A PROCEDURE TO SELECT TIME-HISTORIES FOR SHAKING TABLE TESTS ON NONSTRUCTURAL COMPONENTS

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Abstract. *In the last years, the scientific community research effort is moving towards the investigation of the seismic behaviour of nonstructural components. In this paper, a procedure to select time histories to perform full-scale shaking table tests on nonstructural components is proposed. In particular, the experimental tests are designed and implemented to investigate the seismic behaviour of a typology of nonstructural components: the plasterboard continuous suspended ceilings.*

A set of five accelerograms, used as input for the shakings, are opportunely selected matching a target response spectrum or required response spectrum (RRS), provided by the USA code ICBO-AC156 "Acceptance criteria for seismic qualification testing of nonstructural components".

The RRS is obtained as a function of the design spectral response acceleration at short periods, SDS, depending on the site soil condition and the mapped maximum earthquake spectral acceleration at short periods. The selection procedure is performed, for a RRS corresponding to SDS=1.50g; the so obtained record is then scaled to match other four levels of the target spectrum (corresponding to SDS 0.30g, 0.60g, 0.90g and 1.20g).

These accelerograms, representative of different intensity levels, are then applied to a test setup opportunely designed and realized to perform the shaking table tests. Two typologies of continuous plasterboard ceilings are tested and three limit states (occupancy, damage and life safety limit state) are considered in this study to characterize the seismic response. The ceilings tested shows no damage at all intensity level (the acceleration on the ceiling ranges from 0.40g to 2.36g), resulting in a low fragility.

1   INTRODUCTION

The failure of ceiling systems has been one of the most widely reported types of nonstructural damage in buildings during past earthquakes [1, 2]. The recent L'Aquila earthquake, occurred on April the 6th, 2009, in central Italy, has widely confirmed the last assertion: the most part of the evacuated buildings showed undamaged structural elements and moderate-to-heavy damaged nonstructural components, especially ceiling systems [3].

The damage of the nonstructural components gives the largest contribution to the economic loss due to an earthquake. In fact, structural cost represents a small portion of the total one, corresponding to 18%, 13% and 8% for offices, hotels and hospitals respectively [4]. For these reasons, the knowledge of the seismic performance of nonstructural elements is essential.

Very limited studies were conducted in the past on the seismic behaviour of nonstructural components, even though they are very common both in residential and industrial buildings [5, 6]. The presence of nonstructural components may strongly influence the lateral stiffness of the portion of the structure in which they are inserted [7], and may also affect the regularity of the whole structural system [8-10]. For this reason systematic studies on their seismic behaviour are needed.

An extensive study aimed at the fragility curve evaluation of ceiling system composed of tiles supported by metallic grids was carried out in Buffalo via shake table test [2, 11]. Shaking table tests were also performed to investigate the seismic behaviour of plasterboard partitions in [12, 13].

In this paper, the seismic behaviour of plasterboard continuous suspended ceilings under strong earthquakes is investigated, focusing the attention on the definition of the input accelerogram time histories. The ceiling system differs from the systems of the previous studies for its "continuous" nature: it consists of a unique plasterboard panel obtained connecting few boards 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 since suspended ceiling systems are not amenable to traditional structural analysis.

