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Seismic Retrofitting of RCC Buildings Using GFRP Wrapping Techniques: Analytical and Experimental Evaluation

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ABSTRACT

This study investigates the seismic retrofitting of reinforced concrete (RC) buildings using Glass Fiber Reinforced Polymer (GFRP) wrapping techniques. The research focuses on the structural behavior of beams strengthened with single and double layers of GFRP under seismic loading, particularly in Zone-III regions such as Coimbatore. Analytical models were developed using SAP2000 to perform pushover analysis, examining parameters like base shear, displacement, moment-rotation, and ductility indices. The findings reveal that GFRP wrapping significantly enhances the load-carrying capacity and ductility of RC beams. Specifically, single-layer GFRP wrapping (GB1) resulted in a 60% increase in ultimate strength, while double-layer GFRP wrapping (GB2) achieved a 119% increase compared to unstrengthened beams. Furthermore, the use of GFRP laminates delayed the formation of initial cracks and improved the overall load-deflection behavior. The study also highlights the importance of retrofitting columns to prevent premature failure in infill buildings. The enhanced performance of GFRP-strengthened beams in terms of displacement and energy ductility indices underscores the effectiveness of this retrofitting technique in mitigating seismic risks. The research recommends incorporating these findings into relevant Indian Standards (IS 13935-1993 and IS 1893-2002) to improve the seismic resilience of existing structures in earthquake-prone areas.

Keywords: Seismic retrofitting, Glass Fiber Reinforced Polymer (GFRP), Reinforced concrete beams, Pushover analysis, Ductility indices, Zone-III earthquake forces

INTRODUCTION

The introduction of the research paper sets the stage by outlining the context, significance, and objectives of the study. In this study, the focus is on the seismic retrofitting of reinforced concrete (RC) beams using Glass Fiber Reinforced Polymer (GFRP) materials. Seismic retrofitting is crucial for enhancing the resilience of structures, particularly in earthquake-prone regions. The introduction provides an overview of the challenges posed by seismic events and the importance of retrofitting existing structures to mitigate damage and ensure safety.The significance of the study lies in its contribution to improving the seismic performance of RC beams through the application of GFRP strengthening techniques. By examining the effectiveness of GFRP wrapping in increasing the strength, ductility, and resilience of RC beams, this research addresses a critical need in the field of structural engineering.

The introduction also outlines the objectives of the study, which include evaluating the performance of GFRP-strengthened RC beams through experimental testing and analytical analysis. By achieving these objectives, the research aims to provide insights into the efficacy of GFRP retrofitting methods and inform best practices for seismic retrofitting of existing structures.

Costantino Menna et al. [1] Sustainable retrofitting of existing buildings is crucial for meeting the EU's climate and energy goals. This study reviews tools, protocols, and methods for combined energy and seismic assessment. It evaluates independent and integrated approaches, considering criteria like life-cycle costs and multidisciplinary integration, to advance sustainable, resilient retrofitting of European buildings against energy inefficiency and seismic hazards**Cheonghoon Baek et al. [2]** examined the potential for reducing greenhouse gas emissions from existing residential buildings in Korea, emphasizing that political efforts have largely focused on new construction. The study identified major barriers to improving energy performance in existing buildings, including lack of awareness, financial constraints, insufficient information, and absence of regulatory systems. To address these barriers, the authors considered systems implemented in developed European countries and assessed their feasibility for adoption in Korea, suggesting political measures to enhance the energy performance of existing residential buildings. **Peter Oluwole Akadiri et al. [3]** investigated the barriers to selecting sustainable building materials among construction professionals in Nigeria. Through a questionnaire survey and case studies of three completed projects, the study identified the perception of higher costs and lack of information on sustainable materials as the primary obstacles. The paper concludes with recommendations for overcoming these barriers, aiming to promote the use of sustainable materials in building design and construction**M. Santamouris et al. [4]** critically examine the energy and environmental state of the building sector, exploring pathways towards its decarbonization. The article analyzes economic, employment, energy, environmental, climate, and social impacts, considering challenges such as overpopulation, climate change, urbanization, energy use, material use, and poverty. It assesses recent technological developments and their potential impacts. The study also examines future energy consumption drivers, presents scenarios, and discusses proposed decarbonization pathways, highlighting key advantages and potential issues**Helen Crowley et al. [5]** examined the spatial and temporal evolution of seismic design across Europe as part of the European Seismic Risk Model 2020 (ESRM20). The study aimed to classify reinforced concrete buildings and map them to vulnerability models based on seismic design levels. The developed model identifies the introduction of low, moderate, and high seismic codes in various European countries and estimates lateral forces for typical mid-rise buildings. Findings indicate that ~60% of Europe's reinforced concrete buildings are seismically designed, with ~60% to low code, ~25% to moderate code, and 15% to high code. The model is dynamic and continuously updated, with data available on GitLab.**M. Economidou et al. [6]** present a comprehensive review of EU energy policies spanning over the last five decades, with a particular focus on energy efficiency measures in buildings. Beginning with early responses to the Oil Embargo in the 1970s, the paper traces the evolution of EU policies towards promoting energy efficiency in both new and existing buildings. It discusses key policy instruments such as the SAVE Directive and the updated Energy Performance of Buildings Directive, highlighting successes and remaining challenges in achieving energy efficiency goals. The review also examines how political priorities have shaped EU energy policy, leading to a more holistic approach to addressing energy efficiency in buildings.

