Proceedings of 2nd International Conference on Climate Change and Emerging Trends in Civil Engineering CCETC-2025

Comparative Analysis of Partial and Full CFRP Retrofitting Approaches for Enhancing Structural Integrity in Reinforced Concrete Frames After Column Removal

Muhammad Zikria Luqman[1*], Mohammad Aamir[1], Hamza Yousaf [1], Rizwan Syed[1]

[1] Department of Civil Engineering, Ghulam Ishaq Khan Institute of Engineering Sciences and Technology, Pakistan

* Correspondence: zikriyaluqman@gmail.com

Abstract

Columns form an important part of structural RC frame because they carry the vertical and lateral loads down towards the foundation. When they collapse or are torn down because of the changes in space or accidental destruction, the threat of successive collapse appears much more probable. The conventional retrofitting process of carbon fiber-reinforced polymer (CFRP) normally involves full surface application that ultimately demand clearance of site, exposure of buildings, and discontinuation of business. This paper is fitted with yet another area of retrofitting in which bare column faces are isolated in order to be retrofitted so as to ensure that the impact is reduced to a minimum in an effort to produce a major improvement in the building. Partial and full CFRP retrofitting method was applied in determination of structural behavior of a three-story reinforced concrete frame under column removal loading conditions using state of the art modeling software (such as Tekla and ETABS). It shows that retrofit using bare surfaces can be highly effective, especially in load capacity and in stability, and it provides a low cost and operationally feasible option. The approach minimizes downtimes, does not require demolition and makes it possible to have constant functioning, so it is most appropriate in retrofitting projects of existing structures.

Keywords: Column Removal, Retrofitting, CFRP, Unconventional Methods

1. Introduction

Column is the simplest elements of the reinforced concrete (RC) structures as columns are the base loading members of the buildings to transfer the vertical and lateral loads to the foundations. They also act as structural components resisting dynamically and statically any seismic loads and winds. The component of loss of integrity of these columns due to damage or wear and tear of the materials or even a systematic removal done during the alteration of space has the possibilities of progressive collapse, failure condition in which the collapse of one component triggers a cascade effect that endangers the rest of the structure. [1]

Column removal or alteration is widely desirable to accommodate the new architectural trends in the form of open spaces. Despite the fact that such modifications are made to satisfy both functional and aesthetic requirements, this disrupts the load paths and introduces structural performance weaknesses. Redistribution of loads surpasses member strength around the member, which increases the probability of localized failure, a reason as to why it is important to consider retrofitting to be able to reinstate stability and safety.[2]

Retrofitting is a crucial intervention into structural retrofit to offset the shortcomings brought about by either damage, faulty design or the changed loading conditions. Among the other ways of retrofitting, carbon fiber-reinforced polymer (CFRP) has emerged by way of its exceptional properties of high tensile strength, light weight and freedom to environmental degradation. Flexural and shear, strengths of beams and load capacity of columns ductility have responded well through CFRP application. The amount of additional weight due to the CFRP retrofitting on the structure is very little compared to other conventional methods such as steel jacketing or concrete overlays and it hence emerges as a better alternative to retrofitting needs today. [3]

Although there are many benefits available that come with concrete fiber-reinforced polymer (CFRP) retrofitting, the traditional methodologies usually involve a full surface coverage of the structure. This kind of method requires a thorough work on site involving clearance, demolition, and exposure of structural elements which can halt building occupancy and activity. At times of partial cover - and in most cases columns are covered with partition walls or architectural finishes and enclosing the shaft entirely with a fiber-reinforced polymer is impractical. Such situations pose difficulties to development of retrofit strategies that would correct structural faults and at the same time maintain functionality, without extensive demolition.[4]

The given study examines the retrofitting approach that focuses on improving the exposed surfaces of partly exposed columns instead of the whole structure to consider the situation where thorough accessibility may not be achieved. The technique uses reinforcement with CFRP on limited areas and positions that can be accessed easily and plans to regain the stability of structures with less impact on the other services that are run, or additional expenses needed. Partial retrofitting is possible, and structural modelling and analysis, performed using the advanced programs like Tekla and ETABS confirm this possibility. Sequential column removals on a three-storey reinforced-concrete framed building using computational simulations indicate performance due to a variety of commonly applied loads, dead, live, seismic and wind as well as full- and partial-retrofitting situations. The research report shows partial retrofi tting to be an effective option to address in-service inadequacies and a viable and cost-effective alternative to optimise the resiliency of the structure with limited access. [5]

