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Research Paper

Analysis of the behavior of composite steel beam and lightweight concrete slab with glass fiber reinforced composite

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ABSTRACT

This study proposes a novel design for lightweight concrete slabs reinforced with glass fiber-reinforced polymer (GFRP) for application in steel girder bridges. The lightweight concrete, with a compressive strength of 30 MPa, incorporates Keramzit as a lightweight aggregate and GFRP reinforcement to construct the bridge deck slabs. Numerical simulations are conducted to analyze the behavior of the slabs under both static and dynamic loading conditions, adhering to standard load combinations. The results demonstrate that the proposed lightweight concrete slabs offer significant weight reduction, improved load-bearing capacity, and enhanced durability compared to traditional concrete. The finite element analysis using Midas FEA software reveals minimal deformation and cracking under dynamic loading, with a maximum displacement of 0.641 mm, well within safety limits. Furthermore, GFRP reinforcement exhibits superior performance in reducing tensile stress and minimizing crack propagation. These findings validate the feasibility of integrating GFRP-reinforced lightweight concrete slabs in steel girder bridges, offering a cost-effective, sustainable, and efficient solution for modern bridge construction, particularly in Vietnam's demanding infrastructure environment. The study provides a strong foundation for future computational modeling and experimental investigations to further optimize this innovative structural design.

1 Introduction

The optimization of structures and reduction of loads in construction projects have yielded significant advantages for the construction industry as a whole and for bridge engineering in particular. Acknowledging the importance of this,

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researchers are actively seeking alternatives to conventional concrete, focusing on developing more advanced concrete solutions. This issue has become increasingly pressing in Vietnam, where the transport sector demands the construction of new roads and bridges and upgrading existing ones to handle greater traffic speeds and heavier loads. One promising solution that has been investigated is using lightweight concrete reinforced with glass fiber composite (GFRP) to create slab components. These can replace traditional concrete slabs in composite steel bridges, offering potential applications for new constructions and retrofits.

Lightweight concrete (LWC) has been successfully implemented worldwide in various construction industry sectors, particularly road and bridge projects. Notable examples include the Sun Bridge (1992), Lewis & Clark Bridge (1996), and Greenland Bridge (1996) [1-3]. The benefits of lightweight concrete are clear: reducing the structure's overall weight increases its live load capacity. LWC can lower the weight of concrete structures by up to 25% compared to traditional concrete, facilitating faster assembly and lowering transportation costs through precast components. In Vietnam, lightweight concrete has been used effectively in projects like the Fortuna Hotel, Long Bien Sports Center, and Green Place Restaurant, receiving positive feedback from investors and users. The idea of applying lightweight concrete in bridge structures has recently gained attention, with economic and technical comparisons showing its advantages over conventional concrete bridge designs. Vu Ngoc Anh et al. (2017) investigated concrete incorporating sea sand and seawater with GFRP glass fiber reinforcement [4]. The study found that GFRP reinforcement demonstrated superior durability in saline conditions. Non-metallic materials, such as GFRP bars, have seen widespread use in multiple industries due to their ability to reduce structural weight, enhance durability, and extend the lifespan of structures. Given these benefits, GFRP bars are increasingly considered replacements for traditional steel reinforcements.

Currently, the application of lightweight concrete in bridge construction remains relatively novel. However, research exploring the replacement of conventional concrete with GFRP-reinforced lightweight concrete panels shows great scientific and practical potential. Combining these two materials results in more durable and lighter structures and offers superior performance compared to conventional concrete. This study addresses the significant challenge of load-bearing capacity in composite steel girder bridges, which often require larger girder sizes, thus increasing construction costs. By proposing using GFRP-reinforced lightweight concrete slabs as a replacement for traditional concrete, this research presents a promising solution to reduce costs while enhancing structural performance. The preliminary design meets Vietnamese standards and includes comprehensive geometric and engineering considerations. Through various static and dynamic analyses, key findings such as fundamental vibration frequency, dynamic amplification factors, and stress distribution are discussed, demonstrating the slabs' feasibility in improving composite steel bridge designs. This research establishes a solid foundation for further computational modeling and simulations of composite slabs. It aims to advance the integration of GFRP-reinforced lightweight concrete in steel bridge construction, ultimately contributing to more efficient, durable, and cost-effective future designs [5-7].

