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SEISMIC FRAGILITY ASSESSMENT OF MEDICAL COMPONENTS

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Abstract. *Shake table tests on a full scale three-dimensional model of a consultation room has been carried out at the University of Naples, Federico II ,Italy . The sample room contains a number of typical medical components, which are either directly connected to the panel boards of the perimeter walls or are simple free-standing elements. System identification was firstly carried out in order to identify the modal properties of the tested components. Selected ground motion records were scaled to detect different limit states for the medical devices. Fragility analysis has also been carried out; in so doing, the fragility curves have been evaluated according to a systemic approach. Simplified yet reliable finite element models of the experimentally tested sample components are defined upon the laboratory outcomes through the computer platform routinely used for practical applications. The implemented numerical model is capable to simulate the variations of natural frequency as provided by the experimental tests, in case the component is shaken along the two horizontal directions. The main finding of the present analytical study is therefore that simple models are able to adequately simulate the dynamic properties of the tested cabinets.*

1 INTRODUCTION

Surveys carried out in the aftermath of recent major earthquakes world-wide [1-3], 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) earthquakes, have emphasized the poor performance of existing hospital buildings.

As a result, in the last decades, numerous governmental actions, aiming at ensuring the life safety and collapse prevention of acute healthcare facilities, have been promoted worldwide. For example, in California, in addition to safety standards, over time, it is enforced that, by 2030, hospitals should also meet performance levels meant to ensure that they are capable of providing services to public after an earthquake or any other disaster. Several initiatives have also been promoted by the World Health Organization (WHO) and the United Nation International Strategy for Disaster Reduction (UNISDR), e.g. the global campaign "Hospital Safe From Disasters" [4]. However, designing for resilient hospitals still remains a challenging task; it needs an interdisciplinary approach encompassing the physical, namely structure, non-structural components and building contents, and non-physical components, i.e. procedures and organization, of a hospital system [5].

Recently, few studies have been initiated to analyze the seismic performance of a variety of furniture items, medical appliances and service utilities of typical hospital buildings and pharmacies [6]. Full scale shake table tests were carried out on a base-isolated four story RC hospital structure [7, 8].

The need to maintain the functionality of health care facilities is essential in the aftermath of earthquake strong motions. The health care facilities are, indeed, classified as critical buildings and the limits on the structural and nonstructural components, as well as building contents, are highly stringent. The hospitals may show several damage when they are struck by an earthquake, especially those that were designed primarily for gravity loads or do not employ base isolation. Due to the scarcity of analytical and theoretical studies on the earthquake response of building contents, there is a urgent need to evaluate the capacity of such contents. Actually, the building contents are not protected by the existing design standards that especially affect the hospital buildings.

The present paper focuses on an ongoing experimental and theoretical research study that was funded by the Consortium Reluis at the University of Naples Federico II. The study is aimed at evaluating the seismic performance of freestanding cabinets, which are typically included in health care rooms.

A shake table test on a full scale three-dimensional consultation room has been carried out in the laboratory of the University of Naples, Federico II. Such room contains a number of typical medical components, which are either directly connected to the panel boards of the perimeter walls or are simple free-standing elements. From the experimental standpoint, the system identification was firstly carried out in order to identify the modal properties of the sample components. The records were scaled up to the onset of different limit states for the building contents. The fragility curves were evaluated according to a systemic approach.

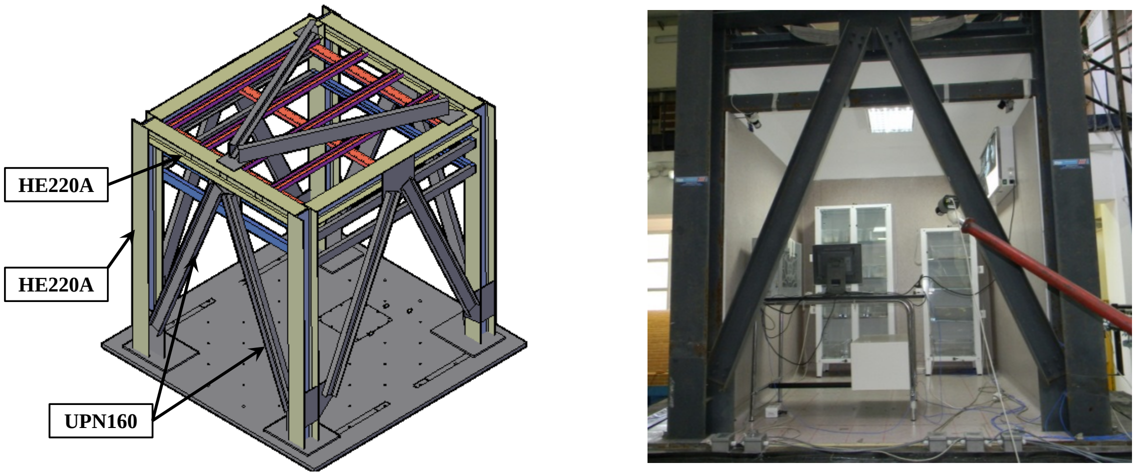
Simplified finite element models of the experimentally tested sample components are defined upon the laboratory outcomes through the computer platform routinely used for practical applications. Their dynamic response is compared to the experimental results, in order to validate such an approach.

