Ενίσχυση Φορέων ΟΣ με Τοιχοπληρώσεις ΟΣ

Ελπίδα Γεωργίου¹, Νικόλας Κυριακίδης², Κρίστης Ζ. Χρυσοστόμου³

ΠΕΡΙΛΗΨΗ

Η αποτελεσματικότητα της σεισμικής ενίσχυσης φορέων ΟΣ με τη μετατροπή επιλεγμένων ανοιγμάτων σε νέα τοιχώματα μέσω τοιχοπληρώσεων ΟΣ, μελετήθηκε πειραματικά με τη χρήση ενός δοκιμίου πλήρους κλίμακας τεσσάρων ορόφων χρησιμοποιώντας τη ψευδοδυναμική μέθοδο (PsD). Τα πλαίσια σχεδιάστηκαν και οπλίσθηκαν για κατακόρυφα φορτία μόνο. Χρησιμοποιήθηκαν διαφορετικές λεπτομέρειες σύνδεσης μεταξύ των τοιχοπληρώσεων και του πλαισίου. Προκειμένου να προσομοιωθεί η πειραματική απόκριση του δοκιμίου, αναπτύχθηκε ένα μοντέλο πεπερασμένων στοιχείων (ΠΣ), το οποίο βαθμονομήθηκε χρησιμοποιώντας τα πειραματικά αποτελέσματα. Για να συμπληρωθούν τα πειραματικά αποτελέσματα και να μελετηθεί η αλληλεπίδραση μεταξύ των τοιχοπληρώσεων ΟΣ και του περιβάλλοντος πλαισίου τόσο σε συνολικό όσο και σε τοπικό επίπεδο, χρησιμοποιήθηκε το βαθμονομημένο μοντέλο για την εκτέλεση αριθμητικών πειραμάτων προσομοίωσης μειώνοντας τον αριθμό των βλήτρων εξαφανίζοντας από απόσταση 100 mm (μονολιθική απόκριση του δοκιμίου) μέχρι μηδενικό αριθμό βλήτρων. Πραγματοποιήθηκε μη γραμμική ανάλυση χρονοϊστορίας για κάθε περίπτωση. Σε αυτή την εργασία περιγράφονται και παρουσιάζονται τα πειραματικά αποτελέσματα καθώς επίσης και το μοντέλο ΠΣ του δοκιμίου μαζί με τα αποτελέσματα της παραμετρικής μελέτης και εξάγονται συμπεράσματα.

¹ Υποψήφια Διδάκτορας, Τεχνολογικό Πανεπιστήμιο Κύπρου, es.georgiou@edu.cut.ac.cy
² Λέκτορας, Τεχνολογικό Πανεπιστήμιο Κύπρου, nicholas.kyriakides@cut.ac.cy
³ Καθηγητής, Τεχνολογικό Πανεπιστήμιο Κύπρου, c.chrysostomou@cut.ac.cy
Retrofitting of RC frames with RC infill walls

Elpida Georgiou¹, Nicholas Kyriakides², Christis Z. Chrysostomou³

ABSTRACT

The effectiveness of seismic retrofitting of RC-frame buildings by converting selected bays into new walls through infilling with RC walls was studied experimentally using a full-scale four-storey model tested with the pseudo-dynamic (PsD) method. The frames were designed and detailed for gravity loads only. Different connection details between the infill walls and the bounding frame were used. In order to simulate the experimental response of the specimen, a finite element (FE) model was developed, which was calibrated using the experimental results. To complement the experimental results and to study the interaction between RC infills and the bounding frame both in the global and local level, the calibrated model was used to perform numerical simulation experiments by reducing the number of dowels starting from a spacing of 100 mm (monolithic response of the test specimen) to no dowels. Nonlinear response-history analysis was performed for each case. In this paper, the experimental results as well as the FE model of the test specimen are described and presented along with the results of the parametric study and conclusions are drawn.

1 INTRODUCTION

The seismic retrofitting of reinforced concrete (RC) buildings by the conversion of selected bays into new RC infill walls, especially on the perimeter, is a popular, simple and cost-effective strengthening method [1,2]. According to [3] this is the most effective and economic method for retrofitting multi-storey RC buildings, especially those with pilotis (soft-storey). The use of RC infill walls with the same thickness as the frame members that bound the new wall for retrofitting RC buildings is relatively a new retrofit method. This method can be applied to increase the strength, stiffness and ductility of the building.

