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## Research Paper

### Study on Pipe Strut Dimensions Optimization for Strutted Box Girder Bridge Using FEM

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#### ABSTRACT

Although the concept of a concrete box girder bridge with strutted wing slabs was proposed long ago as a means to expand the width of bridge sections without significantly increasing the self-weight of the superstructure, research on this structural system remains limited. Using data from a full-scale box girder bridge experiment conducted as part of the Ring Road II Viaduct Project in Vietnam, a finite element model was developed to investigate the influence of the steel struts' geometrical dimensions on the structural behavior of box girders. This paper examines key structural responses, including deflection, stress in the concrete slab, and stress in the steel struts, under varying steel strut dimensions—namely, thickness and diameter. The findings reveal that the diameter and thickness of the steel struts significantly affect beam deflection and strut stress, while their impact on slab stress is negligible. Furthermore, the paper provides practical recommendations for selecting optimal steel strut dimensions and highlights future research directions to enhance the design of such structures. These insights aim to benefit both practicing engineers and researchers in the field.

## 1 Introduction

A concrete box girder bridge with strutted wing slabs is a type of box girder bridge that incorporates struts to support cantilever wing slabs. This design features large cantilever slabs, known as wing slabs (typically over 4 meters in length), supported by diagonal struts made from materials such as concrete, steel pipes, or advanced composites. These wide wing slabs not only increase the bridge's traffic capacity but also enable the use of struts to reduce the bottom width of the girder and its overall self-weight. As a result, the dimensions of substructures, including pier columns, abutments, and foundations, can be significantly minimized [1, 2]. Moreover, the strutted box method allows a two-lane segmental bridge to be designed and constructed with the flexibility to be expanded into a three-lane or four-lane bridge in the future [3]. Up to now, numerous strutted box girder bridges have been built across Europe, with notable examples including the Kochertal Viaduct in

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Germany, the Rogerville Viaduct in France, the Piedrafita Viaduct in Spain, and the WA 19 Viaduct in Portland. However, despite these advantages, strutted box girder bridges have not achieved widespread adoption outside Europe. In Japan, this type of bridge was first introduced in the early 2000s, primarily for highway projects such as the New Tomei Expressway [1]. Korea followed with its first strutted box girder bridge, the Incheon Bridge, which commenced operation in 2009. In 2023, the first box girder bridge with strutted wing slabs in Vietnam was put into operation as part of the Ring Road II Viaduct Project in Hanoi. As this was a completely new type of bridge in Vietnam, an experimental program was conducted prior to the project's commencement to verify the construction technology and gather experimental data [4].

Although strutted wing slab box girder bridges have been developed and implemented for many years, research on their structural behavior remains relatively limited, particularly studies focused on optimizing geometric dimensions for design purposes. Prior work has investigated enhancements in transverse and longitudinal performance. For instance, Zhou et al. [5] demonstrated that incorporating transverse stiffened ribs into wide prestressed concrete box girders significantly increases transverse stiffness and alleviates stress concentrations, particularly around the ribs, thereby improving load distribution and overall structural performance. Finite element analysis (FEA) confirmed that ribbed designs effectively optimize stress responses, enabling wider girder spans while maintaining safety and stability. Natário et al. [6] examined the shear behavior of reinforced concrete deck slabs in box girder bridges subjected to concentrated loads near linear supports. The study underscored the importance of two-way force redistribution and arching effects in enhancing shear strength. Shushkewich [3] evaluated the practical implementation of the Strutted Box Widening Method (SBWM) by analyzing the longitudinal behavior of both a variable-depth cast-in-place segmental bridge and a constant-depth precast segmental bridge using struts to expand the bridge width. His findings indicated minimal variation in longitudinal flexural, shear, and torsional responses across different construction stages, validating the method's effectiveness for bridge widening. Additionally, he developed the STRUTBOX program to assess the transverse behavior of strutted box girder bridges under design loads in three construction stages, following AASHTO specifications [7]. This research highlighted SBWM as an optimal solution for increasing span length, offering weight savings while enhancing torsional rigidity.

Agarwal, Pal, and Mehta [8] studied the influence of design parameters—such as curvature angle and span length—on key structural responses, including bending moment (BM), shear force (SF), torsional moment (TM), and vertical deflection (VD) in curved concrete box girder bridges. Nguyen [9] conducted a study aimed at improving the performance of traditional concrete box girders by integrating reinforcing ribs and struts. A finite element model was employed to evaluate the structural response of different cross-section types, incorporating modal analysis (natural frequency and mode shapes) and structural analysis (deflection, bending, and torsional resistance) under HL-93 live loads as per AASHTO 2007. The results demonstrated that reinforcing ribs and struts notably enhance structural integrity: ribs improve cross-bridge stiffness, while struts optimize stress distribution and mitigate flange instability. Park et al. [10] investigated the transverse behavior of box girders, revealing significant discrepancies between results obtained from plane frame and three-dimensional analyses. Additional aspects of traditional concrete box girder behavior are discussed in other studies [11–21].

In this study, to contribute to the understanding of optimizing geometric dimensions in strutted box girder design, a validated finite element model (FEM) was developed based on experimental data from a full-scale box girder bridge incorporating steel pipe struts—specifically, the Ring Road II Viaduct Project in Vietnam. This validated FEM was then utilized to explore how variations in strut dimensions affect the behavior of the girder by altering the diameter of four steel struts. The comprehensive results and discussions of this analysis are detailed in the paper. These numerical findings serve as reliable references for engineers in selecting appropriate geometric dimensions for future structural designs.

