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STRUCTURAL PERFORMANCE LEVELS FOR MASONRY INFILLED FRAMES

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ABSTRACT

Performance levels in performance-based design procedures have been described in several ways according to the operational status of the structure or the level of damage sustained up to collapse. The selection of the appropriate drift associated with different levels of damage for the design is significant in terms economy and safety. The identification of drift levels associated with different states of damage remains one of the unresolved issues in the development of performance objectives in performance-based design and assessment procedures. The objective of this study is to develop the approach to establish the drift of masonry infilled frames that is associated with different definable levels of damage to use as performance objectives in the design of new structures and the evaluation of the seismic resistance of existing structures. Analytical and experimental data were used to examine the correlation between drift and damage of masonry infilled frames. The analytical procedure included pushover analyses of various designs of reinforced concrete frames with masonry infills. Seismic response has been analysed, considering Inter-storey Drift Ratio (IDR) as main intensity measure. The experimental results were obtained from Experimental Database of Infilled Frames – EDIF and reviewed for the appropriateness and consistency of the data. As a result a new relationship among structural performance, damage levels and Inter-storey drift ratios for masonry infilled frames was developed.

Keywords: Performance level; Infilled frame; Experimental database; Pushover analysis

1. INTRODUCTION

Masonry-infilled reinforced concrete (RC) frames can be frequently found in earthquake prone areas around the world. Masonry infilled walls are often considered as non-structural elements and are overlooked in structural analysis and design, although infills can develop strong interaction with the bounding frames under seismic loads (Stavridis and Shing 2008). Different failure mechanisms induced by the frame-infill interaction, including damage of the infill walls and brittle shear failures of the concrete columns, lead to very complex behavior of masonry-infilled RC frames under cyclic lateral loading. Therefore, the evaluation of the seismic performance of masonry-infilled RC frames poses a challenging task for structural engineers (Stavridis and Shing 2008).

Over the past 60 years, most of the papers concerning the behavior of infilled frames and the interaction between masonry infills and framed structures have regarded the in-plane interaction as of major relevance in the overall response (Asteris et al. 2017). Equivalent strut macromodels, applied in many researches (for example, Stafford Smith and Carter1969, Di Trapani et al. 2015, Asteris et al. 2016) comprise the most effective way to practically include in structural models the strengthening and stiffening effects provided by the infills (Asteris et al. 2017). Also the infills produce a large increase of stiffness with respect to the one owned by the bare framed structure, which modifies their dynamic response (Papia et al. 2003, Fiore et al 2012), thereby completely changing the distribution of damage throughout the structure (Dolšek and Fajfar 2008).

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The occurrence and consequences of structural damage can be considered the greatest cause of life and monetary loss in the majority of seismic events. Analytical fragility curves adopt damage distributions simulated from the analyses of structural models under increasing earthquake loads. In order for fragility curves to be used in a performance-based framework, the damage scale limit states must be clearly defined in terms of the damage expected in the structural and non-structural elements of buildings (Rossetto and Elnashai 2003).
With this in mind, an experimental database containing 113 published tests of one story one bay infilled frames was created to serve as a basis for determining the basic characteristics for analytical modelling of masonry infilled frames. Analytical modelling was based on multi-storey (three, six and nine) three bay (with variable length of 4 or 6m) infilled frames with various reinforcement ratios of the frame members with the height of ground floor and upper floors being 3.75m and 3m respectively. The primary goal of this article is to propose a simple approach for the definition of expected damage states that depend on the value of seismic load, and the basic material and geometric properties of masonry infilled RC frames.

2. PERFORMANCE BASED SEISMIC DESIGN

Despite the application of modern regulations, complete safety against significant damage or even collapse of the structure cannot be realized independent of the application of the deterministic or probabilistic design method. Methods of analysis, especially for structures with irregular configurations, include modelling uncertainty that cannot eliminate or reduce errors even in the case of applying the most sophisticated deterministic methods. This is especially the case for structures that are exposed with the effects of earthquakes, in which, due to the stochastic nature of the action, the uncertainty in designing the response becomes dominant and has significantly greater consequences.

