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Advanced Structural Enhancement of Bridges: ANSYS Simulation, CFRP Retrofitting Techniques, and Fuzzy Logic Integration

Ashwini Satyanarayana[1*], Amogha H[1], Geetha L[1]

[1]*Department of Civil Engineering, Dayananda Sagar College of Engineering, Bengaluru - 560111, India*

**Corresponding Author. E-Mail:* ashwini-cvl@dayanandasagar.edu

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Abstract

Older bridges often incorporate reinforced concrete (RC) girders paired with non-composite concrete slabs. With time, these structures degrade due to aging, increased traffic loads, and environmental exposure, which compromises their load-carrying capacity. Strengthening these bridges by creating composite action between RC girders and slabs is a cost-effective approach to restoration. This study investigates using Carbon Fiber Epoxy Plates (CFEP) to reinforce bridge girders, aiming to improve their structural integrity and prolong service life. Full-scale RC beams retrofitted with CFEPs underwent rigorous testing to assess flexural and shear capacities under various loads. Additional simulations with ANSYS software provided further insights into interactions between RC girders and CFEPs. Results from both experimental and numerical analyses showed substantial increases in load capacity, stiffness, and reduced deflection in retrofitted beams. Fuzzy logic-based structural health monitoring enhances safety and maintenance protocols, providing real-time assessment. Findings from this research offer valuable design recommendations, proving CFEPs as an effective, economically beneficial solution for extending the lifespan of aging bridge structures while minimizing maintenance costs.

Keywords: Carbon Fiber Epoxy Plate (CFER); RC Girder; Ansys; Bridge Assessment; Non-composite Concrete Slabs.

1. Introduction

India has a vast number of bridges, with thousands of structures spanning an extensive network of rivers, railways, and highways. The precise number of bridges can vary depending on the source; however, estimates suggest that there are more than 100,000 bridges in the country. Many of these bridges are aging and require retrofitting to maintain safety and functionality. According to various reports and studies, a significant proportion of these bridges, particularly those built before modern engineering standards, require maintenance, rehabilitation, and complete retrofitting. The exact number of bridges needing retrofitting is not readily available in consolidated form; however, it is acknowledged that a substantial percentage of older bridges fall into this category. Retrofitting efforts often focus on enhancing the structural integrity of bridges to meet the current safety standards and accommodate increased traffic loads(D H *et al.*, 2023; Kudari *et al.*, 2024). Common retrofitting techniques include strengthening floor systems, using advanced materials, such as fiber-reinforced polymers, and improving the connections between structural elements to develop composite actions(Bhavana, 2024; P G and Satyanarayana, 2023). Reinforced concrete (RC) structures can be strengthened either by changing the design scheme or by enhancing the existing scheme without altering the fundamental structure(Wulin Li *et al.*, n.d.). Both the methods have specific applications and benefits, particularly when dealing with bending elements. There are two main methods for strengthening existing bridges. By changing the design scheme, this technique involves adding new structural elements that redistribute external stresses and internal forces to less-loaded parts of the structure. The key objectives are to reduce the design span and enhance the bending stiffness of the reinforced cross-section. Strengthening without changing the design scheme involves either increasing the cross-sectional area of the structural elements or using external reinforcement to improve the performance without adding significant bulk(Schnerch *et al.*, n.d.; Sharba *et al.*, 2021). This can be achieved using several methods including the use of advanced materials. RC structures can be effectively strengthened using various methods depending on the specific requirements and constraints of the project.

The aging infrastructure and increased traffic loads have strengthened existing bridges, which is a crucial concern in structural engineering. Many bridges that were originally designed for lighter loads require rehabilitation to ensure safety and functionality. Strengthening methods are essential for extending the service life of these structures and meeting the contemporary load requirements(Nair *et al.*, 2019; Skokandić *et al.*, 2022). The deterioration of bridge components due to environmental factors and increased traffic demands has led to a significant number of bridges being classified as understrength or obsolete. Rehabilitation, which often involves the strengthening of bridge elements, is a cost-effective alternative to complete replacement. This requirement is particularly pressing in regions such as Iowa, where numerous continuous composite bridges constructed in earlier decades now require upgrading (Hu *et al.*, 2020; Kenneth Dunker *et al.*, n.d.). The use of composite materials for strengthening bridges has garnered considerable attention owing to their advantages over traditional materials such as steel. Composite materials such as carbon fiber-reinforced polymer (CFRP) strips and steel plates offer benefits such as reduced weight, ease of handling, and high strength-to-weight ratios(Durgadevi *et al.*, 2021; Kim, 2019). These materials can be used to enhance the flexural and shear capacities of bridge components, thereby improving their overall structural performance (Kwon *et al.*, n.d.; Makarov and Rekunov, 2019). Various methods have been explored to strengthen composite bridges. One effective technique involves post-tensioning, which applies external forces to the bridge to counteract loads. This method improves the stress distribution in both the positive and negative moment regions of a bridge, thereby enhancing its load-bearing capacity. Numerical studies using tools, such as ANSYS, have demonstrated the effectiveness of different strengthening materials and configurations, thereby providing insights into optimal designs for practical applications (Hu *et al.*, 2020; Makarov and Rekunov, 2019). Despite these advantages, the application of composite materials for bridge strengthening presents several challenges(Sen *et al.*, n.d.; Trent Miller *et al.*, n.d.). Proper bonding of the composite plates to the existing structure is critical, and requires careful surface preparation and adhesive application. Mechanical anchoring provides a more reliable alternative under field conditions where perfect bonding is difficult to achieve. Additionally, the introduction of stress concentrations and the potential for brittle failures necessitate a thorough evaluation and optimization of strengthening designs (Kwon *et al.*, n.d.; Narmashiri and Jumaat, 2009). Discussed "Structural Health Monitoring (SHM)" and focused on damage pattern recognition using fuzzy similarity prescriptions. The introduction states that SHM aims to detect, locate, and assess the severity of structural damage by analyzing in situ behavior(Sasmal *et al.*, n.d.; Satyanarayana *et al.*, 2024). Traditional SHM methods rely on vibration-based techniques and statistical analyses, which primarily address random uncertainties(Lau *et al.*, 2018; Parks *et al.*, 2018). However, the method proposed in this paper introduces fuzzy sets to account for other types of uncertainties, such as ambiguity and vagueness, thereby enhancing the accuracy of damage pattern recognition in structures.

Using actual bridge data, this study aims to

- To examine the potential for strengthening bridge structures.
- To evaluate the structural behavior and develop design recommendations.
- To increase the strength and durability of bridge structures using the proposed method.

