Strengthening and Cost Efficiency of GFRP-Reinforced Bridge Deck Slabs: A Case Study

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ABSTRACT

Bridges are essential for national and regional connectivity, yet their deck slabs often deteriorate over time due to excessive loads, material fatigue, and environmental exposure, potentially reducing their structural safety. This study evaluates (1) the structural performance improvement of the Pute Bridge-river deck slab after strengthening with Glass Fiber Reinforced Polymer (GFRP) and (2) the cost efficiency of GFRP compared to conventional slab replacement. The methodology involved structural modeling using the SAP2000 v22, static load testing using a Deflection Multimeter (DMM), and cost analysis based on Analisa Harga Satuan Pekerjaan (AHSP) translated as Unit Price Analysis. The results indicate a 20.80% increase in load capacity (from 274 to 331 tons) and over 90% reduction in deflection at critical points, with mid-span deflection decreasing from -66.70 mm to -3.50 mm. Economically, GFRP strengthening costs 518,792,152.60 Rp, making it 28.62% more economical than slab replacement. Overall, GFRP proves both technically effective and cost-efficient, making it a significant solution for bridge deck slab rehabilitation due to its time efficiency, minimal traffic disruption, and long-term durability.

Keywords-bridge deck slab; structural strengthening; GFRP; load testing; building design; cost efficiency

I. INTRODUCTION

Bridges are crucial components of transportation infrastructure that support regional connectivity and economic development. However, increasing traffic loads, environmental exposure, and material aging gradually reduce the structural performance and serviceability of bridge components, particularly deck slabs [1]. Deck slab deterioration can lead to excessive deflection, cracking, and reduced load-carrying capacity, which may compromise the safety and functionality of the entire bridge system. Consequently, timely strengthening or rehabilitation interventions are important to ensure long-term structural reliability and operational continuity.

Advances in structural engineering emphasize the need for performance-based evaluation and material optimization in infrastructure systems. Studies on structural behavior and strengthening strategies indicate that variations in material properties and structural configurations significantly affect strength, stiffness, and serviceability performance. In parallel, the development of high-performance concrete using advanced materials has demonstrated improved mechanical behavior and durability, supporting more sustainable and resilient structural solutions [2]. These findings highlight the importance of integrating advanced materials and analytical approaches in bridge assessment and rehabilitation.

Conventional rehabilitation of bridge deck slabs typically involves full replacement, which requires extensive construction time, high cost, and significant traffic disruption. As an alternative, Fiber Reinforced Polymer (FRP) materials have been widely adopted for structural strengthening due to their high strength-to-weight ratio, corrosion resistance, and ease of installation. GFRP has gained attention for bridge applications because of its favorable mechanical properties and economic viability compared to carbon-based systems [3-5]. GFRP strengthening can effectively enhance the flexural capacity and reduce service-load deflections in reinforced concrete elements [6-8].

The structural efficiency of GFRP in bridge components has been confirmed. For instance, improved deflection control in reinforced concrete beams strengthened with FRP systems has been reported, whereas enhanced stiffness and crack control in GFRP-reinforced concrete slabs have been observed [9, 10]. GFRP-reinforced slabs exhibit satisfactory fatigue resistance and durability under aggressive environmental and traffic loading conditions [11, 12]. These findings indicate that GFRP strengthening is a technically viable solution for extending the service life of deteriorated bridge deck slabs.

Despite extensive research on FRP strengthening, most existing studies are limited to laboratory-scale experiments or numerical simulations, with relatively few investigations incorporating full-scale field testing and economic evaluation [13, 14]. Moreover, although the life-cycle cost and environmental assessments of GFRP systems have been discussed [15, 16], direct comparisons between GFRP strengthening and conventional deck slab replacement based on local unit price analysis remain limited. This gap is particularly evident in developing regions, where budget constraints and local construction costs significantly influence rehabilitation decision making.

The Pute Bridge-river in Maros Regency, South Sulawesi, Indonesia, represents a typical case of an aged bridge subjected to heavy traffic loads and long-term environmental exposure. Field inspections revealed significant structural deficiencies in the deck slab, including extensive surface cracking, concrete spalling, and localized deterioration, which collectively indicated a reduction in structural capacity and serviceability [8]. These existing failure conditions are visualized in Figure 1, which presents representative photographs of the Pute Bridge-river deck slab during field inspection. The documented damage patterns confirm the urgency of rehabilitation measures and justify the selection of GFRP strengthening as a technically feasible and minimally invasive retrofitting solution, compared to full deck slab replacement.