2 Modeling of lightweight concrete slab steel beam structure reinforced with GFRP bars

The proposed slab structure in this study is a lightweight concrete slab with a length of 2.7 m, a width of 0.4 m, and a thickness of 0.1 m, using glass fiber reinforced plastic (GFRP) as the supporting reinforcement. The geometrical dimensions of the lightweight concrete slab are shown in Figure 1. The lightweight concrete (LWC) deck is connected to the steel beam by anchor bolts. The two fixed support points are placed 2.5 m apart. Other details are also illustrated in Figure 1.

The lightweight concrete used is Karemzit lightweight aggregate concrete with a design strength of 30 MPa. GFRP reinforcement of different sizes is arranged to ensure the requirements of static and dynamic load-bearing of vehicles participating in traffic. The design work complies with the regulations outlined in the bridge design standard TCVN 11823-2017, along with the design guidelines for reinforced concrete structures such as TCVN 5574:2012, ACI 318, and design guidelines for GFRP-reinforced structures including ACI 440.1R and CAN/S806-02. [8-12]. Details of the physical and geometrical parameters of these two materials are introduced in section III. The structural modelling is carried out using Midas FEA software, where the concrete slab and steel beam is represented by solid elements. Additionally, the GFRP bars are represented by beam elements. Due to the close connection of the nodes of the concrete slab with those of the steel beam, we can affirm that there is a strong bond between the concrete and the steel, thus eliminating the need to model bond anchors. Regarding the boundary conditions for the support connections, the authors decided to fix both ends of the structure to ensure that the reactions and deformations of the system are accurately controlled.

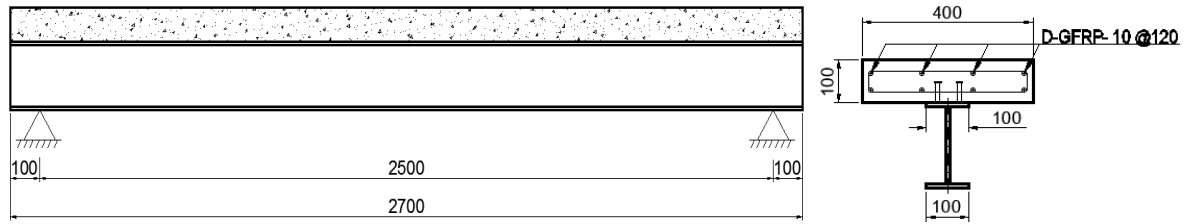


Fig. 1 – Lightweight concrete slab steel beam structure reinforced with GFRP bars

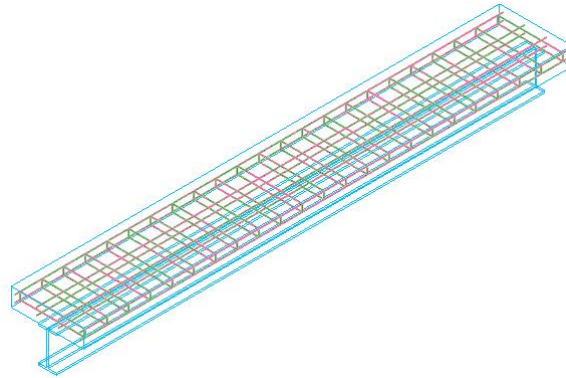


Fig. 2 – GFRP reinforcement model in lightweight concrete slab.

Before simulating the overall load-bearing structure, the author conducted simulation tests to assess the suitability of the materials. The tests were performed on the adhesion between the GFRP and steel reinforcement within the concrete to ensure that the fabricated concrete slab could endure both tensile and compressive forces. This evaluation allowed the author to determine whether GFRP reinforcement could effectively replace traditional steel reinforcement [13].