The results of the present study prove that retrofitting of only the exposed sides is likely to be a good approach in significantly increasing the compressional strength of reinforced-concrete (RC) columns, as well as its stability. This will not be subject to the scale of complete retrofitting whose process requires total destruction of the structure together with its closure on-site with all the inconvenience that would come with it and losses to productivity. The partial retrofitting is also very cost effective which makes the technique especially appealing in cases of facility/project that is restricted in terms of time or constrained finances. Whereas beams often pose less complications since they are easily accessible, columns demands a more creative method of reaching internal or otherwise unreachable surfaces. This is the approach that fits into the modern construction priorities to give more priority on being sustainable, usable and economical and yet keep structures that are safe and resilient.[6]

2. Materials and Methods

This research aims to evaluate the structural behavior of a three-story reinforced concrete (RC) frame building, focusing on the effects of column removal and the application of CFRP retrofitting. Figure 1 illustrates the flow chart outlining the methodology, which includes the following key steps:

2.1 Target Structure and Dimensional Setup

The structure consists of three bays, each with a width of 4 meters, and a height of 3 meters for each story. The total building height is therefore 9 meters. The building is modeled in Tekla software, considering all columns as part of the initial design.

2.2 Materials

The materials used for the building framework are concrete, steel, and CFRP (Carbon Fiber Reinforced Polymer), each of which has been picked based on its characteristics. The compressive strength of the concrete is 4000 Psi, which is required for the load bearing on the structure. The steel chosen has a tensile strength of 60 ksi, which offers the required strength to counteract tension and provide stability to the structure. To reinforce, CFRP is used with particular properties of 83,333.33 MPa for shear modulus, 0.5% for elastic modulus, 0.5% for damping ratio, and 0.05 sec for the stiffness coefficient. All these properties of the material are significant for realizing the building performance under dynamic loading conditions like seismic and wind forces.

2.3 Modeling and Boundary Conditions

The model is developed in Tekla Structures with restraint at the foundation level, representing actual foundation restraints. All columns are initially included, but two middle columns are cut out during the analysis later to observe the structure's behavior under the modified configuration. After the primary analysis, the model is transferred to ETABS for the retrofitting procedure, where further alterations and reinforcement measures are carried out to enhance the building's performance under different loads.

2.4 Loading Combinations

To achieve more realistic results, a building structure will be put under various forms of load. It is a uniform dead load making a slab dead load of 1.1kN/m 2 and a beam dead load of 0.9 kN / m 2 - which is referred to as the weight of the elements of building and walls. Slab is then subjected to a dead load of 2.28 kN/m 2 together with a uniform live load of 2.63 kN/M 2 prescribed to represent the building occupation and use. The default seismic parameters applicable to the site with regard to X and Y directions of seismic loading as per ASCE 7-22 are used. According to ASCE 7-22, wind loads will be applied in both the X and the Y directions, with a wind speed of 85 mph and an exposure type D based upon the location of Islamabad. These diversely loaded conditions give a fair analysis of how the structure will respond when exposed to different environmental forces.

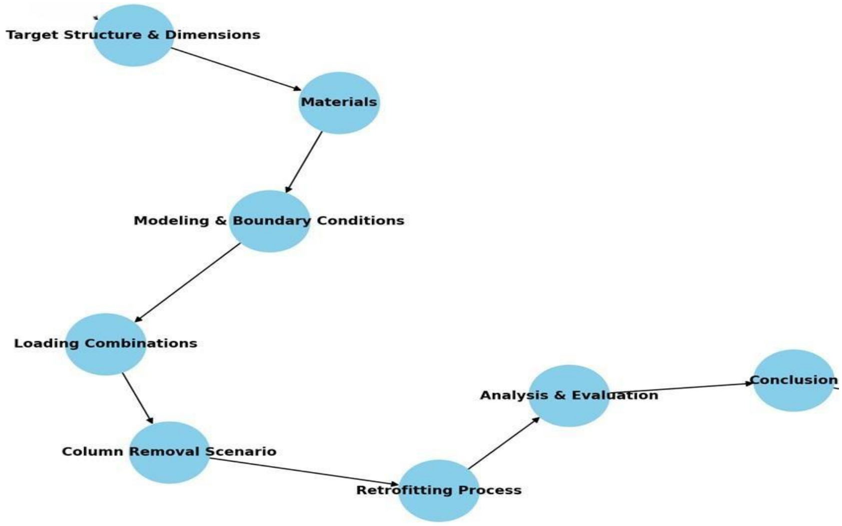


Figure 1: Flow Chart

2.6 Column Removal Scenario

The column removal scenario is modeled by deleting two centrally located columns at the middle span of the building. This modification is first applied in Tekla, which does not allow for retrofitting within the software. After column removal, the design is transferred to ETABS for further analysis and retrofitting, Fig 2& fig. 3 shows column removal at base.

