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Static Pushover Nonlinear Analysis To Assess Rc Frames With Masonary Infill and Concrete Jacketing Retrofitting Techniques

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Abstract Reinforced concrete frame (RC) structures with soft first storeys are one of the most common structural systems in the world. However, when these buildings are subjected to strong earthquakes, the seismic forces concentrate in the first storey, resulting in large inter-storey drifts. This can lead to significant damage or even collapse. In this paper, the seismic performance of a four-, five-, and six-storey RC frame building in New Tiba City is analysed for three different cases: a bare frame, a soft first storey, and a fully infilled frame. Pushover analysis is used to compare the capacity curves of the considered cases. The results show that the soft first storey cases have significantly lower seismic performance than the fully infilled frame case. To improve the seismic performance of the soft first storey cases, reinforced concrete jacketing is conducted. The results show that jacketing can significantly improve the seismic performance of RC frame buildings with soft first storeys.

Keywords: Soft storey Frame, Pushover Analysis, Capacity Curve, RC Jacket.

1. INTRODUCTION

RC frame buildings with masonry infill walls are common today. In crowded cities, parking is a major issue. Building regulations often require the first floor to be used as parking, which limits the use of infill walls on this floor. This configuration, known as a soft-storey [1], is a structural weakness. Infill walls are often ignored in structural analysis [2,3], but they can significantly increase the stiffness and strength of buildings. Irregularly distributed infill walls can lead to undesirable failure mechanisms, such as soft-storey failure. This is especially true when the first floor has no infill walls, as this can lead to premature failure [4, 5].

In Egypt, new urban planning rules require the ground floor to be used as open area parking or for commercial use. This study investigates the effect of an open ground floor on the overall structural behaviour using different performance assessment methods. It also investigates the use of concrete jacketing at ground floor columns of different sizes. Concrete jacketing is a retrofit strategy that has become popular due to its ease of construction and cost-effectiveness. In general, retrofit strategies aim to either modify key structural properties such as strength, ductility, and stiffness or to reduce seismic demands [6]. This paper uses pushover analysis to assess the vulnerability of soft-storey buildings and evaluate the feasibility of concrete jacketing

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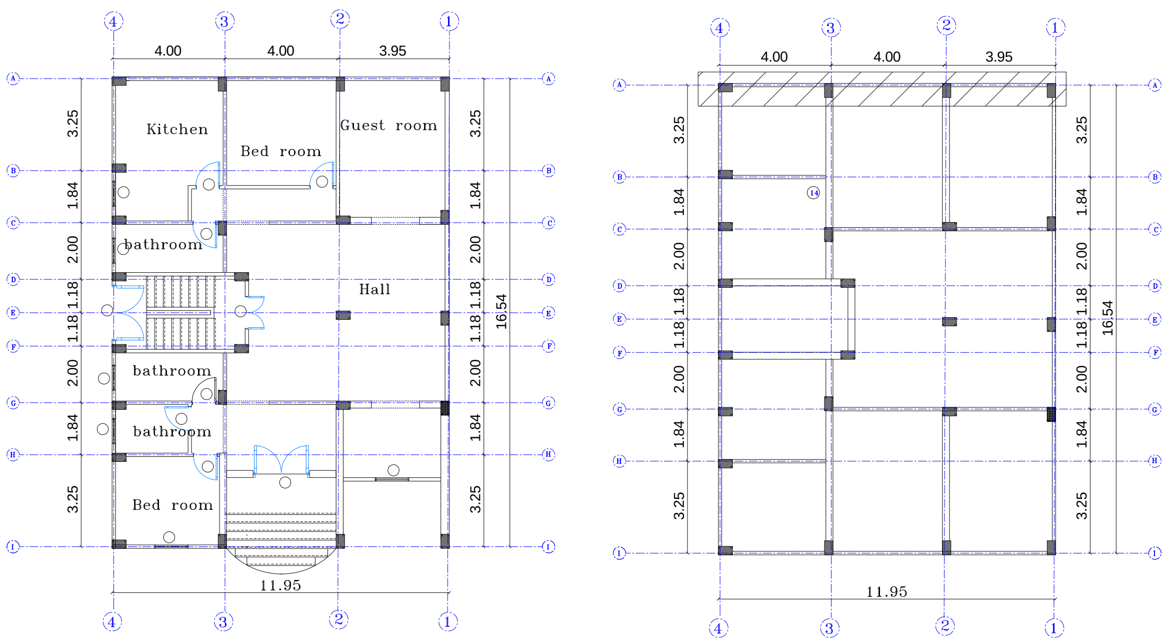
as a retrofit strategy to improve their seismic performance.

2. STUDY CASES DESCRIPTION

A residential RC building located in the new Tiba City was selected to be a study case. This building is termed hereinafter B2 with area of 200 m^2. The architectural plan and the structural system of the building is presented in Figure 1. the frame of the horizontal axis A between the vertical axes 1-4, termed hereinafter as frame FA 1-4 is used to assess the performance of B1. This frame was analysed with different configurations (bare, fully infilled and soft-storey frames) and with three different numbers of storeys (four, five and six storeys) as shown in Figure 2. The used material's properties are given in Table 1. The designed element cross-sections details for frame FA1-4 are shown in
Table 2.



a) B)

Figure 1 plan view for Residential building B1:a)architectural plan b) structural system and showed the considered frame (FA 1-4).

