SECOND EUROPEAN CONFERENCE ON EARTHQUAKE ENGINEERING AND SEISMOLOGY, ISTANBUL AUG. 25-29, 2014

PERFORMANCE BASED EVALUATION AND DESIGN OF REINFORCED CONCRETE FRAMES WITH STRONG MASONRY INFILL

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ABSTRACT

Within a scope of the Croatian project "Seismic design of infilled frames" the contribution of various types of masonry infill, commonly used in Croatia, to the behaviour of RC frames has been investigated. As a part of the project, one story RC infilled frames were designed according to the EC8 and built in a scale 1:2.5 according to the complete similarity rules. They were subsequently infilled with high strength hollow clay brick blocks, without additional shear connection to the frame. One additional RC frame has been built for the comparison reasons.

The specimens were tested under constant vertical and cyclic lateral loads applied in a direction along the plane. They were instrumented to monitor the applied loads at each loading point, displacements at the frame top and bottom, elongation of the diagonals on the frame and on the infill and deformations of the critical frame portions. The experimental results were analysed in the form of the failure types, shear deformations, hysteresis loops and load-displacement envelope curves.

One of the goals of this paper is to compare the experimental results with the results of analytical and numerical modelling. As an analytical model of the infilled frame's ultimate capacity an already well known expressions from the scientific literature in the form of bilinear capacity curve were used. In numerical calculations a substitute diagonal macro model approach for modelling of the infill wall was used by means of Seismostruct computer program. Guided by the results of experiments and using well known analytical behaviour models, computer models of the reinforced concrete masonry infilled frames were calibrated.

All three approaches corresponded well and they all showed that infill walls have a beneficial effect on the structural response, provided that they do not cause shear failures of columns. The possibility of applying such calibrated models for analysis of the behaviour of infilled frames with different geometrical and mechanical characteristics was evaluated.

In order to implement these results in common engineering practice and guided by the results of the experiments and numerical analysis, a substitute equivalent design and evaluation methodology, based on linear calculation of reinforced concrete frame with infill is proposed. According to the methodology, reinforced concrete frame with infill wall is designed and analysed as a system ("frame + wall"). Numerically, it is based on modelling the infill wall as compression members (diagonal strut) that connect the opposite corners of the reinforced concrete frame. Based on model calibration, an expression for the substitute diagonal member's width is proposed. Also, the behaviour factor is corrected according to the observed equivalent damping coefficients determined by the experiments.

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Seismic performance based approach is introduced by means of the evaluation of the expected behaviour of models (demand vs. capacity), using the N2 method, i.e., determining the expected nonlinear drifts. The results corresponded well and showed that taking into account the infill wall is fully justified.

Keywords: reinforced concrete frame, masonry infill, experimental test, analytical model, numerical model, results comparison, performance based design methodology.

1 INTRODUCTION

Reinforced concrete (RC) frame structures filled in with brick masonry walls are commonly used in low and medium-high buildings. Infill walls primarily serve architectural purposes and demands, while its constructive contribution is ignored; thus, the wall should be detached from the frame. This kind of construction is very rare, and usually the infill is glued to the frame or is even used as its formwork. However, the composite behaviour of the infill and frame often remains unconsidered. Besides having some adverse effects, these structures often exhibit increased stiffness, strength, and dissipation capacity along with decreased displacement and second-order effects. Nevertheless, design provisions for new frame-masonry buildings, as in EN 1998-1, are mainly devoted to avoiding any potential consequences of infill wall; however, it does not account for the benefits of their contribution. EN 1998-3 does not include any provisions that consider infill, even as a strengthening intervention, when evaluating the safety of existing buildings. Thus, this paper deal with RC frame structures designed for some lateral action while disregarding the influence of masonry infill.

Frame-wall structures are composite structures made of an RC frame and masonry infill. These structures are often divided into weak and strong categories without clear distinction. A strong frame typically means a frame designed for seismic actions that has the following characteristics: strong columns – weak beams; small spacing of transverse reinforcement in columns, beams, and their connections; higher compressive strength of concrete. The strength of the masonry infill almost always refers to its compressive strength, which can be roughly divided into soft, medium, and strong categories. The failure mechanism and ductility of frame-masonry buildings depend on additional factors such as geometry (bay span to height ratio), relative stiffness and strength of the frame and masonry infill, ductile detailing of the frame, reinforcement of the infill when the infill controls the failure and on the infill distribution in the building plan and the elevation of the building. If brittle inelastic effects can be prevented (e.g. extensive cracking of the infill, bond-slip failure in the frame, or shear failure in frame members), then stiffness degradation and strength deterioration under cyclic loading are acceptable. The designs of contemporary earthquake-resistant structures should reliably limit damage in low and medium-strong earthquakes and prevent collapse during strong earthquakes. The goal of these designs is to meet customer requirements with rationally designed and constructed buildings for a given level of reliability. Thus, this research will contribute to a better understanding of the composite behaviour of RC frames and masonry infill.

2 EXPERIMENTAL MODEL

One storey, one bay reinforced-concrete frame specimens were modelled at a 1:2.5 scale. All the RC frame models were designed and constructed to comply with the C30/37 concrete strength class and the B500B reinforcement grade according to Eurocode rules [1, 2, 3, 4].

