Available online at www.eccomasproceedia.org
Eccomas Proceedia COMPDYN (2019) 3100-3113

ECCOMAS
Proceedia

COMPDYN 2019
7th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Crete, Greece, 24–26 June 2019

NONLINEAR NUMERICAL PARAMETRIC STUDY OF DOWELS FOR THE SEISMIC STRENGTHENING OF RC FRAMES WITH RC INFILL WALLS

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Abstract

The parametric study of the contribution of dowels that connect a new reinforced concrete (RC) infill wall to the surrounding RC frame members was performed through nonlinear dynamic analyses of a numerical finite element (FE) model. The FE model was simulated in DIANA finite element analysis (FEA) software in order to study the effectiveness of the seismic retrofitting of existing structures with the conversion of selected bays into new infilled RC walls for the retrofitting of a multi-storey multi-bay RC frame building. A 2D frame was modelled and nonlinear transient analyses were performed in order to simulate the experimental results obtained from a full-scale experiment. The calibration of the FE model that simulated the experimental nonlinear cyclic behavior of the tested RC building is provided in [1]*. Based on the calibration results it was concluded that the number of dowels used in the experiment resulted in a monolithic behavior of the RC infilled frame. In order to complement the experimental results and to study the interaction between RC infills and the bounding frame both in the global and local level, numerical simulation experiments were performed by reducing the number of dowels starting from a spacing of 100mm (monolithic) to a spacing of 380mm. Time-history was performed for each case and the results show that the maximum spacing of 380mm is sufficient to provide the required stiffness and ductility. In this paper, the FE model of the test specimen is described and presented along with a parametric study of the number of dowels connecting the wall to the bounding frame. These results contribute to the development of a general model for the application and the design of RC infills in existing RC frames.*

Keywords: Finite Element Model, Dynamic Analysis, Dowels, Parametric Study, Seismic Strengthening.

ISSN:2623-3347 © 2019 The Authors. Published by Eccomas Proceedia.
Peer-review under responsibility of the organizing committee of COMPDYN 2019.
doi: 10.7712/120119.7135.19654

1 INTRODUCTION

The addition of RC infilled walls in selected bays within existing RC frames, especially on the perimeter, is a popular method for seismic retrofitting and a simple and cost-effective method [2, 3]. According to [4] this is the most effective and economic method for retrofitting multi-storey RC buildings, especially those with pilotis (soft-storey). With the full infill of selected bays of an existing RC frame, the effectiveness of the retrofitting is increased, and the construction cost is reduced. The use of RC infill walls with the same thickness as the frame members that bound the wall for retrofitting RC buildings with openings is a relatively new retrofit method, which can be used to increase the strength, stiffness and ductility of the building. However, the RC infills as retrofitting method is commonly applied to guarantee monolithic behavior between the old and new members in order to design the new RC walls according to Eurocode 8 – Part 3 (EC8-3) [5]. This 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 reinforced outside the existing members and the details of reinforcement as in a new wall [2]. In this way, the new infill walls are much stronger than what is needed for the strengthening of the structure, and this ‘over-strength’ causes additional issues like the weakening of the foundations of the existing buildings [2]. Hence, a significant rotation is expected at the foundation [6].

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 [5]. On the other hand, [6] refers to the introduction of RC infills within a frame, only in terms of forces, providing tools for calculating their deformations (at yield and failure) and stiffness only if they are integral with the bounding frame. Although for other strengthening methods of existing structures there are guidelines regarding the retrofit design and certain aspects of the seismic response of the retrofitted structure, there are still open issues about the studies 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 [2, 5]. 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. It is apparent that the codes or standards for seismic retrofitting do not provide proper guidance for the design and detailing of the attachment of new walls to existing frames. Furthermore, regulations do not exist for modeling or evaluation of frame bays converted into RC walls depending on the type and details of the connection.

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, in particular the use of fibre-reinforced polymers (FRP) and the concrete jackets despite the common field practice of new walls which encapsulate the frame members [7]. There is no adequate experimental research work on the use of RC infill walls and most research has mainly targeted large specimens with high resistance [7]. The tests have been limited to small-scale specimens with new webs thinner than the surrounding beams or columns (possibly owing to the technical limitations of testing walls of very large shear-force resistance) [2, 8]. Another drawback of past investigations is that they did not propose or even follow a quantitative procedure for the design of the connection between the RC infilling and the surrounding frame members. Furthermore, they have not led to, or supported, any procedure or the quantification of the engineering properties of the RC infilled frame which is essential for its analysis and design in the context of modern performance based seismic design, that is the effective stiffness, the moment and shear resistances, the deformation at yielding and the cyclic deformation capacity [9]. Subsequently, data is lacking for taller full-scale specimens that reflect real applications [7].

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 converting selected bays into new walls through infilling with RC was studied experimentally through a full-scale pseudo dynamic (PsD) test within the project named SERFIN at the ELSA Laboratory of Structural Assessment (ELSA) facility at JRC, in Ispra. The research was under the project “Seismic Engineering Research Infrastructures for European Synergies” (SERIES). Further details can be found in [8, 10, 11]. This prototype model reflects correctly the real situation and its results and data are very useful. 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 in order to study the behavior of the RC infills within RC frames.

In this paper the numerical simulation of the frame that was tested in Ispra is briefly described. A full description of the numerical model that simulates and validates the experimental results as well as the comparison of the numerical results to the experimental results can be found in [1]. This validated FE model was used to perform numerical experiments and various parametric studies were developed including the investigation of shear connectors (dowels) contribution. The aim of the FE simulation was a numerical parametric study by varying the number of dowels that connect the existing frame with the new infill wall and the web reinforcement of the wall. A parametric study that covers a range between the monolithic behavior and infilled frame, by varying the number of dowels connecting the wall to the bounding frame was performed and results of this study are presented and described in the following sections.

