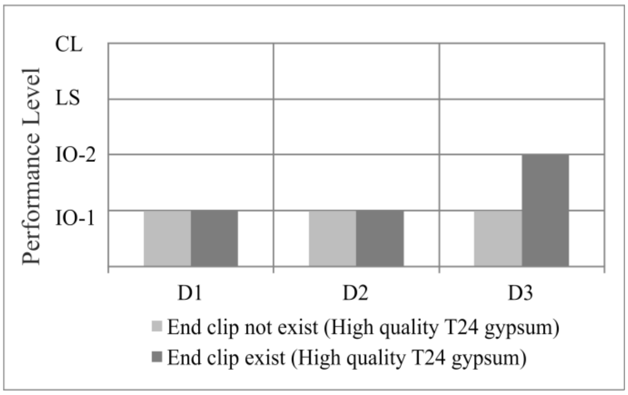
(b) Low quality material and workmanship

Fig. 14 The effects of different weight tiles on the performance of T24 type grid system

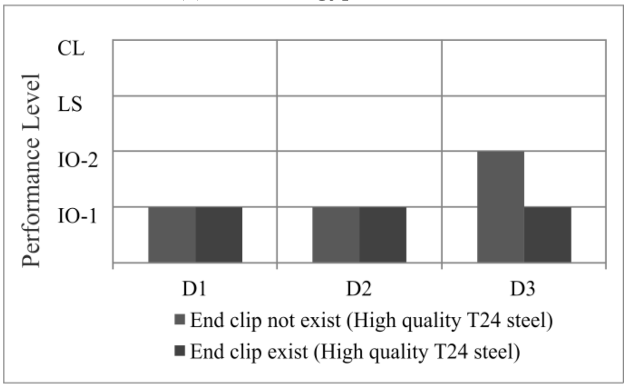
cases, the clip-in grid system perform similarly under the excitation levels considered with slightly better performance when the quality is high (see the results for the D3 level excitation). Overall, it can be said that T24 suspension grid is more sensitive to the material quality and workmanship than the clip-in type grid systems (the reason for that is the same as the reasons listed above).

In Figs. 14(a)-(b), effect of tile weight on the performance of the T24 type suspension grid explicitly considered. As shown in Fig. 14(a), in case of high quality material and workmanship, T24 type grid with steel and gypsum tiles exhibited IO-1 performance level at D1 and D2 level excitation whereas in D3 level, the same systems showed IO-1 level with gypsum tiles (heavier) and IO-2 level with steel tiles (lighter). It seems that there is a controversy in the results; but actually in the case of high quality system, lighter steel tiles are more prone to unseating from the grid system (which is a lay-on type system) than the heavier gypsum tiles which in turn lowers the performance level one step down from IO-1 to IO-2. On the other hand, as shown in Fig. 14(b) in the case of poor quality material and workmanship, the performance of the T24 type grid system depends heavily on the weight of the tiles. In this case, even at D1 level excitation, the system with gypsum tiles performed worse than the one with steel tiles. Moreover, at D2 level excitation the system with gypsum tiles reached to the CL performance level whereas the one with the steel tiles was at IO-1 level. At D3 level, both systems performed at CL level. It can be said that, as the material and workmanship qualities get poorer, tile weight plays a very important role in determining the performance level of T24 type grid systems.

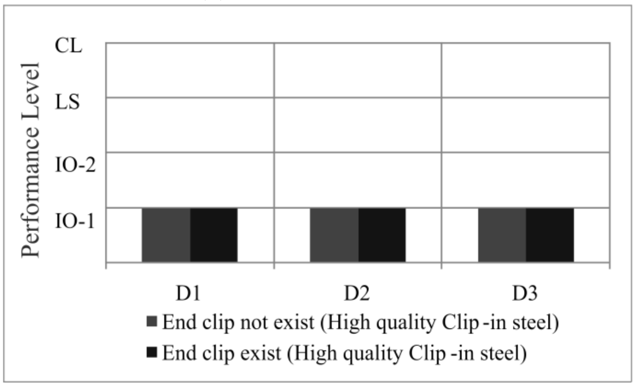
Figs. 15(a), (b) and (c) show the effects of seismic perimeter clips on the performance of T24 and clip-in type grid systems. Notice that here only high quality material and workmanship case is considered, since it is expected that in low quality cases, these end-clips will not be used which is



(a) T24 with gypsum tiles



(b) T24 with steel tiles



(c) Clip-in with steel tiles

Fig. 15 The effect of end-clips to the performance of T24 and clip-in type suspension grid

consistent with real-life applications. From the figures, it seems that the end-clips for both T24 and clip-in grid systems as well as for both gypsum and steel tiles affect the performance of high quality systems marginally. In Fig. 15(a), it seems that there is even a negative effect of these auxiliary fastening elements. Although an utmost attention has been shown in the assembly process, there might still have been some small differences in the assembly phase, and this result may be attributed to these differences.