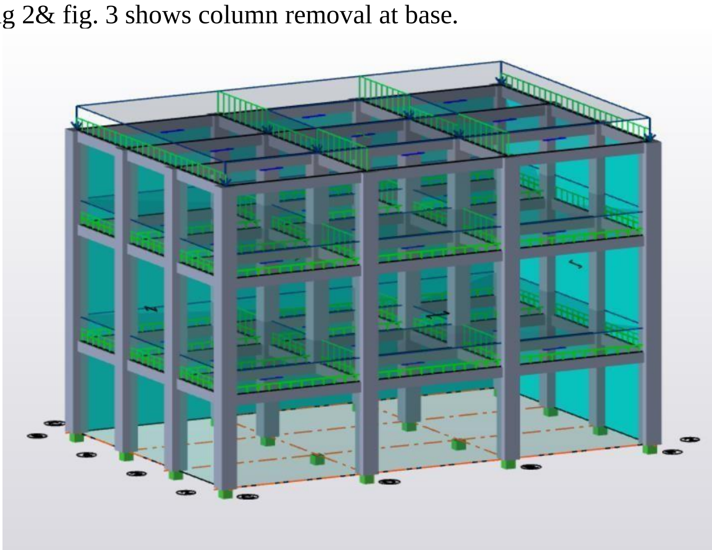


Figure 2: 3D view of Column Removed Structure at Base

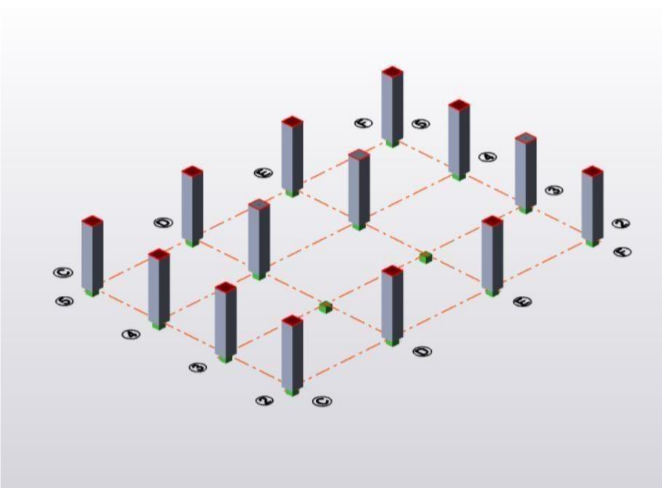


Figure 3: 3d View of Columns Removed at Base

2.6 Shifting Model to ETABS for Retrofitting Analysis

Tekla Structures is a self-needed element in terms of structural modeling but does not have an official system of members classification as acceptable or unsatisfactory. Further, the software software platform is not compatible with retrofitting design directly, which means that the model will have to be migrated to ETABS, a more analytically robust tool, having, among other features, a retrofitting capability that will allow the model to be rigorously strengthened. One such transfer of design facilitates accurate retrofitting analysis and a resolution on probable structural changes where columns are to be removed or where other major changes are proposed, whereby the relevant decision making needs to be taken after lot of investigation on possible changes that may have structural implications in terms of cost, structural integrity and so on.

2.7 Retrofitting Process:

According to codes of engineering, retrofitting deals with the recovery of the load bearing capacity by reinforcement of damaged beams and columns with carbon-fiber-reinforced polymer (CFRP). The approach is implemented in partial and complete approaches, depending on the limitations of the structure and the goals pursued in the project. Foremost on the list of the considerations is the choice of the composite parts integrating Concrete and CFRP sheets; this design ensures that retrofit members can support sufficient design strength. Figure 4 and 5 graphically illustrates the difference in the fully retrofitted elements and the partially retrofitted elements respectively showing the difference in the coverage of reinforcement.