Table 1. Mechanical properties of infill walls

Infill type	Brick block MO10
Mean compressive strength, $f_{cw,sr}$ [N/mm^2]	2.62
Mean modulus of elasticity, E [N/mm^2]	6572
Mean initial shear strength, f_{vo} [N/mm^2]	0.536
Mean internal friction, α [°]	22.17

The three infilled RC frame models (GROUP I) use MO10 strong masonry infill brick blocks (Table 1) while one bare RC frame (GROUP IV) was made for comparison reason. Model testing was performed in a closed steel frame, as shown in Figure 1. The steel testing frame was horizontally supported with braces in order to prevent horizontal movement. The test setup (steel frame and corresponding braces) was connected to the strong floor.

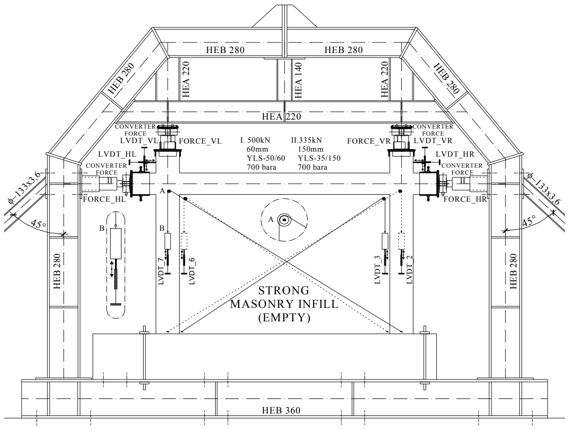


Figure 1. Test setup

Cyclic lateral load was applied to the beam ends of the specimen by using two double-acting hydraulic jacks fixed to the steel columns of the test frame; steel columns were also connected with L-shaped steel beams in place of the horizontal hydraulic jacks. Vertical load was applied to the tops of the columns by using two hydraulic jacks placed on a carriage wheel, which allowed them to move horizontally and prevented their rotation (Figure 1). The foundation beam of each specimen was fixed to the steel frame and to the strong floor.

3 EXPERIMENTAL RESULTS

The hysteretic relationships between the lateral load and displacement of the frame and infill for both, infilled and bare frame, are presented in the Figure 2; these figures also show the primary curves (resistance envelopes) for horizontal force and displacement.

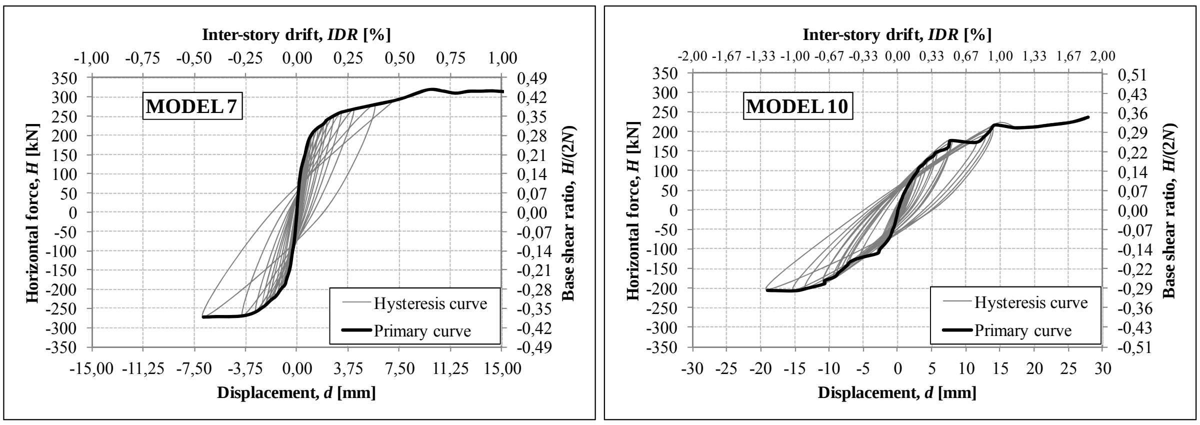


Figure 2. Lateral load – displacement curves of the representative RC infilled specimen of GROUP I and of the RC bare frame model GROUP IV

Figure 3 show the primary curves of each test group model as well as the optimized primary curves that describe the behaviour of the group. The experimental resistance envelope curves ("backbone curve") are represented by a bi-linear idealisation in Figure 4. To idealise the experimental envelope, the equations for calculating the lateral resistance and deformability of masonry walls described in Tomaževič [5] were used.

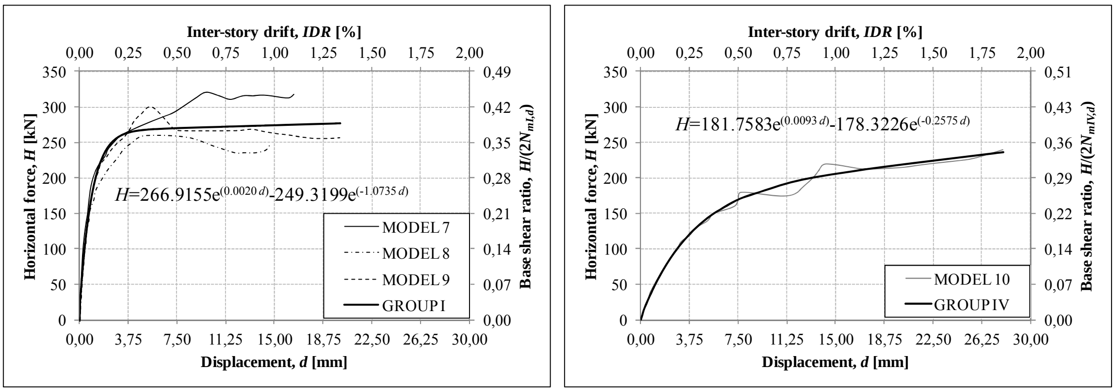


Figure 3. Model primary curves and their optimized primary curve, GROUP I and GROUP IV

