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A Study on Effect of Retrofitting Technique on Nodal Displacements and Beam Displacements on RC Bridge Using Finite Element Model

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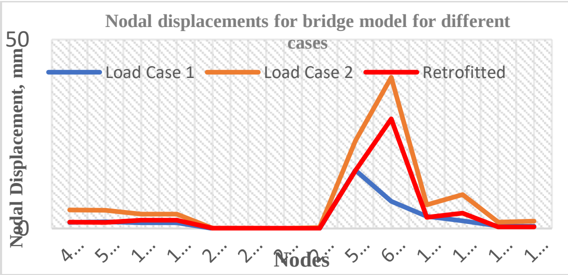
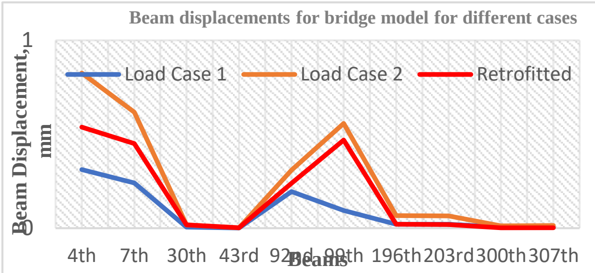
Abstract: Traffic loading can cause various failure modes in bridges, including bending moments, shear forces, stresses, and displacements. The complexity of bridge structures makes it challenging to evaluate their fatigue damage. To study these issues, numerical simulation offers a viable approach. This paper explores methods to enhance bridge stability and safety through retrofitting techniques, particularly for aging structures and those under heavy traffic conditions. The research proposes a novel retrofit method for reinforced concrete (RC) highway bridge columns in demanding construction environments. This approach combines carbon fiber reinforced polymer (CFRP) sheets with steel jacketing. The paper introduces this retrofit method, detailing the CFRP-steel bonded connection and explaining how it provides increased stiffness to RC bridge columns.

Graphical Abstract:





Keywords: Displacement, Retrofitting, Carbon fiber reinforced polymer (CFRP) sheets, Steel Jacketing, FE Model, RC Bridge

1. Introduction

Throughout human history, bridges have played a crucial role. Cities often developed around bridge locations where crossing waterways was challenging year-round. This is evident in places like London, Oxford, Cambridge, and Innsbruck. Major conflicts have frequently centered on urban areas and their bridges. In warfare, an army's ability to move is often determined by the presence or absence of river crossings. As a result, military training emphasizes techniques for both destroying existing bridges during retreats and rapidly constructing new ones during advances.

Importance of Bridge Analysis and Retrofitting

1.1. Safety Assurance:

1.1.1. Structural Integrity: Bridge analysis is crucial for ensuring the structural integrity of a bridge. Regular inspections and detailed analysis help identify any signs of wear, damage, or structural weaknesses that could lead to catastrophic failures. Ensuring the safety of the public who use these bridges is paramount.

1.1.2. Load Capacity Assessment: Bridges are designed to carry specific loads. Over time, due to increased traffic, heavier vehicles, and environmental factors, the load capacity may be exceeded. Analysis helps in assessing whether the bridge can still safely carry current loads or if there is a need for reinforcement.

1.2. Longevity and Durability:

1.2.1. Preventive Maintenance: Regular analysis of bridges allows engineers to detect issues before they become severe, facilitating preventive maintenance. This proactive approach can significantly extend the lifespan of a bridge by addressing problems early.

1.2.2. Material Degradation: Over time, materials like steel, concrete, and asphalt can degrade due to factors like weathering, corrosion, and fatigue. Analyzing these materials ensures that the bridge components are still within safe operating conditions, reducing the risk of sudden failures.

1.3. Cost-Effectiveness:

1.3.1. Economic Impact: Bridges are critical infrastructure that supports economic activities by connecting different regions. The collapse or closure of a bridge due to neglect or unforeseen damage can have significant economic repercussions. Regular analysis helps avoid such costly interruptions.

1.3.2. Retrofitting vs. Replacement: Retrofitting is often a more cost-effective solution compared to replacing an entire bridge. Through detailed analysis, engineers can determine if retrofitting is a viable option to strengthen the existing structure, saving time and money.

1.4. Adaptation to Modern Requirements:

1.4.1. Changing Codes and Standards: Engineering standards and codes evolve over time. Older bridges might not meet current design requirements, which can include factors like seismic resistance, wind loads, or traffic patterns. Analysis helps in identifying these gaps and planning appropriate retrofitting strategies.