## 2 A Brief of Girder Segment Experiment

To assess the structural performance of an innovative full-scale concrete box girder system incorporating diagonal steel tube struts, an experimental load test was conducted under three distinct load cases. Each load case was designed to simulate the most critical service conditions in accordance with the Service Limit State criteria [22, 23]. The primary objective was to investigate the behavior of both the concrete slab and steel struts under these adverse conditions, including a maximum negative moment in the left-wing slab (at Section B, as shown in Fig. 1), a maximum positive moment in the right-wing slab (at Section A, as indicated in Fig. 1) and a maximum axial load in the steel pipe struts.

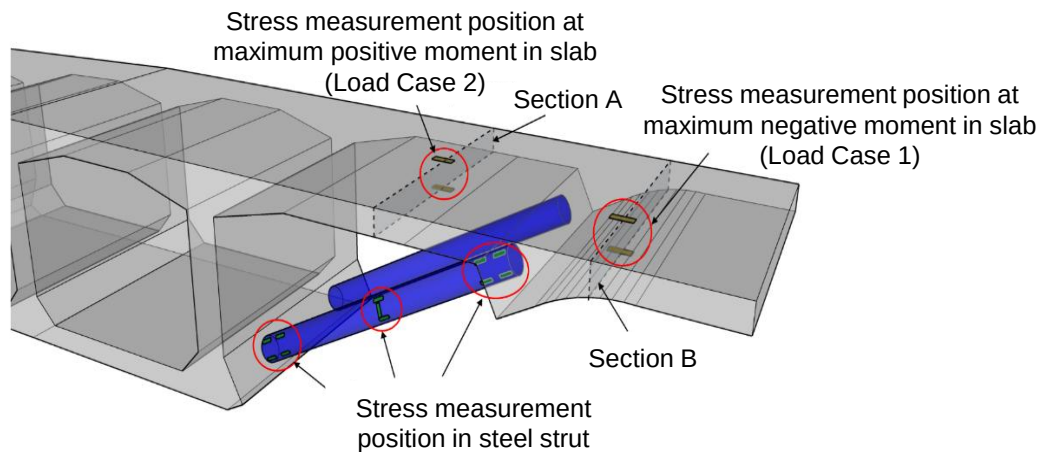


**Fig. 1 – Critical sections in the wing slabs**

The experimental results indicated that, for concrete box girders with steel struts, proper detailing of the connections between the concrete and struts is essential to ensure stability and prevent cracking during fabrication. Improper reinforcement and casting can weaken the concrete and cause cracks, while clear guidelines for tightening bolts are necessary to avoid issues during construction. Cracks were observed at the construction joint between the core segment and cast-in-place wing slabs in Load Case 2, underscoring the importance of managing interfaces between concrete layers cast at different times to prevent early cracking. In all load cases, with loads ranging from 1.2 to 1.5 times the Service Limit State load, both the wing slabs and steel pipe struts maintained their load-bearing capacity and exhibited linear behavior. The steel struts provided adequate rigidity during testing, confirming the design's effectiveness under service loads. However, as the tests used static loads, further analysis of dynamic effects is recommended to better understand the performance of the struts under real-world conditions.

### 3 Numerical Modelling

#### 3.1 Finite Element Model

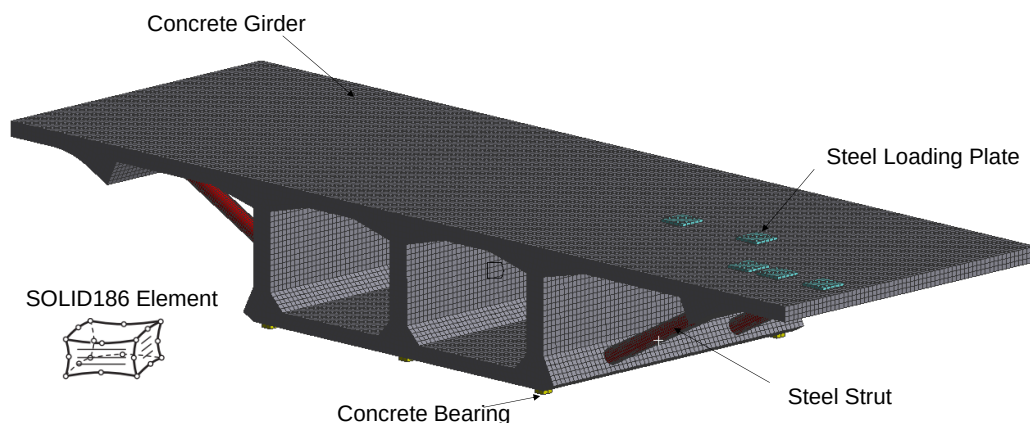


**Fig. 2 – Finite element model for girder segment in ANSYS software**

ANSYS Workbench 2021 was used to develop the three-dimensional static model of the strutted box girder segment tested in the full-scale experiment. This study focuses exclusively on the transverse structural behavior of the box girder under design loading, specifically the HL-93 live load as defined by AASHTO standards. The effects of cumulative construction-stage loads and prestressing due to prestressed steel were not considered. Therefore, to simplify the finite element model (FEM), both reinforcement and prestressing steel were omitted. The influence of reinforcement is typically accounted for by modifying the elastic modulus of the concrete material. The girder segment was supported on six concrete

blocks, which were pinned in the vertical direction at the bottom along both ends of the girder to simulate bearings. Additional nodal restrictions were applied to prevent rigid body movement of the girder while allowing for rotational deformation. The test loads were simulated as vertical downward pressures applied via 500 mm wide square steel plates positioned on top of the box girder segment. These plates transmitted the pressure to the girder's top flange through bonded contact interactions. Four steel struts were modeled as being fixed to the core box girder via bonded contact regions at their connection points with the concrete surface on the girder's end sides. The material properties of the steel struts and concrete girder were derived from material testing, as summarized in Table 1.