2 EXPERIMENTAL TESTS

2.1 Test setup, specimen and testing protocol

A steel single-story framed system was designed (Figure 1a) with the purpose of simulating the seismic effects on the medical contents of a typical hospital room. 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. To simulate the effects of the earthquake at different floors on a hospital building, the geometry of the test frame was designed to prevent the onset of the resonance. As a result, the steel frame possesses a large lateral stiffness. Further details on the steel test setup are included in [9, 10]. The total weight of the sample structure is 19.2 kN.

A realistic hospital ambulatory 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 1b).



(a) (b)

Figure 1: Global perspective of the test setup (a); photo of the hospital ambulatory room contents (b).

The building contents used for the ambulatory room include: (a) a hospital medicine cabinet made of cold formed sheet with dimension 80x60x165 cm, having double moving glass doors with locker and five mobile glass shelves; (b) a hospital medicine cabinet made of cold formed sheet with dimension 53x36x144 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. Cabinet contents with different slenderness such 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.

High quality digital accelerometers are used to monitor the response of the hospital building contents. They are characterized by a measurement range equal to ±10 g and by a frequency range from 0.5 Hz to 3000 Hz. 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.

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” [11]. Additional information on testing input and testing protocol is provided in [12, 13].

The definition of a realistic condition for the sample cabinets is a crucial issue of the research study. Different variables, related to the arrangement of the contents on the different shelves, are considered. A few variables are investigated in the six test groups of the undertaken test campaign. Test group 100 assesses the 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 and single-window cabinet, respectively; the mass 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 their shelves; the contents are simulated through the use of sand boxes in order to avoid damaging and replacing the contents after each shaking. Test group 200 investigates the 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. Instead, 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 300. The contents are equally placed on the different shelves of each cabinet. They are filled with colored sand, that simulates the presence of water. In this test group the behavior of real contents is also investigated.

In Figure 2a the plan configuration of the different components in test groups 100, 200 and 300 is shown. A different plan configuration is defined in test groups 400, 500 and 600 (Figure 2b). 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 400, 500 and 600 the same content mass configurations of test groups 100, 200 and 300, respectively, are chosen.

Random vibration inputs are also applied in order to dynamically identify the sample components, before executing the shake table tests. In particular, random tests 1000 are performed before the test group 100, random tests 2000 before test group 200, and so on.

For the whole test campaign it is chosen to lock the cabinet windows and do not 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.

2.2 Results and discussion

A damage scheme is defined in order to correlate the visual damage to the achievement of a given damage state. 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 [14]. 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.

In Table 1 and Table 2 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.

