The 9th European Congress on Computational Methods in Applied Sciences and Engineering
ECCOMAS Congress 2024
3 – 7 June 2024, Lisbon, Portugal

INVESTIGATING SFRC JACKETING FOR SEISMIC RETROFITTING OF REINFORCED CONCRETE MULTISTOREY BUILDINGS

Ernie Van Antwerpen[1], Kevin Braun[2] and George Markou[3,4]

[1] EDS Engineering Design Services, 473 Lynwood Road, Lynwood, Pretoria, South Africa,
ernie@edseng.co.za

[2] University of Pretoria, cnr Lynwood Road, and Roper Street, Hatfield, South Africa,
u17031215@tuks.co.za

[3] University of Pretoria, cnr Lynwood Road, and Roper Street, Hatfield, South Africa,
george.markou@up.ac.za

[4] Neapolis University Pafos
Department of Civil Engineering, 2 Danais Avenue, Pafos 8042, Cyprus;
g.makrou@nup.ac.cy

Keywords: *Machine Learning, Predictive Models, Train-Test Ratio, Error Metrics, Structural Mechanics*

Abstract

Within this research work, experimentally validated numerical models were developed to investigate the efficiency of Steel-Fiber-Reinforced-Polymer Concrete (SFRPC) jacketing when used to retrofit multistorey reinforced concrete (RC) buildings. The numerical models were validated through the use of a full-scale 4-storey RC building that was tested in Italy and parametrically investigated by Markou (2021). Thereafter, several models were modelled foreseeing different Steel Fibre-Reinforced Concrete (SFRC) jacket configurations. The models were numerically analyzed and it was concluded that the most effective retrofitting technique is achieved when all the structural joints are retrofitted excluding the roof joints. This resulted in an overall base shear increase of 42.7% and also resulted in significantly less strain accumulation in the structure joints.

1. INTRODUCTION

Seismic retrofitting is the strengthening of existing structures to make them resistant to seismic loads (Campbell, 1995). An in-depth study was performed on the effects that SFRC jacketing has on multi-storey buildings. SFRC consists of steel fibres mixed uniformly inside the concrete mixture giving it increased durability and ductility (Ruano et al., 2013). This effect leads to an increase in material toughness and strength. SFRC jacketing can be applied to beams, columns or joints depending on the reinforcing that is required to mitigate the effects of seismic loading.

Modelling large-scale RC structures by using Finite Element Modelling (FEM) is the most common numerical approach used by engineers (Ruano et al., 2013). FEM is highly effective in accurately capturing nonlinearities between the different materials in the geometry of the structure (Ruano et al., 2013). FEM is especially useful when a structure's complexity increases. At this point, calculations performed by an engineer tend to become extremely time-consuming and strenuous, leading to an increase in overall cost.

This research work uses advanced FEM modelling to capture accurate results in relation to the effect of retrofitting. The developed numerical models were compared to a full-scale 4-storey building that was created in Italy at the European Laboratory for Structural Assessment (ELSA) Facility (Dal Lago et al., 2018). The 4-storey building was modelled using the Hybrid Modelling (HYMOD) approach. The HYMOD approach simplifies the structure of the 4-storey building to reduce the number of elements present in the model which in return reduces the global stiffness matrix. If the HYMOD approach was not utilized then the computational demand would be high, and it would be extremely time-consuming to run the analysis of the model. This is due to the fact that more Random Access Memory (RAM) have to be allocated and more complex calculations need to be processed by the CPU when a full 3D detailed model is adopted.

Two primary types of retrofitting strategies are presently used, namely, global retrofitting and local retrofitting (Ranjan, 2016). Global retrofitting involves adding shear walls, steel bracing and infill structures. Local retrofitting involves the reinforcing of structural members like beams and columns by using RC jacketing, SFRC jacketing or Carbon Fibre-Reinforced Polymer (CFRP) jacketing (Ranjan, 2016). Steel fibres with higher pull-out strengths limit the propagation of cracks which leads to an increase in the material’s overall strength, toughness and ductility. Limiting the crack width in the retrofitting material is extremely important. If large cracks form in the retrofitted material, then there is an increased risk of debonding between the existing material and the retrofitted material (Ruano et al., 2013). By adding steel fibre to the mixture additional resistance is gained to plastic shrinkage cracking, fatigue resistance, shrinkage reduction and toughness (Ranjan, 2016).

For SFRC to be applied effectively to structures the outer layer of the existing joint needs to be chipped away to ensure adequate bonding between the layers (Tsonos, 2000). Additional horizontal ties and vertical reinforcement must be placed at the joint to provide adequate shear strength (Figure 1). However, it must also be noted that the biggest advantage of this scheme is that it can be used to repair and strengthen joints that have already suffered minor damage during previous earthquakes (Tsonos, 2000).