However, the RC infills as a retrofitting method is commonly applied to guarantee monolithic behavior between the old and new members to design the new RC walls according to Eurocode 8 – Part 3 (EC8-3) [4]. The monolithic behavior is achieved by the construction of new thicker web than the beams and the columns of the existing frame panel with the location of the new reinforcement outside the existing members and the details of reinforcement as in a new wall [1]. In this way, the new infill walls are much stronger that what is needed for the strengthening

¹ PhD Candidate, Cyprus University of Technology, es.georgiou@edu.cut.ac.cy
² Lecturer, Cyprus University of Technology, nicholas.kyriakides@cut.ac.cy
³ Professor, Cyprus University of Technology, c.chrysostomou@cut.ac.cy
of the structure, and this ‘over-strength’ causes additional issues like the weak ending of the foundations of the existing buildings [1]. Even though the RC infills is a common retrofitting method and it is extensively applied, it is not addressed quantitatively by the codes, not even by EC8-3 [4]. There are still open issues about the studied retrofit method. For example, their interaction with the bounding frame, their design and detailing between the new web and the surrounding frame members need to be regulated [1,4]. The inadequacy of design codes in this respect is due to our poor knowledge of the behavior of walls created by infilling of a bay of an existing frame with RC.

Regarding the experimental research work that has been performed in the last decades most of the experiments cover sufficiently the other frequently used typed of retrofitting, but there is no adequate experimental research work on the use of RC infill walls and most of research has mainly targeted large specimens with high resistance [5]. In order to start filling the gap of knowledge regarding infilling of existing RC frames with RC walls, the effectiveness of seismic retrofitting of multi-storey multi-bay RC frame buildings by concerting selected bays into new walls through infilling with RC was studied experimentally through a full-scale PsD test within the project named SERFIN at the European Laboratory of Structural Assessment (ELSA) facility at Joint Research Center (JRC), in Ispra. The research was under the project “Seismic Engineering Research Infrastructures for European Synergies” (SERIES). Further details can be found in [6–8]. The results from the full-scale experiment that took place within the project SERFIN were studied and data from this test was used for the simulation of RC walls in FE software to study the behavior of the RC infills within RC frames.

In this paper, the experimental results of the frame that was tested in Ispra are briefly described. The FE model that simulates and validates the experimental results as well as the comparison of the numerical results to the experimental results are described and presented along with the results of the parametric study by varying the number of dowels that connect the existing frame with the new wall and conclusions are drawn.

2 SERFIN EXPERIMENT

The subject of the project SERFIN was the retrofitting of multi-storey multi-bay RC frame building by the conversion of selected bays into new infilled RC walls. The purpose of the SERFIN experiment was to study the efficiency of the retrofitting method, and to examine the amount of the web reinforcement in the walls and the connection details between the wall and the bounding frame. Two parallel planar frames were infilled with RC infills and then they were unidirectional pseudo-dynamically tested. In this section, the specimen geometry and design will be briefly described, and the experiment test and results will be presented. The full description and discussion of the experimental campaign, the specimen geometry and design and of the experimental results of SERFIN experiment can be found in [3,6–10].

2.1 Specimen geometry and design
The specimen was a full-scale prototype building structure that was designed to represent the two exterior three-bay frames of the prototype structure. The center-line length dimension of the specimen was 8.5m, the storey height 3m, and the total height of the specimen (excluding the foundation) 12m. The RC infill walls in the two frames were in the central bays of the specimen and they had the same thickness of 0.25m equal to the beams and columns framing them. These frames were named North and South as it is defined in Figure 1. Hence, the direction towards the reaction wall of the experiment is East and the one opposite direction is West. The results of the South frame of the experiment were simulated and calibrated in the FE software and will be presented as the results of the validated model.

The proposed structure represents a typical construction of the late ‘70s and beginning of the ‘80s in Cyprus. At that time, there were no provisions for earthquake loading, so the structures were designed for gravity loads only. For the mock-up design, it was decided to use the provisions of BS8110. It was decided to use concrete C20/25 for both the frame and the walls, of unit weight 25kN/m³ and modulus of elasticity, E=30GPa.

In order to facilitate the study of the effect of as many parameters as possible, the two frames of the specimen were reinforced with different amount and arrangement of reinforcement, with the North wall being the strongest of the two. These details and the full description of the specimen design, are described in [3,7–10].

