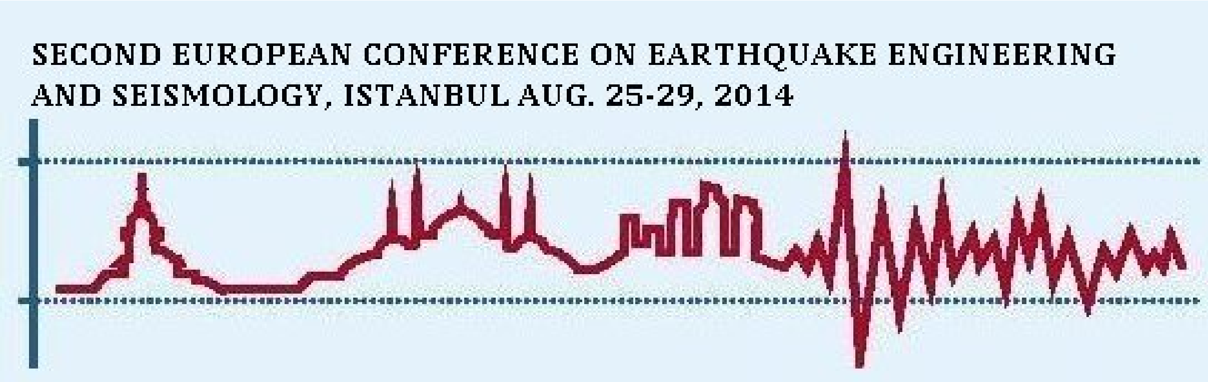

SHAKE TABLE TESTS TO EVALUATE THE SEISMIC DEMAND, CAPACITY AND DYNAMIC PROPERTIES OF HOSPITAL CONTENTS

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ABSTRACT

Health care facilities may undergo severe and widespread damage that impairs the functionality of the system when it is stricken by an earthquake. Such a detrimental response is emphasized either for the hospital buildings designed primarily for gravity loads or without employing base isolation/supplemental damping systems. Moreover these buildings need to warrant operability especially in the aftermath of moderate-to-severe strong motions.

The provisions implemented in new seismic codes have been calibrated to obtain adequate seismic performance for the hospital structural components; nevertheless, they do not provide definite yet reliable rules to design and protect the building contents. A limited number of experimental tests have been carried out so far on hospital buildings equipped with non-structural components as well as building contents.

The present paper is aimed at establishing the limit states for a typical health care room and deriving empirical fragility curves by considering a systemic approach. Towards this aim, a full scale three-dimensional model of an ambulatory room is constructed and tested dynamically by using the shaking table facility of the University of Naples, Italy. An ambulatory room is selected as sample layout for the experimental seismic performance assessment of the core units of hospital buildings. The building contents utilized for the ambulatory room include two cabinets, i.e. 1 window- and 2 windows-cabinets, a desktop computer and a desk; different glass contents are also included in the cabinets in some tests.

INTRODUCTION

In health care facilities, the occurrence of nonstructural damage, encompassing primarily failure of windows, doors, partition walls, suspended ceilings, lighting and floor coverings, should be inhibited as it may detrimentally affect the emergency response and, in turn, it may cause the medical evacuations (Federal Emergency Management Agency (FEMA), 2007a). Additionally, the architectural, mechanical and electrical components account for nearly 45% of the capital cost; thus their failure may cause massive losses for the social communities. Notwithstanding, surveys carried out in the aftermath of recent major earthquakes world-wide (Achour et al., 2011; Di Sarno et al., 2013; McIntosh et al., 2012), e.g. the 2008 Sichuan (China), the 2009 L'Aquila (Italy), the 2010-2011 Darfield-Christchurch (New Zealand), the 2011 Van (Turkey) and the 2012 Emilia-Romagna (Italy)

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earthquakes, have emphasized the inadequate performance of existing hospitals. Widespread nonstructural damage was primarily detected in buildings that were not compliant with modern seismic codes. Nevertheless, the failure of services and building contents was surveyed both in newly built hospital and in structures designed only for gravity loads.

