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Letter to Editor

Composite bridge deck configured and designed using tailor processing technique.

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Abstract
Composite materials have gained considerable attention in bridge engineering due to their perfect corrosion resistance, strength-to-weight ratio, and durability. However, the relatively high cost of composite materials necessitates the development of structures with optimized material distribution to minimize both cost and weight. In structural engineering, topology optimization is a complex tool. It serves to optimize material distribution within a prescribed design space. Its primary objective is to achieve the highest attainable material performance while adhering to a set of constraints. We employ a Tailor Processing Technique (TPT) to transform these optimization results into feasible designs, addressing this challenge. Utilizing this technique, a unit-model bridge deck is meticulously designed through topology optimization. Subsequently, composite materials are incorporated, and their performance is evaluated. The main purpose of this work is to perform topology optimization to design the unit model deck as light as possible while keeping important parameters like load-bearing capacity, stiffness, and constraint. The refinement process achieves this by using composite materials instead of concrete. A comparative analysis is conducted between a composite bridge deck designed using TPT and a traditional reinforced concrete unit model bridge deck. This comparison highlights the significant advantages offered by this innovative design approach, notably its exceptional stiffness,enhanced corrosion resistance,strength-to-weight ratio, and superior fatigue resistance. A TPT-designed deck achieves a remarkable weight reduction of 88% compared to the traditional deck and 13% compared to published GFRP decks. Additionally, a novel deck cross-section is introduced.

INTRODUCTION

Bridge design must integrate different goals, such as structural efficiency, durability, and sustainability, in order to reach an effective structural solution. As a result, engineers increased the priority of developing more effective design techniques to create lighter, stronger, and more cost-effective bridge designs. Topology optimization is considered as one of the most efficient structural design tools. The essence of topology optimization is to find out the ideal distribution of material through a given design domain, subject to stated performance objectives and restrictions[1-3].

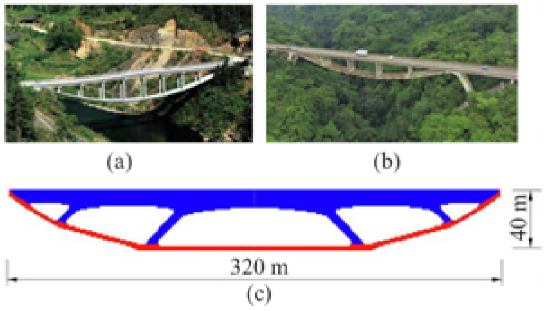


Fig. 1: (a) Taojin Bridge. (b) Rio Colorado Bridge. (c) topology optimization result presented by Li and Xie[4].

Li Yu and Xie Yimin[4] established a progressive topology optimization technique for structures that include many materials with distinct behaviors in tension and compression. They also declared that the resulting topology presented in Figure 1.c is similar to the pre-constructed Taojin bridge in China, and the Rio Colorado bridge in Costa Rica, as shown in Figures 1.a and 1.b, respectively. In another study by Li and Xie[5], further topology investigation is performed on the spatial steel-concrete structure. The work investigated the use of evolutionary algorithms to optimize the structure and topology. The work presented a systematic approach to achieving optimal structural configurations. It concluded that the results are similar to those of the Rio Colorado Bridge, as presented in Figure 1.b. Additionally, they designed the floor using topology optimization, as shown in Figure 2.

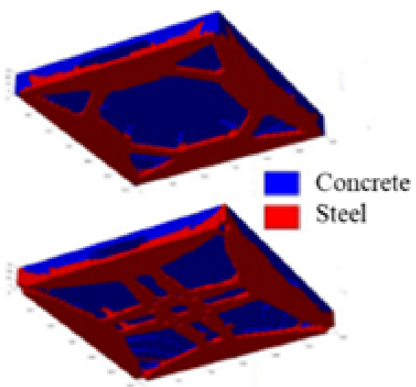


Fig. 2: Topology optimization on a floor performedby Li and Xie [5]

The tool for enhancing the results of topology is to choose an applicable cross section and configuration of composite bridge deck, as it has advantageous characteristics. These characteristics include a better strength-to-weight ratio, the capacity to modify mechanical properties, and corrosion resistance. As well as improving design flexibility and performance in difficult conditions[6].