Fig. 1. Existing failure conditions of the Pute Bridge-river deck slab. Surface cracking, concrete spalling, and localized deterioration were observed during the field inspection.

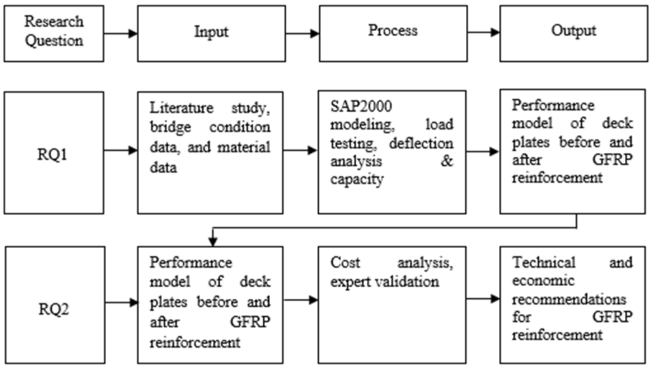
This study aims to evaluate both the structural performance improvement and cost efficiency of GFRP strengthening applied to the Pute Bridge-river deck slab. It integrates numerical modeling using SAP2000, full-scale static load testing with deflection measurements, and a detailed economic analysis based on the local unit price standard AHSP. The novelty of this work lies in combining structural analysis, field experimentation, and cost evaluation within a single case study, providing practical evidence to support decision-making in bridge maintenance and rehabilitation, particularly in regions with limited budgets and increasing traffic demands.

II. MATERIALS AND METHODS

The present study employed a quantitative experimental approach integrating structural modeling, full-scale field static load testing, and economic analysis to evaluate the effectiveness of GFRP strengthening for bridge deck slab rehabilitation. The case study was conducted on the Pute Bridge-river located at KM 37+800 in Maros Regency, South Sulawesi, Indonesia. This research aimed to assess the structural performance improvement and cost efficiency of

GFRP strengthening compared to conventional deck slab replacement.

The operational research framework was developed to ensure a systematic and logically connected evaluation process. As illustrated in Figure 2, the framework consists of four sequential stages: visual inspection, numerical modeling, field static load testing, and economic analysis. Each stage provides critical input for the subsequent phase, ensuring consistency between the observed damage conditions, analytical predictions, experimental verification, and economic feasibility.



Research Question	Input	Process	Output
RQ1	Literature study, bridge condition data, and material data	SAP2000 modeling, load testing, deflection analysis & capacity	Performance model of deck plates before and after GFRP reinforcement
RQ2	Performance model of deck plates before and after GFRP reinforcement	Cost analysis, expert validation	Technical and economic recommendations for GFRP reinforcement

Fig. 2. Operational research framework illustrating the sequential relationship between visual inspection, numerical modeling, field static load testing, and economic analysis.

The first stage involved a comprehensive visual inspection of the existing deck slab to identify structural deficiencies, such as flexural cracking, shear cracking, concrete spalling, and excessive deflection. The inspection results were used to define the critical slab regions and represent the degraded material conditions in the analytical model. The general geometric and structural characteristics of the bridge deck slab are summarized in Table I, which provides the technical specifications used throughout the analysis.

TABLE I. TECHNICAL SPECIFICATIONS OF SUNGAI PUTE BRIDGE RIVER DECK SLAB

Parameter	Value
Bridge span length	85 m
Deck slab length	5 m
Deck slab width	8.29 m
Deck slab thickness	0.30 m
Concrete compressive strength	30 MPa (normal), 24.35 MPa (cracked)
Number of load points	1/4L, 2/4L, and 3/4L

In the second stage, numerical modeling was performed using SAP2000 v22 to simulate the structural behavior of the deck slab before and after GFRP strengthening. The model geometry and boundary conditions were based on as-built drawings, and the material properties of concrete, steel reinforcement, and GFRP were obtained from field data and technical specifications. The structural model of the Pute Bridge-river developed in SAP2000 is shown in Figure 3, and serves as the basis for predicting the deflection response and identifying critical strengthening zones.