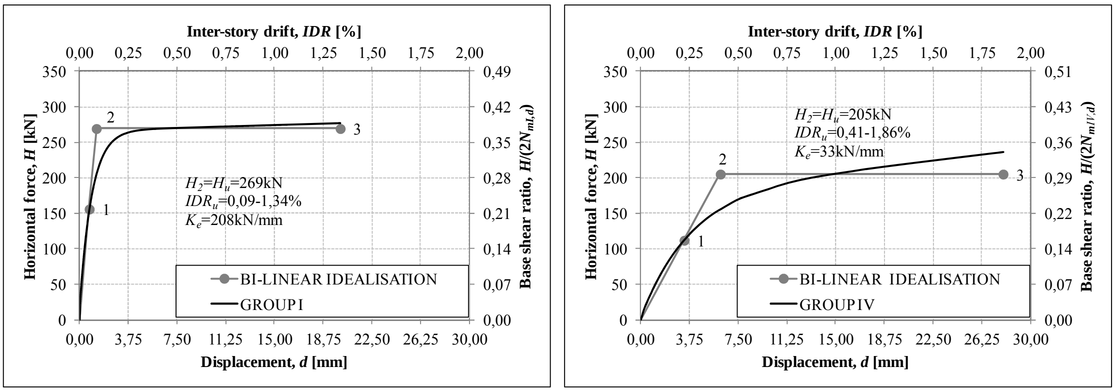


Figure 4. Idealisation of experimental hysteretic behaviour for GROUP I and GROUP IV

Structural performance beyond the elastic range is usually expressed in terms of ductility ratio, μ. Because the lateral resistance never decreased under 90% of the H_{max}, displacement ductility ratio was determined as the ratio between the displacement at which the infill had deteriorated extensively and the idealised yield displacement, i.e. according to the following formula [5]:

$$\mu = d_3 / d_2 . \qquad (1)$$

The damping coefficients as functions of the coefficient of ductility at various storey displacements are shown in Figure 5b. The damping coefficient clearly increases with increased ductility and storey drift. Additionally, Figure 5b shows that the contribution of the infill wall (GROUP I) to the damping coefficient is significant compared to the bare RC frame (GROUP IV).

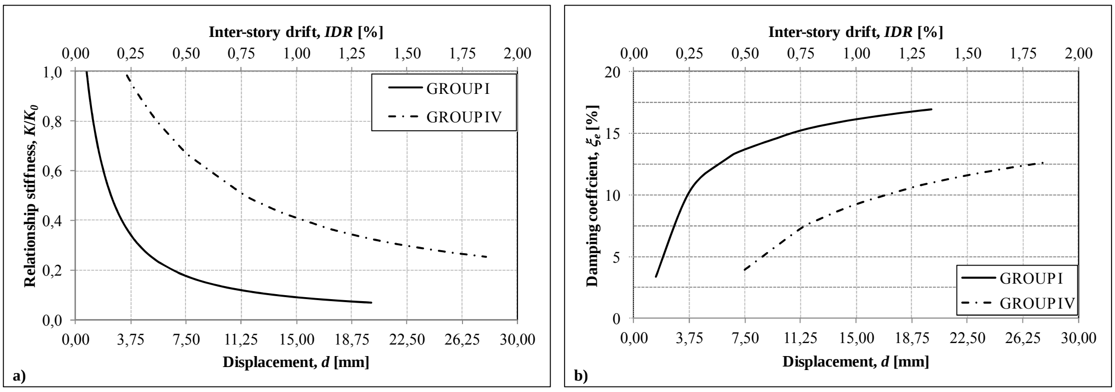
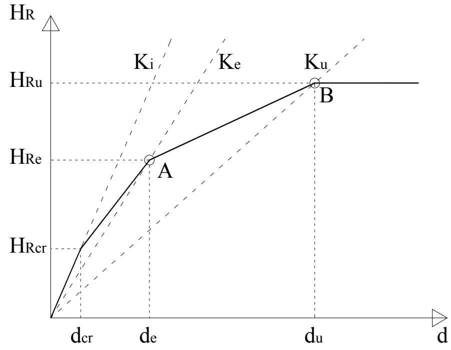


Figure 5. Stiffness degradation for all model structures and damping coefficient as a function of horizontal displacement (storey drift) levels

4 ANALYTICAL MODEL

In the literature there are several authors (Smith, Mehrabi , Simic, Tomaževič, Žarnić, Klinger, Abrams and others) who have dealt with the capacity RC frames with infill wall in their own plane. In this paper, the analytical model according to Slovenian research results was chosen in which the walls are treated as a diagonal struts connecting the RC frame's opposite corners. Based on his experiments, Tomaževič proposed a model simulating inelastic behaviour of RC infilled wall. The model describes a structural response in the form of three-linear load-displacement relationship where:



H_{Rcr} shear resistance of RC infilled frame at the onset of the first significant cracks in the wall,
H_{Re} shear resistance of RC infilled frame at the separation of infill wall and RC frame,
H_{Ru} ultimate shear force i.e. capacity of RC infilled frame,
K_i initial stiffness of RC infilled frame,
K_e stiffness of RC infilled frame at the separation of infill wall and RC frame,
K_u stiffness at the time RC infilled frame reaching it's capacity.

5 NUMERICAL MODEL

The objective of the experimental tests on RC infilled frames, scaled or in full size, are not only in yielding the collapse mechanism of such structures, but also in calibration of an appropriate numerical model in order to propose a simple method that could be used to simulate the experimental behaviour of such structures, especially the behaviour of infill walls. Several methods developed for modelling the wall infill can be divided into two main categories:
a) Macro-model, a method based on the equivalent diagonal strut (Figure 6),
b) Micro-model, a method based on finite elements.

