Testing of R/C frames with masonry infill of various strength

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SUMMARY:
This paper presents parts of the results of the Croatian project "Seismic design of infilled frames". Within this part we have investigated the contribution of various types of masonry infill to the behaviour of “strong” R/C frames. Ten one-bay, one storey R/C frames were built in a scale 1:2,5 and subsequently infilled with masonry blocks of various strength properties. The masonry blocks used were: high strength hollow clay brick blocks, medium strength hollow clay brick blocks and low strength lightweight AAC blocks. Three frames infilled with each masonry type and one additional bare R/C frame were tested under constant vertical and cyclic lateral loading. The experimental results are presented in the form of observed failure types, shear deformations, hysteresis loops and load-displacement envelope curves. The results show that masonry infill strength influenced the maximum lateral load and energy dissipation capacity of the "frame-wall structure" while deformation capacity remained the same.

Keywords: reinforced concrete infilled frame, masonry infill, experimental testing, hysteretic behaviour

1 INTRODUCTION

In many countries in Southern Europe, reinforced concrete (R/C) frames are usually filled in by brick masonry. This composite system (framed-masonry structure) serves both architectural and structural demands efficiently and people in seismic regions live and will continue to live in buildings of this type. The masonry infill panels significantly enhance stiffness, strength and energy dissipation of a frame [1]. Their composite behaviour often remains unconsidered as the common vision on the effects of masonry infill still remains to be achieved within the research community. Design provisions for new framed-masonry buildings in the EN 1998-1 [2] are mainly devoted to avoid possible detrimental effects that infills may cause, but the beneficial effects are not accounted for. Also, for safety evaluation of the existing buildings the EN 1998-3 [3] does not include any provisions for the consideration of infill in the assessment of existing buildings and not even for its consideration in strengthening interventions. Therefore, further research is needed for upgrading the "framed-masonry" into a full- fledged structural system, defining a reliable analysis tools for sound engineering decisions and improving the analysis methods for their performance assessment [4]. Framed-masonry structures are composite structures consisting of the R/C frame and masonry infill. They are often divided into “weak” and “strong” without clear distinction. A "strong" frame typically means a frame designed for seismic actions with strong columns vs. beams, small spacing of transverse reinforcement in columns, beams and their connections, and with higher compressive strength of concrete. Strength of the masonry infill is, almost always, associated with the infill’s compressive strength that can be roughly divided into soft, medium and strong. Failure mechanism and ductility of the "framed-masonry" system depends on additional factors such as: frame length/height, stiffness and strength of the frame and masonry infill, ductile detailing of the frame, reinforcement in the infill when it controls the failure. If brittle inelastic effects are prevented (e.g. cracking of infill, bond slip failure or shear failure in frame members) then stiffness degradation and strength deterioration under cyclic loading are acceptable [5, 6].

The main objective of this research was to investigate the behaviour and strength of seismically designed reinforced concrete frames later infilled with masonry wall of a type commonly used in Croatia. Nine one story-one bay reinforced-concrete infilled frames built in a 1:2,5 scale were tested at the Laboratory for experimental mechanics of the University of Osijek, Faculty of Civil Engineering. The tests were performed under constant vertical and reversed cyclic loading simulating the seismic effect [7]. All frame models were the same and represented "strong" ductile frame and were infilled with unreinforced masonry infill that could be divided into soft, medium and strong. The infill had no shear connection to the frame outside adhesion. The experiments were performed in order to determine the contribution of the infill to lateral stiffness and strength of the R/C frames, to evaluate the behaviour of each element and of the system as a whole. It was observed that in all "framed-masonry" models first crack occurred at the storey drift of about 0.05% and retained their carrying capacity up to 1,0% storey drift. Experimental results showed an evident contribution of the masonry infill to initial stiffness and an increase in initial and maximum strength depending to infill's strength. Also, the energy dissipation capacity of the infilled frames was much larger at lower drift ratios than that of the bare frame. If the performance behaviour criteria are important, than "framed-masonry" shifts the building behaviour from Life Safety to the Operational Level.

2 TESTED MODELS

Within this part of the research project, a total of nine one storey- one bay R/C model frames with three strength types of infill and one bare R/C model frame were constructed and tested. The model dimensions were 2,2m by 1,5m (L/H) with the columns and the beam cross section of 20x20 cm and 12x20 cm, respectively (Figure 1 and 2.).

