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PROBABILISTIC SEISMIC ASSESSMENT OF A HIGH-RISE URM BUILDING

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ABSTRACT

Several European urban nuclei are constituted by a significant number of ancient structures that belong to constructive typologies in which the seismic demand was not considered in their design at the time. Both, the accurate definition of the mechanical properties of their materials, and a proper seismic demand, are two of the major difficulties in the seismic damage assessment of structures due to their respective large associated uncertainties and variability, respectively. A representative high-rise unreinforced masonry (URM) building of the Eixample district in the city of Barcelona (Spain) is taken as a case-study. The building is modelled as an isolated load-bearing walls system with unidirectional iron beams-brick vaults slabs. The seismic demand variability is addressed by means of different ground motion records, which were selected following the conditional spectrum procedure, and subsequently scaled to different levels of demand (pga) according to the incremental dynamic analysis methodology. On the other hand, and due to the lack of homogeneity and level of knowledge associated with the large diversity of manufacturing and construction techniques, the compressive strength, shear modulus, shear strength and Young modulus are chosen and modelled as random variables in order to encompass the material uncertainties. Sufficient and representative samples are selected from both the population of mechanical properties of materials and the population of incrementally scaled dynamic analyses. Results are categorized in accordance to each of the selected random variables and seismic demand inputs (record and/or pga), providing, in varying degrees, their different correlations and tendencies among them.

Keywords: Unreinforced masonry; Incremental dynamic analysis; Fragility; High-rise; Probabilistic.

1. INTRODUCTION

An important percentage of the housing stock of a several European cities is constituted by unreinforced masonry (URM) buildings, the majority of which overpass 100 years. Broad similarities can be found in most of the structures that correspond to this typology; however, unlike for newer materials such as steel or concrete, a lack of technical knowledge, and consequently available tests and data, is also common among these structures.

Two of the most relevant sources of variability and epistemic uncertainties in the assessment of structures are: 1) the plausible ground motion demand, and 2) the mechanical properties of the materials. Probabilistic studies allow to overcome these shortcomings by the introduction of random variables in order to represent one or more sources of uncertainty and analyze their effect(s) in the response of the structure.

The range of values and the distribution that they follow should be carefully defined for each mechanical property (variable) of interest. On the other hand, computational and time limitations, are addressed by the design of an appropriate and sufficiently representative sample.

Modal and incremental dynamic analysis (IDA) results are obtained from numerical simulations performed with the 3MURI software. Accordingly, comparisons of the grade of influence and correlation among the different selected random variables are presented.

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2. THE BUILDING

Barcelona was funded as a roman colony and its physical growth and development occurred in different stages along the time. Due to its strategic military and commercial emplacement in the Mediterranean Basin, it was subjected to different enlargements of its surrounding walls in order to solve its temporary needs. Finally, in 1856, a complete urban expansion beyond its walls was approved and executed by the civil engineer Idelfonso Cerdà. Over the years the original project was subjected to different changes in order to accomplish the authorities and stakeholders needs and demands (Sobrequés i Callicó, 2008).
The study case selected for this work is fully representative of the URM typology, which constitutes nearly the 70% of the totality of housing buildings, and that can be easily found in the Eixample district of Barcelona City (Lantada, 2007). Additionally, a common feature of this type of structures is the lack of any seismic provision and that the age of most of them overpass 100 years old. According to the classification proposed by Paricio, Ratera, and Casanovas (1999) of the buildings of the Eixample district, our structure belongs to the Post-modernism period (1910-1936).

