Numerical studies on the strength enhancement of reinforced concrete building through the application of carbon fiber reinforced polymer

Sreekanth Gandla Nanabala\textsuperscript{a} | Balamurugan S.\textsuperscript{b}

\textsuperscript{a}Centre for Disaster Mitigation and Management, Vellore Institute of Technology, Vellore, India.
\textsuperscript{b}School of Civil Engineering, Vellore Institute of Technology, Vellore, India.

Abstract In recent years, there has been a significant increase in the use of externally bonded carbon fiber-reinforced polymers (CFRPs) for retrofitting structural components due to their high modulus of elasticity, high strength, low weight, durability, high resistance, corrosion resistance, and ease of installation. However, the use of CFRP in buildings raises several questions. In this study, a G+5 building is modeled using SAP 2000 software to determine the applications of CFRP in structural enhancement. Lateral forces are calculated using the seismic coefficient method and applied to the building. Nonlinear static pushover analysis is performed on the building to identify the formation of plastic hinges. The failed beam from the pushover analysis is then considered for static analysis in Abaqus software. Four beams of uniform dimensions are analyzed: unwrapped beams, beams wrapped with 50 mm strips along the length with 50 mm spacing, beams wrapped with 50 mm strips at 90 degrees with 50 mm spacing, and beams wrapped with 50 mm strips at 45 degrees with 50 mm spacing. An incremental load ranging from 1 kN to 50 kN is applied to the beams, and the maximum deflections and cracks at the center of the beam are recorded. The beam wrapped with 50 mm strips at 45 degrees showed the best results based on maximum deflection values and is therefore considered for wrapping beams in the building. For the wrapped building, the flexural details of the individual beam, load-carrying capacity, capacity spectrum curve, and displacement are calculated and compared with the building without wrapping.

Keywords: concrete structures, strengthening, retrofitting, pushover analysis

1. Introduction

In recent years, there has been a significant increase in the use of advanced materials in structural engineering, with Carbon Fiber Reinforced Polymer (CFRP) emerging as a notable choice for improving the structural strength of buildings. The focus has shifted toward implementing advanced materials and innovative techniques to fortify the structural robustness of reinforced concrete buildings. CFRP has emerged as a promising solution for enhancing the strength and resilience of concrete structures, offering numerous opportunities for sustainable and effective strengthening. These numerical studies aim to investigate the strength enhancement of reinforced concrete buildings through the strategic application of CFRP.

Reinforced concrete, a fundamental construction material known for its versatility and durability, faces challenges related to structural deficiencies over time. These challenges are especially pronounced in regions with seismic activity, increased loads, or where environmental considerations require higher performance standards. Using CFRP as an external strengthening material provides a compelling solution to these challenges, offering a lightweight, high-strength alternative that addresses the shortcomings of traditional reinforcement methods.

This research aims to contribute to the evolving discourse on strengthening reinforced concrete structures by leveraging the capabilities of CFRP. The investigation utilizes advanced numerical modeling techniques, primarily focusing on finite element analysis (FEA) and using specialized software such as SAP2000 (Ravichandraan & Krupakaran, 2016). By systematically studying the interaction between CFRP and concrete elements, the research seeks to elucidate the mechanisms that enhance the strength and ductility of the overall structure.

The research landscape in structural engineering has been significantly shaped by the exploration of numerical analysis of beams using Abaqus software. Renowned for its unparalleled versatility in finite element analysis (FEA), Abaqus stands out as a powerful and comprehensive tool for simulating the complex behavior of beams under various loading conditions (Chaudhari et al., 2012). This versatile software has become essential for researchers, enabling them to delve into the intricacies of beam structures, analyze their dynamic responses, and optimize configurations for different geometric parameters and material properties (Heydari et al., 2023).
Parametric studies, often conducted with Abaqus, have been pivotal in unveiling the nuanced relationship between geometric variations and structural performance, providing invaluable insights for engineers and designers seeking optimal solutions for specific applications (Panchal & Mayank, 2023). Furthermore, the dynamic analysis capabilities of Abaqus have facilitated a deeper understanding of vibrational behavior in beams, playing a crucial role in designing structures capable of withstanding dynamic forces, including those induced by seismic events (Gokul & Sabarigirivasan, 2022).