1.4.2. Environmental and Sustainability Considerations: Modern analysis techniques consider environmental factors such as the impact of climate change, which can lead to increased flooding, temperature fluctuations, or other environmental stresses. Retrofitting can make older bridges more resilient to these changes.

1.5. Enhancing Resilience:

1.5.1. Natural Disasters: Bridges in areas prone to earthquakes, floods, or hurricanes need to be particularly resilient. Analysis of a bridge's ability to withstand such events and subsequent retrofitting ensures that the structure remains safe and functional even under extreme conditions.

1.5.2. Redundancy and Reliability: Retrofitting can introduce additional structural elements that provide redundancy, enhancing the overall reliability of the bridge. This ensures that even if one part of the bridge fails, the overall structure can still remain intact.

1.6. Preservation of Historical and Cultural Heritage:

1.6.1. Conservation of Historic Bridges: Many older bridges are considered historic landmarks. Retrofitting allows for the preservation of these culturally significant structures while bringing them up to current safety and performance standards.

1.6.2. Balancing Aesthetics and Functionality: Retrofitting allows engineers to maintain the aesthetic value of historic bridges, ensuring that any modifications blend seamlessly with the original design.

From the above discussion, it can be said that, Bridge analysis and retrofitting are integral to maintaining the safety, functionality, and longevity of bridges. Regular analysis helps in identifying potential issues early, while retrofitting provides a cost-effective way to strengthen and modernize existing structures. These processes are essential not only for economic reasons but also for ensuring public safety, adapting to changing standards, and preserving historical structures. Investing in thorough analysis and appropriate retrofitting measures is crucial for sustainable infrastructure management.

2. Literature Review

Study by Harshitha [1] review techniques for strengthening RC beams using steel jacketing, focusing on addressing structural weaknesses due to factors like seismic activity, aging, and fire. The study highlights the use of galvanized iron (GI) wire mesh in retrofitting rectangular RC columns, which delays crack formation and buckling, thus extending the structure's lifespan. The performance of columns wrapped with varying percentages of GI mesh is compared, showing that higher percentages improve durability more effectively.

Study by M. Amala et al. [2] examines the effectiveness of using high-performance ferrocement mortar mixes for retrofitting RC square columns to enhance axial and shear strength. The experimental investigation involved developing a ferrocement mix with 10% silica fumes and 1% superplasticizer, then applying it as a jacket to both intact and distressed column specimens. The results showed that the 1:1.5 ferrocement mix significantly improved load-carrying capacity by 8.85% compared to control specimens. The study also utilized Carbon Fibre Reinforced Polymer (CFRP) sheets for additional reinforcement.

Experimental study by Sang-Hyun Park et al. [3] evaluated the seismic performance of reinforced concrete columns retrofitted with lap-spliced Textile Reinforced Mortar (TRM) jackets after exposure to high temperatures (up to 250°C). Eight column specimens were tested, focusing on the amount of carbon fiber mesh and surface treatment in lap-spliced areas. The results showed that TRM jackets effectively increased the strength and deformation capacity of the columns even after high-temperature exposure. An analytical model for predicting the seismic performance of these retrofitted columns was also developed and validated against experimental data.

Study by Mahmoud Elsayed et al. [4] examines the effectiveness of using steel fiber-reinforced self-compacting concrete (SFRSCC) jackets for retrofitting RC columns exposed to high temperatures. Eleven columns were tested, with some heated to 400°C and 600°C, and then retrofitted with varying SFRSCC jacket thicknesses. The results showed that SFRSCC jackets significantly improved the structural performance of the columns, particularly in terms of failure load, stiffness, and toughness. The increase in performance was more influenced by the thickness of the jackets rather than the volume of steel fibers. A design equation was also proposed to predict the failure load of retrofitted columns.

Study by Jian Xie et al. [5] conducted compressive tests on 18 stub concrete columns externally confined with ultra-high-performance concrete (UHPC) jackets, focusing on the jacket's thickness and column shape. The results showed that increasing the UHPC jacket thickness significantly improved the compressive behavior of cylindrical columns, but had a lesser effect on square columns. An analytical model was developed to predict the compressive stress-strain behavior, which was validated against test results. Additionally, a 3D nonlinear finite element model (FEM) was used to simulate and accurately replicate the columns' compressive behavior.

