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ORIGINAL RESEARCH PAPER

Shake table tests for seismic assessment of suspended continuous ceilings

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Abstract After an earthquake, the failure of suspended ceiling systems is one of the most widely reported types of nonstructural damage in building structures. Since suspended ceiling systems are not amenable to traditional structural analysis, full-scale experimental testing is planned and executed. In particular, shaking table tests are performed in order to investigate the seismic behaviour of plasterboard continuous suspended ceilings under strong earthquakes. Two kinds of ceiling systems, named single frame ceiling and double frame ceiling, are tested. A steel test frame is properly designed in order to simulate the seismic effects at a generic building storey. A set of five accelerograms, used as input for the shakings, are selected matching the target response spectrum provided by the U.S. code for nonstructural components. Three limit states (occupancy, damage and life safety limit state) are considered in this study in order to characterize the seismic response of suspended ceiling systems. The tested ceilings show no damage at all intensity levels, evidencing a low fragility. Three main aspects may be the cause of this low vulnerability: (a) the continuous nature of the tested ceilings; (b) the dense steel channel grid that supports the plasterboard panels; (c) the large number of hangers that connects the ceiling system to the roof, avoiding any vertical movement of the ceilings. Finally, an interesting comparison is made with a previous vulnerability study on a different typical U.S. ceiling system.

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1 Introduction

Nonstructural elements are defined as those systems and components attached to the floors, roof and walls of a building or industrial facility that are not part of the main load-bearing structural system, but may also be subjected to large seismic actions (Villaverde 1997). The ceiling system considered in this paper certainly belongs to nonstructural components category.

The failure of ceiling systems has been one of the most widely reported types of nonstructural damage in building structures during past earthquakes (Badillo-Almaraz et al. 2006; Gilani et al. 2010a). The recent L'Aquila earthquake, occurred on April the 6th, 2009, in central Italy, has widely confirmed the last assertion: the majority of the evacuated buildings showed undamaged structural elements and moderate-to-heavy damaged nonstructural components, especially ceiling systems (Magliulo et al. 2009).

As studies available in bibliography point out (Taghavi and Miranda 2003), the damage of the nonstructural components gives the largest contribution to the economic loss due to an earthquake. In Fig. 1 a typical cost distribution is shown for the most common buildings: structural cost represents a small portion of the total one, corresponding to 18, 13 and 8 % for offices, hotels and hospitals respectively (Taghavi and Miranda 2003). Within the nonstructural components category, the interior construction, to which the suspended ceilings belong, represents the largest source of cost (about 30 % of the nonstructural components cost). The economic impact is much more severe if losses of inventory and business income are considered: the cost related to nonstructural components failure may easily exceed the replacement cost of the building (EERI 1984). Furthermore, their failure may also represent a threat to life safety. A partition or infill overturning or a ceiling collapse may easily result in injuries or death.

For these reasons and especially for emergency or strategic buildings (that must be operative immediately after an earthquake), the knowledge of the seismic performance of nonstructural elements is essential. Their behavior is also strongly inserted in the framework

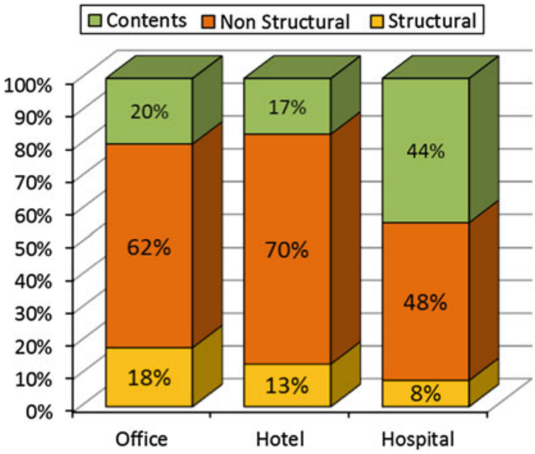


Fig. 1 Typical distribution of costs in three different building typologies (Taghavi and Miranda 2003)

of the "Performance-based earthquake engineering" (PBEE). With this approach, the building seismic performance is defined considering the behavior of both structural and nonstructural elements. Hence, the fragility evaluation of nonstructural components becomes a relevant issue, also considering that they usually exhibit damage even for low-intensity earthquakes.

Although nonstructural components assume a crucial importance within the PBEE, limited study was conducted in the past on their performance evaluation. In particular, concerning plasterboard ceiling systems, since 1980s and 1990s few research studies were conducted on typical ceiling systems, dynamically excited with real and artificial strong-motion (ANCO 1983, 1993; Rihal and Granneman 1984; Yao 2000). An extensive study aiming at evaluating the fragility curve of a ceiling system composed of tiles supported by metallic grids was carried out in Buffalo via shaking table test (Badillo-Almaraz et al. 2007; Gilani et al. 2010a). The influence of some innovative devices, such as the use of retainer clips and compression posts, on system fragility was investigated; the difference between normal and undersized tiles was also addressed. A typical fragility curve for the ceiling systems is also reported in Miranda et al. (2004). The interaction between plasterboard partitions and continuous ceilings was studied in McCormick et al. (2008) via unidirectional horizontal shake table tests; this ceiling typology demonstrated an excellent performance up to very large interstorey drifts (0.03rad) and accelerations (2.1g). In Maddaloni et al. (2010) ceiling tests are discussed, presenting a procedure for the best simulation of floor response spectra in shake table experiments.