Abaqus’s proficiency in nonlinear analysis and advanced material modeling has significantly enhanced the realistic representation of structural responses, incorporating factors such as large deformations, material nonlinearity, and post-yield behavior (Sader Mohammed & Ahlam, 2019). These numerical simulations are often validated against experimental data, ensuring the credibility and reliability of the models (Hemamathi et al., 2022).

Despite the commendable strengths of Abaqus, challenges persist, with computational demands being a primary concern. Future research directions aim to address these challenges by exploring advanced techniques such as multiscale modeling to enhance the efficiency and accuracy of simulations (Panchal & Mayank, 2023). As the literature underscores the pivotal role of Abaqus in advancing our understanding and design capabilities for beam structures, ongoing research endeavors are expected to further refine methodologies, deepen insights, and confront emerging challenges. These efforts will contribute to the continual evolution of structural engineering practices (Hemant et al., 2006).

The research aims to enhance the structural understanding and design efficiency of buildings through a comprehensive numerical analysis employing Abaqus software, with a specific focus on the application of Carbon Fiber-Reinforced Polymer (CFRP). The study seeks to investigate the interaction between buildings and CFRP strengthening, examining the material’s impact on structural performance under various loading conditions (Akhlageh, 2020). Utilizing Abaqus capabilities, the research aims to simulate and optimize the behavior of building structures, considering dynamic responses, nonlinear material behavior, and the influence of CFRP in enhancing structural integrity. Addressing challenges such as computational demands, the research aims to contribute to refining methodologies and providing valuable insights for the efficient and reliable numerical analysis of buildings with CFRP using Abaqus.

The research aims to enhance the understanding and efficiency of building design through a comprehensive numerical analysis using Abaqus software, specifically focusing on Carbon Fiber-Reinforced Polymer (CFRP). This study investigates the impact of CFRP strengthening on structural performance under various loading scenarios and examines the interaction between building components and CFRP. The maximum deflection values for wrapped and unwrapped beams are compared based on the analysis outputs. Additionally, the study computes and compares the building’s load-carrying capacity, displacement, capacity spectrum curve, and individual beam flexural characteristics with those of an unwrapped building.

2. Numerical modeling of RC Building

2.1. Geometry Details

For analysis, a G+5 building measuring 25 m x 25 m with five bays along the long direction and five bays along the short direction as shown in Figure 1 and Figure 2 is modeled in SAP 2000 software. All columns are assumed to be restrained at the base in all possible directions, with a depth of 3 m below the ground level. The characteristic compressive strength of concrete, rated at 30 MPa, is used. The modeled building is considered a commercial building and is loaded with 100% gravity loads of all the structural elements (Colangelo, 2005).
As per Table 1 of IS 875: 1987 (part 2), a live load intensity of 3 kN/m² is considered. Additionally, from Table 5 of IS 1893: 2002 (part 1), an earthquake load of the highest zone V with a factor of 0.36 is applied. The building undergoes pushover analysis to identify potentially weaker sections by observing the formation of plastic hinges and failed members during concrete design (Kaushik et al., 2009).

### Table 1 Lateral Forces on each floor.

<table>
<thead>
<tr>
<th>Floor</th>
<th>Lateral Force (kN)</th>
<th>Lateral Force acting at each joint (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VI</td>
<td>672</td>
<td>112</td>
</tr>
<tr>
<td>V</td>
<td>653</td>
<td>108.84</td>
</tr>
<tr>
<td>IV</td>
<td>418</td>
<td>69.67</td>
</tr>
<tr>
<td>III</td>
<td>235</td>
<td>39.17</td>
</tr>
<tr>
<td>II</td>
<td>104</td>
<td>17.34</td>
</tr>
<tr>
<td>I</td>
<td>26</td>
<td>4.34</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

The beams, with a cross-section of 0.25 m in width and 0.40 m in depth, and an overall length of 5 m, are assigned in the building and designed.