2.1 Structural features

The structure is supported by a system of solid clay brick load-bearing walls with unidirectional iron beams – brick vaults slabs. High ceilings and diaphanous areas can be found in the ground floor, in which hospitality and commercial activities are normally held. On the other hand, bearing and partition walls accompanied with lower heights are common in upper levels, which are mostly used for housing purposes.
The principal load-bearing walls system is composed mainly by the façade walls, the lateral (intermediate) walls between adjacent buildings, and the inner core courtyard walls. Additional metallic load-bearing columns and beams were placed in the ground floor in order to support the different walls distributed along the upper levels.
The floor system was composed by iron beams every 70-80 cm, connected by two layers of thin-brick-vaults. Additionally, an additional rubble and mortar compression layer could be found, accompanied by a top ceramic pavement cover, which resulted in slabs with a thickness of 17 to 20 cm (Figure 1c).
Connection among the different walls and floor systems is poor or even non-existent. Different lintels, parapets and arches can be found above the distinct openings (i.e. doors and windows) along the walls.
Regarding the considered permanent and variable loads, values of 350 kg/m^2 and 100-200 kg/m^2 can be found in many different technical documents and council regulations from the period. Construction materials were carefully selected and placed in different elements and levels of the structure according to their manufacturing quality, which was mainly handmade at that time. Further structural details can be found in González-Drigo et al. (2015).

2.2 Computational model

The Frame by Macro Element (FME) method included in the 3MURI software was used for the analysis of the modelled structure (Galasco, Lagomarsino, and Penna, 2002; Lagomarsino, Galasco, and Penna, 2002; Lagomarsino, Penna, Galasco, and Cattari, 2013; S.T.A. DATA, 2012).
The main structural and architectural features introduced in the model were obtained from original floor plans, guidelines and documents from the period, judgment of experts and technical in-situ visits.

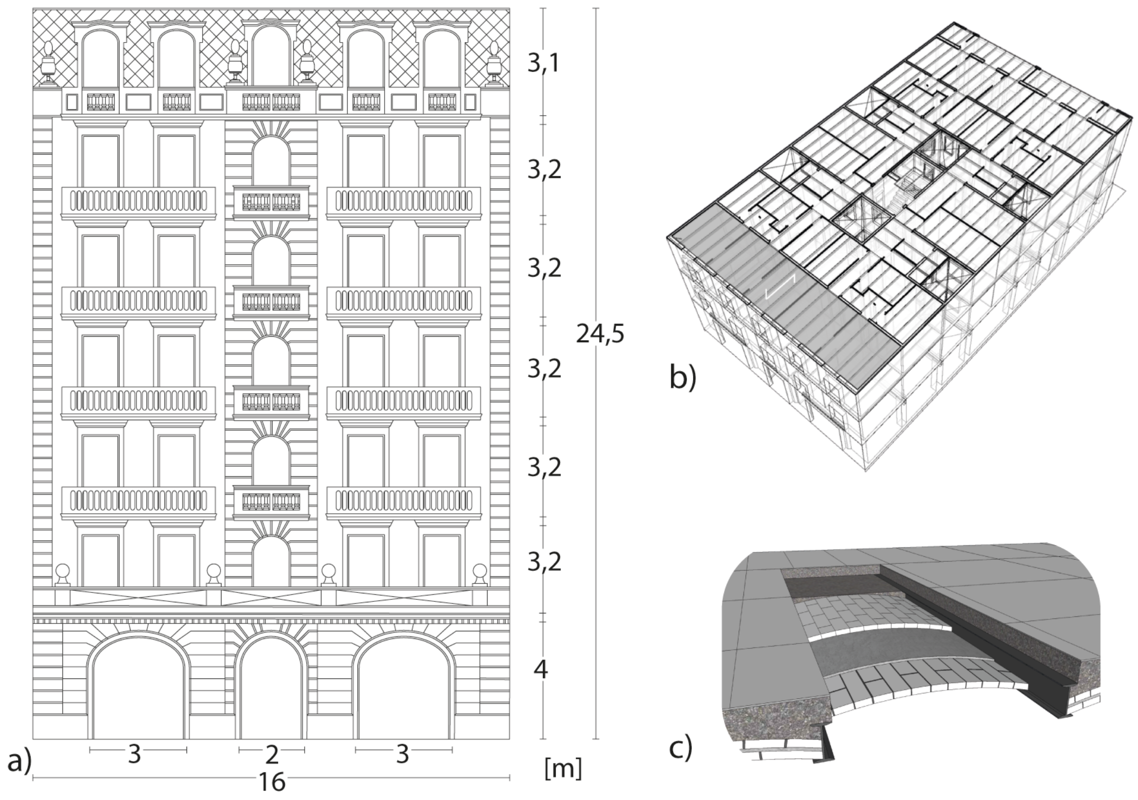


Figure 1. Post-modernist period building: a) Façade and elevation; b) Floor plan (upper level); and c) Steel beam and brick vaults floor system

3. MECHANICAL PROPERTIES OF MATERIALS

Among the different sources of epistemic uncertainties, we can mention: the handmade manufacturing process of the ceramic products at the time, the use of rudimentary tools and local materials, as well as the fluctuations in the quality and characteristics of the final products due to the used firing process (Jones, 1996). Therefore, all of the above is taken into account in the probabilistic assessment of the structure by means of random variables.