The paper concludes by offering insights and suggestions for further leveraging the EU's potential to save energy in the building sector**A Power et al. [7]** discuss the historical context and current debate surrounding the demolition or refurbishment of older housing in the UK, dating back to the late 19th century. The paper examines government proposals for large-scale demolition and new construction since 2003, focusing on their potential impact on reducing greenhouse gas emissions from buildings. It argues that while demolition may not effectively address energy and climate change targets or social needs, refurbishment offers clear advantages in terms of time, cost, community impact, and energy efficiency.

Refurbishment also promotes the reuse of existing infrastructure and protection of existing communities, making it a more socially and environmentally beneficial approach**Helena Monteiro et al. [8]** explore the energy consumption and sustainability aspects of buildings, emphasizing the potential of new houses to contribute to more sustainable societies. The study evaluates the life-cycle non-renewable primary energy improvement potential of new houses compared to equivalent existing ones in Portugal. By analyzing various operational assumptions, including different heating systems and electricity generation mix scenarios, the research highlights the importance of considering operational conditions in assessing building energy performance. Results indicate that new houses can effectively reduce primary energy consumption, with attention needed on building materials, components, and operational habits. Recommendations include prioritizing energy-efficient construction elements and incorporating future electricity generation trends into lifecycle studies of houses**Marco Corradi et al. [9]** explore sustainability considerations in the remediation, retrofit, and seismic upgrading of historic masonry structures.

The paper discusses various rehabilitation techniques, focusing on successful applications in the Balkans and Italy, with a particular emphasis on shear reinforcement of wall panels. These techniques aim to enhance seismic performance while preserving architectural and heritage values, and minimizing environmental impact. The use of cross-laminated timber (CLT), natural fibers, and fiber-reinforced polymers (FRP) jacketing with natural lime coatings is examined for their sustainability benefits, including reduced carbon dioxide emissions and low energy consumption. The paper concludes by highlighting key successes and suggesting further applications in conservation engineering**Alessandra Marini et al. [10]** propose an integrated approach for renovating post-Second World War reinforced concrete buildings in urban outskirts, focusing on sustainability, safety, and resilience. Building on the concept of camouflage practices for energy efficiency and architectural restyling, the solution involves adding a technological double skin supported by an independent exoskeleton. This approach enables not only energy efficiency but also enhances structural safety and resilience. Life cycle thinking informs the selection of materials and technologies to ensure safety, minimize costs, and reduce environmental impacts over the building's lifespan. The intervention is carried out externally to avoid displacing inhabitants and minimize building downtime. The paper introduces a framework for designing holistic renovation interventions, proposing innovative structural techniques coupled with energy refurbishment. A proof of concept demonstrates the benefits of combining structural safety measures with an integrated intervention for building renovation**Paolo Ricci et al. [11]** examine the damage to reinforced concrete (RC) structures following the 6th April 2009 earthquake in the Abruzzo region, with the epicenter near L'Aquila. The study analyzes the seismic characteristics of the event and assesses the existing RC building stock in the area to identify main causes of structural and non-structural damage. By scrutinizing official data on building types and construction times, combined with a review of seismic codes over the past century, the study highlights weaknesses in the building stock. Damage analysis is conducted using photographic evidence collected shortly after the event, aiding in understanding the primary causes of damage to structural and non-structural elements.**Romina Sisti et al. [12]** examine the seismic performance of buildings in Campi Alto affected by the 2016 central Italy seismic sequence, comparing them with buildings in Norcia. Many buildings in both towns underwent strengthening between 1980 and 2000 following previous earthquakes. However, while buildings in Norcia experienced limited damage, those in Campi Alto showed significant and widespread damage despite strengthening. The study investigates the reasons for this difference by comparing seismic actions, evaluating vulnerabilities, and analyzing 20 past strengthening interventions submitted to the Civil Engineering Department of the Umbria Region. This analysis, coupled with empirical damage post-2016, provides valuable insights for future applications in seismic risk mitigation.