The design base shear needs to be estimated initially before being distributed along the height of the building. Based on the floor diaphragm action, the design lateral force obtained at each floor level will then be transferred to specific lateral load-resisting parts. The following expression should be used to calculate the overall design lateral force or design base shear along any direction.

$$V_B = A_h \times W$$

Where,

- $A_h$ = Design horizontal seismic coefficient for a building which is solved by $(Z/2)(I/R)(S_a/g)$
- $W$ = Seismic weight of building
- $Z$ = Zone Factor
- $I$ = Importance Factor
- $S_a/g$ = Spectral acceleration coefficient

$R$ represents the response reduction factor, which varies depending on the structure’s estimated ability to withstand seismic damage and is characterized by brittle or ductile deformations. For instance, $R = 5$ is considered for a more ductile structure like a special moment-resistant frame.

$I$ denote the importance factor, which varies based on the functional usage of the structures and is characterized by factors such as historic value, economic significance, and functional needs following an earthquake. As per Table 6 of IS 1893 (Part 1): 2002, the importance factor is taken as 1.5.
According to Figure 2 of IS 1893 (Part 1): 2002 and the formulas described in Clause 6.0 for various soil conditions based on appropriate natural periods of the structure, \( S_{a/g} \) represents the average reaction acceleration coefficient for rock or soil sites. These figures are provided for 5% damping of the structure; additional damping levels are adjusted following IS 1893 (Part 1): 2002 Table 3. These curves depict ground motion in a free field.

The basic natural period for buildings is provided in IS 1893 (Part 1): 2002, Clause 7.6, and can be summarized as follows:

\[
T_a = 0.075h^{0.75}
\]

Where \( h \) = total height of building

The total weight (W) of the building is calculated by finding the volume of each element in the building and multiplying it by the density of concrete, which is 25 kN/m³. The total weight calculated for this building is 2108 kN. This weight (W) is used to calculate the design lateral force on each floor.

The fundamental period of vibration determines the amount of lateral forces in the equivalent lateral force method. According to the expression given below, IS 1893 (Part 1): 2002 uses a parabolic distribution of lateral force along the height of the building.

\[
Q_i = V_b \frac{W_i h_i^2}{\sum_{i=1}^{n} W_i h_i^2}
\]

Where \( Q_i = \) Design lateral force at each floor \( i \),

\( W_i = \) Seismic weight of floor \( i \),

\( h_i = \) Height of floor \( i \) measured from the base and

\( n = \) Number of stories in the building is the number of levels at which masses are located

Using the seismic coefficient method as specified in IS 1893: 2002 (Part 1), the lateral forces acting on each floor of the structure are calculated and are shown below in Table 1.

These lateral forces are divided by the number of joints available on each floor, which is six joints, to determine the individual forces at each joint. This output force is then applied at every joint on the corresponding floor to find the displacement of each floor. Hinges are created at every column and beam joint. Static nonlinear pushover analysis is applied to the structure to identify the formation of plastic hinges that can lead to damage to structural components (Negro & Verzeletti, 2016).

2.2. Methodology for pushover analysis

A non-linear static study called pushover analysis is used to determine the structure's capacity. The structure can be analyzed by applying force or displacement in parabolic, triangular, or uniform patterns (Goutam & Sudhir, 2008). Damage to the structure is caused by inertial forces generated by displacement induced at the base of the structure. This analysis facilitates the understanding of how shear, flexural, and plastic hinges form within the structure. Even with a seismically resistant design, a structure may still sustain damage; otherwise, it would not be cost-effective. As a result, some damage is permitted, with the amount allowed varying according to the required performance. Damage to the structure is necessary to understand its behavior and collapse pattern (Sahoo, 2013). In this investigation, non-linear static pushover analysis is performed using SAP 2000.