Study by Yi Ding et al. [6] proposes a new seismic retrofitting method for RC columns in buildings with outdated designs by using stainless steel grid-reinforced UHPC jackets in the plastic hinge zone. Pseudo-static loading tests on four rectangular columns showed that the retrofitting method, especially with two layers of stainless-steel grids, significantly enhanced the columns' ductility, bearing capacity, and energy dissipation. The method effectively confined the columns, reducing damage and residual displacements. A finite element model was developed and verified, further analyzing parameters like axial compression ratio and jacket thickness.

Study by Mohammed A. Al-Osta et al. [7] evaluates the strengthening of reinforced concrete (RC) columns using ultra-high-performance concrete (UHPC) through both experimental and numerical methods. Fifteen columns were tested under static eccentric loading with varying UHPC thickness and loading eccentricity. A 3D numerical model, validated against experimental results, was developed using ABAQUS software. This model was used to explore UHPC strength effects on column performance. An analytical model was also proposed to predict the failure load and moment for rectangular RC columns strengthened with UHPC. The study confirmed that UHPC jacketing effectively enhances RC columns' performance under eccentric loading, with improvements proportional to the UHPC thickness and inversely related to loading eccentricity. The analytical model provided accurate predictions of failure loads and moments for these columns.

Study by Chunxu Hou et al. [8] introduces a new prefabricated steel cage-reinforced UHPC jacket (PSRUJ) for improving the efficiency of retrofitting reinforced concrete (RC) columns compared to traditional cast-in-place UHPC jackets. The PSRUJ was combined with the near surface-mounted (NSM) technique, incorporating glass fiber-reinforced polymer (GFRP) bars, to enhance seismic retrofitting. Cyclic loading tests on RC columns retrofitted with PSRUJ alone or with PSRUJ and NSM GFRP bars showed increased load-carrying capacity (30-46%), deformation capacity (54-74%), and stiffness (24-40%). The addition of NSM GFRP bars further improved load-carrying capacity and reduced residual drift ratio, though it had minimal impact on ultimate drift ratio. A damage index was proposed to assess concrete damage, and models for peak strength, strain, and flexural strength of PSRUJ-confined damaged concrete were developed.

The study by Azam Amir et al. [9] examine the use of a combination of Fiber Reinforced Polymer (FRP) and wire mesh to strengthen critical sections of building columns, enhancing seismic resistance and structural strength. In their approach, FRP sheets were used for horizontal wrapping in one strengthening scheme, while wire mesh was used in another. The FRP sheets provided high strength, while the combination of FRP and wire mesh improved ductility. The research suggests that FRP jacketing is effective for future retrofitting projects.

Study by A.B.M. Amrul Kaish et al. [10] explores enhancements to the square jacketing method for reinforcing RC building columns. Conventional square jacketing often struggles with providing sufficient lateral confinement due to stress concentration and corner cracking. To resolve this, the study examines two strategies: (a) reinforcing all corners and (b) reducing stress concentration at the corners. The findings indicate that while both strategies are effective, the approach that strengthens all corners is more practical and better at addressing stress concentration problems.

3. Methodology

The task is to evaluate the deterioration and modernization of the bridge. The bridge has experienced wear due to heavy traffic loads and some deficiencies in bending moments, shear forces, stresses, and displacements. This excessive fatigue could lead to failure if not addressed. Technical upgrades, such as applying FRP sheets, are typically used to strengthen columns, especially where longitudinal stiffeners have been prematurely terminated without adequate length. CFRP sheets are applied around the end sections of longitudinal stiffeners in both the longitudinal and circumferential directions to enhance resistance to bending and shear. Additionally, FRP sheets are used to improve the ductility of columns by wrapping them around the plastic hinge area in the circumferential direction.

The bridge is analyzed to assess its current condition and future traffic loads. Given that the bridge will experience fatigue under future traffic conditions, retrofitting measures are implemented to mitigate this fatigue. The bridge model is evaluated using STAAD.Pro software.

1st case: In this scenario, the traffic load over a 50-year period, considering population growth, is assessed, and the corresponding results are obtained. The analysis is conducted using STAAD.Pro software.

2nd case: In this scenario, the bridge is evaluated for its ability to handle heavy traffic over the next 50 years due to population growth. The bridge experiences significant load movements, displacements, and stresses, resulting in fatigue. While the bridge can support these loads for a few more years, it is not designed to handle heavy traffic indefinitely. Adaptations have been successful in improving its load-bearing capacity, but the bridge's long-term performance under heavy traffic remains a concern.