The above discussion demonstrates that there is still an urgent need to further investigate the earthquake performance of medical equipment and typical hospital components. The present paper illustrates the preliminary results of comprehensive shake table experimental tests carried out on a full-scale examination (out patients consultation) room unit equipped with typical architectural finishing, freestanding furniture items, desktop computer and medical equipment. The study aims at the seismic qualification of hospital building contents, such as free-standing cabinets, through the experimental method. Vulnerable freestanding components and medical appliances were identified on the basis of survey questionnaires and simplified evaluation forms compiled by hospital staff for numerous healthcare facilities world-wide (McIntosh et al., 2012). Examination rooms are departments that are critical to their functioning in healthcare facilities (Myrtle et al., 2005). Thus, such rooms were selected as representative layouts for the experimental seismic performance assessment of the core units of hospital buildings. Different configurations were analyzed and relevant limit states identified for each component and the whole room unit. Acceleration time histories with increasing amplitudes were used to derive seismic fragility curves for the whole medical room, according to a systemic approach. Different mass distributions are selected to distribute such contents in the single- and double-window cabinets. 63 shakings are performed during the whole test campaign.

TEST SETUP, SPECIMEN, INSTRUMENTATION AND INPUT DEFINITION

The seismic tests on hospital building contents are carried out by the earthquake simulator system available at the laboratory of Structures for Engineering and Architecture Department of University of Naples Federico II, Italy.

With the purpose of simulating the seismic effects on the medical contents of a typical hospital room a steel single-story framed system was designed (Fig. 1). The layout of the model consists of a 2.42 m x 2.71 m x 2.72 m test fixture of S275 steel material with concentric V-bracings. Further details on the steel test setup are included in Magliulo et al. (2012).

A typical hospital examination (out patients consultation) room background is reproduced within the sample steel frame. Plasterboard partitions and ceilings are mounted; linoleum sheets are also installed to cover both the floor and a large portion of the internal partitions. An overhead light and a ray film viewer are also installed in the room.

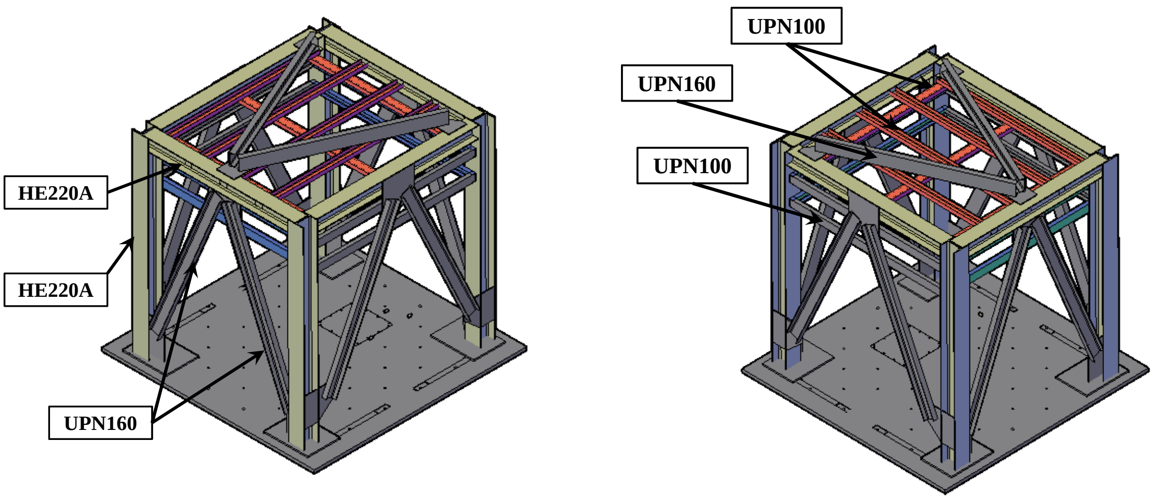

Figure 1. Global perspective of the test setup.

The building contents used for the examination room include: (a) a hospital medicine cabinet (Fig. 2a) made of cold formed sheet with dimension 75x38x165 cm, having double moving glass doors with locker and four mobile glass shelves; (b) a hospital medicine cabinet (Fig. 2b) made of cold formed sheet with dimension 53x36x139 cm, having single moving glass door with locker and four mobile glass shelves; (c) a desktop computer (monitor, case, keyboard and mouse); (d) a desk made of a steel pipes frame and a wooden desktop and having two drawers with locker (Fig. 2c). The mass of the two cabinets is 20 kg and 15 kg for the single-window and the double-windows cabinets, respectively; the mass of the desk is 31.6 kg. Cabinet contents with different slenderness as glass bottles, flasks and test tubes, are placed in the cabinets to simulate the actual conditions of a typical hospital room. Different mass distributions are also selected to distribute such contents in the single- and double-window cabinets.

