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Finite Modeling of RC Column Strengthen by Different Retrofitting Techniques and Their Comparisons

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Abstract

Reinforced Concrete (RC) columns are the most important structural elements that may deteriorate due to aging, environmental exposure etc. Then it requires strengthening to enhance their load-carrying capacity, ductility, and durability. In this study, three dimensional finite element model was developed by using advanced FEM software (ABAQUAS), incorporating material property, interfacial bond behavior, and contact interactions for each retrofitting techniques. From FEM analysis, the effectiveness of each retrofitting techniques in improving load-bearing capacity, and failure mechanisms under axial loading conditions and cost effectiveness was evaluated. Results found from analysis indicate that all three techniques significantly enhance the strength and deformation capacity of RC columns. Concrete jacketing showed the highest strength gain at low cost but introduced challenges related to increased cross-sectional dimensions. FRP wrapping showed moderate strength gain but it is very costly. Steel plate bonding showed lowest strength gain at moderate cost among the three techniques. A comparative framework to guide the selection of retrofitting techniques based on structural requirements and economic.

Keywords: *Concrete Jacketing; Steel Plate Bonding; FRP Wrapping; FEM.*

1 Introduction

The stability of buildings and other infrastructures forms one of the most vital issues in civil engineering particularly in the areas susceptible to earthquake occurrences, deterioration of older infrastructures or initial substandard design and contracting. As a main load-bearing member in most of the buildings, reinforced concrete (RC) columns are effectively critical to the stability and safety of buildings. But over a period due to exposure to the environmental conditions, any sudden load or due to design faults, most of the RC structures can be structurally deficient or due to incompetent designs rendered as functioning obsolescence. In some of these cases, demolition and ensuing construction may not necessarily be either economically or logistically possible. Rather, retrofitting methods are becoming more common as source of sustainable and viable strategy to improve existing buildings and putting off their commencement of service. This study will focus on retrofitting techniques such as: Concrete Jacketing, FRP Wrapping, Steel Plate bonding.

Reinforced Concrete (RC) Jacketing has a huge advantage in terms of increased both axial load carrying capacity and ductility but entails a large increase in section size and curing time. Anand et al. (2020) recorded 156.4 % load increase capacity in columns under the RC jackets 100 mm thick, however 16.25 % overestimation is obtained because of idealizations of bond conditions. Sakr et al. (2019) stated that self-compacted concrete jackets using shear connectors do not result in de-bonding due to the ability of showing the performance of near monolithic behavior. Nevertheless, the mass of this method and space requirements do not allow its use in cramped spaces. Steel Plate Bonding is fast to implement, has excellent strength-to-weight ratio, diminishes ductility and may be corrosive. Mohsen et al. (2024) discovered that the optimum plate thickness was 6 mm, where maximum failure loads were increased by 52.6 % and yield strength was augmented by 60 % and that the deflections were decreased by 51 %. According to Ahmed et al. (2015), they observed diminishing returns greater than 6 mm thickness. Zhang et al. (2012) recorded that the yield load increased at 44 kN (5 mm plates) and 169 kN (8 mm plates). Healthy economics is undermined by the necessity of corrosion protection. Fiber-Reinforced Polymer (FRP) Systems are preferred in seismic retrofits because of their lightweight nature and not being corroded thus encountering anchorage problem and expensive. Del Zoppo et al. (2018) proved the advantage of a CFRP for low-strength columns of concrete because high-rigid fabrics (FRP) contribute 81 % more to ductility. The increase in CFRP load capacity was between 39 % and 99 %, although the ductility was also lower than in RC jackets, Vandoros et al. (2008). But the large scale project cannot use material cost that is prohibitively expensive.

Key research gaps includes FEM based comparison of different retrofitting techniques and their cost comparison is limited in respect of Bangladesh. The key objective of the study is to simulate retrofitted RC columns using different strengthening technique, assess their structural behavior and comparison. The structural behavior will be evaluated by determining the load-bearing capacity, energy absorption capacity before failure and failure modes for each technique. Finally, the retrofitting methods will be compared to identify which technique can sustain the highest load, how their failure modes differ from each other and which option proves to be the most cost-effective.