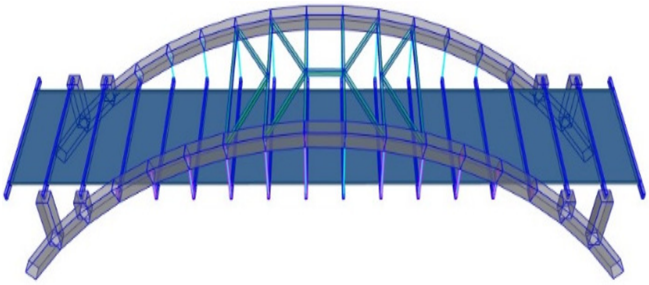


Fig. 3. Structural modeling of the Sungai Pute Bridge in SAP2000.

Incremental static loading was applied in the numerical analysis and experimental program using four predefined stages up to 74% of the estimated ultimate load. The loading levels were set at approximately 25%, 45%, 60%, and 74% to represent progressive service and near-service load conditions while preventing premature structural failure. This approach allowed the evaluation of stiffness, deflection behavior, and crack development under realistic field loading scenarios.

The third stage consisted of full-scale field static load testing, conducted to validate the numerical predictions and directly measure the structural response of the deck slabs. Fourteen dump trucks were used to apply a total load of 331 tons on the strengthened slab and 274 tons on the existing slab. Vertical deflections were measured at 1/4L, 2/4L (midspan), and 3/4L using DMM sensors with a resolution of 0.5 mm. The static load testing configuration and DMM sensor placement are presented in Figure 4.

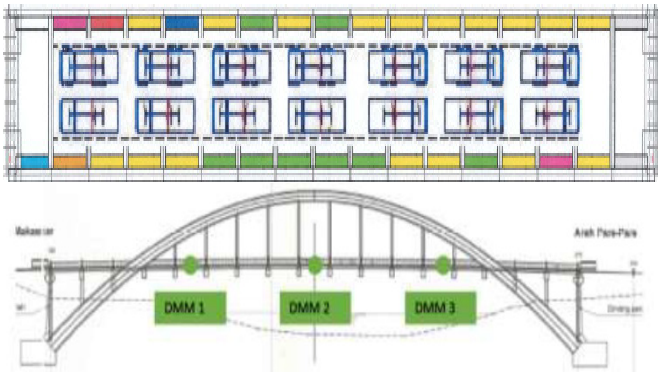


Fig. 4. Static load testing configuration and DMM sensor setup.

The GFRP strengthening system was designed in accordance with ACI 440.2R-17 and SNI 8971:2021 specifications for externally bonded FRP systems. The strengthening aimed to enhance the flexural capacity and serviceability while maintaining safe stress limits and effective composite action between the concrete substrate and GFRP laminate. Design assumptions included linear elastic behavior of GFRP, perfect bond conditions, and strain compatibility between concrete, steel reinforcement, and GFRP [17, 18].

The SEH-51A GFRP laminate used in this study had a nominal thickness of 2 mm per layer, a modulus of elasticity of 50 GPa, and an ultimate tensile strength of 1,000 MPa. One to two layers of GFRP were applied to the underside of the deck slab at critical segments (S1, S2, S3, S15, and S17), based on the bending moment distribution from numerical modeling and visual inspection results. This configuration ensured sufficient strengthening while avoiding excessive stiffness increase or premature debonding.

Numerical analysis using SAP2000 was conducted as a complementary tool to support the experimental findings rather than to simulate the full nonlinear failure behavior. Static incremental loading consistent with the field test stages was applied, allowing a direct comparison between the predicted and measured deflection responses. This modeling approach reflects common engineering practices and provides reliable support for interpreting field test results [19].

Finally, an economic analysis was performed using the AHSP method based on local construction costs in Maros Regency. The cost components included materials, labor, equipment, and inspection/testing for both GFRP strengthening and conventional deck slab replacement. The analysis focuses on local pricing conditions and does not account for regional price variations, long-term maintenance, traffic disruption costs, or environmental impacts. Therefore, the results should be interpreted as indicative of local cost efficiency rather than universally applicable conclusions.