A plot representing the relationship between roof displacement and foundation shear is shown in the pushover curve, which can be used to determine hinge locations and performance points at different stages, as seen in figure 3. The range of immediate occupancy is from B to IO, while the elastic range is from A to B (Ozkaynak et al., 2013). The life safety range extends from IO to LS, and the collapse prevention range is from LS to CP. The construction is considered safe if every hinge remains within the CP limit. However, hinges that fall beyond the IO range may also require retrofitting, depending on the importance of the structure (Sahoo, 2013; Sahoo, 2010).
2.3. Numerical modeling of RC beam

The beam connections at element 393, located on the third floor, have exceeded the Immediate Occupancy (IO) threshold, necessitating retrofitting. For this purpose, the beam element is modeled and wrapped with CFRP using Abaqus software (Lee et al., 2020). In this research, a double-textured CFRP material is preferred for wrapping. The CFRP material has a tensile strength of 3700 MPa, a Young’s modulus of 230 GPa, a density of 1.8 g/cm³, and a thickness of 0.208 cm.

The beam elements are scaled to 50% in all dimensions and wrapped with CFRP sheets both experimentally and numerically. Figure 4 shows the scaled element for modeling in Abaqus software.

By applying the loads (Abdulridha, 2018), the displacements of the structural components are recorded. Further, the CFRP sheets are wrapped on the beams with four different orientations: 0°, 45°, 60°, and 90°. When the load is applied, the wrapped beams undergo various changes, which can lead to strength enhancement compared to the unwrapped beam (George et al., 2017). Figures 5, 6, and 7 represent the FRP orientation in the modeled software.
3. Results and Discussions

In this particular design, where the initial hinges are at point B, Figure 8 shows how plastic hinges form by progressively increasing the number of steps. Between points B and E, the structure undergoes phases of immediate occupancy, life safety, and collapse prevention. At step 21, the formed hinges transition from point B to point E, indicating that the failed elements must be retrofitted.

Figure 8 Hinge formations after Pushover analysis.

The beam connections at element 393, i.e., third-floor edge beams, fail at step 21 after applying pushover analysis. The failed beam is then analyzed using Abaqus software and strengthened with CFRP laminates.

The Capacity Spectrum curve provides a visual assessment of how a structure will behave during an earthquake by comparing its ability to withstand lateral forces to the requirements of earthquake reaction spectra in a graphical display (Alidad & Mosalam, 2006). The curve shown in Figure 9 is plotted between spectral acceleration and spectral displacement. According to ATC-40, which is a seismic evaluation and retrofit code for concrete buildings, the capacity spectrum curve is plotted. The performance point is identified at 0.125g in spectral acceleration and 0.113 in spectral displacement. The base shear from the capacity curve is 1065 kN, which is less than the calculated base shear. Therefore, the designed structure is considered safe (Constantinou et al., 2001).

Figure 9 Capacity Spectrum Curve for unwrapped Building.

The simulated building's pushover curve is shown in Figure 10 below. As the modeled building is analyzed for monitored displacement, the overall displacement attained by the applied lateral load is 16.2 mm. After reaching the maximum
displacement, the applied shear suddenly decreases from 2700 kN to 1890 kN, indicating potential failure in both the reinforcement and concrete. To prevent this failure, wrapping the element is recommended.

![Nonlinear pushover curve](image)

Figure 10 Nonlinear pushover curve.

The flexural details of the failed beam element are represented in Figure 11. The beam can carry a positive design moment of 118 kNm. The longitudinal and transverse reinforcements are calculated to withstand the developed torsion and shear. The reinforcement is not uniform from left to right. The reinforcement is calculated and can be modified to achieve uniform reinforcement throughout the beam (Paulay & Priestley, 2002).

