Seismic evaluation of suspended ceilings in a hospital building: a case study

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ABSTRACT: Downtime and repair/replacement costs are significant consequences of non-structural components' failure, even under the effect of moderate earthquakes. Beside the life safety requirement, continuity of service must be guaranteed in important buildings such as hospitals. Damage reports from recent earthquakes have demonstrated that suspended ceiling systems' collapse has been a major cause of functionality interruption and closure of several hospitals.

In this study, seismic performance of suspended ceiling system in an existing hospital building in Italy is explored. In this hospital, similar to most public buildings, the suspended ceiling system is distributed over the entire building, including the emergency areas. The ceiling system's fragility curve is based on the components' fragility, obtained through experimental testing and probabilistic analysis. The seismic demand on ceilings at different limit states, obtained from nonlinear structural analyses of the hospital building is compared with the ceilings' fragility curves in order to evaluate the ceiling's performance at different levels of excitation.

1 INTRODUCTION

In any country, hospitals are among critical facilities, called "strategic buildings" along with fire service and police stations. The critical role of hospitals during large-scale disasters such as earthquakes, with a large number of injuries typically associated, defines them as distinctive structures. According to Achour et al. (2011), 97% of earthquake-related injuries occur within the first 30 minutes following the main shock. For this reason the ways of providing continuous service to the population without loss of functionality, minimizing fatalities and providing timely treatment have been extensively researched in recent years. The recent experiences (Christchurch February 2011 and La Aquila November 2009) show that a significant portion of the functional interruption can be attributed to non-structural components and contents' damage, with a related noteworthy loss in economic terms (Taghavi et al. 2003).

Failure of non-structural components can also become a safety hazard or can hamper the safe movements of occupants evacuating or of rescuers entering buildings. Damage to non-structural components can occur at seismic intensities much lower than those required to produce structural one, leading to similar hazard. Among the many non-structural elements in a building, suspended ceilings in particular have often been reported as the major cause of functionality interruption and closure of several hospitals.

In this study, a hospital in Italy is taken into account as a case study (Fig. 1); it is composed of 17 structural units, differently built in terms of years, forms, dimensions, but not in materials and techniques applied. A structural unit (named n°15) which accommodates the most important function of the hospital in case of emergency, i.e. the Emergency Department, is chosen as the subject of investigation in this paper. This paper mainly compares the capacity of this unit's ceilings with different levels of seismic demand in order to evaluate the healthcare facilities response to earthquakes.

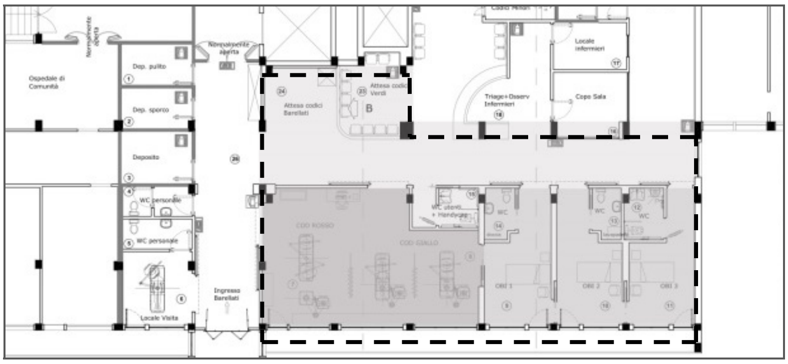

Figure 1. Architectural plan extracted from the hospital (in shadow the Emergency Department).

2 SUSPENDED CEILING SYSTEM

Suspended ceiling systems, categorized as architectural components, are commonly used in public buildings. They are normally expected to satisfy environmental requirements (durability, acoustical behaviour, light reflectance, humidity resistance), and hide ductwork and plumbing while leaving the system accessible for repair.

Suspended ceilings typically consist of a grid system, hanger or bracing wires, perimeter supports and lay-in tiles. The grid system investigated in this study is made up of hot-dipped galvanized inverted T sections that form sqaure or rectangular shaped frames for supporting the tiles. They are provided in two categories; main tees and cross tees. Main tees come in higher capacity and bigger length and cross tees provide the transverse restraint for the main tees. The ceiling systems can be either "perimeter fixed" (surrounding confinement) or "floating" (not connected to the perimeter but supported by means of diagonal bracing wires to the top floor). In the first case inertial forces on the ceiling are transferred to perimeter connections whereas in the second system, braces provide the resistance.

