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Seismic assessment of weak masonry infilled r/c frames

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Abstract

Experimental study of seismic behavior and damage assessment of weak masonry infilled r/c frames is presented in this paper with a main intention to contribute to the currently available experimental data. Fourteen one-half scaled one-story, one-bay models were tested under vertical and cyclic horizontal loading. Different parameters of the models in terms of geometric and mechanical properties of "weak" r/c frames and masonry infill were observed. Contribution of each parameter and their combination to the model behavior is observed through strength, stiffness, energy dissipation capacity and failure mode. The infill contribution could be defined as positive as it improves overall structural behavior of models. Robustness of masonry units along with mortar properties appeared to be a governing parameter for the infill damage severity and overall behavior of the models. Adverse effects of the infill were not observed, except in case of frame inadequate transverse reinforcement ratio. Following the *EMS-98* principles, damage and failure mechanism description for each damage grade of framed-masonry system is presented. Additionally, relationship between building performance levels according to *EC8 - 3* with *EMS-98* damage grades and limit states of tested specimens was established, and drift threshold values are presented. For selected earthquake intensity levels specimens with masonry infill have reduced damage grades if compared to bare frames. In terms of structural safety, masonry infill has significantly contributed to collapse prevention.

Keywords: weak r/c frames, experimental study, damage grades, performance levels, collapse prevention

1. Introduction

In Croatia, as well as in other countries worldwide, many buildings have framed structures with partitions and infills made up of unreinforced hollow or solid brick masonry. This type of structures represent composite structural system "framed-masonry" whose behavior under seismic excitation is highly influenced by the interaction of the constitutive components i.e. frame and infill. Observations after recent strong earthquakes and experimental campaigns have shown that masonry infill, defined by modern seismic codes as non-structural element, had both beneficial and detrimental influence on the seismic behavior of framed-masonry system depending on frame and infill properties. Nevertheless, most studies, as design rules provided by codes, have aimed their attention to contribution of masonry infill to stiffness and strength capacity, as well as securing ductile behavior of reinforced concrete frame during interaction with masonry infill. Special case is represented by the weak framed-masonry systems as they constitute significant portion of current building stock worldwide. Term weak represents moment resistant frame designed for gravity loads only i.e. non seismically (non ductile) designed frame. These frames have number of inherent deficiencies which in combination with detrimental influence of masonry infill can led to disastrous consequences.

Evaluation of potential damage is one of the fundamental steps in seismic assessment of existing and design of new structures with in a performance-based design philosophy. Performance-based design is a general design philosophy in which the design criteria are expressed in terms of achieving stated performance objectives when the structure is subjected to stated levels of seismic hazard [1]. Performance objectives in performance-based design and assessment procedures are explicitly related to damage states of construction system. Damage states are often expressed by damage scales which consist of finite number of discrete damage grades. These damage grades are usually defined by different damage criteria allowing selection of associated performance level. Although this procedure appears to be pretty straight forward, identification of drift values associated with different damage grades remains one of the unresolved issues in selection of performance objectives. Considering a vast number of construction systems, with emphasis on different materials, it is obvious that selection of same performance objective for two different construction systems will yield different values of associated drift. Selection of appropriate drift value associated with certain performance objective is a cornerstone for economy loss and safety evaluation [2].

To provide threshold values of drifts at certain damage grades i.e. performance objectives of weak framed masonry system a comprehensive experimental and analytical campaign was undertaken at the University of Osijek. Based on experimental results, threshold values of drifts at certain damage grades of *EMS-98* scale and of performance objectives according to *EC8 - 3* are represented. Furthermore, nonlinear response prediction of tested models for three levels of seismic hazard was undertaken to establish a connection between peak ground acceleration and performance objectives.

2. Experimental investigation

2.1 Description of tested models

Characteristics of tested models were chosen in such manner to represent properties generally encountered in common buildings. Total of 14 one-story, one-bay models, grouped into four different series according to reinforced concrete frame properties, with and without masonry infill were tested. Reinforced concrete frames (see Figure 1) were 1:2 scaled and constructed with respect to similitude laws, [3]. Frame properties are given in Table 1, were: $\boldsymbol{\alpha}=h/l$ – aspect ratio, $\boldsymbol{\beta}=I_c/I_b$ – moment of inertia ratio (column/beam ratio) and $\boldsymbol{\rho}$ – reinforcement ratio (ρ_l –longitudinal and ρ_t – transverse ratio in columns and beams). Values given in parenthesis represent transverse reinforcement ratio in the middle third of the beam length. All frames, except *O2*, were constructed with minimum transverse reinforcement ratio prescribed by non-seismic *Eurocode 2* [4].

