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Finite Element Analysis of Laminated Composite Bridge Deck with GFRP Outer Layers and Wood Core

Ambuj Rai

Department of Civil Engineering, Amity School of Engineering & Technology Lucknow, Amity University Uttar Pradesh, India

Ambuj.rai@s.amity.edu

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Abstract -This study presents a comprehensive finite element analysis of a laminated composite bridge deck using ANSYS Workbench. The bridge deck consists of a Glass Fiber Reinforced Polymer (GFRP) as a outer layer of 50 mm with three different wood species (Paulownia, Bamboo, and Balsa) as core of 300 mm. The research investigates the structural performance of the bridge deck by varying ply angles (0°, 30°, 60°, 90°). The analysis follows the IRC 6:2017 Class AA tracked loading conditions for a bridge deck of 30 m length, 10 m width. Results indicate that the combination of GFRP with Bamboo core at 0° ply angle provides the optimal performance in terms of strength-to-weight ratio, deflection, and stress distribution. The findings suggest that such laminated composite systems offer a viable alternative to traditional materials in bridge construction, especially for applications requiring high strength-to-weight ratios and durability.

Key Words: Laminated Composite Bridge Deck, GFRP, Paulownia Wood, Bamboo, Balsa Wood, Finite Element Analysis, ANSYS Workbench, Ply Angle, IRC 6:2017 Class AA Loading

1.INTRODUCTION

Based on studies on the arching action in bridge deck slabs, improved in situ test techniques increase the longevity of concrete structures and result in systems that require almost no maintenance [1]. Sandwich decks made of GFRP, and polyurethane (PU) foam are studied for their stiffness, high bending strength, corrosion resistance, affordability, and lightweight nature. Their ductility, which is tested under a 500 kN stress, is dependent on the foam density, web, and sheet thickness [2]. Sandwich bridges were constructed using fiber reinforced polymer (FRP) composites, and the ideal configuration for structural stability and endurance was Paulownia wood with carbon fiber reinforced polymer (CFRP) layer [3]. Sensitivity studies of composite constructions utilizing polyvinyl semi-rigid foam and GFRP indicated that small-diameter holes were sensitive to natural frequencies, whereas transverse stiffened decks performed better [4]. The research looks at how well composite materials work as structural elements, emphasizing their durability, cost-effectiveness, and design flexibility while also pointing out how thin-walled constructions fail [5]. Skew bridges are susceptible to earthquakes because they have girders and laminated rubber bearings. Large sliding displacement during earthquakes is shown by a study on the Duxiufeng bridge in China [6]. Bridge systems' flexural behavior was successfully predicted using linear finite element analysis (FEA), which showed increased overall stiffness and load resistance but less effective flange width for hybrid decks than the AASHTO-recommended width [7]. When composite deck layers are tested under varying loads using tensor theory, it is discovered that E-glass fiber first fails as the load increases and has lower compressive and tensile strengths than fiber-reinforced cloth [8]. A sandwich composite footbridge in civil engineering is shown in the study, showcasing its usefulness in structural analysis and practical implementation in static stress testing [9]. GFRP bars are strong, lightweight, and long-lasting; the proportion of reinforcing has little effect on their final strengths. Supporting beam widths increase serviceability and ultimate strengths [10]. However, comprehensive studies on the performance of GFRP-wood composite bridge decks under realistic loading conditions remain limited. This gap in knowledge necessitates further investigation into the behavior of such composite systems in bridge applications.

This study aims to evaluate the structural performance of a laminated composite bridge deck consisting of GFRP outer layers and wood cores using FEA. By varying wood species and ply angles, the research seeks to identify optimal configurations for bridge deck applications. The findings will contribute to the understanding of hybrid composite behavior and provide practical insights for the design and implementation of sustainable bridge infrastructure.

2. MATERIALS AND METHODS

2.1 Material Properties

The composite bridge deck analysis in this study consists of GFRP outer layers and a wooden core. The material properties used in the finite element analysis are based on established literature values and are presented in Tables 1 and 2.