In this paper, the seismic behaviour of plasterboard continuous suspended ceilings under strong earthquakes is investigated. The ceiling system differs from the systems of the most of the previous studies in its "continuous" nature: it consists of a unique plasterboard panel obtained by connecting few boards to each other. The vulnerability evaluation of this particular plasterboard ceiling system is the main goal of the research. This aim is pursued via shake table tests: this experimental facility is particularly needed in this case. Indeed, since analytical methods are not easily applicable to nonstructural components, such as ceilings, and data from past earthquakes are not suitable for the characterization of the fragility, the most appropriate technique to evaluate the fragility of such systems is the experimental method.

A comparison with tests on a U.S. common ceiling system is also presented.

2 Experimental facilities and test set up, specimens and input

The shaking table tests, performed in order to investigate the seismic behaviour of plasterboard continuous suspended ceilings, are carried out at the laboratory of the Structural Engineering Department of the University of Naples Federico II.

Two typologies of plasterboard continuous suspended ceilings are tested: single frame ceiling (SFC) and double frame ceiling (DFC) systems. A schematic representation of the two systems used is shown in Fig. 2a, b, respectively. The main components of tested suspended ceiling systems are: the "primary channel", C steel section profiles spaced at 500 and 1,000 mm for SFC and DFC systems, respectively; the "secondary channel", C steel section profiles spaced at 500 mm for DFC system; the "perimetral channel", U steel section profiles laterally restraining the ceiling (used for SFC and DFC systems); the "hangers", pinned bars, spaced every 1,000 mm (500 mm orthogonally to the primary channel direction in SFC), that link the steel grid [made of only primary channel (SFC) or primary and secondary channels (DFC)] with the roof, 200 mm or 500 mm long for SFC and DFC respectively; the "plasterboards", gypsum panels properly sized and horizontally jointed, weighing 89 N/m^2.

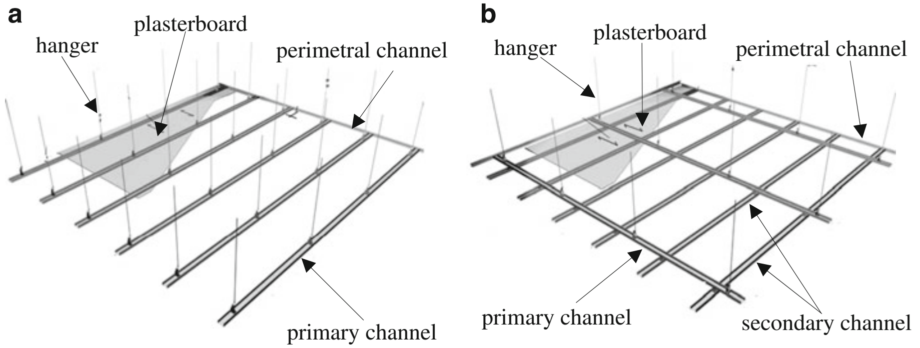


Fig. 2 Suspended plasterboard continuous ceilings: **a** single frame ceiling (SFC); **b** double frame ceiling (DFC)

2.1 Test setup and specimens

The seismic qualification of a suspended ceiling is carried out by the earthquake simulator system available at the laboratory of Structural Engineering Department of University of Naples Federico II. The system consists of two 3 m × 3 m square shake tables. Each table is characterized by two degrees of freedom in the two horizontal directions. The maximum payload of each shake table is 200 kN with a frequency range of 0–50 Hz, acceleration peak equal to 1 g, velocity peak equal to 1 m/s and total displacement equal to 500 mm (±250 mm). Only one shake table is used in this experimental campaign.

A steel test frame is properly designed and built (Figs. 3, 4a) with the purpose of simulating the seismic effects on the ceilings. The geometry of the test frame is defined taking into account two requirements: (a) a low fundamental period, outside of the range of frequencies of nonstructural components range (i.e. about 1–33 Hz, see ICBO 2000) in order to avoid resonance problems: indeed, the tested ceiling system is excited by the acceleration time history that occurs on plasterboard perimeter, which can be strongly influenced by the flexibility of the test frame (Gilani et al. 2010b); (b) height of the specimen sufficient in order to facilitate its assembly. The result is a 2.42 m (X dir.) × 2.71 m (Y dir.) × 2.72 (Z dir.) test structure of S275 steel material with concentric V-bracings (see Fig. 3). The test frame presents rolled H-shaped columns (HE220A profile) and beams (HE180A profile); the connections are bolted. A horizontal frame made of U-section steel profiles (UPN100) is bolted to the beams of the test frame (HE180A), as shown in Fig. 3a, in order to allow the anchorage of the ceiling system to the roof. As mentioned earlier, concentric V-bracing systems are placed as shown in Fig. 3b, c, in order to strongly stiffen the structure; bracing systems are made of steel U-section (UPN160). Two U-section profiles (UPN100) are welded around the perimeter of the test frame, at a distance of 20 and 50 cm from the roof; a 40 mm × 100 mm timber ledger is inserted in the U-section profile in order to easily laterally restrain the ceiling system. Indeed, the plasterboards of the ceiling are connected by a perimeter U-section runner to the timber ledger. Consequently, the light mass and the large stiffness of the timber-channel profiles system represent the typical boundary conditions of a ceiling on structural elements.