2 Methodology

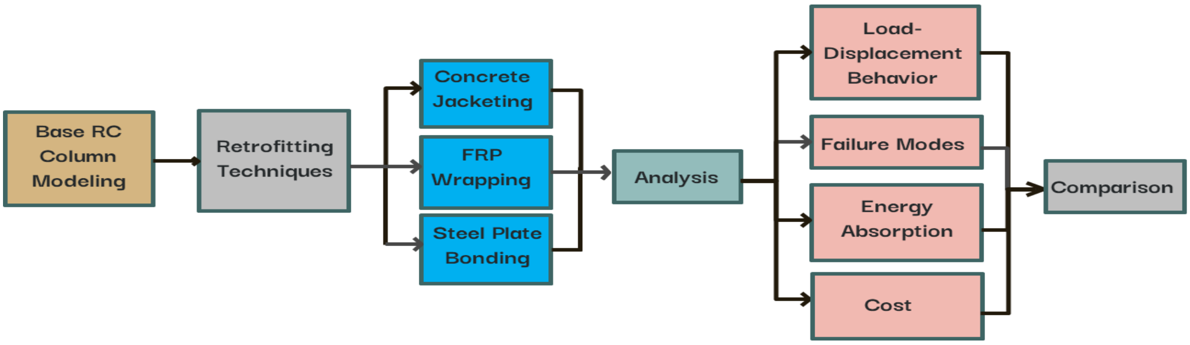


Figure 1. Flow Diagram of the Methodology

Figure 1 shows the overall research methodology followed in this study. The process start with the modeling of a base RC column in ABAQUS using realistic material properties for concrete and reinforcement. After establishing the base model, three retrofitting techniques were applied separately: concrete jacketing, FRP wrapping, and steel plate bonding. For each retrofitted model, detailed specifications were assigned including section size, reinforcement, material grades, and bond interaction properties. Once the models were prepared, a series of analyses were conducted to evaluate load–displacement behavior, peak load capacity, failure modes, energy absorption, and construction cost (calculated using the PWD Schedule of Rates, 2022). Finally, the results from each retrofitting technique were compared to the base column and to one another. The comparison framework allowed assessment of both structural performance (strength gain, ductility, failure mechanism) and economic efficiency (cost per unit strength gained).
Table 1-7 shows the specification, Model name and configuration for base column and each retrofitted column.

Table 1. Specification of Base column

Parameter	**Value**
Column Size	300×300×3000 mm
Main Reinforcement	8 bars of 16 mm
Stirrup	8 mm @ 150 mm c/c
Concrete Grade	M20
Steel Grade	S400

Table 2. Specification of Steel Plate Bonding

Parameter	**Value**
Vertical Plate Size	3000 × 60 × 5 mm (8 plates total)
Transverse Plate Layers	15 layers × 4 straps
Plate–Concrete Interaction	Frictional (μ = 0.3)
Plate–Strap Interaction	Frictional (μ = 0.2)
Modeling Element	C3D8R (Solid for both parts)

Table 3. Specification of Concrete Jacketing

Parameter	**Value**
Total Section Size	450 mm × 450 mm
Jacket Thickness	75 mm (all sides)
Jacket Main Bars	8 bars of 16 mm
Stirrup (Jacket)	8 mm @ 150 mm
Shear Connectors	12 mm @ 200 mm

Table 4. Specification of FRP Wrapping

Parameter	**Value**
FRP Type	CFRP
Thickness	2 mm
Application	External wrapping
Elastic Modulus	150 GPa
Tensile Strength	2400 MPa

Table 5. Model name and configuration for Steel Plate Bonding

Specimen Name	**Column Size (mm)**	**Vertical Plate Size (mm)**	**Plate Thickness (mm)**	**Steel Grade**	**f_y (MPa)**