Table 1 – Frame properties

Frame	α	β	$\rho_{l,c}$ [%]	$\rho_{t,c}$ [%]	$\rho_{l,b}$ [%]	$\rho_{t,b}$ [%]
O1	0.75	0.42	1.0	0.13	3.8	0.13 (0.07)
O2	0.75	0.42	1.0	0.09	3.8	0.13 (0.07)
O3	0.75	1.95	1.0	0.13	3.8	0.13 (0.07)
O4	0.75	1.0	1.3	0.13	3.0	0.13 (0.07)

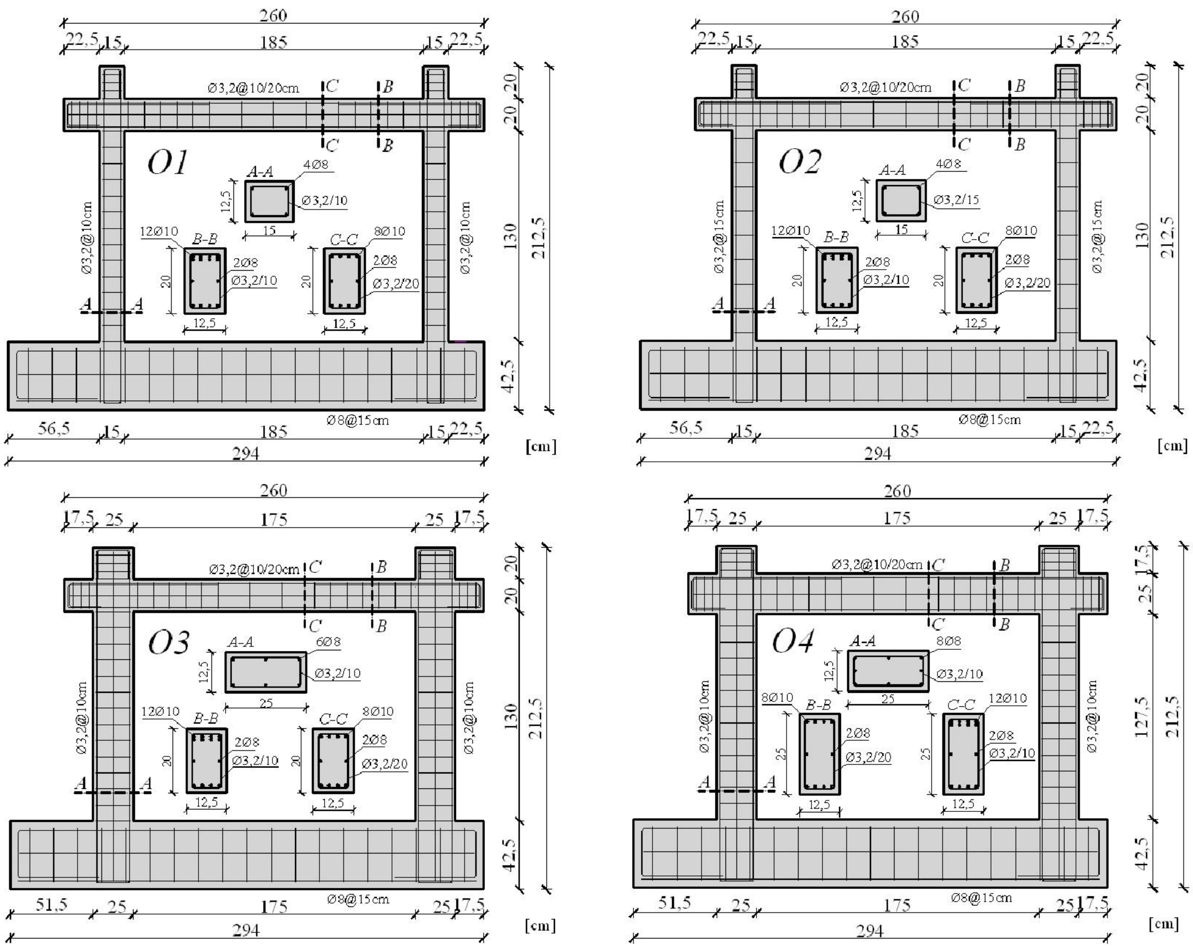

Fig. 1 – Frame specimens.

