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Numerical Evaluation of the Structural Response of a Balsa Wood Truss Bridge under Eccentric Loading Using the Finite Element Method

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Abstract

Eccentric loading is important in bridge design because it can cause asymmetric internal forces and combined bending and torsion. This study evaluates a lightweight balsa wood truss bridge under eccentric loading using the Finite Element Method (FEM). Designed for the 2025 Bridge Design Competition (BDC) at Nanyang Technological University (NTU), the bridge was modeled in SAP2000 with three-dimensional frame elements. Loads of 225, 450, 675, and 900 N were applied two-thirds along the span. Parameters included vertical deflection, axial forces, stress distribution, and structural efficiency, defined as maximum load divided by self-weight. Deflection increased from 0.0580 mm at 225 N to 0.2322 mm at 900 N, showing a linear load–deflection relationship. Differences among main, longitudinal, diagonal, and transverse members reflected their load-transfer contributions. Layered main girders and lateral bracing supported stiffness and stability. In competition, the bridge reportedly sustained 176 N and weighed 18.37 g, producing a load-to-weight ratio of approximately 970–977. These findings demonstrate numerical analysis's value before testing. Experimental validation and torsional assessment remain necessary to confirm predictions and bracing effectiveness.

Keywords Truss Bridge, Eccentric Loading, Finite Element Method, Torsional Behavior, Structural Efficiency

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INTRODUCTION

Bridges are essential infrastructure that supports interregional connectivity, human mobility, and economic activities. Advances in structural engineering have expanded bridge design requirements beyond load-bearing capacity to include material efficiency, stiffness, stability, and the ability to withstand various loading conditions. These demands have encouraged the development of lightweight bridge systems capable of achieving high load-bearing capacity with minimal structural weight. One approach commonly adopted to meet these requirements is the truss bridge system, which utilizes a specific arrangement of structural members to transfer loads efficiently. However, optimizing truss bridge design still requires an assessment of various loading conditions, particularly those involving asymmetrical loading.

One loading condition that requires particular attention is eccentric loading, which occurs when the line of action of a force is offset from a structural reference axis or the shear center. This condition can generate combined bending and torsional responses that affect internal force distribution, deformation, and overall structural stability. In three-dimensional truss bridges, eccentric loading may cause an uneven distribution of axial forces among truss members and increase the tendency for torsional rotation. These effects are particularly significant in lightweight structures with relatively small member dimensions, whose performance depends heavily on truss configuration and lateral bracing systems. Therefore, analyzing the effects of eccentric loading is necessary to understand structural behavior and identify member configurations capable of maintaining stiffness and stability without excessively increasing structural weight.

Advances in numerical methods have created opportunities to evaluate bridge structural behavior in greater detail. One widely used approach is the Finite Element Method (FEM), which enables the analysis of displacement, axial forces, bending moments, and torsional responses through three-dimensional structural modeling. The use of three-dimensional frame elements allows interactions among different force components to be considered simultaneously, providing a more comprehensive understanding of structural behavior under asymmetric loading. Nevertheless, the accuracy of the analysis depends on material assumptions, support conditions, joint representation, and the extent to which the numerical model corresponds to the actual structure.

Several previous studies have provided a foundation for understanding bridge behavior under complex loading conditions. First, Yoganata et al. (2025) investigated the design and testing of balsa-wood truss bridges under variations in concentrated loading. Their study combined numerical analysis and experimental testing to evaluate axial forces, bending moments, and the load-bearing capacity of bridge models. The test results showed that a model weighing 25.91 grams could withstand a load of 30.90 kg, with a reported load-to-weight ratio of 1,161.327. These findings demonstrate the potential of balsa wood as a material for lightweight bridge models and highlight the importance of evaluating the relationship between load-bearing capacity and structural weight. However, the study primarily focused on variations in truss weight and concentrated loading rather than the effects of eccentricity on torsional response.

Second, Zhang et al. (2018) investigated the torsional behavior of a space-truss bridge constructed from fiber-reinforced polymer (FRP) and aluminum through experimental testing and numerical analysis. Their study developed a three-dimensional finite element model and compared its results with the structural responses obtained from experiments. The findings indicated that FEM could represent the torsional behavior of the structure and help explain load-transfer mechanisms among truss members. This study emphasizes the importance of three-dimensional analysis in evaluating the torsional behavior of lightweight bridges. However, the materials and structural configurations differed from those of the balsa-wood truss bridge model examined in the present study.

