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# SEISMIC FRAGILITY OF FREESTANDING BUILDINGS CONTENTS MODELLED AS RIGID BLOCKS

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**Keywords:** Rigid blocks, fragility analysis, hospital buildings, intensity measure, .

**Abstract.** *The loss of functionality of health care facilities, which should be guaranteed particularly in the aftermath of moderate-to-severe earthquake ground motions, is typically caused by damage to nonstructural elements, such as freestanding cabinets. The assessment of the seismic fragility of such components assumes a key role in the evaluation of the performance of a healthcare facility.*

*The present work is aimed to assess the adequacy of the rigid block modeling approach in predicting the seismic response of freestanding nonstructural components with rocking-dominated response. The outcomes of the numerical analyses show that the considered modeling technique can provide a reliable prediction of the occurrence of rocking mechanism and predict the occurrence of the overturning. In particular, the overturning PFA is slightly underestimated in case a 1.0 coefficient of restitution is considered. But the question then arises as to which intensity measure (IM) is well correlated to the seismic performance of rigid blocks. A fragility study on a number of rigid blocks is therefore conducted in the present paper. Comprehensive incremental dynamic analyses on different rigid blocks highlight that the dimensionless intensity measure PGA/(g tanα) is an efficient intensity measures to predict rocking occurrence in a generic rigid block. The intensity measure pPGV/ (g tanα) is the most efficient one only for large, say R larger than 2.0 m, rigid blocks. Very small, say R<1.0 m, rigid blocks tend to overturn as soon as they start rocking and are therefore ''PGA-dominated''. PGA/(g tanα) is therefore more efficient for such blocks. The use of these intensity measures allows assessing a unique fragility curve for rigid blocks characterized by different geometries, which may serve as a simple tool for the estimation of the damage occurred in rigid blocks after earthquakes.*


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## 1 INTRODUCTION

Post-earthquake surveys carried out world-wide in building structures have shown (e.g. [1; 2], among others) that widespread damage affects non-structural components, especially building contents, mechanical and electrical services. Overturning of slender cabinets, e.g. containing medical files with patient details or allocating drug boxes, the failure of electronic units, such control panels, rooters and monitors, have been typically observed in hospitals and medical facilities, especially at intermediate and top floors in multistory structures. The failure of such components generates tremendous losses, which, in turn, impose high economical and societal pressure on the affected communities. Furthermore, they may endanger the functionality of critical facilities which should be designed to remain fully operational in the aftermath of major earthquakes.

To date, the seismic design and performance assessment of building contents in referral medical facilities is poorly addressed (e.g. [3], among others). The existing codes of practice for new (e.g. [4; 5]) and existing structures (e.g. [6; 7] ) provide scarce provisions primarily for unanchored components. Consequently, there has been extensive experimental and theoretical research ([3; 8; 9; 10]) focusing on the seismic performance of a variety of medical appliances and service utilities of typical hospital buildings and pharmacies. The seismic behavior of such components is not straightforward because of the complexity and variety of connections and functioning, thus requiring the use of experimental methods. However, the use of testing facilities is often time-consuming and costly. Conversely, numerical models may be an efficient means to simulate the dynamic response of building contents, as proved especially by studies focusing on sliding-dominated components [11; 12; 13]; their use should be promoted also for routine design office applications.

The aim of the present analytical work is three-fold: (i) use of rigid block analysis for free-standing medical components, (ii) identification of the most efficient seismic intensity measure for rigid blocks and (iii) the influence of the geometric properties of rigid blocks on their dynamic performance. The results of the comprehensive numerical study are presented in terms of fragility analysis.

## 2 DESCRIPTION OF CASE STUDIES

Two rigid block models are considered herein to assess the most efficient IM. Rigid block no. 1 is the block representative of a single-window cabinet, with $R = 0.717m$ and $h/b = 3.9$ (Fig. 1); rigid block no. 2 is taken from Yim et al. [14] and is characterized by a 3.05 m (10 feet) $R$ and an aspect ratio $h/b$ equal to 5 (Fig. 1). The two blocks are respectively representative of a typical cabinet and a large rigid block, in order to investigate the influence of the geometry of the block on the seismic response. The blocks are subjected to incremental dynamic analyses, using the set of earthquake strong motions included in ATC 63 [15]. Two different datasets are considered herein: (a) a far field and (b) a near field dataset. Far field and near field record sets are used to study the rigid block dynamic behavior. The amplitude of vibration decreases with increasing distance from the epicenter in far field input, and the strong motion record moves to lower frequencies for the effects of selective absorption. The decay of the amplitude does not occur with regularity and the characteristics of the shaking are governed mainly by the focal mechanisms in near fault conditions.