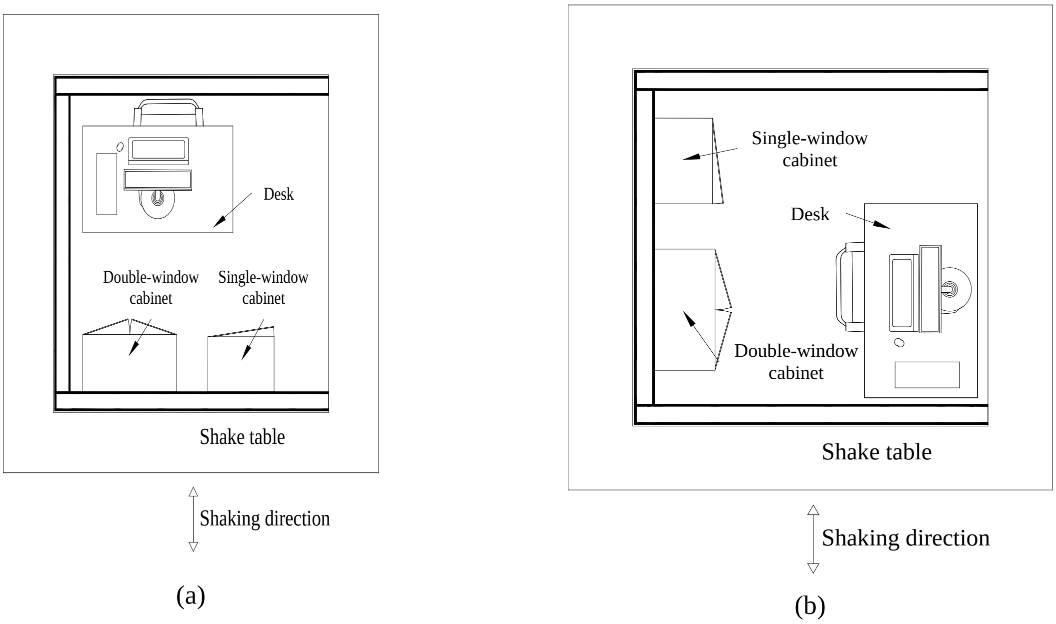


Figure 2: Plan view of the test setup: (a) configuration 1, adopted in test groups 100, 200 and 300 and (b) configuration 2, adopted in test groups 400, 500 and 600.

Table 1. 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 2. 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 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.

Based upon the data in Table 3, the fragility curve for the damage states 1 and 3 are evaluated according to Porter et al. [15, 16] (Figure 3)

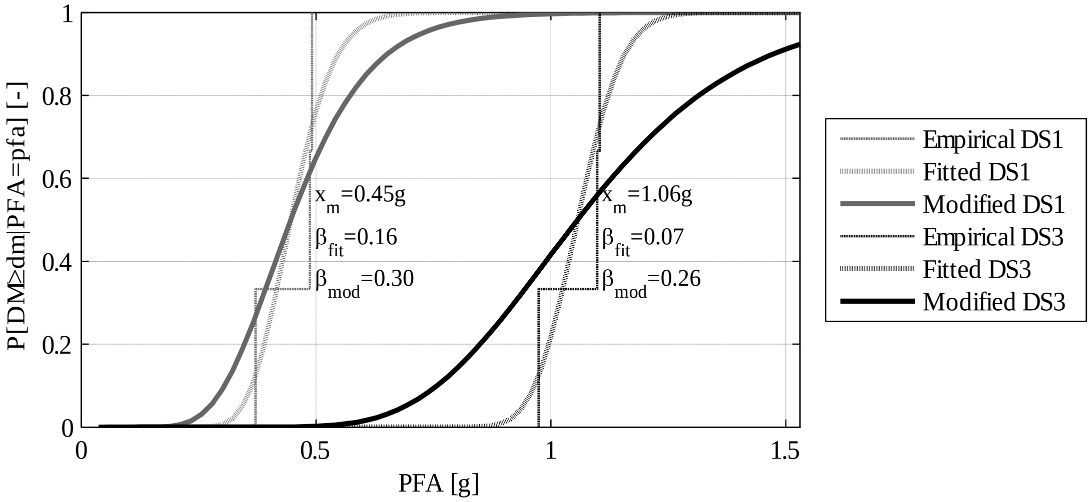


Figure 3: Fragility curves for the damage states 1 and 3 considering mass variability.

3 NUMERICAL MODEL

The tested components are also simulated numerically through the Sap 2000 program [17]. The results of the finite element models are compared to the experimental data measured during the full-scale shaking table tests. The comparison is limited to the linear dynamic response of the tested contents. An accurate survey of the different components is required in order to increase the accuracy of the numerical models.

The cabinets are composed of four steel vertical columns connected each other by steel elements. The global dimensions of both the investigated cabinets are summarized in Table 3.

	height [cm]	width [cm]	depth [cm]
Double-window cabinet	165	74.5	38
Single-window cabinet	139	53	36

Table 3: Dimensions of the investigated cabinets.