3rd case: In this scenario, the bridge is assessed for a 50-year future burden due to heavy traffic from population growth. Unlike the previous case, only the columns, not the slabs, were retrofitted. Despite this, the modernization of the columns is sufficient to support heavy loads effectively.

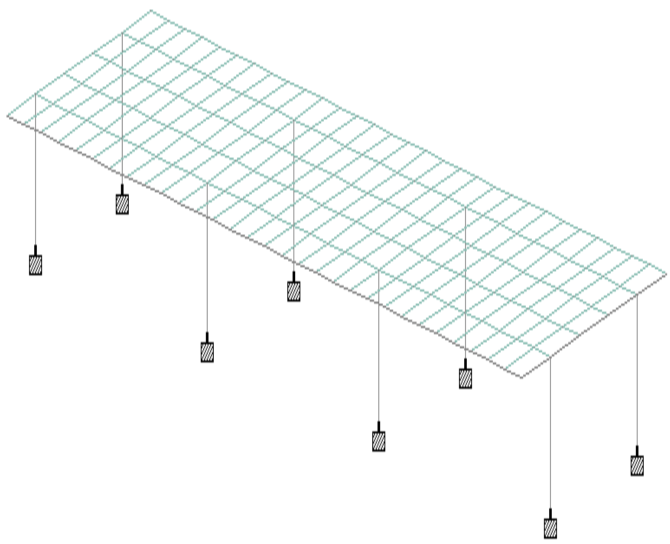
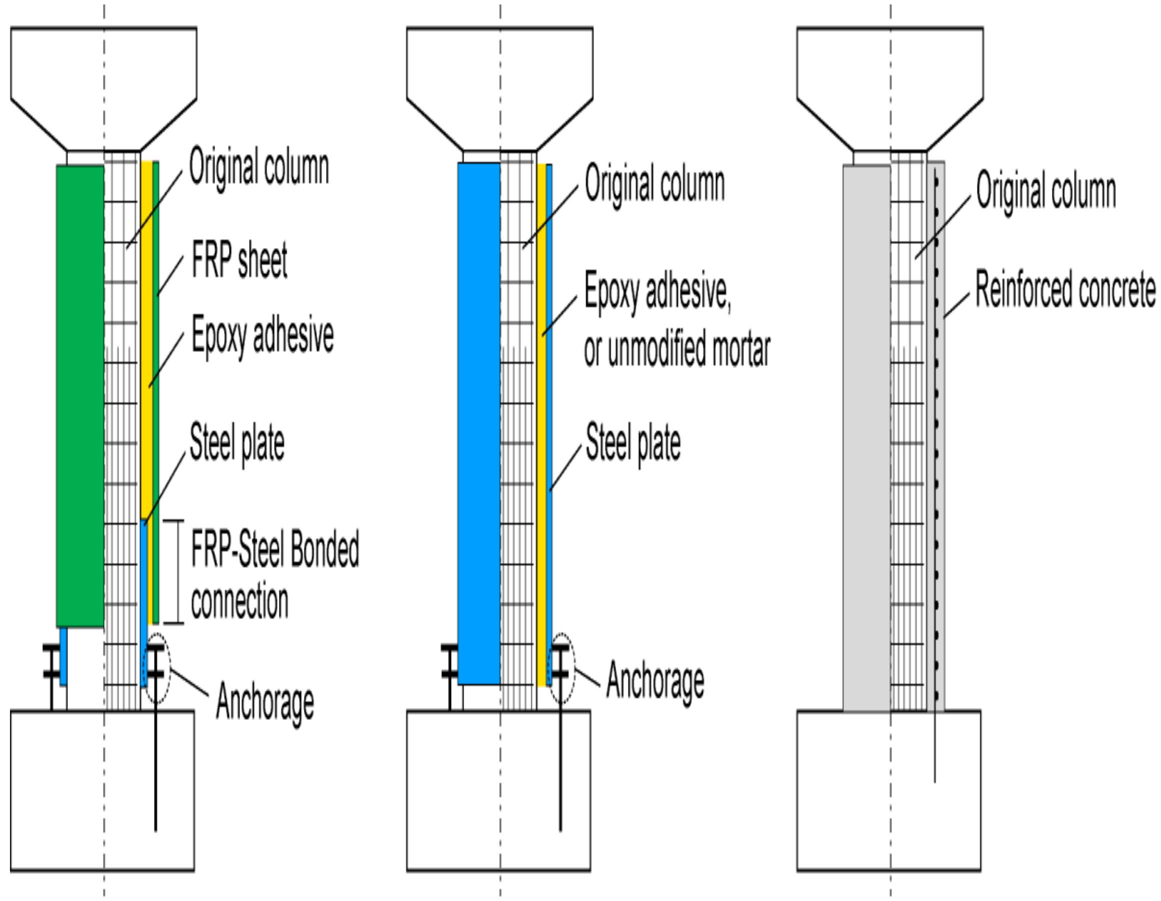