The novelty of bridge retrofitting lies in the diverse methods employed to strengthen existing reinforced concrete (RC) structures, which can be categorized into two main approaches. Changing the design scheme in this technique involves adding new structural elements that redistribute external stresses and internal forces to less-loaded parts of the structure. The key objectives are to reduce the design span and enhance the bending stiffness of the reinforced cross-section. Strengthening without changing the design scheme in this method involves increasing the cross-sectional area of the structural elements or using external reinforcement to improve performance without adding significant bulk. Advanced materials like CFRP (carbon fiber reinforced polymer (CFRP) strips and steel plates, are employed because of their reduced weight, ease of handling, and high strength-to-weight ratios. Both methods aim to extend the service life and performance of concrete structures, thereby addressing the challenges posed by aging infrastructure and increased traffic loads. The use of composite materials, such as CFRP and steel plates, offers advantages over traditional materials, contributing to improved structural performance and load-bearing capacity.

2. Methodology

A structured approach for evaluating both existing and retrofitted bridges using specific parameters is used. The strengthening of the bridge was analyzed using ANSYS software for modeling and simulation. The methodology begins with modeling an actual bridge in ANSYS based on real-world data, including bridge geometry, material properties, and load conditions. This initial model incorporates all relevant parameters such as materials, loads, and boundary conditions. Following the creation of this base model, an analysis was performed to evaluate the bridge performance under these conditions, and a second model of the bridge was developed with identical parameters, geometry, materials, loads, and boundary conditions. However, this version of the bridge is retrofitted with a carbon fiber-reinforced polymer (CFRP) material to strengthen the girder(Picard *et al.*, 1995; Samadi *et al.*, 2021). The retrofitted bridge model was subjected to the same analysis procedure.

After completing the analyses of the original and retrofitted bridge models, the results were compared. The comparison focused on key metrics, including deformation, maximum shear stress, directional deformation, equivalent stress, maximum shear elastic strain, shear stress, and strain energy. This comparative analysis helped to determine the effectiveness of CFRP retrofitting in enhancing the strength and performance of the bridge. This structured methodology ensures a systematic approach to modeling, analyzing, and comparing the structural performance of bridges, thereby providing a clear understanding of the benefits of CFRP retrofitting.

2.1 Description of Bridge Modeling

The existing bridge in Beed, located along National Highway No. 211, spans the Bindusara River. Figs. 1 and 2 measure 42 m in length and 7.95 meters in width, and feature a structure composed of three continuous reinforced concrete girders. The superstructure included a 300-mm-deep reinforced concrete deck slab supported by three girders, each with a depth of 1100 mm. The bridge's solid piers are 4.0 meters in width, 1.0 meters in thickness, and 6 m high, resting on a stable soil stratum (Satyanarayana et al., 2023; H Rajkamal et al., 2023)

Table 1. Primary load cases considered in the modeling.

Load case	Stiffness	Load
Dead	Non-composite section	Girder weight and concrete deck weight
Pre-stress	Non-composite section	Pre-stressing force
Live	Composite section	70R Tracked vehicle load (IRC 6: 2014)

In the bridge modeling process, the deck is represented using thin shell elements, whereas the girders and piers are modeled as 3D elastic elements. This study involved modeling and analyzing the bridge using ANSYS under two different conditions: with the original beams and with retrofitted beams. Table 1 presents the primary load conditions applied to the bridge. The material properties used include concrete with a density of 2300 kg/m³, tensile ultimate strength of 5e+06 Pa, and compressive ultimate strength of 4.1e+07 Pa. Various bridge models were compared based on deflection, deformation, maximum shear stress, directional deformation, equivalent stress, maximum shear elastic strain, shear stress, and strain energy. Figure 1 illustrates a model of the existing bridge.

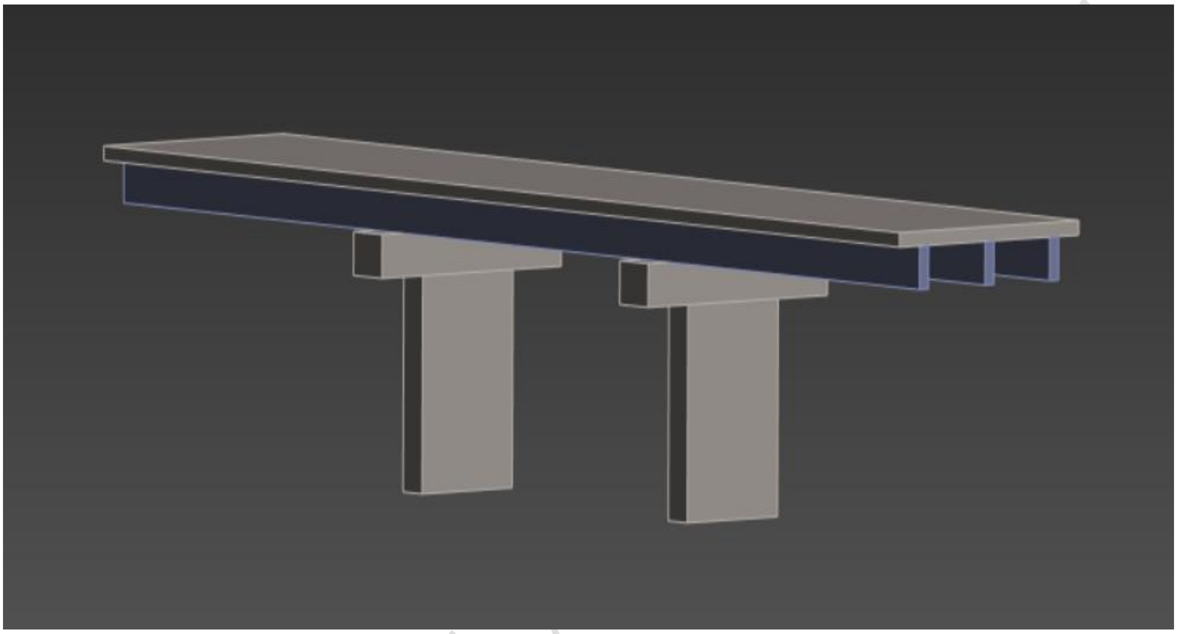

Fig. 1 illustrates the bridge model of an existing bridge.