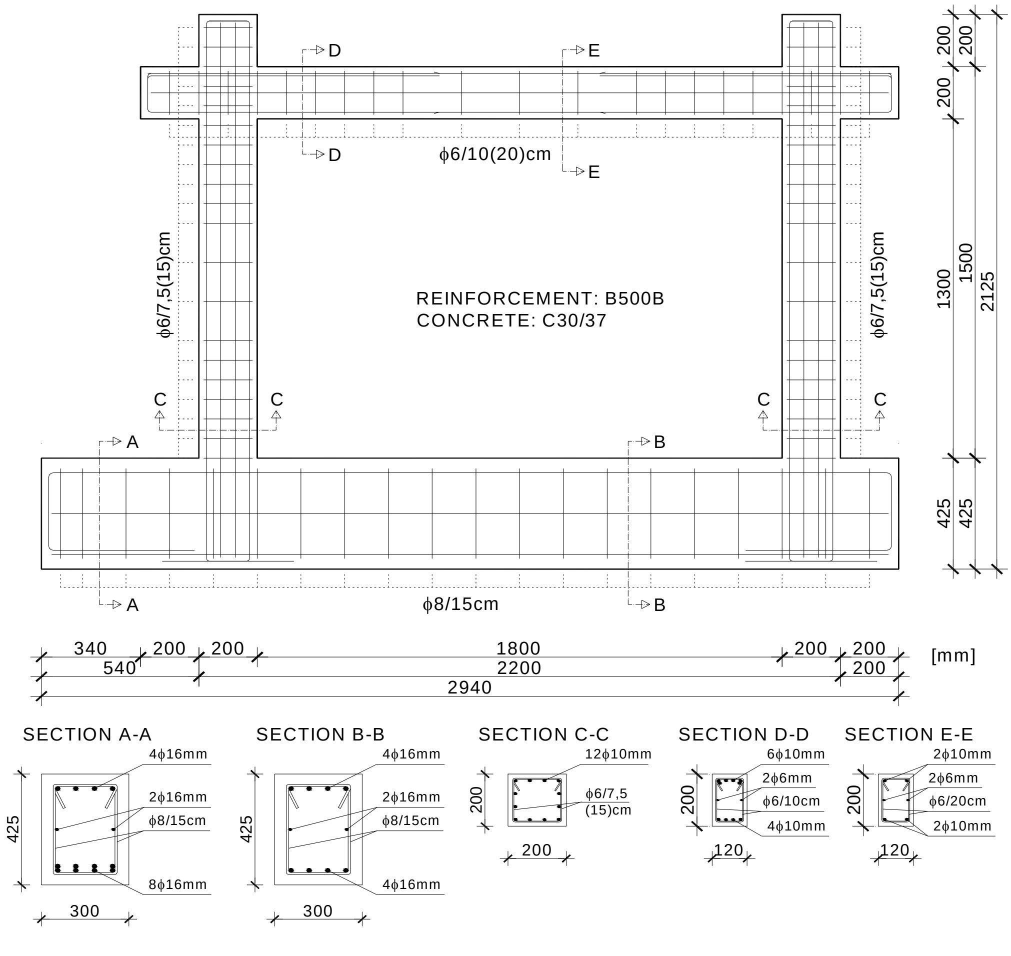

Figure 1. Dimensions and reinforcement of the test model

It is difficult to capture the effect of the overturning moments in one-story test specimens, but it is defensible to hypothesize that moment is resisted almost totally by the columns (unless somehow the wall is stuck to the girder or the column is much softer in axial compression than the wall). If that is correct, we can obtain critical information from a one-story test specimen. The tested models were produced in a scale of 1:2,5 and the experiments were performed on the basis of a true model that maintained complete similarity implying that the prototype and the model had the same material properties. R/C frames were produced first and after 28 days the masonry infill with characteristics described in the Table 3.1 was added. Three types of infill with various strength properties were used, namely: (a) high strength perforated clay brick blocks (Brick block MO10), (b) medium strength perforated clay brick blocks (Brick block MO5) and low strength lightweight Aerated Autoclaved concrete blocks (AAC blocks MO2,5). The mechanical properties of the concrete, infill blocks, mortar and masonry walls were tested according to the European norms [8,9].

Materials used were the concrete of class C30/37 and the reinforcement of type B500B. The exact values are given in Table 3.1. The masonry infill panels were built subsequently, i.e. after the R/C frame was made and hardened. The cement-lime mortar was made "in situ" in the volume proportion of cement:lime:sand=1:1:5 and with the designed nominal strength of 5MPa. The obtained compressive strengths of mortars used in the masonry wall panels are also listed in Table 3.1.