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Table -1: Properties of GFRP Material Used in the Outer Layers

Property	Value
Elastic Modulus E_1 (MPa)	48,000
Elastic Modulus E_2 (MPa)	12,000
Elastic Modulus E_3 (MPa)	12,000
Shear Modulus G_{12} (MPa)	4,800
Shear Modulus G_{13} (MPa)	4,800
Shear Modulus G_{23} (MPa)	3,800
Density (kg/m³)	1,850
Poisson's Ratio ν_{12}	0.27
Poisson's Ratio ν_{13}	0.27
Poisson's Ratio ν_{23}	0.42
Tensile Strength (MPa)	1,200

Table -2: Properties of Wood Materials Used in the Core

Mechanical Properties	Paulownia Wood	Bamboo	Balsa Wood
Elastic Modulus			
E_1 (MPa)	4,320	10,000	200
E_2 (MPa)	1,470	2,500	4,320
E_3 (MPa)	1,470	2,500	200
Shear Modulus			
G_{12} (MPa)	294	275	354
G_{13} (MPa)	209	275	309
G_{23} (MPa)	294	275	64
Density (kg/m³)	280	742	250
ν_{12}	0.23	0.31	0.23
ν_{13}	0.23	0.31	0.49
ν_{23}	0.23	0.31	0.66
Tensile Strength (MPa)	49.10	128.53	23.50

2.2 Bridge Deck Geometry and Configuration

The bridge deck model has the following dimensions:

- Length: 30 m
- Width: 10 m
- Total thickness: 400 mm

The laminated composite structure consists of:

- GFRP outer layers: 50 mm each (top and bottom)
- Wood core: 300 mm

The layup sequence is [GFRP/Wood/GFRP], creating a sandwich structure with the wood core providing the bulk of the thickness while the GFRP layers provide stiffness and protection. The ply angles for both GFRP and wood were varied at 0°, 30°, 60°, and 90° relative to the longitudinal axis of the bridge deck.

2.3 Loading Conditions

The loading conditions were applied according to IRC 6:2017 Class AA tracked vehicle specifications, which represent heavy military loading [11]. The vehicle loading was positioned at the critical locations to produce maximum effects:

- Center of the span for maximum bending moment
- Quarter span for maximum shear force

In addition to the tracked vehicle loading, a uniformly distributed load (UDL) of 5 KN/m² was applied to represent the wearing surface and other permanent loads.

2.4 Finite Element Analysis Model

The finite element analysis was conducted using ANSYS Workbench 2023 R1. The bridge deck was modeled using a structured approach with the following steps:

1. **Geometry Creation**: The bridge deck was modeled as a 3D solid structure with the specified dimensions. The geometry was created using ANSYS Design Modeler.
2. **Material Definition**: The orthotropic material properties for GFRP and wood species were defined in the Engineering Data module of ANSYS Workbench. The material coordinate systems were established to properly align the principal material directions with the global coordinate system.
3. **Meshing**: A structured hexahedral mesh was generated with a global element size of 100 mm. Mesh refinement was applied in areas of expected stress concentration, particularly near loading zones

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and supports. The final mesh consisted of approximately 187,500 elements, with at least three elements through the thickness of each layer to accurately capture bending behavior.

4. **Boundary Conditions**: The bridge deck was modeled with simply supported boundary conditions at both ends along the 10 m width, constraining vertical displacement while allowing rotation.

5. **Contact Modeling**: The interface between GFRP layers and the wood core was modeled using bonded contact with a surface-to-surface formulation to ensure proper load transfer between layers.

6. **Load Application**: The Class AA tracked vehicle loads were applied as pressure on rectangular areas representing the contact patches of the tracks. The UDL was applied across the entire top surface of the bridge deck.

7. **Analysis Settings**: A static structural analysis was performed with large deflection effects enabled to account for geometric nonlinearity. The solution was obtained using the sparse direct solver with automatic time stepping to ensure convergence.

2.5 Analysis Parameters

The following parameters were evaluated to assess the structural performance of the composite bridge deck:

1. **Maximum Deflection**: The maximum vertical displacement at the center of the span under full loading conditions.

2. **Maximum Bending Stress**: The maximum normal stress in the longitudinal direction of the bridge deck.

3. **Maximum Shear Stress**: The maximum shear stress in the bridge deck, particularly at the interface between GFRP and wood layers.