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

2   DESCRIPTION OF THE EXPERIMENTAL TESTS

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 used systems is shown in Figure 1(a) and Figure 1(b) respectively.
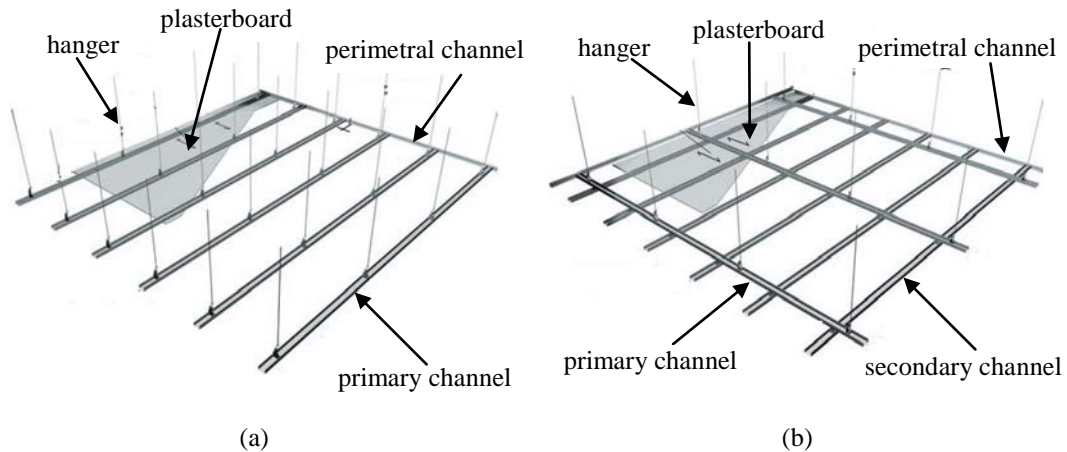
Figure 1: Suspended plasterboard continuous ceilings: (a) single frame ceiling (SFC); (b) double frame ceiling (DFC).

The seismic qualification of 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 x 3 m square shake tables but only is used in this experimental campaign.

With the purpose of simulating the seismic effects on the ceilings, a steel test frame is properly designed and built (Figure 2). The test frame is of S275 steel material with concentric V-bracings made of steel U-section (UPN160). The very stiff test frame is required in order to control the acceleration on the specimen and to avoid shake table – test frame – ceiling system double-resonance issues.

Two U-section profiles (UPN100) are welded around the perimeter of the test frame, at a distance of 20 cm and 50 cm from the roof; a 40 mm x 100 mm timber ledger is inserted in the U-section profile in order to easily laterally restrain the ceiling system. Indeed, the ceiling system plasterboards are connected along the perimeter of the frame 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. The total weight of the test frame is equal to 19.2 kN.

Figure 2: Test frame installed on the shake table.

The tested specimen is composed by three plasterboards connected one another via stucco, both for SFC and DFC. The total dimension of the specimen is 2.20 m x 2.20 m.

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

In order to adequately measure the seismic behaviour of the specimen, three triaxial accelerometers are installed at the centre and at the edges of the roof, as shown in Figure 3; one is also placed at the base of the frame, in order to verify the real input transmitted to the specimen from the shaking table. Further details are given in [14].
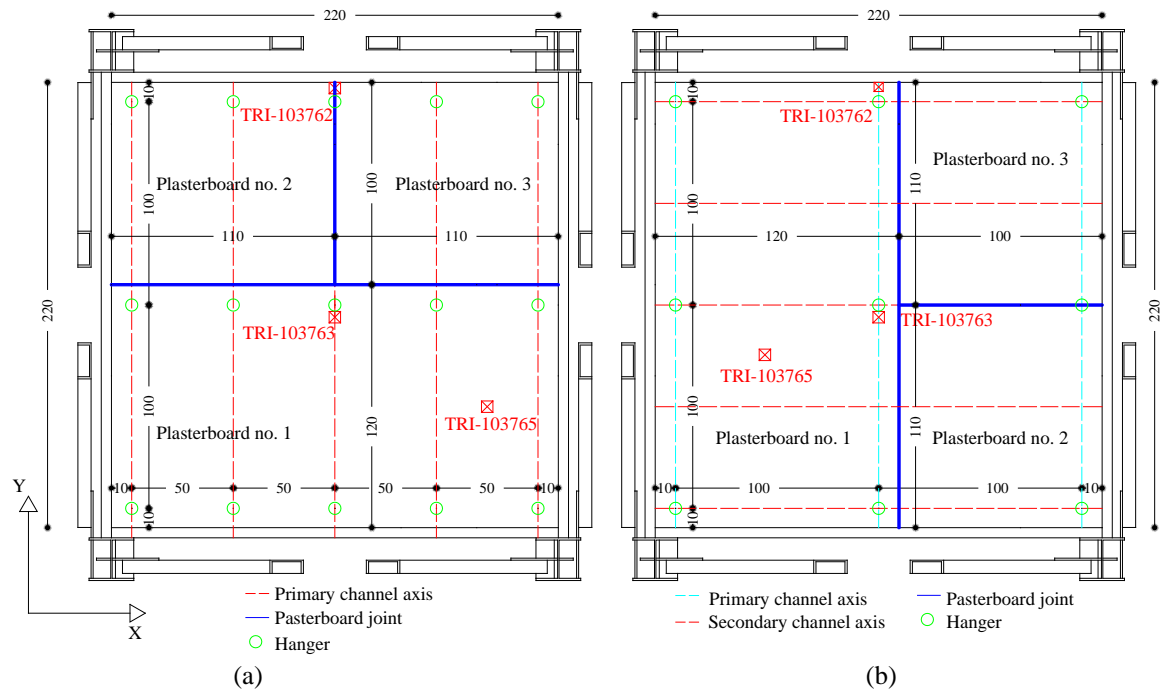