The seismic force which depends on the ceilings' weight and horizontal earthquake acceleration activates a horizontal in-plane diaphragm action, in both directions; while the vertical component of an earthquake excitation causes an out-of-plane vertical force (transverse to the plane of the ceiling).

3 CASE STUDY

The case study investigated herein is an Italian hospital situated in Tuscany. The entire hospital is characterized by a volume of about 50,000 cubic meters and consists of 18 independent structural units. These units have usually three or four levels, were made at different times and all were built with reinforced concrete frames. The investigated structural unit, named n°15, is a two-story building with dimension of approximately 19.5mx12m located in the south part of the building complex. It consists of reinforced concrete frames with two spans of 5.88m and 2.88m length in direction X, and three frames (primary ones) in direction Y, measuring 6.0m, 3.22m and 10.06m in length. Columns have different section sizes at different levels: in the basement floor they are 0.35x0.35m except for the four central columns of dimensions 0.40x1.2m decreasing in section as it goes above to the ground level; at the first floor the columns are all 0.30x0.30m. The primary beams on the first floor have section size of 0.3x0.6m, except those at the ground floor which are larger in size and have a different configuration. The heights of the first and second floors are 3.7m and 3.4m respectively. Only the Emergency Department, located on the first floor, is investigated in this case study. As shown in Figure 2, the emergency unit consists of:

- Emergency Room (ER), in which the severely injured patients are located
- Short Intensive Observation Room (OBI), where patients needing in-depth examination, can wait without being disturbed.

In case of Emergency, all of these rooms will become available for the injured patients and their first assistance. Suspended ceilings are installed over the entire area of these rooms. The lengths of the rooms are indicated in Figure 2, which also shows the direction of suspended ceiling elements; the main tees (MT) and cross tees (CT).

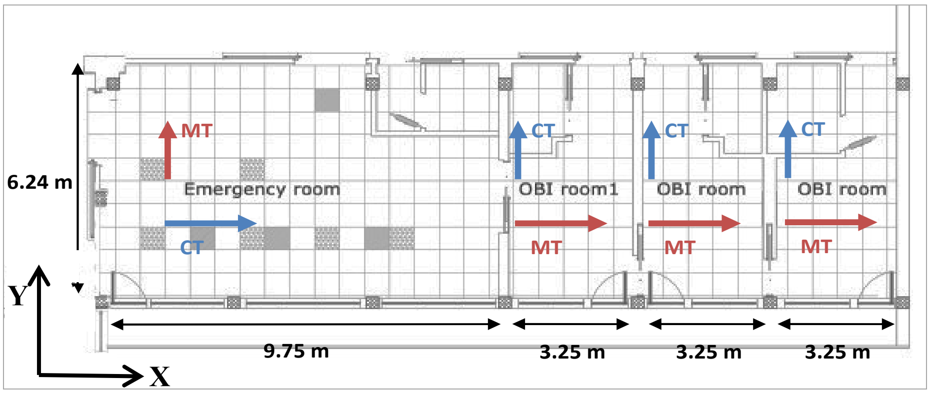

Figure 2. Dimensions and direction of main tees (MT) and cross tees (CT) in different rooms

The area of major interest is the ER Room, both due to the size and the functions carried out. The areas and perimeters of the rooms are listed in Table 1. Since the ER and OBI rooms are both located at the same level of the building, their seismic demands are the same. However, due to the difference in size, the overall capacity of the ceilings in different rooms will vary. It is expected that the capacity of the ceiling in ER room will be lower than the OBI rooms, making it more vulnerable in an earthquake.

Table 1. Size of the different rooms in the Emergency Department

Zone	Area [m^2]	Perimeter [m]
Structural unit area	189.8	62
Emergency room (without Toilet)	53	32
OBI room1 (without Toilet)	14	18
OBI room2 (without Toilet)	14.5	18
OBI room3 (without Toilet)	18.5	14

Due to the dearth of information about the components and the characteristics required for the derivation of fragility curves, assumptions have been made about the directions (MT and CT) and the type of elements used. It is noted that the assumptions made regarding the capacity of the system investigated has a considerable impact on the outcome. The onsite observations show that the characteristic of the ceiling components installed in the hospital are of satisfactory proximity to the ceiling system studies by Paganotti (2010). Further verification by closely reviewing the actual size and mechanical properties of the ceiling components is required to establish their actual capacity.