2.2 Experiment test and results

As it was mentioned before, the specimen was PsD tested and within the testing campaign two PsD tests and one cyclic test were run. The accelerogram was scaled to a maximum acceleration of 0.1g for the first test and 0.25g for the second test. For the final cyclic test, a history of displacements was imposed on the fourth floor.

The maximum top storey displacement was 109mm and the displacement in the opposite direction was -93mm (Figure 2(a)). From the graph of the shear versus the top storey...
displacement of the 0.25g test in Figure 2(b) it is shown that the hysteresis loops are stable and provide some energy dissipation. Some difference was observed in the base shear between the two frames. The maximum base shear in the East direction (towards the reaction wall) were about the same for the two frames, while a negative base shear of -843kN was recorder for the South frame and -1011kN for the North one in the West direction (away from the reaction wall). This was an indication that the South frame has suffered some damage and it could not take further load.

The general behavior of the specimen during the two PsD tests showed that its performance was in accordance with the damage expected from the retrofit design corresponding to a life-safety limit-state for the 0.25g earthquake (475 years return period). In general, the stronger North frame had an overall better behavior compared to the South frame; nevertheless, the differences between the two frames were minor.

3 FINITE ELEMENT MODELING AND CALIBRATION

The results and data from the SERFIN experiment were used to calibrate a numerical model. The model of the South frame of the SERFIN specimen was simulated in DIANA FEA with the same geometry as the prototype specimen, with a 2D continuum FE model. A rigid foundation was assumed for the simulation, with pin supports at the base of the frame. The additional weight of the half of the specimen slab and transverse beams was added to the 16 joints of the model through mass point elements. Rayleigh damping coefficients were used with a damping ratio of 0.25%.

Two distinct models were developed in DIANA FEA and will be presented in this paper. In the first model (Figure 3 (a, b, c)), the infills were monolithic with the bounding frame and all the reinforcing bars were modeled to carry axial loads only. In the second model (Figure 3 (d, e, f)), the interaction between the existing bounding frame and the new RC wall was modeled through interface elements, to allow for the separation of the bounding framing members and the RC wall at their interface when they are in tension. In this case, the dowels were modeled to take both axial and shear forces, as it is the case in the real structure.

The dead and live loads were applied on the beams as edge pressure load with the same values as the prototype model and the earthquake signal with 0.25g peak acceleration was added as
body force for base excitation with the earthquake time history function. Then, the nonlinear transient analysis was executed in the FE software. The secant Newton method (quasi-newton), which is an implicit algorithm iterative method is applied, together with the line search method. The convergence tolerance was applied for force and displacements. The full description of the FE model simulation is given in [11].

3.1 Elements and mesh

For the 2D concrete frame simulation, the regular plane stress quadrilateral elements (CQ16M, quadrilateral, 8 nodes) were used. For the first model, where the infills were monolithic with the bounding frame, all the reinforcements and dowels were modeled as steel reinforcement bars and were meshed as embedded bar reinforcements inside the plane stress elements, which can carry only axial loads (Figure 3 (a, b, c)). In this way, perfect bonding was assumed between the concrete and steel bars, as well as between the existing structure and the RC infilling. In the second model, for the reinforcement elements of the frame and the web reinforcement of the infill, the same 1D embedded bar reinforcements inside the plane stress elements as the ones for the first model were used. For the dowels, to capture the shear and axial stress that they take in the model, the bond-slip reinforcement with beam elements (BAR LINE, INTERF BEAM) of DIANA FEA were selected to model their behavior.

For the interface between the frame and the walls the 2D line interface elements (CL12I) were used, having the same thickness of as that of the thickness of the plane stress elements representing the wall. The second finite element model is shown in Figure 3 (d, e, f). The mass of the half weight (312 Tons) of the prototype building was added in the model by using the point mass elements (PT3T) on the 16 joints of the frame.

3.2 Constitutive laws

The material models describe the hysteretic behavior under cyclic loading. More specifically, the models simulate the stiffness and strength degradation and the material softening behavior, which causes localization and redistribution of strains in the structure.

For concrete, the material model that was used was the Total strain-based crack model, with rotating orientation of the cracks. The behavior of the concrete in compressions was modeled with the Maekawa cracked concrete curves. The compressions strength of concrete was 33MPa. The Young’s modulus of concrete was calibrated in the model to get the behavior of the building in the experiment that was already cracked. Hence, the Young’s modulus was reduced from 30GPa to 15GPa. For the tensile behavior of concrete, the fib Model Code 2010 for Concrete Structures was used with a tensile strength of 2.6MPa.