Figure 2 shows the retrofitted bridge where a 2 mm Carbon Fiber Reinforced Polymer (CFRP) layer was added to the girders on three visible sides. The retrofitting was aimed at enhancing the structural integrity and load-carrying capacity of the bridge. The specific areas of application included the bottom and two lateral sides of the girders, and CFRP was applied using epoxy resin to ensure strong adhesion to the concrete surface. The preparation involved cleaning and roughening the concrete surface to maximize the bond strength. The material properties of the CFRP used in the retrofitting included a thickness of 2 mm, tensile strength of approximately 3.5 GPa, elastic modulus of approximately 230 GPa, and density of approximately 1.6 g/cm³.

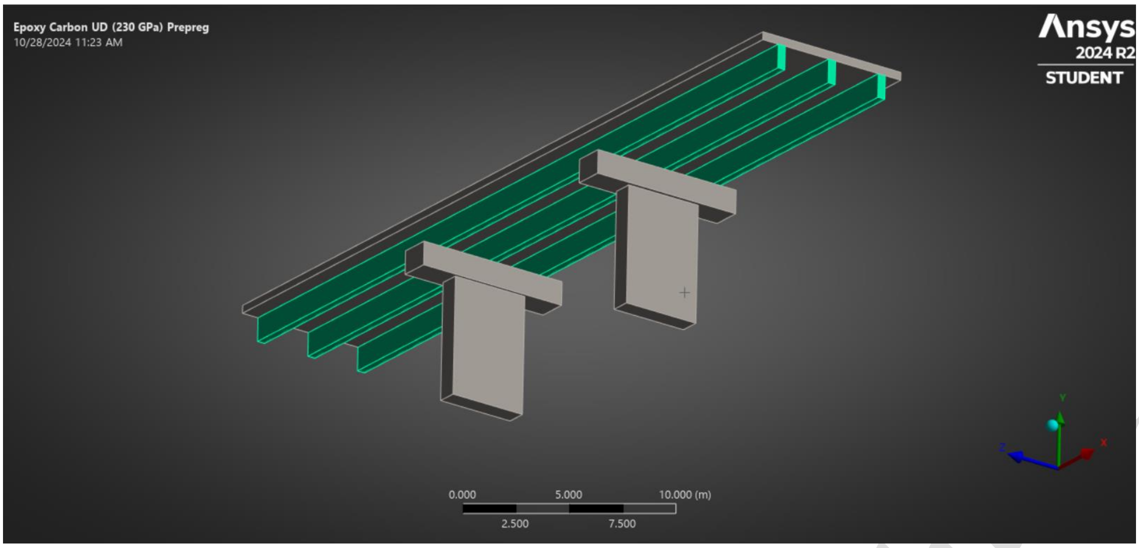

Fig. 2 illustrates the retrofitted bridge model.

The following assumptions were made for the analysis of isolated bridges.

1. Elastomeric bearings are expected to be used near supports.

2. The bridge deck was level and considered to be rigid.

3. Bridge piers were firmly anchored at the foundation level.

4. The impact of the soil-structure interaction is neglected because the bridge is founded on solid rock or stable soil.

3. Results and discussion

Tables 2 and 3 present the results of various parameters for the existing and retrofitted bridges. This comparison aims to evaluate the effectiveness of the proposed retrofitting solutions. The analysis was conducted using linear elastic methods, and the results are illustrated in the accompanying graphs. These results highlight key performance metrics for both the existing and retrofitted structures, providing insights into improvements achieved through retrofitting.

Table. 2: Results of Existing Bridge

EXISTING BRIDGE

RESULT	MINIMUM	MAXIMUM	UNIT
TOTAL DEFORMATION	0	0.0019452	m
DIRECTIONAL DEFORMATION	-0.00013346	0.00012903	m
STRAIN ENERGY	5.0802E-07	1.1712	J
SHEAR STRESS	-851230	676840	Pa
MAXIMUM SHEAR STRESS	208.63	2476000	Pa
MAXIMUM SHEAR ELASTIC STRAIN	2.7122E-09	0.000091778	m/m
EQUIVALENT STRESS	365.01	4361800	Pa

Table. 3: Results of the Retrofitted Bridge

RETROFITTED BRIDGE			
RESULT	MINIMUM	MAXIMUM	UNIT
TOTAL DEFORMATION	0	0.0017123	m
DIRECTIONAL DEFORMATION	-0.00012015	0.00011789	m
STRAIN ENERGY	4.3004E-09	1.5188	J
SHEAR STRESS	-592060	599240	Pa
MAXIMUM SHEAR STRESS	87.339	1694100	Pa
MAXIMUM SHEAR ELASTIC STRAIN	9.3148E-09	0.000048572	m/m
STRESS	152.01	3001600	Pa

3.1 Total Deformation

Fig 4 Compare the total deformation and load of an existing bridge with a retrofitted bridge, where retrofitting was performed using carbon fiber-reinforced polymer (CFRP).

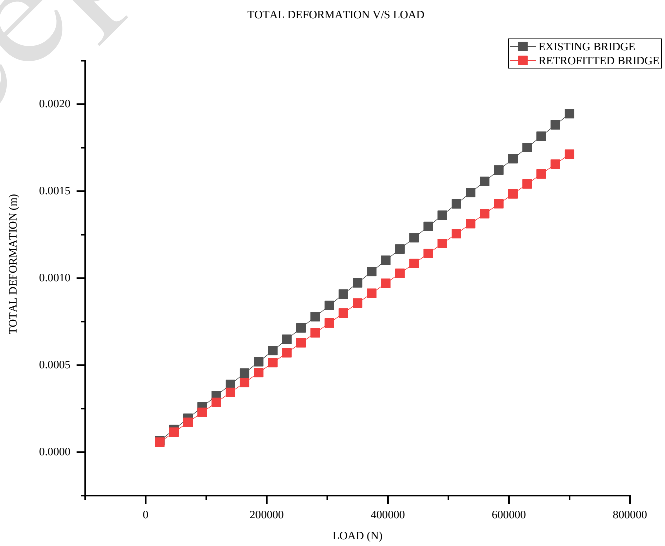

Fig. 4: Total deformation v/s load of existing bridge and retrofitted bridge

- The existing bridge exhibited a steep increase in deformation over time, indicating significant wear and tear. With increasing load, the existing bridge exhibited larger deformation. The higher deformation in the existing bridge is likely due to material degradation and a lack of reinforcement.
- The retrofitted bridge showed a much gentler deformation slope, suggesting that retrofitting measures significantly improved its structural integrity. Under similar loading conditions, the retrofitted bridge exhibited less deformation, thereby highlighting the effectiveness of the retrofitting process. The retrofitted bridge benefits from modern materials and techniques, which enhance its ability to bear loads and resist deformations.