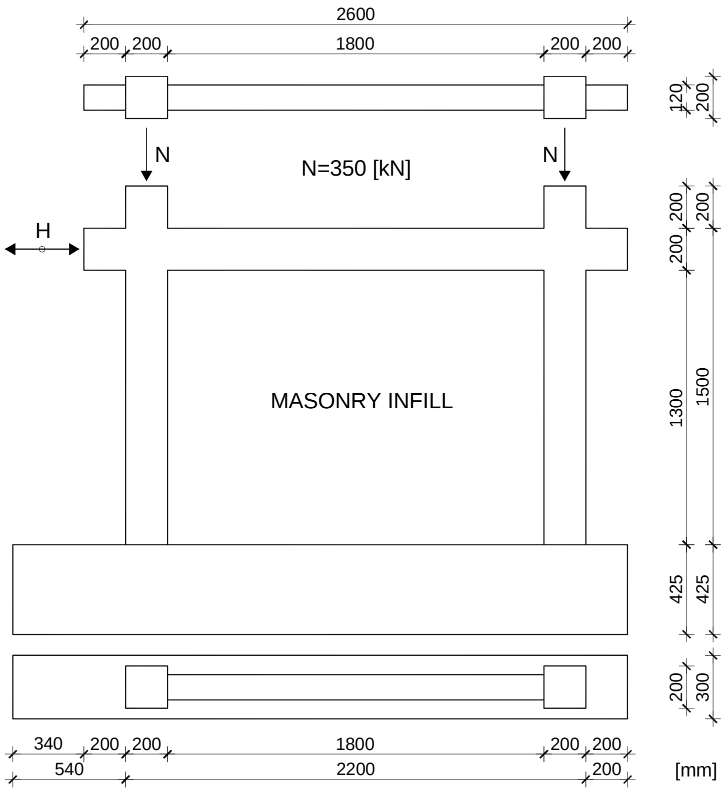

Figure 2 "Framed-masonry" test models

3 MATERIALS USED

The tests of masonry infill wallets, made of high strength perforated clay brick blocks (Brick block MO10) and of medium strength perforated clay brick blocks (Brick block MO5) with lime-cement mortar and low strength lightweight Aerated Autoclaved concrete blocks (AAC blocks) with its mortar as used in Croatia, were performed according to EN 1996-1-1:2005 [9]. Standard tests of mechanical properties were extended by examining the horizontal compressive strength of masonry, thus the modulus of elasticity and ultimate strain, tensile strength and shear modulus of masonry that are also needed for numerical verification. Extensive test results of the masonry, mortar and wallets can be found in [10] and the reduced ones are presented in the Table 3.1.

The compressive strength of concrete was obtained according to the European norms by testing the cube of size 150x150x150mm [8]. Reinforcing bars were of type B500B with experimentally obtained yield strength f_y= 594 N/mm^2, ultimate strength f_u= 699 N/mm^2 and the Young modulus of elasticity E=206957 N/mm^2. Tested compressive strength of masonry brick blocks MO10 was 4,28 N/mm^2, of masonry brick blocks MO5 1,89 N/mm^2 and of AAC blocks 1,63 N/mm^2 [10].

Table 3.1. Material properties

MODEL	COMPRE-SSIVE STRENGTH OF CONCRETE [N/mm^2]	REINFOR-CEMENT TYPE	INFILL TYPE	DECLARED COMPRE-SSIVE STRENGTH OF BLOCKS [N/mm^2]	NOMINAL COMPRE-SSIVE STRENGTH OF BLOCKS [N/mm^2]	MEAN COMPRE-SSIVE STRENGTH OF BLOCKS [N/mm^2]	COMPRE-SSIVE STRENGTH OF MORTAR [N/mm^2]
MODEL8	51,50	B500B	Brick block MO10	10,00	17,03	13,21	5,11
MODEL4	48,50	B500B	Brick block MO5	5,00	4,40	3,87	5,01
MODEL3	35,00	B500B	AAC blocks	2,50	2,33	2,12	13,89
MODEL10	35,00	B500B	-	-	-	-	-

4 TEST SETUP

The test setup consisted of a steel testing frame connected to the strong floor and horizontally supported with braces, as shown in Figure 3. The foundation beams of the models were fixed to the steel frame and to the strong floor. Constant vertical loads were applied at the column tops and cyclic lateral loads were applied at the beam ends (Figure 2). Vertical loads, that simulated loading from the upper floors, were applied on the specimen's columns by means of two hydraulic jacks placed on a carriage that enabled them to move horizontally. The loads were kept constant by means of pressure valves.

