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Optimizing Structural Steel Bridge Design: A Study of Wind Load Analysis Using Staad Pro

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Abstract

In today’s construction industry, time is often valued more than money, and advanced construction techniques are continually evolving to reduce project durations. Steel structural buildings are considered a revolutionary development in modern construction due to their quick erection process. This study aims to assist engineers in selecting the most suitable construction methods based on site conditions and structural requirements. The primary objective is to analyze the impact of load combinations and load cases on steel structures under wind pressure. Additionally, the study seeks to optimize section properties by selecting appropriate steel structure sizes. In this project, the design and analysis of three different steel structure sizes and materials were conducted using STAAD Pro V8i SS6 software. The analysis demonstrates that Load Combination 2 effectively evaluates structural performance under wind pressure by assessing member forces and stresses. Furthermore, the results indicate that different load cases significantly influence internal forces and stresses, providing crucial insights into structural integrity and performance assessment. This study highlights the substantial impact of wind load on structural steel bridge performance, particularly in terms of axial and shear force variations. Through STAAD Pro analysis, optimal section sizes are identified to enhance strength and stability, offering an improved approach for bridge design. Future research should explore material variations and experimental validations to further optimize structural resilience.

Keywords: Steel structure, wind load analysis; Staad Pro; structural optimization; construction efficiency

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1. Introduction

Understanding the impact of wind load on truss steel bridges is crucial for ensuring structural safety and reliability in construction projects. Wind is a significant external force that can exert pressure on bridge structures, potentially leading to deflections or structural failures if not properly accounted for in the design (Divya & Murali, 2021). Engineers must carefully consider various design factors to meet safety standards and codes, which provide guidelines for determining wind loads based on location and geometry (Bhanu Prakash et al., 2021). By studying wind loads, engineers can accurately assess structural components such as truss members and connections, ensuring they are designed and sized appropriately to withstand prevailing wind conditions (Sedovin, 2024).

Moreover, the choice of steel size, material, and grade significantly influences the strength and performance of steel structures. While previous studies have examined the behavior of steel bridges under different parameters, such as the Tacoma Narrows Bridge analyzed by Lin et al. (2022), there remains a gap in the optimization of steel sizes. Often, engineers rely on existing designs without analyzing the steel itself, leading to inefficiencies and potential structural issues. This study aims to address this gap by employing STAAD Pro software to optimize the size and materials of steel structures, ensuring both suitability and cost-effectiveness. By using advanced analytical methods, engineers can enhance the design process and optimize steel structures for maximum efficiency and performance in bridge construction projects.

Wind loads exerted on structures are not static but dynamic and highly fluctuating, posing significant challenges to structural integrity (Yadav & Roy, 2024). The three primary types of structural steel commonly used in steel bridge construction include carbon steel (mild steel), high-strength steel, and heat-treated carbon steel (Goo, 2021). Notably, the choice of material plays a crucial role in structural performance, as evidenced by historical incidents such as the collapse of the Tacoma Narrows Bridge in 1940, which was attributed to aeroelastic flutter exacerbated by carbon steel construction (Huang, 2023). This study aims to evaluate the suitability and economic viability of carbon steel (mild steel) and high-strength steel for steel bridge structures under wind load using STAAD Pro software (Kaaria, 2023).

Steel bridges, characterized by their flexibility, are particularly susceptible to horizontal wind forces. Therefore, it is essential to assess their aerodynamic stability and spatial rigidity, especially for hanging, cable-stayed, and steel beam bridges with spans exceeding 100 meters. The impact of wind-induced forces and vibrations has led to numerous bridge failures globally, underscoring the necessity of designing structures to withstand wind loads, particularly in open areas with minimal barriers (Dharamsi, 2024). Consequently, wind speed tests will be conducted using STAAD Pro software to evaluate the stability of steel bridges under varying wind conditions. In terms of structural design standards, the revised version of the Uniform Building By-Laws (UBBL) incorporated Eurocode to replace British Standards in the construction industry (Looi & Gad, 2022). EN 1993-1-1 (2005) provides guidelines for determining wind actions, catering to land structures and bridges. Additionally, Malaysia's Department of Standards Malaysia has developed the National Annex for wind loading, specifying procedures for determining wind speeds and actions in structural design. Malaysia's tropical climate, characterized by monsoon seasons, further underscores the need for robust bridge designs capable of withstanding environmental pressures (Kurniawan, 2024).