Objective of the Present Study

- Investigate the impact of brick masonry infill walls on a conventionally designed reinforced concrete moment resisting frame.
- Analyze the behavior of the frame under earthquake-induced lateral loads with and without brick masonry infill walls.
- Assess the performance of structural beam elements retrofitted with Glass Fiber Reinforced Polymer (GFRP) composites.

METHODOLOGY

1. **Identification of Typical Deficiencies:**

- Collect relevant structural data from existing reinforced concrete buildings.
- Identify common deficiencies observed in these buildings.

2. **Structural Diagnosis using Nondestructive Techniques:**

- Utilize nondestructive testing facilities to evaluate the structural condition.
- Perform thorough structural diagnosis to assess the extent of deficiencies.

3. **Modeling of Structural System and Seismic Vulnerability Analysis:**

- Create a detailed model of the structural system using SAP 2000 version 11.
- Analyze the model to assess seismic vulnerability and identify potential areas of weakness.

4. **Modeling and Experimental Studies on Retrofitted Deficient Members:**

- Develop models of deficient structural members.
- Conduct experimental studies to retrofit these members and assess the effectiveness of the retrofitting techniques.

5. **Performance Improvement of Existing Buildings:**

- Implement local retrofitting techniques based on SAP 2000 results to enhance the performance of existing buildings.
- Evaluate the effectiveness of the retrofitting techniques in improving the structural integrity and seismic performance.

6. **Recommendation of Suitable Retrofitting Techniques:**

- Based on the findings from structural diagnosis and analysis, propose appropriate retrofitting techniques.
- Aim to enhance the overall strength of the structure and improve its performance during earthquake events.

MODELLING OF THE EXISTING RCC STRUCTURE

The research work was carried out in three phases. In the first phase, a model was created and analyzed to evaluate the performance of a typical selected deficient existing building with different types of lateral load-resisting systems, such as R.C. frame and infilled frame behavior, in terms of seismic vulnerability.

A pushover analysis was performed for this evaluation, which showed the performance levels, component behavior, and failure mechanisms of the building. It also provided the sequence of hinge formation, identifying the elements that needed retrofitting. The process for Phase I is illustrated in Figure 1.

The second phase focused on the seismic strengthening of the existing bare frame structure based on the SAP2000 analysis results. Glass Fiber Reinforced Polymer Composite (GFRP) was extensively used to address the strength requirements related to flexure and shear in the structural system.

This phase highlighted the behavior and performance of composite beams through the moment-rotation relation and ductility of the tested beams. The test results indicated that the beams strengthened with GFRP wraps exhibited better performance. The process for Phase II is shown in Figure 2.

The third phase involved analyzing the bare frame with strengthened beams. After seismic strengthening of the existing hostel building, its behavior during an earthquake was studied based on the wrapped GFRP beams. The improved performance of the existing RCC structure was examined in detail with reference to pushover curves, hinge formation, moment-rotation, capacity spectrum, and performance level of the building using SAP2000.

Finally, GFRP composite retrofitting techniques were suggested to enhance the strength and performance level of the structure during an earthquake. The process for Phase III is shown in Figure 3.