Third, Fu et al. (2023) evaluated the three-dimensional truss behavior and load-bearing capacity of railway bridges through load testing and finite element modeling. Their investigation of these bridges indicated that two-dimensional models may overlook out-of-plane bending effects and the contributions of certain structural members to stress distribution. Three-dimensional modeling provides a more representative understanding of member behavior under actual loading conditions. These findings support the use of three-

dimensional modeling to analyze truss bridges, particularly when the load distribution is not entirely symmetrical. Nevertheless, the study focused on railway bridges and their load-bearing capacity rather than lightweight balsa-wood models subjected to specific eccentric loading conditions in bridge design competitions.

Fourth, Lalthlamuana et al. (2014) analyzed the dynamic response of a simply supported bridge subjected to moving vehicle loads along an eccentric path. Their study considered the effects of vehicle-path eccentricity on the bending and torsional responses of the bridge. The results indicated that path eccentricity and the relationship between bending and torsional stiffness played important roles in determining the dynamic response of the structure. These findings demonstrate that load position is an important factor influencing bridge behavior, rather than merely the magnitude of the applied load. However, the study examined dynamic loading on a simply supported bridge, whereas the present research focuses on the static response of a lightweight truss bridge model.

Fifth, Chen et al. (2023) investigated the behavior of a composite box-girder bridge with corrugated steel webs under eccentric loading through experimental testing. Their research examined the effects of eccentric loading on structural behavior and the applicability of torsional theories used in structural analysis. The findings indicated that cross-sectional characteristics and deformation mechanisms must be considered when evaluating structural responses to asymmetric loading. Although relevant to understanding the mechanisms associated with eccentricity, composite box-girder systems exhibit structural characteristics that differ from those of balsa-wood truss bridges. Consequently, the findings do not directly explain axial force distribution and torsional responses in lightweight truss models developed for bridge design competitions.

Based on these previous studies, numerical analysis, three-dimensional modeling, and eccentricity evaluation have been applied to investigate various structural characteristics of bridges. However, the studies differ in their research objects, materials, loading conditions, and evaluation parameters. Research on balsa-wood truss bridges has demonstrated their potential for material efficiency and load-bearing capacity, while studies of space-truss systems and bridge girders have provided insights into torsional behavior and force distribution under asymmetric loading. The research gap lies in the limited integration of structural response evaluation under eccentric loading with structural efficiency assessment in balsa-wood truss bridge models designed for competitions. More specifically, the relationships among applied load, deflection, axial force distribution, indications of torsional response, and load-to-weight efficiency need to be examined within a unified analytical framework.

This study introduces a numerical evaluation that integrates structural behavior and efficiency assessment for a balsa-wood truss bridge model subjected to eccentric loading in the context of the 2025 Bridge Design Competition (BDC) at Nanyang Technological University (NTU). The analysis employs the Finite Element Method through SAP2000, using three-dimensional frame-element modeling and assuming linear elastic material behavior. Static loads of 225 N, 450 N, 675 N, and 900 N are applied incrementally at an eccentric position located at two-thirds of the bridge span. The evaluated parameters include maximum deflection, axial force distribution among truss members, indications of torsional response, and the structural efficiency ratio based on the applied load relative to the structure's self-weight. The novelty of this study lies in integrating these parameters into a single evaluation framework, rather than in the use of FEM or eccentric loading analysis

alone, both of which have been addressed in previous research.

Accordingly, this study aims to analyze the numerical behavior of a balsa-wood truss bridge model designed for the 2025 NTU Bridge Design Competition under eccentric loading conditions. Specifically, the study evaluates the relationship between applied load and deflection, identifies axial force distribution and indications of torsional response, and assesses structural efficiency based on the ratio of maximum load to the bridge's self-weight. The findings are expected to provide insights into the effects of asymmetric loading on the performance of lightweight truss bridges and to inform the development of more stable and efficient truss configurations and bracing systems.