**Table 1 - Material properties [4]**

| Material          | Type used                                 | Yield strength, $f_y$ (MPa) | Ultimate strength, $f_u$ (MPa) | Elastic Modulus, E (GPa) |
|-------------------|-------------------------------------------|-----------------------------|--------------------------------|--------------------------|
| Concrete          | Compressive strength, $f'_c = 47.86$ MPa* | N.A                         | N.A                            | 38.5*                    |
| Steel pipe struts | Grade 345                                 | 345                         | 450                            | 200                      |

\* Defined by tests using  $150 \times 300$  mm cylinder specimens

All components of the girder segment were modeled using the SOLID186 element, as illustrated in Fig. 2. SOLID186 is a 20-node structural solid element with three translational degrees of freedom at each node. It is particularly suitable for modeling irregular meshes and can be used for elements with arbitrary spatial orientation.

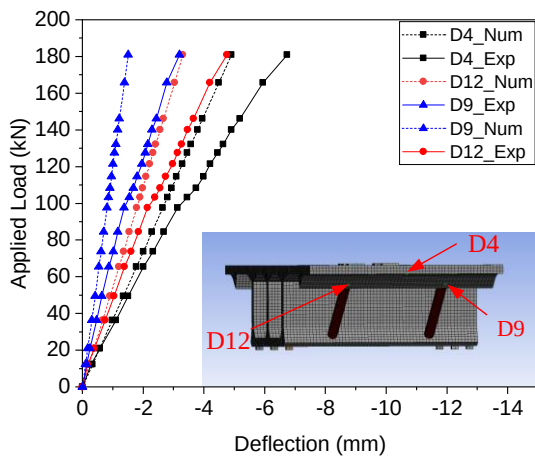
A convergence study was conducted to determine the level of mesh refinement necessary to achieve an accurate solution. The analysis focused on identifying the optimal element size at which the maximum deflection in Load Case 1 meets the predefined accuracy criteria, typically defined in ANSYS as an acceptable error range of 1% to 5% for average stress-related displacements [24]. As shown in Table 2, variations in deflection became negligible—less than 0.5%—when the mesh size was reduced below 200 mm. Hence, a mesh size of 100 mm was selected for the subsequent parametric study to optimize computational time and facilitate the accurate identification of observation points as defined in the design.

**Table 2 - Convergence study**

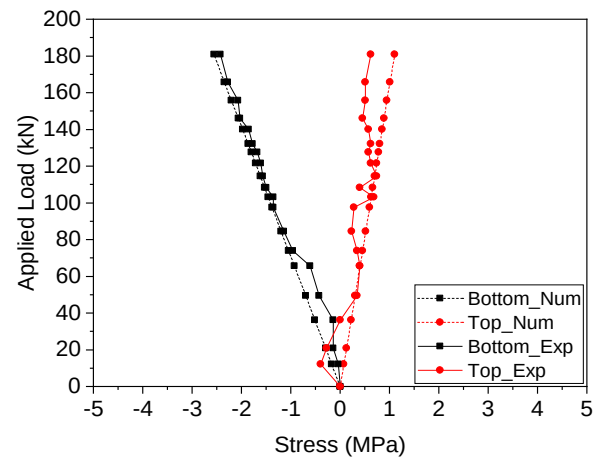
| Mesh size (mm) | Deflection(mm) | Change (%) |
|----------------|----------------|------------|
| 400            | -7.149         |            |
| 300            | -7.184         | 0.50       |
| 200            | -7.223         | 0.54       |
| 150            | -7.257         | 0.47       |
| 125            | -7.281         | 0.34       |
| 100            | -7.304         | 0.31       |

### 3.2 Validation results

The results predicted by the finite element model (FEM) were compared with the experimentally captured measurements. Fig. 3 illustrates a comparison between the numerical and experimental results for Load Case 1. As the applied load increased from 0 to 100 kN, the deflection of the girder segment at the tip of the wing slab (D4) and the upper ends of both struts (D12 and D9) in the experiment exhibited a linear trend, closely matching the numerical results. However, at a load step of 102 kN, a notable jump was observed in the experimental results. This behavior can be attributed to a rotation occurring at the lower end of the east-side strut (location D12) during the load-testing phase. Notably, a comparison of the slab stress in Section B (Fig. 1) indicates similarity between the numerical and experimental results. This similarity becomes particularly pronounced for stress at the bottom slab when the applied load exceeds 70 kN, with the difference between the numerical and experimental results below 9% at all load steps.



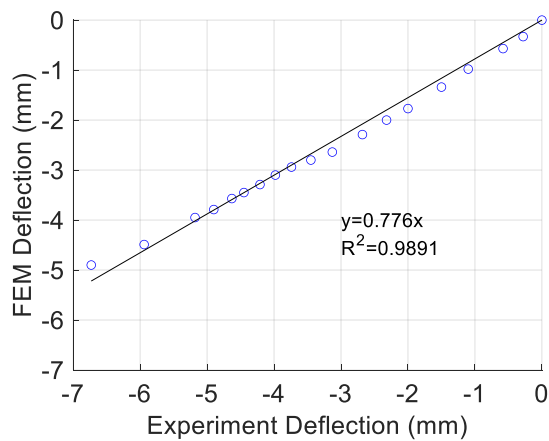
a) Load-deflection of wing slab at three locations