Variation of masonry infill properties was made by combining: (1) two different types of mortar, cement-lime mortar (***pm***, with volumetric ratio of cement: lime: sand= 1:1:5) and lime mortar (***vm***, with volumetric ratio of lime: sand= 1:3), and (2) two types of masonry units, hollow clay units (***b***, with dimensions *b/h/l*= 120/90/250 *mm* – Group 2 according to *Eurocode 6* [5]) and solid clay units (***c***, with dimensions *b/h/l*= 120/65/250 *mm* – Group 1 according to *Eurocode 6* [5]). By combining these, five different masonry infill wall types were obtained, that could be classified according to their compressive strength as weak and strong masonry infill. Strong masonry infill was obtained by combining both masonry unit types with cement-lime mortar (labeled as ***bpm*** and ***cpm***), while weak masonry infill was obtained by combining both masonry element types with lime mortar (labeled as ***bvm*** and ***cvm***). Additionally, masonry infill of one model (*O1_b*) was constructed solely with hollow clay units (labeled as ***b***), and this type of infill was defined as weak to. Masonry infill walls (except *O1_b*) were built with fully mortared bed and head joints of approximately 1 *cm* depth/thickness. No additional connections were provided between the walls and the frame. Properties of all tested specimens are given in Table 2.

Table 2 – Tested specimens

Specimen	Type of frame	Type of masonry unit	Type of mortar
O1+	*O1*	-	-
O1_bpm	*O1*	Hollow clay units	Cement-lime
*O1_bpm**	*O1*	Hollow clay units	Cement-lime
O1_cpm	*O1*	Solid clay units	Cement-lime
O1_bvm	*O1*	Hollow clay units	Lime
O1_cvm+	*O1*	Solid clay units	Lime
O1_b	*O1*	Hollow units	-
O2_cpm	*O2*	Solid clay units	Cement-lime
O3	*O3*	-	-
O3_bpm	*O3*	Hollow clay units	Cement-lime
O3_cpm	*O3*	Solid clay units	Cement-lime
O4	*O4*	-	-
O4_bpm	*O4*	Hollow clay units	Cement-lime
O4_cpm	*O4*	Solid clay units	Cement-lime

+ repaired specimen

2.2 Test setup

Models were tested within a laterally braced steel reaction frame fixed to a strong floor. The foundation beams of models were fixed to a reaction frame were sliding was prevented by steel restrainers. Models were tested under approximately constant vertical and in-plane cyclic lateral loading. Vertical loads were selected to cause 30% of designed concrete compressive strength and applied at each columns end by hydraulic jacks placed on a sliding support which enabled lateral displacement, and prevented rotation. Cyclic lateral in-plane loading was applied at beams end along its centroid axis by two hydraulic jacks. Two types of lateral load history were applied: (1) load controlled cycles with 10 *kN* increments in the small deformation range and (2) displacement controlled cycles with gradually increasing amplitudes. Each load step was repeated twice in order to capture effects of strength and stiffness degradation. Measured were: (1) loads at each application point by force transducers, (2) lateral displacements at both ends of the beam by *LVDT*s and (3) diagonal deformations of frame and infill by *LVDT*s. Eventual foundation beam slippage was monitored by a high resolution dial gauge. All measured data were continuously registered at a sampling rate of 0.1 *sec* by *DEWE-30-16* system with *DEWESoft* ver. 6.6.7 software support. Appearance and propagation of cracks was monitored visually accompanied by *3D* optical measuring system *ARAMIS*. Test setup, instrumentation and loading history are presented in Figure 2.