In the comprehensive parametric analysis, additional four rigid blocks have also been considered for each of the two rigid blocks by modifying alternatively their slenderness $h/b$ and dimension $R$. The four rigid blocks obtained from the single window cabinet are characterized by (a) R=1.43m and h/b=3.91; (b) R=0.359m and h/b=3.91; (c) R=0.717m and h/b=7.83; (d) R=0.717m and h/b=1.96. The four rigid blocks corresponding to the block by Yim et al. [14] are characterized by (a) R=1.52m (5 feet) and h/b=5.0; (b) R=4.57m (15 feet) and h/b=5.0; (c) R=3.05m (10 feet) and h/b=2.5; (d) R=3.05m (10 feet) and h/b=7.5.

## 3 RIGID BLOCK ANALYSIS

Medical components, such as the metallic slender cabinets tested with shaking table in [3], 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 the present analytical study, tested cabinets are modeled 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 adequate model fidelity, the research outcomes presented hereafter are 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.

### 3.1 Numerical modelling

As previously discussed, tested cabinets may be also modeled as rigid blocks, whose dynamic behavior was extensively investigated in past decades (e.g. [16-21], 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 sufficiently large so that there will be no sliding between the block and the base. 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 equation of motion is developed and adopted in several existing studies (e.g. [3], among others). In this study it is solved through Runge-Kutta Ordinary Differential Equations (ODE) solver, available in Matlab [22].

Rocking mechanism occurs alternatively around O and O’ (Fig. 1). It is assumed that the rotation continues smoothly from point O to O’, when the angle of rotation reverses [18]. A reduction of the angular velocity is imposed when the rotation reverses, to account for the energy loss at every impact [21]. 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 $1 – 1.5 \sin^2\alpha$. The sample single-window cabinet is modeled as a rigid block characterized by 0.36 m base ($2b$ in Fig. 1) and 1.39 m height ($2h$ in Fig. 1); the critical angle is 0.250 rad.

### 3.2 Fragility analysis

The experimental-to-numerical comparison described in [23] demonstrates that hospital building cabinets overturning can be modeled by means of rigid blocks. The question arises as to which IM is well correlated to the seismic demand on rigid blocks.

From a performance-based earthquake engineering perspective, the identification of an efficient IM which is valid for a generic rigid block assumes a key role, as well as the assessment of fragility curves for loss assessment [24]. A fragility study of rigid blocks is therefore conducted aimed at two different objectives: (a) assessment of the most efficient IM; (b) influence of geometric properties of the rigid block on its performance. The assessment of the most efficient IM is conducted on the two sample rigid blocks, as discussed earlier, considering both near- and far-field earthquake records.

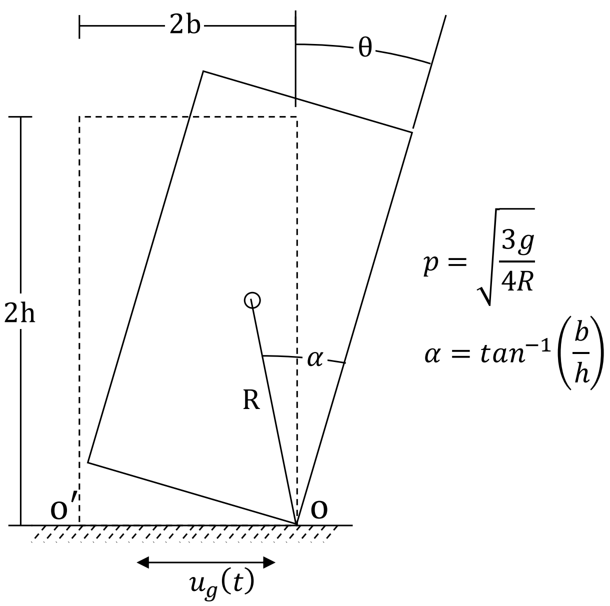



**Fig. 1. Rigid block geometry and parameters.**

Two Damage States (DSs) are defined to study the rigid block fragility during the numerical simulation: a rocking damage state and a collapse damage state.

The rigid block reaches the rocking damage state when the rotation is larger than a conventionally small value, say $0.01\alpha$, whereas it attains the collapse damage state when the rotation is larger than the critical angle $\alpha$ (Fig. 1).