3.1 Description of suspended ceiling used

The installed ceiling is defined as a *subceiling*, having a cavity space between the fixing base and the basic ceiling. The system used in the hospital is perimeter-fixed, provided by Knauff and consists of different elements as shown in Figure 3.

The *primary structure* is composed of different elements: suspension flanges, spiral suspensions and regulation springs. The hanger wires are fixed through a hole in the bulb of the section and wrapped around themselves, spaced in accordance with the manufacturer and project conditions' requirements. A metal grid (*distribution class*) is suspended from the underside of the floor above and is made up of long and short intermediate tees. The *panels* installed in the hospital are of 0.59x0.59x0.018m in dimension and weigh 4.56kg each. These elements are modular and removable, and hide the space between the metal grid on which they are seated and the floor above.

N.1: tees PP 24/38 (primary tees)

N.2: tees IC 24/38 (short intermediate tees)

N.3: tees IL 24/38 (long intermediate tees)

N.4: suspensions: suspension flange (FS); spiral suspension (SS42 90); suspension x PP (SPP), regulation spring (MRU).

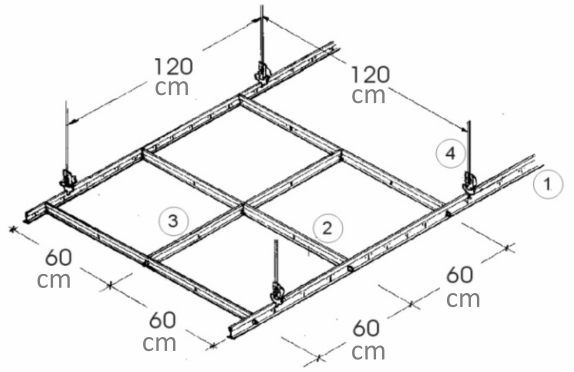

Figure 3. Schematic ceiling components installed in the Emergency rooms.

3.2 Description of the model and modelling assumptions

In order to assess the seismic demand on the ceilings, structural analysis of the entire building is conducted using the general finite element package SAP2000. A three dimensional model of the building is created to undertake the non-linear structural analysis. Beams and columns are modelled as nonlinear frame elements with lumped plasticity at the start and end of each element. SAP2000 provides default-hinge properties and recommends coupled axial-force/biaxial-moment behaviour (called P-M2-M3) in the hinges for columns and M3 hinges for beams as described in FEMA-356.

The floor is considered rigid in plane, due to the presence of the concrete slab. This allows for the assignment of a diaphragm constraint to all nodes on the same floor. The rotational inertia (J_{ro}) and the translation masses (M_{tot}) have been assigned at the centre of the mass of each floor. Data obtained from onsite investigation has been used for the characterization of materials in SAP2000.

The model has been subjected to a modal analysis, pushover analyses and time history analyses. For time history analyses, ground motions are selected and scaled following the Conditional Mean Spectrum methodology proposed by Baker (2011) and utilizing ground motion prediction equation (GMPE) according to Ambraseys et al. (1996) and correlation coefficients according to Cimellaro (2013) for European earthquakes. The seismic intensity and disaggregation data for the site are obtained from "Istituto di Geofisica e Vulcanologia" (INGV) maps for Probability of Exceeding of 22% in 50 years at T=1 sec (Spallarossa and Barani 2007); the suites of ground motions for each intensity level have been selected according to Jayaram et al (2011).

Values of median and standard deviation of the acceleration at a control point (joint 200) located on the first floor of the building are shown in Table 2. The values, in both directions, have been extrapolated for the three Limit States investigated: Serviceability Limit State (SLO, 60-year return period), Damage Limit State (SLD, 101-year return period) and Life Safeguard Limit State (SLV, 949-year return period). Note that names and associated return periods of the limit states are slightly different from those used in New Zealand as they are based on Italian code, which is to be used to evaluate the seismic demand.

Figure 4 shows the probabilistic demand curves obtained from the analysis in both directions: in the X direction the curves for the Serviceability Limit State (SLO) and Damage Limit State (SLD) are close to each other because of the proximity of their return periods (60 and 101 years). They are calculated using the program developed from the "Consiglio del Lavori Pubblici" available online, that allows for the calculation of design spectra for different reference periods, defining the geographical coordinates of the building, the nominal life (VN=50) and class of use (CU=2) of the building and the reference period of the seismic action (VR=100).