2.7.1 Full Retrofitting:

Figure 4 indicates complete retrofitting of column and beam that offers overall strengthening by using CFRP sheets on all sides of the structural members. For columns, CFRP sheets are wrapped completely around all four sides to provide equal confinement and maximize the increase in compressive strength. For beams, CFRP sheets are used on all four sides to greatly enhance flexural rigidity and provide balanced load distribution along the member.

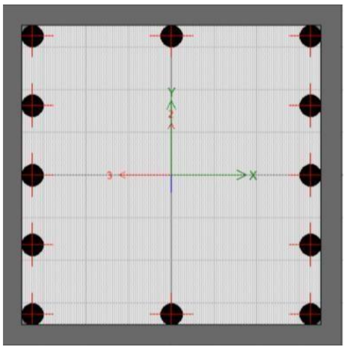


*Figure 4: Full CFRP Retrofitted Column (375*375mm)*

2.7.2 Partial Retrofitting:

Partial retrofit of columns in civil engineering involves the application of carbon-fibre-reinforced polymer (CFRP) sheets to at least two or three of the exposed sides thus increasing the loading bearing capacity with due consideration of accessibility restrictions, especially a case where the partition walls or other obstructions prevent access to all sides. The partial retrofit with complementary introduction, in case of beams, is the compression of a sheet of CFRP in three perimeters, aimed at reinforcing flexion and shear insufficiency without complete surface treatment.

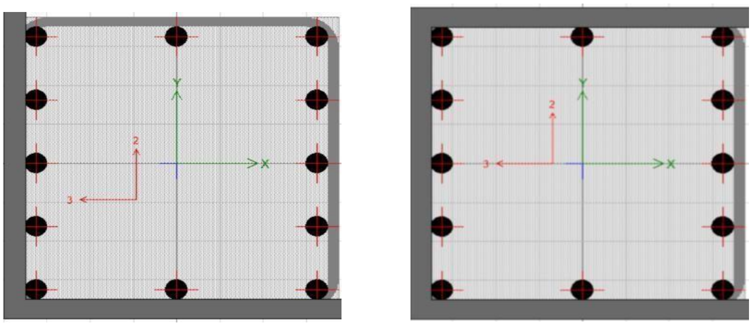


Figure 5: Partial Retrofitted Column (375*375mm)

Once the retrofitting intervention has been carried out, a thorough numerical analysis of the structure is needed; at this point, the software ETABS is used. The numerical analysis questions the structural response to various loading conditions- such as, gravity, seismic, and also wind loads. Special consideration is on the ability of the retrofitted members to resist the redistributed forces and prevent progressive collapse. In this study, the partial retrofitting technique is contrasted to the complete retrofitting option in order to make a determination of the strategy that is more effective as far as safety, resilience, and economic viability are concerned.

3. Results and Discussions

3.1 Structural Failures Following Column Removal:

The base level was stripped off a single column leading to massive failures of design checks in the other members of the structures. The beams at story level (17 beams) in particular and the columns (10 columns) between base to story in particular failed to meet their design requirements as stipulated. These results indicate redistribution of loads which were caused when a column is removed and accentuate stresses and burden on the adjacent structural parts. Subsequently, the site-specific structural interventions (like retrofit, or strengthening) will be required to provide the structure with a stable condition and meet safety requirements according to the updated loading case.

