Rehabilitation of Deteriorated Bridge Deck Slabs Using Lightweight Concrete and Glass Fiber-Reinforced Polymer Bars: A Nonlinear Finite Element Investigation

Bangladesh Univ. of Engineering and Technology, Bangladesh **Md. Imran Hossain**
Bangladesh Univ. of Engineering and Technology, Bangladesh **Ahnaf Tahmid**
Bangladesh Univ. of Engineering and Technology, Bangladesh **A.F.M. Saiful Amin**

Abstract

Bridge deck slabs experience deterioration before they reach their intended service life from repeated loading cycles, thermal gradient changes, and chloride-induced corrosion of the steel reinforcing bar in the deck. This study evaluates whether a lightweight concrete (LWC) slab reinforced with glass fiber-reinforced polymer (GFRP) bars, designed to match the dead load of the original normal-weight concrete (NWC) deck, can recover its flexural performance. A transverse influence-line sweep identified the governing critical section along the span; the AASHTO critical single-lane wheel configuration was then derived and applied through displacement-controlled nonlinear three-dimensional finite element analysis of a typical expressway. All LWC-GFRP configurations tracked the NWC-steel baseline closely, matching it within about four percent in peak resistance and in post-cracking secant stiffness. Therefore, these results confirmed the potential for this method to provide viable means of rehabilitating existing structures.

1. INTRODUCTION

Bridge deck slabs have lower safety margins than the substructure beneath and therefore are the first structural component to reach critical deterioration thresholds. Repeated impacts due to wheel loads, temperature changes, and the penetration of moisture and chlorides into concrete cause extensive loss of serviceability long before the end of the expected design life [1]. The repair of damaged concrete with composite materials such as GFRP bars has been shown to restore the original performance characteristics without the need to replace the entire structure [2]. Furthermore, GFRP bars are resistant to electrochemical corrosion and have been found to be suitable for use in bridge decks [2]. LWC has unit weights lower than NWC, which permits a thicker replacement slab at equivalent dead load. The main comparison metric is secant stiffness (Figure 2), the ratio of total applied load to mid-span deflection at each load step, and it tracks progressive stiffness degradation (Figure 3) of the cracked section and governs deflection performance in the post-cracking service range. The main hypothesis is that the lower unit weight of LWC is compensated for by the deeper LWC slab constrained to the same dead load, thus resulting in an equivalent flexural performance to the original NWC-steel deck.

2. METHODOLOGY

The structural reference was a typical expressway transverse deck strip (Figure 1). Due to mirror symmetry, a strip of 10,779 mm half-width was built along the centerline of the deck with roller supports at each of the four girder-bearing lines [G1-G4] (Figure 1). A linear-elastic influence line sweep was performed by applying a unit load at each node of the mesh on the top surface of the deck at 100 mm intervals and measuring deflections at each node of the bottom face to determine the critical section (Figure 1), which was found to lie in the G1-G2 span (Z = 2,296 mm from the cantilever tip). The influence ordinate is adverse only between G1 and G2, so both wheels of one axle were placed there, at Z = 1,600 mm and Z = 3,400 mm (spacing 1,800 mm; m = 1.20) (Figures 1, 2). A finite element modeling (FEM) software was used to perform non-linear analysis with displacement-controlled increments. Concrete was modeled by SOLID65 elements with a smeared cracking and crushing constitutive law, deformed steel by LINK180 bar elements with a bilinear stress-strain relationship, and GFRP by a linear-elastic-to-rupture relationship [4]. Progressive cracking was dealt with by a comprehensive Newton-Raphson method with adaptive control of the sub-step. Two slab configurations were examined: Normal Weight Concrete (NWC) with 28 MPa compressive strength and deformed steel as a baseline; and Lightweight Concrete (LWC) with 21, 24, and 28 MPa and GFRP as the proposed solution.