3.1 Statistical treatment of the variables of interest

The compressive strength (f_m), Young modulus (E), shear modulus (G) and shear strength (τ_0) of the solid clay masonry were considered as random variables of the solid clay masonry. Available sources, inspection visits and expert opinion allowed to determine a suitable set of values of the mechanical properties of interest. The range of values considered for the compressive strength follows a two tailed normal distribution with a confidence interval of 90% and α=10%, resembling the previously establish lower and upper bounds.
A hypothesis of positive linear correlation is assumed in the relationships between each variable and f_m: $E=E(f_m,\varepsilon)$; $G=G(E,\varepsilon)$ and $\tau_0= \tau_0\ (f_m,\varepsilon)$, where ε is a normally distributed variable with a zero mean value ($\mu_\varepsilon=0$) and a normalized variance ($var(\varepsilon)=1$), introduced in order to include the uncertainty of the hypothesized relationships. Additionally, with the purpose of adjusting the correlation in the distinct relationships and generating different samples of E, G and τ_0 in terms of f_m, a varying parameter is added, correspondingly.
The mean and standard deviation of the variables of interest for both, the target and obtained values, is summarized in Table 1

Table 1. Mean and standard deviation of the variables of interest (all units in [MPa])

Variable	**Target values**		**Generated values**	
	μ	σ	μ	σ
f_m	3.00	0.515	2.982	0.492
E	1500	257.58	1484.71	267.81
G	500	85.86	500.18	101.44
τ_0	0.09	0.016	0.0897	0.016

4. SAMPLING

The process of designing, selecting and studying a sufficiently representative sample is needed in order to optimize the workload and resources needed for making statements and inferences with known accuracy about a population of interest.
Each unit of the population was assumed to have an equal probability of being selected, and the simple random sampling (SRS) method without replacement was applied for this work. The sample size computation was affected by a finite population correction factor (PCF), with the assumption of an equally skewed 50% sample proportion, a 5% margin of error and a 95% confidence level (α=5%). It was also verified that the obtained sample followed a normal distribution with the original population parameters.
The different sets of mechanical properties obtained after the sampling process were applied uniformly in the structure (i.e. same values of one set for all the elements).

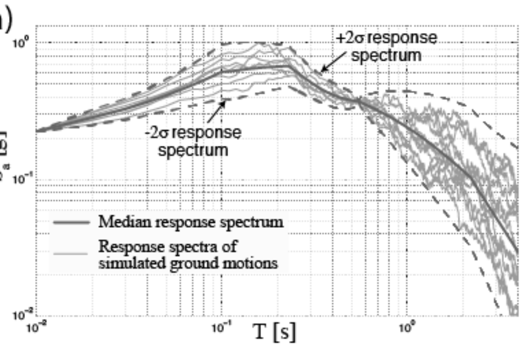
5. MODAL ANALYSIS

As suggested in the literature, the dynamic response of the structure was captured with the consideration of three degrees of freedom per floor (two horizontal translations and one rotation about the vertical), which moved at least 80% of the total mass for any given response direction (Barbat, 1982; Barbat, Oller, and Vielma, 2005; Fardis, 2009; Priestley, Seible, and Calvi, 1996).
A total of 21 modes (GF + 6 levels) were considered for each of the 278 individuals of the selected sample (n), computed from the total population (N) of mechanical properties of materials of 1000 units. For both directions of analysis, +X (parallel to the front façade), and +Y (perpendicular to the front façade), the percentage of activated mass mode confirmed that the behavior of the structure is mainly governed by the first mode, allowing to dismiss the influence of higher ones.