Figure 1: Analysis of the Existing RCC Building

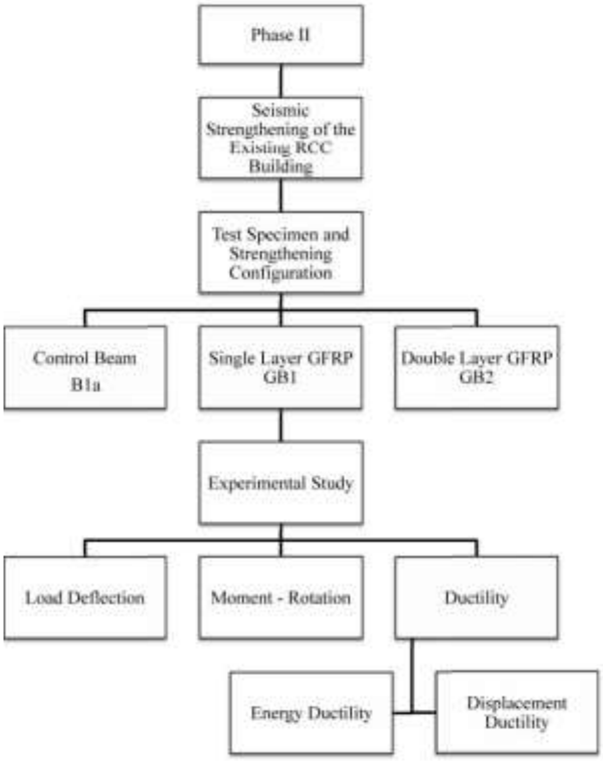

Figure 4.2: Investigation of Seismic Strengthening of the Existing RCC Bare Frame Building

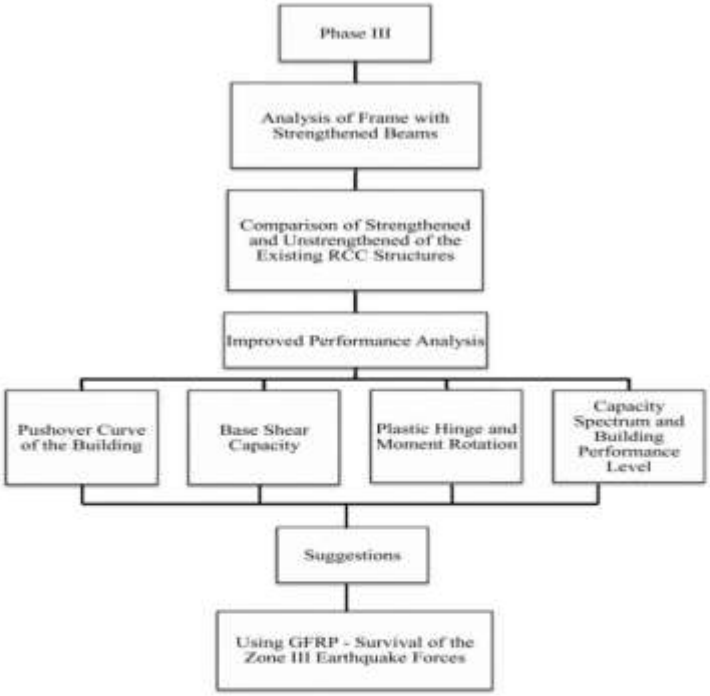

Figure 3: Analysis of Bare Frame with Strengthened Beams

Description of the Framed Structure

The present study aimed to evaluate the behavior of a G+2 reinforced concrete bare frame and infill frame building subjected to Zone III earthquake forces. The three-dimensional reinforced concrete structures were analyzed using nonlinear static analysis (Pushover Analysis) with SAP2000 software. The analysis results provided insights into the performance levels, component behavior, and failure mechanisms of the building, including the sequence of hinge formation. Based on these findings, elements requiring retrofitting were identified.

The study considered a three-dimensional frame of the selected building with different types of lateral load-resisting systems, including reinforced concrete bare frames and infilled frames. The plan of the building, showing the X and Y directions used for analysis. This building, representative of many in the region, was constructed using M15 grade concrete and Fe415 grade steel. Figure 3.9 displays elevations of similar buildings in the area.