S-S235	300 × 300	3000 × 60	5	S235	235
S-S275	300 × 300	3000 × 60	5	S275	275
S-S355	300 × 300	3000 × 60	5	S355	355

Table 6. Model name and configuration for Concrete Jacketing

Specimen Name	**Length including core column (mm)**	**Width including core column (mm)**	**Jacket Thickness (mm)**	**f'_c(MPa)**	**f_y (MPa)**
J-C20,S400	450	450	75	20	400
J-C20,S500	450	450	75	20	500
J-C30,S400	450	450	75	30	400
J-C30,S500	450	450	75	30	500
J-C40,S400	450	450	75	40	400
J-C40,S500	450	450	75	40	500

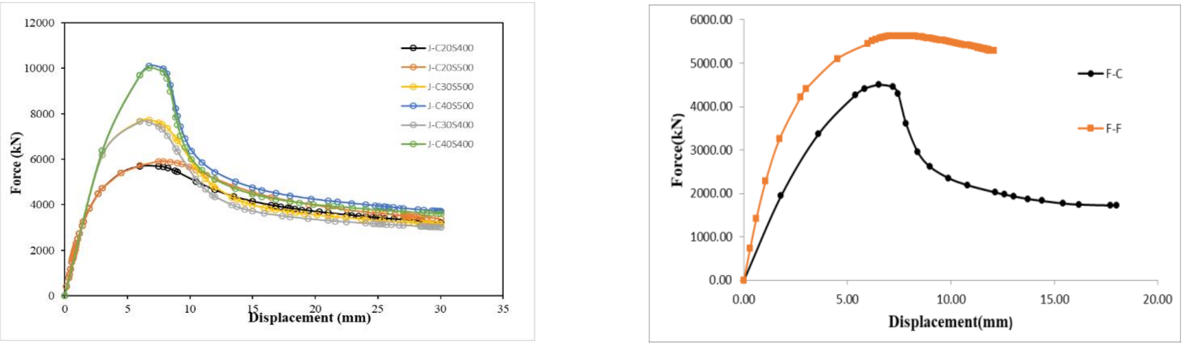
Table 7. Model name and configuration for FRP Wrapping

Specimen Name	**Column Size (mm)**	**FRP Thickness (mm)**	**Bond Type**	**f'_c (MPa)**	**Fiber Type**
F-C	300 × 300	2	Cohesive	20	CFRP
F-F	300 × 300	2	Frictional	20	CFRP

3 Results and Discussions

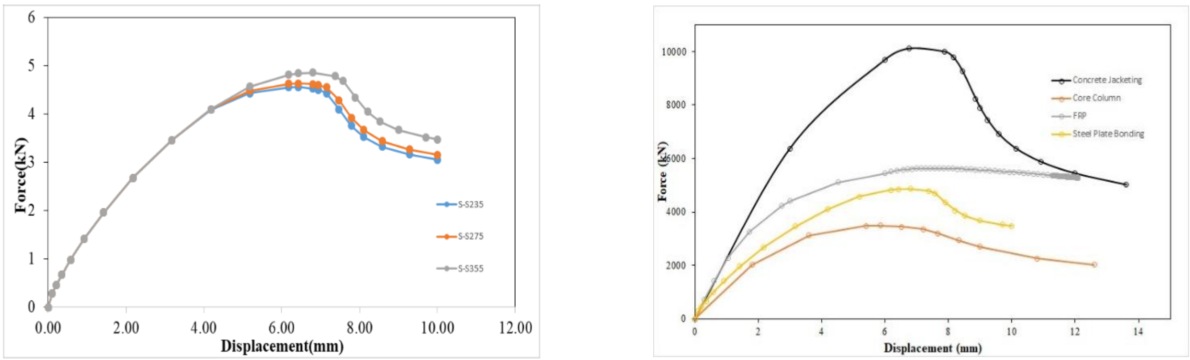
This section presents the outcomes of the finite element analysis for the base RC column and retrofitted columns. The results are discussed in terms of load–displacement behavior, failure modes, cost comparison, and energy absorption. These parameters provide a comprehensive understanding of how each retrofitting technique influences the structural performance and economic feasibility of RC columns.