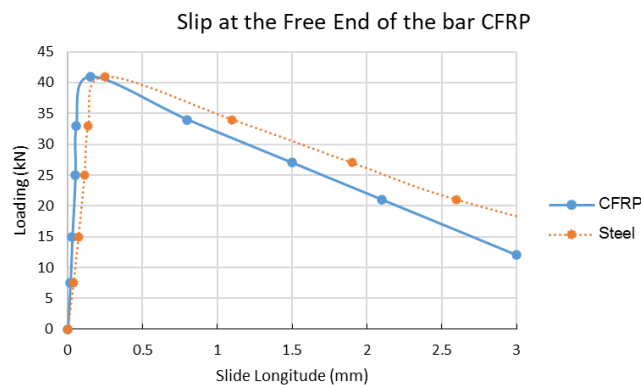


Fig. 3 – Bond stress-slip relationship of GFRP and steel with lightweight concrete.

The author then generated a graph depicting the relationship between the slippage of aggregate bars in lightweight concrete (Figure 3). After simulation, the maximum shear stress for GFRP and steel bars was 7.67 MPa and 7.45 MPa, respectively. The graph shows that at the point of maximum tensile force, GFRP bars experienced less slippage than traditional steel bars. However, traditional steel bars demonstrated better adhesion during the load reduction phase, though this phase is less significant than the initial one. Based on this comparison, it can be concluded that GFRP can fully replace traditional steel bars in lightweight concrete slabs for this study. Consequently, the research team used 100% GFRP aggregates instead of traditional steel bars to reinforce lightweight concrete slabs placed on composite steel beams.

3 Analysis of the behavior of lightweight concrete slabs reinforced with GFRP

3.1 Computational model

Nonlinear material models are applied to lightweight concrete, GFRP bars, and steel beams. The modeling process is conducted with load control. For all materials, Hordijk models are utilized to represent tensile behavior, effectively capturing the mechanical properties, cracking behavior, and load response of lightweight concrete. This enhances predictions of performance under various conditions and improves structural performance assessments. Additionally, Thoenfeldt models are employed for the compressive behavior of all materials. These models are particularly effective in capturing the complex stress-strain relationships in concrete and steel under compression, which is critical for accurately predicting failure modes and overall structural performance. The choice of the Thoenfeldt model is driven by its ability to represent the effects of confinement and loading history, allowing for more reliable evaluations of structural integrity in different loading scenarios.

By integrating both the GFRP and steel beam models alongside the lightweight concrete, the analysis can more accurately predict the interactions between these materials and the concrete, ultimately leading to improved assessments of overall structural performance and safety [14, 15]. Specifications include a compressive strength of 30 MPa, a tensile strength of 3.33 MPa, a modulus of elasticity of 15.949 MPa, a Poisson's ratio of 0.2, and a density of 1700 kg/m³ [16]. GFRP non-metallic reinforcement includes $\Phi 12$ & $\Phi 14$ bars with characteristics: Weight 2500kg/m³, tensile strength 4580 MPa, modulus of elasticity 85.5GPa, ultimate tensile strain 3.3%, Poisson's ratio of 0.22 [17].