2 EXPERIMENTAL CASE STUDY

The subject of the project SERFIN was the retrofitting of a multi-storey multi-bay RC frame building by the conversion of selected bays into new infilled RC walls. Two parallel planar frames were infilled with RC infills and then they were unidirectional pseudo-dynamically tested. The aim 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.

The SERFIN specimen was a full-scale four storey prototype building structure that was designed to represent the two exterior three-bay frames of the prototype structure. A detailed description of the specimen geometry is given in [10, 11]. 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 width of the beams and the 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 in the opposite direction is West (Figure 1). For this paper, the results of the South frame of the experiment that was simulated and calibrated in DIANA FEA will be presented as the results of the validated model.

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. More specifically, an elaborate and varying system of dowels and starter bars was used to join the walls with the frame. The differences are about the diameter and the length of reinforcement mainly in the ground and first floor. In the fourth floor the reinforcement was the same.

Moreover, it is important to mention that the tested model was designed using two different connection details between the new walls and the surrounding frame in order to evaluate the contribution of dowels that connect the new infill wall to the existing RC frame. These details are described in [10–12]. In all cases, the dowels were positioned along the centerline of the elements (i.e. at 0.125m from the face of the wall) and in the first connection scheme they acted as dowels since lap-splice bars were also provided to the wall reinforcement, while in the second scheme they acted both as lap-spices and dowels.

As it was mentioned before, the specimen was pseudo-dynamically (PsD) tested and within the testing campaign two PsD tests and one cyclic test were run. The second 0.25g acceleration test results were used for the calibration of the FE model. More details and results about the calibrated model and verified results of the FE model can be found in [1].

Figure 1: Elevation of the specimen in the lab. The wall shown on the left is the South wall and the one on the right is the North wall.

The full description of the specimen design, the experimental campaign and the experimental results of SERFIN experiment can be found in [10, 11, 13].

3 NUMERICAL SIMULATIONS – PARAMETRIC STUDIES

The experimental results of SERFIN project were complemented through numerical experiments in order 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 and that of a non-integral infilled frame, by varying the number of dowels connecting the wall to the bounding frame was performed and is presented here. The second connection scheme was used as described above.

The validated model that was previously calibrated in DIANA FEA [1], had the same number of dowels like the SERFIN experiment (24 dowels connecting the wall to the columns and 20 dowels connecting the wall to the beams). It was decided to perform another six different cases of the number of dowels in the model. These parametric-study scenarios are shown in Table 1.

Dowels connecting the bounding frame to the wall	**Case 1 Validated model**	**Case 2 10 Dowels**	**Case 3 6 Dowels**	**Case 4 4 Dowels**	**Case 5 2 Dowels**	**Case 6 2 Dowels only on beams**
Ground Floor Columns	24Y20/100	10Y20/250	6Y20/460	4Y20/760	2Y20/2300	2Y20/2300
Ground Floor Beams	20Y20/100	10Y20/210	6Y20/380	4Y20/630	2Y20/1900	2Y20/1900
1st Floor Columns	20Y18/100	10Y18/250	6Y18/460	4Y18/760	2Y18/2300	2Y18/2300
1st Floor Beams	20Y18/100	10Y18/210	6Y18/380	4Y18/630	2Y18/1900	2Y18/1900
2nd Floor Columns	20Y16/100	10Y16/250	6Y16/460	4Y16/760	2Y16/2300	2Y16/2300
2nd Floor Beams	20Y16/100	10Y16/210	6Y16/380	4Y16/630	2Y16/1900	2Y16/1900
3rd Floor Columns	2Y16	2Y16	2Y16	2Y16	2Y16	2Y16
3rd Floor Beams	2Y16	2Y16	2Y16	2Y16	2Y16	2Y16

Table 1: Parametric study scenarios.

The same analysis procedure and a 0.25g earthquake record as explained in [1] were used for all the parametric-study scenarios.

4 NUMERICAL RESULTS

The global and local results from the parametric study of the effect of the dowels are presented in this chapter. Specifically, the top storey displacements of the frame and the base shear-forces of the frame for all the case scenarios that were performed are presented. In addition, the dowel’s axial forces that connect the foundation beam to the RC infill will be presented for the first three case scenarios.

4.1 Top Storey displacements

The top storey displacements of the frames are illustrated for all the case scenarios in Figures 2-4. The percentages of the increase or the decrease from the previous case scenario of the storey displacements are shown in Table 2 for all the case scenarios.

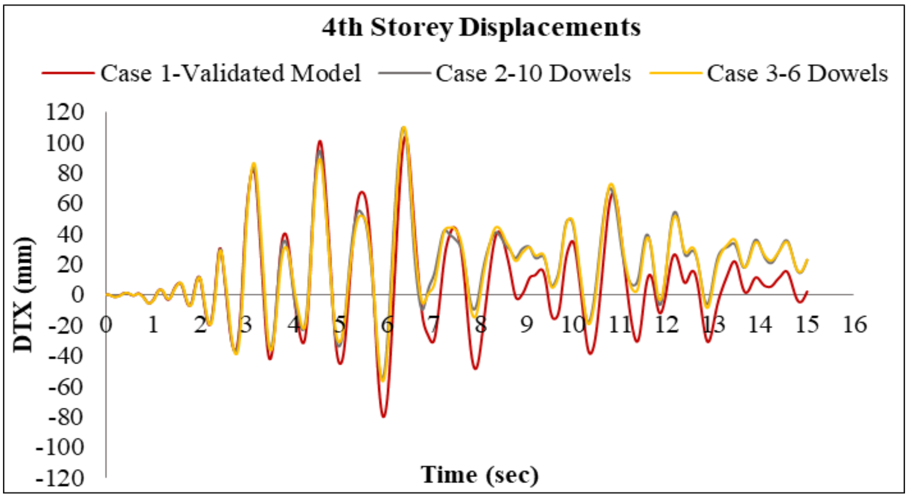

Figure 2: Top storey displacements for Cases 1,2 and 3.