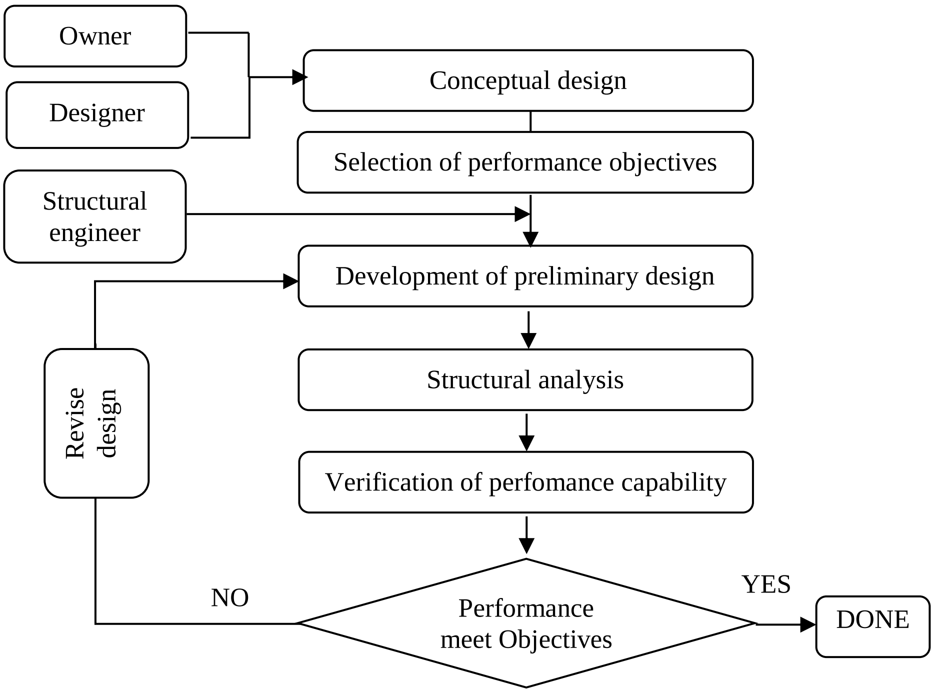

Figure 1. Flow chart of performance based seismic design

Earthquake engineering is a challenging field of research due to a wide spectrum of factors involved: stochastic earthquake, earthquake characterization, dynamic soil response and earthquake amplification, dynamic behaviour of construction and its non-linear response, soil and construction interaction, acceptable constructive reliability in seismic actions. In addition, post-earthquake losses extend beyond building user losses or injuries; there are also losses associated with structural damage, of non-structural elements, installations, as well as those caused by the interruption of the building's use, which are important to its owners and users. As a result, there is a need for a new design approach

that defines the acceptable behavior of the structure under the earthquake excitation of a certain intensity, taking into account all the uncertainties to an acceptable extent, and accordingly designing the load-bearing structure and all elements of the building. Such a way of designing allows owners and other stakeholders to quantify, financially or otherwise, the expected risks to the observed building when selecting acceptable levels of behavior that meets their requirements and needs.
Performance Based Seismic Design (PBSD) assures meeting the needs and goals of the investor, the user and the society with the predetermined expected response of the structure under the minor and extreme earthquake loads (Figure 1). PBSD is the main topic of research in many Earthquake Centers worldwide (PEER, NEHRP, FEMA), where the primary goal is to replace the current design practice with a new one, based on acceptable structural performance at a certain degree of seismic load.
The application of standards and design process for reinforced concrete structures in the current practice largely ignores the influence of masonry infill in framed structures, or only considers the adverse impact resulting in an unrealistic and uneconomic structure in this building type. In traditional practice, earthquake design has been explicitly performed for only a single design event level, at which a level of performance generally termed “life safety” has been targeted. Contemporary efforts in performance-based engineering are seeking to provide reliable methods of meeting these multiple performance goals through explicit design procedures (Hamburger, 1997).

	Design process (current practice)	**PBSD**
	Preliminary construction design	
	Preliminary sizing and detailing of structure elements	
Construction parameters	unique, according to the structure	variability of material and geometric parameters
Analysis	linear	nonlinear dynamic (IDA)
Earthquake load	response spectrum	large number of time- history records
Masonry infill model	not taken into account	included
Nonlinearity	not included	nonlinearity of materials and elements
Results	**Capacity**	**Level of structural damage**

Figure 2. Comparison of current design practice and Performance-Based Seismic Design (PBSD)

PBSD allows design according to acceptable levels of damage at different levels of earthquake. The key differences between the two design approaches are in accepting criteria, design analysis and results (Figure 2). While traditional design requires the achievement of acceptable demand/capacity ratios, the PBSD goal is to achieve a certain degree of behaviour within which we will have controlled damage, correlated with the corresponding consequences that can be measured (including economic). PBSD is based on nonlinear analysis to take into account the cause of the damage and the consequences. The third major difference between the two approaches is in the design steps. In the traditional methods, the earthquake load as well as the acceptable level of damage is determined for the observed construction according to national regulations in accordance with the nationally defined parameters. In PBSD, both parameters are solved during the design process, together with the expected consequences.
In order to make rational design of infilled frames according to PBSD it is necessary to define and develop structural performance levels for masonry infilled frames.

3. STRUCTURAL PERFORMANCE LEVELS

The response can be expressed by an acceptable level of behaviour due to the expected magnitude of the earthquake load. The acceptable level of behaviour is represented by a probabilistic spectrum of damage to structural and non-structural elements. The earthquake risk is the relevant set of earthquakes and associated risks with certain likelihoods of occurrence.