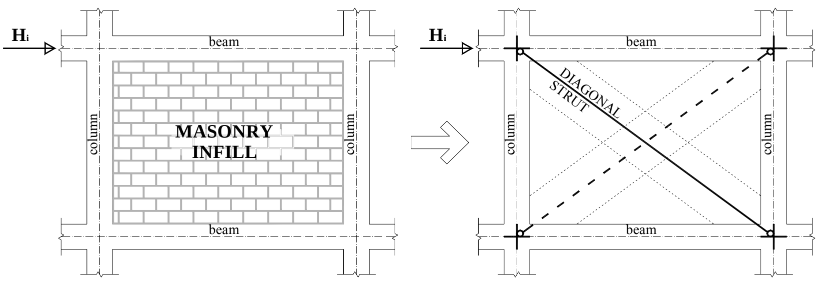


Figure 6. Macro-model using equivalent diagonal strut

The main advantages of the macro-modelling (which is used in this paper) lies in its computational simplicity and in its use of experimentally derived mechanical properties of the infill walls. When selecting the appropriate numerical model for the analysis of seismic behaviour of RC infilled frames, we referred primarily on its simplicity and reliability. In doing so, our analysis were based on results derived by a computer program SEISMOSTRUCT (Ver. 6), based on the finite element method for assessing the behaviour of planar and spatial frames under static and dynamic loads, which take into account both geometric and material nonlinearity. Studies have shown that one of the most acceptable ways of analysing RC infilled frames is by means of diagonally braced frames, i.e. by replacement of the infill wall with the compressive diagonal element.

To define the stress-strain behaviour of concrete, a model by Mander was used while in case of steel reinforcement, a model by Menegotto – Pinto was used. RC frame structural elements (columns and beams) were modelled using inelastic frame elements, *infrmFB*. To define the infill wall, an inelastic panel element introduced by Crisafulliu was used (Figure 7, 8) [6, 7].

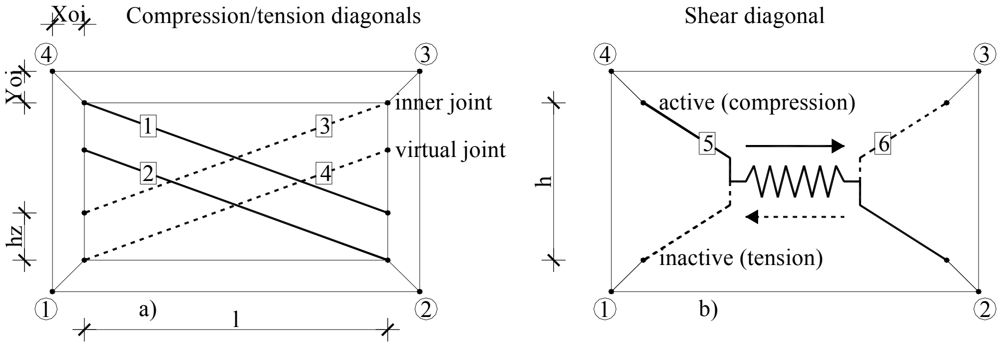


Figure 7. Inelastic panel element, a) compression/tension diagonals, b) shear diagonal

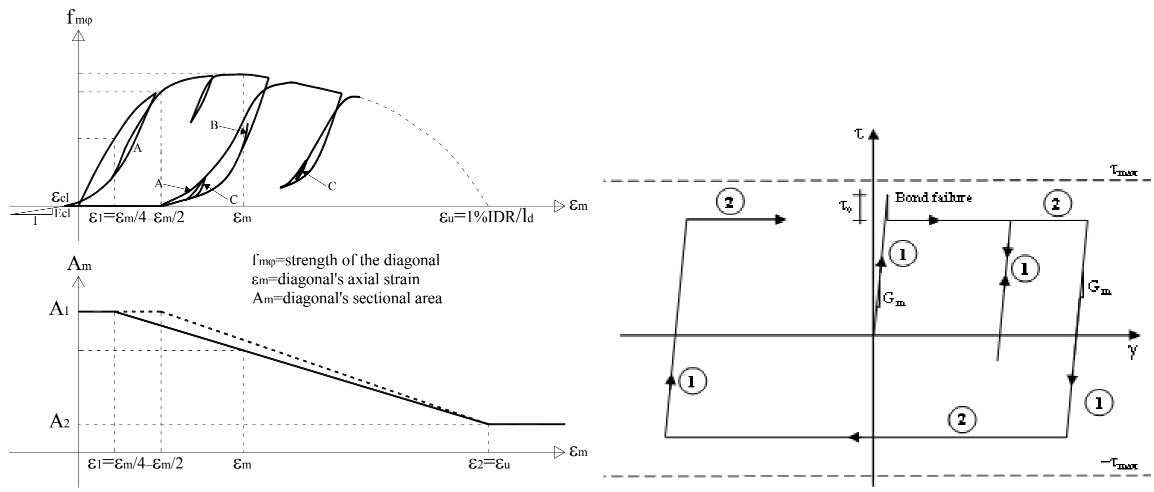


Figure 8. Hysteretic behaviour of the diagonal struts and variation of the area of the masonry strut

6 COMPARISON OF EXPERIMENTAL, ANALYTICAL AND NUMERICAL RESULTS

To compare the results, a shear force expressed by means of the primary curves is selected. The comparison of experimental and analytical as well as of experimental and numerical results for GROUP I models is presented on Figure 9a and Figure 9b, respectively. Based on them, we can conclude that the selected analytical and calibrated numerical models quite well describe the behaviour of RC infilled frames.