3.1 Load Displacement Behavior Comparison



(a) All Concrete Jacketing Model

(b) All FRP Wrapping Model



(c) All Steel Plate Bonding Model

(d) Comparison of only peak load with Base column

Figure 2. Variation of Force with respect to Displacement

Figure 2 (a) shows load capacity for all concrete jacketing models gradually improves when concrete grade and steel strength increase. J-C40, S500 performs best due to the most robust material combination. Figure 2 (b) shows that the friction model carries more load then cohesive model because it allows continuous contact and gradual stress transfer. In the cohesive model, the bond breaks earlier which reduces its load-bearing capacity. Figure 2 (c) shows load capacity for all Steel plate bonding models gradually improves when steel strength increase. S-S355 has higher load-carrying capacity because it uses higher-grade steel, which provides greater strength and stiffness. This allows S-S355 to resist more axial load before yielding or plate buckling occurs. Figure 2 (d) shows the Comparison of three types of retrofitting (Considering only highest one) with base column. All retrofitted models outperformed the core column in both strength and deformation capacity by enhancing the load-bearing capacity and ductility of RC columns.

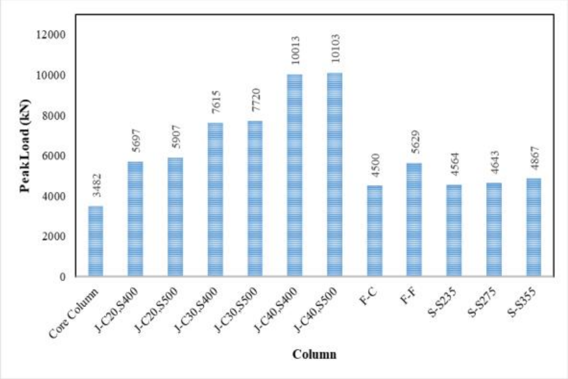


Figure 3. Peak load for different model

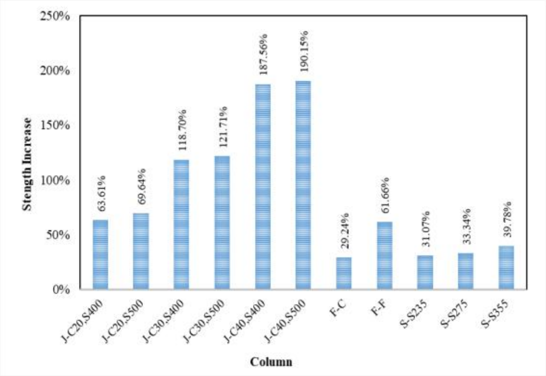


Figure 4. Strength increment for different retrofitted column

Figure 3 shows that all retrofitting techniques has increased the peak load compared with the core column. Among them, concrete jacketing (J-C40, S500) achieved the highest value of about 10,103 kN, nearly double the base column. The improvement was consistent with higher grades of concrete and steel. Steel plate bonding also improved capacity, though with the gain was limited. FRP wrapping showed the lowest capacity, with the frictional model (F-F) performing better than the cohesive model (F-C) due to more continuous stress transfer. The lowest peak load is 4500 kN for FRP (F-C). Figure 4 shows the percentage increase in strength for each retrofitting method. Concrete jacketing showed the highest gain (~190%), making it the most efficient strengthening technique. FRP wrapping provided moderate improvement (~62%), with better performance in the frictional bond model. Steel plate bonding had the lowest gain (~40%), reflecting its limited contribution beyond surface confinement.