III. RESULTS AND DISCUSSION

A. *Visual Inspection Results*

The visual inspection revealed multiple cracks on the underside of the deck slab, mainly flexural and diagonal shear cracks, indicating a significant reduction in load-carrying capacity. Most of the observed damage was concentrated in the mid-span region, particularly between 1/4L and 3/4L of the span, where the bending moments are the highest. Table II provides a detailed summary of the identified damage types, crack patterns, and their locations, while Figure 5 displays representative photographs illustrating the current condition of the Pute Bridge-river deck slab. These visual observations confirm the presence of structural distress and underscore the necessity for strengthening interventions.

Fig. 5. Visual condition of the Pute Bridge-river deck slab.

TABLE II. DETAILS FROM THE VISUAL INSPECTION AND THE CORRESPONDING DECK SLAB DAMAGE

Crack type	Location	Crack length (mm)	Severity level
Flexural	1/4L	1500	Moderate
Flexural	2/4L	2300	Severe
Diagonal	3/4L	1800	Moderate

B. *Structural Performance Before and After Strengthening*

Numerical analysis using SAP2000 indicated that the deck slab experienced excessive deflection under 74% of the maximum test load prior to strengthening, reflecting a reduced stiffness and load-carrying capacity. After the application of GFRP strengthening, a significant reduction in deflection and an increase in load capacity were observed. This numerical outcome is consistent with previous studies reporting improved serviceability and flexural performance of reinforced concrete slabs strengthened with GFRP systems, particularly in terms of stiffness enhancement and deflection control [20, 21]. A quantitative comparison of load capacity and deflection before and after strengthening is outlined in Table III, confirming the effectiveness of the proposed strengthening scheme.

The strengthening performance observed in this study aligns well with established experimental and analytical findings on externally bonded GFRP laminates for bridge deck applications. The use of GFRP laminates with a thickness of 2 mm per layer, an elastic modulus of approximately 50 GPa, and a tensile strength of 1,000 MPa is consistent with the material ranges commonly reported for serviceability-dominated strengthening. It has been demonstrated that GFRP systems with elastic moduli between 40 and 60 GPa and tensile strengths exceeding 900 MPa provide an effective balance between stiffness improvement, crack control, durability, and constructability. Therefore, while the strengthening concept itself is not entirely novel, the originality of this study lies in its integrated structural and economic evaluation applied to an existing bridge deck slab under local Indonesian conditions, which has rarely been addressed in previous research.

TABLE III. COMPARISON OF LOAD CAPACITY AND DEFLECTION BEFORE AND AFTER STRENGTHENING

Location	Load before (tons)	Deflection before (mm)	Load after (tons)	Deflection after (mm)	Reduction (%)
1/4L	274	-44.66	331	-3.50	92.16%
2/4L	274	-66.70	331	-3.50	94.75%
3/4L	274	-43.65	331	-3.50	91.98%

The load–deflection relationships at the critical locations (1/4L, 2/4L, and 3/4L) further illustrate the structural behavior of the deck slab before and after GFRP strengthening. Prior to strengthening, the slab exhibited pronounced nonlinear response at higher load stages, indicating stiffness degradation due to cracking and steel yielding. In contrast, the strengthened slab maintained a linear elastic response throughout the loading stages, reflecting the effective contribution of the GFRP laminate in resisting tensile stress and limiting crack propagation. These observations are consistent with reported trends in GFRP-strengthened concrete members and provide graphical and quantitative evidence supporting the reductions in deflection and improvements in load capacity, as presented in Table III.

C. Cost Comparison Between Strengthening and Replacement

The cost analysis compared the application of GFRP strengthening with complete deck slab replacement, focusing on structural performance and economic efficiency. The results indicate that GFRP strengthening provides a more economical solution while maintaining structural safety, as evidenced by a 20.80% increase in load capacity (from 274 to 331 tons), a reduction in midspan deflection of more than 90%, and a total cost saving of 40.09% compared to conventional slab replacement. A detailed breakdown of the cost components and a comparative economic evaluation between the two rehabilitation strategies are presented in Table IV. These findings confirm that GFRP strengthening is a technically effective and cost-efficient alternative for bridge deck slab rehabilitation, particularly in projects where minimizing construction cost and traffic disruption is important.