3.2 Directional Deformation

Fig 5 Compare the directional deformation and load of an existing bridge with a retrofitted bridge, where retrofitting was performed using carbon fiber-reinforced polymer (CFRP)

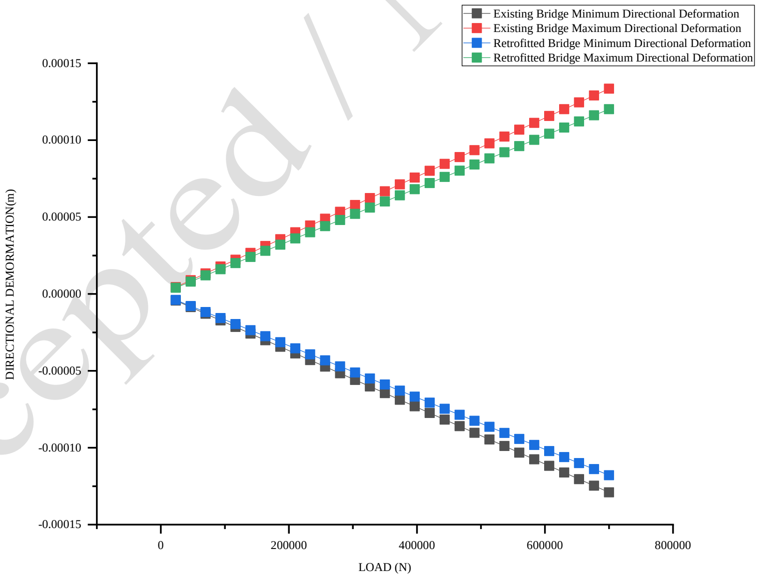

Fig. 5: Directional Deformation v/s Load of Existing Bridge and Retrofitted Bridge

- Directional deformation refers to the displacement or movement of a bridge structure in a specific direction owing to loads, such as traffic, wind, or seismic activity. Existing bridges tend to exhibit more significant directional deformation owing to factors such as material degradation, outdated design standards, and a lack of modern construction techniques. Over time, these factors can lead to increased flexibility and decreased structural integrity, thereby causing the bridge to deform under similar loads.

- Retrofitted bridges typically show reduced directional deformation compared with their original state because the enhancements improve their rigidity and ability to distribute loads more effectively.
- The existing bridge exhibited a larger directional deformation, indicating that it was more susceptible to bending or displacement under loads. The retrofitted bridge exhibited smaller directional deformation, demonstrating improved resistance and stability.

3.3 Equivalent Stress

Fig 6 Compare the equivalent stress and load of an existing bridge with a retrofitted bridge, where retrofitting is performed using carbon fiber-reinforced polymer (CFRP).

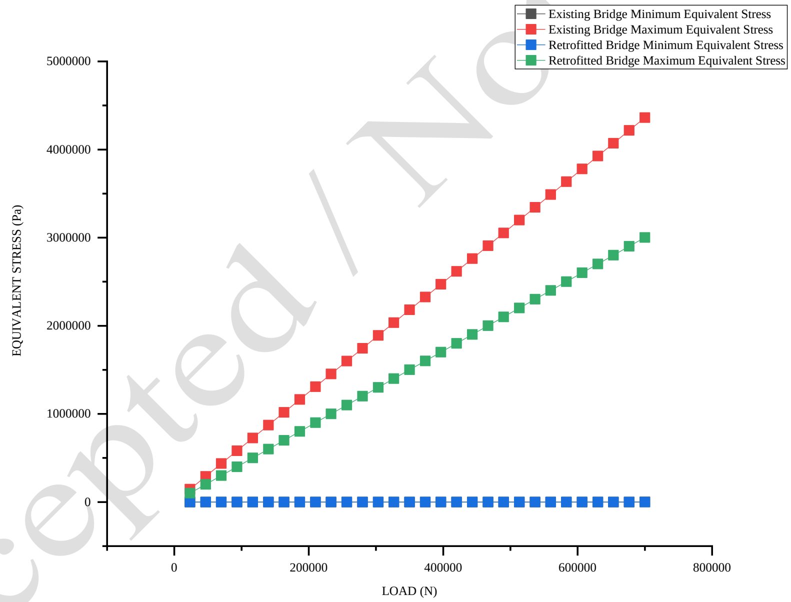

Fig. 6 Equivalent Stress v/s Load of Existing Bridge and Retrofitted Bridge

- This suggests that the existing bridge experienced higher stress levels under the same loading conditions as the retrofitted bridge. A higher equivalent stress indicates a higher likelihood of material yielding, potential structural damage, or failure.
- The retrofitted bridge shows reduced equivalent stress values, implying that the modifications effectively redistribute the loads or increase the capacity of the bridge to handle stress. This reduction in stress suggests improved structural integrity and a lower risk of material failure.

- By comparing the equivalent stress values, we can conclude that the retrofitting process has significantly enhanced the structural capacity of the bridge, making it more resilient and reliable than the existing bridge.

3.4 Maximum shear elastic strain

Fig 7 Compare the maximum shear elastic strain and load of an existing bridge with a retrofitted bridge, where retrofitting is performed using carbon fiber-reinforced polymer (CFRP).

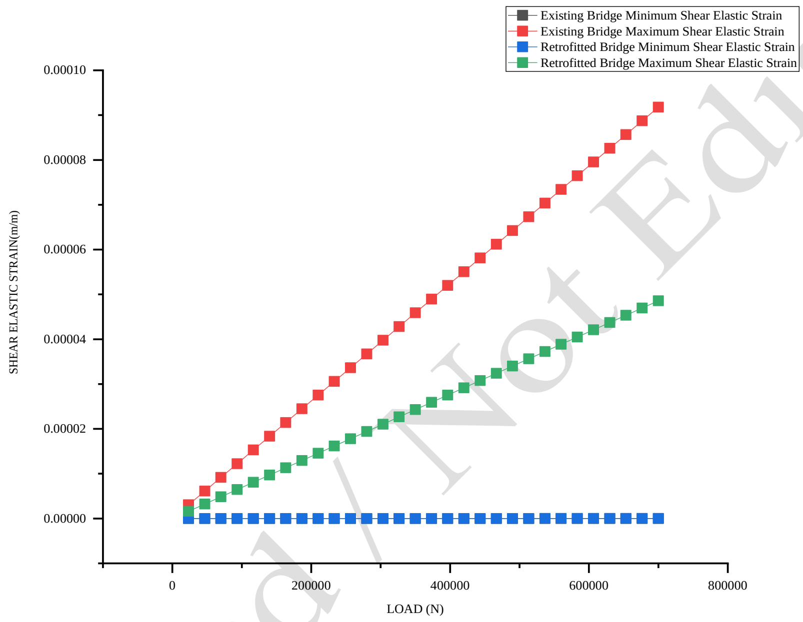

Fig. 7: Maximum Shear Elastic Strain v/s Load of Existing Bridge and Retrofitted Bridge