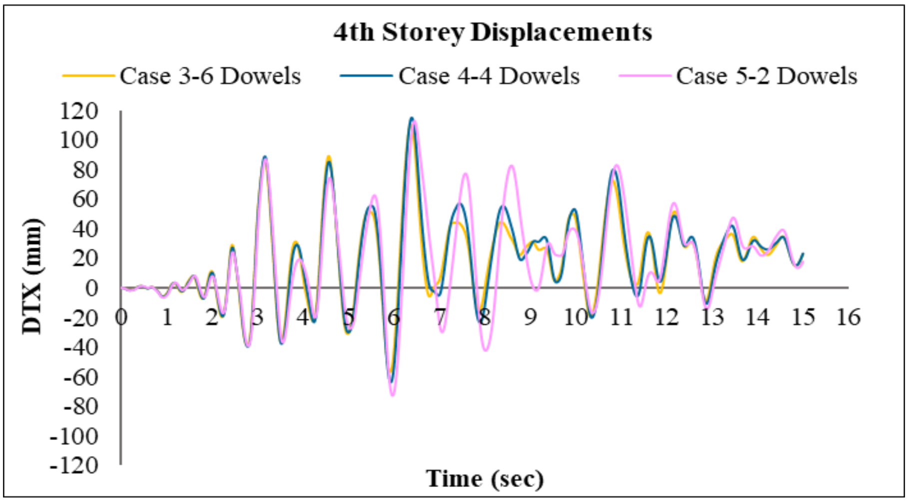

Figure 3: Top storey displacements for Cases 3,4 and 5.

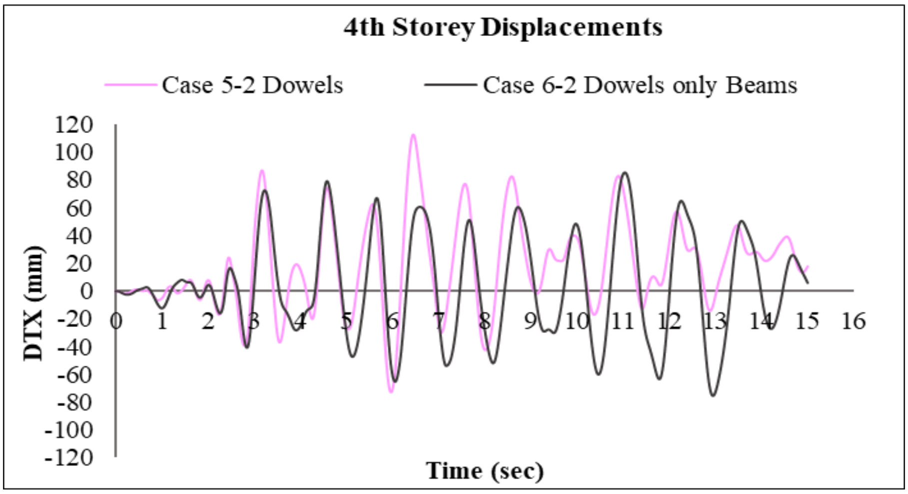

Figure 4: Top storey displacements for Cases 5 and 6.

Case Scenario	Positive DTX (%)	Negative DTX (%)
Case 2	+5.76	-31.27
Case 3	+0.32	+3.04
Case 4	+4.36	+12.33
Case 5	-1.88	+14.14
Case 6	-24.23	+3.58

Table 2: Top storey displacement percentage increase (+) or decrease (-) from the previous case scenario.

It is shown that the top storey displacements in the positive direction are about the same for all case scenarios except the sixth case scenario (two dowels connecting only the beams of the surrounding frame to the RC infill wall) 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. Then, the top storey displacement gradually increases for the third, fourth and fifth case scenarios. For the sixth case scenario, where it was previously mentioned that the positive maximum top storey displacement was decreased by 24.23%, in the negative direction it is at the same level with the fifth case scenario. This is an indication that the building got some permanent deformations in the positive direction in this case scenario which is evident from Figures 2-4.

Another observation that is shown in Figures 5-7, is that the elastic characteristics of the frame have changed with the reduction of the number of dowels 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.

4.2 Base shear-forces

The shear forces at the base of the frame were obtained from the numerical analysis and they are illustrated and discussed in this section. The base shear-force of the infilled frame for all the case scenarios are displayed in Figures 5-9. Furthermore, the base shear-forces of the frame versus the top storey displacements are illustrated in Figures 10-14. These results facilitate the comparison of the infilled-frame stiffness and energy absorption between the various cases studied.

The total base shear-forces shown in Figures 5-14 were obtained through the summation of the base shear of the four columns and the infill wall.