Figure 3: Triaxial accelerometers, plasterboard and hanger position in the case of single frame ceiling (a) and double frame ceiling (b) specimen.

3   DEFINITION OF THE INPUT MOTION

A set of five accelerograms, used as input for the shakings, are opportunely selected matching a target response spectrum or required response spectrum (RRS), provided by the ICBO-AC156 code "Acceptance criteria for seismic qualification testing of nonstructural components" [15].

The equipment earthquake effects are determined considering only horizontal load effects. The Required Response Spectra (RRS) for the horizontal direction are developed based on normalized response spectra shown in Figure 4 and the formula for the evaluation of the total design horizontal force, F_P.
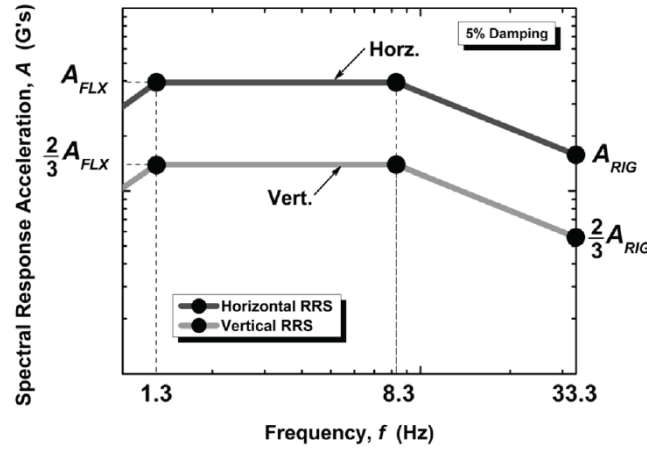
Figure 4: Normalized Required Response Spectrum for equipment and nonstructural components [15].

The RRS is defined using a damping value equal to 5 percent of critical damping. In case the building dynamic characteristics are not known or specified, the horizontal force requirements are determined using the following equation.

$$F_P = \frac{0.4 \cdot a_p \cdot S_{DS} \cdot W_P}{R_P/I_P}\left(1 + 2\frac{z}{h}\right) \tag{1}$$

The height factor ratio (z/h) accounts for above grade-level equipment installations within the primary supporting structure and ranges from zero at the base of the structure to one at roof level.

The site-specific ground spectral acceleration factor, S_{DS}, is taken from the design value maps. The S_{DS} factor is used to define the general design earthquake response spectrum curve and is used to determine the design seismic forces for the primary building structure. The ratio of R_p/I_p is a reduction factor to account for inelastic response of the component and the importance factor of the component. The ratio (R_p/I_p) is set equal to 1. The component amplification factor, a_p, acts as a force increase factor by accounting for probable amplification of response associated with the inherent flexibility of the non-structural component. The component amplification factor, a_p, is taken from the formal definition of flexible and rigid components. By definition, for fundamental frequencies less than 16.7 Hz the equipment is considered flexible (maximum amplification $a_p = 2.5$), which corresponds to the amplified region of the RRS. For fundamental frequencies greater than 16.7 Hz the equipment is considered rigid (minimum $a_p = 1.0$), which corresponds to the zero period acceleration. These results in two normalizing acceleration factors, that when combined, defines the horizontal equipment qualification RRS:

$$A_{FLX} = S_{DS} \cdot \left(1 + 2 \cdot \frac{z}{h}\right); A_{RIG} = 0.4 \cdot S_{DS} \cdot \left(1 + 2 \cdot \frac{z}{h}\right) \tag{2}$$

where A_{FLX} is limited to a maximum value of 1.6 times S_{DS}.