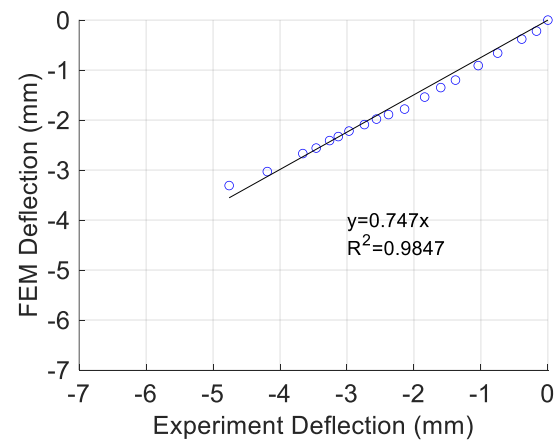
b) Stress of slab at construction joint

**Fig. 3 – Finite element model for girder segment in ANSYS software**

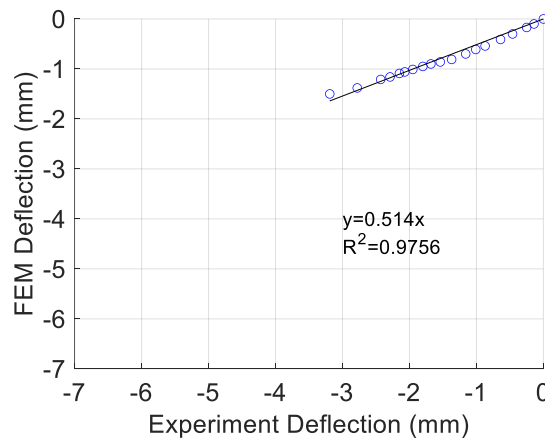
To evaluate the overall correlation between the FEM and the experimental results, the two datasets of deflection were plotted against each other, as shown in Fig. 4.



a) D4



b) D12



c) D19

**Fig. 4 – Experimental and Numerical deflection relationship for Load Case 1**

The linearity of the relationship between the experimental data and FEM predictions serves as an indicator of model accuracy. The correlation coefficient,  $R^2$ , was used to quantify the strength of a linear relationship between two data sets. Its value ranges from 0 to 1, with values close to 1 indicating a high degree of correlation or similarity, while values near 0 signify little to no correlation. The minimum correlation coefficient of 0.98, displayed on the graph, reveals a strong linear relationship between the datasets. This high  $R^2$  value confirms the FEM's high precision in accurately capturing and simulating the deflection behaviour of the wing slab.

Similarly, in the relationship between experimental and numerical slab stress in the bottom fiber at Section B, as shown in Fig. 5., the correlation coefficient of 0.97 also signifies the high accuracy of the FEM in simulating the slab stress of the concrete girder.

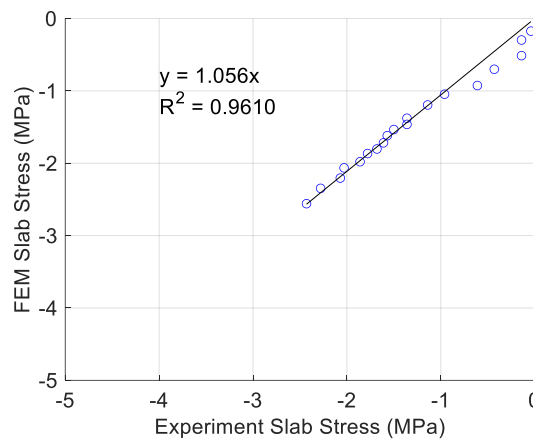


**Fig. 5 – Linear relationship between Experimental and Numerical slab stress in bottom fiber at Section B for Load Case 1**

Fig. 6 shows the strut stress at both the upper and lower ends of the strut. In the stress diagram for the lower end, there is no significant difference between the experimental and numerical results across the initial load steps. At any given load step, the difference between the two results does not exceed 9%. For the stress at the upper end of the strut, a similar trend is observed in both the experimental and numerical results across the initial load steps. However, there is an occurrence of a notable jump in the experimental results at the load step of 230 kN. This discrepancy is attributed to the formation of cracks in the slab near the upper end of the strut, which influenced the experimental results at this load step.

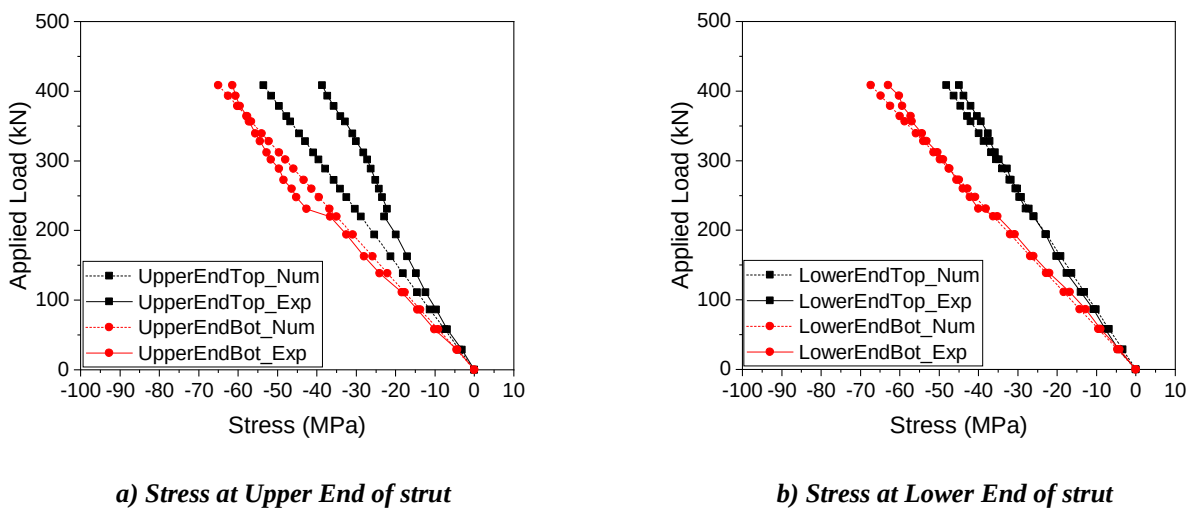


**Fig. 6 – Comparison between Experimental and Numerical results in Load Case 3**

Fig. 7 illustrates the relationship between the experimental and FEM data for strut stress in Load Case 3. Like the deflection comparison results, a strong linear correlation was observed in the strut stress data with a minimum correlation

coefficient of 0.98. This high correlation demonstrates the reliability of the FEM in conducting transverse analysis of the girder.