![Flexural beam details of unwrapped Building](image)

Figure 11 Flexural beam details of unwrapped Building.

From the numerical analysis, the output for all structural components, specifically beams, shows varying strength enhancement when compared to the unwrapped beam. Beams are loaded with a constant incremental load from 1 kN to 50 kN.

The unwrapped beam's cracking behavior is shown in Figure 12, which also indicates important locations for the crack's initiation, propagation, and ultimate failure. Unexpectedly, crack formation appears at about 30% of the peak stress, indicating early structural distress. This early onset of cracking highlights the beam's susceptibility to increased loading conditions.

Cracks propagate over the surface area of the beam as the applied load increases, exhibiting a more pronounced crack growth progression. The ultimate result of this fracture propagation is the failure of the beam, occurring at around 94% of the peak load. These failure modes seriously endanger the system's overall structural integrity, potentially leading to structural collapse (Sivaselvan & Reinhorn, 2001).

To mitigate cracking, the same beam is wrapped with CFRP laminates in three different orientations: wrapping with 50 mm strips along the length of the beam, wrapping with 50 mm strips at 45 degrees, and wrapping with 50 mm strips at 90 degrees, as shown in Figures 5, 6, and 7.

Figure 13 shows the beam's cracking behavior with the impact of longitudinal CFRP wrapping. As loading conditions increase, crack formation starts quite early, at around 36% of the peak load, indicating the early commencement of structural distress. As the applied stress continues to grow, the crack growth process becomes more noticeable, and the cracks spread across the beam's surface area. The final result of this fracture propagation is the failure of the beam, occurring at around 90% of the peak load.
The longitudinally wrapped beam shows a significant 30% increase in shear resistance compared to its unwrapped counterpart. This substantial increase in shear resistance highlights the effectiveness of longitudinally applied CFRP wrapping in enhancing the beam’s structural integrity and load-bearing capability, reducing the likelihood of shear-related failures.

Figure 14 shows the beam’s cracking behavior after being wrapped in CFRP at a 90-degree angle. Crack initiation occurs at about 40% of the peak load, indicating early structural disturbance as the applied load begins to exert its influence. As the load continues to escalate, the development of cracks intensifies, peaking at around 95% of the peak load, ultimately leading to failure.

The beam wrapped at a 90-degree orientation showcases a substantial enhancement in shear resistance compared to its unwrapped counterpart. Specifically, the shear resistance of the wrapped beam exceeds that of the normal RCC beam by 50%. This improvement in shear resistance demonstrates the effectiveness of CFRP wrapping in strengthening the beam’s structural integrity and load-bearing capability, thereby reducing the likelihood of shear-related failures.

Moreover, the peak strain experienced by the wrapped beam at the 90-degree orientation exhibits a significant reduction of approximately 33% compared to the unwrapped beam. This reduction in peak strain highlights the effectiveness of CFRP wrapping in mitigating strain concentrations and redistributing loads more efficiently throughout the beam, thereby enhancing its ductility and resilience.
Figure 14 Concrete Cracking in the wrapped beam along 90 degrees.

Figure 15 shows the beam's cracking behavior with CFRP wrapping applied at a 45-degree angle. The onset of crack formation is observed at approximately 42% of the peak load, serving as an early indication of structural distress as the applied loading conditions intensify. As the load continues to increase, the progression of crack formation becomes more developed, with cracks proliferating throughout the beam's surface area. This crack propagation reaches its final stage at approximately 92% of the peak load, leading to the beam's eventual failure.

Figure 15 Concrete Cracking in wrapped beam along 45 degrees.