The input to the table is provided through acceleration time histories representative of expected/target ground motion; these time histories are selected with the aim of matching the target or required response spectrum of nonstructural components. Two artificial time histories, matching the nonstructural components spectra, are defined and used as drive motion for shaking table test, starting from the one characterised by the lowest intensity to the one characterised by the largest intensity.

The parameter selected to characterize the ground motion for input to the simulator is the spectral acceleration at 0,2 seconds, S_{DS}. For horizontal design-basis earthquake shaking, the

International Building Code [16] defines the short period design basis earthquake acceleration response as:

$$S_{DS} = \frac{2}{3} \cdot F_A \cdot S_s \tag{3}$$

where S_{DS} is the design spectral response acceleration at short periods, F_A is a site soil co-efficient, and S_S is the mapped maximum considered earthquake spectral acceleration at short periods.

The target of shaking levels ranges from S_{DS} equal to 0.30 g to S_{DS} equal to 1.50 g in order to make the problem as general as possible, i.e. representative of general earthquake ground motions.

The earthquake excitations used for the qualification of the ceiling system are generated using a spectrum-matching procedure from the RSP Match program [17]. The values of the spectral acceleration of the response spectrum obtained with the matching procedure are scaled to envelope the target spectrum (ranging from S_{DS} equal to 0.30 g to 1.50 g) over the frequency range from 1 to 33 Hz. The low frequency content is removed from the scaled records for the purpose of not exceeding the displacement and velocity limits of the earthquake simulator. In the followings, the procedure used for the generation of the earthquake records used as acceleration input to the earthquake simulator is presented.

ICBO [15] requires that the response spectra associated with the earthquake histories used for qualification must envelope the required (or target) response spectrum (RRS) using a maximum one- third-octave bandwidth resolution over the frequency range from 1 to 33 Hz, or up to the limits of the simulator. The amplitude of each matched spectrum ordinate must be independently adjusted along each of the orthogonal axes until the response spectrum envelopes the RRS. The response spectrum ordinates must not be lower than 0.9 times RRS and larger than 1.3 times RRS (according to EC8 [18] and AC156 rules respectively). The earthquake histories used for the qualification and fragility testing of the ceiling systems were generated using the following procedure:

1. Select a baseline earthquake that defines the overall duration, the rise time, steady state, and decline time of the resultant acceleration record. The acceleration profile is interpolated to produce a time series.
2. The RSP Match software is applied by means of a time domain modification of the baseline earthquake of step1. in order to make it compatible with RRS (Required Response Spectrum) [17].

The baseline earthquake is defined according to requirements of code [15] according to the following characteristics:

- nonstationary broadband random excitations having an energy content ranging from 1.3Hz to 33.3Hz;
- multiple frequency random excitations, the amplitudes of which adjusted either manually or automatically based on multiple frequency bands;
- one sixth octave bandwidth resolution is used;
- the total duration of the input motion is 30seconds, with non-stationary character being synthesized by an input signal build hold decay envelope of 5 seconds, 20 seconds, and 5 seconds, respectively;
- the input duration of the time history tests contain at least 20 seconds of strong motion.

For the purpose of reaching the desired levels of shaking without exceeding the limits of the earthquake simulator, the maximum accelerations, velocities and displacements for the obtained records at all the shaking levels were calculated and were compared to the simulator

limits. In particular the earthquake simulator velocity and displacement limits are 100 cm/sec and ± 25.0 cm, respectively.

Acceleration limits have not been properly taken into account because the value of masses to be tested are small; in particular the mass allows reaching acceleration values of the earthquake simulator up to 5.0g. Then the matched record so obtained, is band passed filtered over the range of frequency 1 ÷ 33 Hz.

