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VALIDATION OF NUMERICAL MODELS FOR HOSPITAL BUILDING CONTENTS: RIGID BLOCK AND FEM MODELS

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Abstract

In this study, simplified finite element models of the tested components have also been implemented in software platforms to adequately simulate the dynamic properties of sample medical components. Different numerical modeling approaches are validated upon the outcomes of a comprehensive experimental campaign on hospital building contents carried out by shake table testing at the University of Naples Federico II, Italy.

Finite element modeling approach is adopted to investigate the dynamic behavior of hospital cabinets in case they do not exhibit any rocking mechanism, i.e. pre-rocking behavior. The validation of a FEM model for the dynamic performance of cabinets is presented. Its ability to reproduce horizontal acceleration in the cabinets is also discussed. The developed numerical model gave a fairly good matching in terms of natural frequencies of the sample components. Nonlinear dynamic analyses are performed on the defined models. Recorded table acceleration are applied at the base of both the cabinets for the three different test groups. It is concluded that the defined model is able to recognize the occurrence of the rocking mechanism in the cabinets.

Medical components, such as the tested cabinets, typically exhibits a rocking behavior as the seismic intensity increases. Thus, the dynamic behavior of rigid blocks is investigated for the post-rocking behavior of cabinets. Tested cabinets are modelled as equivalent rigid blocks and subjected to the experimental base accelerations. The ability to predict the occurrence of both rocking mechanism and overturning is verified. Given the good model fidelity, a preliminary study is performed aimed at the identification of the most efficient seismic intensity measure (IM) for rigid blocks and the influence of the geometric properties of rigid blocks on their dynamic performance.

Keywords: nonstructural components, seismic fragility, numerical model, rigid block, FEM model

1. Introduction

Health care facilities may undergo severe and widespread damage that impairs the functionality of the system when they are stricken by an earthquake. Such a detrimental response is emphasized for the hospital buildings designed either primarily for gravity loads or without employing base isolation/supplemental damping systems. Moreover such buildings need to warrant functionality especially in the aftermath of moderate-to-severe earthquake ground motions. The post-earthquake functionality of hospital buildings is an essential performance objective to achieve in a modern resilient community [1]. Such a performance may, however, be impaired due to the damage to non-structural components and building contents. Recent surveys carried out in the aftermath of major world-wide earthquakes (e.g. [2; 3; 4], among others) have shown that the overturning of cabinets, containing medical files with patient details, the failure of electronic panels is a typical non-structural component damage recorded after moderate-to-large earthquakes. Hazardous contaminants may also be released when medical cabinets and bookshelves overturn; hence there is a number of dangerous consequences caused by the lack of adequate seismic design.

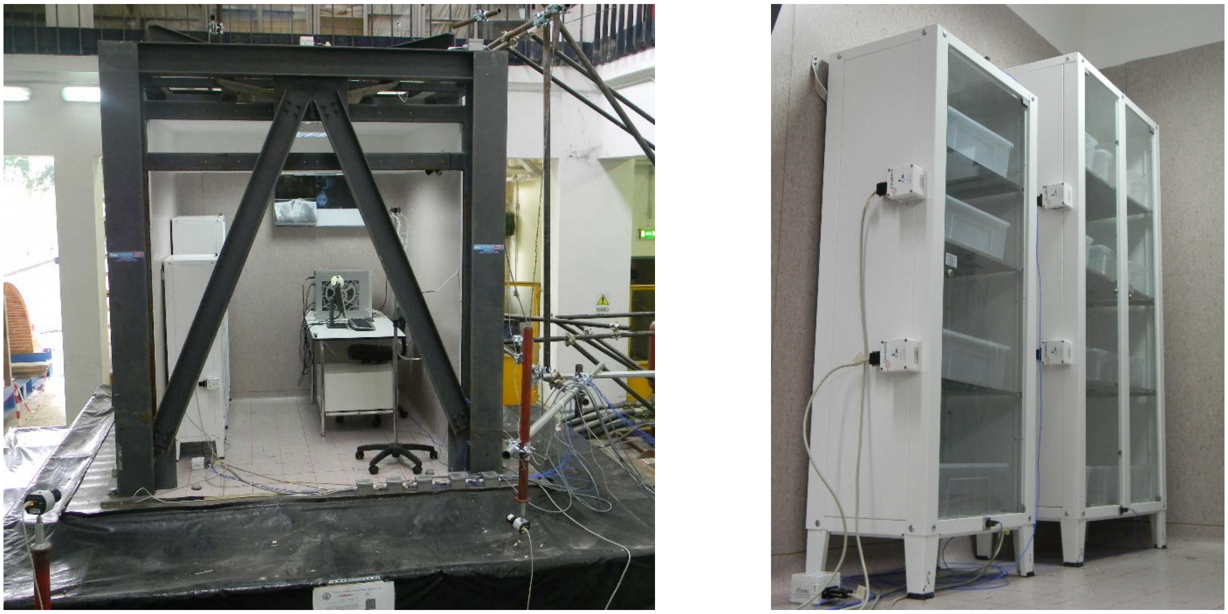
Comprehensive experimental and numerical studies were carried out in the last decade to investigate the seismic performance of a variety of furniture items, medical appliances and service utilities of typical hospital buildings and pharmacies, e.g. [5; 6; 7]. To date, there is a lack of comprehensive theoretical and experimental results dealing with the performance evaluation of the building contents for health care facilities. The earthquake response of such contents is not straightforward because of the complexity and variety of connections and functioning. So far, while few experimental tests have been carried out on buildings equipped with nonstructural components as well as hospital building contents (e.g. [5; 8; 9; 10] among some others), the modelling of hospital building contents is not extensively investigated in literature. Indeed, while the features of several nonstructural components typically require the use of experimental methods, nonstructural component testing tends to be expensive and time-consuming. Therefore the need to define numerical models for the prediction of hospital building content performance is claimed. Some models for sliding-dominated components were investigated in past research studies [11; 12; 13]; the absence of numerical models for rocking-dominated hospital building contents is, however, clearly denoted. The aim of the research study is to provide simple tools to both researchers and practitioners for the assessment of the seismic performance of hospital building contents.