So, composite materials are widely used in the construction of bridges as bridge decks. Fiber Reinforced Polymers (FRPs) or Glass Fiber Reinforced Concrete (GFRC) are common materials used to construct bridge decks[7–9]. Rahane and Suryawanshiy[7] investigated the dynamic behavior of FRP bridge deck constructions. And from a dynamic analysis standpoint, they investigated the benefits and drawbacks of adopting FRP materials in bridge deck construction. Several studies provided reviews of hybrid GFRP-concrete bridge deck systems, most likely looking at the use of hybrid systems in bridge deck construction that blend Glass Fiber-Reinforced Polymer (GFRP) materials with regular concrete or ultra-high-performance concrete.

Zhu and Lopez[10] investigated the efficiency of a low-weight GFRP composite bridge deck when subjected to both positive and negative bending. Awad *et al.*[11] examined various optimization techniques for designing fiber composite structures used in civil engineering applications, such as genetic algorithms, finite element analysis, neural networks, and other advanced optimization algorithms.

Valbona Mara *et al.*[12] discussed the environmental effects of using FRP in bridge construction. Utilizing FRP in bridge building results in a decrease in carbon emissions as a result of its low weight and effective transportation. Recyclability facilitates the establishment of a circular economy, while the implementation of sustainable design techniques and the deliberate selection of materials help to reduce the negative effects on the environment. FRP provides environmental advantages in terms of carbon footprint, recyclability, and sustainable design principles.

This article introduces Tailor Processing Technique (TPT) that should be used by designers to evaluate better structural elements. This work starts with the choice of the real case study bridge, which is the Hybrid Composite Beam (HCB) bridge in Virginia or Maine[13,14], as it has the same layout. The second step is to apply topology optimization, followed by enhancing the results to be applicable using composite materials under two load cases. Finally, the performance of the design is assessed through a rigorous analysis of the obtained results of the traditional deck and the designed deck according to tailor process technique. TPT clarifies the synergistic potential resulting from the fusion between topology optimization and its impact on the design of composite bridge decks.

METHODOLOGY:

The methodology of this work depends on TPT. This technique follows the flow chart shown in Figure 3 and is summarized as follows:

1. Define scope: design a light-weight composite bridge deck to minimize the weight of the deck by replacing it with a composite bridge deck, which will also minimize the dimensions of the supporting beams as the deck weight is reduced. (purpose of this work).

2. Decide design process:

This work follows the steps shown in Figure 4 and described in the modeling paragraph: -

a. Choose a unit model deck.
b. Topology optimization.
c. Enhancing the results of topology optimization.
d. Final design.

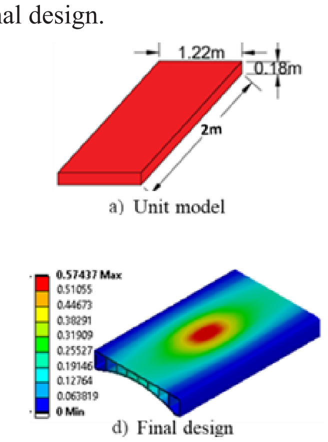


Fig. 4: Design process

There are too many designs, cross sections, and materials that researchers and designers use[5-10] as shown in Figure 5.

3. Develop project content: apply steps decided in the previous step to a real case. The chosen deck is shown in Figure 4(a).

4. Decide the tools used: using ANSYS package to design and vacuum assisted resin transfer molding (VARTM) as a manufacturing technique.

Assign process: assigning the design steps and the chosen manufacturing technique.

Unit model deck: -

Geometry: -

The chosen geometry is the unit model indicated in Figure 4, having the same depth of the reinforced concrete slab as 0.18 m with 1.22 m and 2 m width and length respectively.

This geometry is part of the HCB bridge superstructure located in Colonial Beach, Virginia[13] and another bridge with the same configuration and cross section, the Knickerbocker Bridge, constructed in Boothbay, Maine[14]. This bridge is constructed with a composite casing that includes arch concrete and foam filling spaces between the arch and casing, as illustrated in Figure 6. These HCBs are spaced 1.2 m apart.