Bridge failures are influenced by various factors, including regional economy, structural type, material selection, and service age (Chen et al., 2020). Steel bridges, in particular, have faced challenges due to historical design limitations and susceptibility to environmental damage, necessitating regular maintenance and inspections to mitigate failure risks (Tang & Huang, 2024). In conclusion, comprehensive research efforts are essential to enhance our understanding of wind effects on steel bridge structures and to inform robust design practices that ensure structural safety and longevity in the face of dynamic environmental conditions.

2. Methodology

2.1 Model Construction

To ensure an accurate analysis of the structural steel bridge, a solid three-dimensional (3D) deformable model was constructed, as a two-dimensional (2D) model was inadequate for capturing the structural complexities. Material consistency was rigorously maintained throughout the modeling process to accurately reflect real-world conditions. The selection of an appropriate element type for the model was guided by the capabilities and considerations inherent to STAAD Pro V8i SS6 software.

The use of a 3D solid model is particularly advantageous for structures with intricate geometry and complex loading conditions, providing a comprehensive understanding of wind load effects on steel bridges. Within STAAD Pro, the structural model was meticulously developed, including the definition of nodes, elements (beams and columns), supports, and connectivity between members.

Furthermore, in this study, the sizes of the steel bridge structures were selected in accordance with BS EN 1993-1-1:2005, as outlined in Table 1. This meticulous approach ensures the robustness and accuracy of the structural model, facilitating a thorough analysis of wind load effects on steel bridge structures. A research flowchart (Figure 1) is provided to illustrate the methodology, outlining the step-by-step process followed in this study.

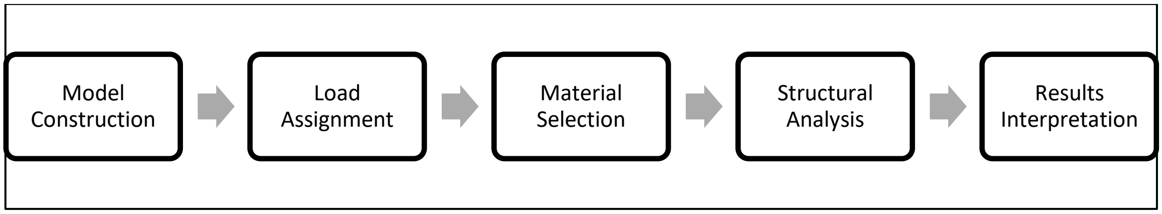


Figure 1. Flowchart

Table 1. The size of steel structure referring to BS EN 1993-1-1:2005

Size (kg/m) Universal Beam (UKB)	Depth of section, h (mm)	Width of section, b (mm)	Area of section, A (cm^2)	Mass per metre (kg/m)
686 x 254 x 125	677.9	253.0	159	125.0
533 x 210 x 122	544.5	211.9	155	122.0
457 x 191 x 82	460.0	191.3	104	82.0

2.2 Load Assignment

The next crucial step involves applying appropriate loads to the structure. In this truss steel bridge design, ten types of loads are considered, including the self-weight of the bridge, the concrete deck, Ha UDL (uniformly distributed load), and the superimposed dead load (SIDL). Additionally, wind loads are applied on both the right and left sides of the bridge, while service limit state (SLS) conditions are evaluated with and without wind load. Similarly, ultimate limit state (ULS) conditions are assessed under scenarios both with and without wind load. The loading analysis, conducted using STAAD Pro, adheres to BS 5400 Part 2 (1978) to ensure accuracy and compliance with engineering standards. Figure 2 illustrates the load cases utilized in designing the truss bridge, while Figure 3 delineates the flow of load combinations assigned to the steel structure, incorporating the appropriate safety factors. These comprehensive load assignments ensure that the structural integrity of the bridge is thoroughly analyzed and optimized, meeting stringent safety and performance standards.