The low frequency content is eliminated from the scaled records for the purpose of not exceeding the displacement and velocity limits of the earthquake simulator.

Finally, the aforementioned procedure briefly consists of:

- defining a baseline earthquake;
- matching the required response spectrum;
- band – pass filtering over the frequency range 1 ÷ 33 Hz.

The procedure is performed for a Required Response Spectrum corresponding to SDS=1.50g; the so obtained record is then scaled to match the different levels of the target spectrum defined previously, i.e. SDS=0.30g, SDS=0.60g, SDS=0.90g, SDS=1.20g.

The input motion for the different intensities and the elastic spectrum are presented in Figure 5 and Figure 6.
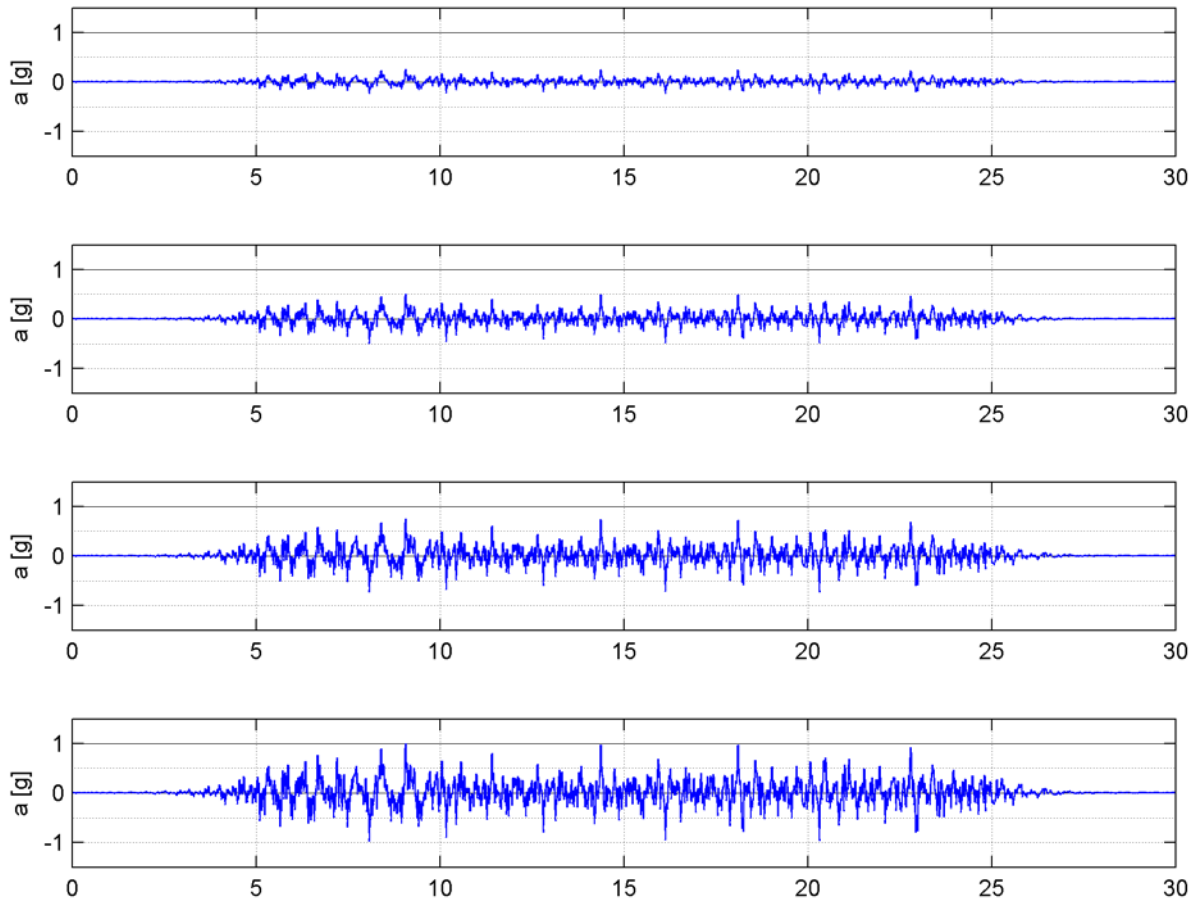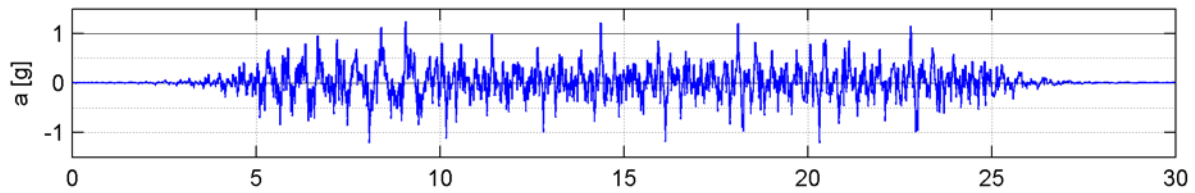
Figure 5: Input acceleration time histories for Y direction corresponding to SDS equal to 0.30g, 0.60g, 0.90g, 1.20g and 1.50g.
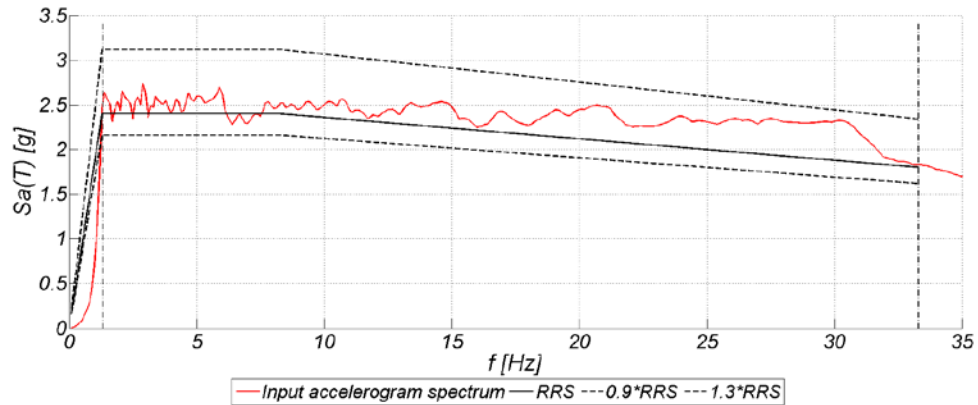