Table 2. Median and Standard deviation of the first floor accelerations

Limit State	Values	DirX J200 [cm/s^2]	DirY J200 [cm/s^2]
SLO (TR60)	ln(Median)	1.312256	0.980001
	ln(Stdv)	0.403952	0.329234
SLD (TR101)	ln(Median)	1.363643	1.378647
	ln(Stdv)	0.47026	0.334729
SLV (TR949)	ln(Median)	2.044856	1.772754
	ln(Stdv)	0.350696	0.230324

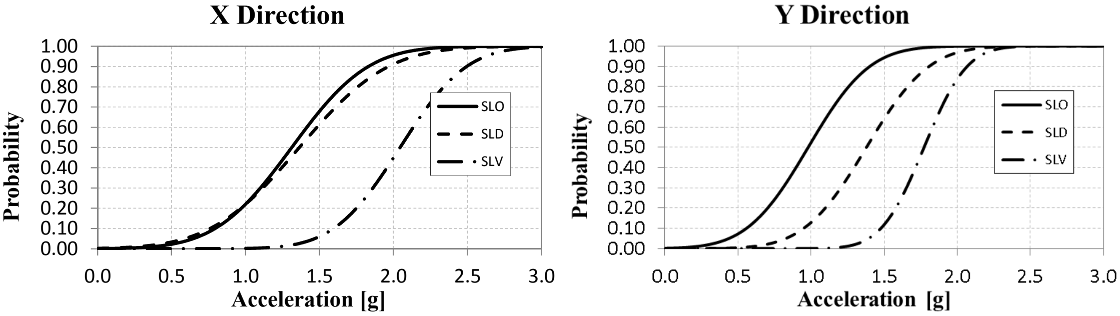

Figure 4. Probabilistic demand curves of the structure for different limit state: SLO, SLD and SLV in two directions

4 FRAGILITY CURVES

In order to evaluate the performance of the ceilings, the capacity of the suspended ceiling systems installed needs to be compared with the seismic demand on the floors of the hospital building. Due to the scarcity of available data, assumptions have been made regarding the capacity of the system. The components of the ceiling system provided for the hospital were compared with the common ceiling systems in New Zealand, in terms of size and material. Quantitative comparisons showed that the system elements used in the hospital were similar enough to the suspended ceilings manufactured in New Zealand which were tested in a previous study at University of Canterbury (Paganotti 2010). The compressive and tensile strength of the tee components and their joints and shear capacity of the rivet connections were assumed to be similar to the New Zealand system. Therefore, it has been concluded that the fragility curves resulting from these experiments can be used to represent the capacity of the ceilings in the current study.

Ceilings located in the ER area were designed based on the guidelines provided by the manufacturers of the adopted New Zealand system, and the allowable size of the main and cross tees were checked. Fragility curves were then derived for the most critical components of the system -Rivets on both tees (R3.2mm), connections in Cross tees (CT-con) and splices in Main tees (MT-Sp)- with floor acceleration as the intensity measure. Since the system is considered a failure as soon as any of its components reaches its capacity, it is possible to assume that the weakest element governs the capacity of the whole. An envelope curve, as shown in Figure 5, was therefore drawn on the far left side of the graphs, showing the overall fragility of the ceilings. These enveloping fragility curves were then compared with the demand acceleration resulting from the numerical analyses of the hospital. For the ER Room, the envelope is considered as the curve of the weakest element, while in the OBI Room, since the curves of the elements are crossing each other, an overall failure envelop is derived from the individual component fragility curves.