A FEM model of the test frame is assembled by means of the computer program SAP2000 (Computers and Structures 2010). Each element of the test frame is implemented as elastic "beam" finite element. The FEM model is implemented in order to perform the analysis and

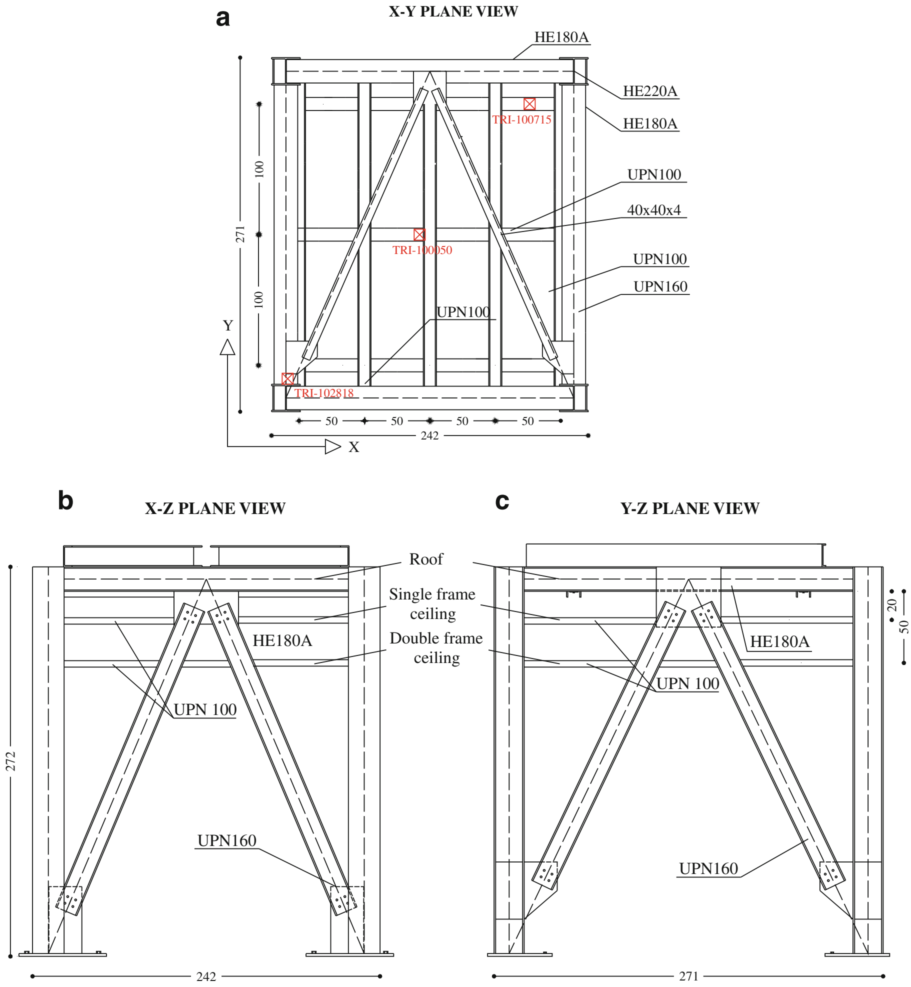


Fig. 3 Technical scheme of the test setup: **a** plan view, **b** and **c** lateral views