- The existing bridge exhibited higher maximum shear elastic strain. This implies that under the same amount of shear stress, the existing bridge deforms more than the retrofitted bridge. A higher maximum shear elastic strain indicates that the bridge material or structure is less stiff or more compliant. This could be due to the aging materials, outdated designs, or deterioration over time.
- The retrofitted bridge exhibited lower maximum shear elastic strain. This suggests that the retrofitting process increases the stiffness and strength of the bridge, allowing it to resist shear deformation more effectively. A lower shear strain in the retrofitted bridge indicates an improved performance and a higher capacity to bear shear loads without significant deformation. This improvement can be attributed to the use of modern materials, reinforcement techniques, and up-to-date engineering practices.

- The reduced maximum shear elastic strain in the retrofitted bridge indicates a more robust structure capable of handling shear stresses than the existing bridge. This is a clear indication of the success of retrofitting efforts to enhance the durability and load-bearing capacity of bridges.

3.5 Shear stress.

Fig 8 Compare the shear stress and load of an existing bridge with a retrofitted bridge, where retrofitting was performed using carbon fiber-reinforced polymer (CFRP).

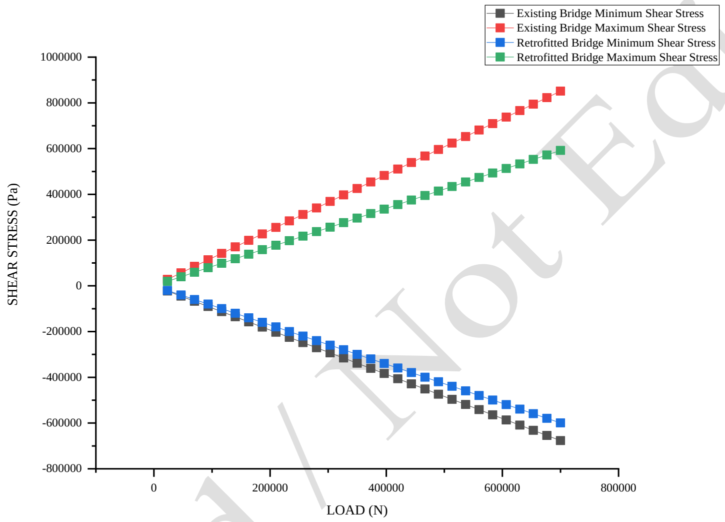

Fig. 8: Shear Stress v/s Load of Existing Bridge and Retrofitted Bridge

- In existing bridges, shear stress might be higher because of several factors, such as material degradation, outdated design standards, or insufficiently high shear stress, which can lead to structural issues such as cracking, deformation, or even failure if not addressed.
- After retrofitting, the shear stress in bridges is typically reduced. This is due to the improved load distribution, enhanced material properties, and modern engineering methods applied during the retrofitting process. A reduced shear stress implies that the bridge can handle higher loads, is safer, and has a longer lifespan.
- The comparing of the strain energies of the existing bridges shows that they would exhibit higher values of shear stress across the sections or over time. A retrofitted bridge exhibits lower shear stress values, indicating the effectiveness of the retrofitting process.

3.6 Strain Energy

Fig 9 Compare the shear stress and load of an existing bridge with a retrofitted bridge, where retrofitting was performed using carbon fiber-reinforced polymer (CFRP).

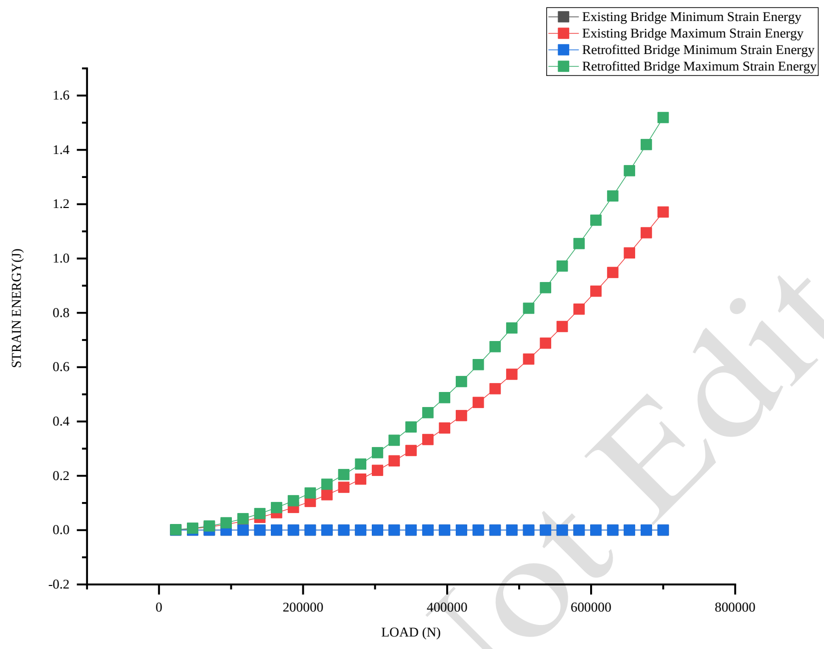

Fig. 9: Strain Energy v/s Load of Existing Bridge and Retrofitted Bridge

- Lower Strain Energy Figure 15 indicates that the existing bridge has less strain energy. This implies that the existing bridge can absorb less energy before reaching its failure point. The lower strain energy suggests that the existing bridge is more prone to damage under load and has a lower capacity to handle stress. They are likely to deform more easily and have a higher risk of structural failure.
- Higher Strain Energy The retrofitted bridge shows a higher strain energy on the graph. This indicates that the retrofitted bridge could absorb more energy before failure. A higher strain energy suggests that the retrofitted bridge is more robust and can handle greater loads without excessive deformation. The retrofitting process likely improved the structural integrity, allowing the bridge to distribute and absorb the stresses more effectively.
- This compares the strain energies of the existing and retrofitted bridges and shows that retrofitting significantly improves the structural performance of the bridge. By increasing the strain energy, the retrofitted bridge can handle greater loads and stresses, making it safer and more reliable than existing bridges. This comparison highlights the effectiveness of retrofitting in extending the life and enhancing the safety of aging.