The present work is targeted at defining and assessing the adequacy of existing numerical modeling approaches in predicting the seismic response of freestanding nonstructural components whose response is rocking dominated. Towards this aim, the results of an experimental study of a full scale three-dimensional model of a consultation room are employed to validate the numerical models. Two different modeling techniques are selected to analyze the seismic performance of two freestanding cabinets included in the consultation room: (a) finite element method (FEM) and (b) rigid block modeling. Reference experimental tests are briefly presented. Then the paper provides two distinct sections, dealing with the behavior of the cabinet before and after rocking mechanism is initiated.

2. Experimental tests

Numerical models developed in the following sections have been calibrated on the outcomes of a comprehensive experimental campaign on hospital building contents [7]. The shake table tests were carried out at the laboratory of Structures for Engineering and Architecture Department of University of Naples Federico II, Italy. A typical hospital examination (also named patients consultation) room background was reproduced within a sample steel frame (Fig. 1). The behavior of two full scale building contents used for the examination room was investigated in this study (Fig. 1b): (i) a hospital medicine cabinet made of cold formed sheet with dimension 75x38x165 cm, having double moving glass doors with locker and four shelves; (ii) a hospital medicine cabinet made of cold formed sheet with dimension 53x36x139 cm, having single moving glass door with locker and four shelves.

The mass of the two (empty) cabinets was respectively 20 kg for the double-window cabinet and 15 kg for the single-window cabinet. Contents were also included within the cabinets. Different mass distributions, obtained either by bowls filled with sand or realistic glass contents, were also considered for both the double- and single-window cabinets.



(a) (b)

Fig. 1 - (a) Global view on the tested hospital examination room and (b) close-up view on the two cabinets.

Three different test campaigns, named test groups, were considered hereafter. In test group 100, 6 kg mass was added to each shelf of the double-window cabinet, whereas 4 kg mass was added to each shelf of the single-window cabinet. The total added mass amount, which is 120% and 107% of the cabinet mass respectively, is representative of the mass of typical contents inserted in such a cabinet. In test group 200 the dynamic behavior of the cabinets with a decreasing mass distribution along the height was investigated. From the base to the top, 6 kg, 4 kg, 4 kg and 2 kg masses (totally 80% of cabinet mass) were placed on the four shelves of the double-window cabinet, while 4 kg, 2 kg, 2 kg and 0 kg masses (totally 53% of cabinet mass) were placed on the four shelves of the single-window cabinet. This configuration is representative of cabinets where, as typically recommended, the heaviest contents are placed at the lowest shelves. In test group 300, typical glass contents, equally placed on the different shelves of each cabinet, were tested. Glass bottles with different dimensions, i.e. 100 ml, 250 ml and 500 ml, were included in the double-window cabinet, whereas 250 ml and 100 ml glass beakers, flasks and test tubes are placed in the single-window cabinet. They were filled with colored sand, which simulated the presence of any typical medical content. Further details on the experimental test program are included in Cosenza et al. [7].