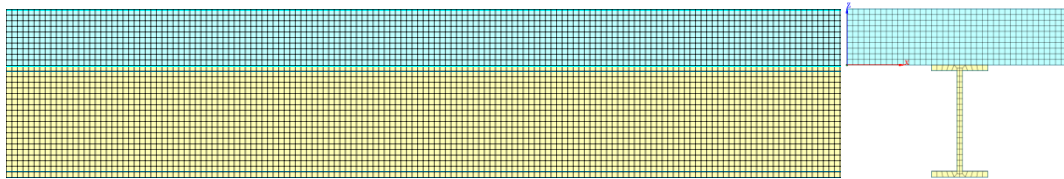


Fig. 4 – FEM mesh of considered beam

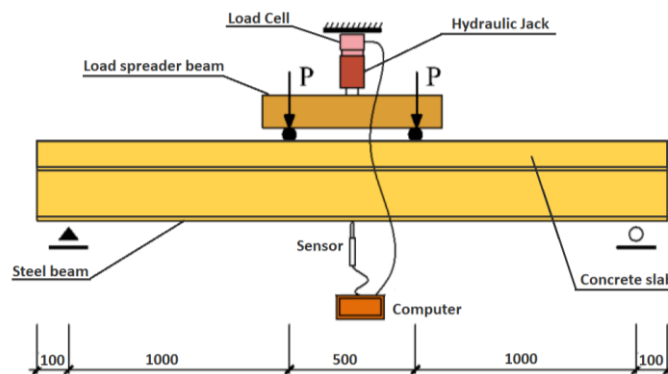


Fig. 5 – Four-point bending test diagram

Vertical load up to T22 value is within the allowable dynamic load range [3, 8, 9], which is 20.163kN. The standard axial load of vehicles used in Vietnam is 220kN. Considering the impact coefficient $(1+IM) = 1.6$. Therefore, the model is loaded from 0 kN to $P = 400\text{kN} > P_{\text{max}} (1+IM) = 352 \text{ kN}$. The finite element mesh is shown in the figure. The model includes 3D geometries created using precise Boolean operations [14]. It allows for automatically generating 3D meshes with accurate control over element sizes and customized mesh node positioning. The size of each mesh edge is set to 10 mm. The total number of mesh nodes is 14769, ensuring high accuracy for the model.

Alongside the modeling process, the research team also conducts practical experiments, gradually applying a load up to 400 kN under loading conditions like those in the simulation model. The sensors are attached to the beam and connected to a computer to record displacement results at various locations [18].

3.2 Static analysis results

The concrete stress field and the fiber's axial force are considered the model's output.

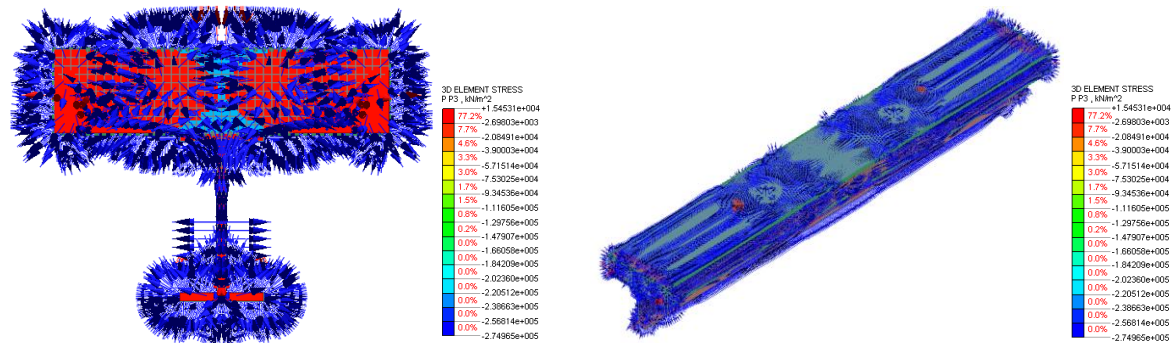


Fig. 6 – Stress field at Cross section of LWC lightweight concrete slab.

Figure 6 shows that the local compressive force at the loading position reaches 15-16 MPa, below the concrete's failure threshold of 28 MPa. This indicates that the designed lightweight concrete slab remains within safe limits under the converted static load T22. However, some cracks have developed due to high tensile stress at the force transmission points from the slab to the anchor. Finite element analysis reveals these cracks are concentrated in the anchor connection area and the lightweight concrete slab.

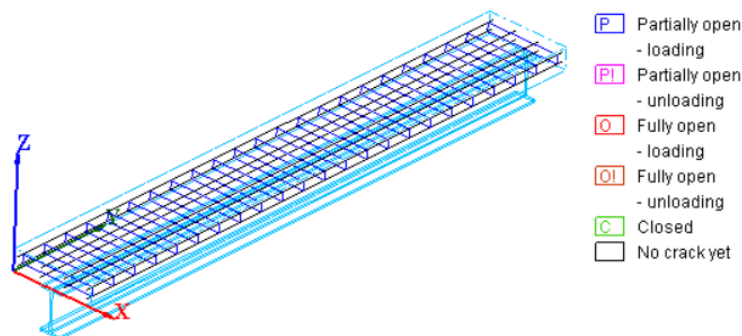


Fig. 7 – Plastic state of solid elements.

Local locations, specifically the junction between the anchor and the deck and the junction between the steel beam and the deck, show plastic yielding. Thus, these locations can be identified as the first cracks in the deck. The effect of live load causes this cracking phenomenon. The load of traffic on the deck compresses the upper fibers of the deck and tensions the lower fibers. Therefore, reinforcement is necessary at this location to limit cracking.