Figure 1: Bridge model

Table 1: Data for Analysis of bridge

Particulars	Data for Analysis of bridge before Retrofitting	Data for Analysis of bridge after Retrofitting
Length of the bridge	30 m	30 m
Width of the bridge	10m	10 m
Effective span of the bridge	10.4m	10.6 m
Width of the support	0.4m	0.6 m
Number of lanes	2	2
Thickness of deck slab	0.21m	0.21m



(a) Combination of CFRP (b) Steel jacketing (c) RC jacketing and steel jacketing

Figure 2: Retrofit methods for RC bridge columns

4. Results And Discussions:

The nodal displacements and Beam displacements values for different cases are tabulated below.

Table 2: Nodal displacements for bridge model for different cases

Nodes	1st case displacement(mm)	2nd case displacement(mm)	Retrofitting displacement(mm)
4th	1.65	4.95	1.62
5th	1.78	4.82	1.6
12th	1.5	3.8	2.2
13th	1.5	3.8	2.2
20th	0.015	0.081	0.071
21st	0.020	0.072	0.076
28th	0.004	0.038	0.049
29th	0.015	0.265	0.030
57th	15.427	23.22	15.31
61st	7.215	40.01	29.005
111th	3.218	6.24	3.004
115th	2.01	9.002	4.064
165th	0.702	1.701	0.408
169th	0.608	1.914	0.431

Table 3: Beam displacements for bridge model for different cases

Beams	1st case displacement (mm)	2nd case displacement (mm)	Retrofitting displacement (mm)
4th	0.312	0.826	0.538
7th	0.241	0.618	0.451
30th	0.005	0.018	0.017
43rd	0.001	0.002	0.003
92nd	0.194	0.309	0.239
99th	0.094	0.558	0.469
196th	0.021	0.067	0.021
203rd	0.021	0.066	0.020