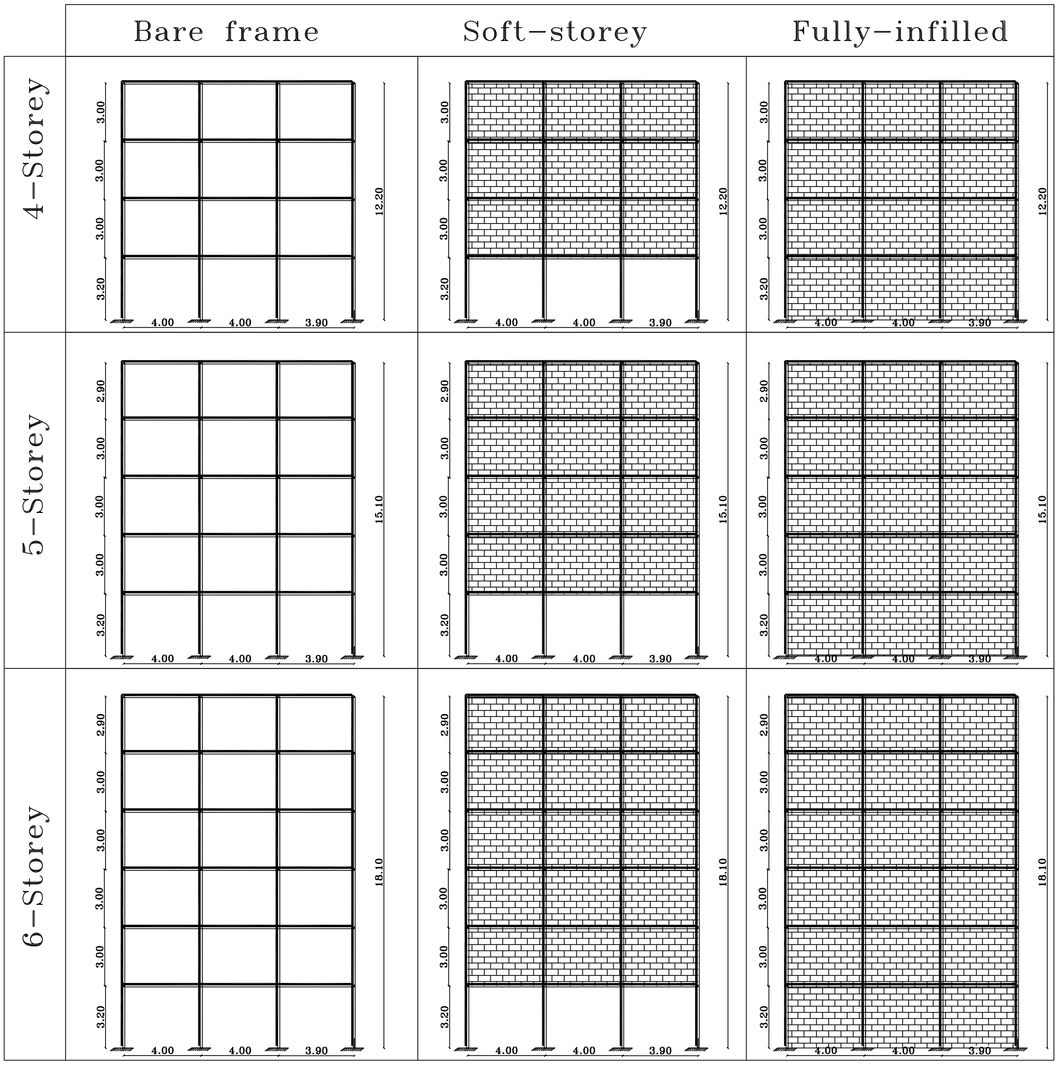


Figure 2 Different configurations of (FA 1-4)

Table 1 Mechanical properties of the material

Steel		**Concrete compressive strength f_c (Mpa)**	**Infill material**	
Elastic modulus E_s (Gpa)	**Yield stress σ_y (Mpa)**	25.0	**Brick compressive strength f_m (Mpa)**	**Mortar compressive strength f_{mo}**
131.0	360.0		2.00	1.00

Table 2 Cross-section details for frame FA1-4.

No of storeys	Columns			Beams				
	Axis	Section (cm)	Reinforcement	Section (cm)	Reinforcement			
					Start		End	
					Upper	Lower	upper	Lower
Four storeys	1	50×30	10 Ø 16	12×40	4Ø12	4Ø12	4Ø12	4Ø12
	2	30×50	10 Ø 16	12×40	4Ø12	4Ø12	4Ø12	4Ø12
	3	30×50	10 Ø 16	12×40	4Ø12	4Ø12	4Ø12	4Ø12
	4	30×50	10 Ø 16	12×40	4Ø12	4Ø12	4Ø12	4Ø12
Five storeys	1	50×30	10 Ø 16	12×40	4Ø12	4Ø12	4Ø12	4Ø12
	2	30×50	10 Ø 16	12×40	4Ø12	4Ø12	4Ø12	4Ø12
	3	30×50	10 Ø 16	12×40	4Ø12	4Ø12	4Ø12	4Ø12
	4	30×50	10 Ø 16	12×40	4Ø12	4Ø12	4Ø12	4Ø12
Six storeys	1	50×30	10 Ø 16	12×40	4Ø12	4Ø12	4Ø12	4Ø12
	2	30×50	10 Ø 16	12×40	4Ø12	4Ø12	4Ø12	4Ø12
	3	30×50	10 Ø 16	12×40	4Ø12	4Ø12	4Ø12	4Ø12
	4	30×50	10 Ø 16	12×40	4Ø12	4Ø12	4Ø12	4Ø12

3. Finite element modelling strategy

The open-source software framework OpenSees [7] was used to perform the nonlinear pushover analysis for the considered numerical models The following sections provide modelling descriptions for the different structural components. The following subsections briefly detail the description of each element modelling strategy.