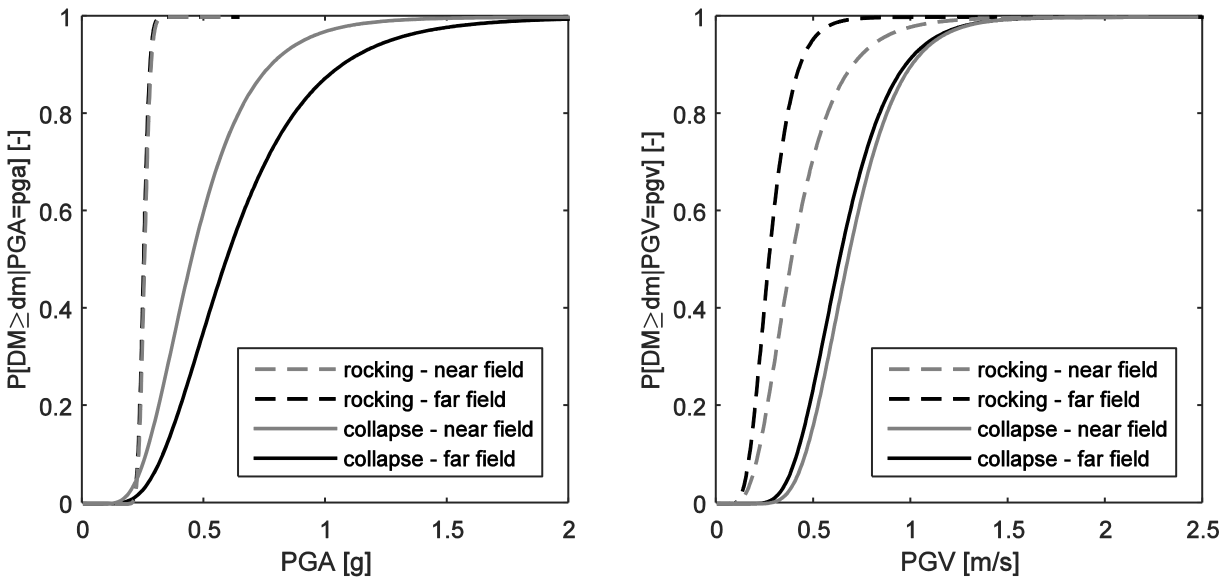
Porter method "A" [25] is employed to create the lognormal fragility curves according to the different intensity measures. Different IMs are adopted to plot the fragility curves [23] among the ones typically adopted in literature studies [26]. Several typical IMs are considered among the most commonly adopted in earthquake engineering. Three IMs are taken from literature: they are defined as dimensionless slenderness IMs.

Fragility curves in terms of peak ground acceleration (PGA) and velocity (PGV) are shown in Fig. 2 for both the damage states and the suite of sample accelerograms. Input type may influence the fragility curve: it is shown that median IM values required to reach a given damage state may significantly vary from far field to near field input motions. The influence of the set of accelerograms on the fragility curve could be more/less evident depending on the damage state, as shown in Fig. 2 for both PGA and PGV.

An IM is efficient when it induces a small variability of a damage measure given IM [27]; an efficient IM would allow reducing the number of nonlinear dynamic analyses required to assess the fragility curve with adequate precision [28].

The efficiency of an IM is typically assessed from the dispersion of the engineering demand parameter (EDP) at a given IM level (e.g. [29] among many others).

For rigid blocks, it should be considered that the occurrence of rocking or overturning is far more important than the attainment of a given engineering demand parameter, e.g. rigid block rotation $\theta$. The behavior of (and the consequences on) the rigid block is not significantly influenced by the amplitude of the rigid block motion, provided it is smaller than the critical angle $\alpha$. Thus, IM efficiency can be directly measured from the standard deviation $\beta$ of the fragility curves: the lower the standard deviation the more efficient the IM.




**(A)** **(B)**

**Fig. 2. Rigid block fragility curves for far-field and near-field inputs considering both (a) PGA and (b) PGV as IM for rigid block no. 2.**

Table 1 includes the logarithmic standard deviation $\beta$ of the different fragility curves, assessed for the different IMs and sets of accelerograms. The values listed in the table show that $PGA$ and $IM_4$, which is derived from $PGA$, are well correlated to the occurrence of the rocking mechanism. Such response is due to the rocking mechanism which is observed when overturning moment exceeds stabilizing moment due to gravity loads; simple equilibrium calculations yield that the minimum acceleration required to let the block rock is $b/h \cdot g$, which is consistent with the observed median values of the fragility curves for the rigid blocks.
Median $PGA\_IM_4$ values are about 20% larger than expected from rotational equilibrium, due to (a) the dynamic nature of the motion and (b) the finite threshold value associated to the occurrence of rocking.
Collapse/overturning damage state is better correlated to $PGV\_IM_5$ than $PGA\_IM_4$ for the rigid block no. 2, as highlighted by the smaller dispersion of the fragility curve in terms of $PGV$-$IM_5$. The standard deviations of the dimensionless intensity measures $IM_4 = \frac{PGA}{g\ tan\alpha}$ and $IM_5 = \frac{p\ PGV}{g\ tan\alpha}$ are equal to the corresponding deviations for $PGA$ and $PGV$, respectively, since the dimensionless IMs are directly estimated from $PGA$ and $PGV$ through some geometric parameters of the investigated block. $IM_{Fajfar}$ intensity measure, which is based on PGV, also provides a good efficiency in predicting overturning of rigid block no. 2. For rigid block no.1, it is noted that PGA is the most efficient IM. The outcomes of the analysis on these two blocks do not allow a unique identification of the efficient IM for overturning.
The dispersion values for the most efficient IMs are not sensitive to the seismic input type, i.e. near-field and far-field motions produce similar dispersion values for the sample rigid blocks.