METHODS

The structural model was developed using SAP2000 based on the Finite Element Method (FEM), with the bridge members represented as three-dimensional frame elements capable of simultaneously capturing axial, bending, and torsional behavior. The balsa wood was assumed to be homogeneous, isotropic, and linearly elastic, with an elastic modulus of approximately 3,000–4,000 MPa, a Poisson's ratio of 0.3, and an average density based on the competition material specifications. The cross-sectional dimensions of the members followed the actual balsa wood dimensions of 3/16 × 3/16 inches. The bridge model had a span of 310 mm, a width of 52 mm, and a height of 60 mm, with a loading plate measuring 49 × 55 mm. The connections between truss members were assumed to be pinned, except for elements designed as lateral bracing. The boundary conditions consisted of a pin support and a roller support to prevent overconstraint while maintaining structural stability. The main girders were constructed using two layers of balsa wood to improve resistance to eccentric loading and torsional effects, while transverse girders and upper lateral bracing were incorporated to enhance overall stiffness and structural stability.

Static loading was applied incrementally at magnitudes of 225 N, 450 N, 675 N, and 900 N. The load was positioned eccentrically at two-thirds of the bridge span, following the loading configuration specified for the 2025 Bridge Design Competition (BDC) at Nanyang Technological University (NTU). The load was modeled as a concentrated force applied to the loading plate and subsequently transferred to the truss joints. This eccentric loading configuration was intended to represent the combined effects of vertical bending, axial tension and compression, and torsion. A linear static analysis was performed to evaluate the structural response under each loading condition. The assessment focused on maximum vertical displacement, axial force distribution among truss members, overall deformation patterns, and indications of torsional response resulting from load eccentricity.

The analysis procedure comprised seven stages: developing the bridge geometry according to the actual design, defining material and cross-sectional properties, establishing boundary conditions, applying incremental eccentric loads, executing the linear static analysis, extracting displacement and internal force data, and evaluating the load–deflection relationship. Maximum vertical displacement was examined at the midspan and along the side subjected to eccentric loading to identify potential torsional rotation. The load–deflection relationship was further evaluated using linear regression to characterize the elastic response of the structure. The resulting numerical data were used to assess the bridge's stiffness, internal force distribution, and structural behavior under asymmetric loading conditions.

RESULTS AND DISCUSSION

Results

Results of Bridge Structural Modeling

The bridge structure was modeled using SAP2000 based on the Finite Element Method (FEM). The model was developed according to the bridge geometry designed for the 2025 Bridge Design Competition (BDC) at Nanyang Technological University (NTU). Each truss member was assigned an identification code to facilitate the interpretation of internal forces and the structural response of individual members under loading. The three-dimensional model employed a pin–roller support system and consisted of main girders, longitudinal girders, diagonal members, transverse girders, and lateral bracing.

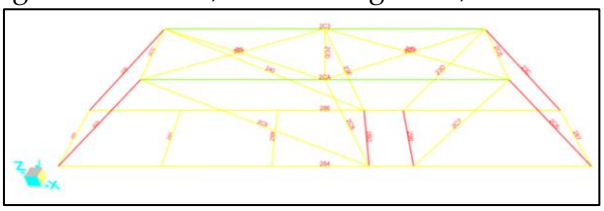


Figure 1. Member identification codes in the bridge model.

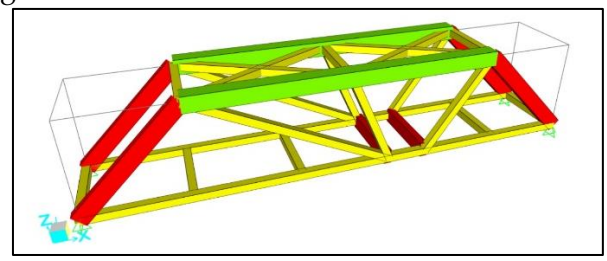


Figure 2. Three-dimensional bridge model with support conditions.

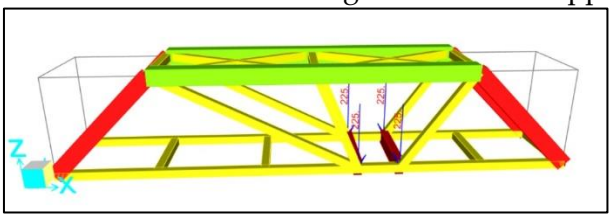


Figure 3. Eccentric loading configuration of the bridge.

The model dimensions and loading parameters used in the analysis are presented in Table 1.

Table 1. Model dimensions and loading variations

Parameter	Value
Bridge span	310 mm
Bridge width	52 mm
Bridge height	60 mm
Balsa wood cross-sectional dimensions	3/16 × 3/16 in
Loading plate dimensions	49 × 55 mm
Loading position	Two-thirds of the span
Load, Stage 1	225 N
Load, Stage 2	450 N

Load, Stage 3	675 N
Load, Stage 4	900 N

Note: The table presents the bridge model dimensions and the static loading variations used in the SAP2000 simulation.