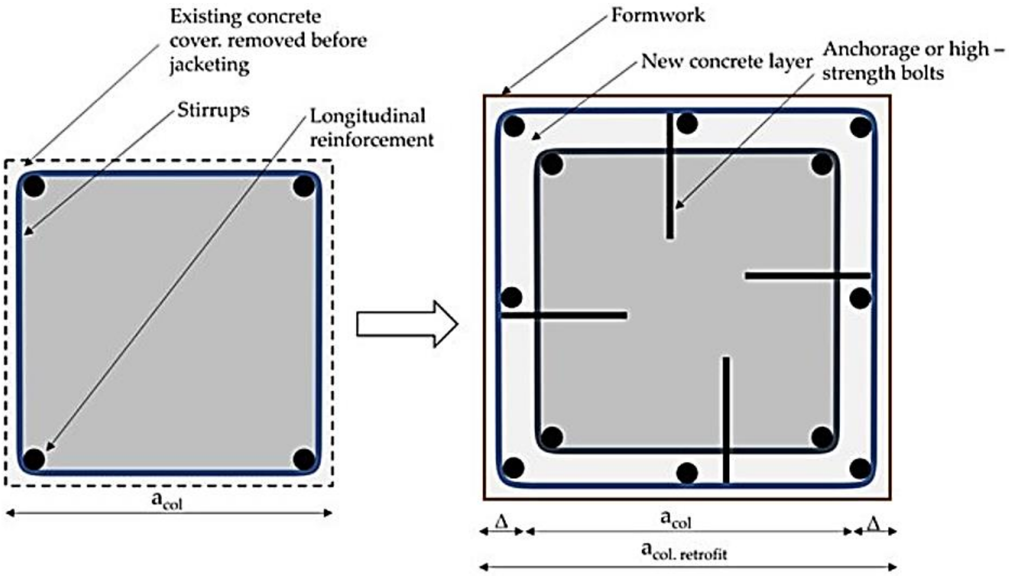

Figure 1: SFRCJacketing Approach (Skokandic, 2022)

When seismic loads develop on a structure the response of the structure is often governed by the joints. If the joints of the structure behave in a ductile manner, then it is likely that the whole structure will derive a ductile response. In addition, if the joints are brittle then the structure will fail in a brittle manner (Sharma et al., 2010). When seismic loads are present in the structure then beam-column connections are subjected to large shear stresses in the joint region. The large shear stress is the result of generated moments and additional shear forces that result from opposing members on either side of the joint (Sharma et al., 2010). These shear forces lead to diagonal cracking and/or crushing of the concrete in the joint (Figure 2).

Figure 2: Cracking of structural joints after an earthquake (Moslam, 2013)

2. NUMERICAL MODELLING

It is important to be able to develop a numerical model that is reliable and accurate therefore different methods were utilised to ensure numerically accurate results. Beam-column elements will be discussed first. The models can be categorized into two sections namely: Macro spring-based flexural-shear also called Euler-Bernoulli beam theory (Figure 3a) and the Timoshenko flexural-shear beam theory (Figure 3b). Euler-Bernoulli beam theory is when the plane sections remain plane and normal to the longitudinal axis of the beam resulting in no shear deformations (Feng & Xu, 2018). The Timoshenko beam theory is when the plane sections remain plane but rotate about the longitudinal axis after deformation. Hence the normal axis and the plane section represent the shear deformation (Mourlas, 2019).

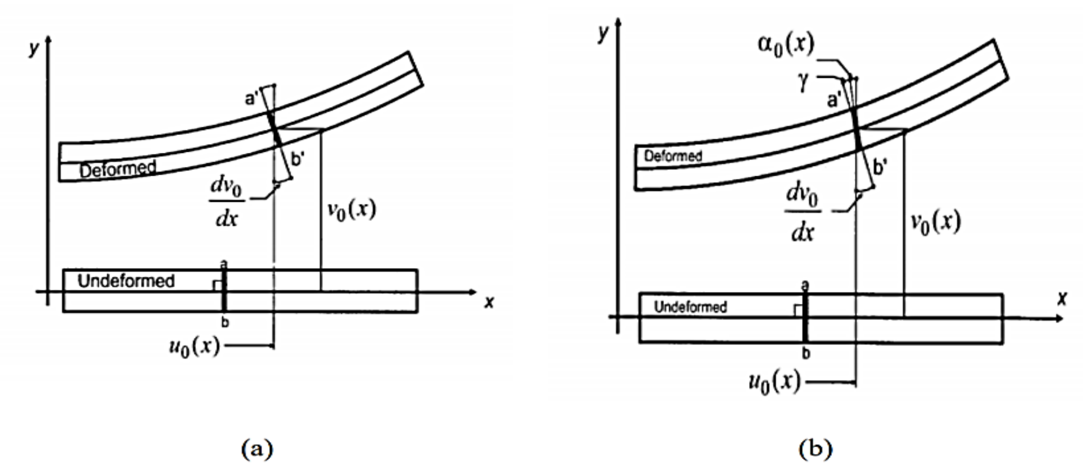

Figure 3: Beam element: (a) Euler Bernoulli beam theory, (b) Timoshenko beam theory (Mourlas, 2019)