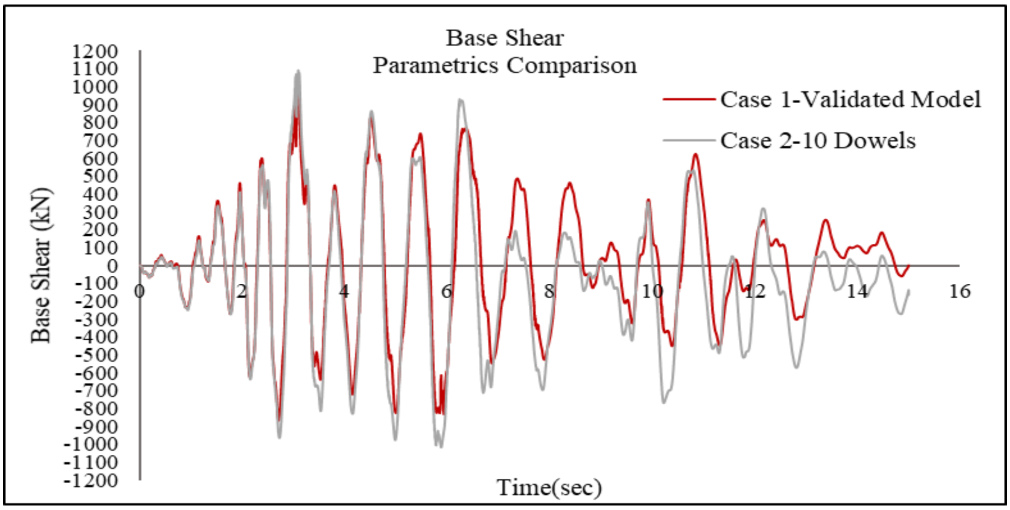

Figure 5: Base shear-force of the frame for Cases 1 and 2.

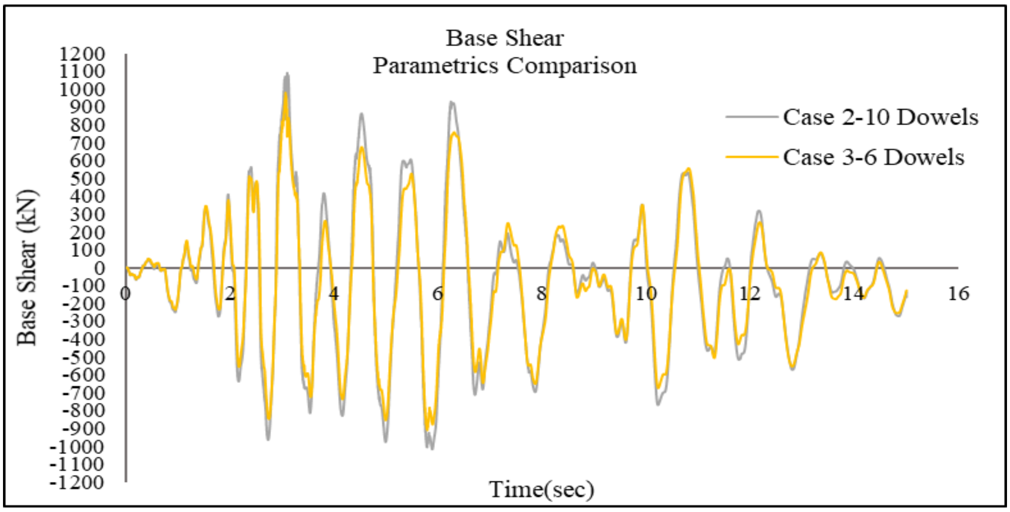

Figure 6: Base shear-force of the frame for Cases 2 and 3.

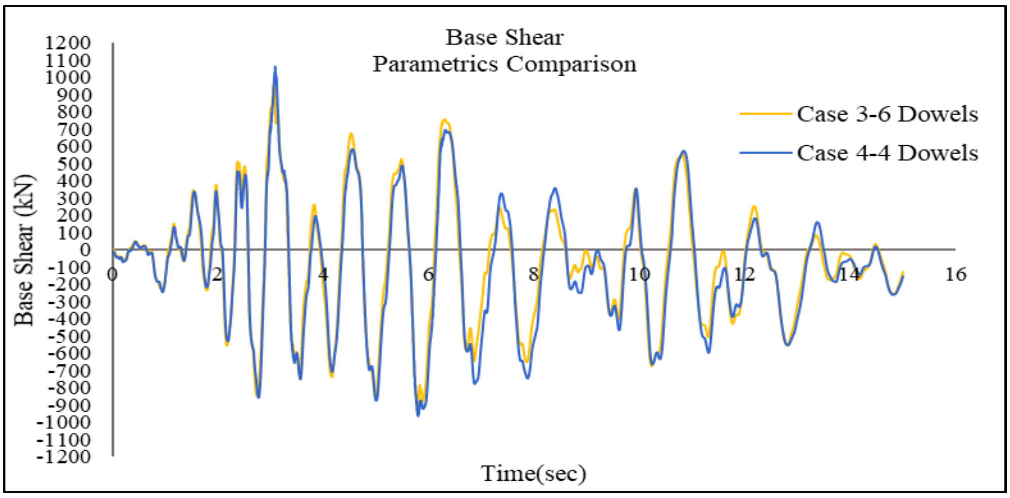

Figure 7: Base shear-force of the frame for Cases 3 and 4.