Deflection Analysis Results

The SAP2000 simulation results show changes in vertical deflection as the eccentric load increases. The maximum deflection values obtained for each loading variation are presented in Table 2.

Table 2. Applied loads and maximum deflection

Load (N)	**Maximum deflection (mm)**
225	0.0580
450	0.1161
675	0.1742
900	0.2322

Note: The data represent the maximum deflection obtained from the SAP2000 simulation for each loading variation.



Figure 4. Bridge deflection under a 225 N load.



Figure 5. Bridge deflection under a 450 N load.

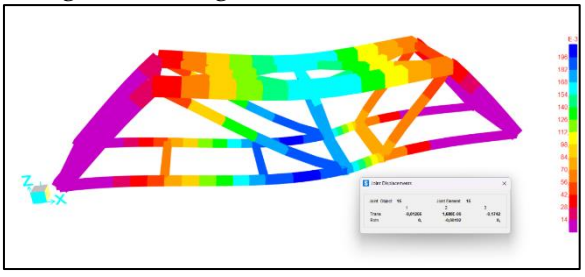


Figure 6. Bridge deflection under a 675 N load.

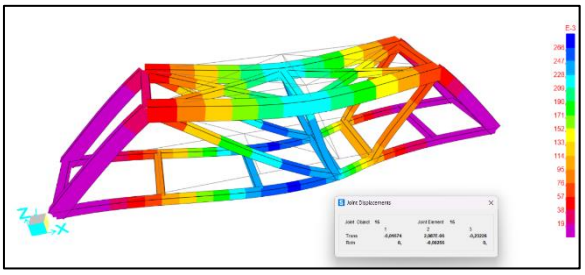


Figure 7. Bridge deflection under a 900 N load.

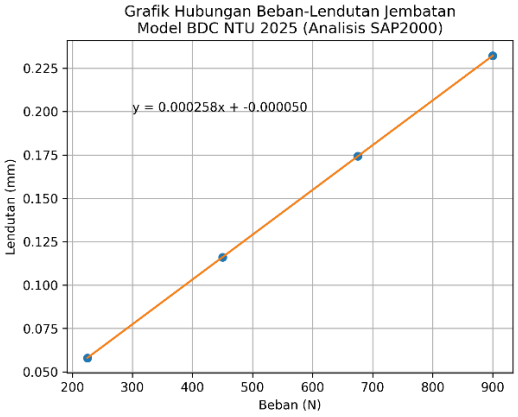


Figure 8. Load–deflection relationship

Based on the data in Table 2, the maximum deflection increased from 0.0580 mm under a 225 N load to 0.2322 mm under a 900 N load. This pattern indicates a generally linear relationship between the applied load and deflection over the loading range considered.

Axial Force and Stress Analysis Results

The axial force and stress results were classified according to the structural functions of the members, namely the main girders, longitudinal girders, diagonal members, and transverse girders. This classification facilitates the identification of internal force distributions within each structural component.

Table 3. Axial forces in the main girders

Member code	Axial force, \(P_u\) (kN)
2C5	-0.246
2CA	-0.423
2C6	-0.405
238	-0.246
2C3	-0.423
23C	-0.405

Note: Negative values follow the sign convention used in the analysis output. Their interpretation as compressive or tensile forces should be verified against the SAP2000 sign convention.

Table 4. Stresses in the main girders

Member code	Stress, \(\sigma\) (MPa)	Reported ratio	Reported assessment
2C5	-14.92	-0.014	Safe
2CA	-15.25	-0.015	Safe
2C6	-15.24	-0.015	Safe

238	-14.92	-0.014	Safe
2C3	-15.43	-0.015	Safe
23C	-15.24	-0.015	Safe

Note: Stress values and safety assessments are presented as reported. The validity of the ratios relative to the allowable stress requires further verification.

Table 5. Axial forces in the longitudinal girders

Member code	Axial force, \(P_u\) (kN)
284	0.242
286	0.242

Note: Both longitudinal girder members have identical reported axial force values.