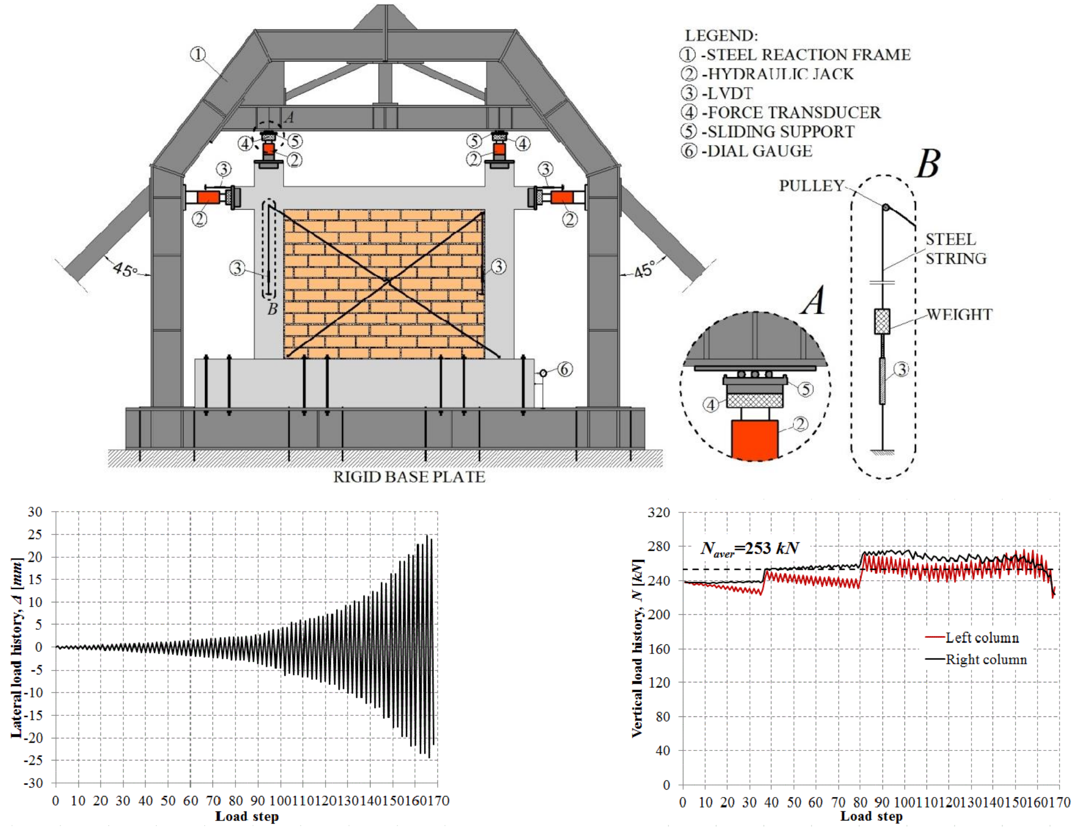

Fig. 2 – Test setup, instrumentation and loading history.

2.3 Response of tested models

Detailed description of global and local behavior of tested models is beyond the scope of this paper (for detailed description see [6]). Nevertheless, conclusions were drawn as follows:

- Global behavior of tested models can be idealized with three limit states, depicting different failure modes of masonry infill and/or frame, defined as: (1) limit state 1 (*LS_1*) defined by the appearance of first significant crack in masonry infill or frame, (2) limit state 2 (*LS_2*) defined by initiation of yielding and (3) limit state 3 (*LS_3*) defined by the failure of one of the models components (loss of composite action). Idealized response of tested models is presented by Figure 3. Drift values (*IDR*) at observed limit states were influenced by masonry infill properties (robustness of masonry unit and mortar type) and frame properties, namely coefficient $\boldsymbol{\beta}$.

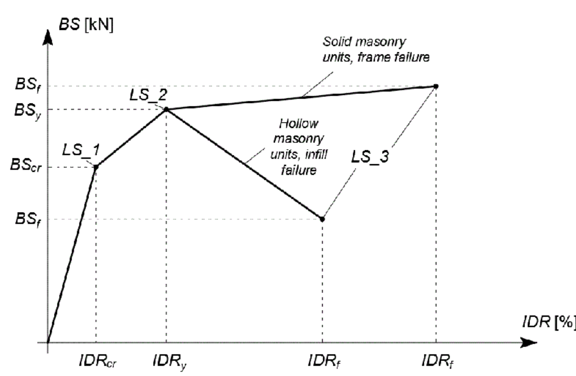

Fig. 3 – Primary curves and limit states of tested specimens.

- Change in failure mode of masonry infill was caused by frame properties, namely coefficient $\boldsymbol{\beta}$, and masonry properties.

- Masonry infill contribution to effective stiffness of tested models was not proportional to masonry wallets modulus of elasticity, and was influenced by frame property ***β*** (weaker the frame higher contribution).
- Masonry infill contribution to lateral strength of tested models was not proportional to tested masonry strengths, and was, similar to stiffness contribution, influenced by frame property ***β***.
- Masonry unit robustness and mortar type arrived to be governing parameters of the infills damage severity and overall behavior of tested models. Robustness of masonry units was defined as a ratio of gross to net cross sectional area, while the influence on global response is best illustrated by Figure 4 a) and b) that depicts hysteretic response of *O4_bpm* and *O4_cpm* model respectively. Regardless to the strength of masonry infill, all models constructed of hollow clay masonry units exhibited virtually same behavior; after the drift of approximately 1% was reached composite action was lost, which ultimately led to a bare frame behavior. This was caused by severe crushing of masonry infill in regions with contact with frame and along failure planes. On the other hand, all models constructed with solid clay units maintained sufficient integrity through performed tests providing ductile inelastic response.