(a) (b) (c)

Figure 2. Tested hospital building contents: (a) double-windows cabinet, (b) single-window cabinet and (c) desk.

To investigate the seismic behavior of the hospital room, a suite of accelerograms, used as input for the unidirectional horizontal shakings, are adequately selected to match a target response spectrum, provided by the ICBO-AC156 code “Acceptance criteria for seismic qualification testing of nonstructural components” (International Conference of Building Officials (ICBO), 2000; Magliulo et al., 2014).

Preliminarily, system identification tests were also carried out using two single-axis loading protocols: low-amplitude sine-sweep and white noise with low-acceleration, i.e. with root-mean-square intensity limited to 0.05 ± 0.01 g, in compliance with the provisions included in Federal Emergency Management Agency (FEMA) (2007b).

EXPERIMENTAL EVALUATION OF MODAL RESPONSE WITH SHAKE TABLE TESTS

A variety of configuration layout, related to the arrangement of the contents on the different shelves, is experimentally investigated (Table 1).

Table 1. Test program definition.

Test group	Plan configuration	Cabinets contents
1000	1	Equivalent mass uniformly distributed along the height
2000	1	Equivalent mass non uniformly distributed along the height
3000	1	Typical glass contents uniformly distributed along the height
4000	2	Equivalent mass uniformly distributed along the height
5000	2	Equivalent mass non uniformly distributed along the height
6000	2	Typical glass contents uniformly distributed along the height

Test group 1000 assesses the dynamic behavior of the cabinet with an equivalent mass, i.e. sand inserted in boxes, at each shelf of the cabinets. 6 kg mass and 4 kg mass is added for each shelf of the double-window cabinet (Fig. 3a) and single-window cabinet, respectively; the mass amount is representative of the mass of typical contents inserted in such a cabinet. The use of the equivalent mass is required in order to investigate the behavior of the cabinets with different contents on the shelves. The contents are simulated through the use of sand boxes in order to prevent damage and replace the contents after each shaking.

Test group 2000 investigates the dynamic behavior of the cabinets with a decreasing mass distribution along the height. From the base to the top, on the four shelves of the double-window cabinet, 6 kg, 4 kg, 4 kg and 2 kg masses are placed (Fig. 3b). On the four shelves of the single-window cabinet 4 kg, 2 kg, 2 kg and 0 kg masses are placed. The aim is to investigate the behavior of cabinets in which, as typically suggested, the heaviest contents are placed at the lowest shelves.

Typical glass contents are tested in test group 3000, as shown in Fig. 3c. The contents are equally placed on the different shelves of each cabinet. Glass bottles with different dimensions, i.e. 100 ml, 250 ml and 500 ml, are placed in the double-window cabinet whereas 250 ml and 100 ml flasks, test tubes and glass beaker are placed in the one-window cabinet. They are filled with colored sand, that simulates the presence of water. In this test group the behavior of realistic contents is also investigated.

(a) (b) (c)

Figure 3. Single-window cabinet in (a) test groups 1000 and 4000, (b) test groups 2000 and 5000 and in (c) test groups 3000 and 6000.

In Fig. 4a the plan configuration of the different components in test groups 1000, 2000 and 3000 is shown. A different plan configuration is defined in test groups 4000, 5000 and 6000 (Fig. 4b). The different components are arranged in such a way that the different components are shaken along the orthogonal direction, given the unidirectional input motion. In test groups 4000, 5000 and 6000 the same content mass configurations of test groups 1000, 2000 and 3000, respectively, are chosen.

This work will focus primarily on the results carried out by applying random unidirectional excitations. The random vibration tests are performed before shake table test at increasing intensity, widely described in (Cosenza et al., 2014).

(a)-configuration 1 (b)-configuration 2

Figure 4. Photo of the test setup: (a) configuration 1, adopted in test groups 1000, 2000 and 3000 and (b) configuration 2, adopted in test groups 4000, 5000 and 6000.

Random vibration excitation are performed in order to dynamically identify the different tested components. The random vibration excitations are characterized by a large frequency content over a wide frequency range.