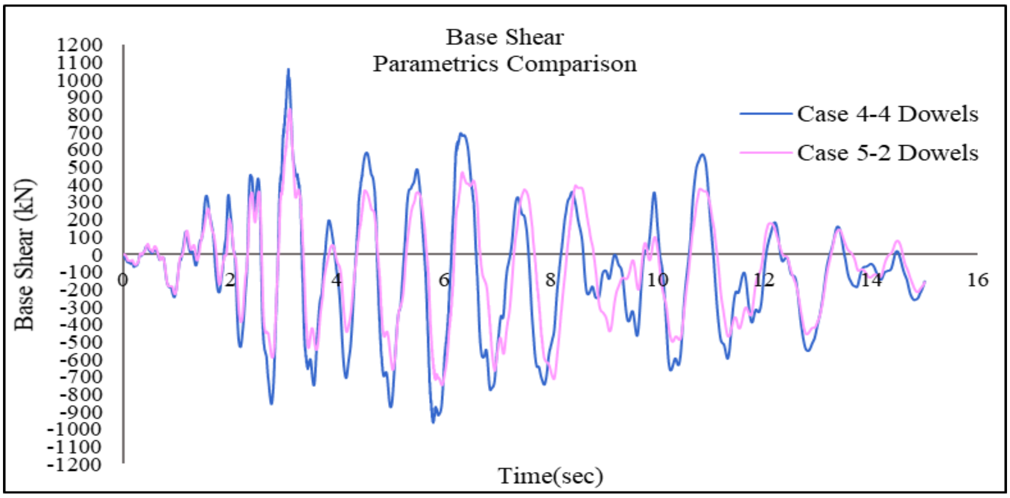

Figure 8: Base shear-force of the frame for Cases 4 and 5.

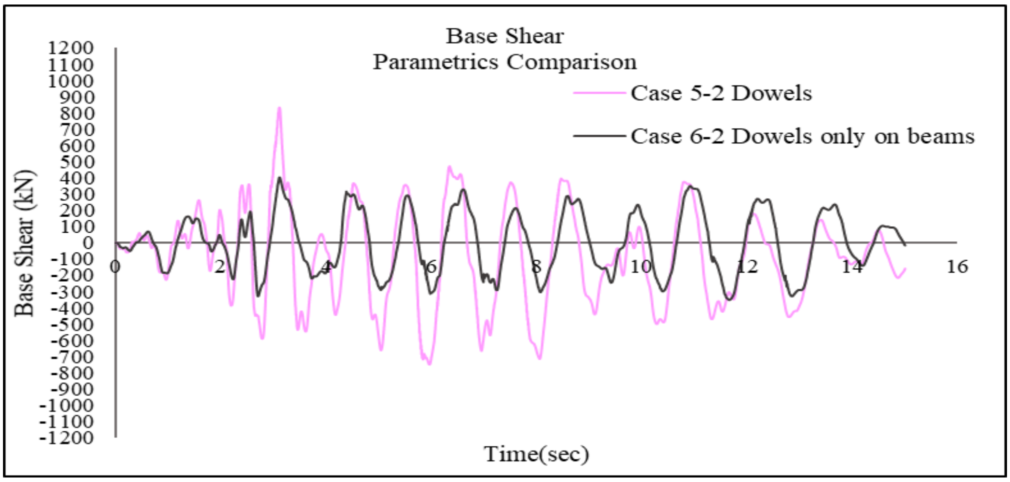

Figure 9: Base shear-force of the frame for Cases 5 and 6.

From Figures 5-9, it can be observed that the lower the number of dowels, the lower the base shear-force of the building. The second case scenario resulted to the highest total base shear-forces. The validated model (first case scenario), also reaches high base shear-forces relatively to the other case scenarios. Generally, it is shown that the first four case scenarios reach about the same values of the total base shear-force. The reduction of the maximum base shear-force is more obvious when the dowels are reduced to two.

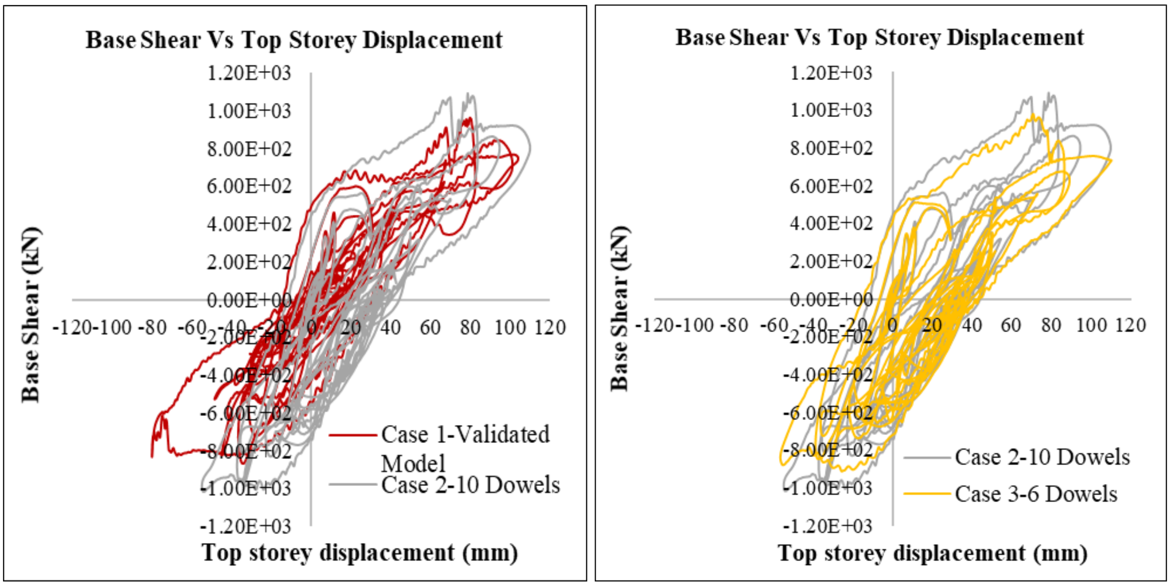

Figure 10: Top storey displacements versus base shear of frames for Cases 1, 2 and 3.