The chosen unit models are the spacing between each HCB, and the connection between the deck and the beam has been assumed to be a fixed joint with the concrete web located at the center of the HCB, as shown in Figure 7.

Material properties: -

Starting the design according to TPT with any isotropic material with a uniformly distributed load to perform topology optimization. Then, using the same mechanical properties as Knickerbocker and Virginia HCB bridges [13-14], the FRP shell consists of quad-woven multilayers of glass fiber infused with vinyl ester resin; these layers have been oriented at 0°, 90°, and ± 45° with varying thicknesses. Poisson's ratios, ν_{xy} and ν_{yz}, were used as 0.26 and 0.3, respectively. The FRP shell mechanical properties (density = 1,682 kg/m3) are indicated in Table 1.

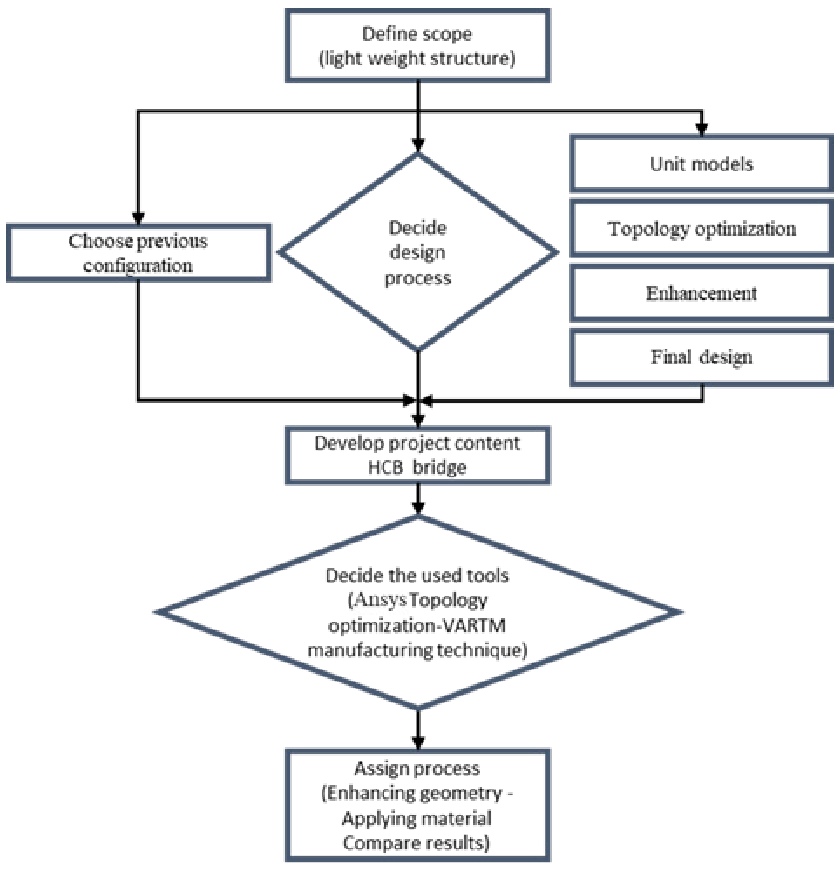


Fig. 3: Tailor process technique

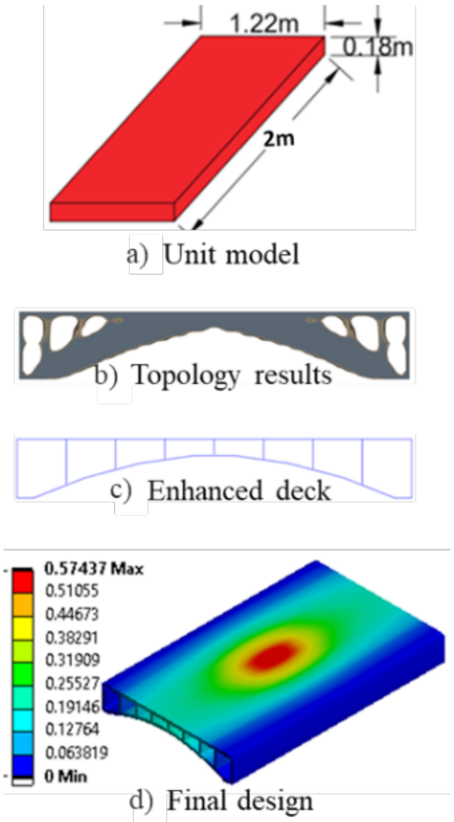


Fig. 4: Design process

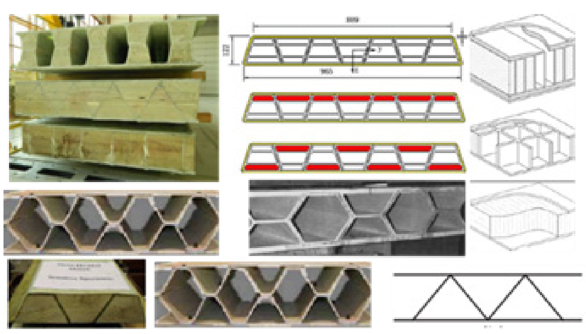


Fig. 5: Cross sections of bridge decks depending on literature or parametric optimization[7-12].

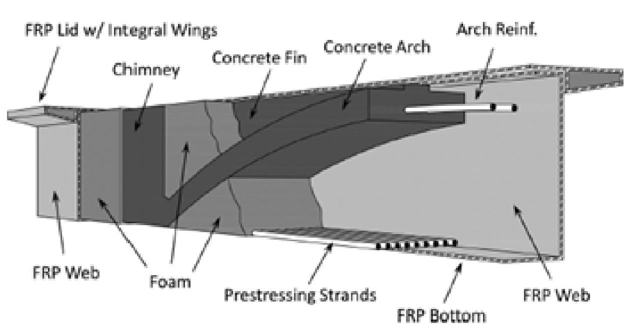


Fig. 6: HCB structural elements[13].

Table 1: mechanical properties of shell material.

Property	Shear modulus [GPa]	Stiffness [GPa]	Strength [MPa]
Tensile properties	GXY = 6.3	$EX^+ = 27.6$	$SL^+ = 372$
	GXZ = 6.3	$EY^+ = 15.7$	$ST^+ = 124$
	GYZ = 3.7	$EZ^+ = 15.7$	$S_{LT} = 21$
Compressive properties	GXY = 6.3	$EX^- = 8.96$	$SL^- = 138$