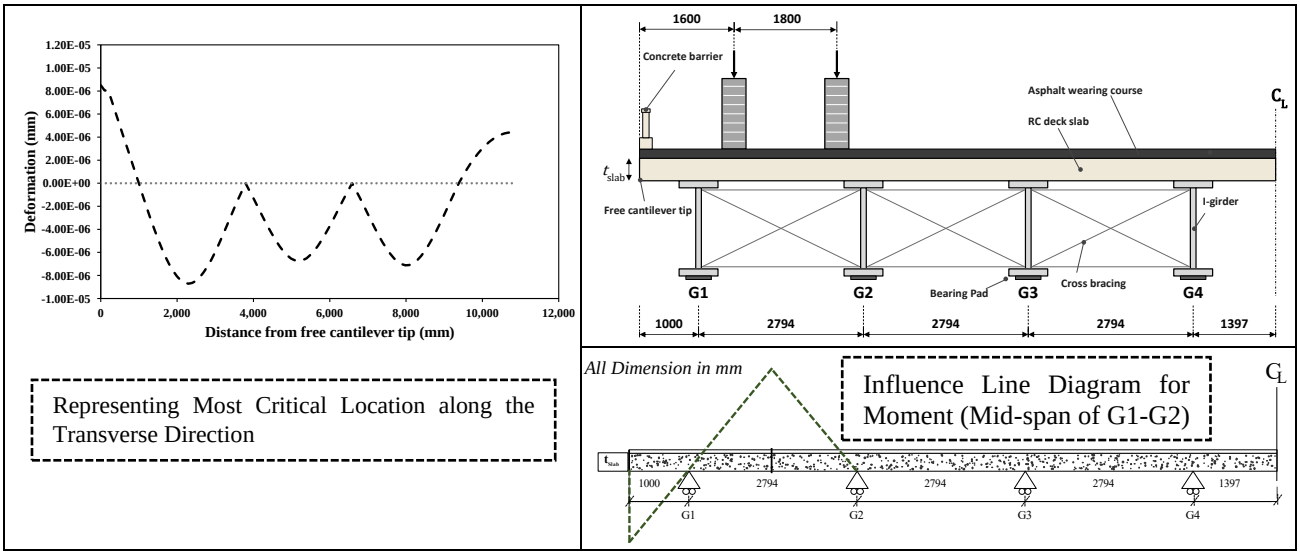


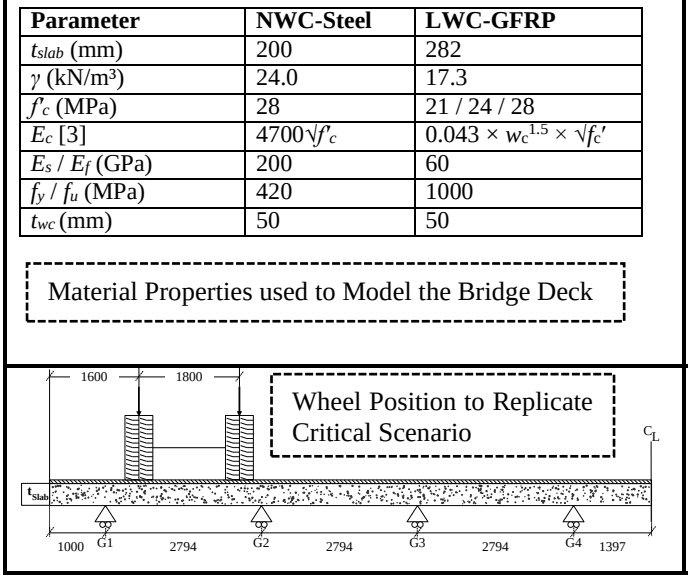
Fig. 1. Influence-line analysis identifying the G1-G2 midspan as the critical section

3. RESULTS AND DISCUSSION

Total applied load against critical-section deflection is shown in Figure 3(a). The four responses form a single narrow band rather than diverging. Beyond initial cracking, each rises almost linearly, so the response is governed by the progressively cracked section rather than by reinforcement yielding. Peak resistance of the LWC-GFRP variants lies within roughly four percent of the NWC-steel baseline. The corresponding secant stiffness degradation is presented in Figure 3(b). Every configuration demonstrates a significant initial decline in stiffness that coincides with the initiation and advancement of flexural cracking, succeeded by a consistent residual plateau.