3.7 Maximum Shear Stress

Fig 10 Compare the shear stress and load of an existing bridge with a retrofitted bridge, where retrofitting is performed using carbon fiber reinforced polymer (CFRP).

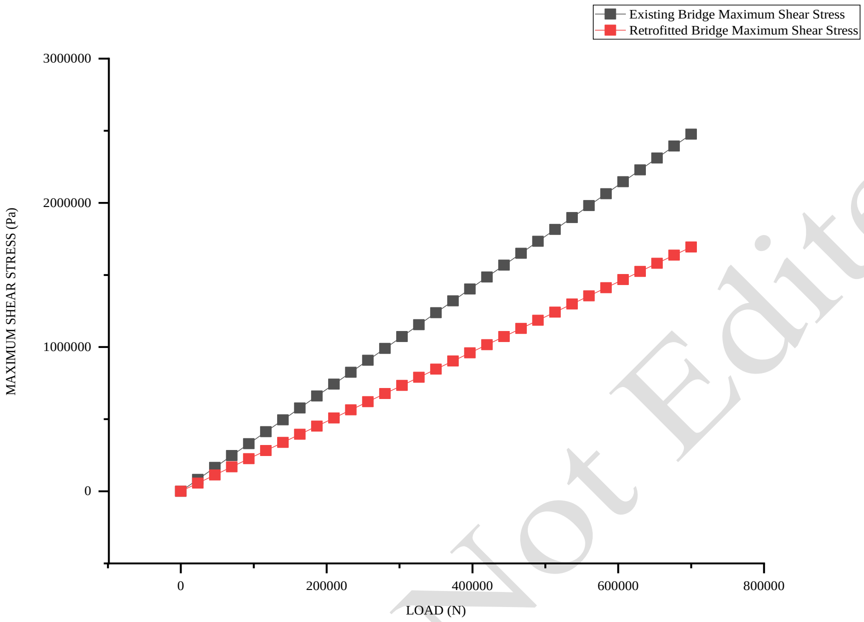

Fig. 10 Maximum Shear Stress v/s Load of Existing Bridge and Retrofitted Bridge

- The existing bridge had a higher maximum shear force. This could be due to various reasons, such as the materials used, design, and lack of modern reinforcements. Higher shear forces indicate that the bridge might be less capable of efficiently distributing loads, making it more prone to structural issues.
- The retrofitted bridge had a lower maximum shear force. This is typically the result of improvements made to strengthen bridges. Retrofitting may include adding additional support structures, using higher-quality materials, or incorporating modern design techniques to handle and distribute loads better. The reduction in the shear force suggests that the retrofitted bridge can better manage the applied loads, thereby increasing its durability and safety.
- The retrofitting significantly reduces the maximum shear forces experienced by the bridge. This reduction is beneficial for the longevity and safety of bridges, as lower shear forces reduce the risk of structural failure.

3.8 Maximum Von Mises stress

The Fig 11 and Fig 12 shows the relationship between the applied load (in Newtons, on the x-axis) and the maximum Von Mises stress on CFRP (Carbon Fiber Reinforced Polymer) and Concrete material (in Pascals, on the y-axis). The graph has two data series labeled as "MAXIMUM" and "MINIMUM," represented by black and red markers, respectively.