	GXZ = 6.3	$EY^- = 9.5$	$ST^- = 152$
	GYZ = 3.7	$EZ^- = 9.5$	$S_{LT} = 21$

SL+, SL- and S_{LT} are the longitudinal, the transverse and the shear strength respectively

MODELING AND BOUNDARY CONDITIONS:-

1. Choose a unit model deck.

Choosing the unit model dimensions of 2m x 1.22m x 0.18m.

2. Topology optimization.

The design procedure started with the topology optimization of the dimensions of the bridge deck. The topological loads are assumed to be distributed loads on top of the deck of the element model to have a manufacturable symmetric geometry. The continuity of the bridge deck is achieved through a 50 mm flat concrete wearing surface over all decks.

3. Enhancing the results of topology optimization.

The topology results are enhanced by replacing the kept materials with upper plate, lower arch, and vertical stiffeners.

4. Final design.

The modeling of the deck was simulated using ANSYS workbench. The simulation was performed using a shell element named Shell 181, which is a four-node element. It has six degrees of freedom which is suitable for the simulation of composite materials. Figure 8 shows the meshing of the designed deck.

Figure 9 shows the boundary conditions, wearing surface load, and vehicle patch loads.

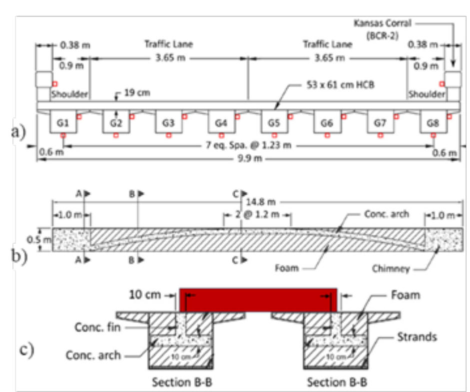


Fig. 7: a) cross section of Knickerbocker and Virginia bridges, b) side view of HCB And c) the unit model and its connection location with HCB[13]