Probabilistic approach for definition of structural behaviour includes accomplishment of multiple objectives eg. if "extensive damage" is expected for rare earthquakes, level "moderate damage" is already achieved for occasional earthquakes and there is “near collapse” expected damage for very rare earthquakes (Figure 3).

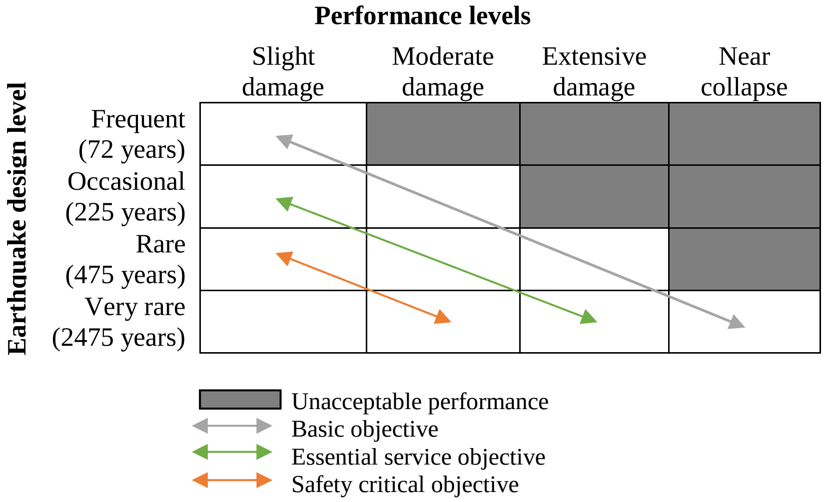

Figure 3. Performance objectives for buildings

Possible structural performance levels are: slight damage=Immediate occupancy, moderate damage=damage control, extensive damage=life safety, near collapse=collapse prevention (HAZUS, 2001). They are presenting the physical damage of buildings that may occur during the earthquake event. Description of the damage for every structural performance level is necessary for understanding of the physical state of the building for the end user/investor. Damage levels are introduced for the convenience and the associated eligibility conditions expressed in the terms of Inter-storey Drift Ratio (IDR) (Table 1).

Table 1. Comparison of IDR (%) according to structural performance levels and structure type (Ghobarah, 2004)

Structural performance level	infilled frames	RC walls	RC frames
Slight damage	<0,10	<0,20	<0,20
Moderate damage	<0,40	<0, 80	<1,0
Extensive damage	>0,70	>0,80	>1,0
Near collapse	>0,80	>2,5	>3

4. DEFINITION OF STRUCTURAL PERFORMANCE LEVELS FOR MASONRY INFILLED FRAMES

The identification of drift levels associated with different states of damage remains one of the unresolved issues in the development of performance objectives in performance-based design and assessment procedures. The objective of this study is to develop the approach to establish the drift of masonry infilled frames that is associated with different definable levels of damage for performance objectives in the design of new structures and the evaluation of the seismic resistance of existing structures. Analytical and experimental data were used to examine the correlation between drift and damage of masonry infilled frames. The experimental results were obtained from Experimental Database of Infilled Frames (Kalman Šipoš et al. 2013) and reviewed for the appropriateness and consistency of the data. The analytical procedure included pushover analyses of various designs of reinforced concrete frames with masonry infills. Seismic response has been analysed, considering Inter-storey Drift Ratio (IDR) as main intensity measure.

4.1. Experimental database of infilled frames, EDIF

The results of one-story one-bay infilled reinforced-concrete frame with masonry infill were collected, systematized and processed (Kalman Šipoš et al. 2013) in the database called EDIF. The tests that were observed had no shear connection, outside adhesion, between the frame and infill, and without openings in infill.

Table 2. Experimental database: authors and samples list

Author	Year	Laboratory	Scale	Load	No of samples
Combescure	2000.	LNEC, Lisbon	1:1,5	C	1
Colangelo	1999.	L'aquila, Italy	1:2	C	11
Cavaleri	2004.	-	1:2	C	1
Lafuente	1998.	U.C.V. Caracas, Venezuela	1:2	C	10
Kakaletsis	2007.	-	1:3	C	2
Dukuze	2000.	-	1:3	M	23
Žarnić	1985.	Institute for Testing and Research in Materials and Structures (ZRMK), Ljubljana	1:2	C	1
	1992.		1:3		3
Al-Charr	1998.	USACERL, Illinois	1:2	M	2
Angel	1994.	University of Illinois, Champaign	1:1	C	7
Mehrabi	1994.	University of Colorado, Boulder	1:2	C	8
				M	3
Crisafulli	1997.	-	1:1,33	M	2
Fiorato	1970.	University of Illinois, Urbana	1:8	C	3
Yorulmaz	1968.	University of Illinois, Urbana	1:8	M	7
Benjamin	1958.	Stanford University, California	1:2,94	M	5
			1:1,33		2
			1:1		1
			1:4		5
			1:2,38		7
Zovkić	2012.	Faculty of Civil Engineering, Osijek, Croatia	1:2,5	C	9