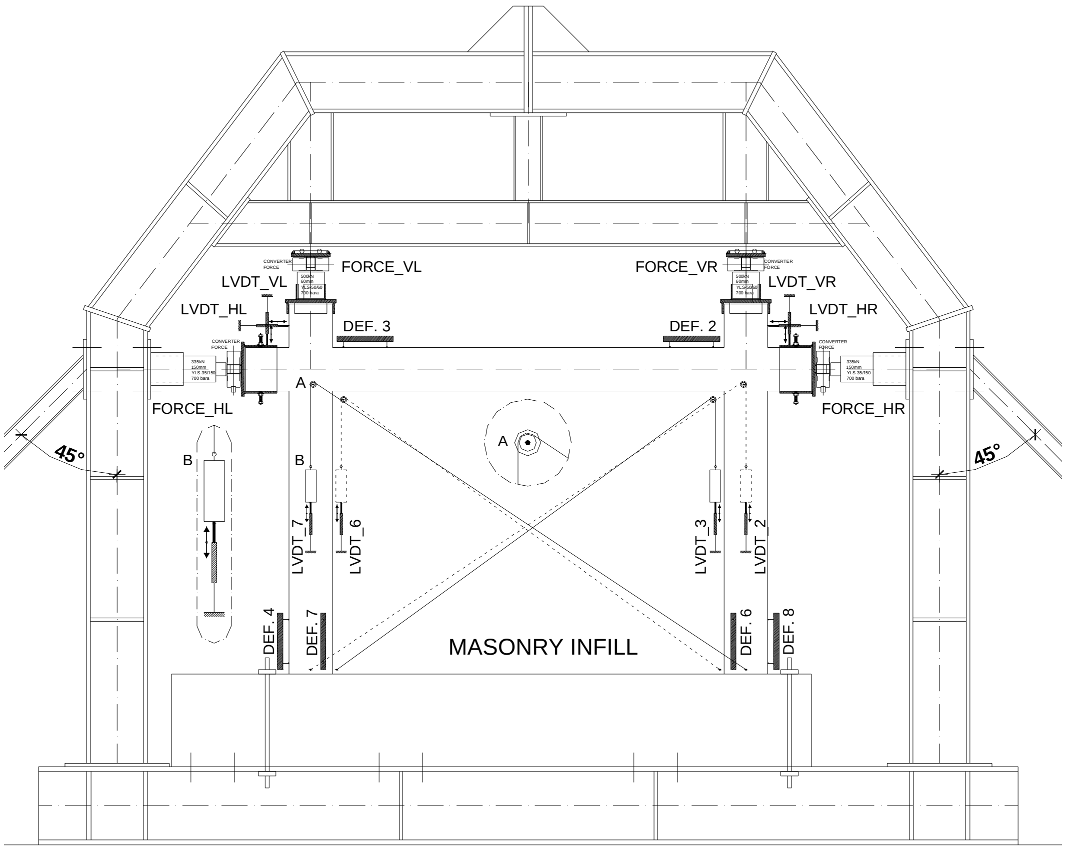

Figure 3 Reinforced concrete infilled frame test setup

The lateral load was applied cyclically to the beam ends by double-acting hydraulic jacks. The tests were performed initially as force controlled and later as displacement controlled (after the model lost its stiffness and the maximum lateral load was reached). It was increased steadily by increments of 10kN in the load controlled phase and in the displacement controlled phase it was only measured. The tests were stopped when damage in the infill was such to endanger the test safety. Time history of the

lateral loading is shown on the Figure 4. During testing following values were measured: applied loads at each loading point, vertical and horizontal displacements of the frame, foundation movement, elongations/shortening of diagonals (on the frame and on the infill) and deformations at frame critical points (expected plastic joints). Optically observed and registered were the first significant and later cracking in the masonry and all significant phenomena that occurred during testing (masonry crushing, crack developments in masonry and concrete, crack pattern).
All model specimens were tested in the same manner and the results were registered. In the latter part presented are the results for MODEL3 ("weak infill"), MODEL4 ("medium infill"), MODEL8 ("strong infill") and MODEL10 (bare frame).

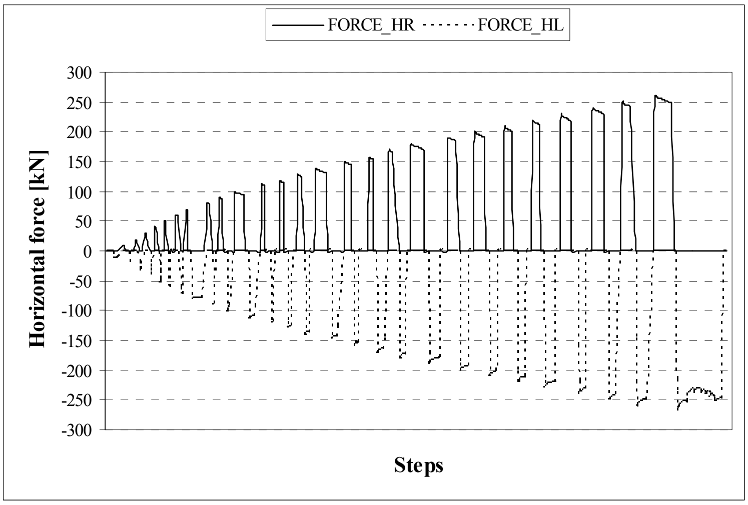

Figure 4 Time history of the horizontal (lateral) loading

5 TEST RESULTS

Presented are the results obtained on the models in a scale 1:2,5 and for the model dimensions. For each of three infill types cyclic experimental response curves were determined (hysteresis curves) from which the primary curves (resistance envelope) for cyclic lateral loading were obtained.
In order to be able to simulate the structural performance of "framed-masonry" in a nonlinear response history analysis it is necessary to accurately, as much as possible, estimate the stiffness, strength and deformation characteristics of the system. This inelastic response is idealized by a backbone curve (resistance envelope) that relates the base shear to top displacement of the system [11]. Performance evaluation, using the nonlinear response history analysis, requires a set of criteria defining an acceptable performance at two performance levels [6]: (1) Service level evaluation and (2) Maximum Considered Earthquake (MCE) level evaluation. This generally involves comparisons of force and deformation demands imposed by the specified earthquake hazard to the corresponding limit state capacities of the structural system. Here, the emphasis is given on the definition of the capacities for two structural limit states:
(1) The onset of structural damage requiring repair and
(2) The onset of significant degradation in structural components.