The vertical steel elements are characterized by an angular 55 cm x 50 cm “L” section with 0.1 cm thickness, with the 55 mm wide flange parallel to the transversal side of the cabinet. They are connected by two steel horizontal plates with side stiffeners and bolted connections, at the top of the cabinet and at 17 cm height (Figure 4). The steel plates and their stiffeners are characterized by 1 mm thickness, whereas the stiffeners are 3.0 cm high. Three of the four vertical bays are infilled with 1 mm thick steel plates, whereas glass windows are installed in the fourth bay. The double-window cabinet is also characterized by a 5 cm x 0.1 cm rectangular vertical steel element that separates the two glass windows.

(a) (b)

Figure 4: Global view of the sample cabinets.

3.1 Single-window cabinet

The vertical steel columns are modelled according to their actual geometry. The presence of the steel horizontal plates is modelled through four horizontal steel elements characterized by a 0.1 cm (width) x 3 cm (height) rectangular cross section both at the top and at 17 cm height of the cabinet. These horizontal elements are characterized by a large out-of-plane stiffness, i.e. large moment of inertia about the vertical axis, to simulate the presence of the steel horizontal plate element. Furthermore, two diaphragm constraints are imposed between the 4 points at the top and the 4 points at 17 cm height. The vertical panels are not included in the model, since they are connected so as not to increase the lateral stiffness of the cabinet. The glass window is modelled with a properly meshed shell element, assuming a 80000 N/mm^2 elastic modulus. Hence, the adopted model is able to capture both the global modes in the two horizontal directions, which involve the whole cabinet, and the local ones, which involve a portion of the cabinet. Rigid elements in the out-of-plane direction are included between the steel elements and the glass window in order to model the restraint given by their connection, whereas the glass window does not contribute to the in-plane stiffness; indeed, the glass window is connected to the cabinet only along one of the two vertical sides. A rigid element in the out of plane direction is also included to model the lock of the glass window.

The single-window cabinet mass is 15 kg, excluding the window mass; for the sake of simplicity, the mass is equally divided between the top and the base of the cabinet. The steel elements are characterized by no mass, whereas the mass is included in the glass window in order to correctly estimate the local vibrational modes of the glass window. Different mass amounts are inserted at the shelf levels, according to the actual mass adopted in the experimental phase for the different test groups. The first and the second vibrational modes in test group 1000 are characterized by 6.18 Hz and 7.38 Hz natural frequencies (Figure 5). A local mode that involves the glass window, characterized by a larger natural frequency (23.12 Hz), is also identified.

(a) (b) (c)

Figure 5: Single-window cabinet modal shapes in tests 1000 and 4000: (a) I vibration mode (6.18 Hz), (b) II vibration mode (7.38 Hz), (c) III vibration mode (23.12 Hz).

FEM results match very well the experimental results, evaluated through the use of the transfer curve method [18, 19]. The peak represented in the transfer curve that occurs at 26 Hz is compatible with the frequency of the local mode in the FEM model. The comparison between the numerical and the experimental natural frequencies for the different test groups is summarized in Table 4.

Test group	FEM model	Experiment	Δ [%]
1000	7.38 Hz	7.03 Hz	+5.0
2000	8.84Hz	6.64 Hz	+33.1
3000	6.88 Hz	7.03 Hz	-2.1
4000	6.18 Hz	7.03 Hz	-12.1
5000	7.64 Hz	8.20 Hz	-6.8
6000	5.92Hz	7.81 Hz	-24.2

Table 4: Comparison between the fundamental frequency results from the FEM analysis and the transfer curve.

The numerical and the experimental frequencies of the tested cabinet are close. Considering the low level of accuracy of the model with respect to the complexity of the geometry and the mechanical connections between the elements, the outcomes of the numerical analyses give a good approximation of the experimental ones. It is therefore demonstrated that simple models are able to capture the dynamic properties of the tested cabinet.

3.2 Double-window cabinet

The modelling approach of the double-window cabinet is very similar to the one provided for the single-window cabinet. However, the dimension and the mass, i.e. 20 kg, are slightly different than the corresponding values in the single-window cabinet. The vertical steel element between the two windows is properly modelled according to its own geometry; such an element is hinged to the cabinet, in order to model the single-bolted connection. The connection between the cabinet and glass window is modelled by rigid elements in the out of plane direction, similarly to the single-window cabinet. The rigid elements simulate the actual restraints given to the glass window by a steel connector. The different mass amounts corresponding to the different performed test groups are inserted at the shelf levels. The first two modes involve the whole cabinet, the third one is a local mode that involves the vertical element between the two glass windows and the fourth mode involves the glass windows.