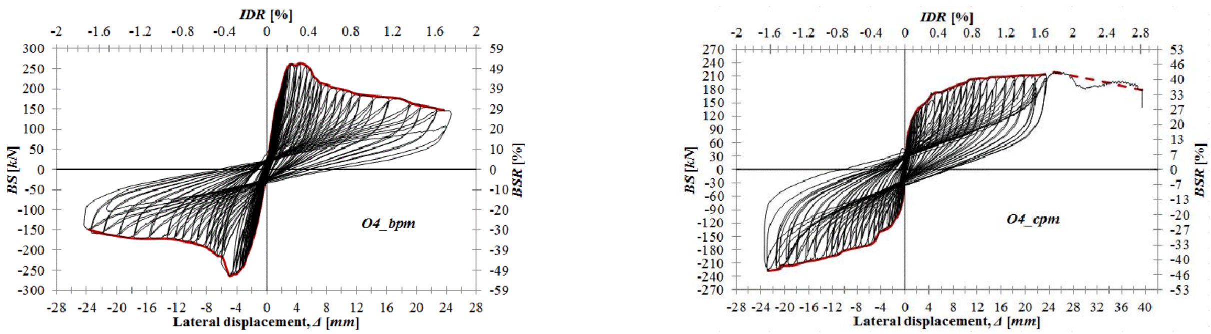

Fig. 4 – Influence of masonry unit robustness on global response of tested specimens.

- Ductility of framed masonry models was equal or slightly higher that ductility of bare frames, except in case of *O2_cpm* model.
- Minimum transverse reinforcement ratio, as prescribed by non-seismic *Eurocode 2*, seems to be sufficient in preventing premature shear failure of frame columns caused by interaction. <u>This needs further testing!</u>
- Energy dissipation capacity of framed masonry models was enhanced with the respect to bare frames and was governed by masonry unit type and frame property ***β***.

Response of all tested models, in terms of response envelope curves, is presented in Figure 5 according to reinforced concrete frame type. Additionally, comparison of response envelope curves of *O1_cpm* and *O2_cpm* model is presented by Figure 6. These models differ only in transverse reinforcement ratio, were 50% reduction of transverse reinforcement ratio in *O2_cpm* model caused 70% reduction of ultimate displacement, implying key role of transverse reinforcement ratio in preserving global stability of framed-masonry structures.

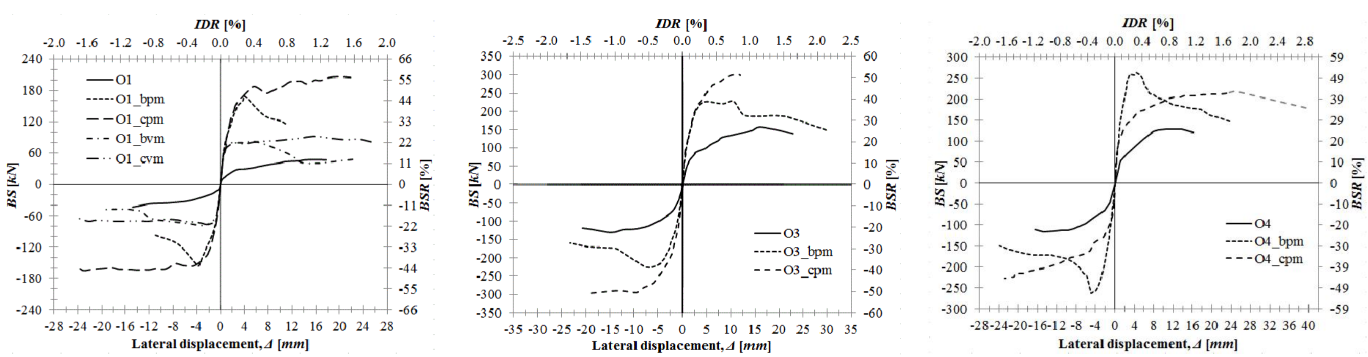

Fig. 5 – Response envelope curves of tested specimens.

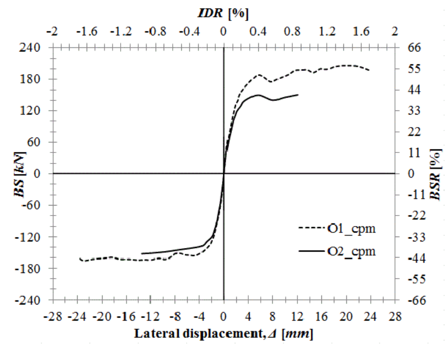

Fig. 6 – Response envelope curves of *O1_cpm* and *O2_cpm* specimens.