Distributed models were also incorporated into the analysis of the building. These models distribute the material nonlinearity at Finite Element (FE) sections. The element behaviour is then derived by integrating at the section response level. Each cross-section describes the element in terms of stresses and strains (Mourlas, 2019). The fibre approach assumes that each cross-section is divided into separate layers forming fibres as shown in Figure 4. The stresses in each fibre are added together over the entire cross-section where the forces and the stiffness of the desired cross-section are calculated. The only drawback is that in the case of inelastic behaviour beams and columns must be subdivided into multiple elements for accurate results leading to high computational intensity (Mourlas, 2019). Therefore, an alternative and modified formulation has been developed to address this issue which is known as the force-based beam formulation (Markou & Papadrakakis, 2013). These natural beam-column flexibility-based

(NBCFB) finite elements are used for the needs of this research work where the HYMOD approach is adopted.

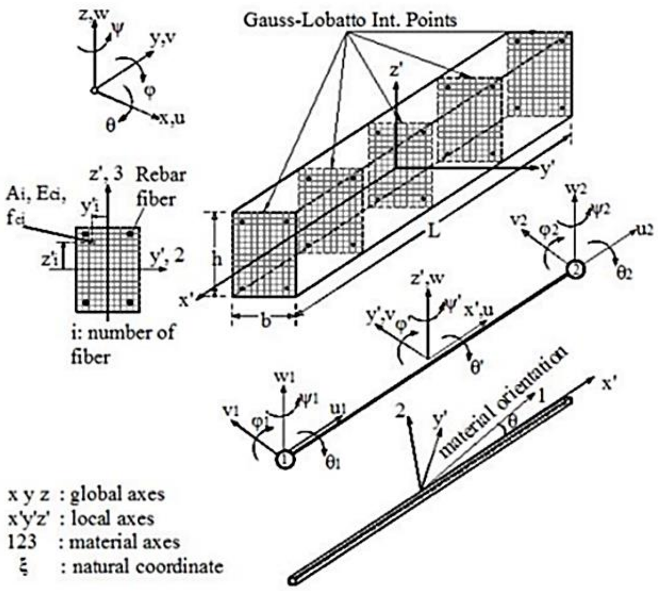

Figure 4: Distributed model method (Markou & Papadrakakis, 2013)

The HYMOD method foresees the use of hexahedral elements for discretizing the joints and shear walls, while rebars are modelled through the use of the embedded rod or beam FEs. When considering the steel reinforcement, the shear and bending stiffness are generally considered insignificant. However, when excessive cracking occurs with large shear deformations then the stiffness of the steel reinforcement can have a crucial role in the RC structure's behaviour. The interaction between hexahedral concrete elements with truss and beam-column steel bars is illustrated in (Figure 5).

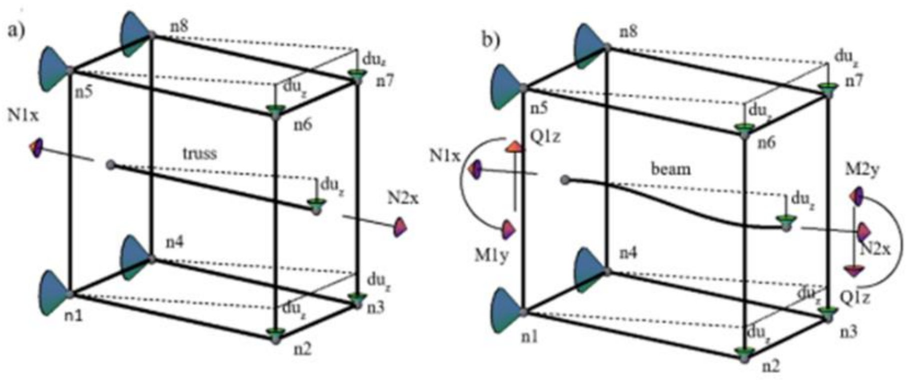

Figure 5: Embedded rebar elements under transverse deformation, (a) truss and (b) beam element (Mourlas, 2019)

The HYMOD approach was adopted to decrease computational requirements and still retain numerical accuracy (Markou & Papadrakakis, 2013). For the HYMOD method to be successfully applied two elements need to be combined namely: the isoparametric hexahedral finite element and the NBCFB fibre elements. The NBCFB element is a one-dimensional element and the 8-noded isoparametric hexahedral element is a three-dimensional element that consists of 24 Degrees Of Freedom (DOF). By implementing the HYMOD method, a mesh can be created that combines different types of elements that reduce the computational demand and still maintain numerical accuracy as investigated by Markou and Papadrakakis (2015).