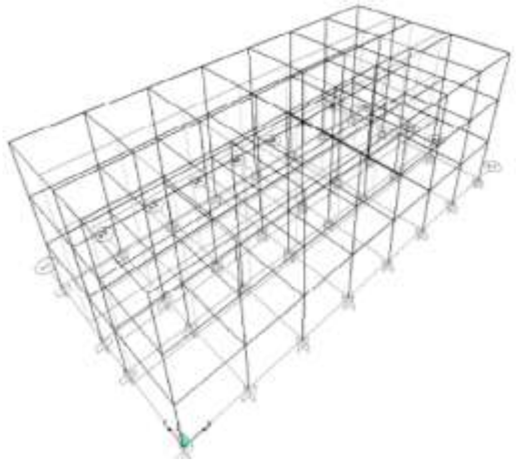

Figure 4: Three-Dimensional View of the Bare Frame

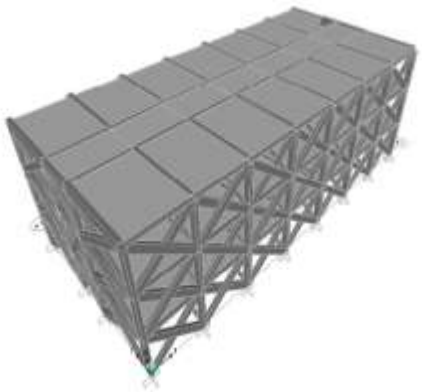

Figure 5: Three-Dimensional view of the representing Infills Frame with Braces

Seismic Retrofiting on Existing RCC Frame Building

Many existing structures in Bihar fall short of meeting current seismic design standards, and recent earthquakes have underscored the urgency of mitigating seismic risk. Seismic retrofitting stands out as a highly effective method for reducing this risk. Over the years, considerable research has been dedicated to exploring different strengthening techniques aimed at enhancing the seismic resilience of RC structures. However, simply applying retrofit measures may not automatically improve a structure's seismic performance; it requires careful consideration of the structure's seismic evaluation.Before selecting an appropriate retrofit scheme, engineers must first assess the basic requirements for rehabilitation and explore various retrofit techniques. The effectiveness of seismic retrofitting depends on selecting the right intervention technique, which necessitates a thorough understanding of the structure's seismic vulnerabilities.

Before bonding the composite fabric onto the concrete surface, the designated region was prepared by roughening it using coarse sandpaper and then cleaning it thoroughly with an air blower to remove any dirt or debris. Once the surface met the required standards, the epoxy resin was mixed according to specifications in a plastic container until achieving a uniform color. After preparing the resin mixture, the fabric was cut to the required size, and the epoxy resin was applied onto the concrete surface, as depicted in Figure 6. Subsequently, the composite fabric was carefully placed over the epoxy resin coating, and a roller was used to ensure that the resin permeated through the fabric's roving while eliminating any air bubbles trapped at the epoxy/concrete or epoxy/fabric interface, as illustrated in Figure 7. Following this, a second layer of epoxy resin was applied, and another layer of GFRP sheet was placed over it, repeating the process depicted in Figure 5.5. Throughout the hardening process of the epoxy resin, a consistent and uniform pressure was applied to the composite fabric surface to extrude any excess resin and ensure proper contact between the epoxy, concrete, and fabric. This process was conducted at room temperature. Finally, the concrete beams strengthened with glass fiber fabric were left to cure for 24 hours at room temperature before testing.

The load-deflection histories of all beams were meticulously recorded. Each beam's mid-span deflection was compared to that of its corresponding control beam, B1a. Furthermore, the load-deflection behavior was assessed between beams wrapped with the same reinforcement. It was observed that the flexural deficient beams, when bonded with GFRP sheets, exhibited improved behavior compared to their respective control beams. Graphs were generated to compare the mid-span deflection of wrapped beams with their corresponding control beams. The use of GFRP sheets had the effect of delaying the growth of crack formation.

The control beam, B1a, was designed to fail due to flexure. It was tested up to a load of 42 kN, corresponding to a deflection of 20 mm. Steel yielding occurred at 37 kN, resulting in a deflection of 8 mm. Using this load and deflection data, a load versus deflection curve was plotted.