3.1 Reinforced concrete frame elements.

Reinforced RC elements, i.e. columns and beams were modelled using force-based element known as "*forceBeamColumn"* element in OpenSees with modified Radau plastic hinge integration. This element is defined based on the fibre section that discretizes the RC section into three materials as shown in Figure 3, concrete material for the cover, steel material for longitudinal rebars and concrete at the section core. Concrete01 was used to define the nonlinear behaviour of concrete at the cover zone. This material has no tensile strength and relies on Kent-Scott-Park concrete material model [8]. Furthermore, this material has degraded linear unloading/reloading stiffness according. The core of the cross-section is defined with concrete material known as concrete (02) in OpenSees. This material has the same constitutive model as Concrete01 but with tensile strength. For the longitudinal steel rebars, steel (02) was used to construct a uniaxial Giuffre-Menegotto-Pinto steel material object with isotropic strain hardening. For defining precisely, the length of plastic hinges, several methods were found in the literature. However, Paulay and Priestly [9-10] method to calculate plastic hinge length (L_P) was found to be adequate[11]. Lp can be quantified using the following equation.

$$L_P = 0.08\, L_e + 0.022 d_b\, f_y \qquad (1)$$

Where: L_e is the element length, d_b is the steel diameter, and f_y is the yield stress of steel in MPa.

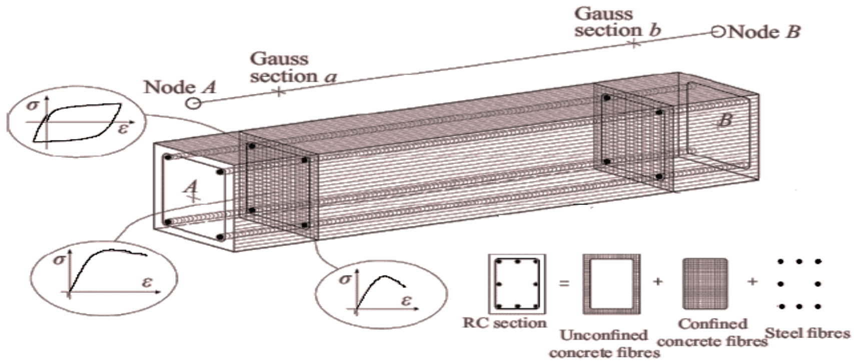


Figure 3 Illustrative example for the section discretization into different fibres with different materials.

3.2 Infill wall modelling

For the infill wall two diagonal struts element are connected to the column-beam joints were used to model the behaviour of the infill walls. The geometric section of the strut is defined according to the following equation:

$$A_S = w \times t \quad , \qquad (2)$$

Where w and t are the widths of the strut and thickness of the infill wall respectively.

For the strut width *w* several proposals were found (e.g. see among others,[12-14]) the proposal of [15] has been adopted herein to calculate the strut width. According Mainstone [15] the width of strut can be given as:

$$w = 0.175\ (\lambda_h)^{-0.4}\ d \ , \qquad (3)$$

Where *h* is the height of the storey, *l* is the length of the bay and λ can be calculated as:

$$\lambda = \sqrt[4]{\frac{E_m\, t\, \sin(2\theta)}{4\, E_c I_c h}} \qquad (4)$$

Where E_m and E_c are the elastic modulus of the masonry wall and column, respectively, θ is the slope angle for the diagonal strut, and Ic is the column moment of inertia. The driven area of the strut is combined with concrete01 material in OpenSees to define the strut element.

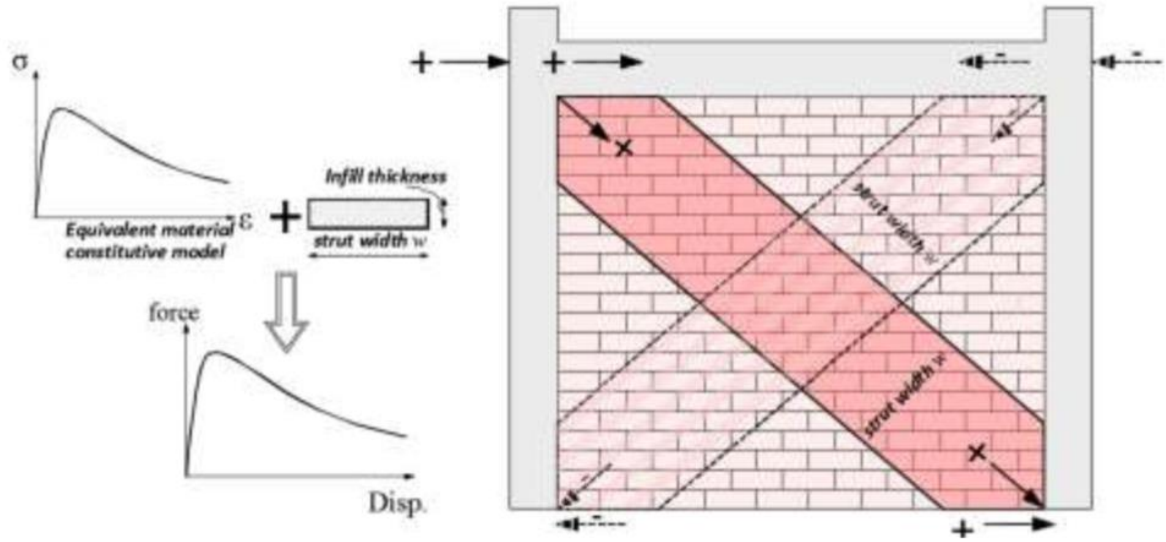


Figure 4 Equivalent single strut model for masonry infill wall in RC frame structure

4. METHODOLOGY ANALYSIS

To investigate the behaviour of the RC frames with masonry infill that has open ground floors with and without retrofitting interference. As such, the pushover of the building without and with two scenarios of using concrete jacketing are analysed using traditional pushover analysis. The capacity curves were obtained then repeated analysis for all involved cases including with retrofitting techniques and their responses were compare *Table 3* shows all cases that have been analysed.