| IM | Rocking | | | | Overturning | | | |
|---|---|---|---|---|---|---|---|---|
| | Far field | | Near field | | Far field | | Near field | |
| | Block no. 1 | Block no. 2 | Block no. 1 | Block no. 2 | Block no. 1 | Block no. 2 | Block no. 1 | Block no. 2 |
| $PGA\ [g]$ | **0.063** | **0.078** | **0.066** | **0.080** | **0.230** | 0.459 | **0.208** | 0.428 |
| $PGV\ [m/s]$ | 0.360 | 0.367 | 0.470 | 0.468 | 0.338 | **0.335** | 0.398 | **0.309** |
| $I_A\ [m/s]$ | 0.583 | 0.561 | 0.853 | 0.883 | 0.644 | 0.880 | 0.920 | 0.881 |
| $IM_4$ | **0.063** | **0.078** | **0.066** | **0.080** | **0.230** | 0.459 | **0.208** | 0.428 |
| $IM_5$ | 0.360 | 0.367 | 0.470 | 0.468 | 0.338 | **0.335** | 0.398 | **0.309** |
| $IM_6$ | 0.245 | 0.244 | 0.312 | 0.296 | 0.312 | 0.445 | 0.400 | 0.522 |
| $IM_{Fajfar}$ | 0.385 | 0.392 | 0.509 | 0.513 | 0.357 | **0.310** | 0.452 | **0.358** |
| $CAV\ [m/s]$ | 0.578 | 0.567 | 0.816 | 0.832 | 0.584 | 0.588 | 0.816 | 0.766 |
| $ASI\ [m/s]$ | 0.173 | 0.156 | 0.265 | 0.251 | 0.248 | 0.486 | 0.271 | 0.427 |
| $S_a(T_p)\ [g]$ | 0.576 | 0.770 | 0.600 | 0.721 | 0.510 | 0.481 | 0.494 | 0.519 |
| $S_v(T_p)\ [m/s]$ | 0.576 | 0.770 | 0.600 | 0.721 | 0.510 | 0.481 | 0.494 | 0.519 |
| $HI\ [m]$ | 0.173 | 0.156 | 0.265 | 0.251 | 0.248 | 0.486 | 0.271 | 0.427 |

**Table 1. Fragility curve logarithmic standard deviation for different intensity measures; lowest standard deviation values for rocking and overturning are in bold.**

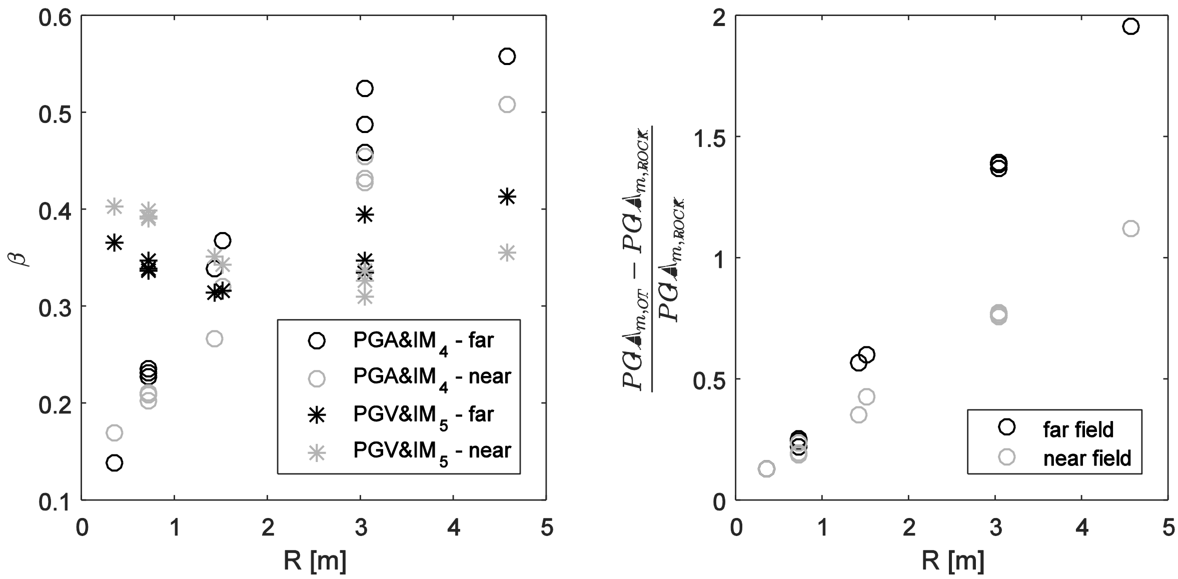
Since there was no agreement between the two selected rigid blocks, other four rigid blocks are considered for each of the two rigid blocks by modifying alternatively their slenderness $h/b$ and dimension $R$, as mentioned earlier. Incremental dynamic analysis with the two above mentioned sets of accelerograms are performed and lognormal fragility curves are estimated for each block subjected to each input motion set, as detailed above.