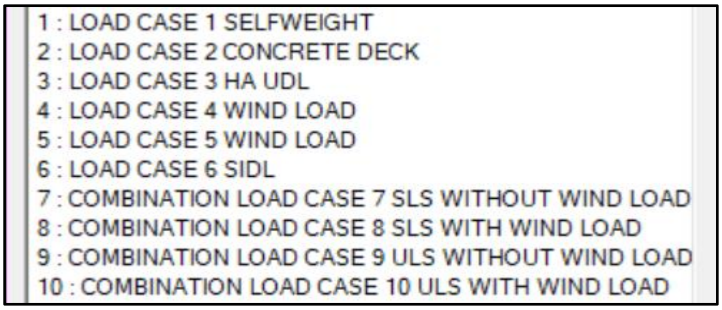
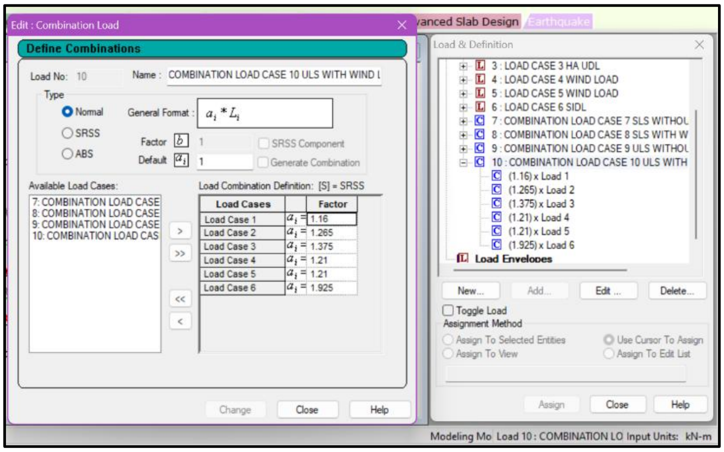

1 : LOAD CASE 1 SELFWEIGHT
2 : LOAD CASE 2 CONCRETE DECK
3 : LOAD CASE 3 HA UDL
4 : LOAD CASE 4 WIND LOAD
5 : LOAD CASE 5 WIND LOAD
6 : LOAD CASE 6 SIDL
7 : COMBINATION LOAD CASE 7 SLS WITHOUT WIND LOAD
8 : COMBINATION LOAD CASE 8 SLS WITH WIND LOAD
9 : COMBINATION LOAD CASE 9 ULS WITHOUT WIND LOAD
10 : COMBINATION LOAD CASE 10 ULS WITH WIND LOAD

Figure 2. Types of load cases



Edit : Combination Load

Define Combinations

Load No: 10
Name : COMBINATION LOAD CASE 10 ULS WITH WIND L
Type: ● Normal ○ SRSS ○ ABS
General Format : $a_i * L_i$
Factor b: 1
Default a_i: 1
☐ SRSS Component
☐ Generate Combination

Available Load Cases:
7: COMBINATION LOAD CASE
8: COMBINATION LOAD CASE
9: COMBINATION LOAD CASE
10: COMBINATION LOAD CAS

Load Combination Definition: [S] = SRSS

Load Cases		Factor
Load Case 1	a_i =	1.16
Load Case 2	a_i =	1.265
Load Case 3	a_i =	1.375
Load Case 4	a_i =	1.21
Load Case 5	a_i =	1.21
Load Case 6	a_i =	1.925