Table 3 the case of study that are presented in this thesis

Building	**No. of storey**	**Bare frame**	**Soft-storey**	**Fully infilled**	**Retrofitting scenario**	
					5 cm concrete jacketing	5 cm concrete jacketing
FA 1-4	4	FA 1-4-B4	FA 1-4-S4	FA 1-4-F4	FA 1-4-S4-M1	FA 1-4-S4-M2
FA 1-4	5	FA 1-4-B5	FA 1-4-S5	FA 1-4-F5	FA 1-4-S5-M1	FA 1-4-S5-M2
FA 1-4	6	FA1-4- B6	FA1-4-S6	FA1-4-F6	FA1-4- S6-M1	FA1-4- S6-M2

M > refers to retrofitting solution

S> frame with soft storey

B> bare frame

F>fully infilled frame

5. RESULTS AND CONCLUSIONS

Infill walls play an essential role in the performance of reinforced concrete (RC) frame buildings. However, their irregular distribution over the building height can lead to undesirable failure mechanisms, such as soft-storey failure [16-17]. This is especially true when the first floor has no infill walls. To mitigate the consequences of earthquakes on buildings and improve seismic performance, structural retrofitting is often required. Retrofitting involves adding new materials to enhance and improve the performance of the building to reduce the seismic risk to an acceptable level. In this study, two scenarios of column concrete jacketing were used at the ground storey of an RC frame building with masonry infills: 5 cm RC jacketing and 10 cm RC jacketing. The fibre sections of the altered columns were modified by adding new batches of steel and concrete along their outer perimeter. The performance of the reference cases and their counterpart retrofitted cases were determined using pushover curves. Based on this comparison, several conclusions have been drawn for this type of structure.

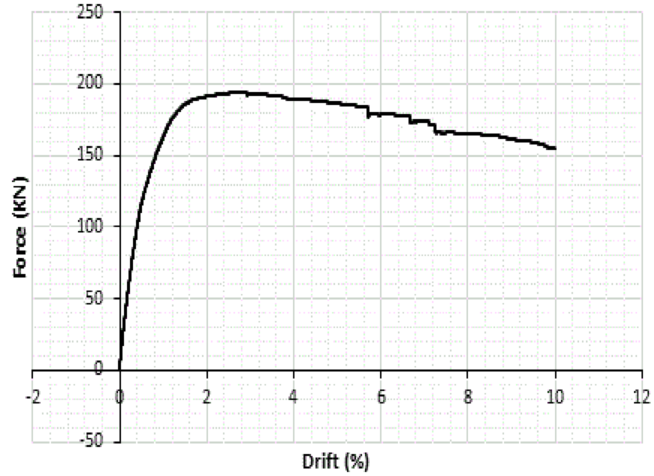
5.1 Pushover Analysis

Pushover analysis using the distribution of inertia force along with the height and the seismic demands are evaluated by mitotically increasing lateral force concerning the height until reached the target displacement. The pushover curve represents the capacity of the building by plotting the relation between the base shear and the roof displacement. This relation usually called the capacity curve is used to evaluate whether the structure is suitable to bear a certain level of seismic load, and this has to be compared with requirements.

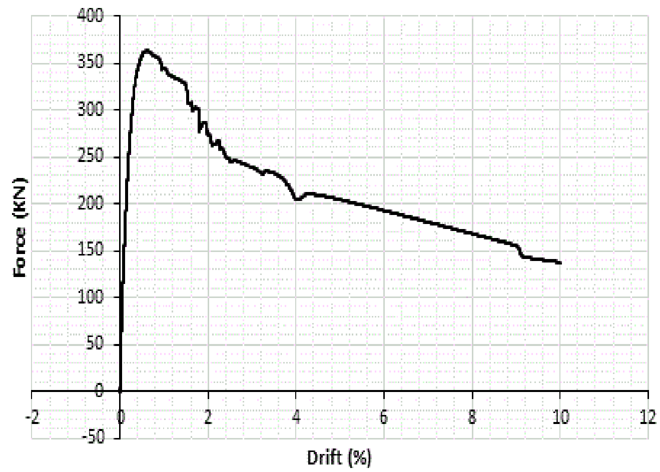
5.2 Capacity curves for reference case

OpenSees program was used to run the analysis for all frames, as such, the gravity loading is analysis first followed by lateral loading for the pushover from the result compares the initial storey drifts ratio and ductility. The capacity curves for cases (i.e., bare, soft storey frame and fully infilled frame) were plotted in Figure 15, Figure 6 and Figure 7. In general, bare frame cases shows the lowest lateral strength over all considered cased regardless the number of storeys.

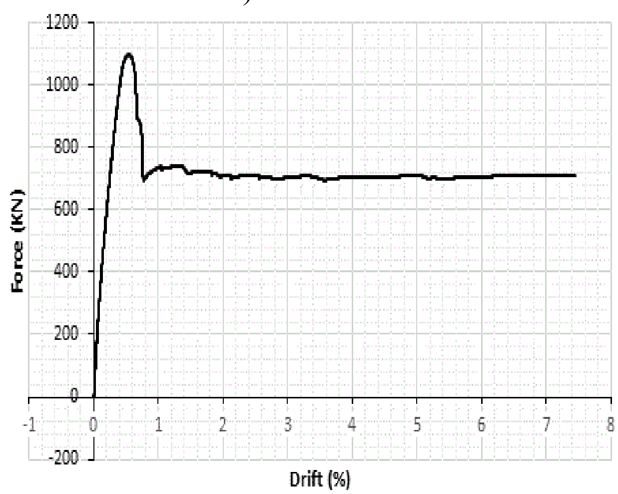
On another hand, the cases with open ground storey (soft storey cases) show roughly twice the strength of the bare frame but less ductility level that can monitored by the top storey drift corresponding to the ultimate lateral strength. For the fully infilled cases, these cases show higher strength (almost three folds of the bare frame) and adequate level of ductility after losing the infill contribution. Also, it is worth noting that these cases show higher stiffness up to the ultimate strength due to infill contributions. However, such higher stiffness, leads to brittle failure particularly cases with six storeys. In term of failure mechanism, first mode drift was the typical failure mode for bare and fully infilled cases but soft storey failure mechanism were dominated in cases with open ground floor.