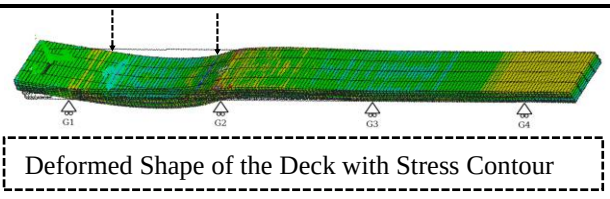
Parameter	NWC-Steel	LWC-GFRP
t_{slab} (mm)	200	282
γ (kN/m³)	24.0	17.3
f'_c (MPa)	28	21 / 24 / 28
E_c [3]	$4700\sqrt{f'_c}$	$0.043 \times w_c^{1.5} \times \sqrt{f_c'}$
E_s / E_f (GPa)	200	60
f_y / f_u (MPa)	420	1000
t_{wc} (mm)	50	50

Material Properties used to Model the Bridge Deck



Load-Deformation Curve Representing Secant-Stiffness

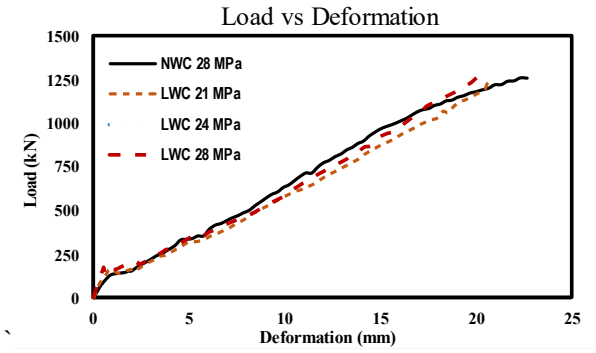
Wheel Position to Replicate Critical Scenario



Deformed Shape of the Deck with Stress Contour

Fig. 2. FEM: half-width transverse cross-section of a typical expressway deck with model parameters.

This equivalence arises from the 41% greater slab depth imposed by the equal dead-load condition. Cracked-section stiffness grows with the cube of effective depth, whereas the reduced moduli of the lightweight matrix and GFRP bars enter it only linearly, so the depth gain offsets the modulus loss. Because geometry rather than matrix strength governs, the three LWC grades converge beyond early cracking provided the thickness constraint holds. From a cost perspective, GFRP bars are currently priced approximately 2.5-3.5 times those of deformed steel in the Bangladeshi market. However, the corrosion immunity of GFRP eliminates the principal driver of premature deck deterioration, substantially reducing lifecycle expenditure on repairs and traffic disruption.



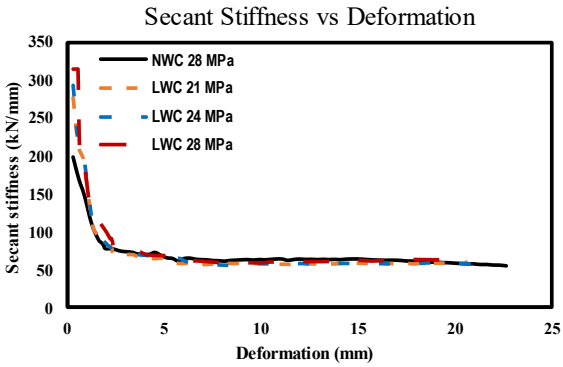


Fig. 3. Nonlinear FE results: (a) load-deformation response; (b) secant stiffness degradation

4. CONCLUSION

Influence-line analysis of a typical expressway deck confirmed the G1-G2 span as the governing critical region. Nonlinear finite element analysis under the AASHTO critical single-lane wheel loading demonstrates that all LWC-GFRP rehabilitation configurations match the NWC-steel baseline in peak resistance and post-cracking secant stiffness. Future work should address long-term fatigue performance, creep and shrinkage of LWC, and temperature-dependent GFRP behavior to support code-calibrated design guidance for corrosion-critical bridge rehabilitation.

REFERENCES

[1] Amin, A. F. M. S. and Okui, Y. (2015), "Design, construction, and maintenance of bridges in Bangladesh: In the past, present, and future," IABSE-JSCE Joint Conf. on Advances in Bridge Engineering-III, Dhaka, 57-76.

[2] Benmokrane, B., El-Salakawy, E., El-Ragaby, A., and Lackey, T. (2006), "Designing and Testing of Concrete Bridge Decks Reinforced with Glass FRP Bars," Journal of Bridge Engineering, ASCE, 11(2), 217-229.

[3] ACI Committee 318. (2019), "Building Code Requirements for Structural Concrete (ACI 318-19)," ACI, Farmington Hills, MI.

[4] ACI Committee 440. (2022), "Building Code Requirements for Structural Concrete Reinforced with Glass Fiber-Reinforced Polymer (GFRP) Bars (ACI CODE-440.11-22)," ACI, Farmington Hills, MI

Acknowledgments: The LWC-GFRP mix-design data used in this study were developed by BUET Team 4302 for the 2026 ACI-FRP. Composites Competition.