300th	0.005	0.012	0.002
307th	0.004	0.014	0.003

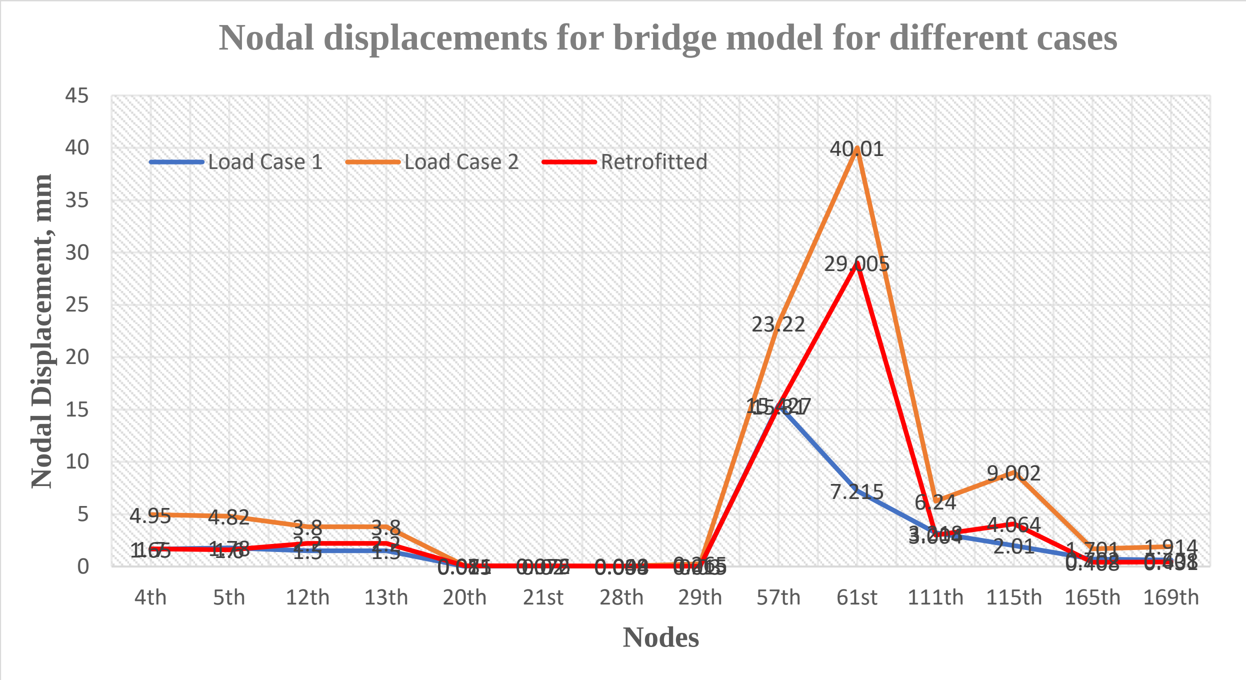


Figure 3: Comparisons of results between Nodal Displacements of different cases

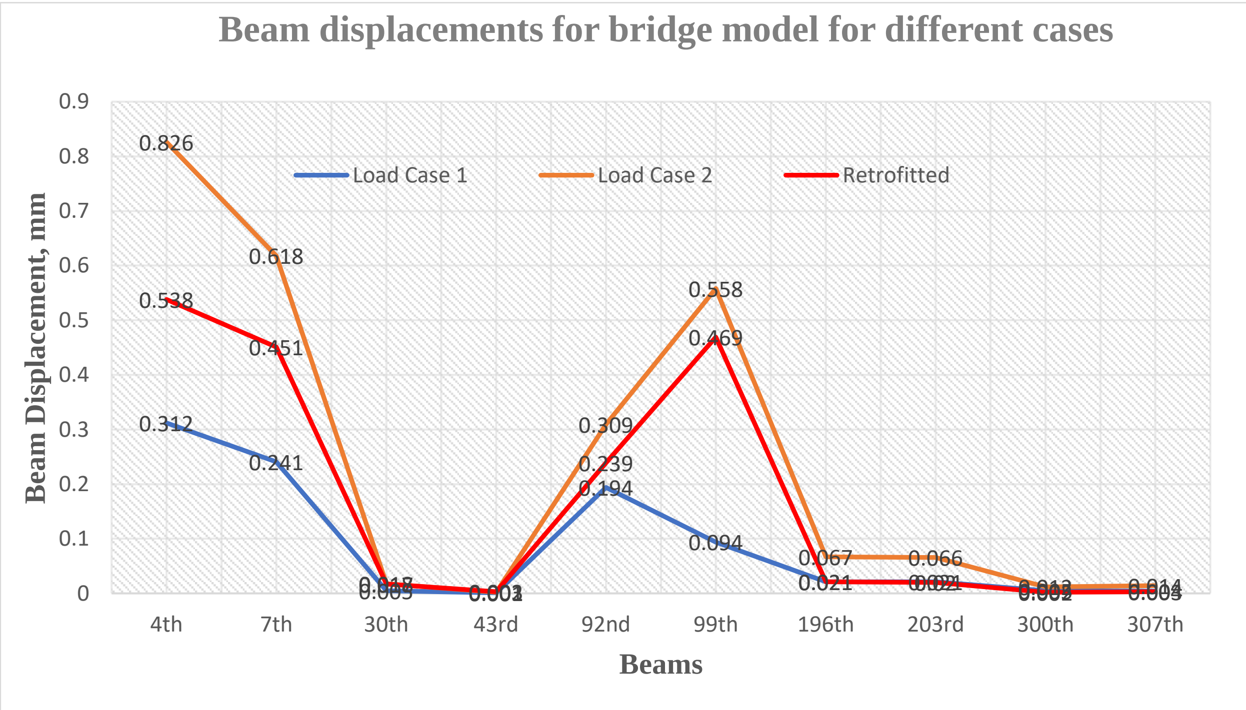


Figure 4: Comparisons of results between Beam Displacements of different cases

5. Conclusions:

In this work, a detailed finite element model of a bridge was developed to analyze displacements by accurately representing the spatial configurations of the original structure. The findings suggest that simple technological adaptations, without disrupting traffic, can significantly extend the lifespan of bridges. The model also considered the effects of truck groups on road responses under load. The results demonstrate that the proposed FE model is effective for analysis. Additionally, the study introduces a method for retrofitting RC bridge columns using a combination of CFRP lining sheets and steel coatings to address severe structural conditions.

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