To determine the accuracy and reliability of the simulation results, the authors conducted a static compression test. In this experiment, lightweight concrete samples were subjected to a specific load, and the resulting displacements were recorded. The displacement results from the experiment were then compared with the simulation results obtained from finite element analysis software. This comparison not only helps to assess the compatibility between the theoretical model and real-world performance but also provides insights into the load-bearing capacity and response of the structure under compression. As we can see in the chart above, the experimental results are quite similar to the simulation results, with an error of less than 0.01 mm. This is a very small error in the simulation, indicating that the simulation can be considered reliable for predicting the behavior of the structure under the given loading conditions.

The modeling results indicate that concrete failure occurs before the plastic deformation stage of the GFRP reinforcement. The analysis distinguishes between the local compression zone and the tensile zone. The non-metallic aggregate has not yet reached its full potential at lower, less complex loads. However, as the load increases and becomes more complex, the non-metallic aggregate maximizes its effectiveness, ensuring structural strength and safety. Figure 8

illustrates that the relationship between load and displacement is nearly linear. This demonstrates that the fiber reinforcement performs effectively and can support large and extreme loads. In contrast, with traditional steel reinforcement, after the elastic stage, its capacity to work diminishes significantly, leading to a rapid increase in cracks during the cracking process.

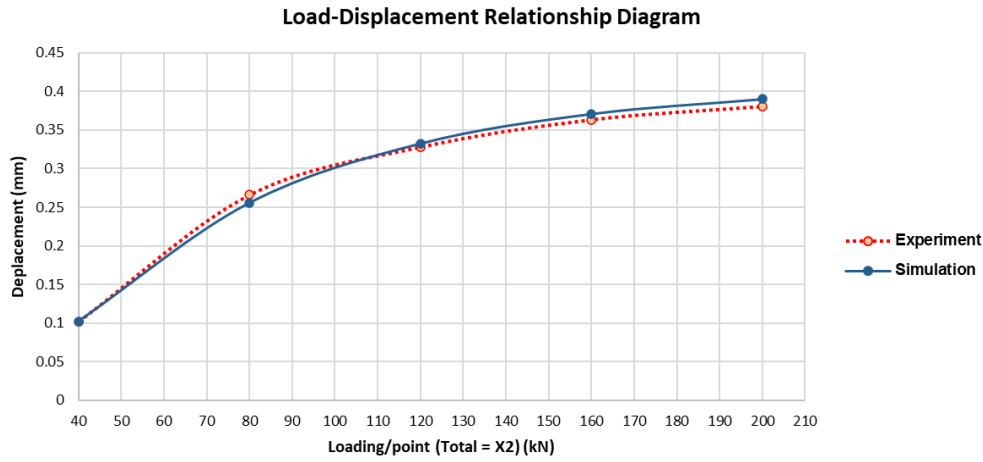


Fig. 8 – Relationship between load and mid-span deflection of the bridge deck

3.3 Dynamic analysis results

Dynamic analysis is performed under the load combinations of ACI and TCVN standards [8-11].

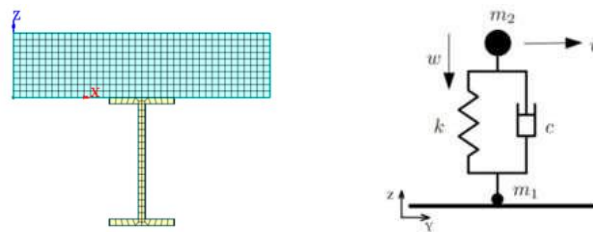


Fig. 9 – Model of a vehicle moving at a constant speed.

Figure 10 shows the first four eigenvectors of lightweight concrete and their corresponding fundamental frequencies of 11.39 Hz, 20.74 Hz, 32.65 Hz, and 37.05 Hz. These frequencies are much higher than those of a normal vehicle, estimated at around 11.39 Hz.

According to the results, the experimental sample has a fairly large reserve of stability under the impact of dynamic loads. Then, the frequency of the model is too high while the frequency of the vehicle falls around 10-15Hz. In this simulation, the vehicle is used and modeled as a block with two degrees of freedom in two directions: Horizontal direction (y-axis): The velocity in this direction is assumed to be equivalent to the velocity of the vehicle, $v = 50 \text{ km/h}$. Vertical direction (z-axis) oscillation is considered a simple oscillation of the object supported by a spring and a shock absorber. Using FEA Midas software [14, 19], the modeling is performed with some details as follows:

- + Because the velocity does not change, this study chooses the time $t = 0.008\text{s}$ (from $t = 0$): the shaft with a mass of 22 tons passes through the point.