Load & Definition

3 : LOAD CASE 3 HA UDL
4 : LOAD CASE 4 WIND LOAD
5 : LOAD CASE 5 WIND LOAD
6 : LOAD CASE 6 SIDL
7 : COMBINATION LOAD CASE 7 SLS WITHOL
8 : COMBINATION LOAD CASE 8 SLS WITH W
9 : COMBINATION LOAD CASE 9 ULS WITHOL
10 : COMBINATION LOAD CASE 10 ULS WITH
  (1.16) x Load 1
  (1.265) x Load 2
  (1.375) x Load 3
  (1.21) x Load 4
  (1.21) x Load 5
  (1.925) x Load 6
Load Envelopes

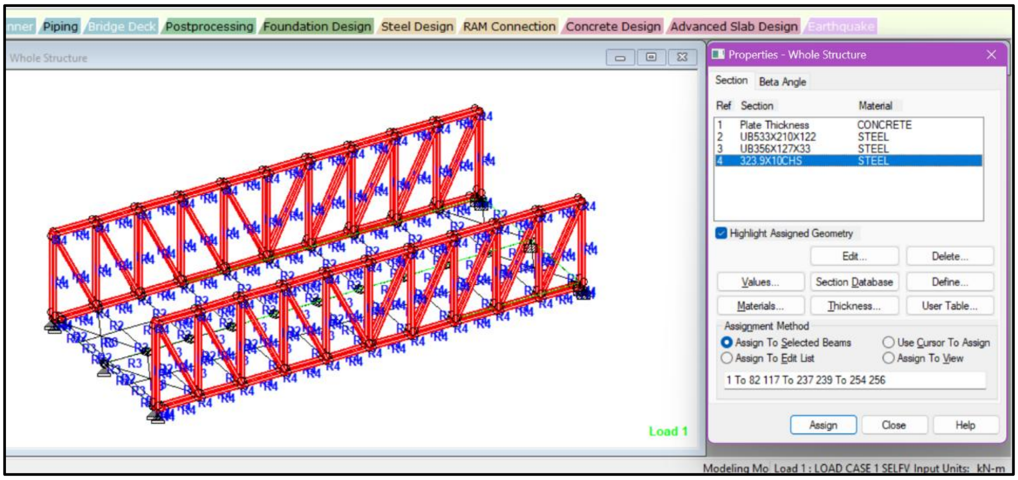
☐ Toggle Load
Assignment Method: ○ Assign To Selected Entities ● Use Cursor To Assign ○ Assign To View ○ Assign To Edit List

Modeling Mo Load 10 : COMBINATION LO Input Units: kN-m

Figure 3. Load definition and factor of safety

2.3 Material Properties

This section meticulously defines the essential properties of the steel beam and truss. The design process involves selecting three distinct steel beam sizes, each with unique material properties to meet structural requirements. Simultaneously, the truss design incorporates a circular hollow section, with the steel shape designated as Cold-Formed Steel (CFS). Figure 4 illustrates the material properties assigned to the steel bridge, highlighting critical parameters essential for ensuring structural integrity and optimizing performance.



Properties - Whole Structure

Ref	Section	Material
1	Plate Thickness	CONCRETE
2	UB533X210X122	STEEL
3	UB356X127X33	STEEL
4	323.9X10CHS	STEEL

☑ Highlight Assigned Geometry

Assignment Method: ● Assign To Selected Beams ○ Use Cursor To Assign ○ Assign To Edit List ○ Assign To View