Table 6. Stresses in the longitudinal girders

Member code	Stress, \(\sigma\) (MPa)	Reported ratio	Reported assessment
284	30.91	0.030	Safe
286	30.91	0.030	Safe

Note: Both members have a reported stress value of 30.91 MPa.

Table 7. Axial forces in the diagonal members

Member code	Axial force, \(P_u\) (kN)
2C7	0.324
2C8	0.048
2C9	0.323
240	0.323
23F	0.048
23D	0.324

Note: The axial forces in the diagonal members range from 0.048 kN to 0.324 kN.

Table 8. Stresses in the diagonal members

Member code	Stress, \(\sigma\) (MPa)	Reported ratio	Reported assessment
2C7	28.81	0.028	Safe
2C8	14.02	0.014	Safe
2C9	21.80	0.021	Safe
240	21.80	0.021	Safe
23F	14.02	0.014	Safe
23D	28.81	0.028	Safe

Note: Based on the reported data, the stresses in the diagonal members range from 14.02 MPa to 28.81 MPa.

Table 9. Axial forces in the transverse girders

Member code	Axial force, \(P_u\) (kN)
285	0
287	0
296	0.00008361
297	0.00001296
299	-0.000002909

2B0	-0.0001154
2CC	0.033
2CD	0.065
2CE	0.034

Note: The axial forces in the transverse girders vary, with the highest value of 0.065 kN occurring in member 2CD.

Table 10. Stresses in the transverse girders

Member code	Stress, \(\sigma\) (MPa)	Reported ratio	Reported assessment
285	0.4000	0.000040	Safe
287	0.0460	0.000046	Safe
296	0.0290	0.000029	Safe
297	0.0083	0.000008359	Safe
299	-0.0016	-0.000001601	Safe
2B0	-0.0054	-0.000005481	Safe
2CC	1.4600	0.001467	Safe
2CD	3.2700	0.003277	Safe
2CE	1.5100	0.001514	Safe

Note: The data show variations in stress among the transverse girders. The reported ratios and allowable stresses should be verified before they are used as the basis for safety assessments.

Structural Efficiency Results

Structural efficiency was calculated using the ratio of the maximum load sustained by the bridge to its self-weight. The maximum competition load and bridge weight are presented in Table 11.

Table 11. Data for calculating bridge efficiency

Parameter	Value
Maximum load in the competition	176 N
Equivalent load mass	17.94 kg
Reported bridge mass	18.37 g
Reported efficiency ratio	970

Note: The efficiency ratio is calculated by dividing the maximum load mass, expressed in grams, by the bridge mass in grams, using the reported values.

The efficiency ratio is expressed as:

$$\mu=\frac{P_{\max}}{W}$$

When calculated using mass values, the equation is applied as follows:

$$\mu=\frac{m_{\text{load}}}{m_{\text{bridge}}}$$

Using a load mass of 17,940 g and a bridge mass of 18.37 g, the calculated ratio is approximately 976.59. Therefore, the reported value of 970 represents an approximate figure that should be reconciled with the original measurement data and rounding procedure.

Discussion

Load–Deflection Behavior and Structural Stiffness

The simulation results demonstrate an increase in deflection as the eccentric load increases. Under a load of 225 N, the maximum deflection was 0.0580 mm, whereas under a load of 900 N, it reached 0.2322 mm. In general, a fourfold increase in the applied load resulted in approximately a fourfold increase in deflection. This pattern is consistent with linear elastic behavior, in which structural displacement is proportional to the applied load as long as the system stiffness remains constant. Theoretically, this relationship can be explained using the structural stiffness equation: $$\{F\}=[K]\{u\}$$ where $\{F\}$ is the force vector, $[K]$ is the global stiffness matrix, and $\{u\}$ is the nodal displacement vector. In linear analysis, the stiffness matrix is assumed to remain constant, meaning that changes in the applied load produce proportional changes in displacement. This finding supports the interpretation that the model exhibits elastic behavior within the simulated loading range. However, numerical linearity alone does not demonstrate that the actual structure is free from buckling, connection failure, or material failure.

Given a bridge span of 310 mm and a maximum deflection of 0.2322 mm, the span-to-deflection ratio can be calculated as follows: $$\frac{L}{\delta} =\frac{310}{0.2322} \approx 1335$$. This value indicates relatively small deflection compared with the span in the numerical model. Nevertheless, determining whether this stiffness satisfies design criteria requires consideration of applicable deflection limits, support conditions, and the characteristics of the analyzed model. The span-to-deflection ratio cannot be used as the sole basis for declaring the structure safe.