Regarding the reinforcement, the Menegotto-Pinto model was chosen for the reinforcement bar elements of the existing frame and for the dowels and web reinforcements for the monolithic model. For the second model, where the dowels were modeled to capture the shear as well as the tensile stresses, the Menegotto-Pinto model was replaced with the von Mises plasticity
model. In both cases, the yield stress of existing frame reinforcement was 400MPa and the yield stress of the infill wall web reinforcement and dowels was 450MPa.

For the interface behavior between the new infill wall and the bounding frame members of the second model, the Coulomb friction material model was used to represent the cohesion and the friction between the interfaces, and at the same time to facilitate the opening of a gap when tensile stresses exist between two interfaces. To achieve this, the brittle gapping model was applied, with small tensile strength, to let the dowels carry the tensile and shear stresses at the interface. The linear material properties of the Coulomb friction model were calibrated through trials to achieve the outcomes that were the closest to the results of the experiment.

![Figure 3](image)

(a) RC frame monolithic with infills with plane stress elements, (b) Embedded reinforcement bars which can take only axial loads, (c) Complete first model, (d) RC frame with 2D line interface elements at the interfaces and plane stress elements, (e) Embedded reinforcement bars for the existing frame and web reinforcements and dowel special elements which can take shear and axial forces, (f) Complete second model

### 3.3 FE model results

The global results of the experiment of the South wall are compared to the monolithic (first model) and non-monolithic (second model) outcomes of DIANA FEA for both models in Figures 4 and 5, respectively. In those figures, the fourth-floor displacements and the base shear vs. the top storey displacement are shown. From these results, it is obvious that the FE model captures the real structure very well. The peak values are captured in both forces and displacements and the stiffness degradation is captured as well. Moreover, it is clearly shown that the model captures the period of the actual structure. Comparing the two FE models, it can be observed that in the second more complex FE model, the peak displacement of the frame is not captured as closely as in the monolithic frame. Nevertheless, the second model is very close to the experimental results as well.
Figure 4: First model global results: (a) Fourth floor displacements versus time, (b) Base shear force versus top storey displacement.

Figure 5: Second model global results: (a) Fourth floor displacements versus time, (b) Base shear force versus top storey displacement.

4 PARAMETRIC STUDY

The experimental results of the SERFIN project were complemented through numerical experiments to study the interaction between RC infills and bounding frame both in the local and global level. A parametric study that covers a range between the monolithic behavior (validated model) and that of an infilled frame without dowels, by varying the number of dowels connecting the wall to the bounding frame was performed and is presented in this section. The calibrated model (2nd model in the previous section), had the same number of dowels like in the SERFIN experiment. Another six different cases of the number of dowels in the model were performed as it is shown in Table 1. The same analysis procedure and a 0.25g earthquake record were used for all the parametric-study scenarios.

<table>
<thead>
<tr>
<th>Dowels connecting the bounding frame to the wall</th>
<th>Case 1: Validated model</th>
<th>Case 2: 10 Dowels</th>
<th>Case 3: 6 Dowels</th>
<th>Case 4: 4 Dowels</th>
<th>Case 5: 2 Dowels</th>
<th>Case 6: 2 Dowels only on beams</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground floor columns</td>
<td>24Y20/100</td>
<td>10Y20/250</td>
<td>6Y20/460</td>
<td>4Y20/760</td>
<td>2Y20/2300</td>
<td>-</td>
</tr>
<tr>
<td>Ground floor beams</td>
<td>20Y20/100</td>
<td>10Y20/210</td>
<td>6Y20/380</td>
<td>4Y20/630</td>
<td>2Y20/1900</td>
<td>2Y20/1900</td>
</tr>
<tr>
<td>First floor columns</td>
<td>24Y18/100</td>
<td>10Y18/250</td>
<td>6Y18/460</td>
<td>4Y18/760</td>
<td>2Y18/2300</td>
<td>-</td>
</tr>
<tr>
<td>First floor beams</td>
<td>20Y18Y100</td>
<td>10Y18/210</td>
<td>6Y18/380</td>
<td>4Y18/630</td>
<td>2Y18/1900</td>
<td>2Y18/1900</td>
</tr>
<tr>
<td>Second floor columns</td>
<td>24Y16/100</td>
<td>10Y16/250</td>
<td>6Y16/460</td>
<td>4Y16/760</td>
<td>2Y16/2300</td>
<td>-</td>
</tr>
<tr>
<td>Second floor beams</td>
<td>20Y16/100</td>
<td>10Y16/210</td>
<td>6Y16/380</td>
<td>4Y16/630</td>
<td>2Y16/1900</td>
<td>2Y16/1900</td>
</tr>
<tr>
<td>Third floor columns</td>
<td>2Y16</td>
<td>2Y16</td>
<td>2Y16</td>
<td>2Y16</td>
<td>2Y16</td>
<td>-</td>
</tr>
<tr>
<td>Third floor beams</td>
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<td>2Y16</td>
<td>2Y16</td>
<td>2Y16</td>
<td>2Y16</td>
<td>2Y16</td>
</tr>
</tbody>
</table>