The NBCFB elements ensure that the concrete section that needs to be simplified is divided into separate fibres. Each fibre is assigned a maximum tensile strength that is associated with that particular fibre. Each fibre is assigned a compressive strength of the material according to its location. The coupling between the hexahedral and NBCFB elements is achieved through kinematic constraints (as seen in Figure 6). The kinematic connection is illustrated in Equation 1.

$$u_{i_{(3x1)}}^{HEXA} = T_{im_{(3x6)}} . u_{m_{(6x1)}}^{NBCFB} \qquad \text{Equation 1}$$

with

$$T_{im_{(3x6)}} = \begin{bmatrix} 1 & 0 & 0 & 0 & z_i - z_m & y_m - y_i \\ 0 & 1 & 0 & z_m - z_i & 0 & x_i - x_m \\ 0 & 0 & 1 & y_i - y_m & x_m - x_i & 0 \end{bmatrix}$$

Where u_i^{HEXA} and u_m^{NBCFB} are the hexahedral nodes with 3 DOF per node and the displacement vectors of the NBCFB having 6 DOF. The subscript *i* of the coordinates in the global subspace x, y, z correlates to the hexahedral node ID found at the interface Ω_j^1, while subscript *m* refers to the NBCFB elemental node ID that controls the displacements of the interface section Ω_j^1 as depicted in Figure 6. The connection matrix is calculated from the compatibility condition of the NBCFB and hexahedral nodal coordinates.

The nonlinear behaviour of concrete is characterized by micro-cracks that form within the concrete domain, initiating larger cracks and ultimately failure of the concrete. The simulation of cracking on concrete is an important aspect of FEM to ensure accurate results when the model is analysed. When tensile forces reach the tensile strength of the concrete a crack is considered to occur (Mourlas, 2019). There are two major categories of modelling cracking namely: discrete and smeared crack methods. The smeared crack approach was utilised in this study. The smeared crack approach modifies the stiffness matrices and stresses at the respective integration points. Thus, the smeared crack approach uses simulations of individual cracks with (Figure 7b) or without (Figure 7a) re-meshing. To predict the direction of crack propagation the approach utilizes a failure criterion based on principal stresses. Therefore, it can be concluded that the re-meshing of the model is not needed when the approach is used as the smeared crack approach does require adding discontinuities in the FE mesh.

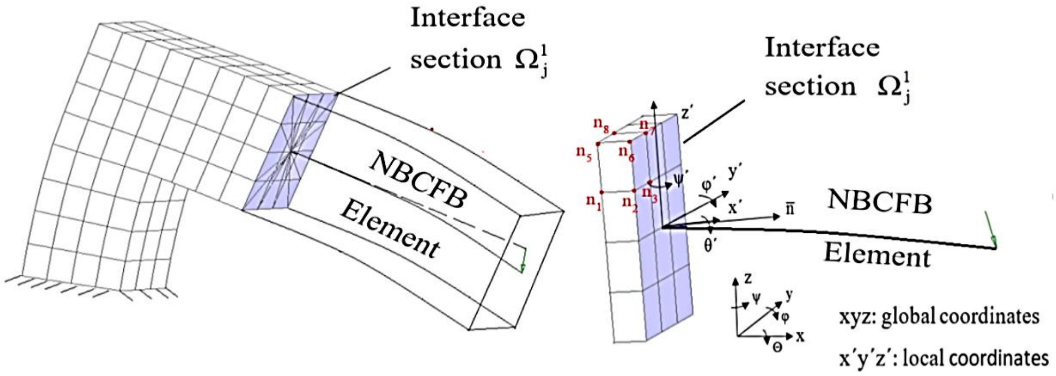

Figure 6: Hybrid model showing the interface between 1D and 3D elements (Markou & Papadrakakis, 2015)

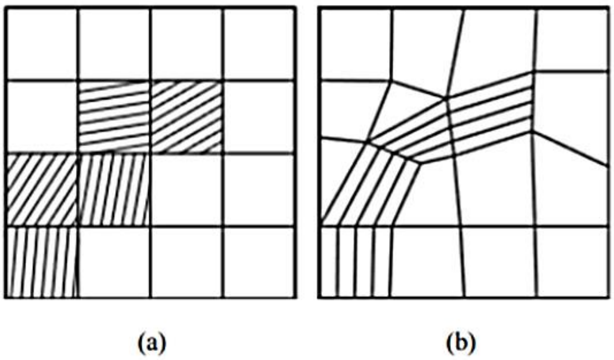

Figure 7: Smeared approaches: (a) Without re-meshing, (b) With re-meshing (Rama et al., 2014)