Figure 6: Input accelerogram spectrum, RRS (bold line), upper and lower matching limits (dashed line) for a level of shaking corresponding to S_{DS} equal to 1.50g.

4 RESULTS

Using the selected drive motions, five unidirectional shaking tests are performed for both ceiling systems. In Figure 7 the acceleration time history recorded on the ceiling is presented, while in Table 1 and Table 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 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. This aspect may be crucial when the build of a fragility curve is the main goal of the research. For this reason, the procedure described in [19], concerning the optimization of a signal recorded at desired locations, i.e. on the ceilings, will be taken into account in the next experimental campaigns.
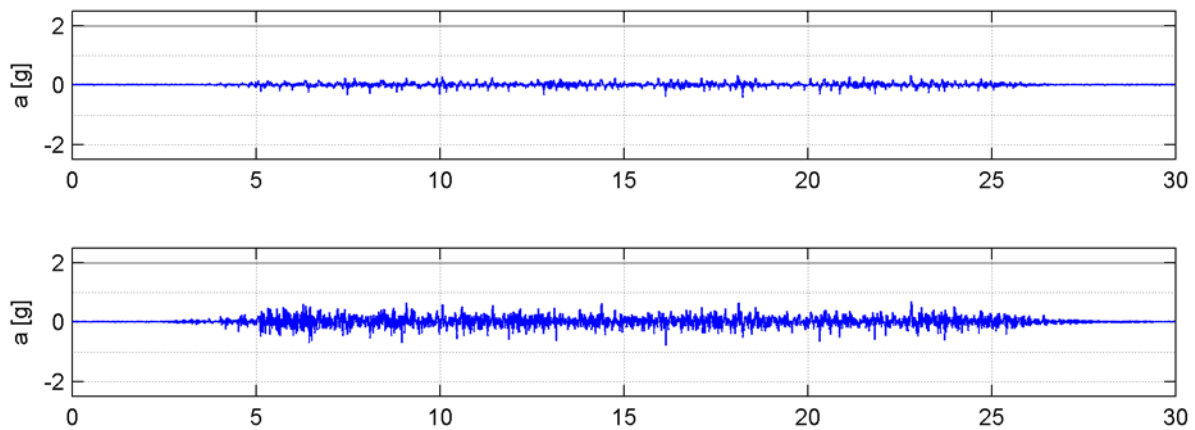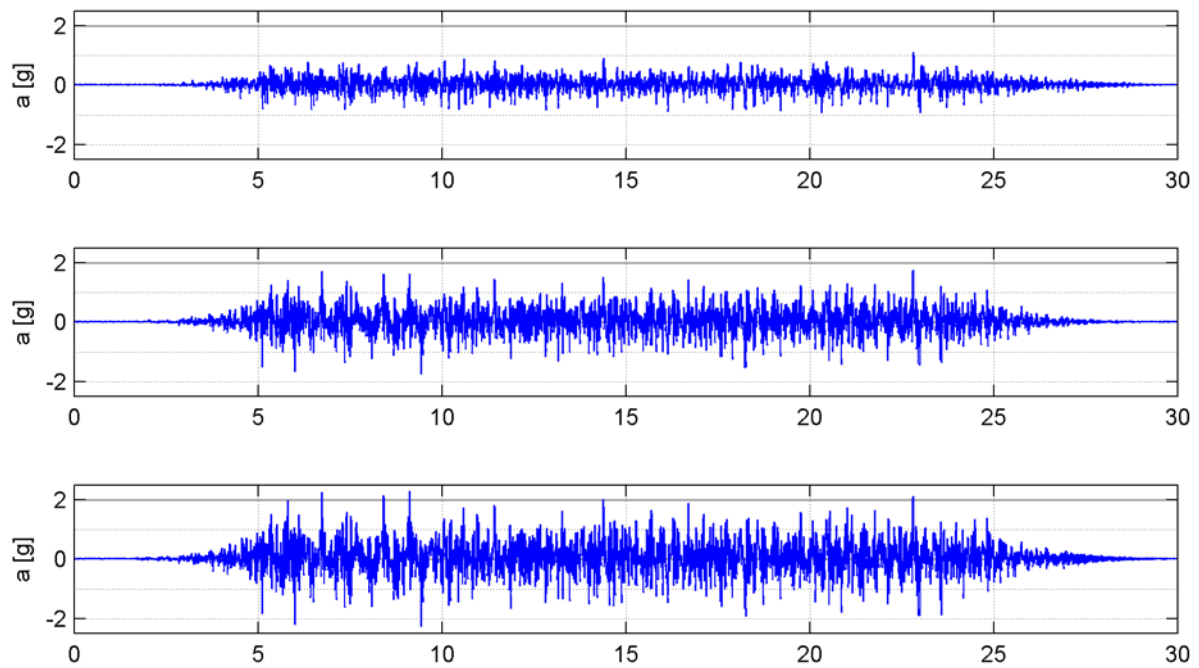
Figure 7: Acceleration time histories recorded on the ceiling (Accelerogram no. 103763) for single frame ceiling (SFC) for the intensity levels corresponding to SDS equal to 0.30g, 0.60g, 0.90g, 1.20g and 1.50g.

Position	Ceiling	Roof	Base
test no. 1	0.42g	0.45g	0.25g
test no. 2	0.78g	0.78g	0.50g
test no. 3	1.10g	1.15g	0.69g
test no. 4	1.79g	1.90g	1.04g
test no. 5	2.28g	2.51g	1.36g

Table 1: Maximum recorded accelerations at base, roof and ceiling level - single frame ceiling test.