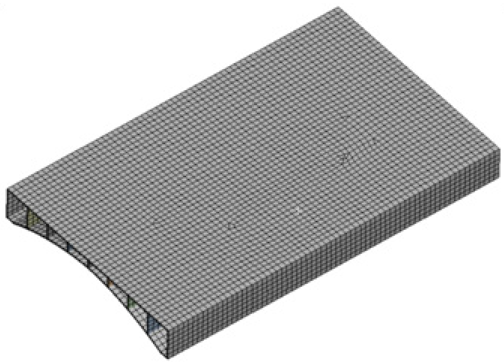


Fig. 8: Meshing of the TPT designed deck

The assumed boundary condition is a fixed support at the contact position between the concrete web of the HCB and the unit model, as shown in Figure 7.c.

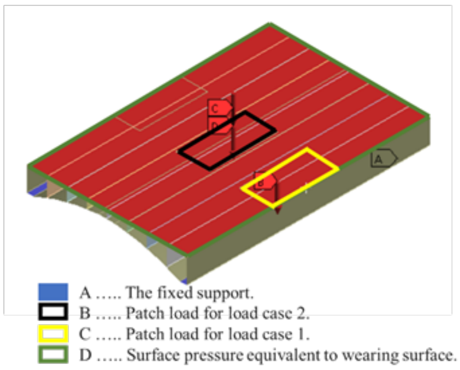


Fig. 9: Supports and loads of the unit model deck

TOPOLOGY OPTIMIZATION-

Using ANSYS density-based topology optimization, the resulting geometry is indicated in Figure 10. (a) retained value is 40 % with penalty factor 3, (b) retained value is 35 % with penalty factor 5, and (c) The reserved value is 35%, with penalty factor 4. The default penalty factor in ANSYS is 3, The more penalty factor increases, the more the complex geometry results. Therefore, the most applicable result is a penalty factor equal to 3.

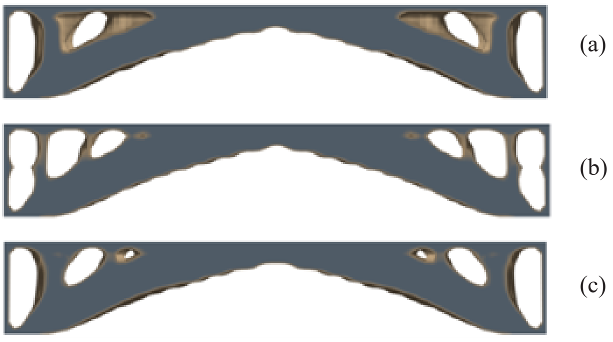


Fig. 10: Results of topology optimization

ENHANCING THE RESULTS OF TOPOLOGY OPTIMIZATION: -

1. The results of topology optimization shown in Figure 10 aren't applicable directly; they need enhancement before construction, as shown in Figure 11. The bridge deck case study was designed according to the AASHTO LRFD[15]. In this work, a surface pressure of 0.127 MPa is assumed as the wearing surface. According to the HS-20 truck load, the rear axle load is equal to 145 kN. Therefore, a wheel load equal to 72.5 kN has been simulated as a patch load of 254x508 mm2. This patch load has been applied over two critical load cases, at the center of the unit model as the most critical bending stress. For the other load case, the patch location was 100 mm away from the support to simulate the critical shear and the most critical buckling load for the first stiffener, as shown in Figure 12.

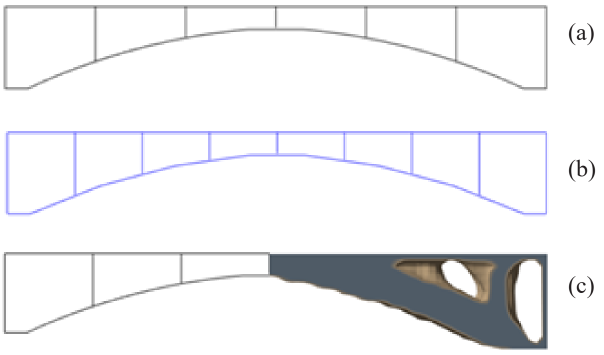


Fig. 11: The enhanced geometry of topology optimization: (a) 5 stiffeners in each side of the unit model (b) 7 stiffeners in each side of the unit model (c) schematic view of the enhancement