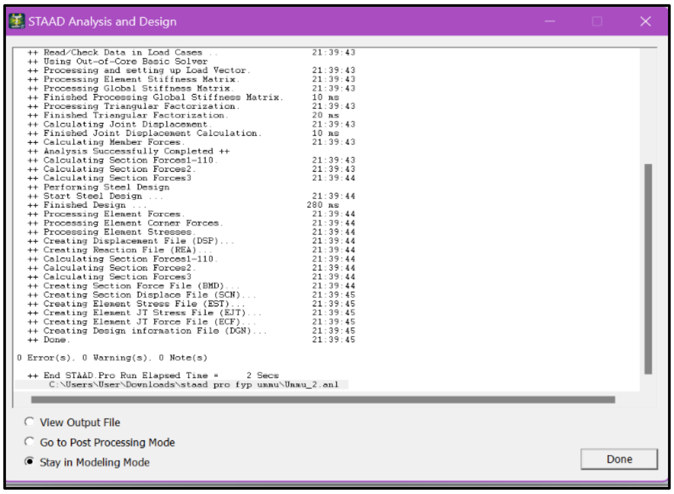
1 To 82 117 To 237 239 To 254 256

Modeling Mo Load 1 : LOAD CASE 1 SELFV Input Units: kN-m

Figure 4. Material properties

2.4 Design Analysis

Subsequently, the structural analysis is performed using STAAD Pro software, utilizing the defined loads, material properties, and design parameters. Through rigorous computational algorithms, the software accurately calculates essential structural parameters, including member forces, member stresses, reactions, deflections, and other critical variables. Figure 5 visually illustrates the data analysis process conducted within STAAD Pro, offering insights into the complex computations and assessments necessary to evaluate the structural integrity and performance of the steel bridge.



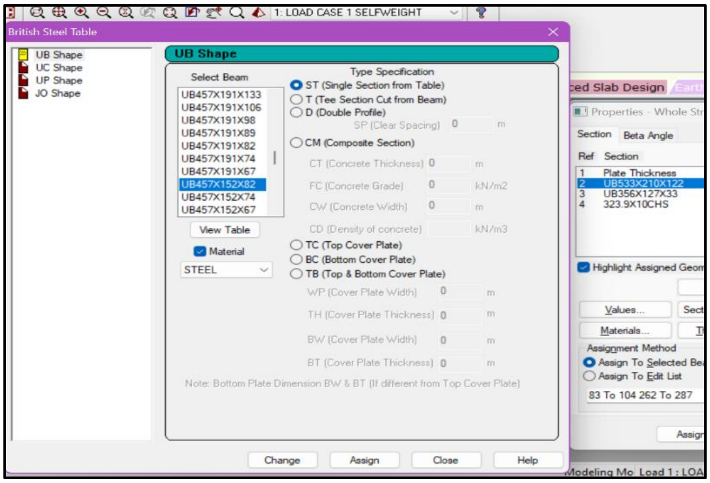
```
  ++ Read/Check Data in Load Cases ..                21:39:43
  ++ Using Out-of-Core Basic Solver
  ++ Processing and setting up Load Vector.          21:39:43
  ++ Processing Element Stiffness Matrix.            21:39:43
  ++ Processing Global Stiffness Matrix.             21:39:43
  ++ Finished Processing Global Stiffness Matrix.    10 ms
  ++ Processing Triangular Factorization.            21:39:43
  ++ Finished Triangular Factorization.              20 ms
  ++ Calculating Joint Displacement.                 21:39:43
  ++ Finished Joint Displacement Calculation.        10 ms
  ++ Calculating Member Forces.                      21:39:43
  ++ Analysis Successfully Completed ++
  ++ Calculating Section Forces1-110.                21:39:43
  ++ Calculating Section Forces2.                    21:39:43
  ++ Calculating Section Forces3                     21:39:44
  ++ Performing Steel Design
  ++ Start Steel Design ...                          21:39:44
  ++ Finished Design ...                            280 ms
  ++ Processing Element Forces.                      21:39:44
  ++ Processing Element Corner Forces.               21:39:44
  ++ Processing Element Stresses.                    21:39:44
  ++ Creating Displacement File (DSP)...             21:39:44
  ++ Creating Reaction File (REA)...                 21:39:44
  ++ Calculating Section Forces1-110.                21:39:44
  ++ Calculating Section Forces2.                    21:39:44
  ++ Calculating Section Forces3                     21:39:44
  ++ Creating Section Force File (BMD)...            21:39:44
  ++ Creating Section Displace File (SCN)...         21:39:45
  ++ Creating Element Stress File (EST)...           21:39:45
  ++ Creating Element JT Stress File (EJT)...        21:39:45
  ++ Creating Element JT Force File (ECF)...         21:39:45
  ++ Creating Design information File (DGN)...       21:39:45
  ++ Done.                                           21:39:45

0 Error(s). 0 Warning(s). 0 Note(s)

  ++ End STAAD.Pro Run Elapsed Time =     2 Secs
       C:\Users\User\Downloads\staad pro fyp ummu\Ummu_2.anl
```