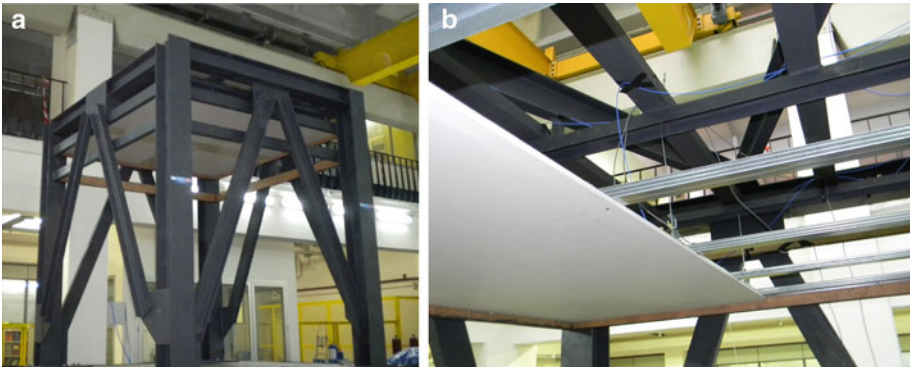


Fig. 4 **a** Test frame installed on the shake table; **b** SFC specimen detail

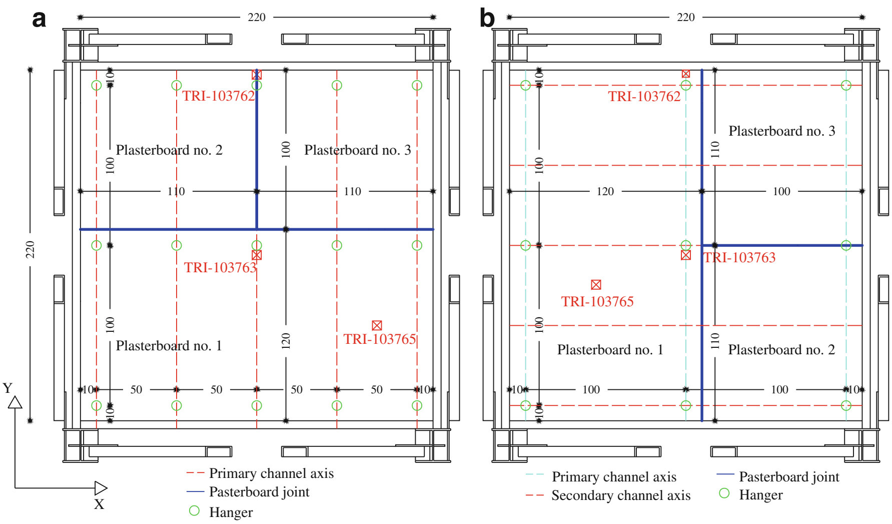


Fig. 5 Triaxial accelerometers, plasterboard and hanger position in the case of single frame ceiling (**a**) and double frame ceiling (**b**) specimen

to obtain an estimation of the first period along both orthogonal directions of the test frame: along X direction it is 0.02 s, along Y direction it is 0.018 s. The test frame is designed according to Eurocode 3 (CEN 2005a,b) and Eurocode 8 (CEN 2004) provisions by elastic modal response spectrum analysis. The total weight of the test frame is equal to 19.2 kN. In Fig. 4 a picture of the installed final setup on the shake table is shown.

The tested specimen is composed by three plasterboards connected one another via stucco, both for SFC and DFC (see Figs. 4b, 5). The total dimension of the specimen is 2.20 m × 2.20 m.

2.2 Instrumentation

Accelerometers and strain gauges are used to monitor the response of the test frame and plasterboard ceilings in both ceiling system configurations.

Three strain gauges are installed in SFC tests in order to monitor deformations in the above mentioned perimetral channel (SG1) and in the plasterboard panels (SG2, SG3). Two additional strain gauges are adopted in DFC tests, in order to measure the primary (SG4) and secondary (SG5) channels stress level.

In order to adequately measure roof rigid rotation and unexpected relative displacements, three triaxial accelerometers (named TRI-100050, TRI-102818, TRI-100715) are installed at the centre (TRI-100050) and at the edges of the roof (TRI-102818, TRI-100715) (Fig. 3a).

In Fig. 5 the position of other three accelerometers is indicated. In particular, for both tests performed on single and double frame ceiling systems, one accelerometer is placed on the top side of the plasterboard (TRI-103765), one on the "primary channel" steel profile (TRI-103763) and one on the "perimetral channel" steel profile (TRI-103762).

In order to complete the accelerometers layout, one triaxial accelerometer is placed at the base of the frame, in order to verify the real input transmitted to the specimen from the shaking table.

2.3 Input and testing protocol

In order to investigate the seismic behaviour of plasterboard continuous suspended ceilings, a set of five accelerograms, used as input for the shakings in Y direction (see Fig. 3), are specifically selected to match a target response spectrum, as provided by the ICBO-AC156 code "Acceptance criteria for seismic qualification testing of nonstructural components" (ICBO 2000).

The first step consists in the definition of the target spectrum or required response spectrum (RRS). According to ICBO, the RRS is obtained as a function of the design spectral response acceleration at short periods, S_{DS}, depending on the site soil condition and the mapped maximum earthquake spectral acceleration at short periods (for more details see section 6.5 in ICBO-AC156). The procedure is performed for a Required Response Spectrum corresponding to $S_{DS} = 1.50g$. In details, as recommended by the AC156 code procedure, a baseline signal is defined starting from nonstationary broadband random excitations having an energy content ranging from 1.3 to 33.3 Hz and one-sixth-octave bandwidth resolution. The total length of the input motion is 30 s. Then, the signal is enhanced by introducing wavelets using the spectrum-matching procedure of the RSP Match program (Hancock et al. 2006). The matching is obtained when, over the frequency range from 1.3 to 33.3 Hz, the elastic response spectrum ordinates are not lower than the RRS ordinates by more than 10 percent and do not exceed the RRS ordinates by more than 30 percent (according to EC8 (CEN 2004) and AC156 rules respectively). In order to obtain a drive motion compatible with the shaking table velocity and displacement limits, the so obtained matched record is driven through a high pass filter for frequencies larger than 1.0 Hz.

Figure 6 shows the obtained acceleration time history, its elastic response spectrum, namely the test response spectrum (TRS), the RRS corresponding to S_{DS} equal to 1.50g and the RRS scaled to 90 and 130 %.

The procedure is performed, as mentioned, for a RRS corresponding to $S_{DS} = 1.50g$; the so obtained record is then scaled to match other four levels of the target spectrum (corresponding to S_{DS} 0.30g, 0.60g, 0.90g and 1.20g). The range of S_{DS} corresponds to peak ground accelerations from 0.12g to 0.60g on stiff soil, representative of low-to-high seismic zones.

Additional information on testing specifications is present in Magliulo and Manfredi (2011).