It is confirmed that $PGA$ and $IM_4$ are the most efficient IMs for rocking, while the most efficient IM for overturning is influenced by the dimension $R$ of the block (Fig. 3a). The dispersion of $PGV - IM_5$ overturning fragility curves is not influenced by $R$; it is included in the range between 0.3 and 0.4 for the different blocks and input considered. The logarithmic standard deviation of $PGA - IM_4$ overturning fragility curves is influenced by the dimension of the block; an increase in $R$ corresponds to an increase in $\beta$. It is concluded that $PGA - IM_4$ are the most efficient IMs for small rigid blocks, say R smaller than 1.0m, whereas $PGV - IM_5$ are more efficient for large rigid blocks, say R larger than 2.0m.

Housner [21] also suggested that the overturning of blocks was well correlated to the energy required to uplift and rotate the block by an $\alpha$ angle, which can be inferred by the peak velocity. For intermediate $R$ values the efficiency of $PGA - IM_4$ and $PGV - IM_5$ is similar.

It is worth mentioning that overturning fragility increases as dimension $R$ decreases, as also discussed in [21, 30]. Very small rigid blocks tend to overturn as soon as they start rocking, as highlighted by the discrepancy between median rocking PGA and median overturning PGA (Fig. 3b) for the ten different rigid blocks considered herein.

Additionally, the ratio in Fig. 3b tends to zero as the dimension $R$ tends to 0. At such small $R$ values, the dispersion of the overturning fragility curve (Fig. 3a) tends to be the same as the rocking fragility curves, which is in the range 0.05-0.08 for the different rigid blocks. Very small rigid blocks, say $R < 1.0m$, are therefore "PGA-dominated", with the overturning fragility curve that approaches the rocking one, both in terms of median value and dispersion.




**(A)** **(B)**

**Fig. 3. (a) Logarithmic standard deviation of overturning fragility curves for different rigid blocks and (b) discrepancy among overturning median PGA and rocking PGA.**

The influence of block dimensions on its behavior is also highlighted in the trend of median fragility curve values for the dimensionless IMs used by Dimitrakopoulos and Paraskeva [20] (Fig. 4). Median $IM_5$ values tend to be constantly around 0.5 and there is negligible discrepancy among near and far field input motion for large $R$ values, which confirms that $IM_5$ may be a good generalized intensity measure for overturning in large rigid blocks.

At small $R$ values, instead, median $IM_5 = \frac{p\,PGV}{g\,tan\alpha}$ deviates from 0.5 and there is a significant discrepancy among far field and near field, since the failure is "PGA-dominated". Interestingly, $IM_4 = \frac{PGA}{g\,tan\alpha}$ median values are not influenced by the nature of the input motion at small R values, which confirms that the PGA governs the overturning of small rigid blocks. $IM_4$ median values tend to assume value close to the ideal value of 1.0 as R becomes close to zero.

It can be also demonstrated that $IM_5$ median value scales with $1/\sqrt{R}$ for very small $R$ values if it is assumed that overturning occurs as soon as the block starts rocking, i.e. $IM_{4,overt} = IM_{4,rock} \cong 1.23$ (Fig. 5a). Under such an assumption the overturning $IM_5$ can be estimated as $IM_{5,overt} \cong \frac{1.23p\,PGV}{PGA}$. Considering that $\frac{PGV}{PGA}$ is a feature of the selected accelerogram and it is not influenced by the block, it can be concluded that $IM_{5,overt} \propto p$ or, alternatively, $IM_{5,overt} \propto \sqrt{\frac{1}{R}}$. Moreover, $IM_5$ median value is proportional to $PGV/PGA$, justifying the discrepancies of the $IM_5$ median values for near- and far-field input motions at low $R$ values. It should be finally highlighted that the influence of block slenderness on overturning and rocking is not significant when dimensionless IMs are adopted.