3.2 Failure modes Comparison

Table 8. Failure mode comparison of core column and three retrofitting techniques

Technique	Generalized Failure Mode
Core Column	concrete crushing and diagonal shear cracks
Concrete Jacket	Flexural/Shear failure with gradual concrete crushing
FRP Wrapping	FRP De-bonding or Interface Slip
Steel Plate Bonding	Interface De-bonding or Plate Yielding

Table 8 presents comparison of the generalized failure mode of core column and three retrofitting techniques. The core column experienced a brittle failure characterized by unconfined concrete crushing and the development of diagonal shear cracks. In contrast, the concrete jacket retrofitting technique exhibited a more ductile failure mode, combining flexural and shear mechanisms with a gradual process of concrete crushing. Failure of the FRP wrapping system occurred primarily through de-bonding of the FRP material or interface slip as tensile strain increased. Similarly, the steel plate bonding technique failed due to either interface de-bonding or yielding of the steel plate. Each retrofitting method altered the failure mechanism from the original brittle shear failure of the core column, introducing varying degrees of ductility and stress redistribution, though all ultimately reached a limit governed by the integrity of their respective interfaces or the tensile capacity of the strengthening material.

3.3 Cost comparison

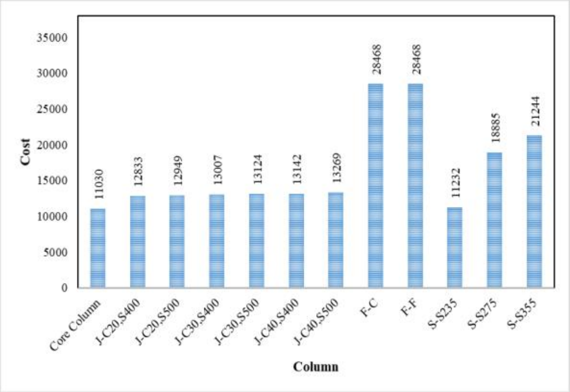


Figure 5. Total cost for different retrofitted column

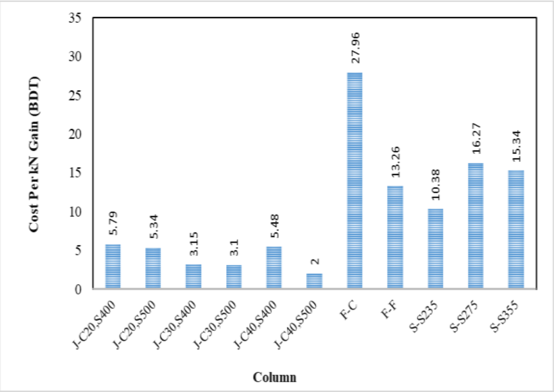
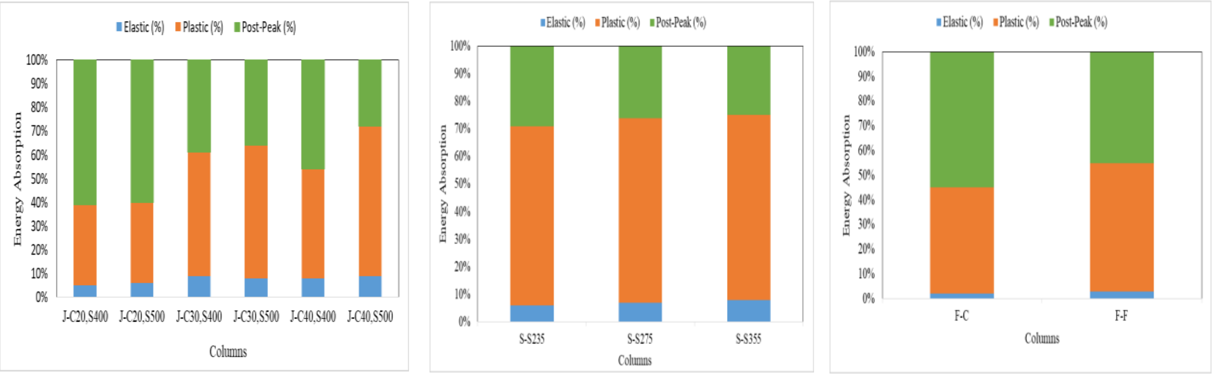