The onset of structural damage requiring repair is envisioned as one of the several possible metrics for assessing direct economic losses and disruption of the building functionality. Initiation of structural damage also corresponds to the point at which an elastic analysis is no longer adequate for assessing the performance. The onset of significant degradation is related to structural integrity and collapse assessment. While component criteria alone are not sufficient for assessing collapse, collapse can be interpreted through limit states ranging from local onset of degradation in individual components, to global instability in the overall structural system.
The experimental results presented in Table 5.1 show the values of horizontal forces at the onset of the

first crack in infill and the corresponding horizontal displacement and that for both loading direction of the model. The primary curves were obtained based on the average values of the horizontal displacements, while the shear deformations of particular model were constructed according to expressions (1).

Table 5.1 Horizontal forces at the onset of the first crack

R/C frame with	Crack No.	V_{cr} [kN]	δ_{cr} [mm]	Inter-story drift [%]
Brick block MO10 (MODEL8)	1	100	0,58 (-0,31)	0,04 (-0,02)
	2	110	-0,36 (0,56)	-0,02 (0,04)
Brick block MO5 (MODEL4)	1	70	-0,26 (0,25)	-0,02 (0,02)
	2	80	-0,29 (0,29)	-0,02 (0,02)
AAC blocks (MODEL3)	1	137	0,87 (-0,80)	0,06 (-0,05)
	2	149	-0,68 (0,74)	-0,05 (0,05)

5.1 The hysteresis curves

At low levels of lateral displacements, the "framed-masonry" composite acted as monolithic composite structural system (as one element). The masonry infill, due to its high stiffness, stiffened the flexible frame and also increased its initial strength. As the cracks developed in masonry and wall separated into two or more parts, the R/C frame deformed, depending on the type of separation and the length of the remaining contact zone between the masonry wall and frame members [12]. Once the masonry crack propagated, whether it was horizontal or inclined, masonry lost its strength and the column became the line of resistance.

The hysteretic curves are presented in Figure 5 illustrating the above described lateral load – displacement type of behaviour. The peak loads of the models depended on the masonry strength and they were the biggest for "strong" and smallest for the "weak" infill. Hysteresis energy dissipation was the best for the AAC infill in MODEL 3.