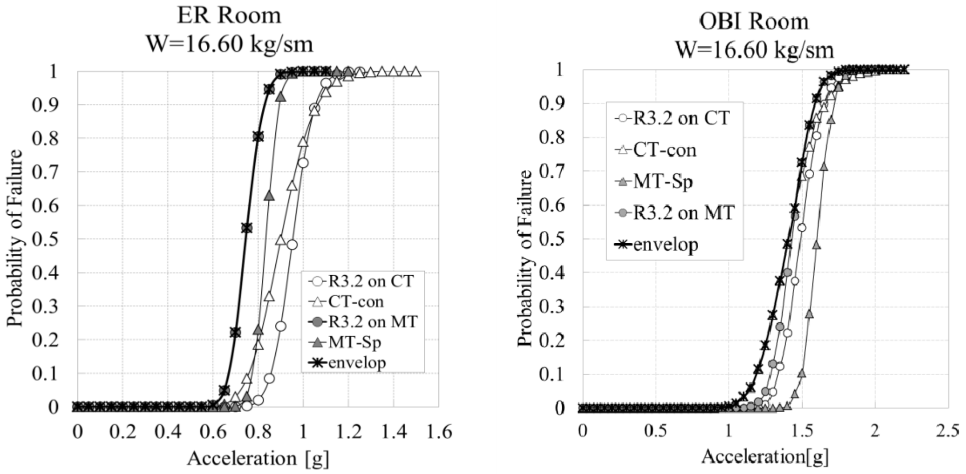

Figure 5. Fragility curves of the elements and envelop curve for the ER Room and the OBI Room.

5 RESULTS

5.1 Procedure

The comparison between structural demand and non-structural components capacity has been performed through a deterministic method, as an alternative for probabilistic approach that will be subject to future in-depth analyses. By this procedure, the probability of failure for non-structural components is estimated considering different demands associated with various limit states. According to the Italian Code (Nuove Norme Tecniche per le Costruzioni 2008), seismic demands corresponding to the Ultimate Limit State (called SLV in this paper) and the Damage Limit State (associated with Serviceability Limit State -SLO- and Damage Limit State -SLD) are derived from the analyses of the building. Similarly, the envelope curve of the components' fragility curves has been taken into account as capacity.

The technique presented in this study consists of comparing multiple probabilistic demand curves obtained for the analysed structure and associated with different limit states with the fragility curve derived for the ceiling, all obtained considering acceleration as the EDP. Figure 6 illustrates an application of this procedure: the acceleration associated with a fixed probability of exceeding a certain limit state (60% in this case) is determined using the demand curve for the limit state under consideration. Once the value of the EDP is known, it is possible to quantify the probability of failure for the non-structural component associated with the same acceleration from the fragility curve. This procedure can be repeated for different limit states of the building.

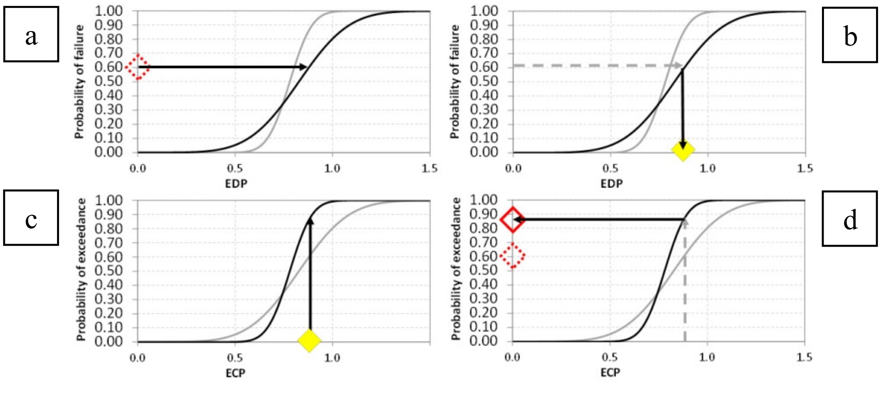

Figure 6. Schematic representation of the procedure used to compare demand from the structure and same capacity of the ceiling system.

The envelope fragility curve for the ceiling system is compared with the three limit states of the structure in directions X and Y; specifically for 50% and 84% probability of exceeding the limit states. The results of this comparison are shown in Table 3. The procedure is repeated both for the Emergency Room and the OBI Room, since the areas are different.

For the ER Room under the Serviceability level demand, the ceilings have 100% probability of failure within the confidence levels investigated (50%-84%). Obviously for other higher limit states, the suspended ceiling systems will reach 100% probability of failure, as the associated floor accelerations are higher than SLO. In summary, due to its low capacity caused by its larger size, the ER room ceiling is highly likely to fail even in minor earthquakes and therefore, needs immediate strengthening (Fig. 7).