High quality digital accelerometers are used to monitor the response of the hospital building contents. Four accelerometers are placed at the base, i.e. at the lowest shelf level, and at the top of the front side of each cabinet; one accelerometer is positioned at the top of the desk and at the top of the monitor; one accelerometer records the acceleration at the shake table level. The sampling frequency of the accelerometers is equal to 400 Hz.

DYNAMIC IDENTIFICATION THROUGH THE EXPERIMENTAL METHOD

The transfer curve method is adopted to evaluate the natural frequency of the different components. The length of each block, i.e. NFFT, defines the resolution of the transfer curve. Moreover, a 50% block overlap is also selected. The length of each block is adequately selected in order to define a fairly regular transfer curve. The method is applied for the sample two cabinets and for the desk.

Typical transfer curves are plotted in Fig. 5. The NFFT is selected equal to 1024 and to 4096 for the transfer curves of the cabinets and the desk, respectively. Considering that the sampling frequency of the accelerometers is equal to 400 Hz, the frequency resolution of the transfer curve is 0.391 Hz for the cabinets and 0.098 Hz for the desk.

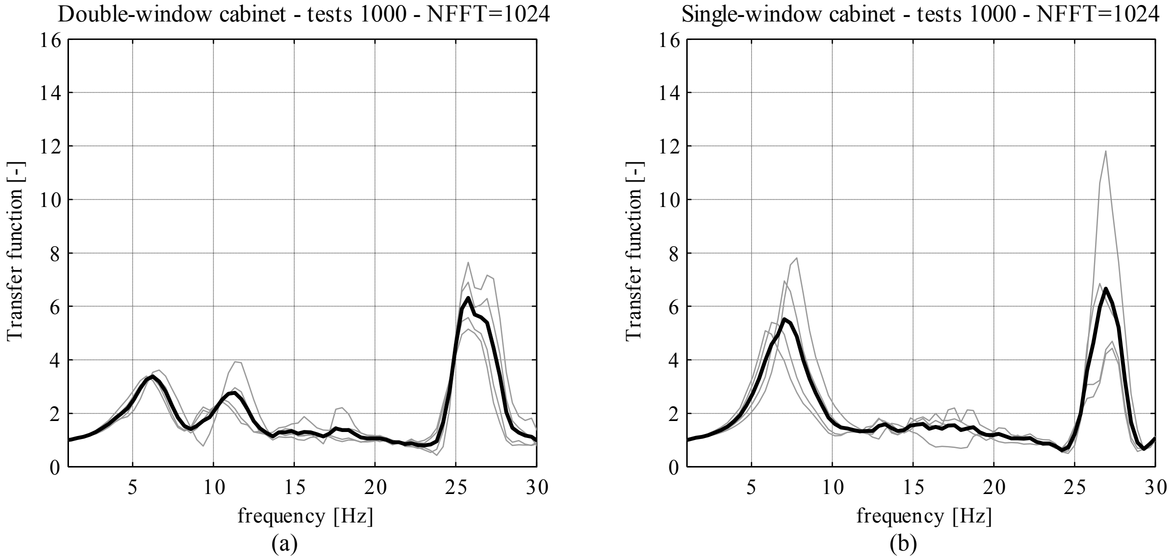

Figure 5. Transfer curves for (a) double-window cabinet – tests 1000, (b) single-window cabinet – tests 1000.

An average transfer curve is evaluated for each test group from the gray curves corresponding to each single test. The peak in the mean transfer curve denotes the natural frequency associated to one of the vibrational modes. The transfer curves in Fig. 5 emphasizes the presence of multiple modes of vibration. The fundamental frequencies for the different random tests are summarized in Table 2.

Table 2. Natural frequency of the tested components for the different random test groups.

Test group ID	2-window cabinet	1-window cabinet
1000	6.25 Hz	7.03 Hz
2000	5.08 Hz	6.64 Hz
3000	6.25 Hz	7.03 Hz
4000	4.68 Hz	7.03 Hz
5000	5.08 Hz	8.20 Hz
6000	4.30 Hz	7.81 Hz

EXPERIMENTAL TEST CAMPAIGN

To investigate the seismic behavior of the hospital room, a suite of accelerograms, used as input for the unidirectional horizontal shakings, are adequately selected to match a target response spectrum, provided by the ICBO-AC156 code “Acceptance criteria for seismic qualification testing of nonstructural components”.

As already descript, different variables, related to the arrangement of the contents on the different shelves and to the position of the cabinets with respect to the wall behind, are considered. A few variables are investigated in the six test groups of the undertaken test campaign (Table 3).