3 Results, comparisons and observations

In order to define the experimental fundamental period in the Y direction of shaking, a dynamic identification procedure is performed using a white noise test. A frequency value of about 30 Hz, i.e. 0.03 s, is obtained; it is close to the numerical results and confirms the high stiffness of the test frame. This feature, in addition to the test frame-to-ceiling rigid connection and the ceiling in-plane stiffness, causes, as desired, an acceleration on the ceiling (Tables 1, 2) close to the horizontal spectral acceleration for rigid equipment, i.e. A_{RIG} in AC 156 (ICBO 2000). Indeed, continuous ceiling systems can be classified as rigid non structural components ($16.7\ \text{Hz} < f < 33.3\ \text{Hz}$) in the horizontal direction.

Using the selected drive motions, five unidirectional shaking tests along Y direction (see Fig. 3) are performed for both ceiling systems. In Tables 1 and 2 the maximum recorded values of acceleration on the ceilings and on the test frame roof are listed and compared to the maximum acceleration registered at the base of the shaking table. This comparison

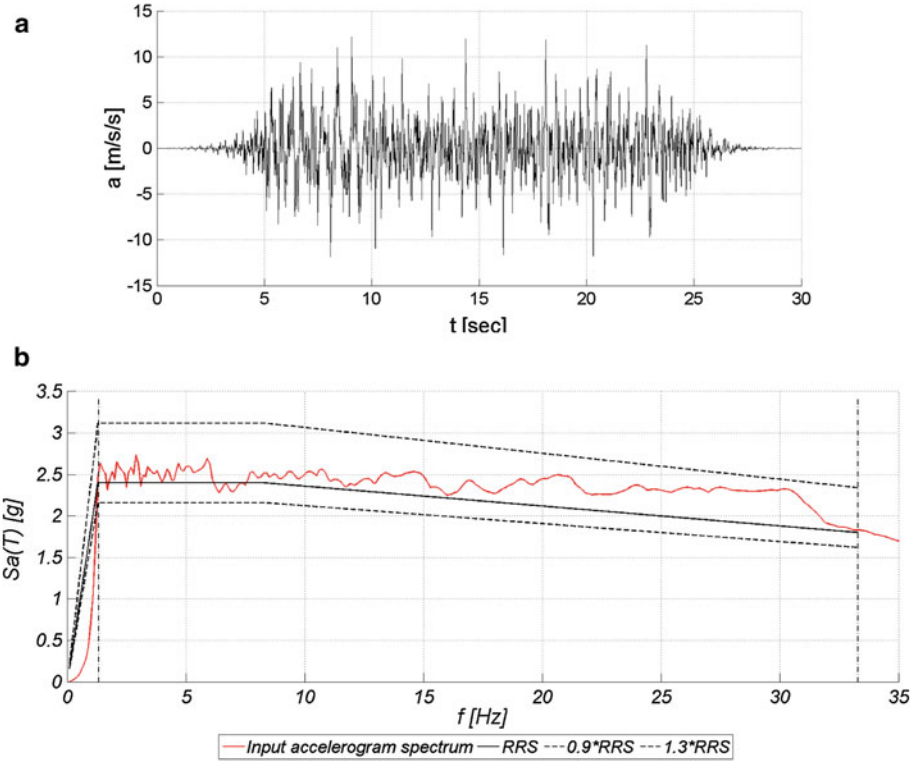


Fig. 6 Earthquake time history and spectra for a level of shaking corresponding to S_{DS} equal to 1.50g: **a** acceleration time-history; **b** input accelerogram spectrum, RRS (*bold line*), upper and lower matching limits (*dashed line*)

Table 1 Maximum recorded accelerations on the specimen (*Ceiling*), test frame top (*Roof*) and at the shake table level (*Base*) as indicated in Fig. 3: single frame ceiling test

Position	Ceiling			Roof			Base
Accel. no.	103763	103762	103765	100050	100715	102818	103766
Test no. 1	0.42g	0.40g	0.42g	0.45g	0.42g	0.41g	0.25g
Test no. 2	0.78g	0.78g	0.75g	0.78g	0.74g	0.78g	0.50g
Test no. 3	1.10g	1.04g	1.02g	1.15g	1.04g	1.18g	0.69g
Test no. 4	1.75g	1.79g	1.66g	1.90g	1.70g	1.93g	1.04g
Test no. 5	2.28g	2.28g	2.19g	2.51g	2.22g	2.48g	1.36g

is done both for single (Table 1) and for double frame ceiling (Table 2). Values greater than 2.0g, due to dynamic amplifications in the specimen, are recorded on the ceiling. As known, usually, the signal recorded at desired locations is completely different from the expected effect of shake table motion. The dynamic amplification aspect may be crucial when the build of a fragility curve is the main goal of the research since the values of acceleration recorded on the component can be not predict before the test is performed. For this reason, the procedure described in Maddaloni et al. (2010), concerning the optimization

Table 2 Maximum recorded accelerations on the specimen (*Ceiling*), test frame top (*Roof*) and at the shake table level (*Base*) as indicated in Fig. 3: double frame ceiling test

Position	Ceiling			Roof			Base
Accel. no.	103763	103762	103765	100050	100715	102818	103766
Test no. 1	0.42g	0.42g	0.42g	0.46g	0.43g	0.42g	0.28g
Test no. 2	0.68g	0.69g	0.69g	0.75g	0.68g	0.74g	0.52g
Test no. 3	1.07g	1.06g	1.05g	1.17g	1.11g	1.18g	0.75g
Test no. 4	1.84g	1.77g	1.85g	2.06g	1.81g	2.03g	1.06g
Test no. 5	2.29g	2.36g	2.25g	2.58g	2.36g	2.52g	1.35g

of the drive motion to predict the signal recorded at desired locations, i.e. on the ceilings, using a compensation procedure, will be taken into account in the next experimental campaigns.