a) FA 1-4-B4

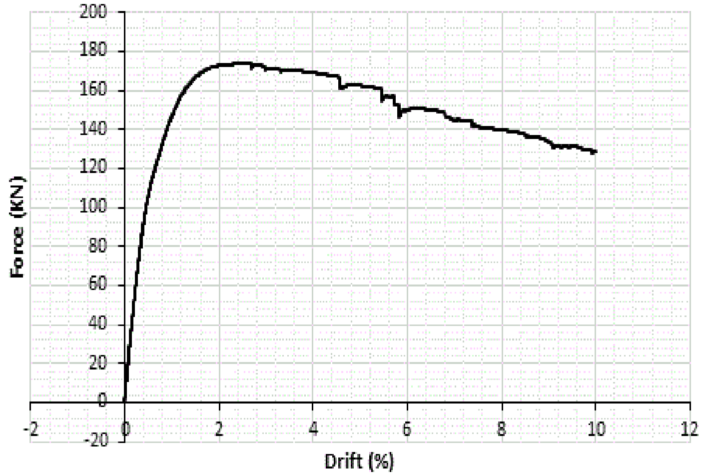


b) FA 1-4-S4



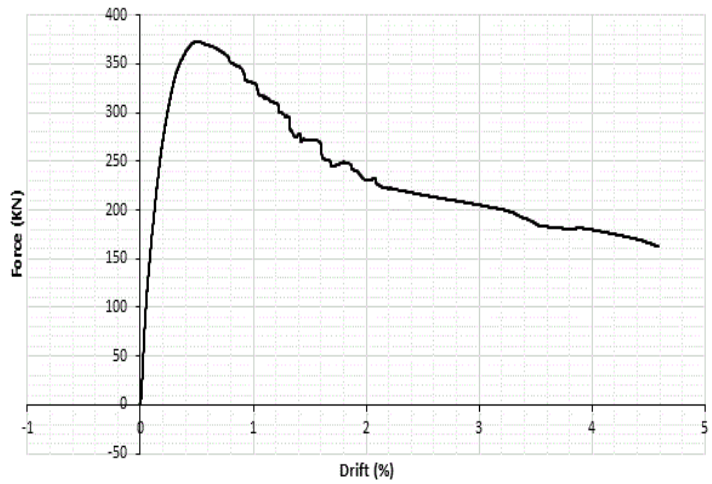
c) FA 1-4-F4

Figure 5 Force-top storey drift relation for FA 1-4 with four storeys with three different configurations a) bare frame b) soft-storey c) fully infilled frame

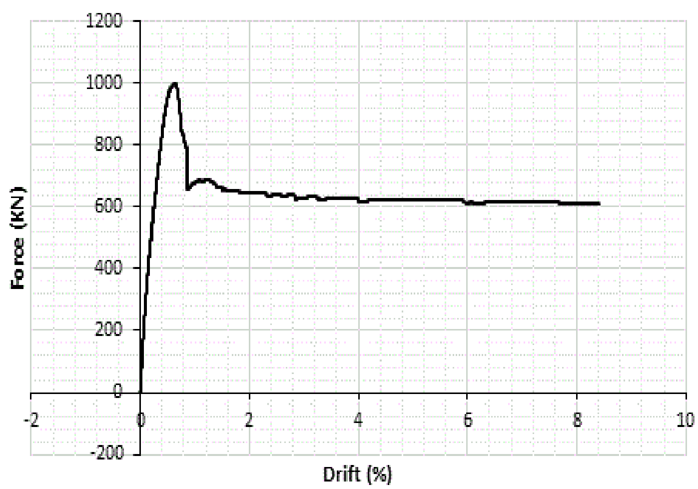


a)