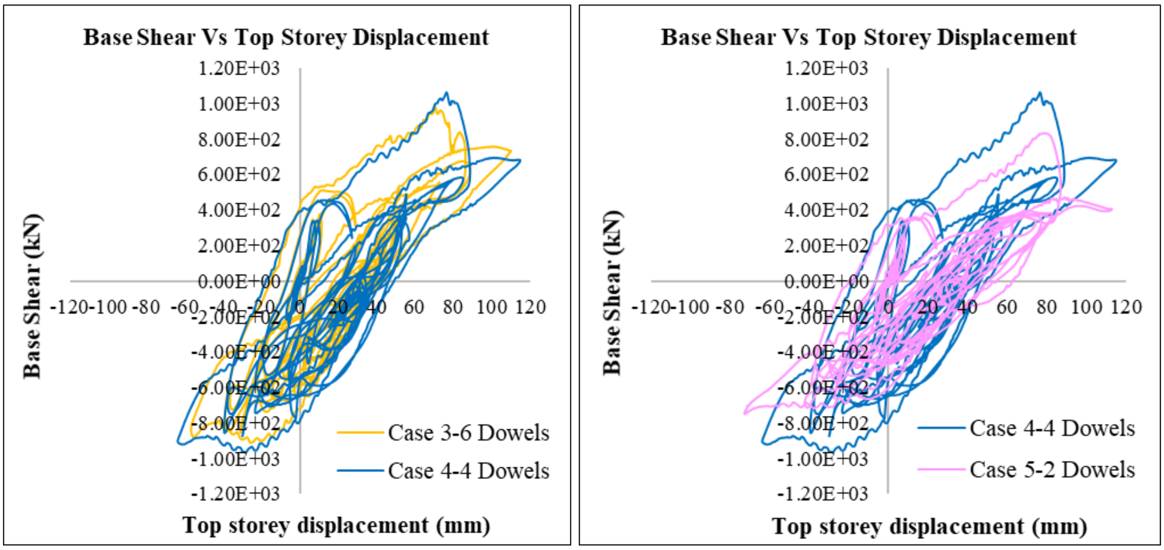

Figure 11: Top storey displacements versus base shear of frames for Cases 3, 4 and 5.

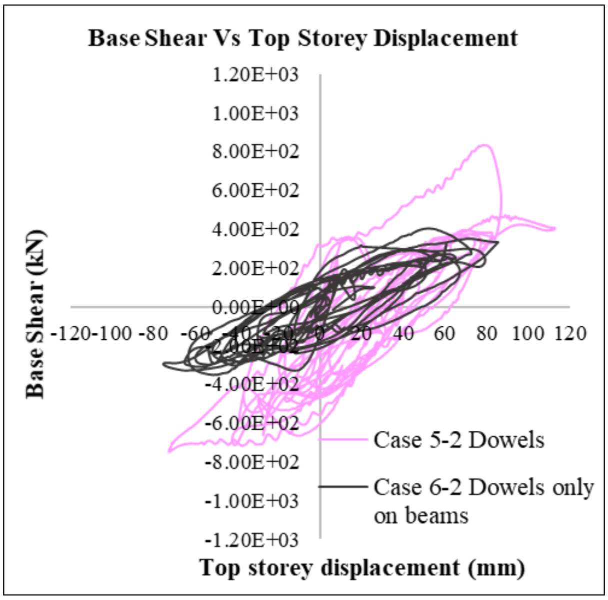

Figure 12: Top storey displacements versus base shear of frames for Cases 5 and 6.

From Figures 10-12, it is shown that the stiffness of the building is decreased with the reduction of dowels. In addition, it was observed that the energy absorption of the frame is less with the reduction of the dowels. These observations are more apparent after the fifth case scenario. For the first three case scenarios, the base shear-forces of the frames are higher in comparison with the next case scenarios whereas the top storey displacements are about the same.

It was also observed that for the first three cases the stiffness and the energy absorption of the buildings are about the same in the positive direction, whereas in the negative direction the validated model in the first case scenario clearly takes lower base shear-force and higher top storey displacement than the second, third and fourth case scenarios. For the fifth case scenario, even though the frame takes similar (little lower) base shear-force and top storey displacement with the previous case scenarios, the stiffness of the frame is reduced.

In general, it is shown that the stiffness and the energy absorption of the frame are not varying considerably for the first four case scenarios. However, when the dowels are reduced to two the decrease of the base shear-force of the frame is apparent and the stiffness and energy dissipation reduction is obvious.

4.3 Dowels behavior at the base

The axial load in all the dowels at the base interface when the total base shear-force of the frame is maximum (in both directions) is shown in Figures 13 and 14 for the first three case scenarios. As shown in the figures the maximum values occur at different instances during the analysis for each case.