The shake table tests were performed according to the testing protocol included in AC 156 [14], which is applied to acceleration-sensitive nonstructural elements. The selected strong motion time-histories were artificially generated from a baseline signal characterized by non-stationary broadband random excitations with energy content from 1.3 to 33.3 Hz and one-sixth-octave bandwidth resolution. The artificial earthquake record had a total length of 30 seconds. Its frequency content was modified in order to match the required response spectra, defined by AC 156 for the seismic qualification of nonstructural components. Further details on the selected input motion are included in [15]. Several tests were performed at increasing intensity in order to assess the acceleration threshold value required to attain a given damage in the components. For instance, ten shake table tests were performed for test group 100, namely tests from 101 to 110, corresponding to peak table accelerations which range from 0.11 g to 1.25 g. The latter accelerations can be considered typical peak floor accelerations (PFAs) recorded at mid-height of multi-story hospital buildings located in moderate-to-high seismicity. Unidirectional motions were applied shaking the cabinets along their transversal direction, i.e. along their shorter sides (Fig. 2). High quality digital accelerometers were used to monitor the response of the hospital building contents. Four accelerometers were positioned at the base, i.e. at the lowest shelf level, and at the top of the front side of each cabinet; one accelerometer recorded the acceleration at the shake table level.

3. Numerical modelling

3.1 FEM model

This section deals with the investigation of the dynamic behavior of hospital cabinets when they do not exhibit any rocking mechanism, i.e. for pre-rocking behavior. Low-amplitude random vibrations were utilized to validate a numerical FEM model of the tested cabinets [16; 17], developed in SAP 2000 [18]. The developed numerical model provided a fairly good matching in terms of natural frequencies of the sample components. In this study, the numerical-to-experimental comparison is extended to the shaking table tests performed according to AC156. The reliability of the selected model to reproduce the recorded accelerations, e.g. top cabinet accelerations, when subjected to a predefined ground motion is assessed. Such a model would allow the estimation of the acceleration demand at each shelf of the cabinet, which excites the contents; moreover, it could be also used to check the likely occurrence of any rocking mechanism, as shown in the following.

The cabinets are composed of four steel vertical columns connected each other by steel elements. The steel vertical columns are characterized by 0.1 cm thick “L” cross-section. They are connected by two steel horizontal plates, at the top of the cabinet and at 17 cm height from their base. Three of the four vertical bays are infilled with 0.1 cm thick steel plates, whereas glass windows are installed in the fourth bay. The double-window cabinet is also characterized by a vertical steel element that separates the two glass windows.

The vertical steel columns are modeled with beam elements in SAP 2000, according to their actual geometry (Fig. 2). The presence of the steel horizontal plates is modeled through four horizontal beam elements both at the top and at 17 cm from the base. Two diaphragm constraints are imposed between the nodes at the top and at 17 cm height. Bi-dimensional elements are adopted to model glass windows. Further details on the developed models can be found in [16]. Masses are lumped at shelf levels according to the actual mass adopted in the experimental phase for the different test groups.

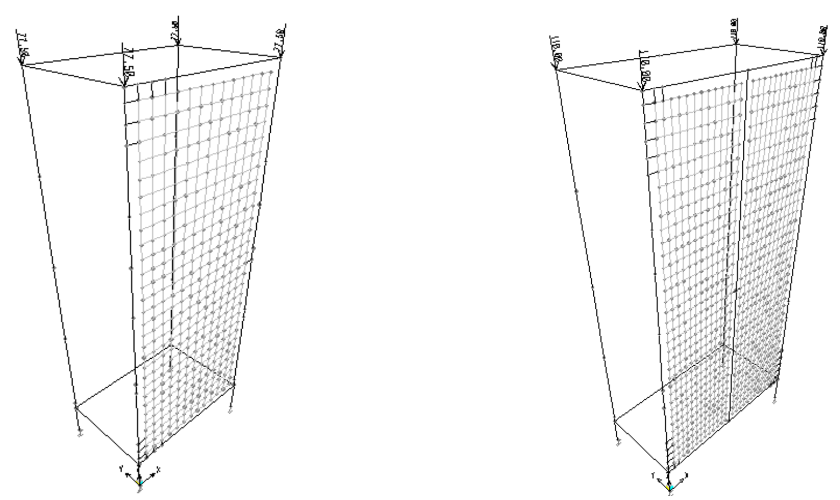


Fig. 2 - Finite element model of the tested cabinets for test group 100 (applied forces are in N).

Vertical nonlinear links, i.e. nonlinear springs, are added at the base of the cabinets. They are characterized by compression-only behavior in order to model the unilateral restraint of a freestanding cabinet at its base (Fig. 3). The cabinets are not connected at their base and are free to uplift. Vertical loads are applied at the top of the cabinets, simulating their own weight, as shown in Fig. 2. Finally, damping ratio is assumed equal to the experimental damping ratio, evaluated in [16]. Nonlinear dynamic analyses are performed on the defined models. Recorded table accelerations are applied at the base of both cabinets for the three different test groups. Top cabinet horizontal accelerations resulting from numerical model are compared to recorded horizontal accelerations for two different tests at two different intensities (see Fig. 4 and 5). A close numerical-to-experimental matching is observed for low-intensity shake table tests (Fig. 4), when the cabinet is laterally deforming without any evident rocking mechanism. At larger amplitudes the FEM model is not capable to reproduce the recorded accelerations (Fig. 5), particularly due to the presence of some spikes in the recorded accelerograms. These spikes are caused by the occurrence of a rocking mechanism, as highlighted in [7]. It can be therefore concluded that the developed numerical model is efficient until the cabinet exhibits the rocking mechanism. The numerical-experimental comparison is performed for all experimental tests. The same comments can be drawn from such comparisons, which are omitted here for the sake of brevity.