The twenty fragility curves, i.e. for each rigid block subjected to one of the two input motion typologies, tend to overlap on a unique curve (Fig. 5) if expressed in terms of $IM_4 = \frac{PGA}{g\,tan\alpha}$ for rocking and $IM_5 = \frac{p\,PGV}{g\,tan\alpha}$ for overturning, respectively. The overlapping fragility curves for rocking with $IM_4$ suggest that the adopted dimensionless IM is an adequate candidate for generalized IM. The overturning fragility curves tend to overlap only for $R > 1.0m$, as anticipated above. A generalized IM is intended as an intensity measure which induces a unique fragility curve for all the rigid blocks regardless of their geometric properties. The definition of a generalized IM would be a powerful means in simplifying the assessment of seismic fragility of components behaving as rigid blocks.

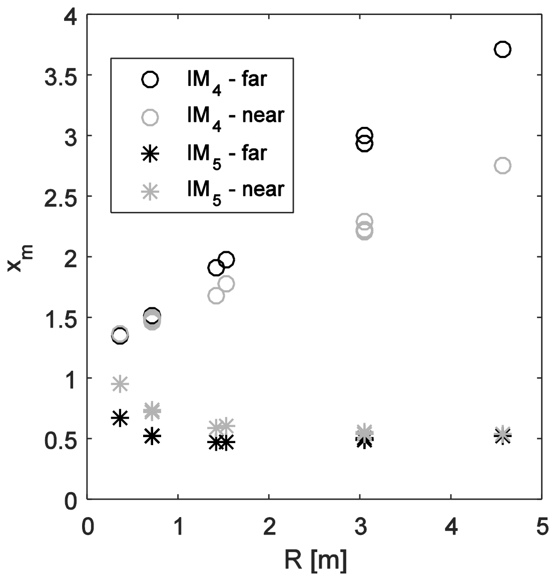



**Fig. 4. Median values of the overturning fragility curves for different dimensionless intensity measures.**

A unique fragility curve can be therefore assessed, considering the numerical data of the ten considered rigid blocks subjected to both far field and near field input motions for rocking and only the blocks with $R > 1.0m$ for overturning. A generalization cannot be made for small rigid blocks. However, median overturning $PGA$ is not much larger than rocking $PGA$ for such blocks, i.e. less than 30% (Fig. 3b). As such, future investigations might be focused on the definition of a generalized fragility curve for overturning of small rigid blocks by considering a PGA-based intensity measure.

It is therefore concluded that the curves in Fig. 5 can serve as a simple tool for the estimation of the damage occurred in rigid blocks after earthquakes. Moreover, they can be also included in performance-based design software for the estimation of the expected loss due to earthquake, for a rapid assessment of the damage occurred in non-structural components which behave as rigid blocks.

The above results apply to a rigid block placed at a given story of a structure. They suggest that structural engineers should also control peak floor velocities in addition to peak floor accelerations, in order to assess the performance of freestanding rigid nonstructural components. This preliminary analysis can be rigorously applied only to rigid blocks placed at the ground floor of buildings, due to the assumed set of accelerograms.

Future studies will deal with the investigation of rigid blocks subjected to typical floor motions, whose frequency content may be significantly different than base motion content. Moreover, more refined modelling techniques, which take into account the interaction between elasticity and rigid block behavior [22], will also be considered.

## 4 CONCLUSIONS AND FURTHER WORK

The present analytical study has assessed the reliability of using rigid block analysis to predict the earthquake response of freestanding medical cabinets. The outcomes of the parametric analysis demonstrate that, when a 1.0 coefficient of restitution is considered, a slightly safe-sided estimation of the overturning PFA threshold can be achieved. The rocking initiation is well predicted. Thus rigid block models can be employed in assessing reliably the performance of hospital cabinets, especially for routine applications in design offices.