b) FA 1-4-B5

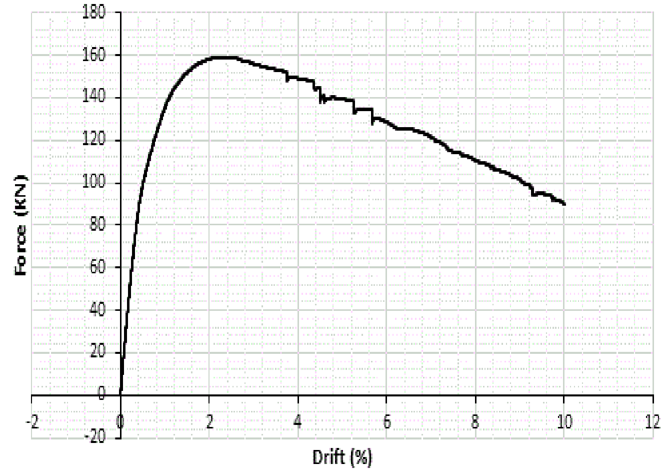


b) FA 1-4-S5

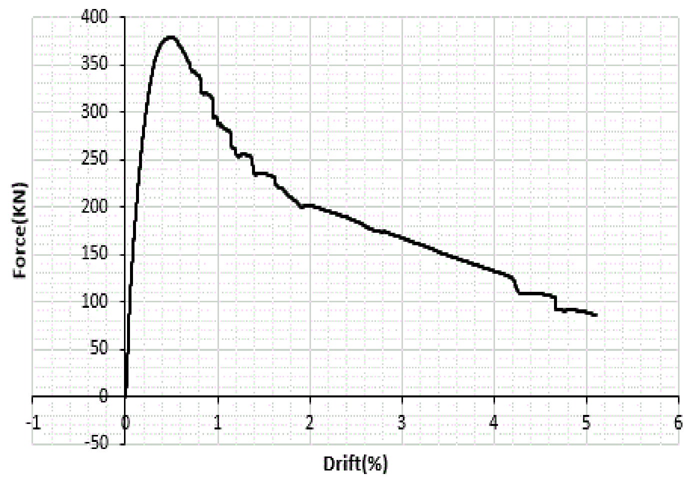


c) FA 1-4-F5

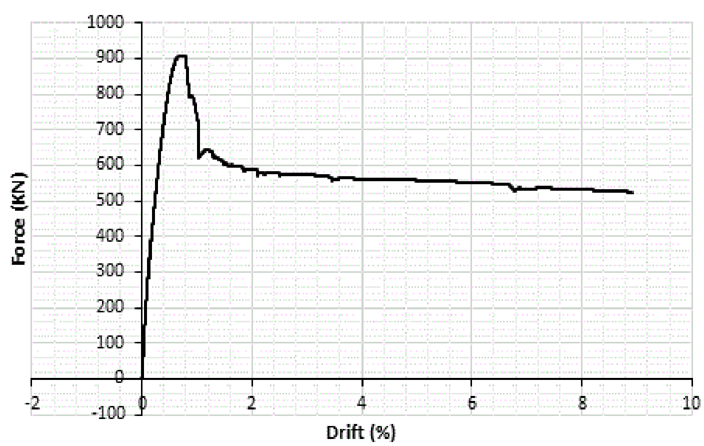
Figure 6 Force-top storey drift relation for FA 1-4 with five storeys with three different *configurations a) bare frame b) soft-storey c) fully infilled frame*



a) FA 1-4-B6



b) FA 1-4-S6

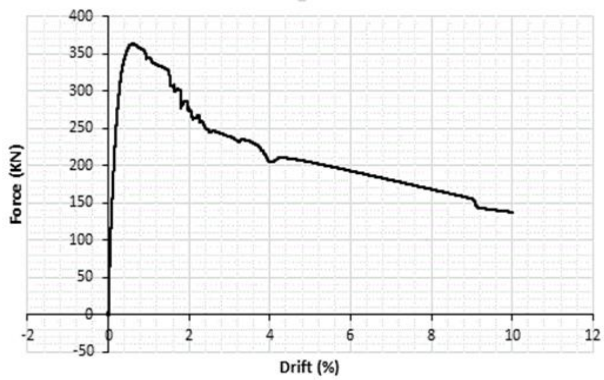


c) FA 1-4-F6

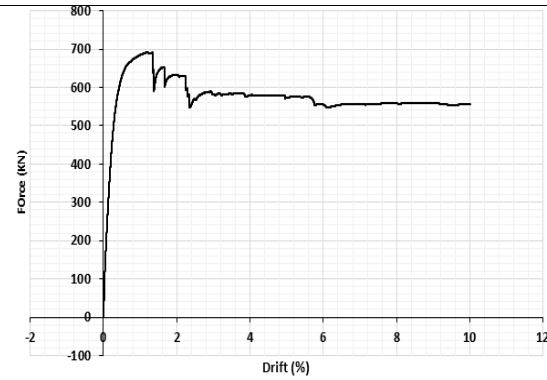
Figure 7 Force-top storey drift relation for FA 1-4 with six storeys with three different configurations a) bare frame b) soft-storey c) fully infilled frame

5.3 Capacity curves for cases with concrete jacketing

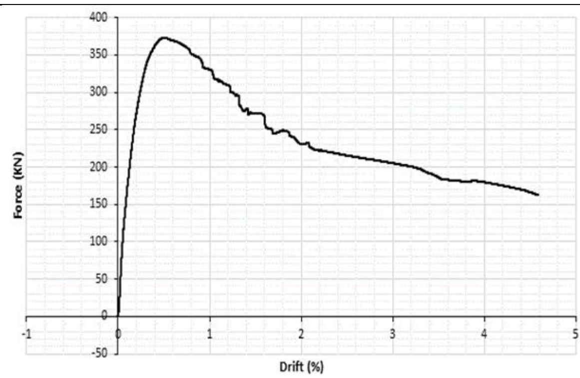
To enhance the performance for frame with soft first storey jacketing with 5&10 centimetres were required to use in columns in ground floor. As such, the fibre sections of the altered columns were modified by adding new batches of steel and concrete along its outer perimeter. Then repeat pushover procedure and the new capacity curves for the modified cases were obtained. For frames with the soft first storey found that have a clear enhancement in performance of the structure compared to the reference case as shown in Figure 8.