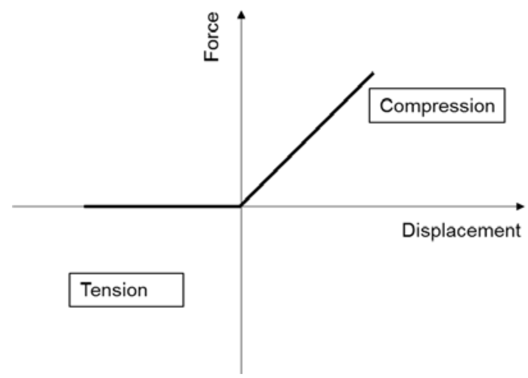


Fig. 3 - Vertical link nonlinear behavior.

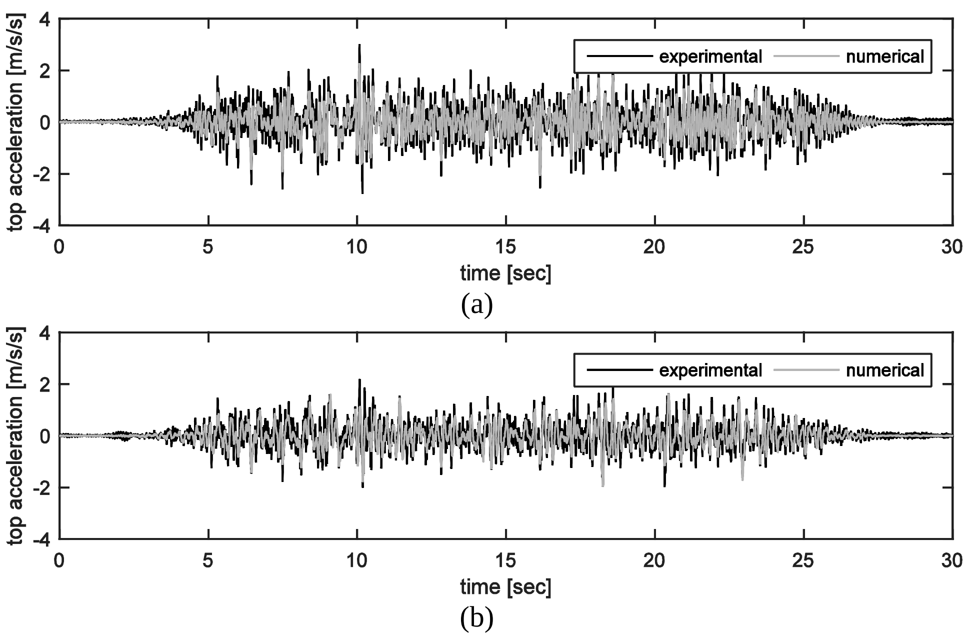
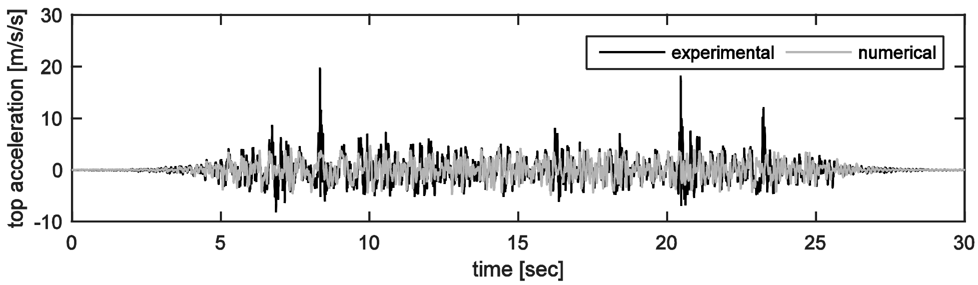
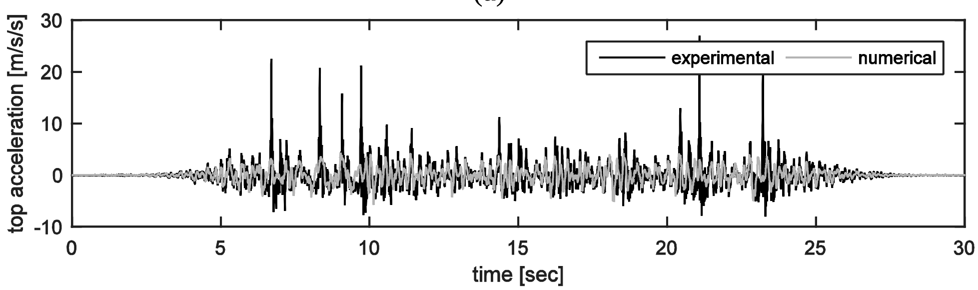


Fig. 4 - Comparison between FEM model and experimental results in test group 100 (0.126 g peak table acceleration) for (a) single-window cabinet and (b) double-window cabinet.