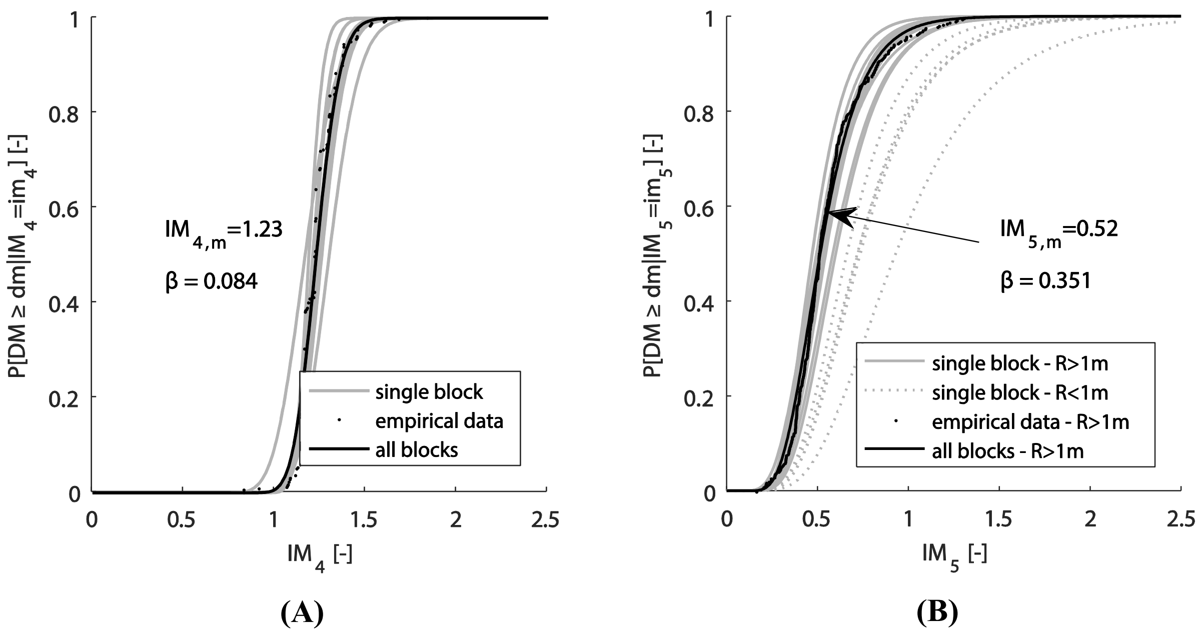



**Fig. 5. Fragility curves considering ten different rigid blocks and both far and near input motions, for (a) rocking and (b) overturning, with dimensionless intensity measures.**

The comprehensive incremental dynamic analyses carried out on different rigid blocks have shown that the dimensionless intensity measure PGA/(g tanα) is an efficient intensity measures to predict rocking occurrence in a generic rigid block.

The intensity measure pPGV/ (g tanα) is the most efficient one only for large, say R larger than 2.0 m, rigid blocks. Very small, say R<1.0 m, rigid blocks tend to overturn as soon as they start rocking and are therefore ‘‘PGA-dominated’’. PGA/(g tanα) is therefore more efficient for such blocks. The use of these intensity measures allows assessing a unique fragility curve for rigid blocks characterized by different geometries, which may serve as a simple tool for the estimation of the damage occurred in rigid blocks after earthquakes. Additionally, the use of the peak velocity is also of paramount importance for the performance assessment of slender cabinets, especially to control the overturning. Thus, structural engineers should also control peak floor velocities in addition to peak floor accelerations, in order to accurately assess the performance of freestanding rigid nonstructural components.

It is suggested that future numerical simulations should focus on the analysis of rigid blocks subjected to typical floor motions, whose frequency content may be significantly different than base motion content. The effects of the elastic response of the typical freestanding components should also be further assessed, both numerically and with experimental testing.

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## REFERENCES

[1] Masi A, Santarsiero G, Gallipoli M, Mucciarelli M, Manfredi V, Dusi A and Stabile T. Performance of the health facilities during the 2012 Emilia (Italy) earthquake and analysis of the Mirandola hospital case study, Bulletin of Earthquake Engineering, 2013: 1-25.

[2] Jacques CC, McIntosh J, Giovinazzi S, Kirsch TD, Wilson T and Mitrani-Reiser J. Resilience of the Canterbury Hospital System to the 2011 Christchurch Earthquake, Earthquake Spectra, 2014, 30(1): 533-554.

[3] Cosenza E, Di Sarno L, Maddaloni G, Magliulo G, Petrone C and Prota A. Shake table tests for the seismic fragility evaluation of hospital rooms, Earthquake Engineering and Structural Dynamics, 2014, 44(1): 23-40

[4] American Society of Civil Engineers (2010) ASCE/SEI 7-10: Minimum Design Loads for Buildings and Other Structures. Reston, Virginia, US

[5] CEN (2006) Eurocode 8: Design of structures for earthquake resistance - Part 1: General rules, seismic actions and rules for buildings. EN 1998-1. Brussels, Belgium.

[6] American Society of Civil Engineers (2010) ASCE/SEI 41-6: Seismic Rehabilitation of Existing Buildings. Reston, Virginia, US.

[7] CEN (2006) Eurocode 8: design of structures for earthquake resistance - Part 1: Assessment and Retrofitting of Builidngs. EN 1998-1. Brussels, Belgium.