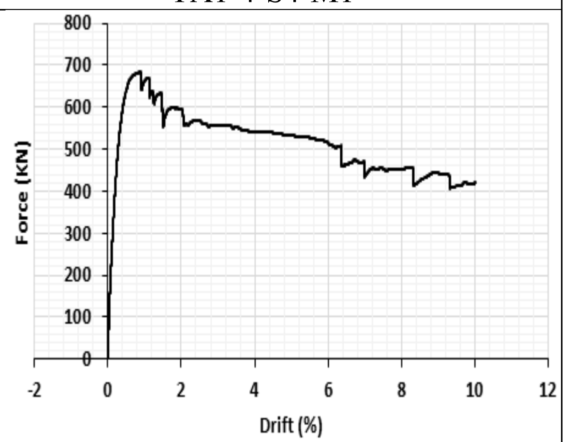
FA1-4-S4



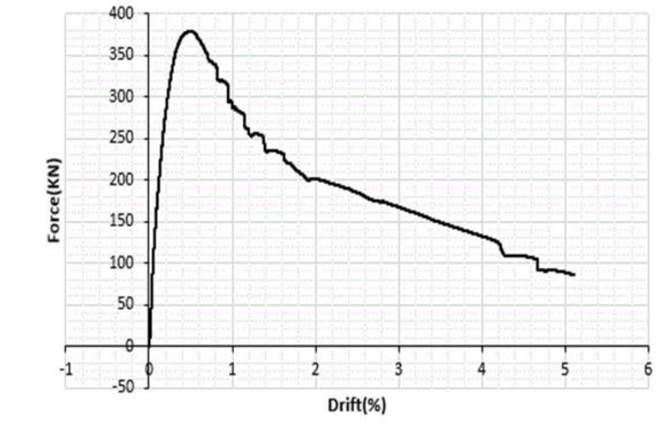
FA1-4-S4-M1



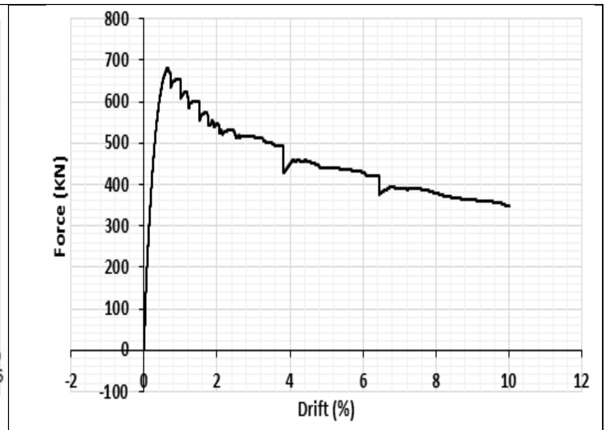
FA1-4-S5



FA1-4-S5-M1

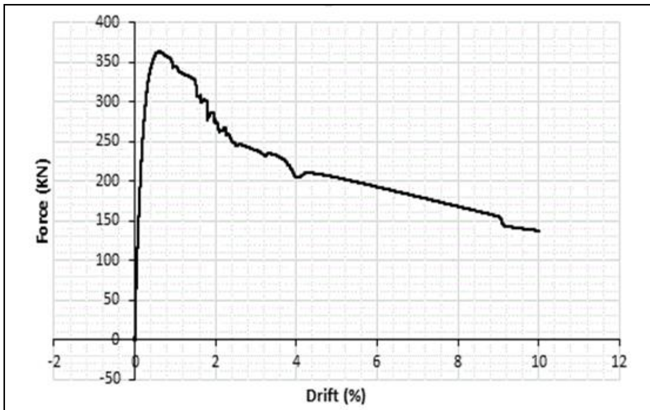


FA1-4-S6

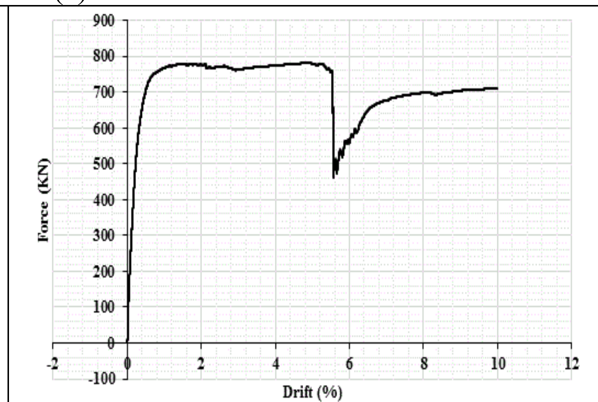


FA1-4-S6-M1

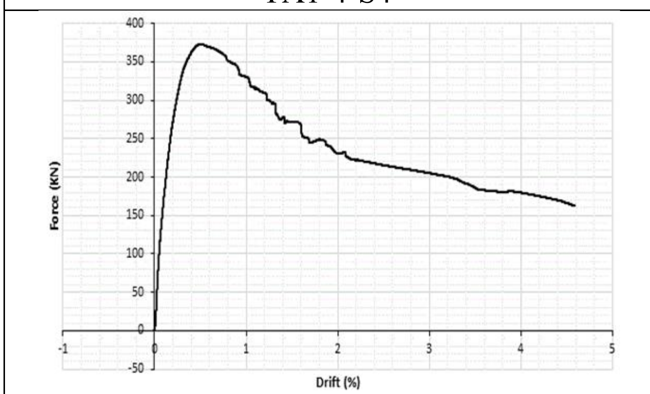
(a)



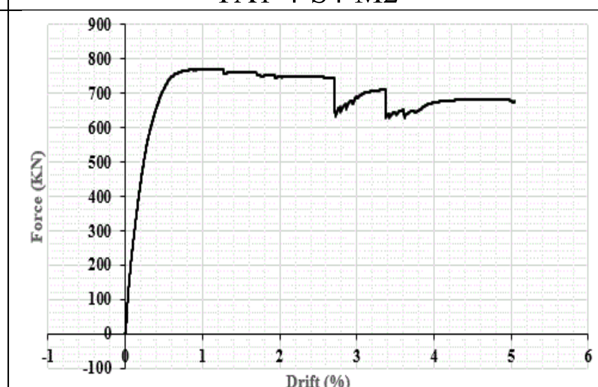
FA1-4-S4



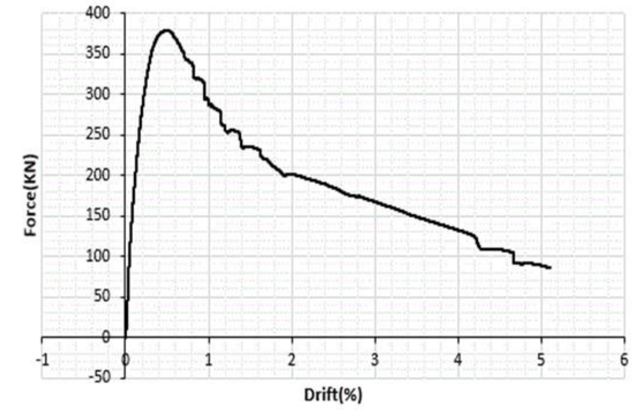
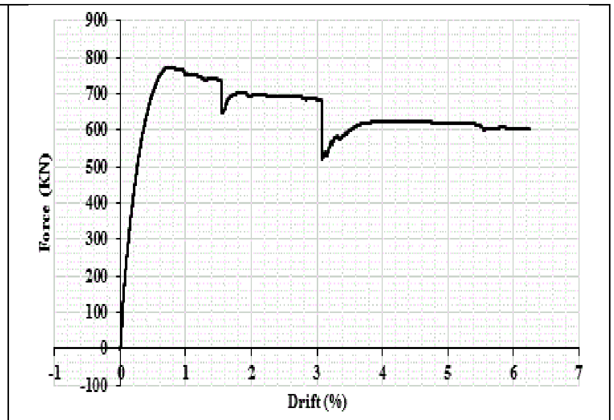
FA1-4-S4-M2



FA1-4-S5



FA1-4-S5-M2

	
FA1-4-S6	FA1-4-S6-M2

(b)

Figure 8 Force-top storey drift relation for FA 1-4 with soft-storey with a concrete jacket of a) 5 centimetres and b) 10 centimetres with four, five and six storeys.