Figure 6. Cost for per kN strength gained by different retrofitted column

The two bar charts in Figures 5 and Figure 6 compare the construction cost of different retrofitted columns and the cost per unit strength gained based on PWD Schedule of Rates (2022). Concrete jacketing was found to be the most economical technique, providing the highest strength gain at the lowest overall cost. Steel plate bonding required a moderate investment, while FRP wrapping was significantly more expensive due to the high material cost of CFRP sheets. When considering cost efficiency per kN of strength gained, concrete jacketing again outperformed the other methods, showing the best balance between structural improvement and expenditure. Concrete Jacketing is the most cost effective for gaining strength. Steel plate bonding offered moderate efficiency but its relatively lower strength increment reduced its cost-effectiveness. FRP wrapping was the least economical option as the additional strength achieved came at a disproportionately higher cost. In summary, concrete jacketing proved to be the most cost-effective retrofitting method, steel plate bonding offered a reasonable balance and FRP wrapping effective in strength enhancement was limited by high material costs.

3.4 Energy Absorption Comparison



(a) (b) (c)

Figure 7. Energy Absorption Comparison (a) Concrete Jacketing model
(b) Steel plate bonding model (c) FRP Wrapping model

Figure 7 based on the comparative evaluation of energy absorption, distinct behavioral trends are observed across the three retrofitting techniques. 7 (a) shows that, as concrete & steel grade increase plastic energy absorption increases for all Concrete jacketing and Post-peak energy absorption decreases meaning more brittle failure tendency. In case of FRP wrapping as bond type shifts from cohesive to friction, plastic energy absorption increases post-peak energy absorption decreases so overall ductility reduces shows in Figure 7 (b). For steel Plate Bonding as steel grade increases Plastic energy absorption increases in small portion and Post-peak energy absorption decreases so overall ductility reduces shows in Figure 7 (c). Consequently, while all three methods enhance plastic energy absorption to varying degrees, this improvement is consistently accompanied by a trade-off reduction in post-peak energy dissipation that compromises overall ductility and promotes a more brittle failure mode.

4 Conclusion

This study numerically evaluated RC columns retrofitted with concrete jacketing, FRP wrapping and steel plate bonding in ABAQUS. All retrofitting method was simulated using realistic material behavior such as Jacketing with shear connectors, FRP with cohesive or friction bonds, Steel Plate Bonding with contact interface etc. Following the simulation phase, the structural behavior of each retrofitted column was evaluated, revealing a consistent improvement in strength after retrofitting for all techniques. Concrete Jacketing shows the highest strength gain (~190%), FRP shows moderate strength gain (~62%) and Steel Plate Bonding shows the lowest strength gain (~40%). Analysis of results indicated that failure mode varies for each retrofitting techniques. Though core column failed in a brittle manner, majority of the retrofitted columns failed in a ductile manner through flexure. Cohesive FRP models exhibited gradual de-bonding as opposed to slip and focal cracking in bonded models with steel plates. A comparative analysis of these retrofitting technique was consequently conducted, highlighting the distinct advantages and limitations of each technique. Concrete jacketing emerged as the most effective solution for maximizing strength gain while remaining relatively low in cost, making it highly suitable for applications. Conversely, FRP, though offering a reasonable strength increase and the benefit of being lightweight, involves higher material costs. While steel plate bonding moderately priced, provides the least strength enhancement among the three methods. The choice of appropriate retrofitting techniques depends a balance of desired strength improvement, budget constraints, and weight considerations. In future, experimental validation, combined, seismic and eccentric loading application, durability assessment, hybrid techniques application, system-level analysis may apply for this study. The benefits of such advancements are that they are needed to ensure safe and good service out of ageing infrastructure as well as in vulnerable and sensitive regions in the world.

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