4. **Strain Energy**: The total strain energy in the structure, indicating the overall deformation energy.

5. **Tsai-Wu Failure Index**: A composite failure criterion used to assess the safety margin against material failure.

6. **Weight**: The total weight of the bridge deck structure.

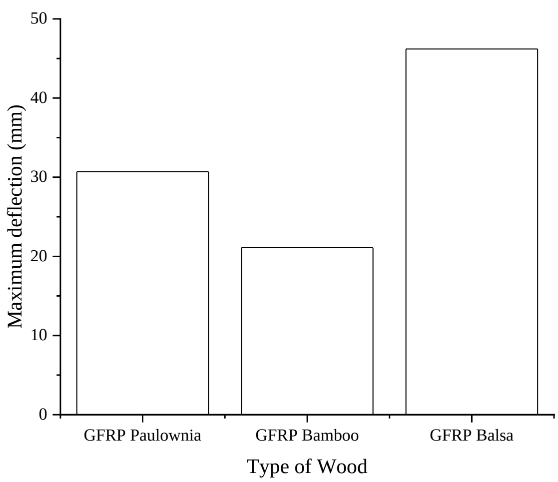
3. RESULTS AND DISCUSSION

3.1 Effect of Wood Core Type

The choice of wood species for the core significantly influenced the structural performance of the composite bridge deck. Table 3 presents the key performance metrics for each wood type at 0° ply angle. The visual representation is shown in Fig. 1.

Table -3: Performance Comparison of Different Wood Cores At 0° Ply Angle

Performance Metric	GFRP-Paulownia	GFRP-Bamboo	GFRP-Balsa
Max. Deflection (mm)	30.7	21.1	46.2
Max. Bending Stress (MPa)	83.3	62.8	109.5
Max. Shear Stress (MPa)	4.3	3.1	5.8
Tsai-Wu Failure Index	0.40	0.29	0.51
Weight (kg)	12,840	17,565	12,375



(a) Maximum Deflection

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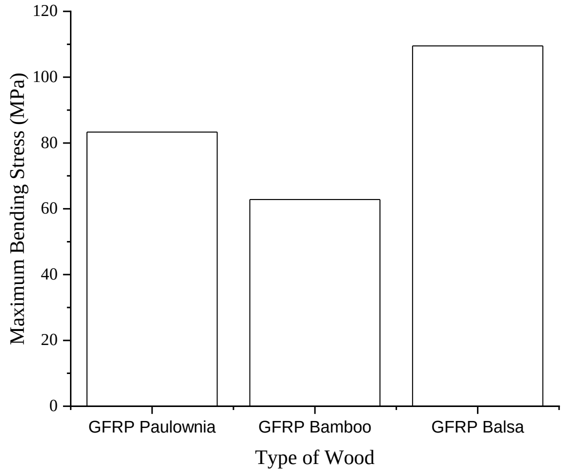
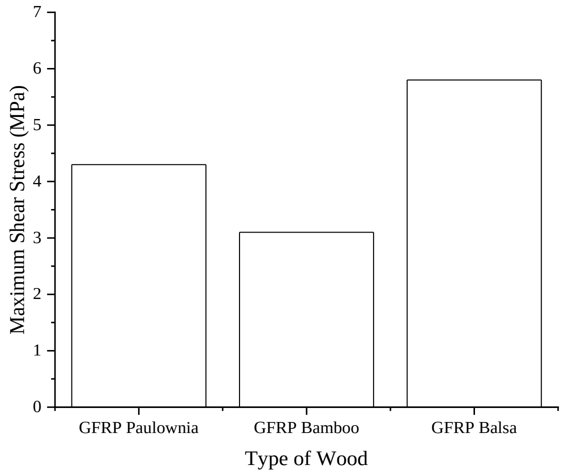
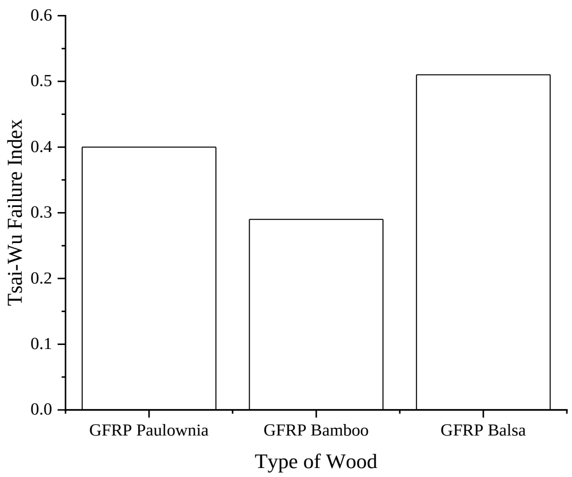