3. Damage classification and performance objectives

3.1 Damage classification

Damage scales currently used in loss estimation consist of a certain number of discrete damage states that represent different levels of building performance. Damage scales *EMS-98* and *US/HAZUS* have been widely used in loss estimation studies in recent time, both in their original and hybrid form, [7]. According to [7] "…good damage scale for loss modeling will be one that provides damage and failure mechanism description for each damage state…" Recently [8] proposed an analytical description of each damage grade of *EMS-98* scale, distinguishing between structural and non-structural elements. This analytical description of damage grades was implemented through failure mode description of structural and/or non-structural element, providing a qualitative tool for damage grade identification and interpretation of damage. However, analytical description of structural damage was emphasized, while for non-structural (masonry infill) damage only vague analytical descriptions were provided for damage grades 2 and 3. Damage grade 2 was defined through strength hierarchy analysis, implying possibility of appearance of several failure modes, while damage grade 3 was defined through corner crushing of masonry infill. Distinguishing between structural and non-structural damage imply that for a given earthquake motion two different damage grades will be assigned to a damaged building. Although this "two grade" scoring system seems inappropriate, especially considering that, except in case of collapse, most of the economical and life loss is related to failure of non-structural elements, it is within a current seismic design philosophy. Considering numerous uncertainties related to the seismic assessment of existing buildings, authors opinion is that framed-masonry structures should be observed as a unique composite structural system, where damage grades i.e. performance levels are defined by the certain sequence of failure modes of composite, depending on frame and masonry infill properties. As stated before, damage severity of tested specimens was related to the masonry infill properties, implying a direct correlation between damage grades and masonry infill deformation capacity, and frame property ***β***. Based upon performed experimental investigation, and following the *EMS-98* principles [9], damage and failure mechanism description for each damage grade of framed-masonry system is presented in Table 3 according masonry infill properties. Failure mechanisms of tested framed-masonry specimens were defined according to [10]. Damage grades of bare frames are presented in Table 4 (bare frame *O2* was not tested). Failure mechanisms of bare frames were virtually the same. Damage grade 1 was initiated by the appearance of tensile cracking, followed by shear cracking, while damage grade 5 was determined by shear/axial failure.

Table 3 – Damage grades and associated failure modes of framed-masonry specimens

Infill	Weak	
Unit	Hollow	Solid
Damage grade	Damage mechanism / **Drift**	
1	Diagonal compression (corners) / **0-0.10%**	Bed joint sliding shear / **0-0.20%**

2	Horizontal sliding shear (one plane) / **0.10-0.45%**	Horizontal sliding shear (one plane) / **0.20-0.45%**
3	Horizontal sliding shear (multiple planes) / **0.45-0.85%**	Horizontal sliding shear (multiple planes) / **0.45-1.0%**
4	Corner crushing + initiation of crushing at shear failure plane / **0.85-1.0%**	Horizontal sliding shear (multiple planes) + diagonal compression / **1.0-1.5%**
5	Corner crushing + crushing at shear failure planes (infill failure) / > **1.0%**	Shear cracking (frame failure) / > **1.5%**
Infill	Strong	
Unit	Hollow	Solid
Damage grade	Damage mechanism / Drift	
1	Diagonal compression (corners) / **0-0.20%**	Bed joint sliding shear / **0-0.35%**
2	Corner crushing if $\beta < 1$ Bed joint sliding shear if $\beta \geq 1$ / **0.20-0.50%**	Horizontal sliding shear (one plane) / **0.35-0.60%**
3	Corner crushing if $\beta < 1$ (increase of affected area) Bed joint sliding shear if $\beta \geq 1$ + initiation of crushing at shear failure plane / **0.50-0.85%**	Horizontal sliding shear (multiple planes) / **0.60-1.0%**
4	Corner crushing if $\beta < 1$ (increase of affected area) Bed joint sliding shear if $\beta \geq 1$ + crushing at shear failure plane / **0.85-1.0%**	Horizontal sliding shear (multiple planes) + diagonal compression / **1.0-1.5%**
5	Corner crushing + crushing along frame – infill contact plane if $\beta < 1$ Corner crushing + crushing at shear failure plane if $\beta \geq 1$ (infill failure) / > **1.0%**	Shear cracking (frame failure) / > **1,5%**

Table 4 – Damage grades of bare frames

Frame \ Damage grade	1	2	3	4	5
O1	0 – 0.20	0.20 – 0.55	0.55 – 0.90	0.90 – 1.20	> 1.20
O3	0 – 0.25	0.25 – 0.70	0.70 – 1.10	1.10 – 1.40	> 1.40
O4	0 – 0.30	0.30 – 0.65	0.65 – 0.90	0.90 – 1.10	> 1.10

3.2 Performance levels

Performance levels are expressed in terms of expected levels of damage resulting from expected levels of earthquake ground motion. These levels are defined by limiting values of measurable structural response parameters which represents acceptability criteria to be verified in design or assessment procedure. Acceptability criteria is usually expressed in term of drift or deformation. Drift threshold values according to *Eurocode 8 - 3* [11] are presented in Table 5.