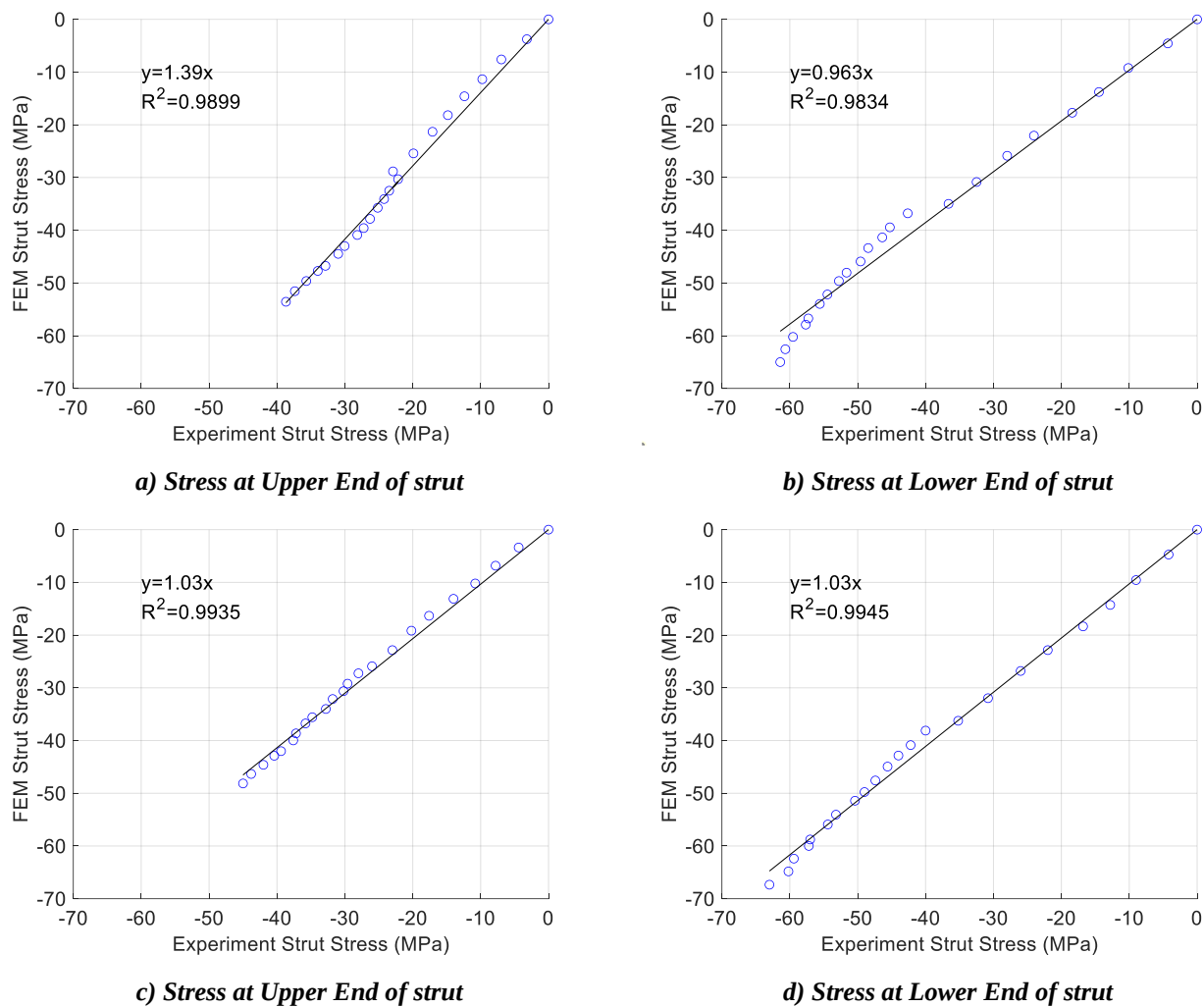
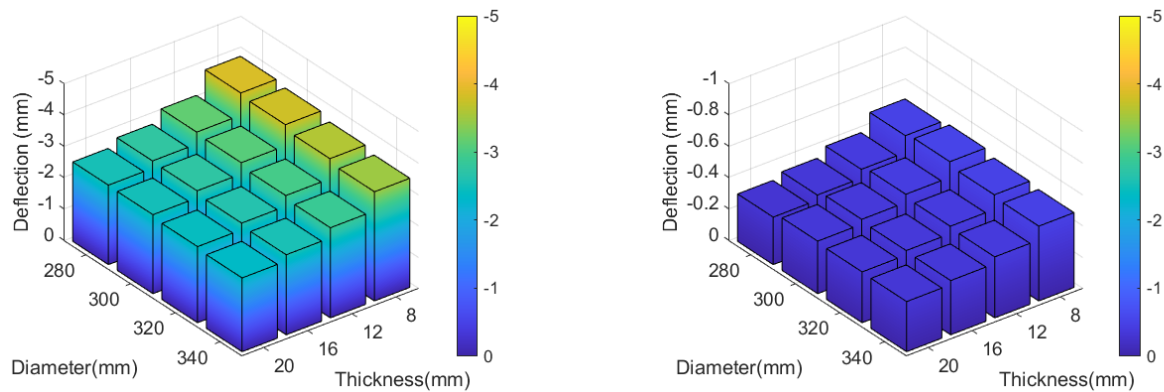


**Fig. 7 – Experimental and Numerical stress of strut relationship for Load Case 3**

#### 4 Influence of Strut Dimension on Girder Behavior

To optimize the dimensions of steel struts in bridge design, two parameters- diameter, and thickness- were independently analyzed. The strut diameter was investigated at four increments: 280 mm, 300 mm, 320 mm, and 340 mm, while the strut thickness was studied at four values: 8 mm, 12 mm, 16 mm, and 20 mm. To assess the influence of these parameters on girder behavior, deflection and stress values for both the slab and struts were analyzed under three load cases, each subjected to 100% of the calculated additional load at the Service Limit States. Deflection and stress at the tip of the wing slab were studied only for Load Case 1 and Load Case 2, while strut stress was evaluated across all three load cases.