TABLE IV. COST COMPARISON BETWEEN DECK SLAB REPLACEMENT AND GFRP STRENGTHENING

Method	Total cost (Rp)	Cost savings (Rp)	Efficiency (%)
Deck slab replacement	726,774,109.47	-	-
GFRP strengthening	518,792,152.60	207,981,956.87	40.09%

D. Structural Effectiveness of GFRP Strengthening

The 20.80% increase in load capacity indicates that the GFRP laminates provided additional tensile reinforcement, improving the flexural strength of the slab. Furthermore, the over 90% reduction in the midspan deflection confirmed the improved stiffness and serviceability of the deck slab.

The application of GFRP significantly enhanced the structural performance of the Pute Bridge-river deck slab. The load–deflection comparison demonstrated a reduction in deflection at all critical measurement points (1/4L, 2/4L, and 3/4L), indicating a substantial improvement in stiffness and serviceability. This structural response is in line with [1], which reported that externally bonded FRP systems effectively increase load-bearing capacity and reduce deflection in reinforced concrete members. The overall performance improvement achieved in this study is summarized in Table V.

TABLE V. STRUCTURAL IMPROVEMENT ACHIEVED BY GFRP STRENGTHENING

Parameter	Before strengthening	After strengthening	Improvement (%)
Load capacity (tons)	274	331	+20.80%
Mid-span deflection (mm)	-66.70	-3.50	-94.75%
Edge deflection (mm)	-44.66	-3.50	-92.16%

The observed increase in the load-carrying capacity and reduction in deflection can be attributed to the structural mechanisms introduced by the externally bonded GFRP laminates. When applied to the tension zone of the deck slab, the GFRP laminates act as additional tensile reinforcement, sharing tensile stresses with the existing steel reinforcement. This stress-sharing mechanism delays steel yielding and limits crack propagation, leading to enhanced flexural strength and stiffness of the slab system. Similar strengthening mechanisms have been extensively reported in experimental and analytical studies on FRP-strengthened concrete elements [5, 12].

The significant reduction in deflection, particularly at the midspan location (2/4L), indicates a significant improvement in flexural rigidity owing to the composite action between the concrete substrate and GFRP laminate. The externally bonded GFRP increases the effective moment of inertia of the slab section, thereby reducing curvature under applied loads. This behavior is consistent with the classical reinforced concrete theory and aligns with the findings of [15, 16], which demonstrated that increased tensile reinforcement directly contributes to reduced serviceability deflections in bridge slabs and beams.

Furthermore, the effective stress transfer between the concrete surface and GFRP laminate suggests that adequate bond performance was maintained throughout the loading stages. No premature debonding or localized failure was observed, which is further supported by the elastic recovery recorded during the unloading stages of the static load test. This confirms that the strengthened deck slab remained within the elastic range under the applied test loads, a behavior also reported in [7] regarding full-scale bridge strengthening applications.

Overall, the 20.80% increase in load capacity and more than 90% reduction in midspan deflection demonstrate the effectiveness of GFRP strengthening in improving both strength and serviceability. Compared to [5, 12, 16], the results of this research further validate the applicability of GFRP strengthening under real bridge conditions by integrating numerical modeling, full-scale static load testing, and economic evaluation. These findings confirm that GFRP is a technically reliable rehabilitation solution capable of enhancing structural performance while minimizing demolition and construction disruption.

E. Economic Advantages of GFRP Strengthening

From an economic perspective, GFRP strengthening provides significant cost advantages over conventional deck slab replacement. The total cost of GFRP strengthening was Rp 518.79 million, which is 40.09% lower than the full deck slab replacement cost of Rp 726.77 million. This substantial cost difference highlights the economic feasibility of GFRP as a rehabilitation solution while maintaining adequate structural safety. A detailed comparison of these costs is presented in Table VI.

The economic evaluation in this study was conducted to compare the cost efficiency of GFRP strengthening with conventional replacement methods under equivalent structural performance requirements. The analysis focused on direct material and installation costs, assuming identical structural geometry, loading conditions, and service demands. Indirect costs, such as traffic disruption, environmental impacts, and long-term maintenance, were intentionally excluded to ensure a conservative and transparent comparison framework. This approach is consistent with previous cost-based evaluations reported in [7, 16].