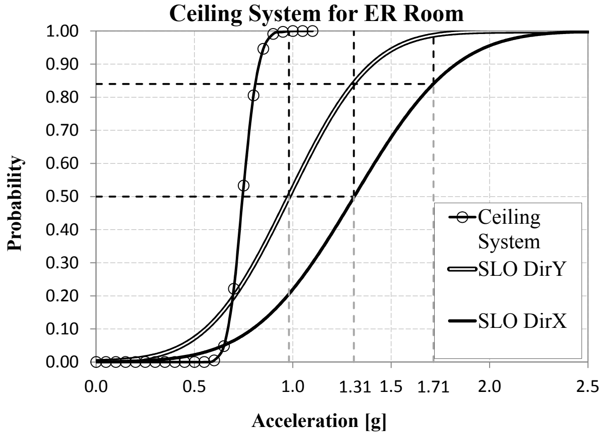

Figure 7. Probability of failure for the ER room ceilings and probability of exceeding SLO for the structure

In the OBI rooms, for the life Safety Limit State in both directions, the ceiling has less than 30% probability of failure for 50% probability of exceeding the SLO, while for 84% probability of exceeding the SLO the failure probability of system reaches 100% (Figure 8). For the damage limit state (SLD), the ceiling is less likely to fail in X direction as the median failure probabilities in X and Y directions are 38% and 48% respectively. However, the failure probability becomes 100% (or close) in this direction if 84% confidence level is desired.

Table 3. Probability of failure for the elements of the OBI room ceiling, given a 50% and 84% probability of exceeding different limit states

Limit State	Dir.	Prob. Of Exceeding	Acceleration [g]	Ceiling System OBI
SLV	X	50%	2.04	100%
		84%	2.39	100%
	Y	50%	1.77	100%
		84%	2.00	100%
SLD	X	50%	1.37	38%
		84%	1.83	100%
	Y	50%	1.38	48%
		84%	1.71	98%
SLO	X	50%	1.31	**27%**
		84%	1.72	98%
	Y	50%	0.98	**0.55%**
		84%	1.31	**27%**

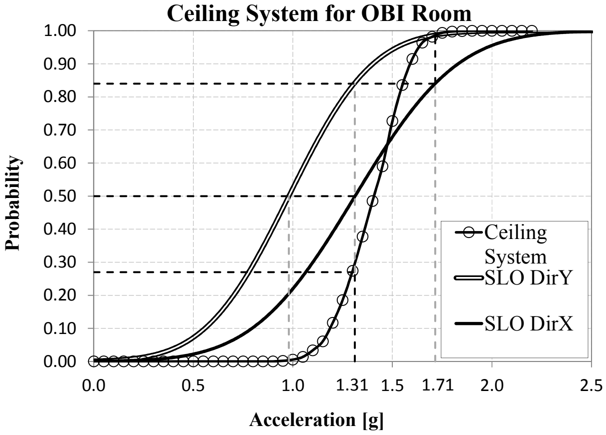

Figure 8. Probability of failure for the OBI room ceiling and probability of exceeding SLO for the structure

6 CONCLUSIONS

The seismic vulnerability of suspended ceiling systems in a case study hospital building was investigated in this paper using a pseudo-probabilistic approach.

Suspended ceiling systems in two different types of rooms in the emergency unit are assessed against three different limit states. Fragility of similar ceiling systems developed at University of Canterbury based on experimental testing is adopted as the capacity curves of the case study ceilings. The seismic demands on the ceilings were derived from 3D nonlinear response history analyses of the hospital building. The results from this comparison show the level of vulnerability of the existing system to seismic excitations corresponding to various limit states. According to this study, the existing suspended ceilings show a satisfactory performance at the serviceability level demand only for the smaller rooms (OBI rooms), with the median (i.e. 50% confidence level) probability of failure limited to 0.55% in Y direction and 27% in X direction. However, the system undergoes 38% (X direction) and 48% (Y direction) probabilities of failure at the damage limit state (corresponding to 101-year return period as per Italian code) and 100% probability of failure in both directions at the life safety limit state (corresponding to 949-year return period as per Italian code). The results show that the ceiling installed in the ER room is more vulnerable due to its larger size and lower capacity in all limit states investigated. The failure probability of the system reaches 100% at a threshold of 50% probability of exceeding the serviceability limit state (corresponding to 60-year return period as per Italian code), and therefore needs immediate strengthening.

7 ACKNOWLEDGEMENT

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