The collected experimental database contains 113 published tests (Table 2) based on all available data: material and geometric properties, type and size of load, failure mode and capacity values obtained from the capacity curves. Although the initial goal was to create a database that had identical parameters for a large number of samples, some parameters were omitted as they were incomplete or unavailable (transverse reinforcement of columns and beams, material properties of mortar and masonry units, masonry shear strength, the maximum drift).

The geometrical parameters were expressed as dimensionless in all possible cases (a=height to length ratio, b= ratio of moments of inertia of beam to column, g= ratio of column width to the thickness of masonry infill, r_b= reinforcement ratio of beam and r_c= reinforcement ratio of column). Material properties of reinforced-concrete frames consisted of the concrete compressive strength (f_{ck}) and modulus of elasticity (E_c), as well as yield strength (f_y) of the reinforcing steel.

Data for masonry infill were: compressive strength (f_k), modulus of elasticity perpendicular to the joints of masonry (E_i) and thickness of the masonry infill (t).

Table 3. The range of input data values in the EDIF Database

	a	**b**	**g**	r_c	r_b	f_{ck} **(MPa)**	E_c **(GPa)**	f_y **(MPa)**	**t (m)**	f_k **(MPa)**	E_i **(MPa)**	**V (kN)**
min	0.33	0.60	1	0.01	0.01	14.2	11.00	203.37	0.02	1.63	0.66	0
max	2.28	8.00	6.1	0.04	0.04	55.16	37.83	607	0.2	22.88	18.3	440.55
average	0.74	2.04	2.01	0.02	0.02	30.03	27.25	406.94	0.09	9.42	5.49	121.49

For evaluation of the performance of infilled frame structures the measured resistance envelope curve from experiments was presented by bilinear curve using the equal energy rule. Thus we obtained two points on the idealized bilinear curve base shear- Inter-storey Drift Ratio (IDR): first yield (V_y and IDR_y) and ultimate point (V_u and IDR_u) of the capacity curve. First yield point is characterized by a sudden decline in stiffness and the ultimate point is associated with the maximum lateral capacity of the system. Post-ultimate behaviour could not be determined by available data since that region was not observed in most tests.
According to main goal of this paper only the values for yielding IDR_y (%) and ultimate IDR_u (%) will be presented (Figure 4 and 5).

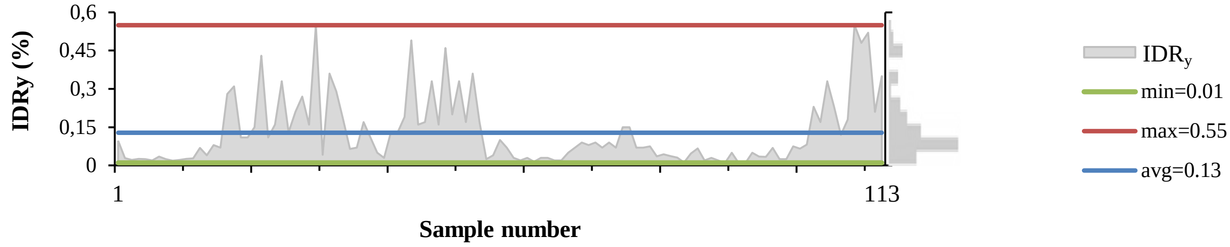

Figure 4. Dispersion of yield drift values

The histograms in Figure 4 and 5 present the frequency of occurrence of drifts in specific areas. The most frequent values of yield drift (IDR_y) were 0,1% and 0,75% for the ultimate drift (IDR_u), therefore these values will be used for evaluation of structural performance levels.