During the experiment, flexural cracks initiated near the mid-span, with further loading leading to the widening of these cracks between the loading points. In later stages of loading, shear cracks began to propagate from the supports, eventually forming diagonal cracks extending to the top of the beam. Ultimately, the beam failed due to flexure. Analysis of Figure 6 revealed that the center dial gauge deflection was greater compared to the right and left dial gauges.

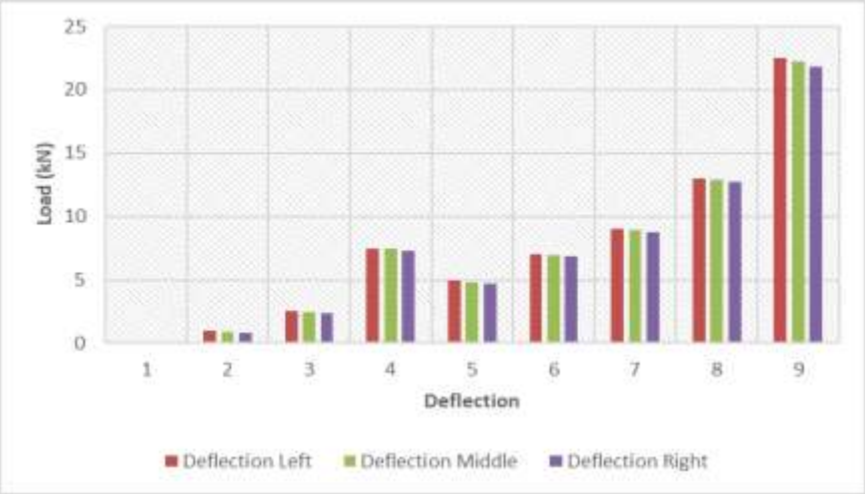

Figure 6: Load versus Deflection Curve for Beam B1a

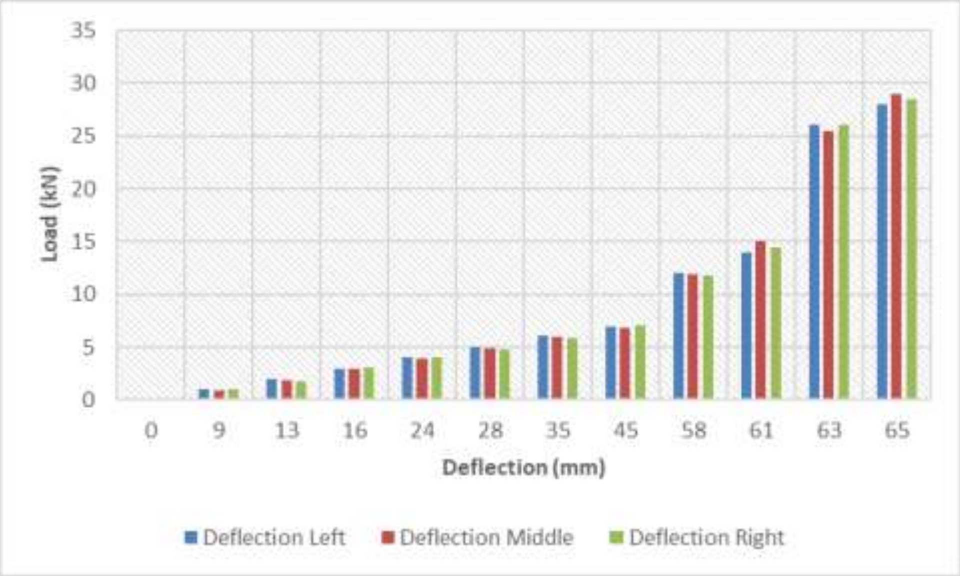

Figure 7: Load versus Deflection Curve for Beam GB1

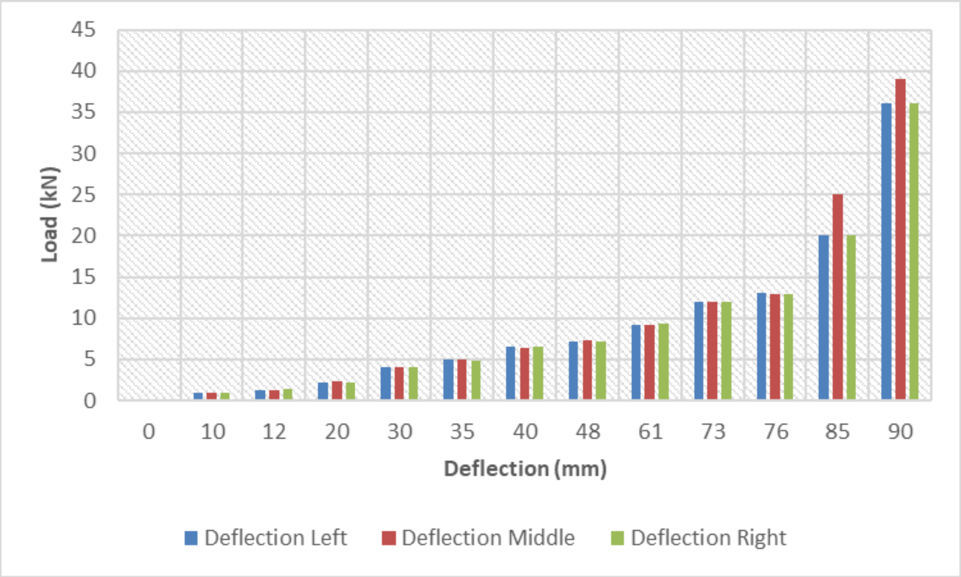

Figure 8: Load versus Deflection Curve for Beam GB2

Analysis of Bare Frame with Strengthened Beams

After seismic strengthening of the existing hostel building, its behavior during an earthquake was analyzed based on the wrapped GFRP beams. The improved performance of the existing RCC structure was thoroughly studied using SAP2000, focusing on various parameters such as pushover curves, hinge formation, moment-rotation behavior, capacity spectrum, and performance level of the building.

Before strengthening, the existing RCC building yielded first in the Y direction due to weak beams, specifically beam B1a. The base shear capacity in the Y direction was lower compared to the X direction at the first hinge formation levels. The total base shear and displacement in the Y direction were 2924 kN and 0.030 m, respectively.