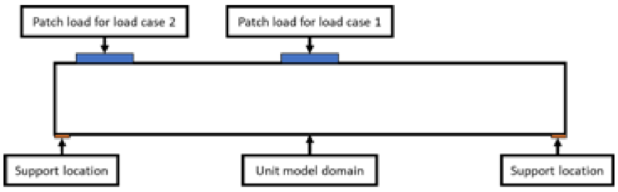
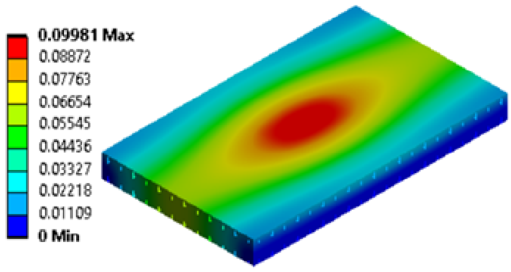


Fig. 12: load cases

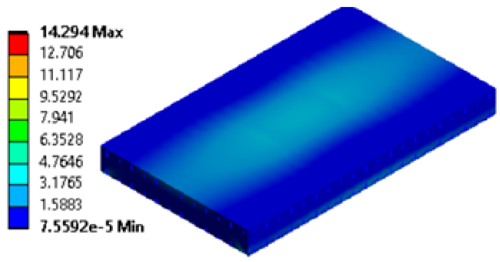
PERFORMANCE EVALUATION: -

To check the efficiency of the used technique, a comparison between the traditional reinforced deck and the designed deck has been performed. The total deformation result is less than the limit of AASHTO of span/500, which equals 2.44 mm; the equivalent Von Mises stress is less than the yield stress of steel and concrete.

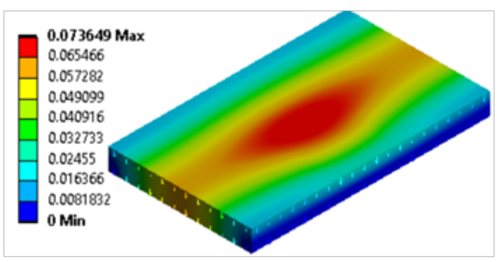
For the traditional deck, the deformations of load case 1 and 2 are 0.1 mm and 0.074 mm, respectively. The equivalent Von Mises stresses of load case 1 and 2 are 14.294 MPa and 9.961 MPa, respectively. Figure 13 (a) shows the deformation, (b) the equivalent stress for load case 1, (c) the deformation, and (d) the equivalent stress for load case 2.



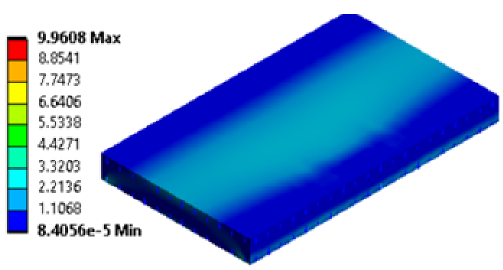
a) Deformations for load case 1



b) Equivalent stress for load case 1



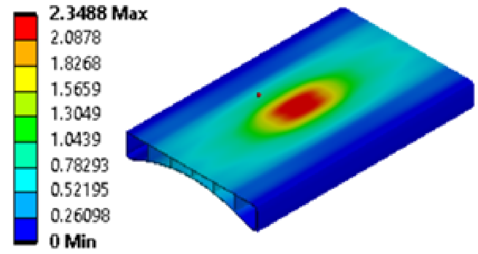
c) Deformations for load case 2



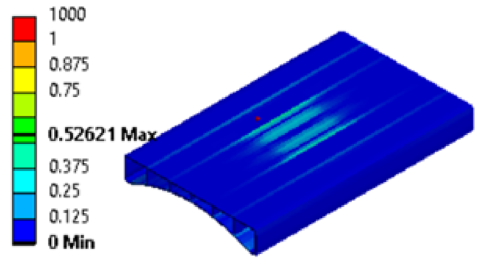
d) Equivalent stress for load case 1

Fig.13: Total deformation and equivalent stress for traditional reinforced concrete deck load cases 1 and 2, respectively

For the designed composite panels, the total deformation is also safe (less than 2.4 mm). Composite inverse reverse factor is less than 1. And the load multipliers for the Eigen value buckling are much more than 1, which means that the stiffeners are safe against buckling.