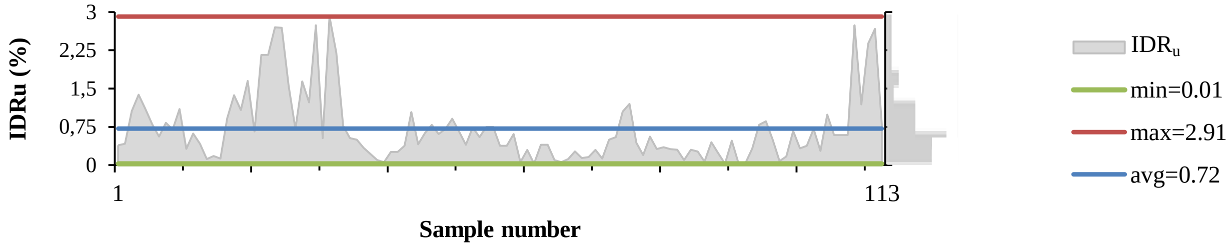

Figure 5. Dispersion of ultimate drift values

4.2. PUSHOVER ANALYSIS OF INFILLED FRAMES

The EDIF database included data from one story one bay infilled frames, therefore analytical modelling was based on multi-storey multi-bay infilled frames.
The ground floor for all model buildings (three, six and nine storeys) has a height of 3.75m, while the upper floors' height was 3m. All model buildings are planar with three bays, with variable length of 4 or 6m. All columns have a square cross-section and constant size in the buildings' height, but a variable reinforcement ratio. All buildings are regular both in plan and in elevation.
In order to achieve consistent and applicable results, classification of RC frame was done according to the reinforcement ratio of the frame members. The design of the buildings was made according to the

provisions of Eurocode 8 and Eurocode 2. Buildings designed to resist seismic loading and buildings designed only for gravity loads are considered. RC frame that was designed only for vertical load has a minimum amount of reinforcement in columns (reinforcement ratio of 1%). The strong RC frame was designed according to Eurocode 8 with a reinforcement ratio of 1.1% to 2.7% depending on building height and earthquake loading. Classification of masonry infill type is done on the basis of material characteristics according to the value of the compressive strength of masonry into weak, medium and strong masonry infill. For weak infill, aerated masonry units (AAC) with a thickness of 30 cm and compressive strength of masonry infill of 1.17 MPa were selected. Medium infill was thermo-block (Euroterm) with a thickness of 25 cm and compressive strength of 2.92 MPa, while the strong infill was solid brick with a thickness of 25 cm and a compressive strength of 5.01 MPa.
The nonlinear numerical model (Figure 6.) for every building was based on calibrated models whose acceptability was previously confirmed on one-storey, one-bay infilled frames (Kalman Šipoš and Sigmund, 2014) in Seismostruct (Seismosoft, 2017).
RC frame members were modelled as FBPH elements - force-based elements with plastic hinges at the end whose length ranged from 7.5-15 %, depending on the dimensions of the cross-section and the length of the reference element. For every RC frame member fiber elements were simulated with longitudinal reinforcement of each individual reinforcing bar. For material properties of the concrete, Mander's confined model (1988) and the Menegotto-Pinto (1973) model for reinforcing steel were used. The masonry infill was modelled as a panel model (Crisafulli, 1997) with calibrated parameters of hysteretic axial behaviour of masonry. Strut widths were determined according to the recommendations of Stafford-Smith and Carter (1969) with calibrated parameters of the material properties.

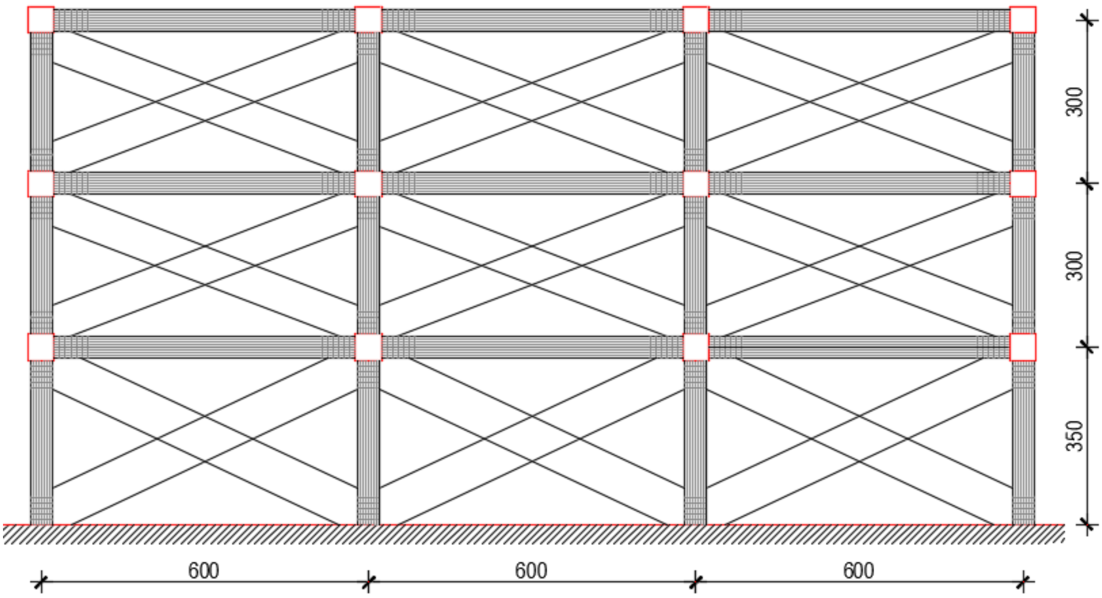

Figure 6. Numerical models for 3-storey building model with 6m bay length

According to variable parameters, pushover analysis study includes 72 numerical models. Each numerical model contains the SLIF tag, with the number representing the value or the classification unit in front of each letter:

- S-storey - number of floors -3, 6 or 9;
- L - length - bay (m) -4 m and 6 m;
- I-infill - masonry fill - masonry infill type: 1-weak, 2-medium and 3-strong
- F-frame- RC frame - frame type: 1-weak, 2-strong

After the SLIF mark, there is also the value of peak ground acceleration (0.1-0.3g) that is used for design of strong frame (variable reinforcement ratio).
Thus, for example, the 3S4L3I2F_0,1g tag presents a 3-storey building (3S) with 4m bay length (4L)

with a strong infill (3I) and a strong frame (2F) designed according to value of peak ground acceleration of 0.1g.

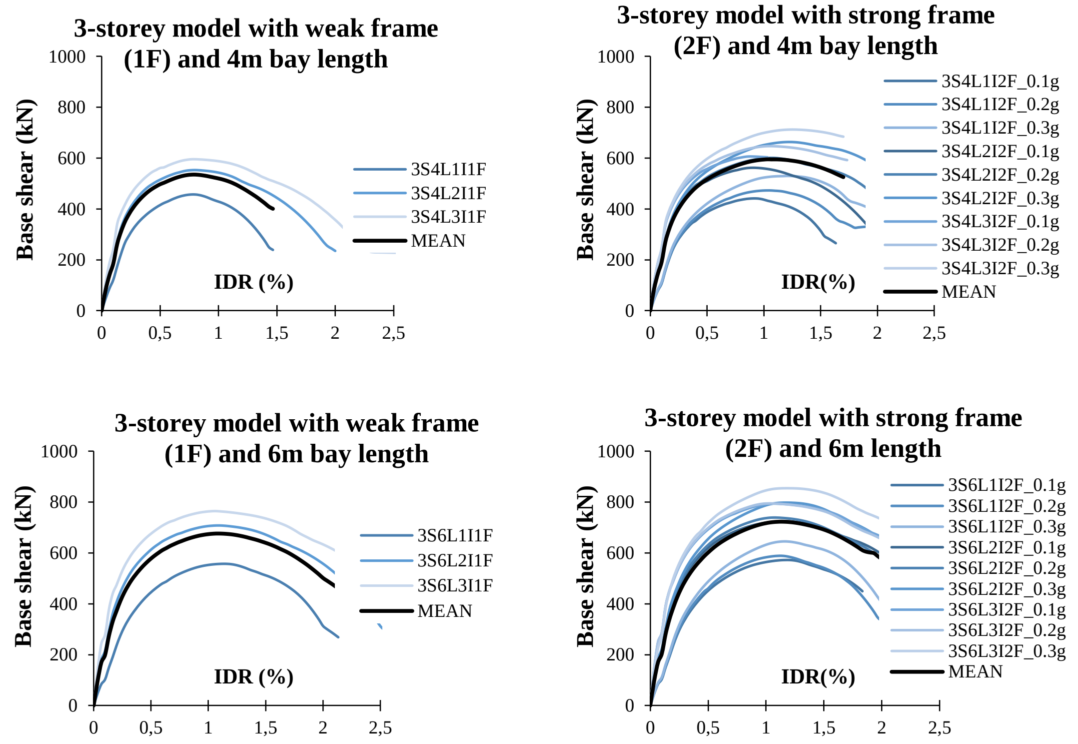

Figure 7. Pushover curves for 3-storey models

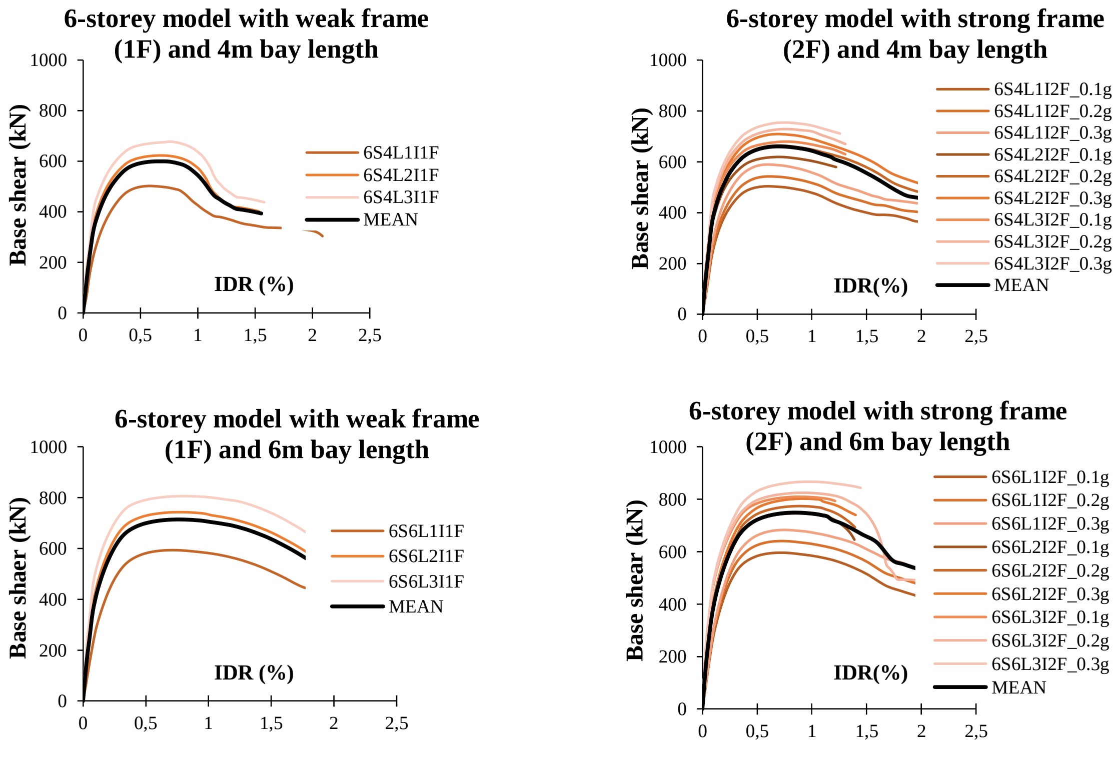

Figure 8. Pushover curves for 6-storey models