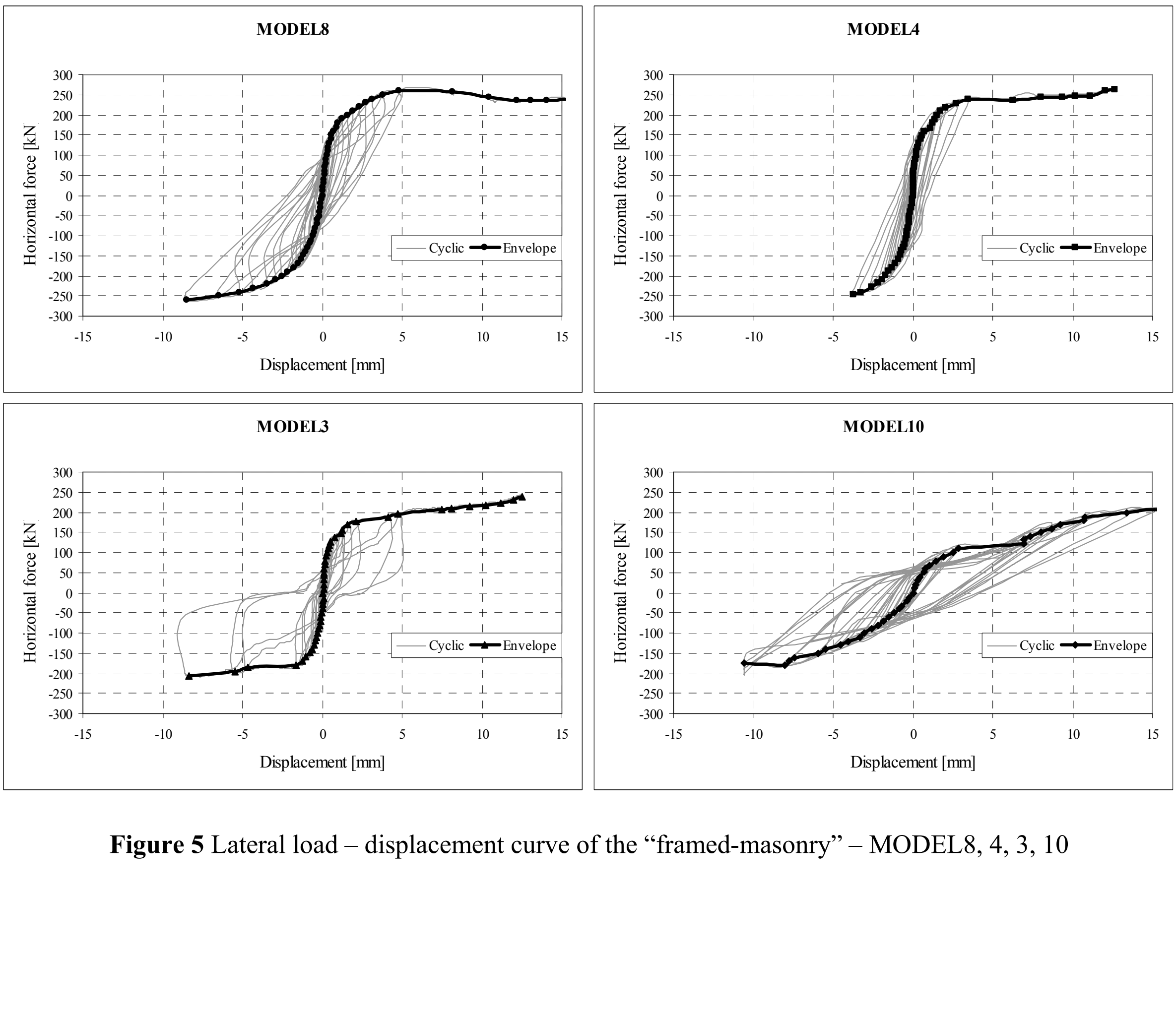

Figure 5 Lateral load – displacement curve of the "framed-masonry" – MODEL8, 4, 3, 10

5.2 Lateral strength

From the hysteresis curves envelopes we produced the model's primary curves that are presented in Figure 6. The Horizontal force - Inter story drift ratio (%) relationship for all presented models is shown. It is obvious that "framed-masonry" system has much bigger stiffness and somewhat higher strength than the bare frame MODEL10. Initial stiffness did not depend on the infill strength. Maximum lateral strength depended on the infill strength. Tracing the hysteresis loop envelopes (primary curves) one can observe an initial linear part indicating the behaviour of infilled frames as a composite "framed-wall" element. When the separation between the infill and the frame occurred and as damage gradually appeared at the infill and later at the frame elements, stiffness of the system decreased gradually until the force response reached its maximum value. A more or less constant, almost smooth branch followed, depending on the degradation process of the infill and joined the R/C frame hysteresis envelope. Ultimate strength and drift capacity of the model depended on the "unbraced" height of the column.

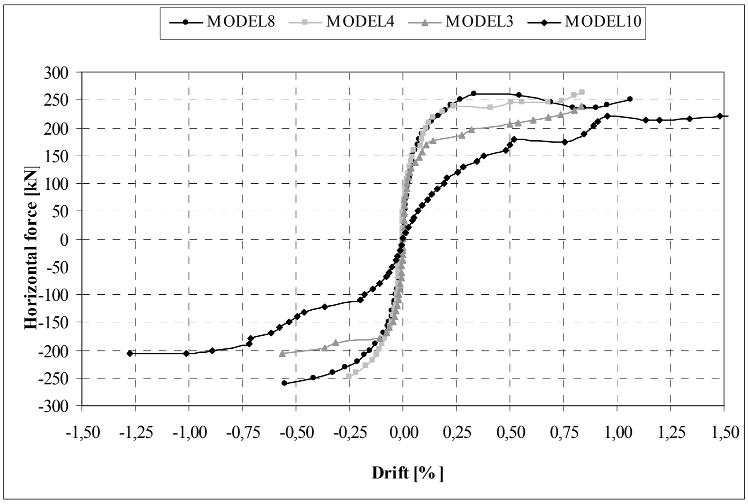

Figure 6 Test models' primary curves

It was observed that in all "framed-masonry" models, the first crack occurred at a storey drift of about 0,05%, they had maximum lateral resistance at storey drift of 0.5% and that they retained their carrying capacities up to 1,0% of storey drift (Figure 6). After that drift level, the positive contribution of the infill can be neglected and the negative one could overtake. Once the masonry lost its capacity due to extensive cracking, the column became the line of resistance.