○ View Output File
○ Go to Post Processing Mode
● Stay in Modeling Mode

Figure 5. Run analysis STAAD.PRO

2.5 Examination of Member Sizes

Subsequently, the analysis results are meticulously reviewed to assess the adequacy of member sizes. Using STAAD Pro, comprehensive data on member forces, moments, and shear forces are obtained and compared against the requirements outlined in the design code to determine their suitability. If any members are found to be inadequate, their sizes or configurations are revised to enhance structural robustness and safety. Figure 6 visually represents the iterative process of modifying steel sizes on the bridge, highlighting the adjustments made to optimize structural performance and ensure compliance with design standards.



Select Beam
UB457X191X133
UB457X191X106
UB457X191X98
UB457X191X89
UB457X191X82
UB457X191X74
UB457X191X67
UB457X152X82
UB457X152X74
UB457X152X67

☑ Material: STEEL

Type Specification
● ST (Single Section from Table)
○ T (Tee Section Cut from Beam)
○ D (Double Profile)
SP (Clear Spacing) 0 m
○ CM (Composite Section)
CT (Concrete Thickness) 0 m
FC (Concrete Grade) 0 kN/m2
CW (Concrete Width) 0 m
CD (Density of concrete) kN/m3
○ TC (Top Cover Plate)
○ BC (Bottom Cover Plate)
○ TB (Top & Bottom Cover Plate)
WP (Cover Plate Width) 0 m
TH (Cover Plate Thickness) 0 m
BW (Cover Plate Width) 0 m
BT (Cover Plate Thickness) 0 m
Note: Bottom Plate Dimension BW & BT (If different from Top Cover Plate)

Ref	Section
1	Plate Thickness
2	UB533X210X122
3	UB356X127X33
4	323.9X10CHS

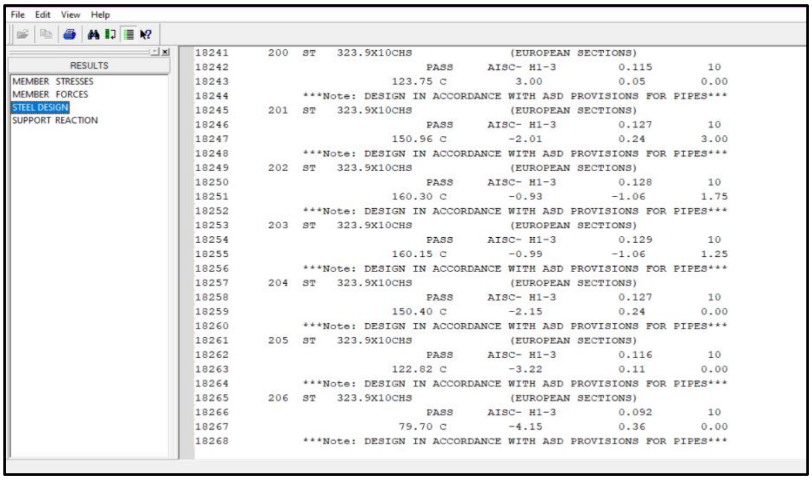
☑ Highlight Assigned Geom

Assignment Method
● Assign To Selected Be
○ Assign To Edit List
83 To 104 262 To 287