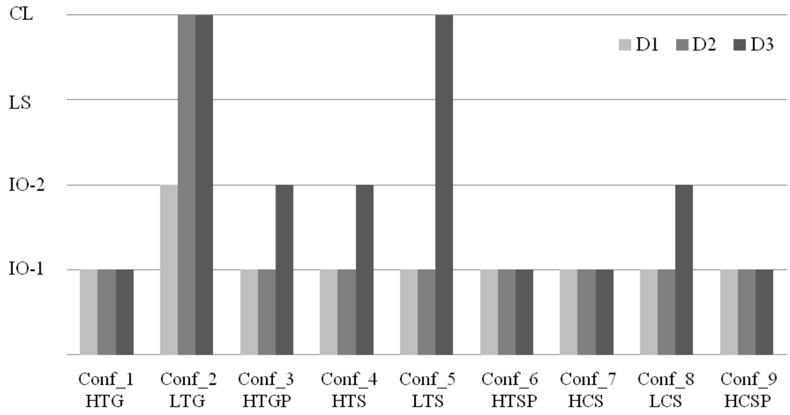


Fig. 16 Performance levels reached for different suspended ceiling systems tested under different seismic demand levels

Fig. 16 shows all the performance levels attained by SCSs from different tests, and their corresponding demand levels. This plot gathers the outcomes given in Figs. 12 to 15, and summarizes the results in one single figure. It is main purpose is to enable easy comparisons among different grid systems, tile types, and workmanship conditions. In Fig. 16, H and L stand for High and Low Quality Material and Workmanship, respectively, T and C stand for T24 and Clip-in Grid Systems, respectively, G and S stand for Gypsum and Steel Tiles, respectively, and P stands for Perimeter Clips. For instance, HTG means High Quality T24 grid system with gypsum tiles. It is clear from the figure that the lowest seismic performance of CL is attained in LTG (even at D2 level) and LTS systems (i.e., low quality material and workmanship cases).

It is also desired to check the design forces acting on the different ceiling systems. The design seismic forces acting on non-structural elements are given in Istanbul Highrise Buildings Code (IHBC) (2008) as follows

$$F_e = \frac{m_e A_e B_e}{R_e} \tag{3}$$

where m_e is the mass of non-structural element (here suspended ceiling system), A_e is the acceleration level experienced by the system in m/s^2, B_e is the dynamic magnification factor, R_e is the response reduction factor. Using the tables provided in the code, B_e and R_e coefficients are chosen to be 1.0 and 2.5, respectively. Acceleration values were measured during the tests at two different levels, namely at the platform and ceiling levels (see Fig. 3). Since the grid system and the tiles were at the ceiling level, the average acceleration values at the ceiling level were designated as A_e. Table 4 summarizes the characteristics of the ceiling systems, values calculated by the equation given above, and corresponding performance levels. It should be noted that accelerations on the platform were slightly smaller than the ones measured on the ceiling level showing that there was a small amount of dynamic amplification (in the order of ~5%) due to the flexibility of the test frame; but for all practical purposes this amplification was considered acceptable.

Table 4 Equivalent dynamic load on suspended ceiling systems and corresponding performance levels

Conf.	Material and Workmanship Quality	Grid Type	Tile	Single Tile Mass [kg/tile]	Total Suspended Ceiling Mass [kg]	Acc. on Platform Level [g]	Acc. on Suspended Ceiling Level [g]	Design Force[(2)] [N]	Performance Level
					m_e		A_e	F_e	
1	High	T24	Gypsum	2.57	61	2.00	2.10	503	IO-1
2	Low	T24	Gypsum	2.22	54	1.98	2.15	456	CL
3	High with PC[(1)]	T24	Gypsum	2.57	61	2.00	2.10	503	IO-2
4	High	T24	Steel	1.53	41	2.10	2.20	354	IO-2
5	Low	T24	Steel	0.57	21	2.10	2.16	178	CL
6	High with PC	T24	Steel	1.53	41	2.10	2.20	354	IO-1
7	High	Clip-in	Steel	1.71	42	2.06	2.15	354	IO-1
8	Low	Clip-in	Steel	0.66	21	2.00	2.14	176	IO-2
9	High with PC	Clip-in	Steel	1.71	42	2.06	2.15	354	IO-1

[(1)]PC in the table stands for Perimeter Clips.