The evaluation of the seismic intensity required to record the rocking mechanism in the cabinet becomes therefore essential. The occurrence of such mechanism can be checked from the onset of tension displacement in the link element. Vertical displacements of both front and rear links can be plotted on the same graph of the recorded top cabinet horizontal accelerations (see Fig. 6 and 6). Negligible vertical displacements are recorded in both front and rear links in case cabinets do not exhibit rocking mechanism, e.g. the test characterized by 0.126 g peak table acceleration in test group 100 (Fig. 6). Large vertical tension displacements in links are instead highlighted as seismic intensity increases. Significant vertical displacements are recorded in links for all the tests which show rocking mechanism, e.g. the test characterized by 0.483 g peak table acceleration in test group 200 (Fig. 7). A time correlation of the rocking mechanism with the tension displacement in the links can be also highlighted: the spikes in the experimental horizontal acceleration time-history typically occur after the vertical link experiences the uplift, as clearly visible in Fig. 7a. The defined model is therefore able to recognize the occurrence of the rocking mechanism in the cabinets, which is denoted by vertical tension displacements in the link at the base of the cabinets.

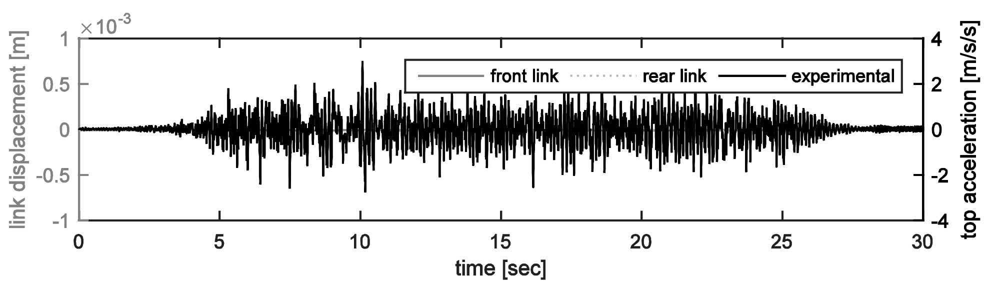


(a)



(b)

Fig. 5 - Comparison between FEM model and experimental results in test group 200 (0.483 g peak table acceleration) for (a) single-window cabinet and (b) double-window cabinet.



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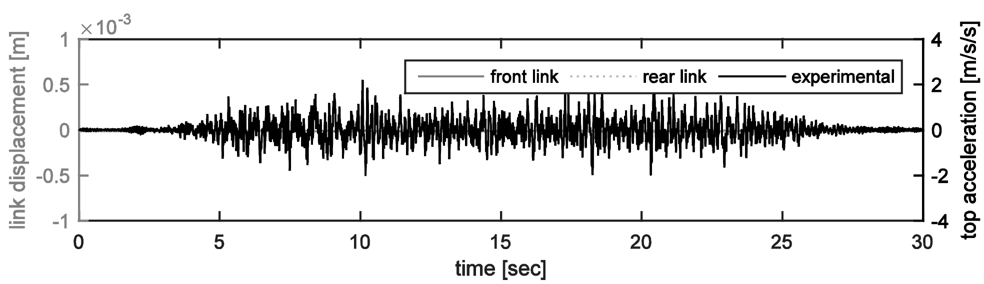
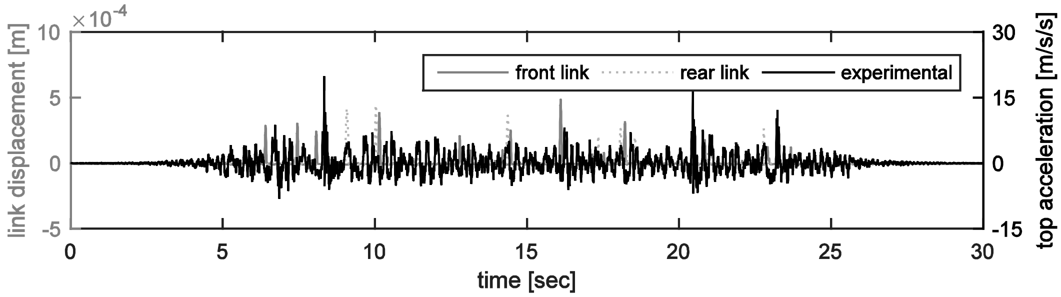
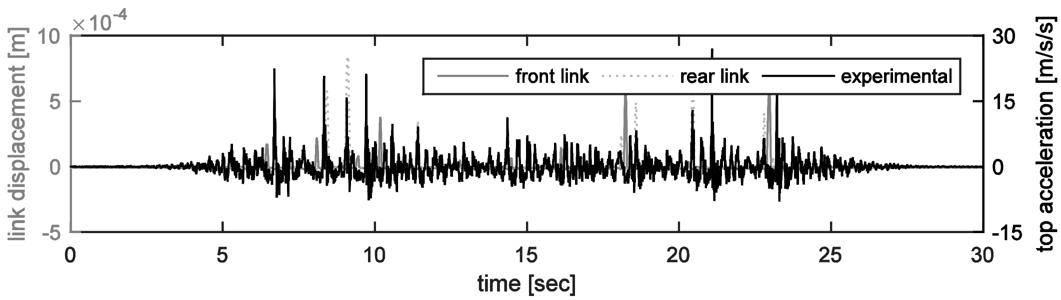