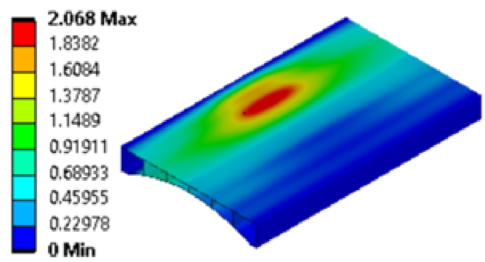


(a)

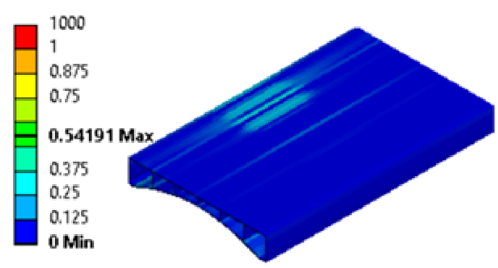


(b)

Fig. 14: results of 5-stiffeners deck load case 1



(a)



(b)

Fig.15: results of 5-stiffeners deck load case 2 (a) deformations, (b) inverse reverse factor.

For the case of 5 stiffeners, the deformations of load case 1 and 2 are 2.348 mm and 2.068 mm, respectively. The maximum inverse reverse factors for load cases 1 and 2 ar/e 0.526 and 0.5419, respectively, at the contact region between the arch and the stiffeners. The minimum load multipliers for load cases 1 and 2 are 11.905 and 14.598, respectively.

Figure 14, results of 5-stiffeners deck load case1 (a) deformations, (b) inverse reverse factor

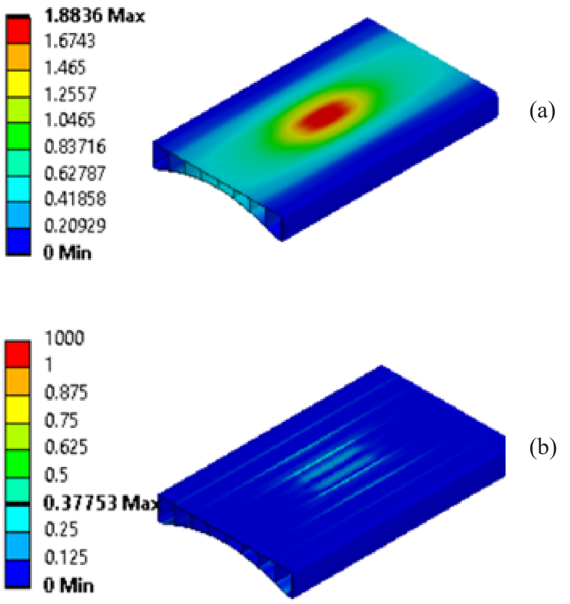


Fig. 16: results of 7 stiffener deck load case1 (a) deformations, (b) inverse reverse factor.

For the case of 7 stiffeners, the deformations of load cases 1 and 2 are 1.8836 mm and 1.7963 mm, respectively. The maximum inverse reverse factors for load cases 1 and 2 are 0.3775 and 0.5409, respectively, at the contact region between the arch and the stiffeners. The minimum load multipliers for load cases 1 and 2 are 18.142 and12.088, respectively.