In addition to the modelling of crack propagation within the concrete domain damage factors were developed that take into account the opening and closing of cracks when computing damage accumulation. The modelling approach utilised in this project was developed by Markou et al. (2021). According to this research work (Markou et al., 2021) proposed a material model with a damage factor that accounts for accumulated damage within the surrounding concrete domain. This also effectively captures the slippage of embedded rebar elements. Mourlas et al. (2019) proposed to use two damage factors to take into account the opening and closing of cracks. This new method proved to work adequately as the model predicted the nonlinear behaviour of structures with pinching accurately. Markou et al. (2021) further extended the work of Mourlas et al. (2019) by integrating a new reduction factor which is defined by the accumulated crack damage. The new method captured the overall mechanical response of severely damaged concrete joints with intense pinching phenomena. Therefore, the new method accurately captures the degradation of concrete as cracks open and close as well as the effect that pinching has on the concrete domain, whereas it is used herein for the needs of this research work.

3. STRUCTURAL MODELLING

The experimental 4-storey building that was constructed in the ELSA facility went through 3 different loading sets that corresponded to 3 different earthquake intensity levels (Poljansek et al., 2013). The three different loading sets were applied with the first loading set experiencing a maximum displacement of 25 mm resulting in a relatively low 0.1g seismic acceleration. The second loading set experienced a maximum displacement of 125 mm corresponding to a high acceleration of 0.25g. On the final loading set the building was loaded with 3 cycles each reaching a maximum displacement between 100 mm and 125 mm until failure was reached at the last cycle (Markou et al., 2018).

A well-defined loading cycle needed to be implemented for the numerical model that had to take material damage into account due to the multiple cycles that the experimental building experienced. Markou et al. (2018) proposed the loading configuration seen in Figure 8 for the numerical investigation of the building. This configuration applies 7 loading cycles to replicate the damage induced by the first cycles in the experiment. The proposed cyclic loading also had a maximum displacement of 125 mm to obtain accurate results. This displacement history applied on the top floor, serves as a set of displacements that force the building to develop damages (preparatory cycles) and then the final cycles are applied in order to investigate the overall mechanical cyclic response of the building. This allows the direct evaluation of the building in cases where different retrofitting techniques are applied.

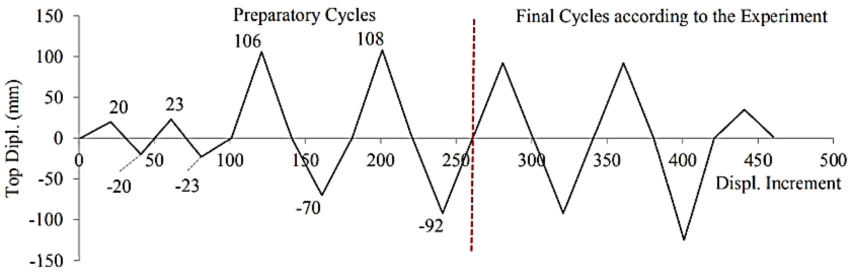

Figure 8: Displacement applied at the upper joints of the model (Markou et al., 2018)

According to the research work presented in this manuscript, the initial numerical model (bare RC frame as presented in Markou 2021) was retrofitted and analysed in 5 different stages resulting in 5 different models. Table 1 showcases the 5 different models, each one with a different SFRX jacket positioning. The entire beam-column joint of the model was retrofitted with 100 mm thick SFRC as shown in Figure 9b. In Figure 9a the modelled structure can be seen without any SFRC retrofitting around the beam-column joints, while in Figure 9b, the entire structure is retrofitted from the top of the foundation up to the roof joints.

Table 1: Type of retrofitting assigned to each model.

Model	SFRC Retrofitting Technique
NU0	Base model with no retrofitting.
NU1	SFRC jacket on top of the concrete to the bottom of the first floor.
NU2	SFRC jacket on the entire first-floor joints.
NU3	SFRC jacket on the entire first-floor and second-floor joints.
NU4	SFRC jacket on the entire first-floor to third-floor joints.
NU5	SFRC jacket on the entire first-floor to fourth-floor joints.