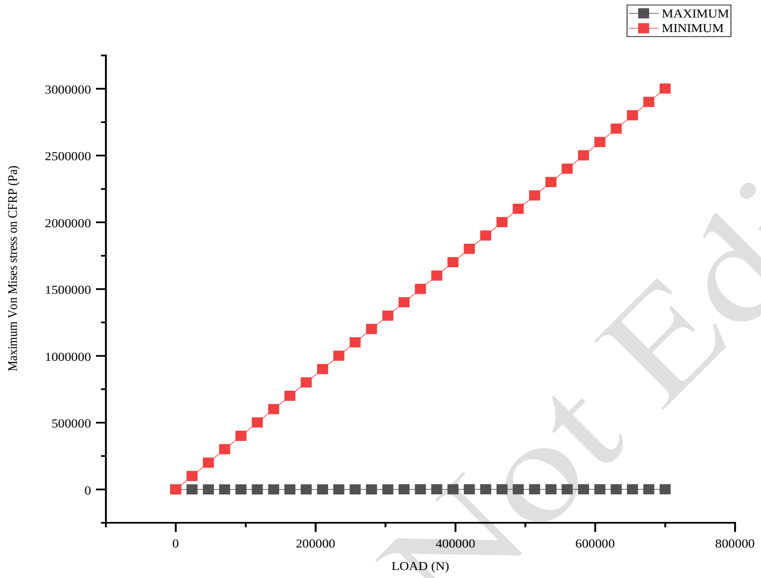

Fig. 11 Maximum Von Mises Stress on CFRP

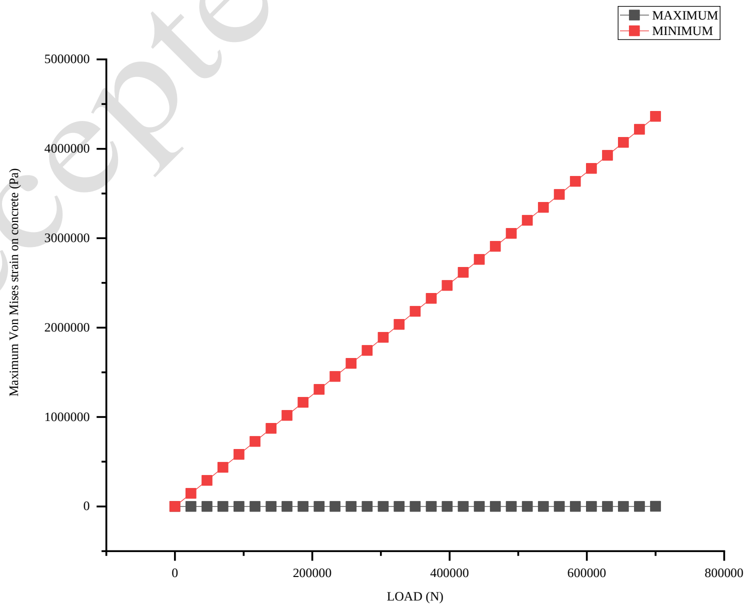

Fig. 12 Maximum Von Mises Stress on Concrete

- The red markers represent the maximum Von Mises stress on the CFRP material. As the load increases, the maximum Von Mises stress also increases linearly.
- This linear relationship suggests that the CFRP material experiences a proportional increase in stress as the applied load increases. The material remains in its elastic range (no yielding) under the loading conditions applied in this analysis.
- The graph shows that the maximum stress value reaches approximately 3,000,000 Pa when the load approaches around 80,000 N, indicating the material's stress level at that loading magnitude.
- The black markers represent the minimum Von Mises stress on the CFRP. In this graph, the minimum stress remains constant and near zero across the load range.
- This constant value indicates that, in some regions of the CFRP material, little or no stress develops, potentially due to load distribution or geometry effects in the model
- The graph shows that the maximum Von Mises stress in the CFRP material increases linearly with load, which is typical for linear elastic behavior. The minimum stress remaining constant at zero suggests that there are regions in the material that experience very low or negligible stress levels under the applied loading conditions. This analysis is useful in understanding the stress distribution within CFRP under load and helps in identifying critical areas where maximum stress occurs.

4. Implementing fuzzy logic code to monitor the structural health of bridges

The development of a slow-load logic approach for structural health monitoring (SHM) encompasses the intricate process of creating a sophisticated system capable of evaluating the structural integrity of buildings and infrastructures relying on uncertain data. Fuzzy logic has emerged as a pivotal tool in SHM because of its unparalleled capacity to navigate through uncertainties and intricacies that are characteristic of complicated and nonlinear correlations often present in structural assessments. This elaborate development journey consists of several pivotal stages, starting with the definition of the problem, followed by meticulous data collection and preprocessing, intricate fuzzy logic system design, meticulous software implementation, thorough validation and testing, comprehensive optimization and refinement procedures, subsequent deployment and maintenance, and the integration of key notions such as uncertainty management, advanced monitoring strategies, and user-friendly interfaces to guide engineers and maintenance personnel efficiently through the system.

The primary aim of this endeavor is to institute a flawless logic infrastructure for SHM, pinpointing and predicting potential threats or system failures with unparalleled precision. This ambitious goal necessitates a meticulous process for defining diverse structures and identifying specific parameters to monitor, which frequently include stress, strain, and vibration levels. Subsequently, the essential stages of data collection and processing become critical, where tasks such as precise point placement, data categorization, thorough data cleansing, and the intricate design of fuzzy logic systems take the center stage.

The quintessential phase of fuzzy-logic system design delves into the complexities of crafting fuzzy sets and corresponding membership functions, delineating explicit rule sets, articulating an effective inference engine, and establishing robust defuzzification mechanisms. The subsequent implementation phase demands sophisticated software development utilizing versatile tools, such as Python. Rigorous validation and testing regimes further enhance the system's reliability through simulated data evaluation and real-world field tests, whereas optimization and refinement demand continual analysis and possible hybrid approaches for enhanced system efficiency.

As the system transitions towards deployment and maintenance, a cyclical process of frequent updates incorporating new data inputs and eliminating redundant rules becomes imperative to uphold the system accuracy. Fundamental concepts, such as efficient uncertainty management, the capacity to monitor multiple structures concurrently, and the realization of an intuitive user interface that empowers engineers and maintenance teams to interpret system outputs effortlessly, are reiterated as critical elements in ensuring the system's overall success and longevity.