(b)

Fig. 6 - Experimental top cabinet acceleration and link vertical displacement in test group 100 (0.126 g peak table acceleration) for (a) single-window cabinet and (b) double-window cabinet.



(a)



(b)

Fig. 7 - Experimental top cabinet acceleration and link vertical displacement in test group 200 (0.483 g peak table acceleration) for (a) single-window cabinet and (b) double-window cabinet.

3.2 Rigid block

Medical components, such as the tested cabinets, typically exhibit a rocking behavior as the seismic intensity increases. Thus, rigid block model becomes a good candidate to model the dynamic response of these components. In this study, tested cabinets are modelled as equivalent rigid blocks and subjected to the experimental base accelerations; the ability to predict the occurrence of both rocking mechanism and overturning is verified.

As previously discussed, tested cabinets may be also modelled as rigid blocks, whose dynamic behavior was extensively investigated in past decades (e.g. [19; 20; 21; 22; 23; 24; 25], among many others). A rigid block may be set into rocking or move rigidly with the ground, depending on its geometric features; if it sets into rocking, it will oscillate about two centers of rotation at its base corners. In this study it is assumed that the block and base surfaces in contact are perfectly smooth so that the block will rock around the edges and no intermediate location. Moreover, the coefficient of friction is assumed to be large enough to avoid any sliding between the block and the base. In particular, the coefficient of friction is larger than the maximum acceleration normalized by the acceleration of gravity. This assumption is typically valid for the tested cabinets, given their slenderness and interface material with the floor. It is assumed that the mass is uniformly distributed within the cabinet. The rigid block is freestanding without any lateral restraint: the restraint provided by the rear wall, which in the reference tests [7] is positioned at 2 cm distance from the cabinet, is not modeled.

The equation of motion of the rigid block subjected to a predefined base motion $\ddot{u_g}(t)$ is derived by considering the equilibrium of moments about the centers of rotation:

$$\ddot{\theta}(t) = -p^2 \left\{ sin\,[\alpha\; sgn[\theta(t)] - \theta(t)] + \frac{\ddot{u_g}(t)}{g} cos[\alpha\; sgn[\theta(t)] - \theta(t)] \right\} \tag{1}$$

where θ is the rigid block rotation, g is the acceleration of gravity, p is the frequency parameter of the block and α is the critical angle (Fig. 8). The equation of motion is developed and adopted in several literature studies (e.g.

[23]). In this study it is solved through Runge-Kutta Ordinary Differential Equations (ODE) solver, available in Matlab [26].

Rocking mechanism occurs alternatively around O and O' (Fig. 8). It is assumed that the rotation continues smoothly from point O to O', when the angle of rotation reverses [23]. A reduction of the angular velocity is imposed when the rotation reverses, in order to take into account the energy loss at every impact [19]. Such a reduction is evaluated by equating angular momentum about O just before and immediately after the impact. The coefficient of restitution, i.e. the ratio between angular velocities after and before the impact, is evaluated as follows:

$$e = 1 - 1.5\sin^2\alpha \tag{2}$$

Single-window cabinet is modelled as a rigid block characterized by 0.36 m base ($2b$ in Fig. 8) and 1.39 m height ($2h$ in Fig. 8). Double window cabinet is modeled assuming 0.38 m base and 1.65 m height. Critical angles α are therefore 0.250 rad and 0.224 rad for single-window and double-window cabinets, respectively.