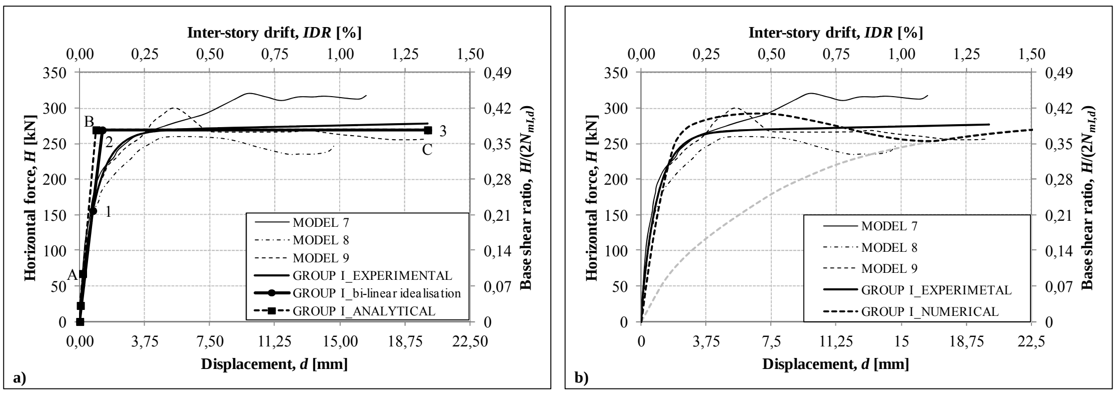


Figure 9. a) Comparison of experimental and analytical results b) Comparison of experimental and numerical results

7 PERFORMANCE BASED DESIGN METHOD OF THE RC INFILLED FRAMES

A linear design and evaluation method of the RC infilled frames suitable for usual engineering practice is proposed. It consists of several steps, as described on Figure 10.

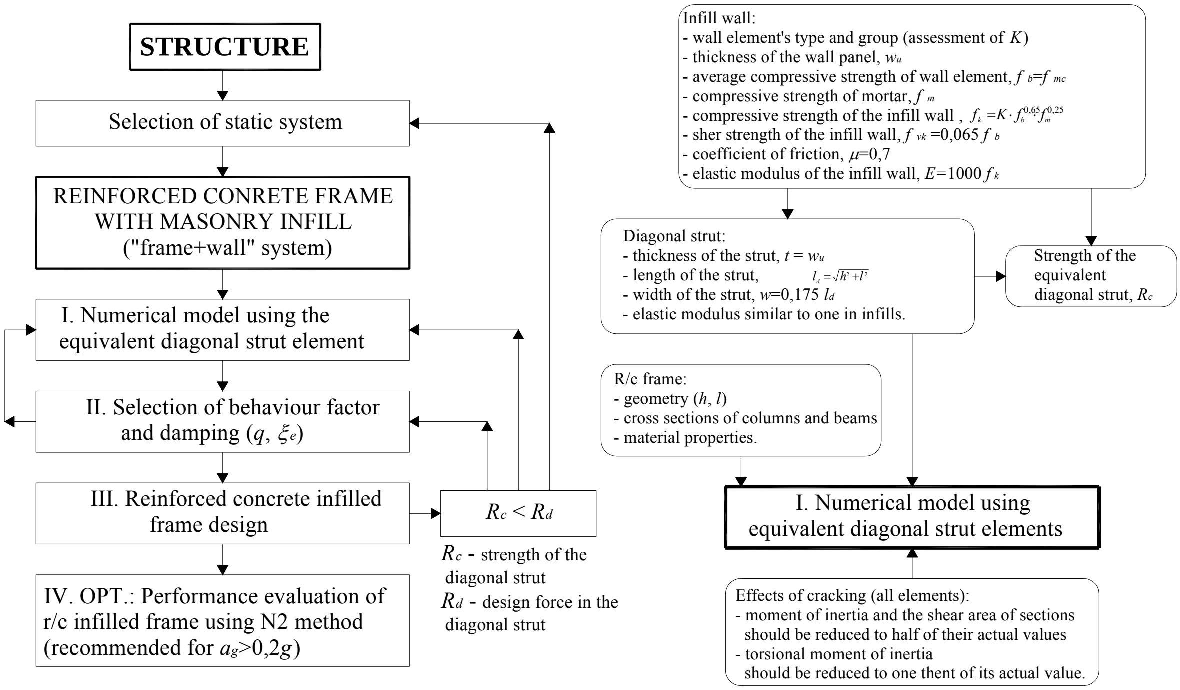


Figure 10. Flow chart of the proposed assessment method

The proposed method is derived mainly from previous experimental, analytical and numerical results (analysis). It is validated and its use justified on numerous models of multi-storey reinforced-concrete frames with infill wall at various levels of earthquake loading. Their behaviour was additionally checked by performing the nonlinear N2 method. The application and a brief description of the proposed evaluation method is given as follows.

ILUSTRATIVE EXAMPLE: Application of the proposed design and evaluation method

The application of the proposed evaluation method is shown on selected numerical models. Models have four stories, and are exposed to various seismic intensities. For the comparison reasons, a total of six models are analyzed: one RC infilled frame and one RC bare frame, each exposed to three seismic intensities - 0.1g, 0.2g and 0.3g. Model layout area and its section in all six cases was the same (Figure 11).