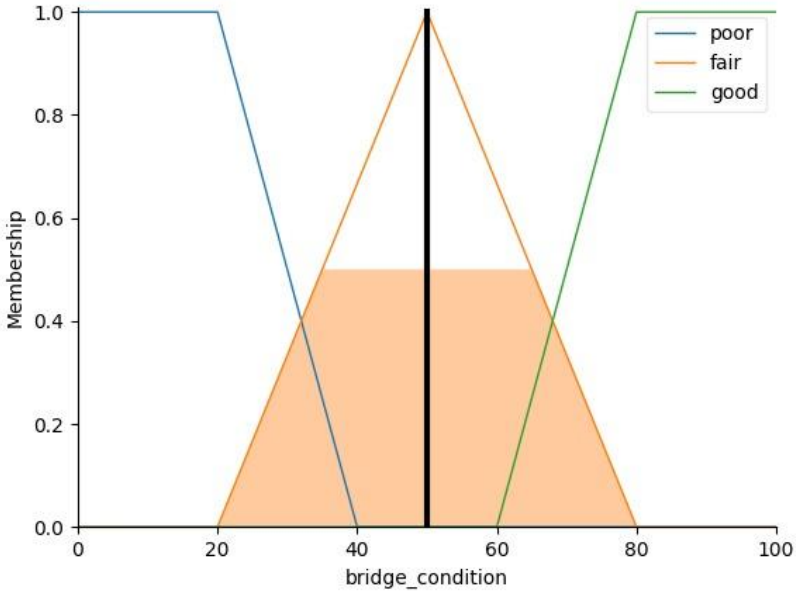

Fig. 13: Membership Functions for Bridge Condition

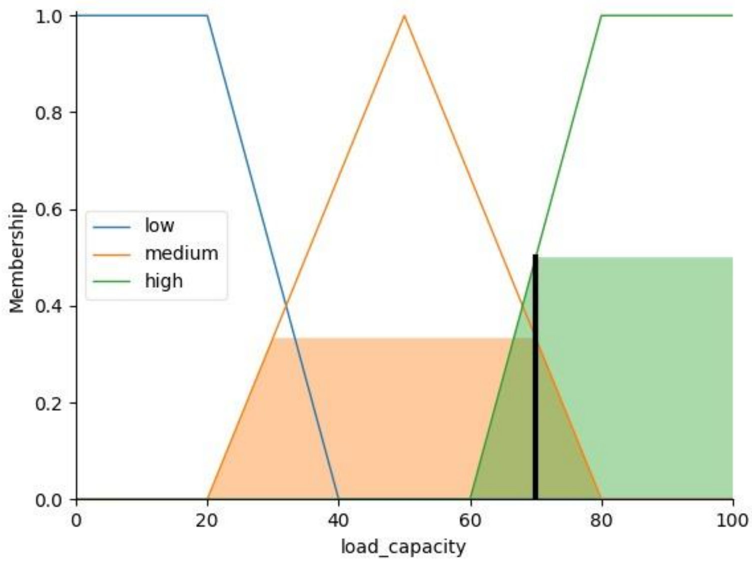

Fig. 14: Membership Functions for Load Capacity

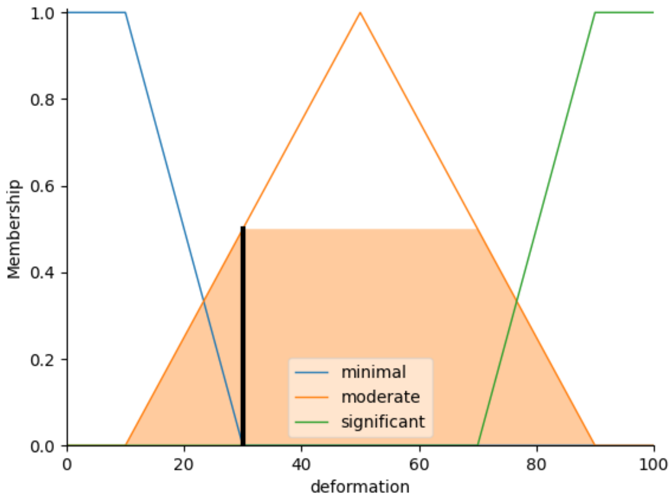

Fig. 15: Membership Functions for Deformation

Fig 13 shows different membership values, with "poor" being high for low bridge conditions (0-20) and decreasing linearly to 0, "fair" being high at 50 and decreasing linearly to 0, and "good" being high for high bridge conditions (80-100). The black vertical line indicates a specific bridge condition value, where the membership values for "poor," "fair," and "good" can be interpreted based on the height of the intersection with the respective membership functions. The plots were used to illustrate the different membership values and their relationship with the bridge condition. Fig. 14 shows the load capacity and membership values. Low load capacity has a high membership function (0-20), while medium load capacity has a high membership function (50-70) and a linear decrease to 0 (30-70). A high load capacity has a high membership function (80-100) and a linear decrease to zero (60). The black vertical line indicates a specific load capacity value (around 75), with membership values for "low," "medium," and "high" based on the height of the intersection with the respective membership functions. Fig. 15 shows the fuzzy logic membership function graph. Here, the x-axis represents "deformation," and the y-axis represents "membership," ranging from 0 to 1. The graph contains three triangular membership functions labeled "minimal," "moderate," and "significant," which correspond to different levels of deformation Minimal: Represented by the blue line, the membership function decreases from 1 to 0 as deformation increases from 0 to about 30. Moderate: Represented by the orange line, this function peaks at 1 around a deformation of 50 and then decreases symmetrically, showing that moderate deformation has the highest membership value at 50. Significant: Represented by the green line, this membership function starts increasing from 0 at approximately 50 deformations and reaches 1 at approximately 70. The shaded area between the black vertical line at approximately 40 deformations and the moderate membership function indicates the degree of overlap between the membership functions. This overlap illustrates the concept of partial membership in fuzzy logic, where a certain amount of deformation can be considered as having both minimal and moderate significance to varying degrees.

5. Conclusion

The reinforcement method using carbon-fiber-reinforced polymer (CFRP) strips extends the service life of the bridge. The approach provided a cost-effective solution compared with complete deck replacement, achieving a strengthening factor of 2.4. Comprehensive checks and quality control measures ensured bond quality and effectiveness of the reinforcement. The evaluation of bridge retrofitting using carbon fiber-reinforced polymer (CFRP) strips revealed significant enhancements in the bridge's structural performance. The key findings are as follows.

- Maximum Von Mises Stress in Pure Bending, During the initial stages of loading, Von Mises stress in CFRP sheets of varying thicknesses is similar. As the load increases, Von Mises stress in CFRP becomes higher than in Concrete. Changes in CFRP thickness do not significantly affect the Von Mises stress in CFRP. Thicker CFRP sheets experience lower Von Mises stress compared to thinner CFRP sheets under the same loading conditions.
- Von Mises Strain in Concrete, The maximum Von Mises strain in concrete occurs beneath the point load, potentially leading to deck punching. Different thicknesses of CFRP do not significantly impact Von Mises strain in the concrete. Thinner CFRP sheets cause more strain on the concrete compared to thicker sheets.
- Load-Bearing Capacity, CFRP sheets are preferable over steel plates for load-bearing in rehabilitation applications. Load-bearing capacity of CFRP sheets is much higher than that of steel plates of the same thickness.
- Maximum deflection of the girder appears in the pure bending region which located in the mid span. If thicker CFRP sheets are chosen, then the maximum deflection of the girder will be less noticeable.
- Strain energy analysis shows that the retrofitted bridge can absorb and dissipate energy more effectively, enhancing its resilience and durability.

- The shear stress and concrete shear stress evaluations indicated that the retrofitted bridge had superior resistance to shear forces, contributing to its overall structural integrity.
- A comparison of existing and retrofitted bridges underscores the importance of retrofitting in improving the performance and safety of existing bridges, ensuring their ability to meet modern load requirements and safety standards.
- An analytical model was developed to predict the flexural resistance of concrete beams strengthened with fiber composite plates. When a beam is strengthened, its curvature at failure an indicator of flexural ductility decreases.

These findings highlight the efficacy of CFRP retrofitting for extending the service life and enhancing the structural performance of existing bridges.

5.1 Declaration

The authors of this manuscript declare that in the writing process of this work, no generative artificial intelligence (AI) or AI-assisted technologies were used to generate content, ideas, or theories. We have used AI in the writing process to enhance readability and refine language, with strict human oversight. They reviewed and edited the manuscript to ensure accuracy and coherence, acknowledging the potential for AI-generated content to be incorrect or biased.

5.2 Limitations

Despite its success, the method faced challenges such as:

- Ensuring proper bonding of CFRP strips to existing concrete, which requires careful surface preparation and adhesive application.
- Potential for stress concentrations and brittle failures, necessitating thorough evaluation and optimization of strengthening designs.
- Environmental factors such as temperature and humidity during the application require careful monitoring to ensure the effectiveness of the bond.

5.3 Future Scope

Further research and development are essential for the following reasons:

- Optimize the design and application methods for CFRP retrofitting to address stress concentrations and bonding issues.
- Explore the long-term performance and durability of CFRP materials under various environmental conditions.

- Develop new materials and techniques to further enhance the load-bearing capacity and lifespan of retrofitted bridges.
- Implementation of real-world applications and field demonstrations to validate the effectiveness of laboratory findings and numerical simulations.

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