This finding is conceptually consistent with numerical bridge studies that employ FEM to evaluate the relationship between applied loads and structural deformation. However, quantitative comparisons with previous research require comparable materials, dimensions, boundary conditions, and loading configurations. Therefore, the present result is more appropriately interpreted as evidence of a linear numerical response under the specified simulation conditions, rather than as universal evidence that all lightweight truss bridges exhibit similar behavior.

3.2.2. Axial Force and Stress Distribution in Truss Members

The analysis results reveal differences in axial forces among the main girders, longitudinal girders, diagonal members, and transverse girders. The reported axial forces in the main girders range from -0.246 kN to -0.423 kN. In contrast, the longitudinal girders each exhibit an axial force of 0.242 kN. The diagonal members exhibit axial forces ranging from 0.048 kN to 0.324 kN, while some transverse girders experience relatively small axial forces. These differences indicate that each group of structural members contributes differently to transferring loads toward the supports. Theoretically, truss members carry axial forces arising from force equilibrium at the joints, while three-dimensional configurations allow the distribution of forces to be influenced by load position and the relative stiffness of individual members. Under eccentric loading, an asymmetric load distribution may increase the forces in certain members while reducing those in others. However, the magnitude of the eccentricity effect must be established by comparing concentric and eccentric loading results for the same structural model.

The stress data show that the main girders experience negative stresses with magnitudes of approximately 14.92–15.43 MPa. The longitudinal girders exhibit a stress of 30.91 MPa, while the stresses in the diagonal members range from 14.02 MPa to 28.81 MPa.

The reported stresses in the transverse girders are considerably lower than those in the other member groups. These differences suggest that the main girders, longitudinal girders, and diagonal members carry a substantial proportion of the internal forces within the model.

Nevertheless, stress values alone are insufficient to determine the safety of individual balsa-wood members. The assessment must account for tensile and compressive strength parallel to the grain, the possibility of buckling in compression members, member slenderness, and connection capacity. In addition, positive and negative signs must be interpreted according to the SAP2000 output convention. Because the reported stress ratios are not fully consistent with the stress values expressed in MPa, the safety classifications in the tables should be regarded as preliminary and require verification. Conceptually, these findings are related to studies of three-dimensional truss structures demonstrating that geometry, member stiffness, and loading conditions influence internal force distribution. However, conclusions regarding force redistribution or concentration caused by eccentricity can only be established more definitively when a concentric loading comparison is available or when forces in the loaded side of the bridge are compared with those in the opposite side.

Effects of Eccentric Loading on Torsional Response

Eccentric loading can mechanically generate a moment due to the distance between the load's line of action and the structural reference axis. This moment can be expressed in a simplified form as: $$T=Fe$$ where T is the moment generated by eccentricity, F is the applied force, and e is the eccentricity distance relative to the relevant axis. In a three-dimensional bridge model, this effect can interact with vertical bending responses and axial forces in the truss members.

The bridge configuration, which incorporates layered main girders, transverse girders, and lateral bracing, can theoretically improve lateral stiffness and help control deformation under asymmetric loading. Layered main girders may increase the stiffness of the primary structural members, while transverse girders and lateral bracing connect different parts of the structure to promote more stable integrated behavior. However, the available vertical deflection and axial force distribution data are insufficient to quantitatively demonstrate that torsional response has increased or been successfully reduced. Such a demonstration requires displacement data from both sides of the bridge, rotation about the longitudinal axis, or a comparison between models with and without lateral bracing. Therefore, torsional effects in this study should be described as a relevant structural mechanism that requires evaluation using specific indicators, rather than as a response that has already been directly quantified.

This discussion is conceptually consistent with Lalthlamuana et al. (2014), who highlighted the importance of eccentric load positioning in determining bridge structural response. Research on the torsional behavior of space-truss bridges by Zhang et al. (2018) is also relevant in explaining the need for three-dimensional models to represent interactions among structural members. Nevertheless, differences in materials, structural scale, and loading types limit direct comparisons between those studies and the balsa-wood bridge model used in the 2025 NTU BDC.