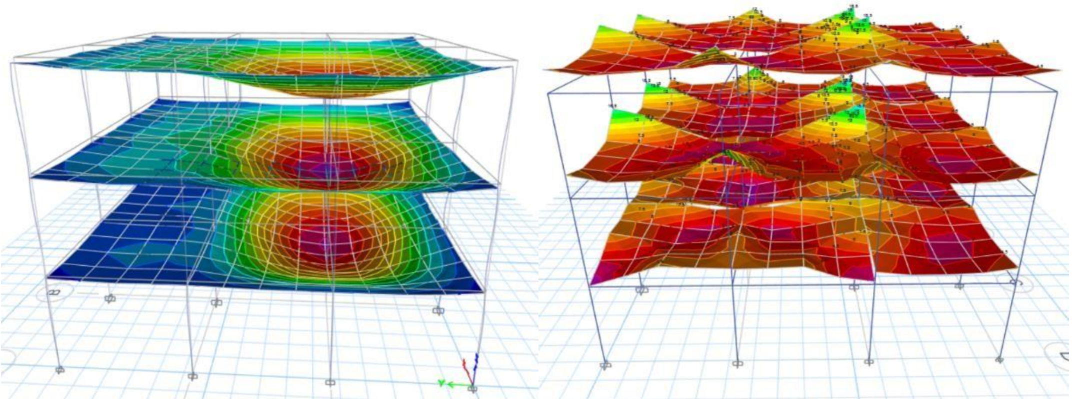


Figure 6: Deformed Shape and Maximum Shear (Force Vmax) following Column Removal

3.2 Retrofitting Results and Capacity Ratio Analysis of Structural Members:

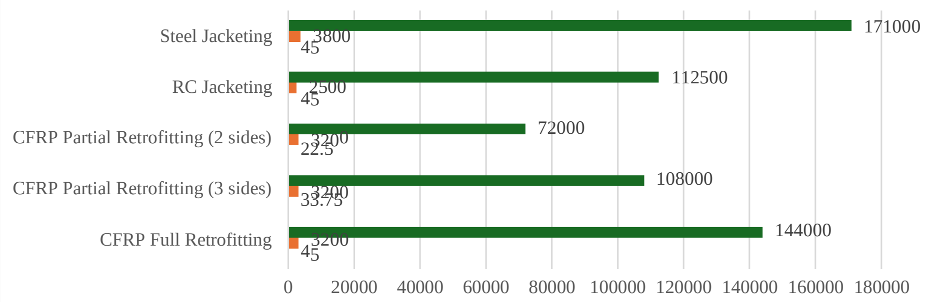
The performance improvement attained because of retrofit of columns with the Carbon Fiber Reinforced Polymer (CFRP) sheets is shown by the data in Table 1. The original condition of columns made retrofits mandatory to restore them into supporting their loads. In the process of retrofitting, one or two layers of CFRP would be put on the columns depending on the option of coverage chosen. After retrofitting, none of its tested samples had failed to meet their set load carrying requirements and this meant that they had met the necessary standards of structural safety. The comprehensive retrofitting by using CFRP showed the largest increase in strength whereas partial retrofitting, particularly two-sided retrofitting has been found to be economically better without losing strength capacity of the building. As it has been supported by the capacity ratio analysis, the full and partial retrofitting strategies achieved the sought after performance targets. An opportunity to achieve further reinforcement of the structural integrity of columns degraded by corrosion using the CFRP retrofitting solution, therefore, offers a competitive way to enhance the performance of the structure in terms of safety without compromising functionality.

Table 1: Retrofitting Results and Capacity Ratio Analysis of Structural Members

Member Type	Number of Members	Initial Condi-tion	Retrofitting Process	Post-Retro-fit Condtion	Capacity Ratio Analysis
Column	10 Columns from Base to Story 1	Fail	Retrofitted with 1 sheet of 25mm thick CFRP (4 sides)	Pass	Passed with Full retrofitting
Column	10 Columns from Base to Story 1	Fail	Retrofitted with 1 sheet of 25mm thick CFRP (2 sides)	Pass	Passed with Partial retrofit-ting of 2 exposed sides
Column	10 Columns from Base to Story 1	Fail	Retrofitted with 1 sheet of 25mm thick CFRP (2 sides)	Pass	Passed with Partial retrofit-ting of 3 exposed sides

3.3 Cost Analysis:

Figure 7 shows that cost analysis of various retrofitting techniques directs towards significant differences in structural efficiency as well as cost-effectiveness. Part CFRP retrofitting is identified as the cheapest option with viable structural efficiency. Two-side exposure columns retrofitting has an area of 22.5 m² with a total cost of PKR 72,000, whereas three-side retrofitting has an area coverage of 33.75 m² with a cost increase to PKR 108,000. Full CFRP retrofitting, with complete structural confinement, is 45 m² in area at a price of PKR 144,000. RC jacketing, a traditional method, is PKR 112,500 for the same 45 m² but contributes significantly to weight, necessitating additional foundation tests. Steel jacketing is stronger but the most expensive, at PKR 171,000 for 45 m² due to high material and labor costs. Of all the methods, partial CFRP retrofitting is the most cost-effective, resulting in huge cost benefits without taking a compromise on strengthening. Steel jacketing and complete CFRP are ideal for heavily loaded buildings where the highest structural strength is required. RC jacketing can be considered in situations where CFRP cannot be implemented, considering the increase in weight while making structural calculations.