Table 5 – Drift threshold values of building performance levels according to *EC8 - 3*

EC8 - 3			
Building performance level (Limit state)	Drift threshold value for unreinforced masonry infill walls	Drift threshold value for concrete frames	Return Period of Seismic Action
Damage Limitation	-	$1\cdot\theta_y$ for 1 class $0.25\cdot\theta_y$ for 2 class	225 years; probability of exceedance 20% in 50 years
Significant Damage	-	$6\cdot\theta_y$ for 1 class $2\cdot\theta_y$ for 2 class	475 years; probability of exceedance 10% in 50 years
Near Collapse	-	$8\cdot\theta_y$ for 1 class $3\cdot\theta_y$ for 2 class	2475 years; probability of exceedance 2% in 50 years

Lack of drift threshold values of building performance levels for masonry infill presents main disadvantage for assessment/design use according to performance base design. Following the *EMS-98* principles and *EC8 - 3* building performance levels certain relationship can be established with limit states of tested specimens (see Figure 3). Damage limitation can be correlated with damage grade 1, significant damage with damage grade 2 and near collapse with damage grade 4. This correlation is exclusively made up on observations made during performed experiments. Drift threshold values for masonry infill at certain building performance level are presented in Table 6.

Table 6 – Experimentally obtained drift threshold values of building performance levels according to *EC8 - 3*

	Strong masonry infill		Weak masonry infill	
	Hollow clay units	Solid clay units	Hollow clay units	Solid clay units
Damage Limitation	0.15	0.15	0.07	0.07
Significant Damage	0.3	0.5	0.15	0.15
Near Collapse	1.0	1.5	1.0	1.5

4. Prediction of expected damage

4.1 Analytical prediction of expected displacement

The selected method for analytical prediction of expected displacement is based on idealized linear response spectrum modified with factor that takes into account nonlinear effects. Basic variables relate to the effective stiffness and yield strength of the structure and frequency content and intensity of earthquake. The method was developed by Shimazaki and Sozen [12] based on parametric analysis of single degree of freedom system with 2% damping, and later modified by LePage [13]. Expected nonlinear displacement is defined by Eq. (1).

$$D_{\max} = \frac{F_a \cdot a_{\max} \cdot g \cdot T_g}{(2\cdot\pi)^2} \cdot T \qquad (1)$$

where: F_a represents acceleration amplification factor (equal to 3,75 [13]), a_{max} peak ground acceleration, g gravitational acceleration, T_g the characteristic period of ground motion and T effective period of system (defined by the stiffness at *LS_1*, see Figure 3).

4.2 Selection of earthquake records

Selection of earthquake records was carried out according to division of the Croatia on the earthquake hazard zones. Three earthquake hazard zones were considered with peak ground acceleration equal to 0.1, 0.2 and 0.3*g*. The records were selected from the *European Strong-Motion Database* and *SIMBAD* using the computer software *REXEL* [14], matching the average value of seven records between 90% and 125% of the target code spectrum (*Eurocode 8*, Type *1*, Soil Type *C*). Selected records (spectrums) for three different intensity levels are presented in Figure 7.

