COMPARISON OF DIFFERENT STRENGTHENING TECHNIQUES OF DAMAGED AND WEAK REINFORCED–CONCRETE FRAMES

Marin GRUBIŠIĆ and Vladimir SIGMUND

ABSTRACT

As part of a broader research project, attention of this study has been focused on the existing, damaged “strong frame” RC buildings and “weak frame” RC buildings, strengthened with clay brick masonry infill walls (“framed–wall”). We experimentally investigated different masonry wall application techniques within the frame that upgrade the seismic capacity of these structures. Seven one–bay, one–storey RC frames were built in a scale 1:2.5 and 1:2, “strong” and “weak” frames respectively. They were tested under constant vertical and reversed cyclic lateral loading up to the drift of 1.5%. The experimental results are presented in the form of observed failure mechanism, hysteresis loops and cyclic envelope curves.

The tests showed that RC frames strengthened with masonry infill wall had the improved lateral load and deformation capacity as well as energy dissipation. The system behaved as composite “framed–masonry” structure which damage could be controlled. Cost–effectiveness and simplicity of the technique by the implementation of the masonry infill wall seems to be much more favourable than just the repair of the existing RC bare structure.

Keywords: RC frames, Masonry Infill, Seismic Strengthening, Framed–masonry, Cyclic Testing

INTRODUCTION

Field and experimental evidence showed that masonry infill walls reduced damage in the reinforced–concrete frame structures during earthquakes. Addition of the masonry infill within the reinforced–concrete frames (“framed–wall”), even if infill has no load–bearing function, could contribute to the seismic performance of building. This can be an economical solution of strengthening the weak and repairing the damaged reinforced–concrete frames. In order to test this hypothesis, a 1:2.5 and 1:2 scale one–storey one–bay damaged “strong” (during previous tests) and “weak” reinforced–concrete frames were strengthened with masonry infill made of solid clay brick units and mortar. Strengthening was applied in many different ways, and tested under constant vertical and cyclic lateral loading. Test results were compared with the results of the same, undamaged, bare frame and the frame with masonry infill. The aim of this investigation was to check various strengthening techniques that would enable existing/damaged frame buildings to meet various performance criteria under expected earthquakes.

1 Ph.D. Researcher, Faculty of Civil Engineering, Department for Technical Mechanics, Josip Juraj Strossmayer University of Osijek, Drinska 16a, 31000 Osijek, Croatia, marin.grubisic@gfos.hr
2 Full Professor, Faculty of Civil Engineering, Department for Technical Mechanics, Josip Juraj Strossmayer University of Osijek, Crkvena 21, 31000 Osijek, Croatia, sigmund@gfos.hr
The traditional and innovative strengthening techniques were considered. Traditional methods of strengthening the infill are cheaper and easier for application, while modern ones, like the one used in these tests (produced by the MAPEI) require more specialized skill.

**THE SPECIMENS**

As part of a broader research project, a total of 10 previously damaged frames were tested. They were infilled with masonry that had two types of masonry units – hollow and solid clay masonry units and the same general purpose mortar. Eight frames were classified as “strong” reinforced–concrete frames (designed according to the EC8) and two as “weak” reinforced–concrete frames (not seismically designed). Within this paper we considered only the tests conducted on the 5 specimens with solid clay (b x d x h=25 x 12 x 6.5 cm) masonry wall. All “strong” were damaged in the previous tests in which they were pushed to drifts higher than 1.5%. They were repaired by replacing the spalled concrete with fast setting concrete mortar. More details about the specimens are described in Zovkic, J. et. al (2012). Strong reinforced–concrete frame specimens were 2.2 m wide and 1.5 m high (scale of 1:2.5) with columns and beam cross section of 20x20 cm and 12x20 cm, respectively. Span to height ratio of the opening was h/l=0.72. Materials used for concrete were C30/37 and reinforcement B500B. Longitudinal reinforcement ratio of the columns was $\rho_{\text{column}}=2.4\%$ and the beams had $\rho_{\text{beam,mid}}=1.3\%$ in the mid–span and $\rho_{\text{beam,end}}=3.3\%$ at its ends.

The “weak” reinforced–concrete frames were non–seismically designed and had some typical deficiencies such as: strong–beams weak–columns behaviour, inadequate amount of transverse reinforcement in joints and potential hinge regions, etc. The specimens were 2.15 m (2.25 m) wide and 1.5 m high (scale of 1:2) with columns and beam cross section of 15x12.5 cm (25x12.5 cm) and
12.5x25 cm, respectively. Their beams were reinforced with the longitudinal reinforcement ratio $\rho_{\text{beam,mid}}=1.0\%$, $\rho_{\text{beam,end}}=1.9\%$, and the columns had the longitudinal reinforcement ratio of $\rho_{\text{column}}=1.1\%$ in #1 frame and $\rho_{\text{column}}=1.3\%$ in the frame #2.