According to the results presented in Figures 7-9 change of infill type from weak to strong in weak frames, besides the increase in capacity, will result in increase of 10% for the Inter-storey Drift Ratio (IDR).

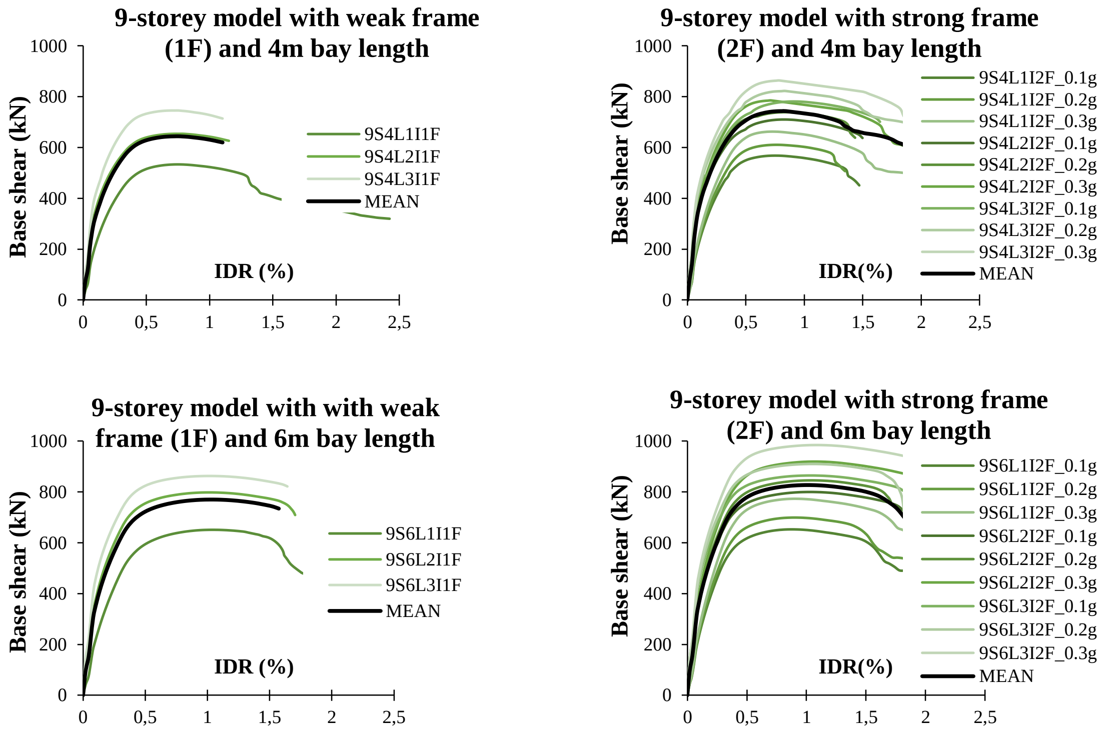

Figure 9. Pushover curves for 6-storey models

Same results are applicable for the strong frame: there is no significant changes in Inter-storey Drift Ratios (IDR), only in bearing capacity. In each of the figures, the mean value curve is also presented. All the mean curves are then shown in Figure 10 and in Table 4. for the purpose of defining the damage levels and the value of the Inter-storey Drift Ratio (IDR) with significant changes in structural behaviour.