Figure 6. Examination of member size

2.6 Result

Upon completing the analysis, the output results are carefully examined to identify any potential failure members. If discrepancies or inadequacies in member sizes or materials are detected, immediate adjustments are made to the structural model, loadings, material properties, or design settings to address these issues. Figure 7 visually presents the STAAD Pro analysis results, offering insights into structural performance and highlighting areas that require attention or modification to ensure integrity and safety.



```
200  ST   323.9X10CHS              (EUROPEAN SECTIONS)
                       PASS     AISC- H1-3         0.115        10
                  123.75 C          3.00           0.05        0.00
     ***Note: DESIGN IN ACCORDANCE WITH ASD PROVISIONS FOR PIPES***
201  ST   323.9X10CHS              (EUROPEAN SECTIONS)
                       PASS     AISC- H1-3         0.127        10
                  150.96 C         -2.01           0.24        3.00
     ***Note: DESIGN IN ACCORDANCE WITH ASD PROVISIONS FOR PIPES***
202  ST   323.9X10CHS              (EUROPEAN SECTIONS)
                       PASS     AISC- H1-3         0.128        10
                  160.30 C         -0.93          -1.06        1.75
     ***Note: DESIGN IN ACCORDANCE WITH ASD PROVISIONS FOR PIPES***
203  ST   323.9X10CHS              (EUROPEAN SECTIONS)
                       PASS     AISC- H1-3         0.129        10
                  160.15 C         -0.99          -1.06        1.25
     ***Note: DESIGN IN ACCORDANCE WITH ASD PROVISIONS FOR PIPES***
204  ST   323.9X10CHS              (EUROPEAN SECTIONS)
                       PASS     AISC- H1-3         0.127        10
                  150.40 C         -2.15           0.24        0.00
     ***Note: DESIGN IN ACCORDANCE WITH ASD PROVISIONS FOR PIPES***
205  ST   323.9X10CHS              (EUROPEAN SECTIONS)
                       PASS     AISC- H1-3         0.116        10
                  122.82 C         -3.22           0.11        0.00
     ***Note: DESIGN IN ACCORDANCE WITH ASD PROVISIONS FOR PIPES***
206  ST   323.9X10CHS              (EUROPEAN SECTIONS)
                       PASS     AISC- H1-3         0.092        10
                   79.70 C         -4.15           0.36        0.00
     ***Note: DESIGN IN ACCORDANCE WITH ASD PROVISIONS FOR PIPES***
```

Figure 7. STAAD Pro result

3. Results and Discussion

The STAAD Pro analysis of the steel structure under wind load provided valuable insights into the complex interplay between structural design and environmental forces. During the modeling stage, meticulous attention was given to constructing the structure based on ten predefined load cases stipulated in BD 37/01 standards. While this phase established a foundation for subsequent analyses, it also revealed challenges in translating theoretical load scenarios into practical design considerations. Notably, discrepancies between theoretical load distributions and real-world conditions underscored the need for nuanced adjustments to ensure the model's fidelity to actual structural behavior.

During model validation, a rigorous comparison of STAAD Pro results with established British Standards formulas served as a benchmark for assessing the reliability of the analysis in real-world scenarios. However, this validation process also highlighted limitations in relying solely on theoretical formulations, particularly in capturing the dynamic and multifaceted nature of wind-induced loads. While validation provided a degree of confidence in the accuracy of the analysis, it also emphasized the importance of complementing theoretical models with empirical data and field observations to enhance predictive capabilities.

The introduction of wind load into the control model offered a unique opportunity to explore the structure's response to varying environmental conditions. This phase of analysis revealed important insights into the structure’s dynamic behavior under wind-induced stresses, particularly in terms of member stresses and forces. However, while the analysis identified notable discrepancies in axial and shear forces under different load cases, the underlying mechanisms driving these variations remained unclear. Future research should delve deeper into the structural dynamics governing these responses to uncover novel insights into wind-structure interaction phenomena.

Furthermore, the examination of steel section weights provided valuable insights into the economic implications of structural design choices. While smaller section sizes demonstrated advantages in cost-effectiveness and material efficiency, questions remained regarding their long-term durability and resilience to environmental factors. Although smaller sections may offer immediate cost savings, their susceptibility to fatigue and corrosion could lead to long-term maintenance challenges, potentially offsetting initial cost benefits. Consequently, future studies should seek to balance short-term economic considerations with long-term structural integrity, exploring innovative design strategies to optimize both aspects simultaneously.