[8] Kuo K-C, Suzuki Y, Katsuragi S and Yao GC. Shake table tests on clutter levels of typical medicine shelves and contents subjected to earthquakes, Earthquake Engineering & Structural Dynamics, 2011, 40(12): 1367-1386.

[9] Furukawa S, Sato E, Shi Y, Becker T and Nakashima M. Full-scale shaking table test of a base-isolated medical facility subjected to vertical motions, Earthquake Engineering & Structural Dynamics, 2013, 42(13): 1931-1949.

[10] Shi Y, Kurata M and Nakashima M. Disorder and damage of base-isolated medical facilities when subjected to near-fault and long-period ground motions, Earthquake Engineering & Structural Dynamics, 2014: 43(11): 1683-1701.

[11] Konstantinidis D and Makris N. Experimental and analytical studies on the response of freestanding laboratory equipment to earthquake shaking, Earthquake Engineering & Structural Dynamics, 2009, 38(6): 827-848.

[12] Konstantinidis D and Nikfar F. Seismic response of sliding equipment and contents in base-isolated buildings subjected to broadband ground motions, Earthquake Engineering & Structural Dynamics, 2015, 44(6): 865-887.

[13] Lin S-L, MacRae GA, Dhakal RP and Yeow TZ. Building contents sliding demands in elastically responding structures, Engineering Structures, 2015, 86: 182-191.

[14] C.-S. Yim, A.K. Chopra, J. Penzien, Rocking response of rigid blocks to earthquakes. *Earthquake Engineering & Structural Dynamics*, **8**, 565-587, 1980.

[15] Applied Technology Council, Quantification of building seismic performance factors. ATC 63. Redwood city, California, 2008.

[16] Y. Ishiyama, Motions of rigid bodies and criteria for overturning by earthquake excitations. *Earthquake Engineering & Structural Dynamics*, **10**, 635-650, 1982.

[17] J. Zhang, N. Makris, Rocking Response of Free-Standing Blocks under Cycloidal Pulses. *Journal of Engineering Mechanics*, **127**, 473-483, 2001.

[18] N. Makris, D. Konstantinidis, The rocking spectrum and the limitations of practical design methodologies. *Earthquake Engineering & Structural Dynamics*, **32**, 265-289, 2003.
[19] E. Dimitrakopoulos, M. DeJong, Overturning of Retrofitted Rocking Structures under Pulse-Type Excitations. *Journal of Engineering Mechanics*, **138**, 963-972, 2012.
[20] E.G. Dimitrakopoulos, T.S. Paraskeva, Dimensionless fragility curves for rocking response to near-fault excitations. *Earthquake Engineering & Structural Dynamics*, **44**, 2015-2033, 2015.
[21] G.W. Housner, The behavior of inverted pendulum structures during earthquakes. *Bulletin of the Seismological Society of America*, **53**, 403-417, 1963.
[22] The MathWorks Inc., MATLAB 8.5 Natick, MA, 2015.
[23] C. Petrone, L. Di Sarno, G. Magliulo, E. Cosenza, Numerical modelling and fragility assessment of typical freestanding building contents. *Bulletin of Earthquake Engineering*, **15**, 1609-1633, 2017.
[24] M. De Biasio, S. Grange, F. Dufour, F. Allain, I. Petre-Lazar, Intensity measures for probabilistic assessment of non-structural components acceleration demand. *Earthquake Engineering & Structural Dynamics*, **44**, 2261-2280, 2015.
[25] K. Porter, R. Kennedy, R. Bachman, Creating Fragility Functions for Performance-Based Earthquake Engineering. *Earthquake Spectra*, **23**, 471-489, 2007.
[26] E. Cosenza, G. Manfredi, Damage indices and damage measures. *Progress in Structural Engineering and Materials*, **2**, 50-59, 2000.
[27] N. Luco, C.A. Cornell, Structure-Specific Scalar Intensity Measures for Near-Source and Ordinary Earthquake Ground Motions. *Earthquake Spectra*, **23**, 357-392, 2007.
[28] N. Shome, C.A. Cornell, Probabilistic seismic demand analysis of nonlinear structures, Reliability of Marine Structures Program Report No. RMS-35. Department of Civil and Environmental Engineering, Stanford University, California, 1999.
[29] J. Donaire-Ávila, F. Mollaioli, A. Lucchini, A. Benavent-Climent, Intensity measures for the seismic response prediction of mid-rise buildings with hysteretic dampers. *Engineering Structures*, **102**, 278-295, 2015.
[30] N. Makris, M. Vassiliou, Are Some Top-Heavy Structures More Stable? *Journal of Structural Engineering*, **140**, 06014001, 2014.