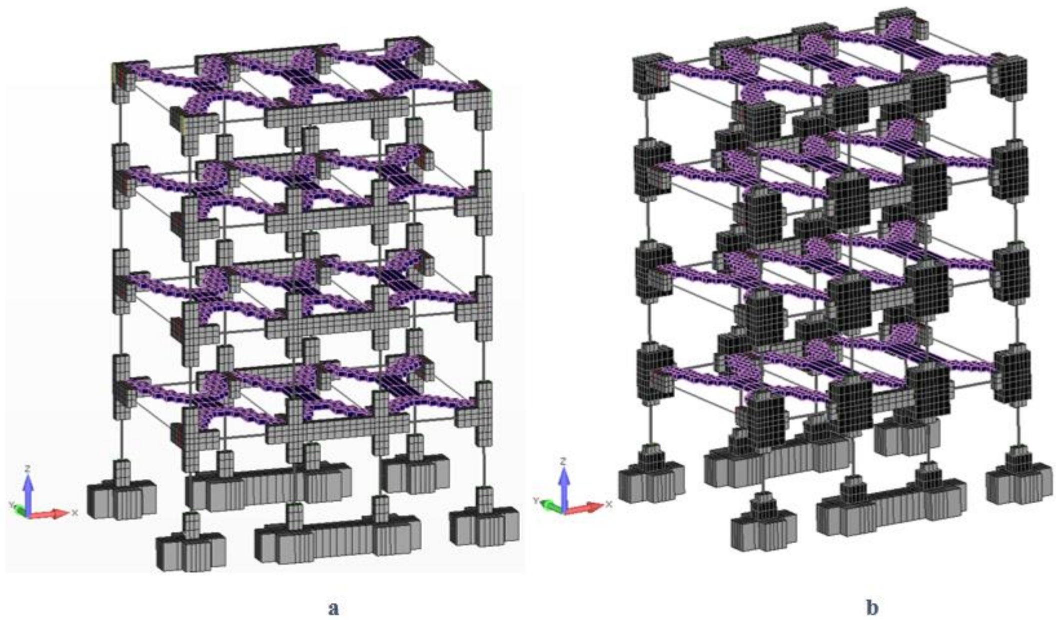

Figure 9: NU0 (a) and NU5 (b) finite element meshes being Depicted

4. NUMERICAL RESULTS

With the introduction of SFRC jacketing to the existing framing system, an increase in the stiffness and carrying capacity of the RC structure can be expected. It can however also affect the structure's mechanical response which can result in unforeseen failures. Therefore, further investigation is needed to be performed by comparing the RC structure with and without retrofitting. By analysing the base shear and strains that develop within the structure, it is possible to predict any unforeseen stress concentrations that develop within the structure's members by investigating the overall mechanical response of the structure under cyclic loading conditions.

By plotting the base shear versus displacement graphs, objective results can be obtained indicating the overall structural response. Base shear is an estimate of the maximum expected lateral force developed at the base of the structure (Fanaie et al., 2023). When the displacement cycle in Figure 8 is imposed on the structure, base shear reaction forces are generated and plotted. Looking at the base shear vs horizontal displacement diagram in Figure 10, it is clear that there was a significant increase in terms of base shear when comparing the base model (NU0) to the fully retrofitted model (NU5). A total base shear increase of 42.7% was observed with the maximum base shear increase being observed at the later cycles.

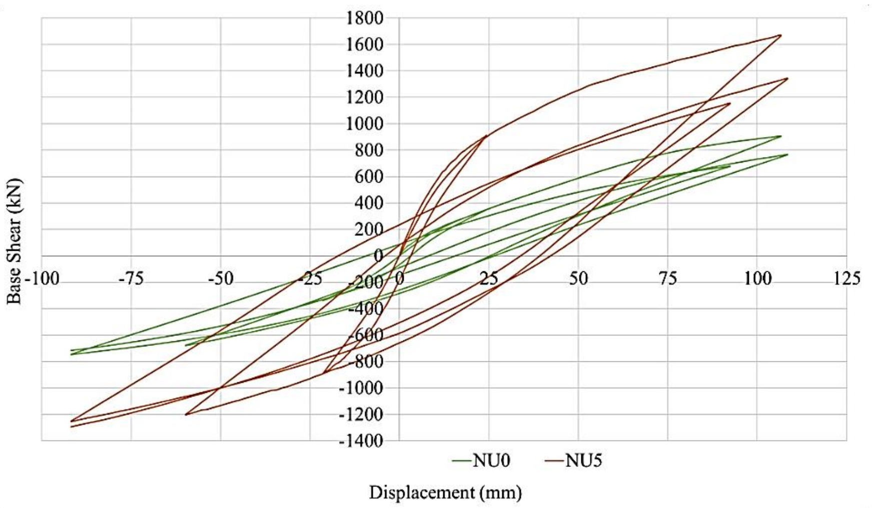

Figure 10: Base shear vs displacement graph for NU0 vs NU5 for the case of the final cycles

Figure 11 represents the percentage base shear improvement for different displacements compared to the base model. From Figure 11 it is clear that as each additional floor was retrofitted the overall base shear increased exponentially with the exception of NU5. The overall base shear increase between NU4 and NU5 was 1.9%, resulting in a minor structural response.

The difference between NU4 and NU5 is that the uppermost joints (roof joints) are retrofitted in NU5 and not in NU4.