- + The end of the lightweight concrete slab (length 0.4m). The table below shows the times when the vehicle axis passes through the positions of the nodes [6, 20].

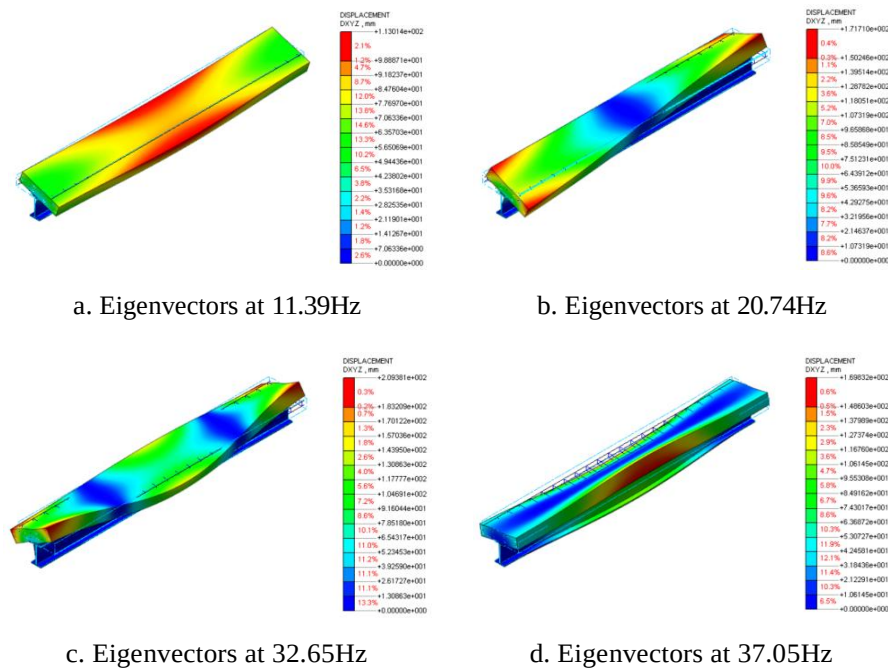


Fig. 10 – First Eigenvectors at Different Frequencies

The results show that the experimental sample has a fairly large stability reserve under the impact of dynamic loads.

Table 1 – Time when the convoy passes through the positions

Nodes	Loadset	Load type	Direction	Direction vector	Time (s)	Ratio
41021	mass	Force	X	1.0,0.0,0.0	0	1
81611	mass	Force	X	1.0,0.0,0.0	0	1

+The vertical oscillation (z-axis) is depicted in the diagram below:

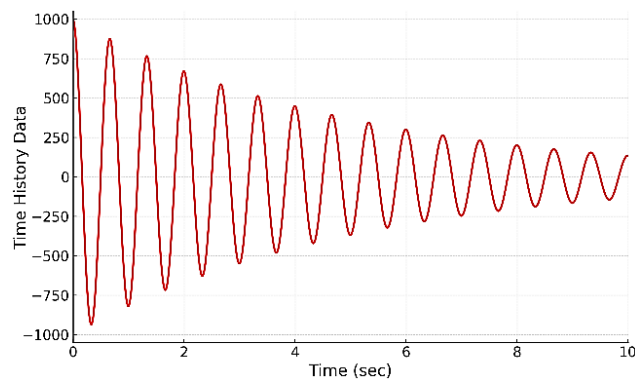


Fig. 5– Oscillation frequency chart of mass.

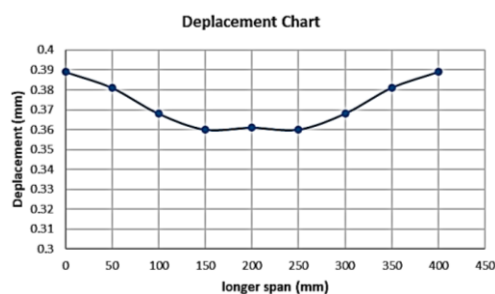
The waveforms depicted above represent "vibration damping," which can be viewed as the inverse of the shock waveform exerted by the shaft on the bridge deck. Only the frequency of mode N°, $f_1=11.39$ Hz, is considered for this analysis.