	CFRP Full Retrofitting	CFRP Partial Retrofitting (3 sides)	CFRP Partial Retrofitting (2 sides)	RC Jacketing	Steel Jacketing
Total Cost (PKR)	144000	108000	72000	112500	171000
Cost per ma² (PKR)	3200	3200	3200	2500	3800
Area Covered (ma²)	45	33.75	22.5	45	45

Figure 7: Retrofitting Results and Capacity Ratio Analysis of Structural Members

4. Conclusion

The current research study examines the behaviour of reinforced concrete (RC) frames retrofitted using carbon-fibre reinforced polymers (CFRP) performance in extreme-load conditions, such as, the collapse of a column. The results reveal that a partial retrofit where the CFRP sheets have only been located strategically on the exposed surfaces can produce massive savings in terms of cost as compared to a full retrofit but not at the expense of structural robustness. Among the main merits of partial retrofitting, it is difficult to ignore the low level of construction activities, site preparation, and continuity of building operations. Fine comparison further shows that the other retrofit methods e.g. reinforced-concrete and steel jacketing come with the advantages and disadvantages of being less expensive to implement but, adding substantially to structural mass and perhaps requiring enhanced foundation support in the former, and better strength and adding great expenditure and construction period in the latter. Therefore, each of the techniques should be considered on the case by case basis. However, the limitations of the research should be the contribution of the foundation to the global structural response; the foundation retrofitting potential and cycle life of the CFRP materials under cyclic loads should be considered as well. The works in the future are thus to include detailed foundation analyses, the alternative of foundation retrofitting to be discussed and study of long term behavior of CFRP under dynamic loads. Further, effectiveness of these retrofitting techniques could use more laboratory scale experiment and real scale experiment to check validity in real world.

Author Contributions: Conceptualization, M.Z.L.; methodology, M.Z.L.; software, M.Z.L.; validation, M.Z.L., M.A., H.Y., and R.S.; formal analysis, M.Z.L.; investigation, M.Z.L.; resources, M.Z.L.; data curation, M.Z.L.; writing original draft preparation, M.Z.L.; writing review and editing, M.Z.L., M.A., and H.Y.; visualization, M.Z.L.; project administration, M.Z.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data is available on reasonable request to the corresponding author.

Acknowledgments: The authors would like to acknowledge the Department of Civil Engineering, Ghulam Ishaq Khan Institute of Engineering Sciences and Technology (GIKI), for providing administrative and technical support throughout the course of this research. TEKLA Structures and ETABS were utilized for structural modeling, analysis, and detailing, which significantly contributed to the technical depth and accuracy of the study.

Conflicts of Interest: The authors declares no conflicts of interest.

References

[1] Zaid A. Al-Sadoon, M Talha Junaid, Usama Al-Sabouni, Saleh Abu Dabous, Haytham Almaghari, Resilience of code compliant reinforced concrete buildings to progressive collapse: A numerical analysis investigation

[2] Baker, Nick & Steemers, Koen. (2000). Energy and Environment in Architecture: A Technical Design Guide.

[3] Sahil, Mehran & Bahrami, Alireza & Waqas, Hafiz &Amin, Fayiz & Mansoor Khan, Muhammad & Iqbal, Fahad & Fawad, Muhammad & Najam, Fawad. (2024). Seismic Performance Evaluation of Exterior Reinforced Concrete Beam-Column Connections Retrofitted with Economical Perforated Steel Haunches. Results in Engineering. 22. 102179. 10.1016/j.rineng.2024.102179.

[4] Delzendeh, Mohamadreza & Fathi, Abbas & Chaallal, Omar. (2024). Retrofitting of Steel Structures with CFRP: Literature Review and Research Needs. Applied Sciences. 14. 5958. 10.3390/app14135958.

[5] Mumtaz, Yasin & Nasiri, Ahmadullah & Tetsuhiro, Shimozato. (2021). A comparative study on retrofitting concrete column by FRP-Wrapping and RC-Jacketing methods: A feasibility study for Afghanistan. Indian Journal of Science and Technology. 14. 652-664. 10.17485/IJST/v14i7.141.

[6] Shivakumar, Gayathri. (2024). Retrofitting Techniques of Columns: A Comprehensive Review of Methods and Materials. International Journal of Latest Research in Engineering and Management (IJLREM). 7. 10.55041/IJSREM27433.