Step I

A hollow clay wall element of MO10 strength class is chosen. Wall panels are built with a general-purpose mortar of strength class M5. For this type of wall element and mortar, the basic infill properties are determined according to the expressions listed in Figure 10 (K=0.45; f_b=10 [N/mm^2], f_m=5 [N/mm^2], f_k=3.01 [N/mm^2], E=3005.76 [N/mm^2], f_{vk}=0.65 [N/mm^2], μ=0.70). Infill wall is modelled using a compression member (diagonal strut) with properties determined as follows.

Table 2. Geometric properties of the equivalent compression elements (diagonal struts)

NUMERICAL MODEL	Width $t=w_u$ [mm]	Base story height $w=0.175\ l_{d,p}$ [mm]	Upper stories height $w=0.175\ l_{d,k}$ [mm]	Elastic modulus E [N/mm^2]
4. floor	300	985.65	916.20	3005.76

All numerical models are designed to be built from concrete class C30/37 and reinforced with ribbed reinforcement of class B500B. The cross sections of compression members (diagonal struts), which simulate the infill wall, are shown in Table 2. Numerical analysis of all the elements was performed with reduced stiffness, i.e. reduced moment of inertia and shear area to half of its value, while the torque is reduced to a tenth of its initial value.

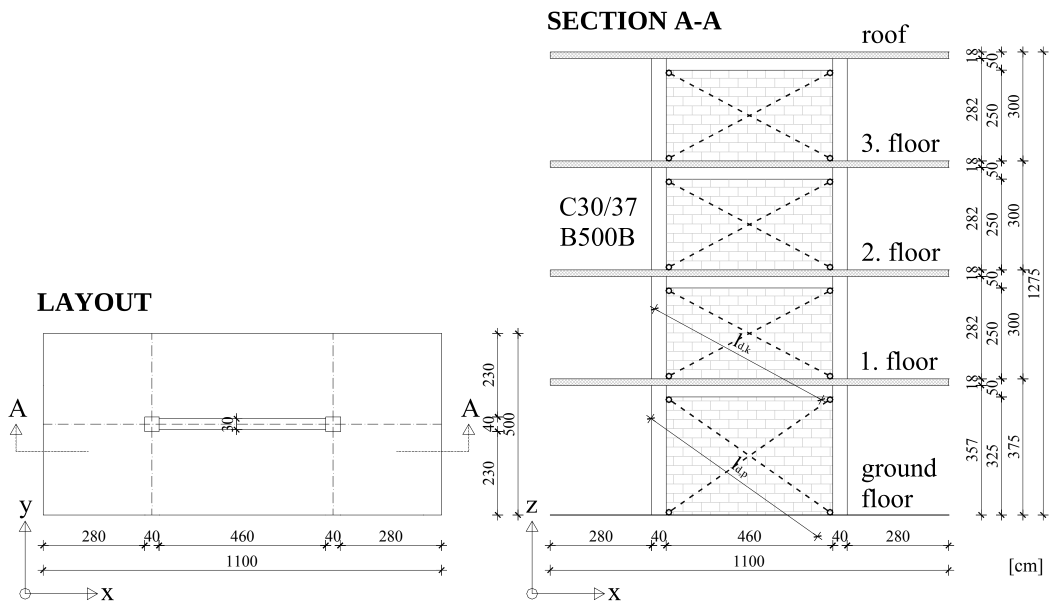


Figure 11. Numerical model – 4 stories

Step II

Calculation of horizontal seismic forces for all numerical models is made all according to EC8 (soil category B, class of importance II, medium ductility class DCM, 5% viscous damping for RC bare frame and 14% viscous damping for RC infilled frame which was obtained on the basis of experimental studies [8, 9] at the level of 0.50% storey drift). Behavior factor for horizontal action for RC bare frame is q = 3.9, while for RC infilled frame is q = 3.25 at the level of 0.5% storey drift.

Table 3. Horizontal seismic forces at the bottom

NUMERICAL MODEL	a_g [m/s^2]	m [kN]	F_b [kN]	F_b/m [%]
RC bare frame	0.98	1884.07	73.94	3.92
	1.96		147.89	7.85
	2.94		221.83	11.77
RC infilled frame	0.98	1884.07	173.91	9.23
	1.96		347.83	18.46
	2.94		521.74	27.69

Maximum internal axial forces in equivalent diagonal struts replacing the infill walls for all numerical models were obtained by linear static analysis (Table 6). For the given infill wall the strength of diagonal strut, f_{mi}, were determined, depending on the possible collapse mechanism of the infill wall and the smallest value, $f_{m,min}$ is checked (Table 4).

Table 4. Strength of diagonal strut for selected infill wall, f_{mi}

NUMERICAL MODEL	Story	f_{m1} [N/mm^2]	f_{m2} [N/mm^2]	f_{m3} [N/mm^2]	f_{m4} [N/mm^2]
RC infilled frame	Ground floor	3.995	3.007	4.097	2.319
	1. – 3. floor	2.499	2.129	2.526	1.565

Load carrying capacity of the compression strut i.e. maximum force which can be withstand, R_c, is calculated by multiplying the selected minimum compressive strength with corresponding area section (Table 5).

Table 5. Capacity of diagonal strut for selected infill wall, R_c

NUMERICAL MODEL	Story	$f_{m,min}$ [N/mm^2]	$Ad=t\,w$ [mm^2]	$R_c=f_{m,min}\,A_d$ [kN]
RC infilled frame	Ground floor	2.319	295694.34	686
	1. – 3. floor	1.565	274861.44	430

Comparison of forces in diagonals obtained by linear static analysis for selected ground accelerations intensities with those determined in Table 5, are shown in Table 6.