Structural Efficiency and Design Implications

According to the competition data, the bridge model had a mass of 18.37 g and sustained a reported maximum load of 176 N, equivalent to a load mass of approximately 17.94 kg under standard gravitational conditions. Based on these values, the load-to-bridge-mass ratio is approximately 976.59. This differs slightly from the reported ratio of 970;

therefore, the final calculation should use the original measurement data and a consistent rounding procedure. The load-to-mass ratio is one of the indicators of efficiency in lightweight bridge design competitions. A high ratio indicates that a structure can sustain a relatively large load compared with the amount of material used. However, this indicator does not capture every aspect of structural performance. A bridge with a high load-to-mass ratio does not necessarily possess high torsional stiffness, uniform force distribution, or adequate resistance to buckling and connection failure.

In this study, the use of layered main girders and lateral bracing represents a design approach that can theoretically improve stiffness and stability. However, the individual contributions of these components to overall efficiency cannot be isolated using the available data. Quantifying their contributions would require comparative analyses of several design configurations with consistent mass measurements, boundary conditions, and loading conditions. These findings are related to the research by Yoganata et al. (2025), which examined load-bearing capacity and mass efficiency in balsa-wood bridge models. Both studies identify the relationship between load-bearing capacity and structural weight as an important consideration in lightweight bridge design. Differences in the resulting efficiency ratios cannot be used directly to conclude that one model is superior, because geometry, testing conditions, material properties, and calculation methods may differ. Therefore, the main contribution of the present study lies in the numerical evaluation of bridge response under eccentric loading, supplemented by efficiency data from competition testing, rather than in claiming that the adopted configuration is more efficient than all previously developed designs.

Synthesis of Findings and Research Contributions

Overall, the findings indicate that the bridge model exhibits a generally linear load–deflection relationship, variations in axial force distribution among different groups of members, and a high load-to-mass ratio based on the competition data. These findings demonstrate that the evaluation of lightweight truss bridges should consider multiple parameters. Deflection characterizes global deformation, axial forces and stresses provide information about internal demands on structural members, and the load-to-mass ratio represents material-use efficiency. The contribution of this study lies in integrating numerical response parameters and efficiency information to evaluate a balsa-wood bridge model designed for a competition. This approach can support preliminary design by identifying members subjected to relatively high internal forces and assessing deformation trends under varying loads. However, the simulation results should still be treated as numerical predictions that depend on the assumptions used in the model. Experimental testing and validation against SAP2000 results are required to determine whether the model accurately represents actual structural behavior, particularly with respect to connections, the anisotropic properties of balsa wood, local buckling, and torsional response.

Accordingly, the findings support the use of finite element analysis as a tool for optimizing lightweight truss bridge design. Nevertheless, claims regarding improved torsional stiffness, the safety of all structural members, and design optimality require additional supporting evidence. This approach ensures that the discussion remains grounded in the available results while identifying relevant directions for further research.

CONCLUSION

Based on the numerical analysis of the bridge model developed for the 2025 Bridge Design Competition (BDC) at Nanyang Technological University (NTU) using SAP2000,

eccentric loading can influence the structural response by introducing asymmetric force distribution and potentially increasing torsional effects and lateral deformation. The analysis revealed that the maximum deflection increased proportionally with the applied load, reaching 0.0580 mm, 0.1161 mm, 0.1742 mm, and 0.2322 mm under loads of 225 N, 450 N, 675 N, and 900 N, respectively. This linear load–deflection relationship indicates that the numerical model exhibited predominantly linear elastic behavior within the investigated loading range.

The axial force results showed variations among the truss members, reflecting differences in their structural roles and the distribution of internal forces under eccentric loading. The structural configuration, incorporating layered main girders, transverse members, and lateral bracing, was designed to improve lateral stiffness and help maintain stability under asymmetric loading. However, the extent to which these components reduce torsional deformation requires further verification through direct torsional measurements or comparative numerical analyses. Therefore, the structural performance should be evaluated not only in terms of vertical deflection but also through axial force distribution, torsional response, and the stability of individual members.

Overall, the application of the Finite Element Method through SAP2000 provides a useful numerical approach for predicting the structural response of lightweight truss bridges subjected to eccentric loading. The results can support preliminary design optimization by identifying deformation patterns and variations in internal forces before physical testing is conducted. Nevertheless, experimental validation is necessary to confirm the accuracy of the numerical model and assess structural behavior under actual loading conditions. Further investigations incorporating direct torsional measurements, connection behavior, and member stability assessments would provide a more comprehensive understanding of the performance and efficiency of lightweight balsa-wood bridge structures.

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