For the whole test campaign it is chosen to lock the cabinet windows and do not to restrain the cabinet to the wall behind, which is representative of the typical conditions in European hospitals. Each test group provides a set of shakings with increasing intensity. A total number of 63 shakings are performed during the whole test campaign. After each shaking the different components are relocated in their original condition.

Table 3. Test program definition.

Test group	Plan configuration	Cabinets contents
100	1	Equivalent mass uniformly distributed along the height
200	1	Equivalent mass non uniformly distributed along the height
300	1	Typical glass contents uniformly distributed along the height
400	2	Equivalent mass uniformly distributed along the height
500	2	Equivalent mass non uniformly distributed along the height
600	2	Typical glass contents uniformly distributed along the height

A damage scheme is defined in order to correlate the visual damage to the achievement of a given damage state (Table 4). Three damage states are defined, i.e. Damage State 1 (DS1), Damage State 2 (DS2) and Damage State 3 (DS3). The damage state definitions are strictly related to the loss that a given damage state would cause, as indicated in Table 4. The level of damage required to reach a limit state is defined for each damage typology of each system component (i.e. cabinet, desk and contents). If possible, the damage type is defined quantitatively. The damage state achieved by the whole specimen is the maximum damage state recorded among the different components. This process is required for the definition the fragility curves described in the next Section.

Table 4. Damage scheme for the correlation of the visual damage to the damage state.

		Damage state 1	**Damage state 2**	**Damage state 3**
Component	**Damage typology**	*Operational interruption*	*Need to replace damaged part of the components*	*Need to replace the whole component and/or threat for life safety*
Cabinet	**Residual displacement**	Displacement larger than 2cm	-	-
	Collapse	Screw loosening	Collapse of one support	Collapse of more than one support
		Residual displacement in shelves less than L/500	Permanent displacement in shelves larger than L/500	Shelves collapse
		Window opening	Window locking	Window collapse
	Overturning	Rocking	Hammering (with damage)	Overturning
Desk	**Residual displacement**	Displacement larger than 4cm	-	-
	Collapse	Screw loosening	Collapse of one support	Collapse of more than one support
		Drawer opening	Drawer slipping out of rail	Desk collapse or overturning
Content	-	Displacement	Collapse (less than 10%)	Collapse (more than 10%)

TEST RESULTS AND FRAGILITY CURVE EVALUATION

In Table 5 and Table 6 the peak shake table acceleration (or peak floor acceleration, PFA) that causes the rocking mechanism initiation and the overturning, respectively, in both the cabinets is reported. The video recordings confirm the results of the "visual" damage detection. As expected, in test groups 400 – 500 – 600, in which the cabinets are shaken along their longitudinal direction, a larger peak floor acceleration is required in order to let the rocking mechanism develop in the single-window cabinet; the double-windows cabinet, instead, does not exhibit the rocking behavior at all, exhibiting a sliding-dominated motion in the same test groups. Moreover, the overturning of the cabinet is recorded only in case the cabinets are shaken along their transversal direction.

Table 5. Peak floor acceleration (PFA) that causes the rocking mechanism initiation for the different test groups and for the two tested cabinets.

Rocking	*single-window cabinet*	*double-windows cabinet*
Test group	PFA [g]	PFA [g]
100	0.37	0.48
200	0.49	0.49
300	0.49	0.61
400	0.74	
500	0.95	
600	0.84	

Table 6. Peak floor acceleration (PFA) that causes the cabinet overturning for the different test groups and for the two tested cabinets.

Overturning	*single-window cabinet*	*double-windows cabinet*
Test group	PFA [g]	PFA [g]
100	1.10	1.24
200	1.24	0.97
300	1.10	
400		
500		
600		

The input motion is unidirectional. In order to correlate the chosen engineering demand parameter, i.e. peak floor acceleration (PFA), to the three defined damage states, the results of the test groups 100, 200 and 300 are combined with the results of the test groups 400, 500 and 600. For instance, the PFA that causes the DS1 threshold is the minimum between the PFA that induces DS1 in test groups 100 and the PFA that induces DS1 in test groups 400. It is assumed that the simultaneous combined effects of the two orthogonal motions are neglected.