The compatibility of the achieved shaking table motions with the RRS is almost guaranteed for the frequency range 1.3–33.3 Hz. In Fig. 7, the accelerogram spectra, recorded at the base of the test frame, for single and double frame ceiling tests are compared with the RRS corresponding to S_{DS} equal to 1.50g.

The acceleration amplification from the base to the roof of the test frame is within the expected behavior of the test, as it was predicted from the spectra in Figs. 6 and 7 for the natural frequency of the test frame, i.e. the spectral acceleration around 30 Hz is very close to the maximum recorded acceleration. No amplification from the test frame roof to the ceiling system is recorded, as clearly shown in Tables 1 and 2, denoting the large in-plane stiffness of the ceiling system and the substantial rigid behavior of the specimen.

In this study, three limit states are considered in order to characterize the seismic response of suspended ceiling systems: (a) occupancy limit state *SLO*; (b) damage limit state *SLD*; (c) life safety limit state *SLV*. The limit states are defined quantitatively by the number of damaged components (indicated as percentage of damage). From the first to the third considered limit states the damage in the ceiling increases (10, 30 and 50 % damage respectively).

After each shaking level, damage is observed by inspecting the physical conditions of the components. Concerning the main components of the SFC system (primary and perimetral channels, hangers, plasterboards panels and connections), the number of damaged elements observed during the test performed with intensity level S_{DS} equal to 1.50g, is indicated in Table 3. The table also reports for each component the total number of elements for the single frame ceiling system, the damage typology and the limit number of damaged elements required to reach a limit state.

As clearly shown in the Table 3, no damage is recorded, though the high level of horizontal accelerations experienced. The same result is obtained for double frame ceiling system. Strain gauges data confirm this statement: low strain/stress values are registered during the earthquake motion within the ceiling system (Fig. 8).

Indeed, the strain gauges described in Sect. 2.2 recorded deformations lower than 0.005 % resulting in a undamaged state both in steel channels and in plasterboards; as expected, the demand in SFC plasterboards is larger than DFC ones (see SG3 in Fig. 8b, c) as well as the demand in the perimetral profile; this is due to the fact that SFC plasterboards are restrained by a less dense horizontal steel channel frame and that in DFC the stresses are better distributed along the perimetral channels, respectively. However both DFC and SFC exhibit an excellent seismic behavior.