Fig. 8 illustrates the deflection of the concrete girder at the tip of the wing slab (D4) with varying strut diameters and thicknesses for Load Case 1 and Load Case 2. The results show that the effect of strut dimensions is more pronounced in Load Case 1 (corresponding to the highest positive moment in the slab), while their influence in Load Case 2 (corresponding to the highest negative moment in the slab) is negligible. Consequently, in this paper, only the deflection of the girder in Load Case 1 was analyzed to evaluate the impact of strut dimensions on girder behavior. The findings indicate that the deflection at D4 increases as either the strut diameter or thickness decreases. Notably, the increase in deflection is more significant when reducing thickness compared to diameter, as detailed in Table 3.



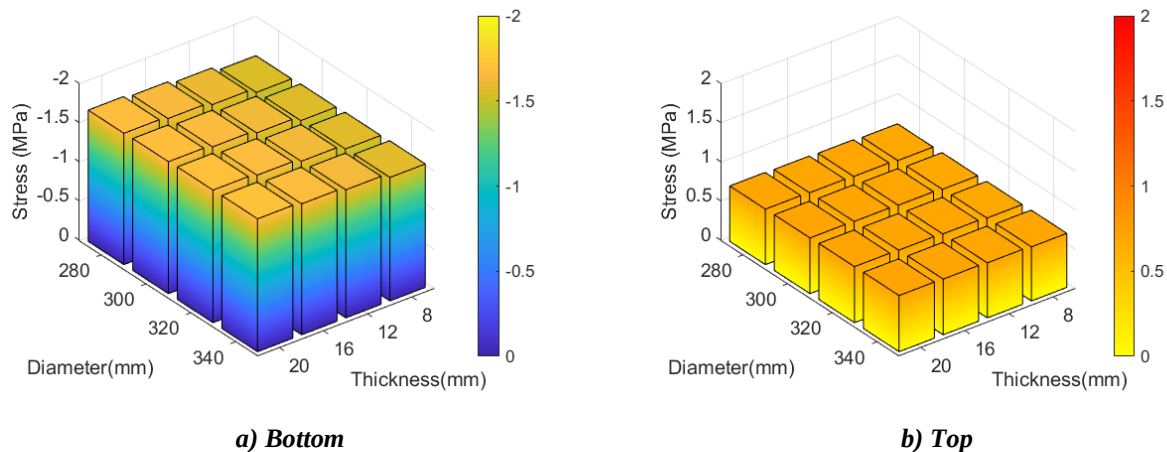
a) Deflection at D4 in Load case 1

b) Deflection at D4 in Load case 2

Fig. 8 – Deflection at tip of wing slab (D4) for Load Case 1 and 2

Table 3 - The difference in deflection

| The difference in deflection when increasing thickness (%)<br>(compared with the deflection at 8mm of thickness) |   |      |      |      | The difference in deflection when increasing diameter (%)<br>(compared with the deflection at 280mm of diameter) |     |     |     |      |
|------------------------------------------------------------------------------------------------------------------|---|------|------|------|------------------------------------------------------------------------------------------------------------------|-----|-----|-----|------|
|                                                                                                                  | 8 | 12   | 16   | 20   |                                                                                                                  | 280 | 300 | 320 | 360  |
| 280                                                                                                              | 0 | 22.5 | 39.2 | 52.1 | 8                                                                                                                | 0   | 2.2 | 6.7 | 10.7 |
| 300                                                                                                              | 0 | 21.7 | 37.6 | 49.7 | 12                                                                                                               | 0   | 1.6 | 5.8 | 9.5  |
| 320                                                                                                              | 0 | 21.5 | 37.1 | 48.9 | 16                                                                                                               | 0   | 1.0 | 5.0 | 8.5  |
| 340                                                                                                              | 0 | 21.2 | 36.5 | 48.0 | 20                                                                                                               | 0   | 0.6 | 4.5 | 7.7  |



a) Bottom

b) Top

Fig. 9 – Stress in Slab for Load Case 1

Fig. 9 shows the slab stress at the location corresponding to the highest negative moment (Section B in Fig. 1) for Load Case 1. In general, the slab stress tends to increase with the diameter or thickness of the steel strut; however, the variation is negligible. The maximum stress difference caused by an increase in diameter is 5%, while changes in thickness lead to a maximum difference of only 2%. This slight upward trend can be attributed to the increased stiffness of the struts with larger dimensions, leading to higher moments in the steel struts as well as in the slab section near the strut ends.

A similar trend is observed for slab stress at the location corresponding to the highest positive moment (Section A in Fig. 1) for Load Case 2 when varying strut thickness, as shown in Fig. 10. For changes in strut diameter, slab stress initially increases slightly as the diameter grows from 280 mm to 300 mm, but then gradually decreases with further increases in

diameter. Despite these variations, the stress values remain significantly lower than the allowable concrete stress under the Service Limit State according to the 22TCN 272-05 Standard (18 MPa for compression and 3.35 MPa for tension) [22]. Hence, changes in the diameter and thickness of the struts have a minimal impact on stress variations in the deck slab. This finding aligns with the results reported in Shushkewich's study, which demonstrated that the presence of struts has minimal influence on the bending moment and axial force in the cantilever flange section under vehicle live loading [7].