The analysis results, including displacement, velocity, and acceleration, are derived using the moving mass model (Figure 12). The maximum displacement occurs at the mid-span section, resulting in higher velocity and acceleration values at the support points. The statistical results are summarized in Table 2.

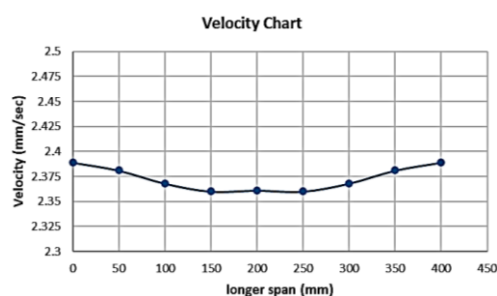
Table 2 – Maximum value when using a block model

Displacement	Velocity	Acceleration	Stress
0.389 (mm)	2.389 (mm/sec)	0.008 (mm/sec ²)	21.056(N/mm ²)

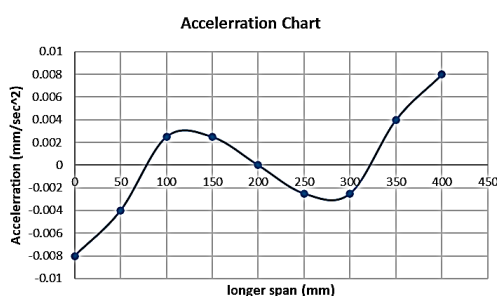
Through the process of analysis and calculation, we obtained the following chart:



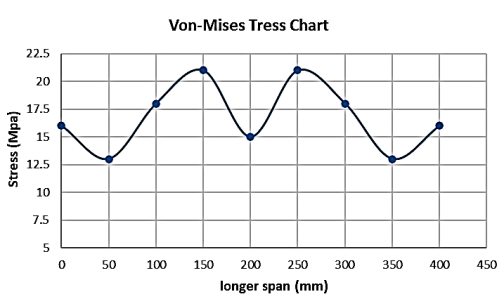
(a) Displacement along the XYZ axis is caused by dynamic loads when the load moves.



(b) The velocity along the XYZ axis is caused by the dynamic load when the load moves.



(c) Acceleration along the XYZ axis due to dynamic load when the load moves



(d) Stress in the XYZ axis is caused by the dynamic load when the load moves.

Fig. 12 – The process of analysis and calculation.

Figures 11 a, b, c, and d show that displacement, velocity, and acceleration values peak at the start and end of the process, highlighting the need for engineers to focus on areas where the bridge deck is cut or connected, as these points are susceptible to significant impulses. Support measures are essential to prevent structural damage when a vehicle's axle exerts force on the cantilever. At the anchor position, stress peaks as the entire load transfers to the bridge deck and supporting steel beam, increasing tensile stress on the lower surface as the vehicle moves to the center of the bridge, potentially leading to cracking if the load is excessive. Therefore, the research team recommends designing a lightweight concrete bridge deck with GFRP reinforcement, particularly at high-stress concentrations. Special attention should be given to the beginning and end points of the deck sections during installation, with improvements to the quality of joints as needed.

4 Conclusions

The research findings indicate that using GFRP-reinforced lightweight concrete slabs to construct composite steel girder bridges is an optimal solution, effectively meeting static and dynamic load requirements. The behavior analysis of the lightweight slab demonstrates compliance with Vietnamese standards (TCVN 11823-2017) and international standards such as ACI 440.1R-06 and CAN/S806-02. The maximum recorded displacement of 0.641 mm is within acceptable limits and significantly lower than previous studies on conventional concrete slabs, affirming the proposed solution's load-bearing capacity and structural stability. Furthermore, the lightweight GFRP slab reduces weight, enhances corrosion resistance, and extends the structure's service life, promoting economic efficiency in bridge construction in Vietnam. This study lays the groundwork for further research and contributes to the sustainable development of the bridge engineering sector, aligning with Vietnam's climatic and environmental conditions.

Acknowledgments

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