Given this assumption in Table 7 the PFA values that trigger the different damage states for the different test groups are reported. It should be noted that DS2 PFA values are omitted. This is due to the fact that DS2 is recorded only in tests 300-600 for the overturning of some contents that are inserted in the cabinets, corresponding to a PFA equal to 0.486 g. In tests 100-400 and 200-500, in which sand equivalent masses are inserted in the cabinets, damage state 2 is not recorded at all, i.e. the specimen directly moves from DS1 to DS3. Hence, experimental data are not sufficient to evaluate the DS2 fragility curve.

Table 7. Peak floor accelerations that induces damage state 1 (DS1) and damage state 3 (DS3) for the different test groups.

Test group	DS1	DS3
100-400	0.371 g	1.103 g
200-500	0.491 g	0.974 g
300-600	0.486 g	1.099 g

Based upon the data in Table 7, the fragility curve is evaluated according to Porter et al. (2007). The fragility curves that fit the experimental data (dotted thick lines in Fig. 6) are clearly evidenced with respect to the ones with the larger dispersion (solid thick lines in Fig. 6). The latter also take into account the logarithmic standard deviation β_u. As expected, β_{fit} is very small, since it includes only the variability due to the different mass configuration.

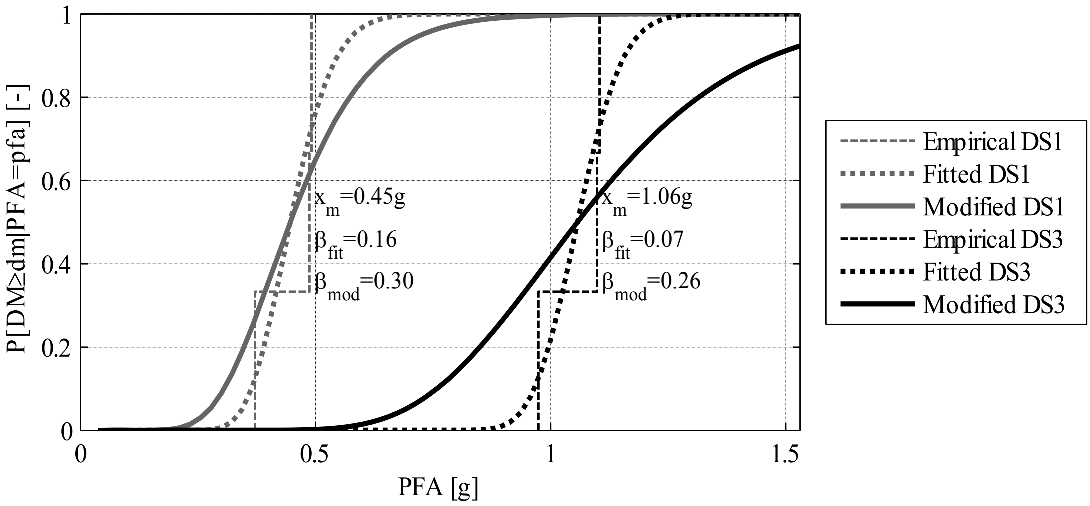

Figure 6. Fragility curves for the damage states 1 and 3 considering mass variability.

CONCLUSIONS

An examination (out patients consultation) room is selected as representative layout for the experimental seismic performance assessment of the core units of hospital buildings. The building contents utilized for the examination room include two cabinets, a desktop computer and a desk; different glass contents are also included in the cabinets in some tests. Different mass distributions are selected to distribute such contents in the single- and double-window cabinets. 63 shakings are performed during the whole test campaign.

The natural frequency of the different components is estimated. It is found that the distribution of the mass along the height assumes a key role to evaluate the natural frequency of the cabinets in case they are shaken along their transversal direction. The experimental natural frequencies match the counterpart values derived by using the numerical models of the tested hospital building contents.

The peak shake table acceleration (PFA) that causes the rocking mechanism initiation and the overturning, respectively, in both the cabinets are analyzed. In particular, the rocking mechanism in the two tested specimen initiates for a PFA that ranges between 0.37 g and 0.61 g; instead the overturning of the cabinets occurs for PFA slightly larger than 1.00 g.

A damage scheme is defined in order to correlate the visual damage to the onset of the selected three-stage damage states in the hospital ambulatory room. Fragility curves are defined for damage state 1 and damage state 3. Such fragility are derived based on a systemic approach, i.e. encompassing the performance levels of the components within the sample ambulatory rooms. Different groups of specimen are considered in the evaluation of the fragility curves in order to investigate the mass variability.

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