6. DEMAND

The target design response spectrum (Irizarry (2004) - probabilistic scenario, soil type 2 and pga= 0.194 g) was matched by means of the conditional spectrum (CS) method (Baker, Lin, Shahi, and Jayaram, 2011; Jayaram, Lin, and Baker, 2011) in order to select a set of 7 unscaled records (Figure 2), capable of characterizing the local conditions of the area obtained in accordance to the micro-zonation studies performed for the urban area of Barcelona and the location site of the building within the city (Cid, 1998; Secanell, Goula, Susagna, Fleta, and Roca, 1998, 2004).

a)



Record No.	Earthquake	Date (dd/mm/yy)	Time	Data Source	Station ID	PGA [g]
①	CHALFANT	07/31/86	07:22	CDMG	54171	0.119
②	HOLLISTER	01/26/86	19:20	USGS	1656	0.100
③	MANAGUA	12/23/72	07:19		3501	0.271
④	COALINGA	06/11/83	03:09	USGS	1606	0.191
⑤	HOLLISTER	01/26/86	19:20	USGS	1656	0.114
⑥	MAMMOTH	01/07/83	01:38	CDMG	54099	0.153
⑦	WHITTIER	10/04/87	10:59	CDMG	24400	0.261

b)

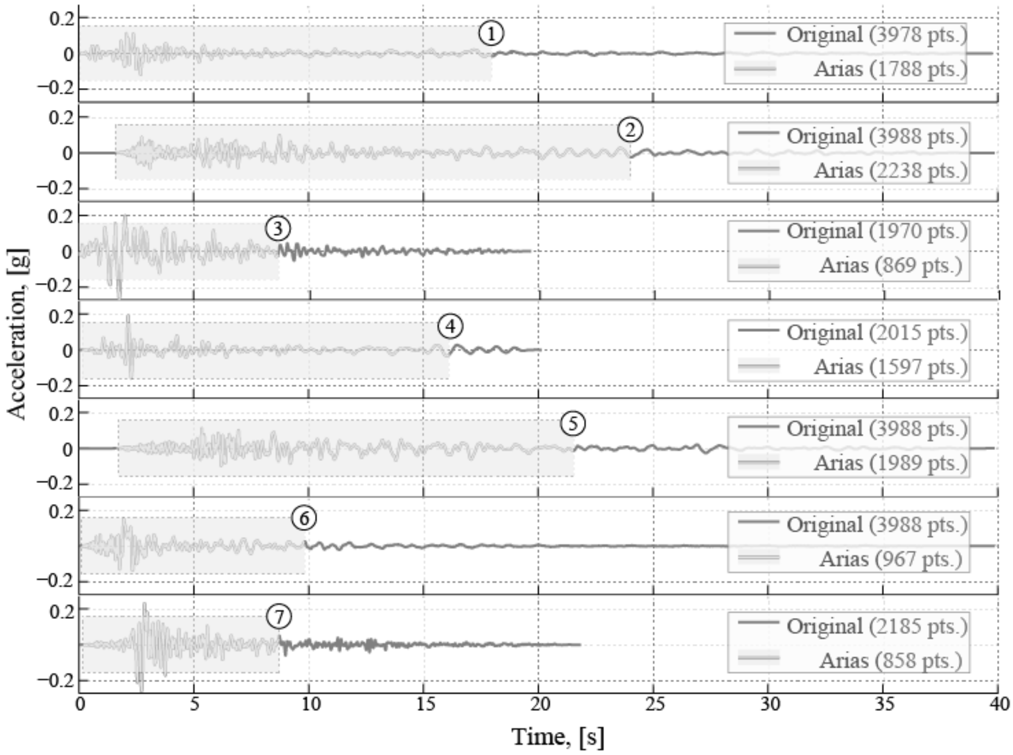


Figure 2. Selected records. a) Matching records by means of the CS procedure; b) Original and reduced records after applying the Arias Intensity method

7. INCREMENTAL DYNAMIC ANALYSIS

As proposed by Vamvatsikos and Cornell (2002), the use of one or more matching ground motion records, which are incrementally scaled to different pga values, allows to take into account the variability to which a structure is subjected.