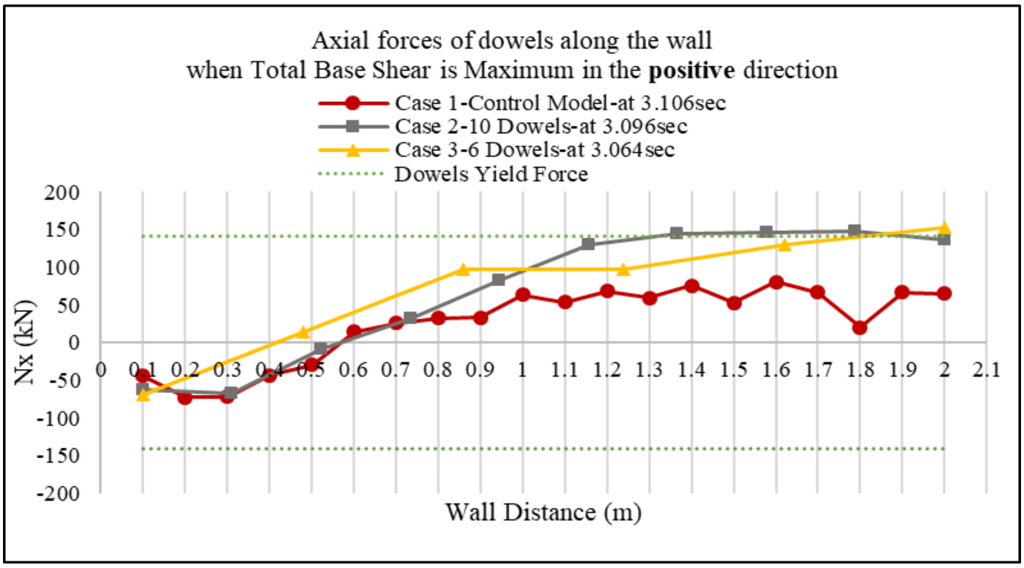

Figure 13: Dowels axial load at the interface when the base shear of the frame is maximum.

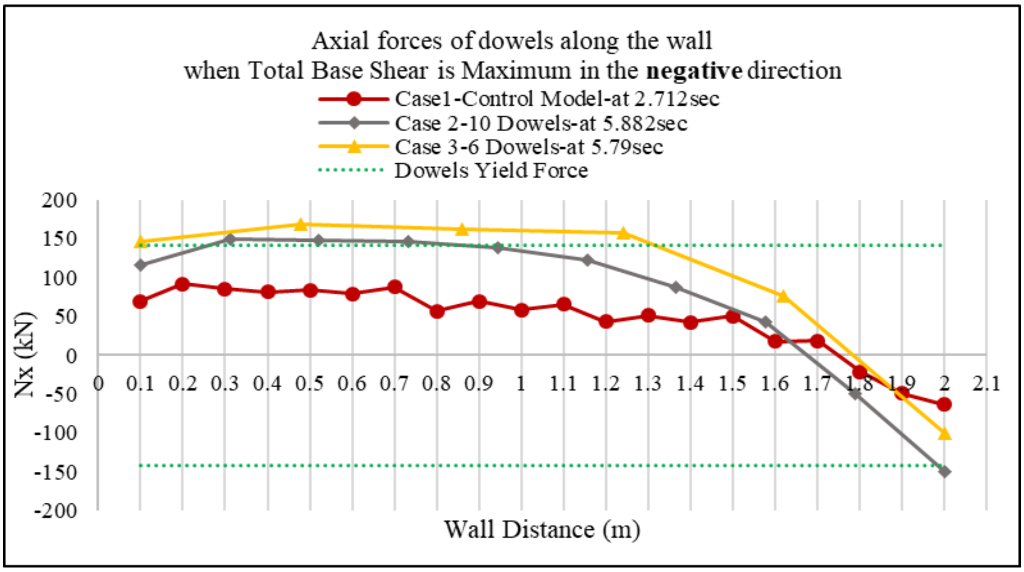

Figure 14: Dowels axial load at the interface when the base shear of the frame is minimum.

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. The dowels in the second and third case scenarios take higher forces (higher than their capacity). In addition, from the graphs in Figures 13 and 14, it is observed that more dowels reached their yield force with the reduction of the number of dowels.

In Figures 15-17, the axial load distribution in the dowels is shown for each case separately when the frame is moving towards both directions. For the first case scenario in (Figure 15 validated model) and the second one (Figure 16), it is shown that the location of the neutral axis is at about 0.55m for the negative direction and about 1.75m in the positive direction from the edge of the wall. With the reduction of the number of dowels in the third case scenario the position of neutral axis is moving to 0.40m in the negative direction and to 1.80m in the positive direction. This indicates that larger number of dowels have yielded resulting in increase of the lever-arm and is consistent with the results shown in Figures 13-14.

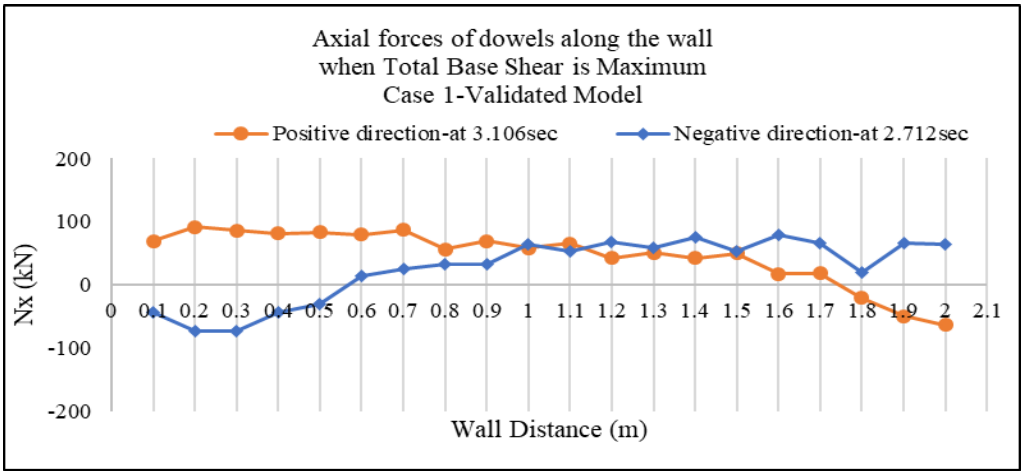

Figure 15: Dowels axial load at the interface when the base shear of the frame is maximum for Case 1.