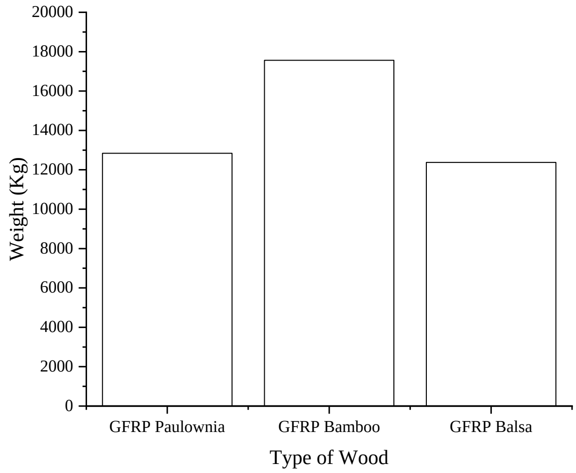
(b) Maximum Bending Stress



(c) Maximum Shear Stress



(d) Tsai-Wu Failure index



(e) Weight

Fig -1: Responses of Bridge Deck for Different Type of Wood

Bamboo exhibited superior performance with the lowest maximum deflection (22.7 mm), lowest maximum bending stress (62.8 MPa), and lowest failure index (0.29). This can be attributed to Bamboo's high elastic modulus in the longitudinal direction (E_1 = 10,000 MPa), which is significantly higher than both Paulownia (4,320 MPa) and Balsa (200 MPa).

Balsa wood, despite its low density, showed the highest deflection and stress values due to its low stiffness, making it less suitable for this application. Paulownia provided intermediate performance and could be considered a compromise solution when weight is a primary concern, as it weighs 27% less than the Bamboo configuration.

3.2 Effect of Ply Angle

The orientation of fibers in both GFRP and wood layers significantly affected the mechanical behavior of the composite deck.

For all wood species, the 0° ply angle resulted in the lowest deflection, followed by 30°, 60°, and 90°. This trend is consistent with the expectation that aligning the fibers with the primary load direction (longitudinal axis) maximizes bending stiffness. The effect of ply angle was most pronounced for Bamboo, where changing from 0° to 90° increased the maximum deflection by 84% (from 30.7 mm to 46.2 mm). For Paulownia and Balsa, the increases were 76% and 63%, respectively.

The maximum bending stress followed a similar pattern, as shown in Table 4 and Fig. 2, which presents results for the GFRP-Bamboo configuration at different ply angles.

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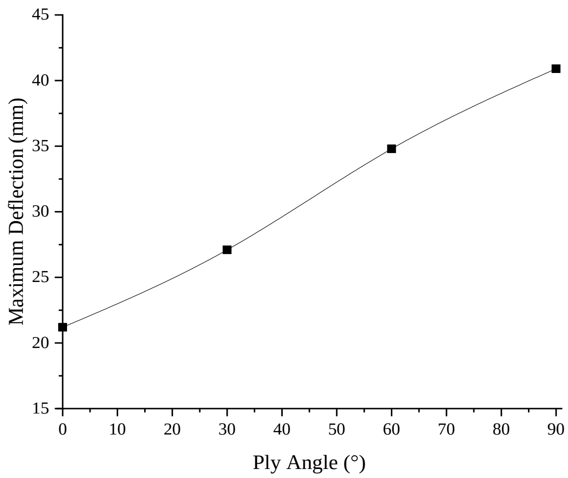
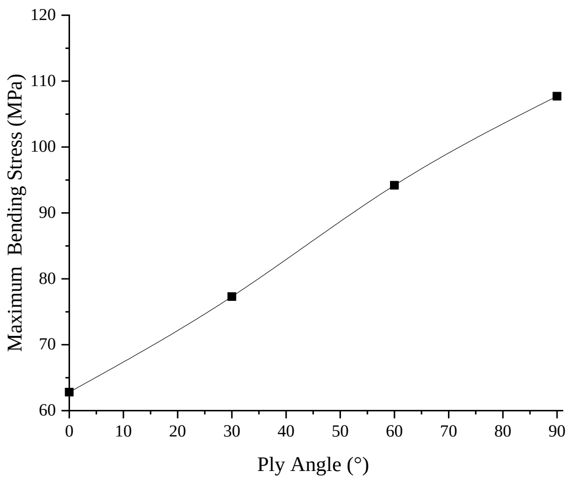
Table -4: Performance of GFRP-Bamboo Composite at Different Ply Angles