The first hinge formation in beam B1a occurred with a base shear of 596.41 kN and a displacement of 0.002 m. This beam ultimately reached the collapse prevention (CP) level at the performance point state, indicating that CP was achieved earlier in the Y direction compared to the X direction, as shown in Figure 9. Therefore, the weak beams in the Y direction were strengthened using GFRP composites.

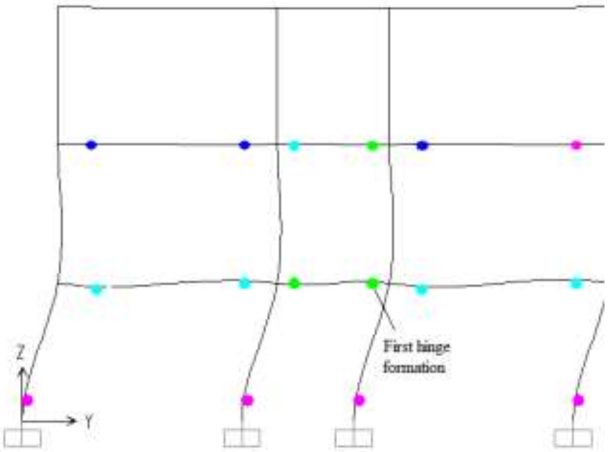

Figure 9: Elevation View of the Formation of First Hinge at the Performance Point Level

Before strengthening the existing building, the first hinge formation occurred at a base shear of 596.41 kN and a displacement of 0.002 m. At the performance point, the structure reached the collapse prevention (CP) level with a total base shear of 2924 kN and a displacement of 0.030 m, as determined by the pushover analysis.

After GFRP strengthening, the formation of the first hinge in the beam was delayed. For the single layer of GFRP strengthening in beam GB1, the first hinge formation occurred at a base shear of 650.042 kN and a displacement of 0.0023 m. This resulted in a 9% increase in the base shear value at the first hinge formation level compared to the unstrengthen building B1a.

The GB1 method allowed the building to carry a higher yield load compared to the unstrengthen building B1a. After strengthening beam GB1, the total base shear increased to 2970 kN, and the displacement was 0.036 m. This represents a 1.57% increase in total base shear compared to the unstrengthened building B1a. At the performance point, the strengthened beam GB1 reached from the Collapse Prevention (CP) level to the Life Safety (LS) level, as shown in Figure 10.