4.1 Numerical results

4.1.1 Global results
The top storey displacements of the frames that were obtained from the numerical analysis are illustrated and discussed in this section for all the case scenarios in Figure 6. Furthermore, the base shear forces of the frame versus the top storey displacements are presented in Figure 7.

From Figure 6 it is shown that the top storey displacements in the positive direction are about the same for all the case scenarios except the sixth one where the top storey displacement is decreased by 24.23% relative to the fifth case scenario. In the negative direction, the top storey displacement of the second case scenario is decreased by 31.27% relative to the first case scenario. For the sixth case scenario, in the negative direction the displacement is at the same level with the fifth case scenario. Another observation that is shown in Figure 6, is that the elastic characteristics of the frame have changed with the reduction of the number of dowels after the 6th second of the response history for all the cases after the third case scenario. This is an indication that the stiffness and the fundamental frequency of the frame are reduced with the reduction of the dowels.

![Figure 6: Top storey displacements for all cases.](image)

![Figure 7: Base shear forces versus top storey displacements for all cases.](image)
From Figure 7, it can be observed that for the first four case scenarios the total base shear force is about the same for all cases. A significant reduction of the maximum base shear force is observed when the dowels are reduced to two. Similar conclusions are drawn for the stiffness and energy absorption.

4.1.2 Dowels at the base

The axial load in all the dowels along the length of the wall at the base interface when the total base shear-force of the frame is maximum in both directions is shown in Figure 8 for the first four case scenarios. As shown in the figures the maximum values occur at different instances during the analysis for each case.

![Axial forces of dowels along the length of the wall when the total base shear is maximum in West and East direction.](image)

It is shown that the dowels of the validated model in the first case scenario take the lowest forces in comparison with the other case scenarios, since the infill wall behaves monolithically with the bounding frame. Some of the dowels in the second and third case scenarios reach their yield stress (cyan dotted line) while most of the them reach their capacity in the fourth case scenario.

5 CONCLUSIONS

This study has shown that RC infills can be used to upgrade successfully structures that have been designed for gravity loads only. The numerical simulation of the experimental results of the SERFIN model have shown that the amount of reinforcement used in the experiment resulted in the monolithic behavior of the infill wall with the bounding frame. The parametric study, which was performed so as to complement the experimental results and investigate the effect of the reduction of the number of dowels starting from the number used in the experiment and going down to only two dowels, has provided some interesting results leading to some general conclusions.

From the results of the parametric study, there were several indications that the building had a nonlinear behavior and that the fundamental characteristic of the frame changed with the
reduction of the number of dowels after the third case scenario (dowels spacing of 380mm). More specifically, it was observed that the stiffness and the fundamental frequency of the frame are reduced with the reduction of dowels. Generally, it can be concluded that the lower the number of dowels, the lower the base shear-force, the stiffness and the energy dissipation of the building. However, it is shown that these characteristics of the building are not varying considerably for the first four case scenarios (dowels spacing of 100mm to 630mm).

Regarding the local results of the dowels along the interface of the wall at the foundation, it is observed that the dowels of the first case scenario had the lowest forces in comparison with the other case scenarios, whereas some of the dowels of the rest of the case scenarios reached their yield values. Moreover, with the reduction of the number of dowels the position of the neutral axis is moving, as expected, towards the edges of the wall in both directions, which indicates that a larger number of dowels have yielded.

These results complement the experimental results and show that the number of dowels used in the experimental study can be reduced significantly, making the use of this method more cost effective. Further numerical parametric studies will be performed to obtain a better understanding of this structural system that will allow the development of design guidelines.

6 REFERENCES