[(2)]The design force, F_e, equals to the total inertial load which is $m_e \times A_e \times B_e$ divided by R_e the response reduction factor.

IHBC code allows some damage to be experienced by the ceiling system by setting the response modification factor to R_e=2.5 for suspended ceiling systems. It is also specified in the code that for important buildings such as hospitals, public buildings etc. which are immediately needed after a damaging earthquake, the performance level under D3 earthquake must be at the life safety level (LS). It should be emphasized here that this performance level is expected from SCSs if these systems are designed and assembled considering the design forces given in Table 4 which was not the case here. SCSs tested were not designed considering the design forces given in the table; but were assembled under similar conditions exist in practice.

From Table 4, it is clear that under the same level of design forces (T24 type grid system with gypsum tiles, see Conf.'s 2 and 3 in the table), the system with low material and workmanship quality performed very poorly, and its performance level occurred as CL (i.e., not satisfying the performance level set by the code). On the other hand, the system with higher quality performs (Conf. 2) as IO-2 (i.e., surpassing the expected performance level by heuristic design and assembling). Conf. 2 went through some small damages as anticipated by the code. It can be said that the low material quality system was not able to withstand D3 level excitation, and performed very poorly. Similar observations can be made for the Conf. 4 and 5 (T24 system with steel tiles) where the low quality system went through an extensive damage therefore not satisfying the performance level under D3 level excitation set forth by the code. Note that for the low quality system (Conf. 5), although the steel tiles weighed considerably lower than the tiles for Conf. 4 (about half), it is still performing worse than the latter system. For configurations 7 and 8 where clip-in systems were used, regardless of the quality, both systems performed better than the expected performance level under D3 level excitation.

5. Conclusions

The experimental work presented in this study investigated the dynamic performance of different type and quality suspended ceiling systems used widely in Turkey. Two different grid and tile types and two different material and workmanship conditions were considered for the tests. Effects of locally developed and produced seismic perimeter clips on the performance of ceiling systems were also investigated. It should be emphasized here that due to certain limitations (limited frequency range and incapability of reproducing random excitations) of the shake table system used, the chosen test protocol was not strictly following the requirements specified in the related codes. Therefore, below given results must be viewed from the perspective of these limitations in order to avoid unrealistic generalizations.

Following conclusions can be made based on the test results and analysis:

• Material and workmanship quality are the most important parameters in affecting the dynamic performance of suspended ceiling system, implying that unregulated manufacturing and installation (as of now there is no specification for installation) may lead to extensive non-structural damage in these systems leading to operational shut-downs in critical facilities and/or fatalities after a damaging earthquake,

• Clip-in grid system performs better than T24 type grid system (lay-on system) regardless of material and workmanship quality,

• When high quality system is used, tile weight does not change the performance of T24 type grid system which performed IO-1/2 levels under severe shaking (i.e., D3 level). On the other hand when poor quality system is used, tile weight becomes a very important factor in determining the performance level where heavier the tiles result in much poorer performance,

• Seismic perimeter clips marginally improve the dynamic performance of T24 type suspension grid system under the shaking levels considered, but it has no effect on the clip-in grid system,

• For T24 type grid system, the distance left between the ends of the main and cross runner and the wall boundaries (wall edges), and number of screws (i.e., 30 cm vs. 60 cm) used to mount the mouldings to these boundaries where the runners sit are other important parameters affecting the dynamic performance of suspended ceiling systems. As the distance gets larger and fewer screws are used runner ends get more prone to crushing and therefore to unseating,

• In high quality systems both for T24 and clip-in grid components, performance levels set by the IHBC code are met; on the other hand in low quality systems for T24 type grid, performance levels set by the code cannot be reached. Note that although the code allows a small amount of damage in the system by lowering the elastic design forces experienced by these systems, in low quality systems very brittle severe damage cases may be observed leading to CL level performance under D3 level excitation.

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