The beam wrapped at a 45-degree orientation exhibits a remarkable enhancement in shear resistance compared to its unwrapped counterpart. Specifically, the shear resistance offered by the wrapped beam surpasses that of the normal RCC beam by an impressive margin of 58%. This significant increase in shear resistance underscores the efficacy of CFRP wrapping in fortifying the beam's structural integrity and load-bearing capacity, thereby mitigating the risk of shear-related failures.
All the beams are numerically wrapped and tested, and it was identified that wrapping at 45 degrees provides better results. Thus, beams wrapped at 45 degrees are compared in terms of cracking concerning the unwrapped beams. The four modeled beams are loaded with a constant incremental load of 5 kN from 1 kN to 50 kN to observe the maximum displacement profile. The output results are shown in Figure 16 and Table 2. From this, it is concluded that beams wrapped with CFRP laminates show less displacement compared to the unwrapped beam. Among all the wrapped beams, those wrapped with CFRP at 45 degrees show the least displacement compared to other alignment patterns.

![Figure 16 Load vs Displacement Curve for beams in Abaqus.](https://www.malque.pub/ojs/index.php/msj)

<table>
<thead>
<tr>
<th>Load (kN)</th>
<th>Beam without wrapping</th>
<th>Beam wrapped longitudinally</th>
<th>Beam wrapped in 90 degrees</th>
<th>Beam wrapped in 45 degrees</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.120</td>
<td>0</td>
<td>0.080</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>0.630</td>
<td>0.429</td>
<td>0.701</td>
<td>1.013</td>
</tr>
<tr>
<td>10</td>
<td>1.270</td>
<td>1.310</td>
<td>1.108</td>
<td>1.013</td>
</tr>
<tr>
<td>15</td>
<td>1.910</td>
<td>1.790</td>
<td>1.812</td>
<td>1.531</td>
</tr>
<tr>
<td>20</td>
<td>2.547</td>
<td>2.070</td>
<td>2.591</td>
<td>1.814</td>
</tr>
<tr>
<td>25</td>
<td>3.185</td>
<td>2.430</td>
<td>3.030</td>
<td>2.134</td>
</tr>
<tr>
<td>30</td>
<td>3.828</td>
<td>2.910</td>
<td>3.615</td>
<td>2.588</td>
</tr>
<tr>
<td>35</td>
<td>4.462</td>
<td>3.089</td>
<td>4.091</td>
<td>2.804</td>
</tr>
<tr>
<td>40</td>
<td>5.101</td>
<td>4.120</td>
<td>4.330</td>
<td>3.190</td>
</tr>
<tr>
<td>45</td>
<td>5.740</td>
<td>4.632</td>
<td>4.710</td>
<td>3.300</td>
</tr>
<tr>
<td>50</td>
<td>6.380</td>
<td>5.384</td>
<td>5.101</td>
<td>4.130</td>
</tr>
</tbody>
</table>

From the above outputs, it is concluded that beams wrapped at 45 degrees provide better results in terms of displacement, load-bearing capacity, and cracking. This is because, in other cases where the load is acting vertically downward on the cross-section of the beam as well as the CFRP wrap, the total load is directly transferred to the CFRP wrap, which may cause debonding and damage to the wraps. In contrast, with CFRP wrapping at 45 degrees, the total load (F) directly acts on the beam’s cross-section, and on the CFRP wraps, the total load is resolved into two forces, Fcosθ and Fsinθ, which are less than the total applied load. Due to this reason, beams wrapped at 45 degrees have fewer debonding issues and more ability to carry the load (Wang et al., 2024).

After modeling the beams in Abaqus software, the best wrapping method of wrapping at 45 degrees is identified and applied to the initial building modeled earlier. The wrapped building shows less displacement compared to the unwrapped...
building. The story drift of the building varies from floor to floor in increments from the ground floor to the top floor shown in Figure 17. The base shear of the wrapped building increases by 40% more than the base shear of the unwrapped building.

![Figure 17 Displacement at floor level.](image)

The development of plastic hinges in the CFRP-wrapped building is depicted in Figure 18, where the initial hinges originate from point B and the number of steps is progressively increased. Between points B and E, the structure undergoes immediate occupancy, life safety, and collapse prevention phases. At step 21, the formed failure hinges in the un-retrofitted building remain in the initial stage of hinge formation. The beam connections at element 393, i.e., the third-floor edge beam, become stable after retrofitting with CFRP following the pushover analysis. The failed hinge pattern observed in the unwrapped building is converted into normal hinge formations with safety.