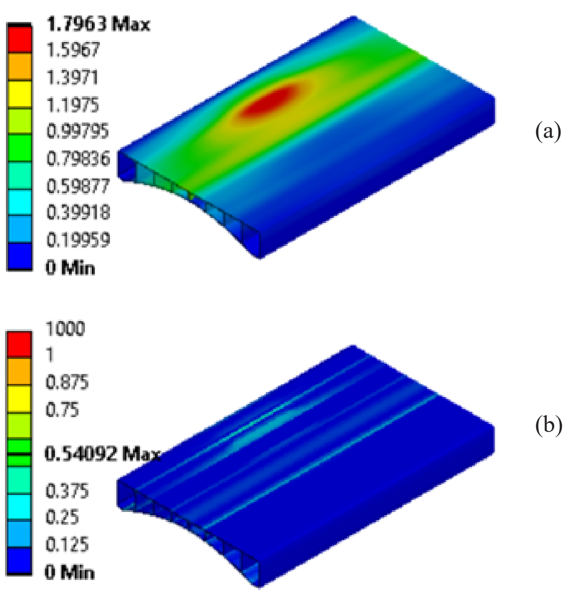


Fig. 17: results of 7 stiffener deck load case2 (a) deformations, (b) inverse reverse factor.

For the total weight of the 2000x1220x180 mm decks with the cross section shown in figure 11.(a and 9.(b with thickness 20 mm, it is 1370 kg, 165 kg and 175 kg for the traditional deck, 5 stiffeners and 7 stiffeners, respectively.

The TPT deck has a weight of 82.5 kg/m. In contrast, the recently developed lightweight composite bridge deck systems consist of pultruded trapezoidal GFRP tubes, with panels with internal divisions filled with various grout materials and grouting patterns[8], and fiber-reinforced polymer bridge deck panels[7] with a polyurethane foam core. These systems have weights of 122 kg/m and 95 kg/m, respectively. The lightweight construction of the TPT deck is readily apparent.

DISCUSSION

Figure 11 shows the best deck cross section resulting from TPT, which results from the fusion of topology optimization and enhancement followed by the application of GFRP. The application of topology optimization removes elements with minimum stresses, which leads to the minimum weight and best utilization of material. The enhancement replaces the unmanufacturable geometry with an applicable one. Finally, the application of composite materials leads to high stiffness, strength to weight ratio, durability, and corrosion resistance. Which means that TPT is the optimum technique to design structural elements.

Figures 12 (a) through 15 (a) show that the TPT designed deck has minimum deflection due to arch action. Also, Figures 12 (b) through 15 (b) show that the inverse reverse factor minimum value is located at the interaction between stiffeners and upper/lower plates. The length of stiffeners at the center of the span is minimum, which leads to a high load multiplier for the load case one. These results show that the TPT designed deck has the optimum material distribution.

Also, the overall cost of the bridge deck comprises material, labor, maintenance, and construction costs. When compared to other composite bridge decks, the variation lies solely in the material cost. The TPT-designed deck utilizes arch action to efficiently support loads, resulting in a reduced amount of materials required. However, when compared to conventional reinforced concrete decks, the material cost is considerably higher, while labor, construction, and maintenance costs are significantly lower. Consequently, although the initial cost may be elevated, it will gradually decrease over time.

Furthermore, the TPT deck can be fabricated using the VARTM manufacturing technique, which offers a significant cost advantage over pultrusion, which is common for the construction of decks.

CONCLUSION

- Innovative Design Approach:

The study presents the Tailor Processing Technique (TPT) as a viable way for optimizing composite bridge decks, delivering significant weight reduction and increased performance.

- OPTIMIZATION AND MATERIAL PERFORMANCE:

Topology optimization and the use of composite materials result in a bridge deck design that is not only lighter but also stiffer, with a higher strength-to-weight ratio and greater durability.

Comparative analysis:

A comparison examination reveals that the TPT-designed deck is superior to typical reinforced concrete decks and other GFRP decks in terms of weight and performance.

The advantages of this technique are: -

- The weight reduction is remarkable, with five stiffeners achieving 88% and seven stiffeners achieving87.2%.

- The TPT deck is lighter than composite bridge decks due to optimal material distribution. It is 15% lighter than pultruded trapezoidal GFRP tubes with grout patterns and 47% lighter than fiber-reinforced polymer bridge deck panels.

FUTURE IMPLICATIONS:

The effective application of TPT in this study indicates that it has the potential for larger use in civil engineering, providing more efficient and sustainable structure solutions. It is recommended to use TPT in the design of beams using composite and nanofiber-reinforced polymers in future work, as well as in the design of mechanical parts. It is also advised to use multi-objective genetic algorithm optimization for optimal design.

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