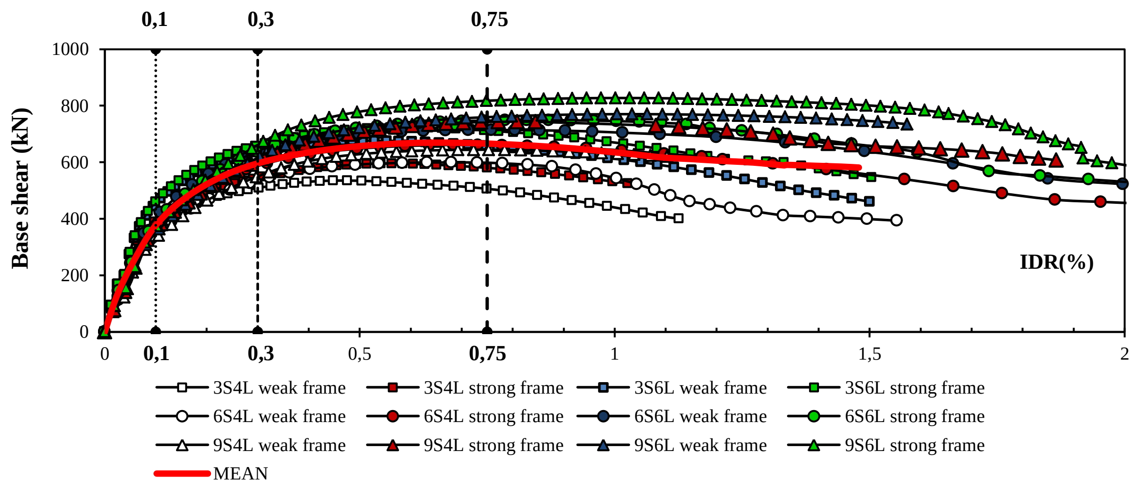

Figure 10. Mean pushover curves for all model buildings

Table 4. The values of IDR (%) for mean pushover curves for all buildings

Story	Structural performance level	L=4m		L=6m	
		Weak frame	Strong frame	Weak frame	Strong frame
3	Moderate damage	0,06	0,08	0,07	0,09
	Extensive damage	0,49	0,53	0,51	0,56
6	Moderate damage	0,09	0,10	0,09	0,11
	Extensive damage	0,68	0,72	0,76	0,83
9	Moderate damage	0,10	0,12	0,11	0,13
	Extensive damage	0,78	0,84	1,01	1,06

With respect to the results, the first damage is defined by IDR of 0.10%, while the state of extensive damage is determined by IDR of 0.75%. Extracted values are in accordance with defined values in the EDIF experimental database (Section 4.1.).
The final definition of structural performance levels for infilled frames is presented in Table 5. Damage states are related to inter-storey drift ratios (IDR) with given description of masonry infill.

Table 5. Description of the damage states and associated inter-storey drift ratios (IDR) (%) in infilled frames

Structural performance level	**Description**	**IDR (%)**	**IDR (%) (FEMA 273)**
Slight damage 	Fine cracks (diagonal or horizontal) in masonry infills	IDR<0.10	IDR<0.10
Moderate damage 	Cracking in infill-frame interfaces, diagonal cracking in infill	0.10≤IDR<0.30	0.10≤IDR<0.30
Extensive damage 	Major damage of infill, failure of infill in corners	0.30≤IDR<0.75	0.30≤IDR<0.6
Near collapse 	Extensive crushing of infills or out of plane	IDR≥0.75	IDR≥0.6

5. CONCLUSIONS

The application of standards and design process for reinforced-concrete structures in the current practice largely ignores the influence of masonry infill in framed structures, or only considers the adverse impact resulting in an unrealistic and uneconomic structure in this building type. In traditional practice, earthquake design has been explicitly performed for only a single design event level, at which a level of performance generally termed "life safety" has been targeted. Contemporary efforts in performance-based engineering are seeking to provide reliable methods of meeting these multiple performance goals through explicit design procedures.
The primary goal of this simple approach is the definition of expected damage states that depend on the value of seismic load, and the basic material and geometric properties of RC infilled frames masonry buildings.
The definition of damage states for infilled frames is necessary for understanding the physical condition of the building for the end user/investor. Structural performance levels are related to Inter-storey drift ratios (IDR) and based on data from the Experimental Database of Infilled Frames - EDIF and numerical analysis based on pushover curves derivation.
In accordance to FEMA 273 (1996) and Ghobarah (2004) given values are qualitative descriptions of the approximate behaviour of infilled frames structures meeting the structural performance levels for limiting damage of frame elements in infilled frames.

6. ACKNOWLEDGMENTS

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