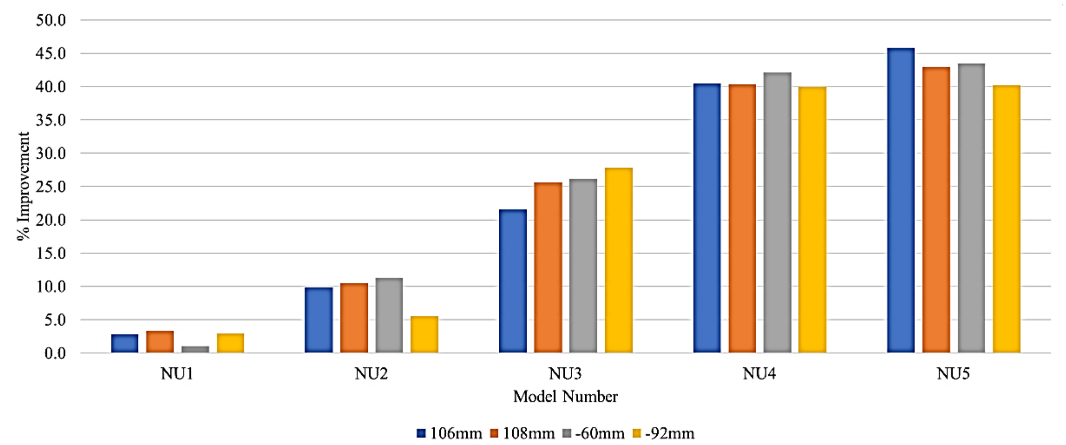

Figure 11: Bar chart indicating the base shear improvement compared to the base model at different displacements

Furthermore, von Mises strain contours are used to identify where damage in a structure concentrates. Therefore, the higher the von Mises strains in a certain region, the more damage occurs in that region. It is clear that the highest von Mises strain contours are observed at the joints of the structure as seen in Figure 12a for the case of the base structure. When comparing the base structure (Figure 12a) with the fully retrofitted structure NU5 (Figure 12b), it is evident that the SFRC retrofitting significantly reduces the strain concentrations within the joints, as well as distributing strain throughout the SFRC jacket.

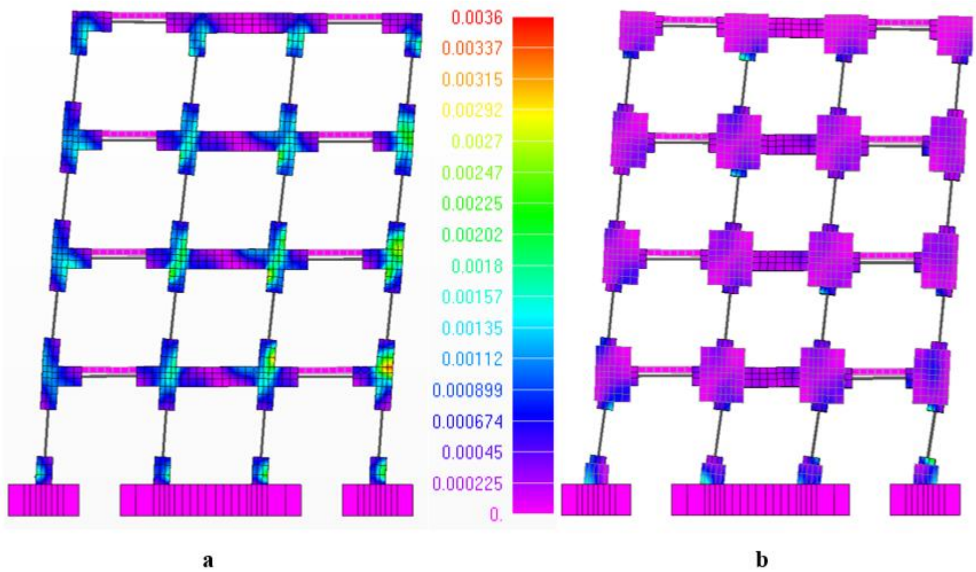

Figure 12: von Mises strain contours of NU0 (a) and NU5 (b)

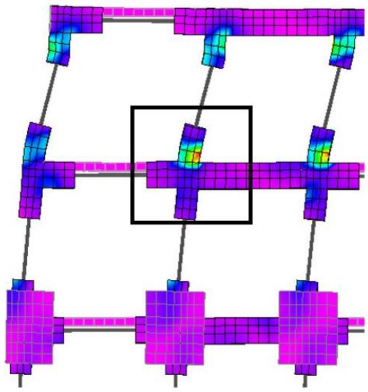

Figure 13: von Mises strain concentrations in model NU3

It is important to note that, the remaining floors of the RC structure that were not retrofitted, experienced an increase in strain concentration compared to the base structure of 9.4% as shown in Figure 13. This is attributed to the fact that as the floors below are retrofitted, they experience an increased stiffness and undergo a smaller displacement. Therefore, as the retrofitted floors are stiffened then the floors that are not retrofitted experience a larger deformation resulting in the development of strain concentrations. It was further observed that the damage reduction between NU4 and NU5 was minor with NU5 performing better by 2.6%.