The FEM outcomes (Figure 6) match very well the results of the experimental transfer curves. The three peaks represented in the transfer curves, which occur at about 6 Hz, 11 Hz and 25 Hz, respectively, are compatible with the frequencies of the first, third and fourth modes in the FEM model. In particular, the numerical model allows justifying the differences in the transfer curves among the single- and the double-window cabinets. Indeed, the double-window transfer curve denotes three different peaks, whereas the single-window one exhibits only two peaks. The comparison between the numerical and the experimental natural frequencies for the different test groups is summarized in Table 5.

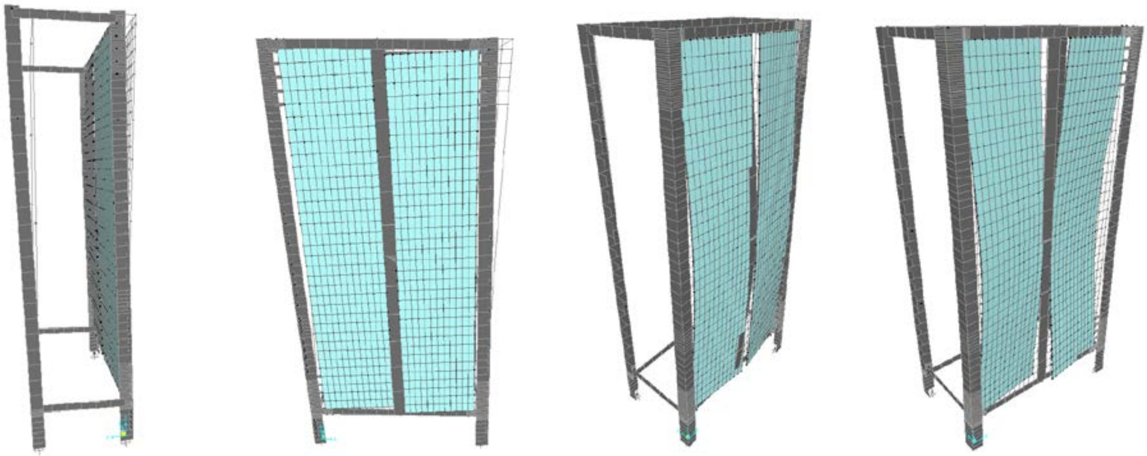

(a) (b) (c) (d)

Figure 6: Double-window cabinet modal shapes in tests 1000 and 4000: (a) I vibration mode (4.74 Hz), (b) II vibration mode (5.08 Hz), (c) III vibration mode (10.35 Hz), (d) IV vibration mode (19.90 Hz).

Test group	FEM model	Experiment	Δ [%]
1000	5.08 Hz	6.25 Hz	-18.7
2000	5.57 Hz	5.08 Hz	+9.6
3000	5.30 Hz	6.25 Hz	-15.2
4000	4.74 Hz	4.68 Hz	+1.3
5000	5.40 Hz	5.08 Hz	+6.3
6000	5.04 Hz	4.30 Hz	+17.2

Table 5: Comparison between the frequency results from the FEM analysis and the transfer curve.

Also for the double-window cabinet, the numerical and the experimental frequencies of the tested cabinet are in similar ranges. It can be concluded that simple models are able to simulate reliably the dynamic properties of the cabinets.

Experimental-to-numerical comparison of both mode shapes and transfer curves [18], omitted here for the sake of brevity, confirms the good agreement.

4 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 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. 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.

Simplified yet reliable finite element models of the experimentally tested sample components are defined upon the laboratory outcomes through the computer platform routinely used for practical applications. The implemented numerical model is capable to simulate the variations of natural frequency as provided by the experimental tests, in case the component is shaken along the two horizontal directions. The natural modes of the two tested cabinets are adequately simulated by the numerical model. The multiple peaks observed in the transfer curves are associated to a mode shape. The dynamic response of the defined models is assessed through the numerical-to-experimental comparison of the transfer curves. Considering the low level of accuracy of the model with respect to the complexity of the components, the outcomes of the numerical analyses provide a close approximation of the experimental ones. The main finding of the present analytical study is therefore that simple models are able to adequately simulate the dynamic properties of the tested cabinets.

Finally, it is emphasized that the outcomes related to the developed models is limited to freestanding components which do not exhibit any rocking mechanism, i.e. they are rigidly connected at their base to the floor.

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