![Figure 18 Plastic Hinge Formation for the wrapped structure.](image)

The flexural details of the failed beam element of the wrapped building are represented in Figure 19. The beam can carry a positive design moment of 133 kNm. The longitudinal and transverse reinforcements are calculated to withstand the developed torsion and shear. The reinforcement is designed to be uniform throughout the beam.

From Figure 20, in a wrapped building, the base shear is 1483 kN, which is still less than the applied base shear, indicating that the structure is safe under the applied load. The performance point is 0.234 g in terms of spectral acceleration and 0.103 in terms of spectral displacement. In the context of capacity spectrum analysis, the performance point values of wrapped buildings are higher than those of unwrapped buildings. This indicates that the wrapped building has a higher ductility capacity, which is desirable for seismic resilience. The comparison of performance point values also reflects differences in structural design, such as material properties, geometry, detailing, and seismic retrofit measures. The results suggest that the design or
retrofit strategies implemented in wrapped buildings are more effective in enhancing seismic performance and ensuring structural safety.

From the above numerical analysis, it is identified that:

The wrapped beam specimens exhibited a slower rate of crack propagation during the loading process compared to the unwrapped beams. The cracks were more distributed at the lower section of the beam than at the top part. This is attributed to the presence of CFRPs, which have a strong bridging effect that successfully prevents cracks from spreading, regulates the rate and quantity of crack formation, and improves the beam’s crack pattern. Consequently, the beam’s flexural bearing capacity is increased.

Through analysis, it has been established that the likelihood of Carbon Fiber Reinforced Polymer (CFRP) delamination from the beam significantly rises as the applied load approaches approximately 96% of the peak load applied. This finding suggests that the structural integrity of the CFRP wrapping becomes increasingly resilient to delamination, thus enhancing their overall structural robustness.

From the pushover curve, the unwrapped structure displays a characteristic pattern of sudden failure, signaling its limited capacity to withstand increasing loads beyond a certain threshold. In contrast, the wrapped structure showcases remarkable resilience, demonstrating a notable ability to bear significantly higher loads before reaching failure. This highlights the transformative impact of CFRP wrapping in enhancing the structural performance and load-bearing capacity of the system.

The analysis indicates that the base shear calculated from the capacity curve is lower than the magnitude of the applied base shear. This critical observation verifies the structural stability and safety of the system. The disparity between the
unwrapped and wrapped base shears provides reassurance that the wrapped structure has sufficient strength and resilience to endure the imposed loading conditions.

The building wrapped with CFRP demonstrates a 45% increase in bearing load compared to the unwrapped building. Based on the above results, it is concluded that the structural components in the building wrapped with CFRP exhibit superior strength compared to those in the normal building. These findings indicate that incorporating CFRP wrapping in real-world construction can notably enhance the durability and structural performance of buildings, particularly in areas susceptible to seismic activity or heavy loading conditions. The implementation of CFRP reinforcement has the potential to prolong the lifespan of structures, decrease maintenance expenses, and improve safety, thereby establishing it as a valuable technique for contemporary civil engineering practices.

6. Scope for further research

Future research endeavors could delve into exploring the boundaries of load-bearing capacity enhancement attainable through CFRP wrapping across various types of structures. Investigations could also delve into assessing the economic and practical ramifications of widespread CFRP integration in both new constructions and retrofitting existing buildings. Furthermore, conducting long-term monitoring of CFRP-wrapped structures in real-world conditions could yield valuable insights into their performance and maintenance needs.

Ethical considerations

Not applicable.

Conflict of Interest

The authors declare no conflicts of interest.

Funding

This research did not receive any financial support.

References