The measurement of a control variable (e.g. roof displacement) for each incremental pga value used for each of the selected records, permits to represent the evolution of the structural behavior of the building by means of a series of response curves. For this work, the pga scaling values for the set of 7 records ranges from 0.02 g to 0.30 g, with a Δpga of 0.01 g.

Together with the previously sampled mechanical parameters (n=278), and the selected ground motion records (7), the 29 *pga* values conform a new analysis population of N'=278x7x29=56434 units.

Despite that the IDA method is considered as a reference for the seismic risk evaluation, it implies important computational efforts and time consumption. Consequently, and in order to address this limitations, a sufficiently representative second sample, n=382, was selected following the sampling procedure explained in previous sections.

A total of 382 dynamic analyses were performed and post-processed for each direction with the 3MURI and MATLAB (The MathWorks, 2017a) programs, respectively.

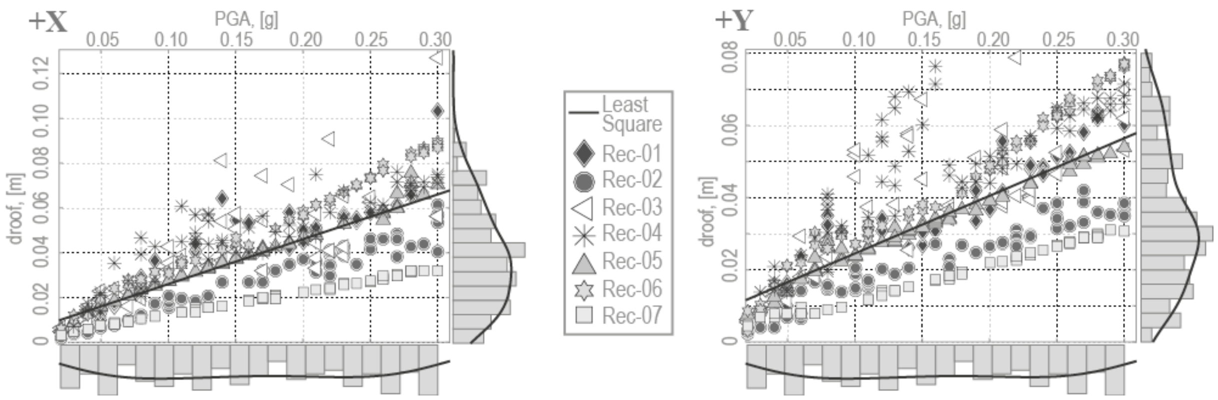


Figure 3. IDA results: *pga* vs roof displacement for both directions of analysis, +X, +Y

The understanding and interpretation of the response of the structure due to the variables of interest can be presented in different ways and for different levels (i.e. individual ground motions or full set of records).