Table 6. Evaluation ot the forces in diagonal struts

FLOOR	R_d [kN] (a_g=0.1g)	R_d [kN] (a_g=0.2g)	R_d [kN] (a_g=0.3g)	R_c [kN]	Evaluation, R_c>R_d
3. floor	56.55	110.49	165.15	430	√
2. floor	103.53	202.31	311.56	430	√
1. floor	137.48	268.60	414.15	430	√
Ground floor	164.10	311.91	473.80	686	√

Step III

Results shown in Table 6 obviously indicate that the selected infill wall, for which the capacity of diagonal strut is calculated, meets all the necessary requirements in all stories and for all seismic intensity levels. Now the next step, which is design of the RC frame elements, may follow all in accordance with Eurocode 2 and Eurocode 8 design rules. Required amounts of reinforcement are calculated for RC infilled frame model as well as for RC bare frame one.

Step IV

The final step of the proposed evaluation procedure is the nonlinear method which introduces seismic performance based approach by means of the evaluation of the expected behaviour of the numerical models (demand vs. capacity), using the N2 method, i.e. determining the expected nonlinear drifts [11]. Gradually pushing the selected model, its capacity curve is obtained which is then idealized by means of the bilinear (RC bare frame, Figure 12a) and multi - linear (RC infilled frame, Figure 12b) force - displacement relationships.

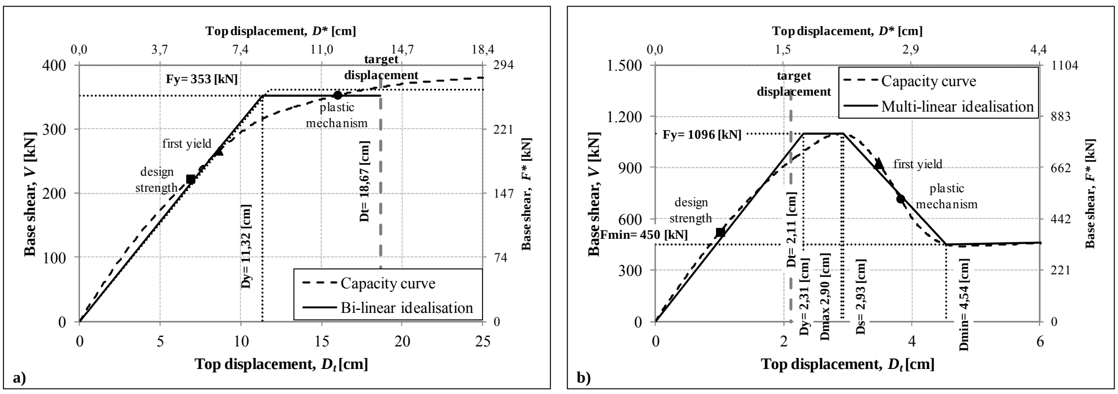


Figure 12. Pushover capacity curves and their multi-linear idealisations (a_g=0.3g)

Tracing the curve on Figure 12a, it is obvious that selected and accordingly designed RC bare frame failed to meet the necessary requirements in displacements. Thus, it is necessary to change, for example, the dimensions of columns or take some similar action. Nevertheless, such result fully justifies the option of nonlinear evaluation method (N2) application.

RC bare frame not meeting the story drift demand (in case of seismic intensity 0.3*g*) is shown also on Figure 13 (inter-story drift exceeds 1.75 %). However, RC bare frame's lateral displacements and story drifts at critical story (1. story) are on average 8.3 times larger than those of RC infilled frame. On the other hand, the corresponding damage level of the infill wall can be classified as moderate one, according to the experimental results [8, 9].

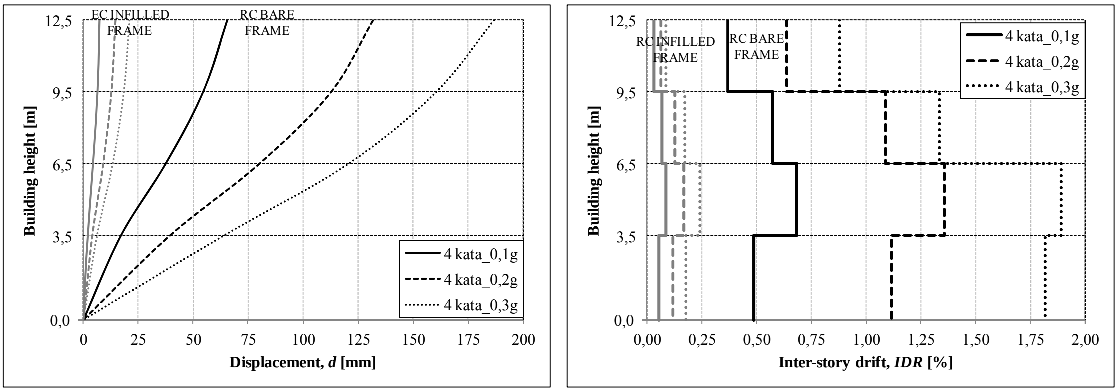


Figure 13. Horizontal displacements and inter-story drifts for the target displacement

Finally, wall damage levels of selected numerical models are shown on Figure 14, depending on inter-story drifts.