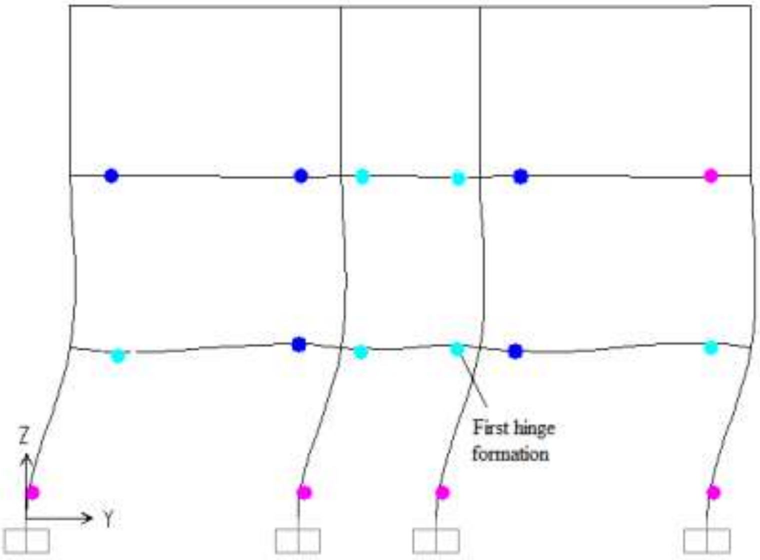

Figure 10: Elevation View of the Hinge Formation of GB1

For the double layer GFRP wrapped beam GB2, the first hinge formation occurred at a base shear of 702.212 kN and a displacement of 0.0030 m. Using the double layer GFRP wrapping method (GB2), the building exhibited a higher yield load compared to beams B1a and GB1. This resulted in an 18% increase in the base shear value at the first hinge formation level compared to the unstrengthened building B1a, and an 8% increase compared to the single layer GFRP wrapped beam GB1.

After strengthening with GB2, the total base shear increased to 3010 kN with a displacement of 0.0370 m. This represents a 2.94% increase in total base shear compared to B1a, and a 1.35% increase compared to GB1. The strengthened beam GB2 reached only the initial yielding (B) during the final analysis, as shown in Figure 11. The GB2 strengthening technique can be effectively employed to withstand Zone III seismic forces.

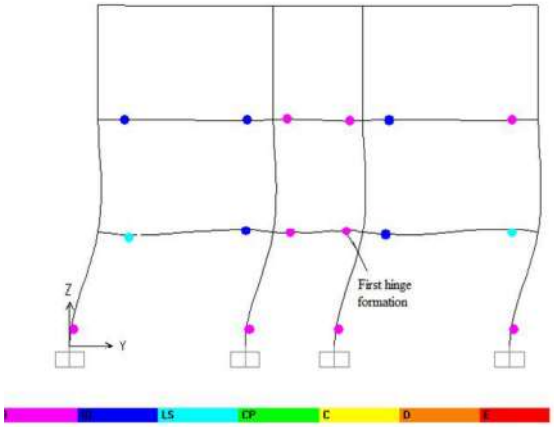

Figure 11: Elevation View of the Hinge Formation of GB2

CONCLUSION

Based on the analytical results obtained from SAP2000:

Without Infill (Bare Frame):

- The analysis indicates that the beams reached their capacity at the performance point level.
- The base shear capacity was lower in the Y direction compared to the X direction at the first hinge formation level.
- In the event of an earthquake in the Coimbatore region, which is in ZoneIII, the building is predicted to first yield in the Y direction due to weak beams.
- Therefore, it is imperative to strengthen the weak beams in the Ydirection using any of the recommended strengthening techniques before any earthquake occurs in this study zone.

With Infill:

- The analysis of bare frame predicts beam failure mechanism first, while in buildings with infills, column failure is predicted before beam failure.
- This indicates a weakness in infill buildings, where columns may collapse prematurely.
- To prevent premature collapse of columns, they need to be retrofitted to have adequate strength so that they do not reach yield level at the performance point.
- Thus, it is essential to strengthen weak columns in both X and Y directions using locally practiced strengthening techniques before an earthquake occurs.

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