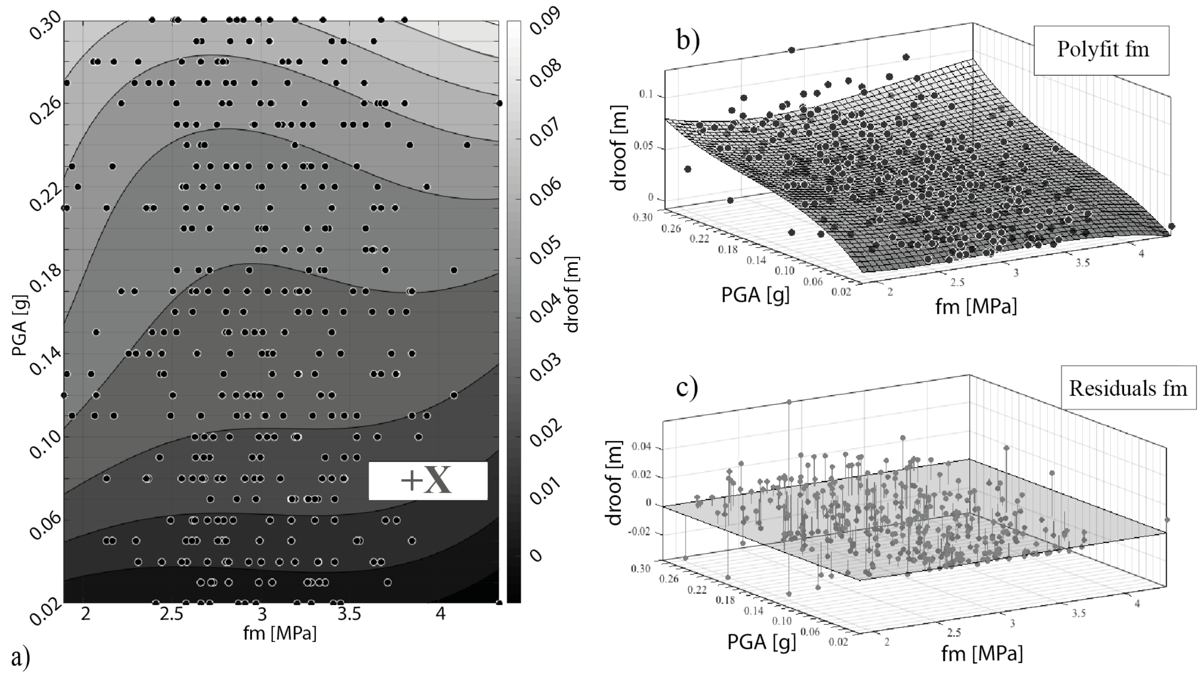


Figure 4. IDA results: *pga* vs roof vs f_m for +X direction: contour plot (left); polyfit surface (right/up); and residuals plot (right/down) for the full set of seven records

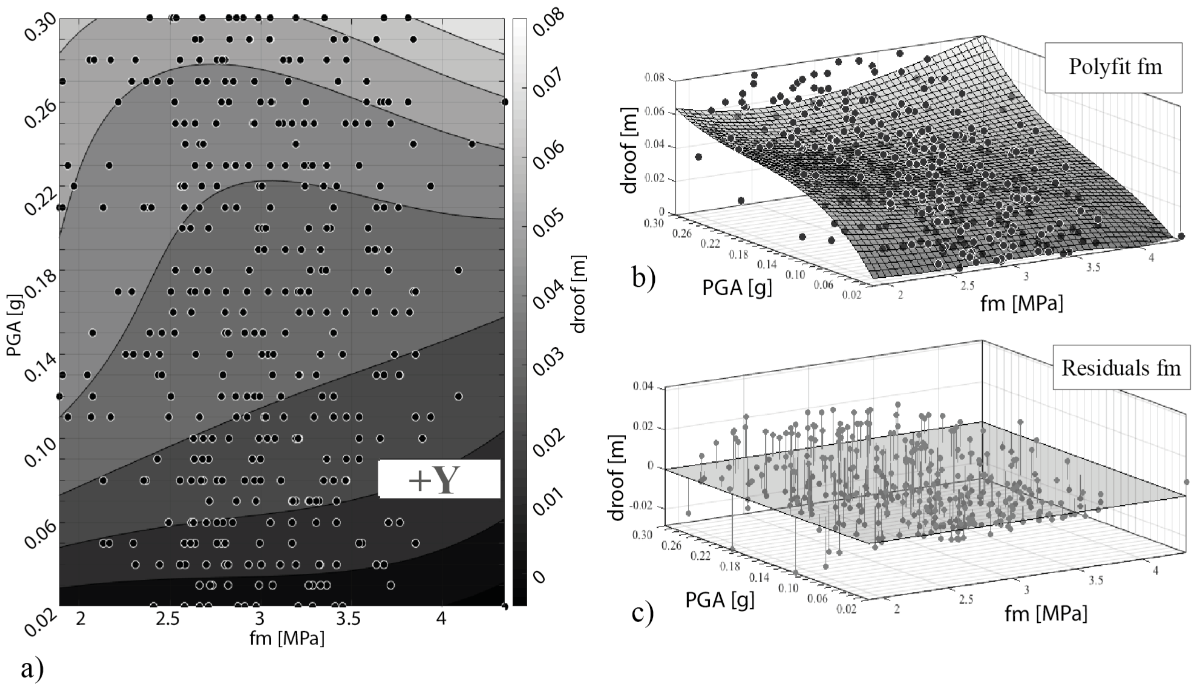


Figure 5. IDA results: *pga* vs roof vs f_m for +Y direction: contour plot (left); polyfit surface (right/up); and residuals plot (right/down) for the full set of seven records