5. CONCLUSION

Different SFRC jacketing configurations influenced the overall structural behaviour of the 4-storey RC structure. As the SFRC jacketing is implemented from floor to floor, the overall mechanical response of the structure improves significantly resulting in a stiffer and more robust structure.

By considering the base shear capacity it can be concluded that the structure experienced a large increase in terms of base shear with an improvement of 42.7% was the NU5 model where the entire structure was retrofitted. It is however not cost-effective to retrofit the uppermost floors of a multi-storey RC structure as it results in minimum improved base shear. This is attributed to the lower bending moments and shear forces that develop at the top floor during the cyclic analysis.

Furthermore, when looking at the von Mises strains it was found that the highest strain concentrations occur at the structural joints of the model. It is also noteworthy that as each additional floor was retrofitted, the damage at the retrofitted joint dissipated throughout the SFRC jacket matrix and therefore a smaller strain concentration was obtained.

In conclusion, it is recommended to retrofit the entire joint of the structure, as this is where the major structural damage occurred. It is also recommended to retrofit all the joints of the multi-storey RC building while excluding the roof joints for cost optimization reasons. When there are floor joints that are not retrofitted, additional strains may form in these joints causing additional damage leading to a poor ductile response of the retrofitted structure. This illustrates the importance of investigating the overall mechanical response of the RC building instead of designing each structural member in an isolated manner. Finally, it is not needed to retrofit the uppermost roof joints of the multi-storey RC structure as the additional capacity obtained is negligible. Furthermore, according to the findings and the numerical investigation, it was found that by using SFRC jacketing as retrofitting, the multi-storey RC structure's mechanical response was improved by more than 40%. Finally, model NU4 is regarded as the most effective solution to the given problem if cost-effectiveness is accounted for.

REFERENCES

Feng, D. and Xu, J. 2018. An efficient fiber beam-column element considering flexure–shear interaction and anchorage bond-slip effect for cyclic analysis of RC structures. *Springer Nature,* Vol 16, No 11, November, pp 5425–5452.

Markou, G. and Papadrakakis, M., Computationally efficient 3D finite element modelling of RC structures. Computers and Concrete, Vol 12, No 4, May, pp 443-498, 2013.

Markou, G., A new method of seismic retrofitting cost analysis and effectiveness for reinforced concrete structures. ELSEVIER, Vol 246, No 1, November, pp 1-22, 2021.

Markou, G. and Papadrakakis, M. 2013. Computationally efficient 3D finite element modelling of RC structures. *Computers and Concrete,* Vol 12, No 4, May, pp 443-498.

Markou, G. Garcia, R. Mourlas, C. Guadagnini, M. Pilakoutas, K. and Papadrakakis, M. 2021. A new damage factor for seismic assessment of deficient bare and FRP-retrofitted RC structures. *ELSEVIER,* Vol 248, No 1, December, pp 113-152.

Markou, G. Mourlas, C. Bark, H. and Papadrakakis, M. 2018. Simplified HYMOD non-linear simulations of a full-scale multistorey retrofitted RC structure that undergoes multiple cyclic excitations – An infill RC wall retrofitting study. *ELESVIER,* Vol 176, No 1, December, pp 892-916.

Mourlas, C. 2019. *An Accurate and Computationally Efficient Three Dimensional Nonlinear Model For The Analysis of Large-Scale RC Structures Subjected to Cyclic and Dynamic Loading Conditions.* PhD thesis. National Technical University of Athens.

Ranjan, P. 2016. *Retrofitting of columns of an existing building by RC, FRP, SFRC and steel jacketing techniques.* PhD thesis. Jaypee University of Information Technology.

Ruano, R. Isla, F. Pedraza, R.I. Sfer, D. and Luccioni, B. 2013. Shear retrofitting of reinforced concrete beams with steel fiber reinforced concrete. *ELSEVIER,* Vol 54, No 1, March, pp 646-658.

Sharma, A. Genesio, G. Reddy, G.R. Eligehausen, R. Pampanin, S. and Vaze, K.K. 2010. *Experimental Investigation on Seismic Retrofitting of Reinforced Concrete BeamColumn Joints.* CORE. 14th Symposium on Earthquake Engineering No A007, Roorkee India.

Skokandic, D. Vlasic, A. Maric, M.K. Sribic, M. and Ivankovic, M. 2022. Seismic Assessment and Retrofitting of Existing Road Bridges: State of the Art Review. *MDPI*, Vol 15, No 7, March, pp 120-144.

Tsonos, A.G. 2000. *Lateral load response of strengthened reinforced concrete Beam-to-column joints.* Indian Institute of Technology. 12th World Conference on earthquake engineering No 1225. Kanpur India.