TABLE VI. ECONOMIC BENEFITS OF GFRP VERSUS REPLACEMENT

Aspect	**Deck slab replacement**	**GFRP strengthening**	**Benefit**
Total cost (Rp)	726,774,109.47	518,792,152.60	-40.09%
Construction time	Long (requires demolition)	Short (no demolition)	Faster
Traffic disruption	High	Low	Reduced
Long-term durability	Standard	Enhanced	Better

Material unit prices were obtained from local Indonesian construction market references and recent supplier quotations to reflect realistic field conditions. The cost components considered included GFRP laminates, epoxy adhesives, surface preparation, installation labor, and quality control procedures. All costs were normalized on a per m² basis to allow consistent comparison across strengthening alternatives. This methodology aligns with the cost assessment approaches used in earlier GFRP and FRP-based bridge rehabilitation studies [8].

The total strengthening cost per m² of the deck slab was calculated by summing the product of the unit cost of each strengthening component and its corresponding required quantity per m². The required quantities were determined based on laminate thickness, material dimensions, and the specific application procedures adopted in the experimental program. This approach ensures that each cost component directly reflects the actual material consumption associated with the strengthening configuration. By linking the cost estimation to the same structural design parameters used in numerical modeling and static load testing, the economic evaluation remains consistently integrated with the structural performance analysis.

Cost efficiency was further assessed by relating the total strengthening cost to the achieved structural performance improvements, particularly the increase in load-carrying capacity and reduction in deflection. The GFRP-strengthened slab demonstrated a lower cost per unit performance gain compared to conventional replacement, primarily due to reduced material volume, shorter installation time, and minimal use of heavy construction equipment. Similar conclusions regarding the superior cost-to-performance ratio of GFRP systems have been reported in [20, 21].

In addition to direct cost savings, GFRP strengthening offers indirect economic benefits that enhance overall feasibility. These include shorter construction durations that minimize traffic disruption, lower labor and equipment requirements that reduce project complexity, and extended service life with minimal future maintenance needs. Although these indirect benefits were not monetized in this study, they further strengthen the economic case for GFRP strengthening, particularly for bridges with high-traffic volumes and limited rehabilitation budgets.

Based on the combined structural and economic evaluation, this study confirms that GFRP strengthening is both technically effective and economically viable for bridge deck slab rehabilitation. The method achieved a 20.80% increase in load-carrying capacity and more than a 90% reduction in deflection at critical locations, while reducing rehabilitation costs by over 40%. These findings, when compared with previous experimental and field studies [8, 16], validate GFRP strengthening as a practical alternative to conventional deck slab replacement for extending bridge service life under real-world conditions.

IV. CONCLUSIONS

This study demonstrated that the application of Glass Fiber Reinforced Polymer (GFRP) laminates is an effective strengthening strategy for deteriorated bridge deck slabs, as evidenced by the improved structural response under incremental static loading. The observed increase in load-carrying capacity and reduction in deflection were mainly attributed to the additional tensile resistance provided by the externally bonded GFRP, which delayed crack initiation and redistributed tensile stresses more efficiently within the concrete slab.

The numerical results obtained from the SAP2000 analysis further explain this behavior, showing that the enhanced stiffness and stress redistribution occurred due to the composite action between the concrete substrate and GFRP laminate. The selected GFRP properties (2 mm thickness per layer, an elastic modulus of 50 GPa, and a tensile strength of 1,000 MPa) play a significant role in achieving this performance by providing sufficient stiffness without causing premature debonding or brittle failure.

Beyond numerical improvements, the importance of this study lies in its practical and economic implications. The results indicate that GFRP strengthening can significantly extend the service life of existing bridge deck slabs without the need for full replacement, thereby reducing construction time, traffic disruption, and overall rehabilitation cost. Although similar strengthening concepts have been reported in previous studies, this research contributes new insights by integrating structural performance evaluation with cost efficiency analysis for an actual bridge in Indonesia. Consequently, the findings provide a scientifically supported and locally applicable reference for decision-makers in bridge rehabilitation projects.

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