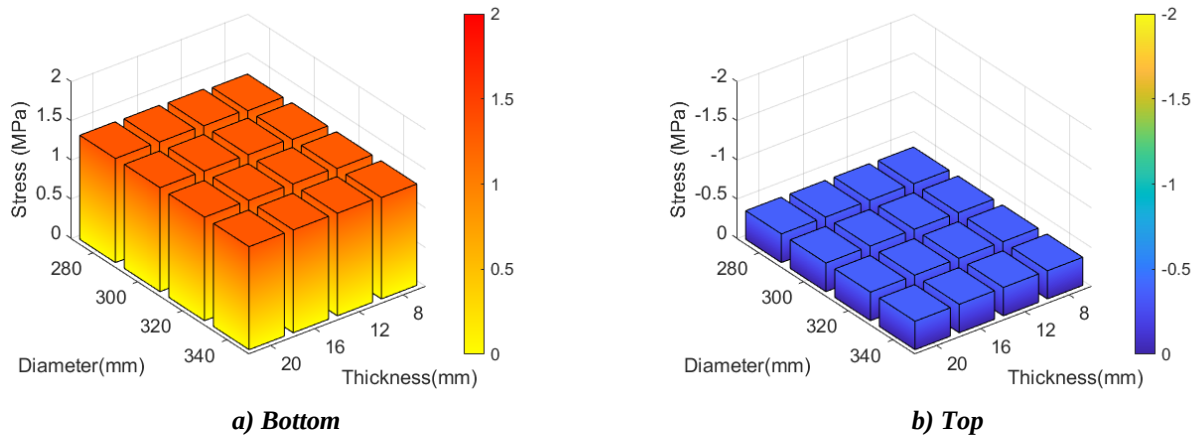


**Fig. 10 – Stress in Slab for Load Case 2**

Since the stress in the strut for Load Case 2 is minimal compared to the other two load cases, this paper focuses on analyzing the effect of strut dimensions on stress variation in the struts for Load Case 1 and Load Case 3. Fig. 11 and Fig. 12 illustrate the stress in the steel struts when the strut parameters are varied.