As the pga increases, it can be seen from the contour plots (Figure 4 and Figure 5), it can be observed that, as the *pga* increases, the response of the structure varies along the f_m axis, the values of which are inversely proportional to the observed displacements.
A lineal tendency can also be observed (Figure 6) for each record, presenting important differences and discontinuities in some cases, which can be associated to the inherent variability of the selected records and the pga values.

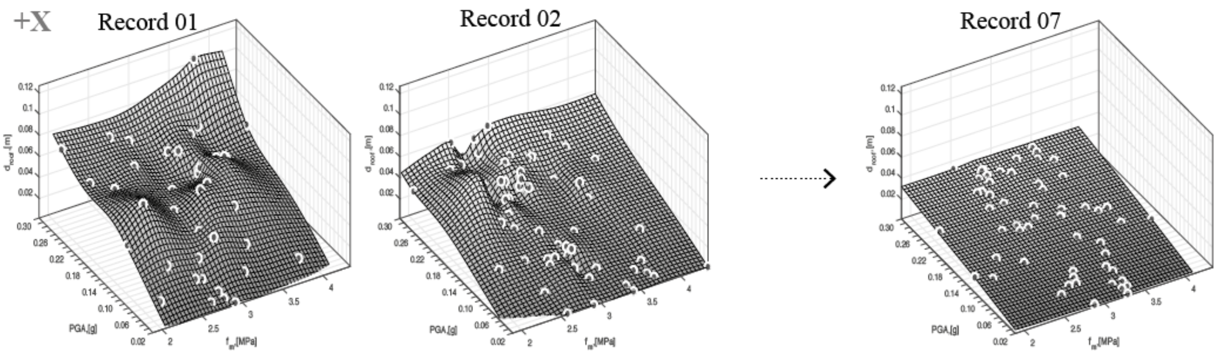


Figure 6. IDA results: *pga* vs roof vs f_m for +X direction of individual records

8. CONCLUSIONS

Lack in the level of knowledge of masonry, compared to newer materials such as concrete and steel, is one of the main sources of variability and uncertainty to the structures that belong to any associated typology.
Unreinforced masonry buildings, represent up to the 70% of the functional housing stock of the City of Barcelona (Lantada, 2007). Specifically, the typology studied in this work is representative of the Post-modernism period comprised between the years 1910 and 1936 (Paricio et al., 1999). The main structural features that characterized these structures were a load-bearing walls system and unidirectional iron beams-brick vaults slabs, with no consideration of the seismic action.

A probabilistic approach in the study and subsequent assessment of this structural typology represents a valuable resource for further research and works, as well as for its better understanding.

Computational and time efforts are common limitations for probabilistic analysis that involve large populations, leading to the use sampling processes. The results and the corresponding quality of any research study are significantly dependent on the representativeness and adequacy of the selected sample(s).

The results of this work showed a lineal dependency between the control variable (roof displacement) with respect to the incremental *pga*. Similarly, lower values of the selected random variables (e.g. compressive strength) can be directly associated with higher values of roof displacement.

The later allows to conclude that the quality of the materials and the level of demand govern the behavior of the structure, and therefore the damages associated to it. Nevertheless, this conclusion should not be generalized since, depending of the selected record, important differences can be observed in the amplitude of the response, particularly for high values of pga.

Direction +X presents higher roof displacements and a more homogenous distribution of results along the different *pga* and f_m values. On the other hand, an important number of results of direction +Y are concentrated in superior levels of roof displacement

The need of a deeper study that includes other parameters for the selection process of the ground motion records would allow a better adjustment and a more adequate representation of the associated variability to this phenomenon. Similarly, additional sources of uncertainty should be considered as well as the distribution of the different mechanical properties within the elements of each level in order to obtain a response closer to reality,

9. ACKNOWLEDGEMENTS

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