Position	Ceiling	Roof	Base
test no. 1	0.42g	0.46g	0.28g
test no. 2	0.69g	0.75g	0.52g
test no. 3	1.07g	1.18g	0.75g
test no. 4	1.84g	2.06g	1.06g
test no. 5	2.36g	2.58g	1.35g

Table 2: Maximum recorded accelerations at base, roof and ceiling level - double frame ceiling test.

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 state the damage in the ceiling increases (10%, 30% and 50% damage respectively).

After each shaking level, damage is observed inspecting physical conditions of the components. Concerning the main components of the SFC system (see Figure 1(a)) indicated as 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.

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				0
		tension	9	26	43	0
		punching shear				0
Plasterboards	3	collapse	-	-	1	0

Table 3: Form for recording damage observed during the test performed on single frame ceiling with intensity level SDS equal to 1.50g [14].

An interesting comparison with a previous vulnerability study performed by Badillo-Almaraz et al. [11] on typical U.S. ceiling system with discrete tiles is made. The tests were performed at the Structural Engineering and Earthquake Simulation Laboratory (SEESL) at the University of Buffalo.

In order to make a comparison, the fragility curve for ceilings with undersized tiles [11] in terms of PFA is considered (Figure 7). This fragility curve, at the acceleration equal to 1.35 g, which is the maximum acceleration of the shaking table (Table 1 and Table 2) attained during the tests performed in Naples, gives 100% probability of exceeding minor and moderate damage state and 29% probability of exceeding major damage state. As already said, 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 mm and 1000 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 connects 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 (2.20m x 2.20m vs 4.88m x 4.88m), considering that very recent studies seem to show that specimen dimensions can affect the ceiling seismic response.
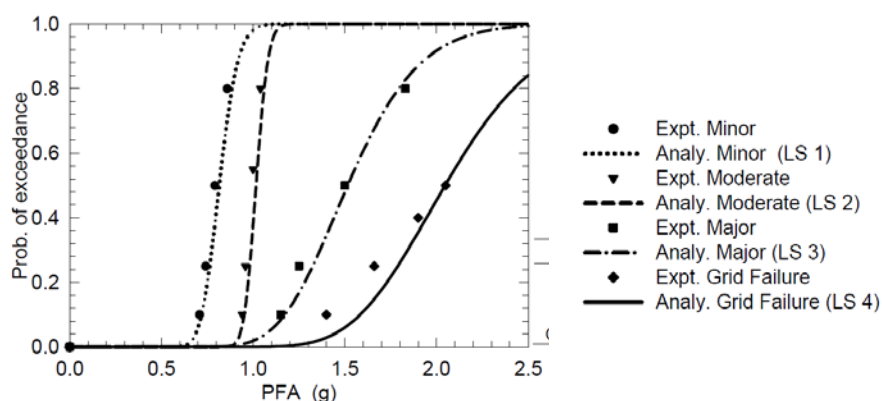

Figure 8: Ceiling fragility curve: ceiling with undersized tiles [11].

The tests are performed shaking the table only in one 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.

5   CONCLUSIONS

Shaking table tests are performed to investigate the seismic behaviour of plasterboard continuous suspended ceilings under strong earthquakes. Two typologies of continuous plasterboard ceilings (i.e. single frame ceiling (CSO) and double frame ceiling (CDO)) are tested. The ceilings tested shows no damage at all intensity level (the acceleration on the ceiling ranges from 0.40g to 2.36g), resulting in a low fragility.

A set of five accelerograms, used as input for the shakings, are opportunely selected matching a target response spectrum or required response spectrum (RRS), provided by the ICBO-AC156 code "Acceptance criteria for seismic qualification testing of nonstructural components". The procedure for the selection of the accelerograms is described in details in the paper.

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, avoiding any ceiling vertical movement.

Finally, an interesting comparison with a previous vulnerability study performed by Badillo-Almaraz et al. in 2007 on typical U.S. ceiling with tiles systems was performed. The comparison points out the lower fragility of continuous plasterboard ceiling systems, tested in Naples, with respect to the ceiling systems with discrete tiles, 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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