Details of the specimens, cross-sections and reinforcement details are given in Figure 1. The masonry infill wall was added within the frame by different techniques (Figure 2), as follows:

a) Unreinforced masonry infill wall was connected to the surrounding r/c frame by dowels (Strong frame – Type 1),

b) Reinforced masonry infill wall was connected to the surrounding frame by dowels (Strong frame – Type 2),

c) Unreinforced masonry infill wall was strengthened with additional vertical confining element (tie–column) and connected to the surrounding frame by dowels (Strong frame – Type 3),

d) Unreinforced masonry infill wall was strengthened from both sides (including columns) with high–performance mortar reinforced with galvanized welded mesh which is connected to the surrounding r/c frame by dowels (Weak frame #1 – Type 4),

e) Unreinforced masonry infill wall was strengthened (including columns) with high–performance mortar reinforced with galvanized welded mesh which is connected to the surrounding r/c frame by dowels (Weak frame #2 – Type 5),

f) Reference specimens of undamaged bare and masonry infilled strong frames (Type 6 & 7).

All specimens had stiff foundation beam that was fixed to the reaction frame and the strong floor. The mechanical properties of the masonry walls, repairing and strengthening material are presented in Table 1.

The thicknesses of horizontal masonry joints were 1 cm and vertical joints were completely filled. Strengthening of specimens TYPE 4 and 5 was applied on both sides of the specimens, with a thickness of 1.5 cm, with galvanized mesh overlap of 15 cm, up to the beam. Mesh was attached to the masonry wall in every 30 cm in order to ensure necessary distance from the face of the wall for application of the high–performance mortar.
Table 1. Mechanical properties of the masonry, repairing and strengthening material

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<tr>
<td>Modulus of elasticity</td>
<td>5 533 MPa</td>
<td>Compressive strength (after 28 days) 35 MPa</td>
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<tr>
<td>Compressive strength</td>
<td>8.3 MPa</td>
<td>Flexural strength (after 28 days) 7 MPa</td>
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<tr>
<td>Tensile strength</td>
<td>0.16 MPa</td>
<td>Modulus of elasticity in compression (after 28 days) 24 000 MPa</td>
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<td>Poissons ratio</td>
<td>0.15</td>
<td>Bond strength to substrate (brickwork) 0.7 MPa</td>
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TEST SETUP AND PROCEDURE

All specimens were tested under constant vertical and cyclic horizontal loading up to the failure (>1.5% drift). Measured were all relevant data and obtained were failure modes, hysteretic loops and hysteretic cyclic envelopes. From them the system base shear capacity, stiffness and hysteretic damping were evaluated. The tests were performed at the University of Osijek, Faculty of Civil Engineering, Osijek, Croatia. In plane static reversed cyclic lateral loading was applied at the ends of the specimen’s beam along its central axis by hydraulic actuator. Vertical loading was applied at the columns’ top and it was kept constant by means of the hydraulic valves.

The time-history of the applied cyclic lateral and constant vertical loads (160 kN for “weak” frame #1, 280 kN for “weak” frame #2, and 365 kN for “strong” frames in each column), are shown in Figure 3. The tests were at the initial stage force controlled and after the first cracks occurred displacements controlled. Cyclic quasi–static lateral load was applied in increments of 10 kN and each loading cycle was repeated twice. In the displacements phase, the displacements were increased in the increments of 1.0 mm.

Figure 3. Time–history of the applied lateral cyclic load (kN) and vertical load oscillation history (%)

TEST RESULTS

The results of these tests were compared with the reference specimens (“strong” frame with infill and bare frame– Type 6 and 7). Hysteresis curves and cyclic envelopes are presented in the Figure 4. The results showed that addition of the masonry infill with proper detailing, increased the base shear capacity and ductility. Strengthened weak reinforced concrete frames behaved well during
the tests, and successfully avoided the columns and beam failure. The observed cracks on the specimens TYPE 4 and TYPE 5 are shown in Figure 5. Measured cumulative hysteretic energy and stiffness degradation are shown in Figure 6 and 7, while discrete cumulative hysteretic energy in terms of inter-storey drift (IDR) levels are shown in Figure 8.
Figure 4. Overview of the hysteresis curves of all tested specimens

Figure 5. Cracks on the specimens with surface strengthening, TYPE 4 (left) and TYPE 5 (right)

Figure 6. The hysteresis envelopes and stiffness degradation curves of all specimens
Presented are the results of six RC frames infilled with masonry infill for strengthening reasons. Four of the specimens were “strong” frames damaged in previous tests and two specimens were “weak” frames. The infill was made of solid clay brick units and general purpose mortar. It was connected to the frame elements by use of various traditional and modern methods. In some cases the planar strengthening technique was used. The specimens were tested under cyclic lateral and constant vertical loading. The test results were compared with the results of the reference frames tested under the same conditions.

Addition of the masonry infill – with some contribution of seismic strengthening – directly affected the strength, stiffness and displacements of the structure under cyclic excitation. Increase in the base shear capacity depended on the strengthening type. Strength of the repaired “strong” frames did not deteriorate even up to drifts of 1.5%. There was no significant contribution of the applied strengthening technique to the stiffness. The biggest contribution of the strengthening was that the failure of the “framed-masonry” system was delayed and that the columns did not fail.

The strengthened weak (“nonductile”) frames had fat hysteresis loops and pronounced strength deterioration after the drifts of 0.9%. In all specimens, the major cracks were formed in the area of

**CONCLUSIONS AND REMARKS**

Figure 7. The cumulative hysteretic energy for cyclic loading

![Cumulative Energy Diagram](image)

Figure 8. Discrete cumulative hysteretic energy at specific IDR levels

![ IDR Levels](image)
masonry infill, while the cracks on the frame members remained mostly within the limits of concrete cover.

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