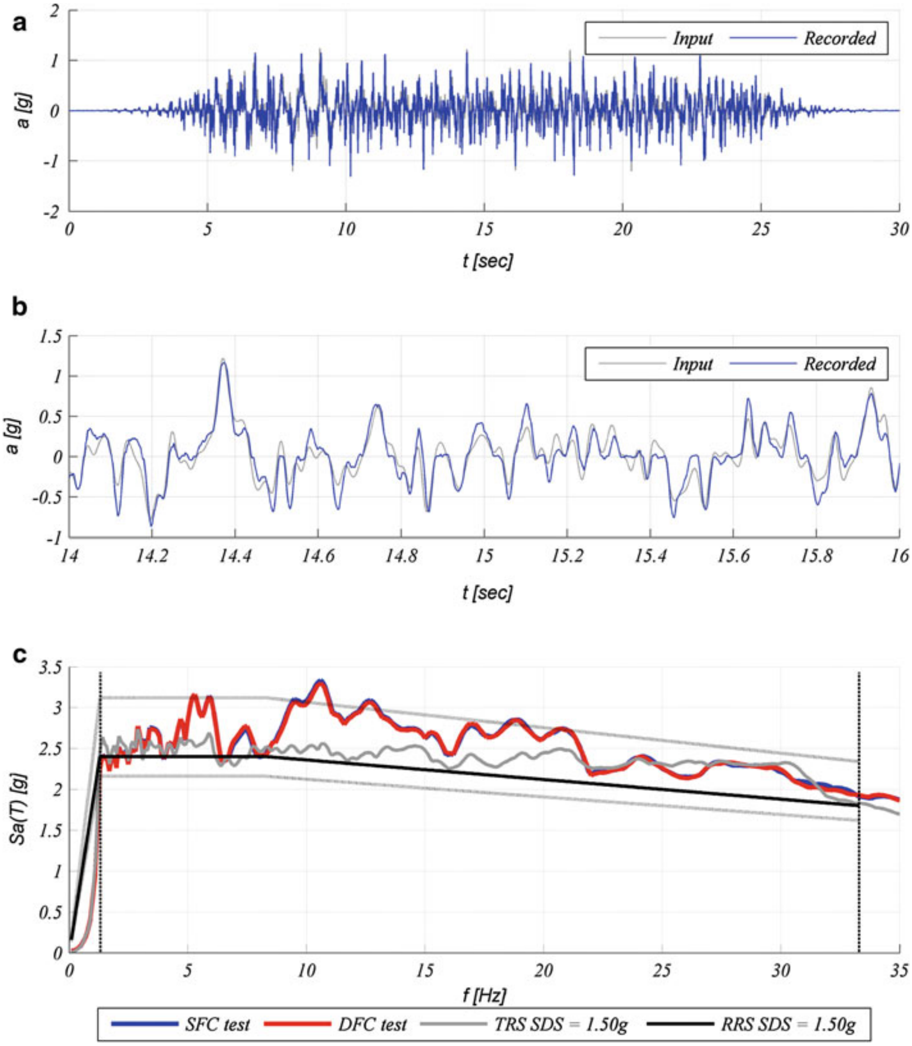


Fig. 7 Tests corresponding to S_{DS} equal to 1.50g: shake table recorded acceleration time histories (**a**) zoomed in a 2 s time range (**b**) for single frame ceiling tests compared to the shake table input; spectra for single frame (SFC) and double frame ceiling (DFC) compared to the RRS and the TRS (**c**)

An interesting comparison with a previous vulnerability study performed by Badillo-Almaraz et al. (2006) on typical U.S. ceiling with tiles, shown in Fig. 9, is made. The tests were performed at the Structural Engineering and Earthquake Simulation Laboratory (SEESL) at the University of Buffalo. A 4.88 m × 4.88 m (16 ft × 16 ft) square test fixture of ASTM Grade 50 steel was constructed in order to test the ceiling systems.

The test fixture was designed in order to simulate one story and one bay of a building with vertical floor frequencies in the range of 9–12 Hz and horizontal frequencies in the range of 10–16 Hz. Four limits states were defined in order to characterize the seismic response of ceiling systems: (1) minor damage, (2) moderate damage, (3) major damage, and (4) grid

Table 3 Form for recording damage observed during the test performed on single frame ceiling with intensity level S_{DS} equal to 1.50g

Elements	Number	Damage	SLO (10 %)	SLD (30 %)	SLV (50 %)	Damaged elements
Hangers	15		2	5	8	0
Primary channels	5	Buckling	1	2	3	0
		Bending				0
Perimetral channels	4	Buckling	1	1	2	0
		Bending				0
Plasterboard-channel connections (screws)	87	Shear	9	26	43	0
		Tension				0
		Punching shear				0
Plasterboards	3	Collapse	–	–	1	0

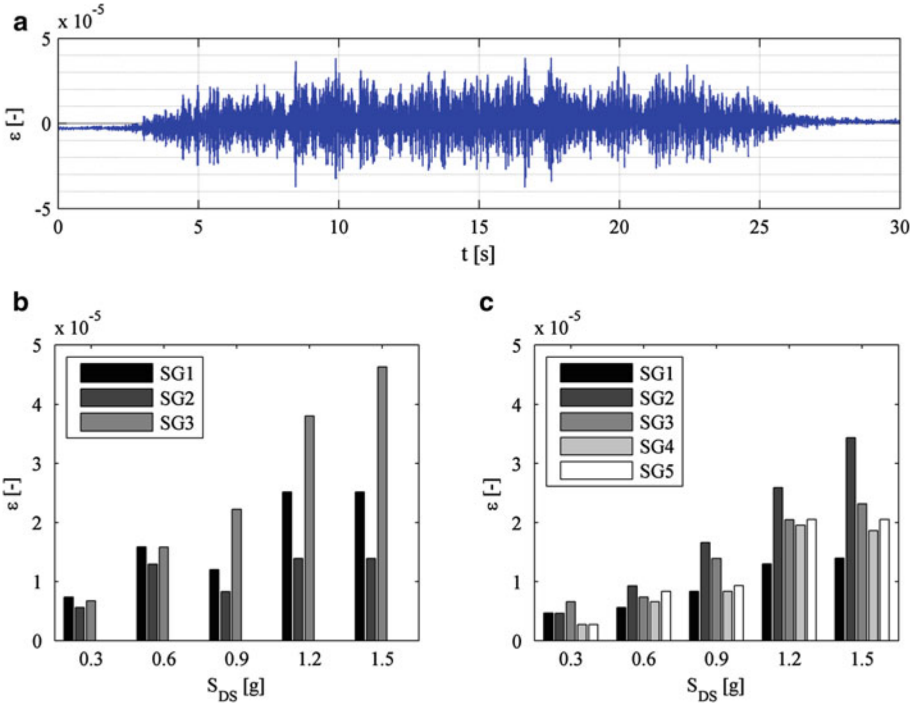


Fig. 8 Tests corresponding to S_{DS} equal to 1.50g: deformation time history recorded by SG3 in single frame ceiling test (**a**); maximum deformations recorded by strain gauges in **b** SFC tests and **c** DFC tests

failure. Limit states from (1) to (3) are defined upon the percentage of tiles that fell from the suspended grid; limit state (4) is associated with structural damage to the suspension grid.