Shear deformation of particular models, shown in Figure 8, was calculated as the average value of the R/C frame shear strain and shear strain of the infill [13]. Shear strains were obtained by measuring the diagonal extension or shortening according to Figure 7 and using the expressions (1):

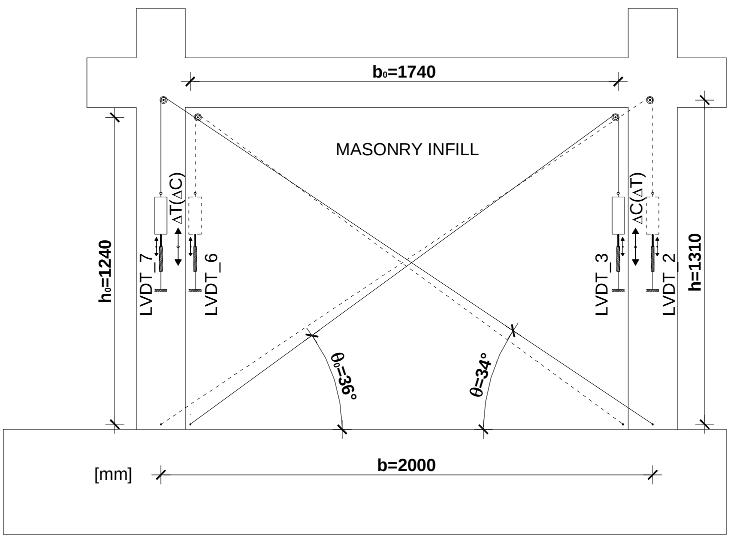

Figure 7 Shear strains measuring

$$\gamma = \frac{\gamma_I + \gamma_{II}}{2}; \quad \gamma_I = \frac{\Delta C + \Delta T}{2 \cdot h \cdot \cos\theta}; \quad \gamma_{II} = \frac{\Delta C + \Delta T}{2 \cdot h_0 \cdot \cos\theta_0} \tag{1}$$

where:

γ – shear strain; γ_I – test frame shear strain; γ_{II} – shear strain of the infill
ΔT – diagonal extension/shortening of the R/C frame (infill)
ΔC – diagonal shortening /extension of the R/C frame (infill)
h, h_0 – effective height of the R/C test frame and its infill
θ, θ_0 – slope of the frame (infill) diagonal and horizontal line of the test specimen.

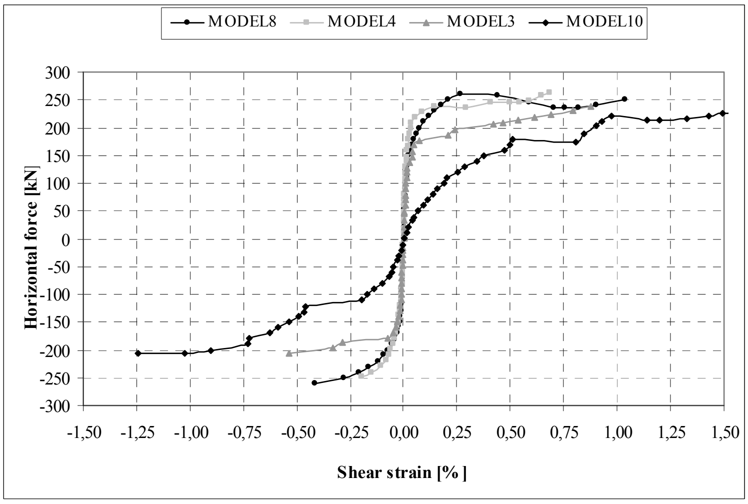

Figure 8 R/C test models' shear strain

It is obvious that in "framed-masonry" shear strength was predominant almost until the maximum load capacity. Shear-load carrying capacity of the masonry infill almost ended by IDR of 0,75%. After that drift level contribution of the infill to the overall load carrying capacity can be neglected.

5.3 Idealization of experimental results

In order to simplify the analysis and design measured primary curves could be represented by a bilinear idealisation (Figures 9 and 10). Bilinear idealisations were made based on the energy equivalence model. They are presented on the figures in parallel to the same idealisation applied to the bare frame model. Yielding point occurred at IDR/Horizontal force of 0,08%/205kN, 0,08%/259kN and 0,10%/269kN for "weak", "medium" and "strong" infill and for the bare frame at 0,57%/209kN.
It is obvious that masonry infill of any type improves the system behaviour at small displacement levels by increasing stiffness and strength at that stage.