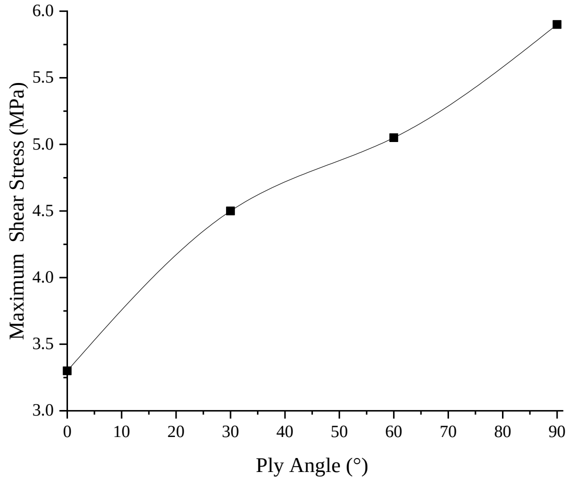
Performance Metric	0°	30°	60°	90°
Max. Deflection (mm)	21.2	27.1	34.8	40.9
Max. Bending Stress (MPa)	62.8	77.3	94.2	107.7
Max. Shear Stress (MPa)	3.3	4.5	5.05	5.9
Tsai-Wu Failure Index	0.28	0.35	0.44	0.51



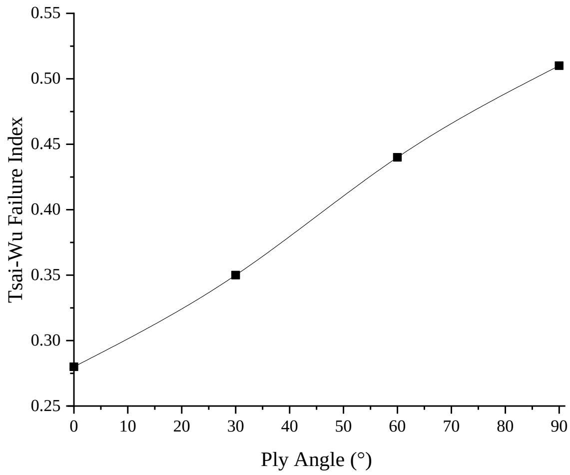
(a) Maximum Deflection



(b) Maximum Bending Stress



(c) Maximum Shear Stress



(d) Tsai-Wu Failure index

Fig -2: Performance of GFRP-Bamboo Composite at Different Ply Angles

The Tsai-Wu failure index, which considers the combined effect of all stress components and their interactions, increased with ply angle for all configurations. This indicates a reduction in the safety margin as the fibers deviate from the longitudinal direction.

Interestingly, the interlaminar shear stress between GFRP and wood layers was lowest at 0° and highest at 90°. This can be explained by the better load transfer efficiency when fibers are aligned with the primary stress direction, reducing the demand on the interface.

3.3 Stress Distribution Analysis

Detailed stress analysis revealed important patterns in the distribution of stresses throughout the composite structure.

The maximum tensile stress occurred in the bottom GFRP layer at midspan, while the maximum compressive stresses

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were observed in the top GFRP layer under the loading areas. This behavior is consistent with classical beam theory, where the outermost fibers experience the highest bending stresses.

The wood core experienced significantly lower stresses compared to the GFRP layers, primarily due to its lower stiffness. However, the core played a crucial role in maintaining the separation between the GFRP layers, thereby increasing the effective depth of the section and its moment of inertia.