6. CONCLUSIONS

Reinforced concrete buildings with an open ground floor are vulnerable to earthquakes. Therefore, it is important to retrofit these buildings to improve their performance during an earthquake. This paper investigates the effectiveness of using concrete jacketing to retrofit a reinforced concrete frame building with masonry infills in Tiba City. The building was named FA1-4. The pushover analysis was used to assess the performance of the building in three scenarios: Reference case (No retrofit), Retrofit case 1 (with 5 cm reinforced concrete jacketing) and retrofit case 2 (with 10 cm reinforced concrete jacketing). In general, the performance of the retrofitted cases was found more adequate compared to reference cases with no intervention. Nevertheless, the building with 10 cm reinforced concrete jacketing performed the best.

REFERENCES

[1] M. Kamal, M. Inel, and B. T. Cayci, "Seismic behavior of mid-rise reinforced concrete adjacent buildings considering soil-structure interaction," Journal of Building Engineering, vol. 51, p. 104296, 2022/07/01/ 2022, doi: https://doi.org/10.1016/j.jobe.2022.104296.

[2] A. Messaoudi, R. Chebili, H. Mohamed, and H. Rodrigues, "Influence of Masonry Infill Wall Position and Openings in the Seismic Response of Reinforced Concrete Frames," Applied Sciences, vol. 12, no. 19, p. 9477, 2022-09-21 2022, doi: 10.3390/app12199477.

[3] H. Mohamed, D. Skoulidou, and X. Romão, "Quantification of the effects of different uncertainty sources on the seismic fragility functions of masonry-infilled RC frames," Structures, vol. 50, pp. 1069-1088, 2023/04/01/ 2023, doi: https://doi.org/10.1016/j.istruc.2023.02.097.

[4] H. Mohamed and X. Romão, "Seismic fragility analysis of RC frames with masonry infills," in 16ECEE, Thessaloniki, Greece, in June 18-21 2018.

[5] H. Mohamed and X. Romão, "Seismic Fragility Functions for Non-Seismically Designed RC Structures Considering Pounding Effects," Buildings, vol. 11, no. 12, p. 665, 2021-12-20 2021, doi: 10.3390/buildings11120665.

[6] K. Aljawhari, R. Gentile, and C. Galasso, "A fragility-oriented approach for seismic retrofit design," Earthquake Spectra, vol. 38, no. 3, pp. 1813-1843, 2022, doi: 10.1177/87552930221078324.

[7] F. McKenna, "OpenSees: a framework for earthquake engineering simulation," Computing in Science & Engineering, vol. 13, no. 4, pp. 58-66, 2011.

[8] J. B. Mander, M. J. Priestley, and R. Park, "Theoretical stress-strain model for confined concrete," Journal of structural engineering, vol. 114, no. 8, pp. 1804-1826, 1988.

[9] X. Zhao, Y.-F. Wu, A. Y. Leung, and H. F. Lam, "Plastic Hinge Length in Reinforced Concrete Flexural Members," Procedia Engineering, vol. 14, pp. 1266-1274, 2011/01/01 2011, doi: http://dx.doi.org/10.1016/j.proeng.2011.07.159.

[10] F. Alemdar, "Plastic hinging behavior of reinforced concrete bridge columns," PhD Thesis PhD, Civil Department, University of Kansas, Kansas, 2010.

[11] S. Bae and O. Bayrak, "Plastic hinge length of reinforced concrete columns," ACI Structural Journal, vol. 105, no. 3, p. 290, 2008.

[12] P. Asteris, D. Cotsovos, C. Chrysostomou, A. Mohebkhah, and G. Al-Chaar, "Mathematical micromodeling of infilled frames: state of the art," Engineering Structures, vol. 56, pp. 1905-1921, 2013, doi: http://dx.doi.org/10.1016/j.engstruct.2013.08.010.

[13] P. G. Asteris, S. T. Antoniou, D. S. Sophianopoulos, and C. Z. Chrysostomou, "Mathematical Macromodeling of Infilled Frames: State of the Art," Journal of Structural Engineering, vol. 137, no. 12, pp. 1508-1517, 2011, doi: 10.1061/(asce)st.1943-541x.0000384.

[14] R. J. Mainstone, "On The stiffness and strengths of infilled frames," ICE Proceedings, vol. 49, no. 2,p.230.[Online].Available:http://www.icevirtuallibrary.com/content/article/10.1680/iicep.1971.6267

[15] P. G. Asteris, C. Z. Chrysostomou, I. Giannopoulos, and P. Ricci, "Modeling of Infilled Framed Structures," in Computational Methods in Earthquake Engineering, vol. 30. Netherlands: Springer, 2013, pp. 197-224.

[16] H. Mohamed and X. Romão, "Seismic fragility analysis of RC frames with masonry infills," in 16ECEE, Thessaloniki, Greece, in June 18-21 2018.

[17] H. Mohamed and X. Romão, "Seismic Fragility Functions for Non-Seismically Designed RC Structures Considering Pounding Effects," Buildings, vol. 11, no. 12, p. 665, 2021-12-20 2021, doi: 10.3390/buildings11120665.