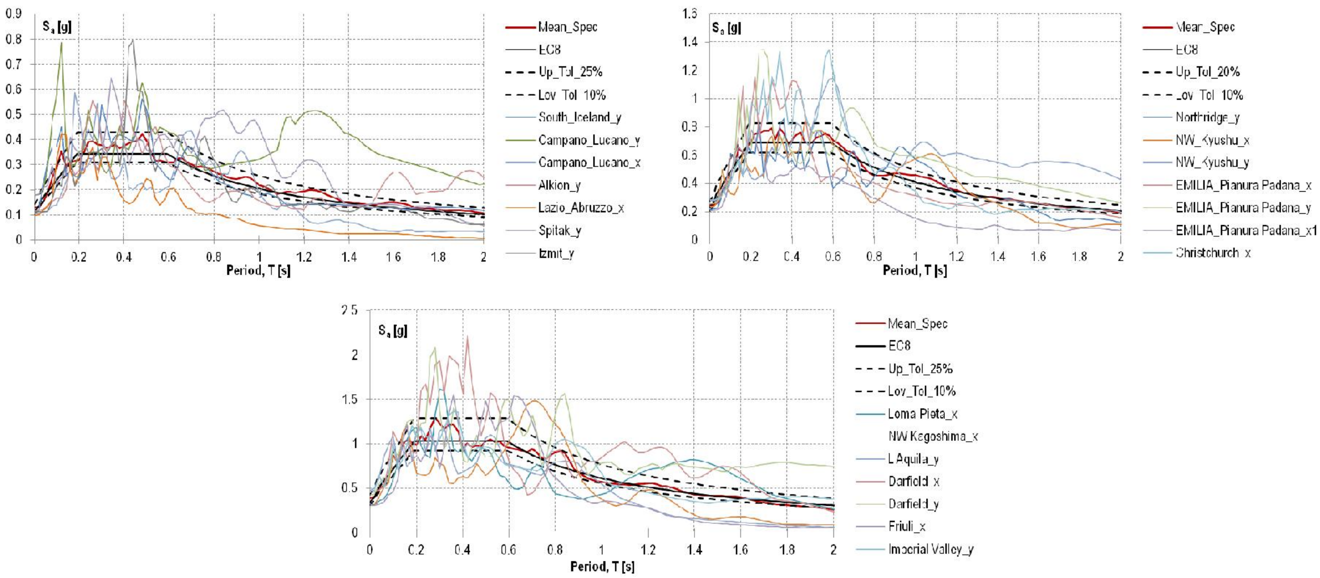

Fig. 7 – Selected earthquake records for three intensity levels (0.1, 0.2 and 0.3*g*).

4.3 Expected damage

Average damage grades together with damage grade range for selected earthquake intensity levels are presented in Table 7. In general, damage grade of certain specimen depended more on frequency content of earthquake record than on peak acceleration. For all three selected earthquake intensity levels specimens with masonry infill have reduced damage grade if compared to bare frames, regardless of frame and masonry infill properties. As expected, stronger bare frames have reduced damage grades if compared to weakest frame *O1*. On the other hand, frame properties of samples with masonry infill did not cause any differences since response was dominated by masonry infill. In addition to damage grade reduction masonry infill also reduced damage grade variation. In terms of structural safety masonry infill have significantly contributed to collapse prevention, especially in case of 0.3*g* earthquake intensity level were predicted drifts of bare frames were several times higher than those presented in Table 4 for damage grade 5. This implies that masonry infill could be employed as effective seismic strengthening measure. However, this conclusion requires additional testing, preferably shake table tests of space masonry infilled frames since certain failure modes could not be achieved on single bay specimens.

Table 7 – Damage grades for selected earthquake intensity levels

Sample	Average damage grade, 0.1*g*	Damage grade range	Average damage grade, 0.2*g*	Damage grade range	Average damage grade, 0.3*g*	Damage grade range
O1	4	2 - 5	5	3 - 5	5	-
O1_bpm	2	1 - 3	3	2 - 5	4	3 - 5
*O1_bpm**	2	1 - 3	3	2 - 5	4	3 - 5
O1_cpm	2	1 - 3	3	1 - 4	4	3 - 5

O1_bvm	2	1 - 2	3	2 - 5	4	3 - 5
O1_cvm	2	1 - 3	3	2 - 4	4	3 - 5
O2_cpm	2	1 - 3	3	1 - 4	4	3 - 5
O3	3	2 - 4	5	2 - 5	5	-
O3_bpm	2	1 - 3	4	2 - 5	4	3 - 5
O3_cpm	2	1 - 3	3	1 - 4	4	3 - 5
O4	3	1 - 5	5	3 - 5	5	-
O4_bpm	2	1 - 3	4	2 - 5	4	3 - 5
O4_cpm	2	1 - 3	4	2 - 5	4	3 - 5

5. Conclusion

Fourteen 1:2 scaled one-bay, one-story specimens of non-seismically designed weak r/c frames infilled with masonry walls (framed-masonry) were tested under constant vertical and in-plane cyclic lateral loading. Their properties were those generally encountered in real buildings and the obtained results are applicable for the assessment of the behavior and strengthening of existing framed-masonry buildings. The robustness of masonry units and mortar type appeared to be governing parameters for damage severity of masonry infill and overall behavior of tested specimens. Severe crushing of masonry infill made of hollow clay units caused their out of plane instability and ultimately led to bare frame behavior at drifts of 1%. Masonry infill made of solid clay units maintained integrity throughout the performed tests (up to drifts of 1.5%) and provided stable nonlinear response and energy dissipation. Detrimental effects of masonry infill on frame elements were observed only in the case of a specimen with a transverse reinforcement ratio lower than the minimum prescribed by the non-seismic *Eurocode 2*. The contribution of masonry infill in general was related to frame and masonry infill properties. Following the *EMS-98* principles, damage and failure mechanism description for each damage grade of framed-masonry system is presented. Additionally, relationship between building performance levels according to *EC8 - 3* with *EMS-98* damage grades and limit states of tested specimens was established, and drift threshold values are presented. Nonlinear response for three earthquake intensity levels (0.1, 0.2 and 0.3*g*) was evaluated by means of analytical equation and expected damage was determined. For all three selected earthquake intensity levels specimens with masonry infill have reduced damage grades if compared to bare frames. In terms of structural safety masonry infill have significantly contributed to collapse prevention, especially in case of 0.3*g* earthquake intensity level were predicted drifts of bare frames were several times higher than those for damage grade 5. This implies that masonry infill could be employed as effective seismic strengthening measure of weak r/c frames.

6. Acknowledgements

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