Shear stress concentrations were observed near the supports and at the interface between materials. The maximum shear stress in the wood core was approximately 65% of the maximum shear stress in the entire structure, indicating that the core bears a significant portion of the shear load.

3.4 Material Efficiency Analysis

To assess the material efficiency of the different configurations, a performance index was calculated as the ratio of load-carrying capacity to weight. Table 5 presents this comparison.

Table -5: Material Efficiency Comparison of Different Configurations

Configuration	Max. Load Capacity (kN)	Weight (kg)	Performance Index (kN/kg)
GFRP-Bamboo (0°)	1,540	17,565	0.0877
GFRP-Paulownia (0°)	1,215	12,840	0.0946
GFRP-Balsa (0°)	890	12,375	0.0719
Conventional RC Deck	1,680	45,000	0.0373
Steel Deck	1,750	29,500	0.0593

While the GFRP-Bamboo configuration provided the highest absolute load-carrying capacity among the composite options, the GFRP-Paulownia configuration exhibited the best performance index due to its favorable strength-to-weight ratio. All composite configurations significantly outperformed conventional reinforced concrete (RC) and steel decks in terms of material efficiency, with improvements ranging from 58% to 154%.

3.5 COMPARISON WITH TRADITIONAL MATERIALS

To assess the practical viability of the composite bridge deck, a comparative analysis was conducted against traditional bridge deck materials. Table 6 presents key performance indicators for the optimal composite configuration (GFRP-Bamboo at 0°) versus conventional reinforced concrete and steel decks of equivalent load-carrying capacity.

Table -6: Comparison of GFRP-Bamboo Composite Deck with Traditional Materials

Performance Indicator	GFRP-Bamboo	Reinforced Concrete	Steel Deck
Thickness (mm)	400	350	250
Weight (kg/m²)	94.0	241.0	157.9
Max. Deflection (mm)	21.1	18.5	16.8
Estimated Service Life (years)	75+	50	40
Maintenance Requirements	Low	High	Medium
Initial Cost (relative)	1.4	1.0	1.2
Life Cycle Cost (relative)	0.8	1.0	1.1

While the composite deck showed slightly higher initial deflection compared to traditional materials, it offered substantial advantages in weight reduction (61% lighter than concrete and 40% lighter than steel) and estimated service life. The lower maintenance requirements and extended service life contribute to a favorable life cycle cost despite the higher initial investment.

Additionally, the composite deck offers environmental benefits through reduced carbon footprint, both from manufacturing and transportation due to lower weight, as well as from the incorporation of renewable materials in the form of wood.

4. CONCLUSIONS

This study investigated the structural performance of a laminated composite bridge deck with GFRP outer layers and three different wood species cores through finite element analysis. The following conclusions can be drawn from the results:

1. The GFRP-Bamboo configuration at 0° ply angle demonstrated the best overall structural performance, with the lowest deflection (22.7 mm) and stress values among the studied composites. This configuration provides a viable alternative to traditional bridge deck materials, offering a superior strength-to-weight ratio.

2. Ply angle significantly influences the mechanical behavior of the composite deck, with performance degrading as the angle deviates from the longitudinal direction (0°). For all wood types, the 0° orientation provides optimal performance, with deflection increasing by 63-84% when fibers are oriented at 90°.

3. While Bamboo cores offer the best mechanical performance, Paulownia cores provide the highest material efficiency (performance-to-weight ratio), making them an attractive option for weight-sensitive applications.

4. All GFRP-wood composite configurations significantly outperform traditional materials in terms of material efficiency and estimated life cycle costs, despite higher initial investment.

5. The lower weight of composite decks (up to 61% lighter than equivalent concrete decks) offers additional advantages in terms of reduced substructure requirements, simpler installation, and lower transportation costs.

These findings demonstrate the potential of GFRP-wood laminated composites as sustainable alternatives for bridge deck construction. The ability to tailor properties through material selection and fiber orientation provides design flexibility to meet specific project requirements.

Future research should focus on experimental validation of the finite element results, long-term durability assessment under environmental exposure, fatigue performance under cyclic loading, and development of optimized connection details for implementation in real bridge structures.

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