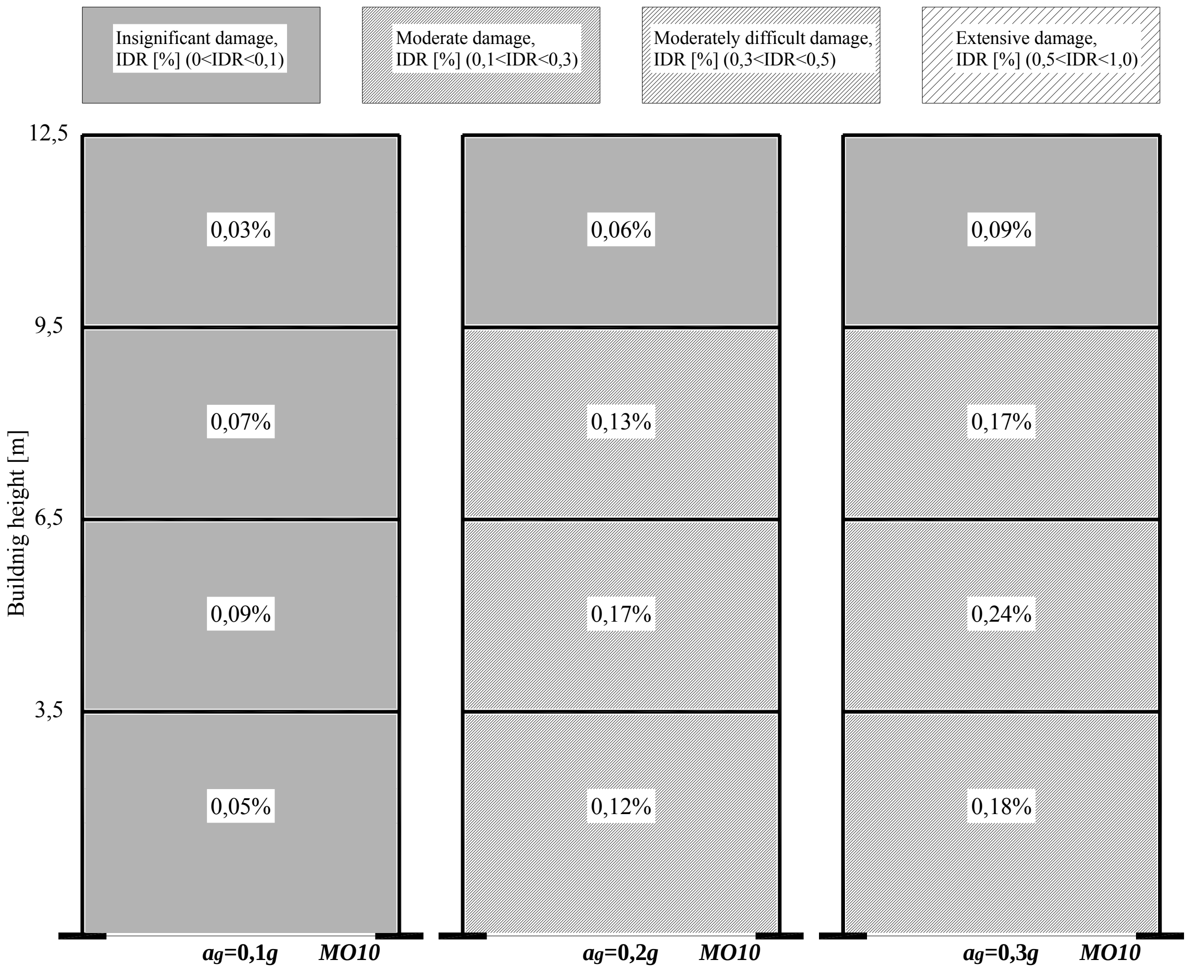


Figure 14. Infill wall's damage levels

CONCLUSIONS

A linear assessment method of the reinforced-concrete infilled frames, suitable for usual engineering practice is proposed. It is derived mainly from previous experimental, analytical and numerical analysis carried out on one storey, one bay reinforced-concrete frame models designed and constructed according to Eurocode rules and subsequently infilled with high strength hollow clay brick blocks.

Experimental studies have shown a significant enhancement in lateral load capacity, stiffness, absorbed and dissipated hysteretic energy of RC infilled frame, especially at low storey drifts. Tracing the resistance envelops, initial linear portion is noticeable which indicates that the RC infilled frame acts as a composite "frame + wall" structural system. Infill wall contributed also to the structural behaviour factor and overall good performance of the structure. As an analytical model of the infilled frame's ultimate capacity, expressions in the form of bilinear capacity curve were used. In numerical calculations a substitute diagonal macro model approach for modelling of the infill wall was used. It was repeatable calibrated guided by the results of experiments and using well known analytical behaviour models. All three approaches corresponded well and they all showed that infill walls have a beneficial effect on the structural response, provided that they do not cause shear failures of columns.

In order to implement these results in common engineering practice by taking the contribution of infills, a substitute equivalent design and evaluation methodology, based on linear calculation of reinforced concrete frame with infill wall is proposed. Accordingly, reinforced concrete frame with infill wall is designed and analysed as a system ("frame + wall"). Numerically, it is based on modelling the infill wall as compression members (diagonal strut) that connect the opposite corners of the reinforced concrete frame. Based on model calibration, an expression for the substitute diagonal member's width is proposed. Also, the behaviour factor is corrected according to the observed equivalent damping coefficients determined by the experiments. Seismic performance is additionally checked by means of the evaluation of the expected behaviour of models (demand vs. capacity), using the N2 method, i.e., determining the expected nonlinear drifts. The results corresponded well and showed that taking into account the infill wall is fully justified.

ACKNOWLEDGMENTS

The research presented in this paper is a part of the research project "*Seismic design of infilled frames*", No. 149–1492966–1536, supported by the Ministry of Science, Education and Sports of the Republic of Croatia and its support is gratefully acknowledged.

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