In order to make a comparison, the fragility curve for ceilings with undersized tiles (Badillo-Almaraz et al. 2007) in terms of peak floor acceleration (PFA) is considered (Fig. 10). This fragility curve, evaluated for the maximum acceleration induced by the shaking table

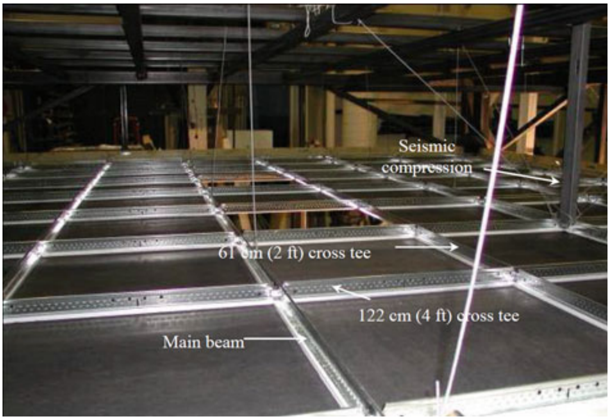
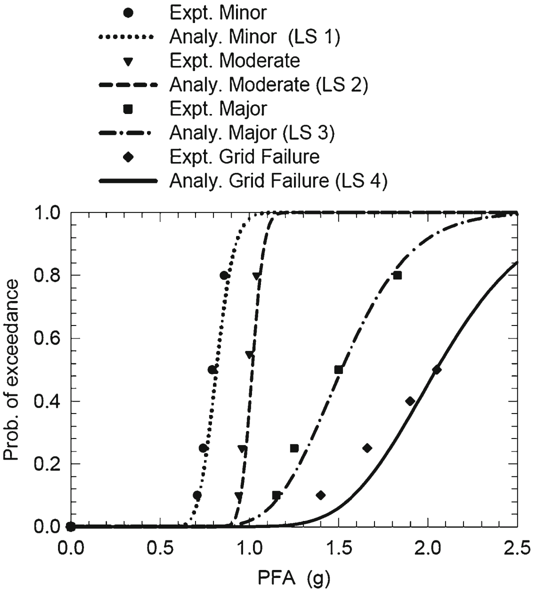


Fig. 9 Ceiling with undersized tiles (Badillo-Almaraz et al. 2007)

Fig. 10 Ceiling fragility curve: ceiling with undersized tiles (Badillo-Almaraz et al. 2007)



in Naples (1.35g, Tables 1, 2), gives 100 % probability of exceeding minor and moderate damage state and 29 % probability of exceeding major damage state.

As already reported, the ceilings tested in Naples, instead, show no damage at all intensity levels of the tests, resulting in a lower fragility with respect to the ceiling systems tested in Buffalo. Three main reasons may be the cause of this different vulnerability: (a) the continuous nature of the tested ceiling, that improves the seismic behaviour with respect to the ceilings with tiles; (b) the dense steel channel grid (the “primary channel” span is 500 and 1,000 mm for SFC and DFC systems respectively, the “secondary channel” span is 500 mm for DFC system), that connects one another the plasterboards in a unique horizontal element, ensuring high in-plane stiffness and strength; (c) the large number of hangers that connect the ceiling system to the roof, ensuring an adequate out of plane stiffness and strength, avoiding any ceiling vertical movement; (d) the smaller dimensions of the specimen tested in Naples with respect to the specimen tested in Buffalo (2.20 m × 2.20 m vs. 4.88 m × 4.88 m), considering that very recent studies seem to show that specimen dimensions can affect the ceiling seismic response.

In test campaign developed in Naples, the issue of scaling is also considered; however this procedure is assessed to be inadequate for this research study, since the behaviour of the specimen is very sensitive to details, such as the connections and the interactions between the different subcomponents.

The tests described in Sect. 2 are performed shaking the table only in the horizontal Y direction. No vertical excitation is applied to the specimen. For the tested continuous ceiling systems, this component is not assumed as crucial. Indeed, the continuous plasterboard is connected to the roof with many vertical steel hangers (span is equal to 1 m along both the horizontal directions) with a sufficient axial stiffness (for steel hanger design, a safety factor larger than 3 is considered). Hence, no failure due to earthquake vertical component is expected.

The boundary conditions adopted in this test campaign may not be representative of a real case. The rigid restraint may not be representative if the partitions/infills, which the ceiling is connected to, overturn or deform differently one another, causing additional stresses within the ceiling. This problem is particularly emphasized when two different typologies of partition/infill restrain the ceiling: due to their different nature, they could deform asynchronously, producing large stresses within the ceiling. However, the boundary condition proposed in this research is realistic: it is representative of partitions/infills that do not exhibit significant relative displacements with respect to the structure they are installed in.

4 Conclusions

The main conclusions of the paper are reported in the following.

The tests performed on shaking table show, for both the tested ceiling systems, no damage at all intensity levels, resulting in a low fragility. Three main reasons may be the cause of this low fragility: (a) the continuous nature of the tested ceilings; (b) the dense steel channel grid; (c) the large number of hangers that connects the ceiling system to the roof and provides a restraint in out-of-plane direction, avoiding any ceiling vertical movement.

This vulnerability study on ceiling systems was carried out without considering any interaction with other components; further studies are needed to investigate this phenomenon, which represents the next step of this research.

Finally, an interesting comparison with a previous vulnerability study performed by Badillo-Almaraz et al. in 2007 on typical U.S. ceiling system with tiles was performed. The comparison points out the lower fragility of continuous plasterboard ceiling systems, tested in Naples, with respect to the ceiling with tiles systems, tested in the U.S.; however, this conclusion could be influenced by the smaller dimensions of the specimen tested in Naples with respect to the specimen tested in Buffalo.

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