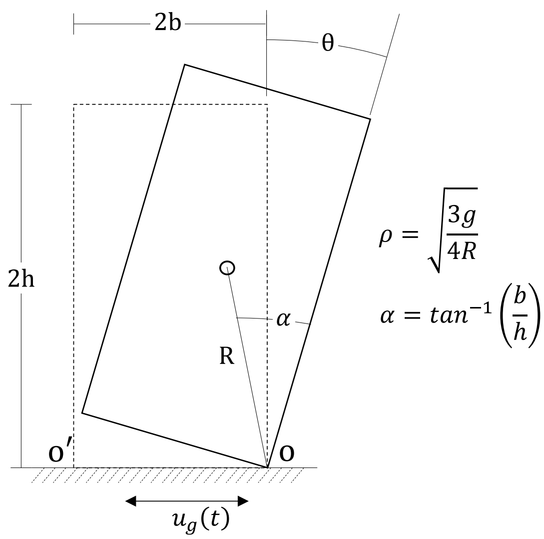


Fig. 8 - Rigid block geometry and parameters.

These models are subjected to the acceleration time history recorded at the base of the cabinets for the different tests. Since the adopted model is not influenced by the mass distribution, it is subjected only to the test group 100 shakings. The response of the rigid block simulating the single-window cabinet under three different input motions is shown in Fig. 9. The three responses refer to different input intensities which produce (a) negligible rocking rotations, (b) initiation of rocking response and (c) block overturning. The seismic intensities required to attain both rocking and overturning, expressed in terms of PFA, are compared for both single- and double-window cabinets with the experimental evidence (The analyses are also performed neglecting the reduction of the velocity after the impact, i.e. a 1.0 coefficient of restitution is considered. The numerical-to-experimental comparison is shown in Table 2. It is shown that the rocking initiation is still well predicted, since it is not influenced by the coefficient of restitution. Moreover, a safe-sided estimation of the overturning PFA threshold is generally demonstrated, in case a 1.0 coefficient of restitution is assumed. It is therefore demonstrated that the rigid block models of tested cabinets can give a safe-sided prediction of the seismic intensity required to induce overturning, provided that a 1.0 coefficient of restitution is assumed. Current and future studies will deal with the refinement of such simple models, e.g. trying to incorporate in the model the external restraint provided by the wall.

Table 1).

The adopted numerical model is able to foreseen the occurrence of rocking mechanism. However, an overestimation of the PFA which causes overturning is also shown. This overestimation may be caused by the assumption that the tested cabinets behaves as rigid blocks, whereas they are also characterized by a significant flexibility [16]. Moreover, the numerical model assumes that the mass is uniformly distributed within the cabinet and neglects the presence of the wall behind the cabinets. These assumptions may have caused such an unsafe-sided estimation of the PFA overturning threshold.