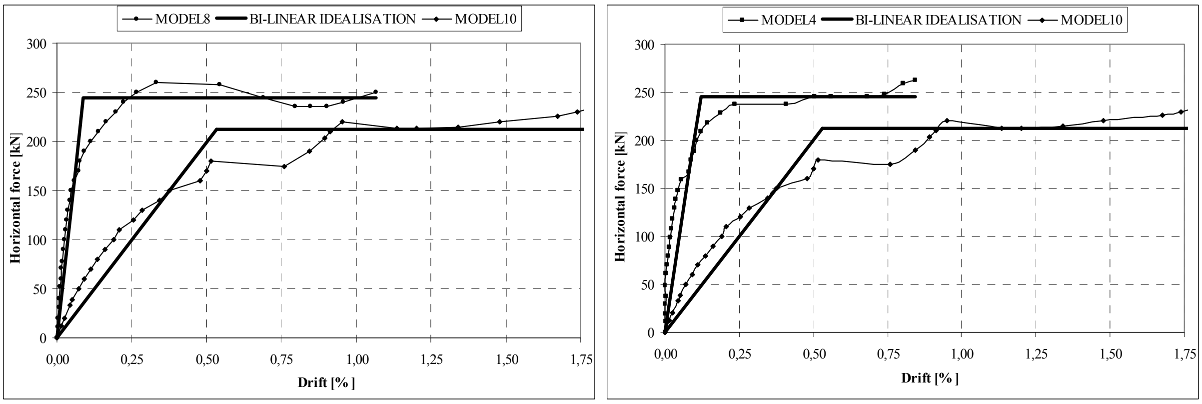

Figure 9 Idealisation of experimental hysteretic behaviour for MODEL8 and MODEL4

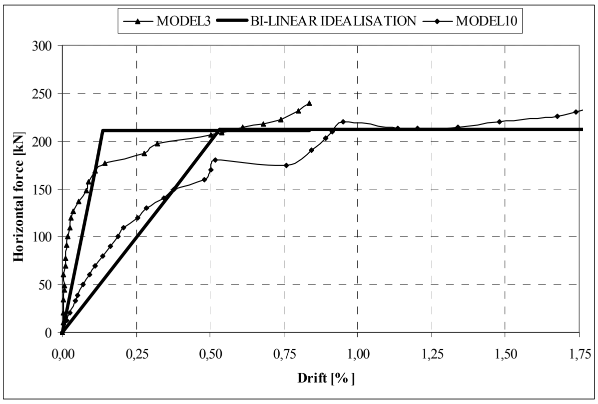

Figure 10 Idealisation of experimental hysteretic behaviour for MODEL3

The contribution of the infill stopped at IDR of 0,75 to 1% and the R/C frame took over the loading. Performance of the structure beyond the elastic range is usually expressed in terms of ductility ratio, μ. In this research, the displacement ductility ratio has been determined as the ratio between the displacement at which the lateral resistance of the test model started to decrease, indicating the intensive deterioration of the masonry infill wall and the idealised yield displacement. Based on the experimental results, the ductility ratio of the "framed-masonry" models is summarized in Table 5.2. Obtained ductility and behaviour factor were somewhat larger than the ones suggested in the norms. The structural behaviour factor, q, determined as indicated in table 5.2, shows an evident contribution of masonry infill walls and good performance of all test models under lateral loadings. Obtained values should be taken with care. The "framed-masonry" system actually lost all of its load-carrying capacity by the IDR of 1%. In multi-story construction, the most important attribute of the structure is its capability to retain its integrity at story drift ratios on the order of 1.5%-2%. Observed tests demonstrated that drift ratios of that magnitude could be achieved by a reinforced concrete frame with masonry infill and with columns that had the ability to sustain the required shear force under reversals of shear and axial forces. In the performed tests the R/C frames had minor damage that could be easily repaired.

Table 5.2 Summary of test models ductility ratios and corresponding behaviour factors

	V_1 [kN]	d_1 [mm]	V_2 [kN]	d_2 [mm]	$\mu=d_2/d_1$	$q=(2\mu-1)^{0,5}$
MODEL8	170	1,070	258	8,175	7,640	3,78
MODEL4	159	0,815	245	7,565	9,282	4,19
MODEL3	157	1,310	239	12,520	9,557	4,26

6 CONCLUSIONS

The object of this study was to investigate the behaviour of "strong" R/C frames infilled with masonry under constant vertical and cyclic lateral loads. Ten specimens of one storey, one bay brick infilled frames with three types of masonry ("weak", "medium" and "strong") infill were tested and their response was compared with that of a bare frame. It was observed that in all specimens the first crack occurred at the IDR 0,05%. Somewhat higher lateral load capacity was attained at IDR 0,08 to 0,10% depending on the infill strength. Load capacity of the bare frame was attained at IDR 0,60 when most of the infill had noticeable damage. Tested frames have easily undergone the IDR 1,5% without serious damage to the frame columns.

If the criteria for assessing direct economic losses and disruption of building functionality is the onset of structural damage of infill walls requiring repair (up to 0,5% drift), then a significant enhancement of stiffness, strength and energy dissipation of a frame is evident, providing the shift in overall damage control ranges from the Life Safety to the Operational Building Performance Level.

For “framed-masonry” the challenge for safe and economical design is to be able to take advantage of the stiffening but to make certain that the increase in lateral forces and reduction in drift capacity do not handicap performance. Available field and laboratory evidence pointed out that shear strength of the confining R/C columns was the "Achiless's Heel" of the “framed-masonry” system. Solution of the problem requires understanding the behaviour of masonry and concrete subjected to dynamic and random loading reversals, a challenge that demands full-scale testing under reasonably realistic conditions for confident analysis of the problem and its generalization

ACKNOWLEDGEMENTS

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