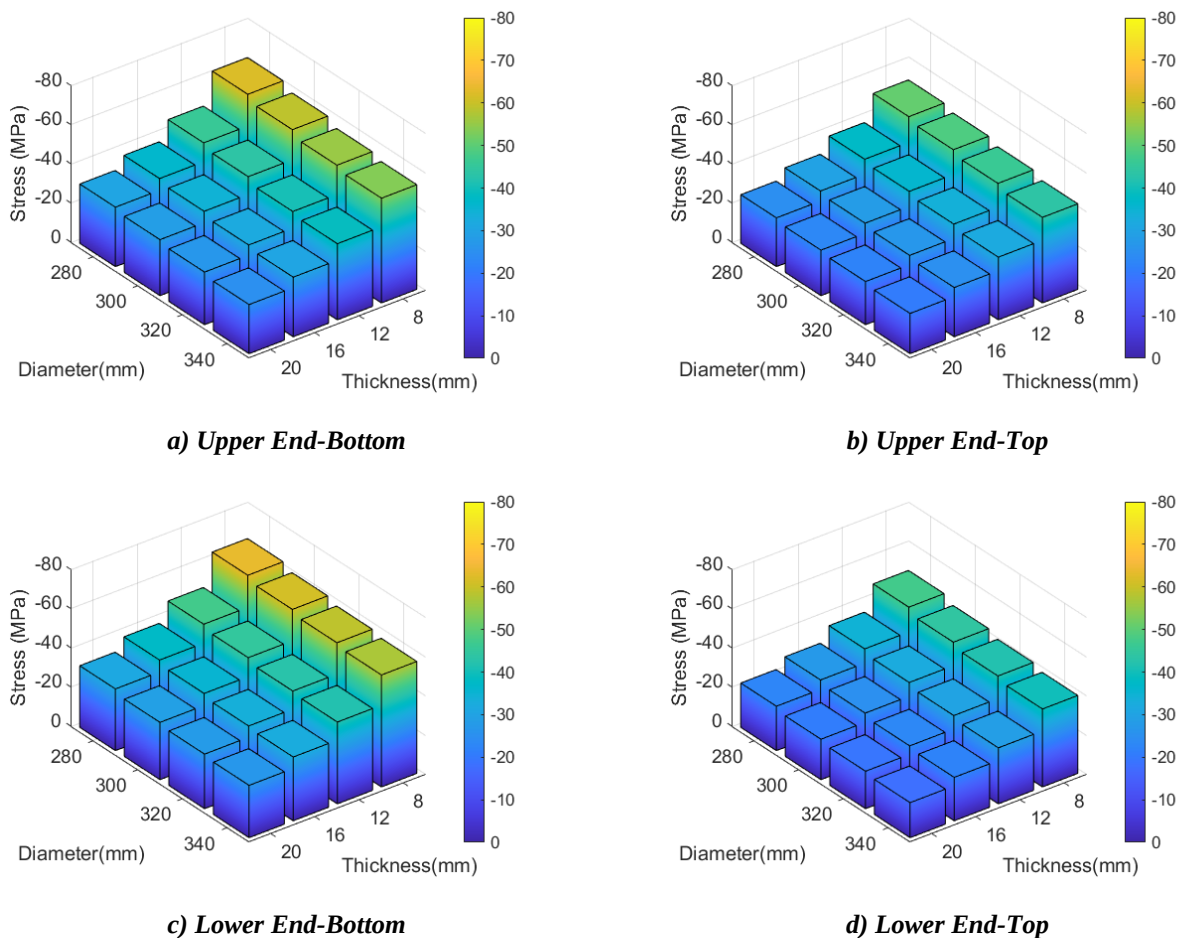


**Fig. 11 – Stress in Steel Strut for Load Case 1**

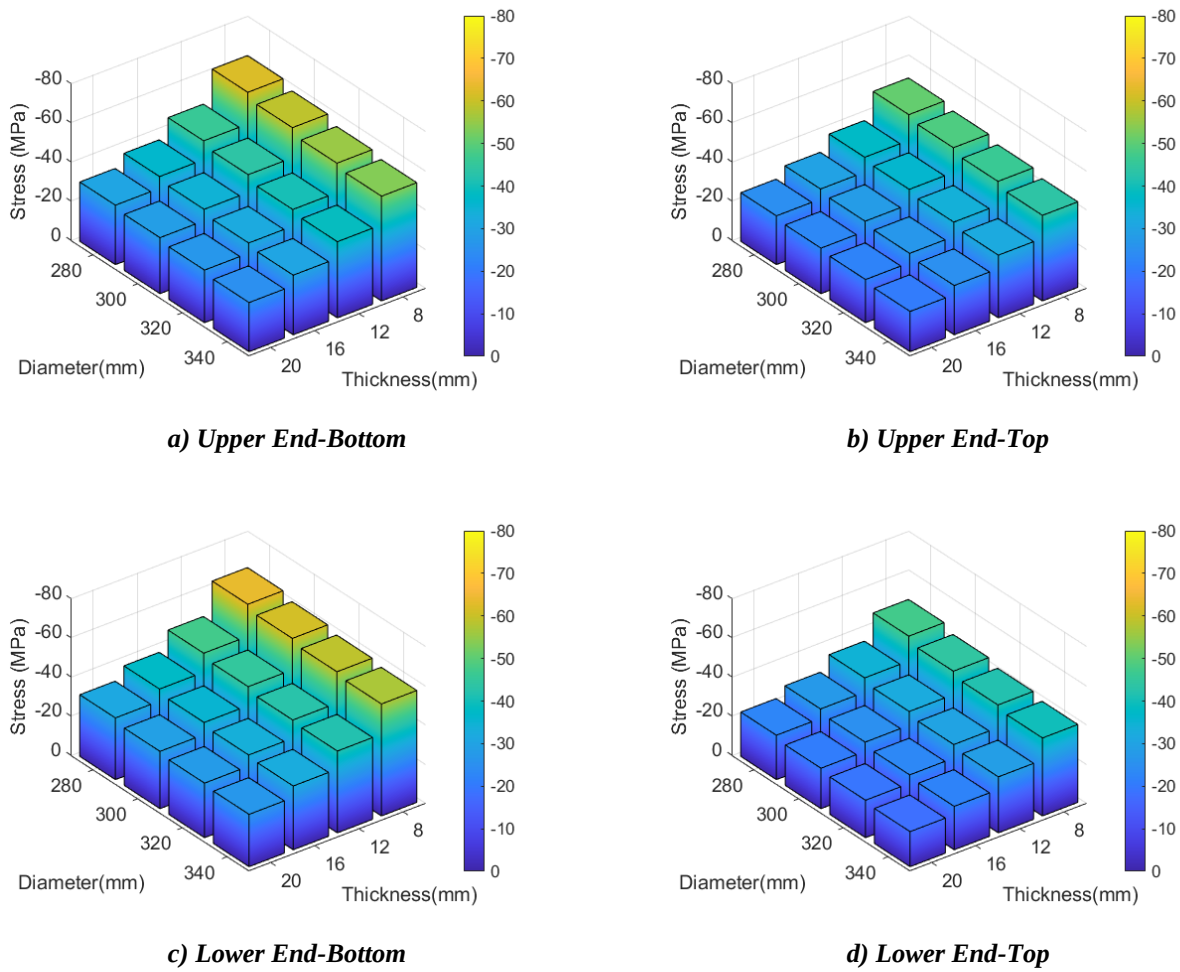


**Fig. 12 – Stress in Steel Strut for Load Case 3**

The results indicate that the stress in the struts increases as either the thickness or diameter of the steel struts decreases. Similar to the observed changes in slab deflection, this effect is more pronounced when reducing the thickness compared to decreasing the diameter. Notably, although the compressive stress in the steel strut more than doubles when the thickness is reduced from 20 mm to 8 mm, these stresses remain significantly lower than the allowable stress for steel material.

The changes in slab deflection and stress, as well as the stress in the strut, can be attributed to changes in the geometric characteristics of the strut. Increasing the diameter or thickness of the strut enhances its stiffness, which leads to a redistribution of internal forces within the structure. This process results in increased moments in the strut and reduced moments in the cantilever wing slab, which in turn causes a decrease in deflection at the tip of the wing slab. Interestingly, despite the rise in internal force within the strut, the stress in the strut decreases. This occurs because the effect of the rising internal force on stress is relatively minor compared to the influence of enhanced geometric characteristics, such as the section modulus and cross-sectional area. This phenomenon is evident when comparing the extent of slab deflection reduction (a maximum reduction of about 52%) to the corresponding reduction in strut stress (a maximum decrease of over 120%) as the dimensions of the strut are increased.

## 5 Conclusions

A finite element model (FEM) was developed and validated against the experimental load test results to investigate the effects of varying strut dimensions on the behavior of the girder. The analysis focused on changes in slab deflection, slab stress, and steel strut stress to inform the optimization of strut dimensions in future designs. Based on the comparative results, the following conclusions were drawn:

- The dimensions of the strut have a significant impact on slab deflection and strut stress, while their effect on slab stress is negligible.
- Reducing the diameter and thickness of the strut results in a notable increase in both strut stress and slab deflection. However, the effect of reducing the thickness is more pronounced than that of reducing the diameter, owing to the larger change in geometric properties (e.g., section modulus, cross-sectional area) associated with altering the strut's thickness compared to its diameter.
- Despite the significant variations in stress and deflection resulting from changes in strut dimensions, the resulting stress values remain well below the allowable limits for the materials used. Therefore, to enhance both the performance and aesthetics of the bridge design, it may be worthwhile to explore adjustments to other geometric parameters, such as strut spacing or slab thickness.

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