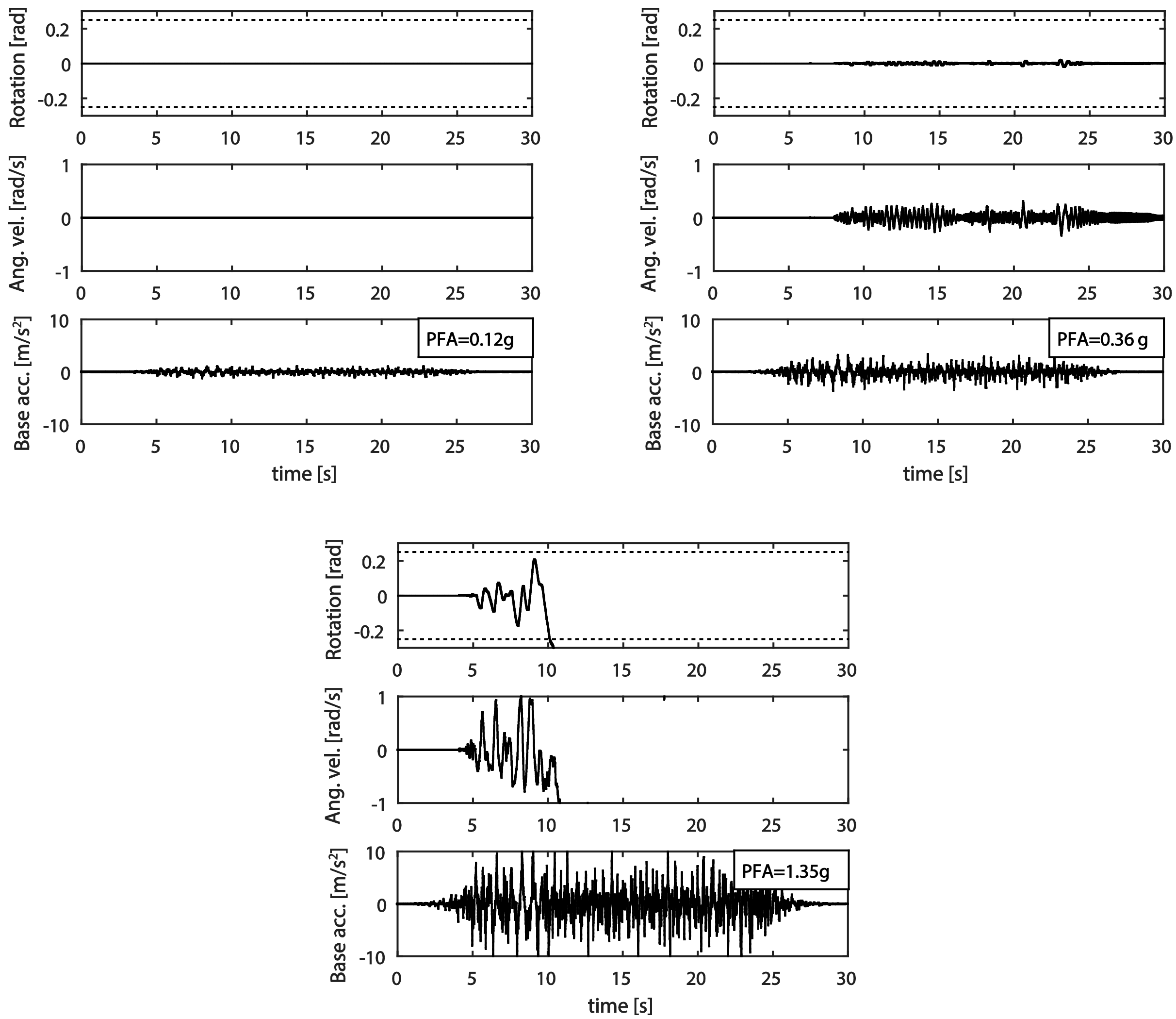


Fig. 9 - Single-window rigid block response to three different input motions recorded in test group 100.

The analyses are also performed neglecting the reduction of the velocity after the impact, i.e. a 1.0 coefficient of restitution is considered. The numerical-to-experimental comparison is shown in Table 2. It is shown that the rocking initiation is still well predicted, since it is not influenced by the coefficient of restitution. Moreover, a safe-sided estimation of the overturning PFA threshold is generally demonstrated, in case a 1.0 coefficient of restitution is assumed. It is therefore demonstrated that the rigid block models of tested cabinets can give a safe-sided prediction of the seismic intensity required to induce overturning, provided that a 1.0 coefficient of restitution is assumed. Current and future studies will deal with the refinement of such simple models, e.g. trying to incorporate in the model the external restraint provided by the wall.

Table 1 - Rocking and overturning PFA thresholds for single- and double-window cabinets: numerical-to-experimental comparison.

	Rocking		**Overturning**	
Cabinet	Experimental	Numerical	Experimental	Numerical
Single-window	0.37g	0.37g	1.13g	1.35g
Double-window	0.37g	0.37g	1.25g	1.47g

Table 2 - Rocking and overturning PFA thresholds for single- and double-window cabinets characterized by a 1.0 coefficient of restitution: numerical-to-experimental comparison.

	Rocking		**Overturning**	
Cabinet	Experimental	Numerical	Experimental	Numerical
Single-window	0.37g	0.37g	1.13g	0.98g
Double-window	0.37g	0.37g	1.25g	0.98g

4. Conclusions

The paper deals with the assessment of the adequacy of existing numerical models in predicting the seismic response of freestanding nonstructural components. Based on a previous experimental campaign on hospital building contents, the study focuses on two different modeling techniques: (a) finite element method (FEM) and (b) rigid block model. The ability to predict the response of two tested hospital cabinets is verified by comparing the numerical response with the experimental one. The applicability and limitations of each modeling technique are also discussed.

The study first develops a simple FEM model for the tested cabinets, subjecting them to the recorded table accelerations. A close numerical-to-experimental matching is observed for low-intensity shake table tests, when the cabinets are laterally deforming without any rocking mechanism. FEM models are not capable to reproduce the recorded accelerations at larger table accelerations, particularly due to the presence of some spikes in the recorded accelerograms, caused by the occurrence of rocking. It can be therefore concluded that the developed numerical model is efficient until the cabinet exhibits the rocking mechanism. The defined FEM models are also able to recognize the occurrence of the rocking mechanism, denoted by the occurrence of vertical tension displacements in the link at the base of the cabinets.

Medical components, such as the tested cabinets, typically exhibit a rocking behavior as the seismic intensity increases. Thus, rigid block model becomes another good candidate to model the dynamic response of these components. In this study, tested cabinets are modeled as equivalent rigid blocks and subjected to the experimental base accelerations. It is concluded that in case a 1.0 coefficient of restitution is considered, a slightly safe-sided estimation of the overturning PFA threshold can be performed. It is also shown that the rocking initiation is well predicted. It is therefore demonstrated that rigid block models can be employed in assessing the performance of hospital cabinets.

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