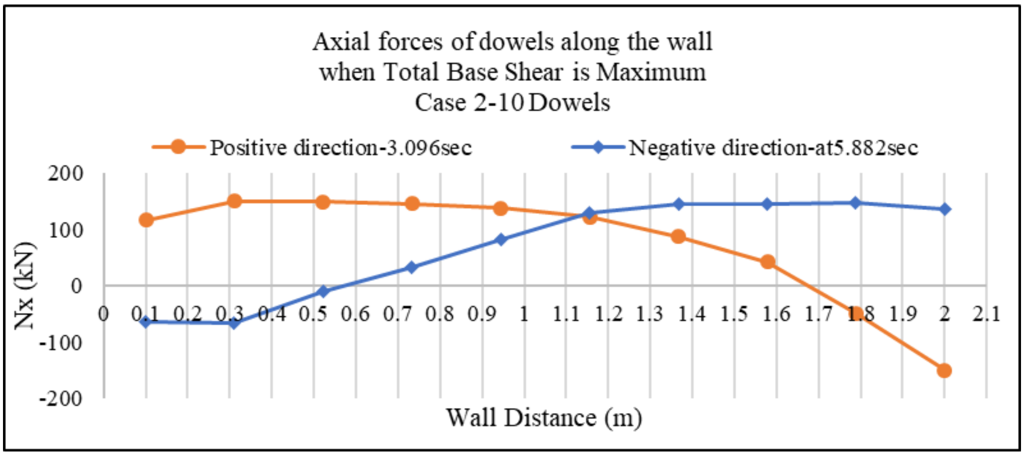

Figure 16: Dowels axial load at the interface when the base shear of the frame is maximum for Case 2.

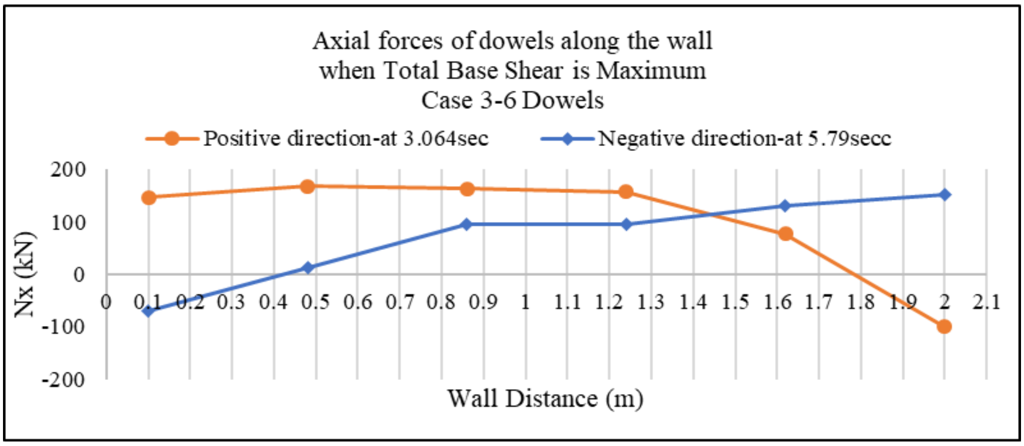

Figure 17: Dowels axial load at the interface when the base shear of the frame is maximum for Case 3.

5 CONCLUSIONS

As it was mentioned at the beginning of this paper, even though the strengthening of existing structures with RC infills has been applied and accepted by engineers, further investigation is required regarding their design and detailing. There is no quantitative procedure for the design and construction of the new walls. The contribution of dowels that connect the new infill wall to the surrounding frame members have not been yet analyzed adequately.

Some general conclusions were drawn about this retrofitting method through the numerical experiments in this paper. The parametric study that was performed covers a range between monolithic behavior (first case scenario) and infilled frame, by varying the number of dowels connecting the wall to the bounding frame. From the parametric study of dowels that were performed to the full-scale FE model that was developed in DIANA FEA, it is shown that the dowels affect the behavior of RC infills and the overall shear resistance capacity of the building. More specifically, the results showed that the maximum spacing of 380mm is sufficient to provide the required stiffness and ductility to the building.

From the results of the parametric study, there were several indications that the building had a nonlinear behavior and that the fundamental characteristics 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 absorption of the building. However, it is shown that these characteristics of the building are not varying considerably for the first four case scenarios (dowel spacing of 100mm to 630mm). On the other hand, the top storey displacements of the frames were about the same.

Regarding the local results of the dowels along the interface of the wall and the foundation, it is observed that the dowels of the first case scenario (spacing of 100mm) had the lowest forces in comparison with the other case scenarios, whereas the dowels of the second and third case scenarios reached their yield values (spacing of 210mm and 380mm, respectively). With the reduction of the number of dowels in the third case scenario the position of neutral axis is moving towards the edges of the wall in both directions, which indicates that larger number of dowels have yielded in this case resulting in increase of the lever-arm.

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 in order to obtain a better understanding of this structural system that will allow the development of design guidelines.

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