In conclusion, the STAAD Pro analysis offered crucial insights into the intricate relationship between structural design, environmental forces, and economic considerations (Divya & Murali, 2021). While the findings illuminated key aspects of structural behavior and design optimization, they also highlighted the need for continued research and innovation to address remaining challenges and uncertainties. By fostering interdisciplinary collaboration and embracing emerging technologies, the field of structural engineering is well-positioned to advance sustainable, resilient, and cost-effective infrastructure design.

Figure 7 illustrates the stress distribution in the steel bridge- members under varying wind load conditions. The results indicate that the highest stress concentrations occur on the windward side of the bridge, particularly in vertical and diagonal truss members. This is attributed to the direct exposure to wind-induced lateral forces, which increase axial tension and compression forces in these members. A comparison of stress values between different steel section sizes reveals that larger sections (e.g., 686 × 254 × 125 mm) exhibit lower stress levels than smaller sections (e.g., 457 × 191 × 82 mm). This suggests that increasing section size enhances structural resilience by distributing forces more efficiently. However, while larger sections provide better load resistance, they may lead to increased material costs. To ensure structural integrity, stress values are compared against the allowable stress limits defined by BS EN 1993-1-1:2005. The analysis confirms that all members remain within safe stress limits, though certain elements approach critical levels under extreme wind conditions. These findings suggest that reinforcing high-stress regions with additional bracing or using higher-grade steel could enhance durability and reduce fatigue failure risks.

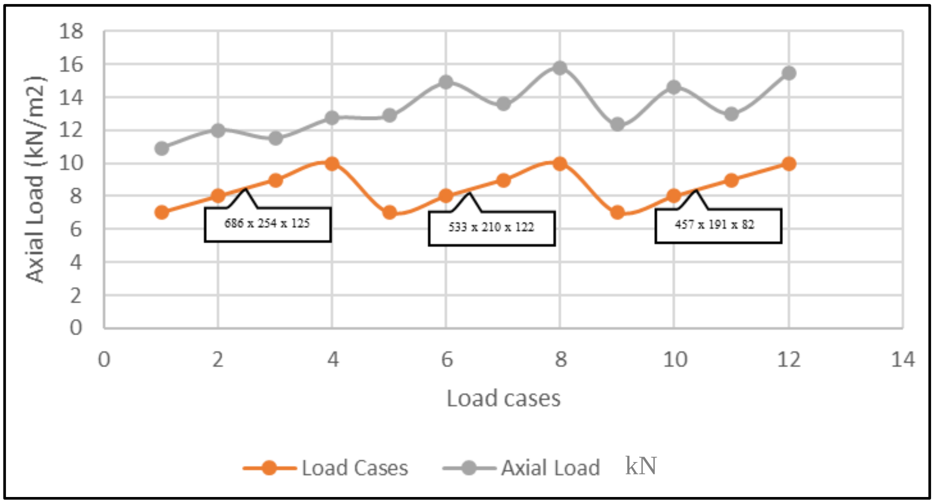


Figure 8. Member stress value

Figure 8 presents the axial and shear forces experienced by different structural members under various wind load combinations. The analysis indicates significant variations in force distribution, with windward-side members primarily experiencing high compressive forces, while leeward-side members are subjected to tensile forces. This pattern aligns with standard wind load behavior, where compression occurs on the wind-facing side, and tension develops on the opposite side due to uplift effects. The results also highlight that shear forces are most prominent at connection points near the bridge supports. These regions exhibit concentrated loads, necessitating reinforced joint designs to prevent failure. The force fluctuations across different load cases demonstrate the influence of wind speed and direction on structural performance. Specifically, load combination 2, which considers maximum wind pressure, generates the highest axial forces, suggesting that this scenario should govern design considerations. The findings underscore the importance of precise load distribution analysis in optimizing steel bridge designs. By incorporating appropriate wind load factors and ensuring proper member sizing, engineers can enhance the stability and longevity of steel structures. Future research should explore dynamic wind effects, such as vortex shedding and aerodynamic instability, to further refine bridge design methodologies.

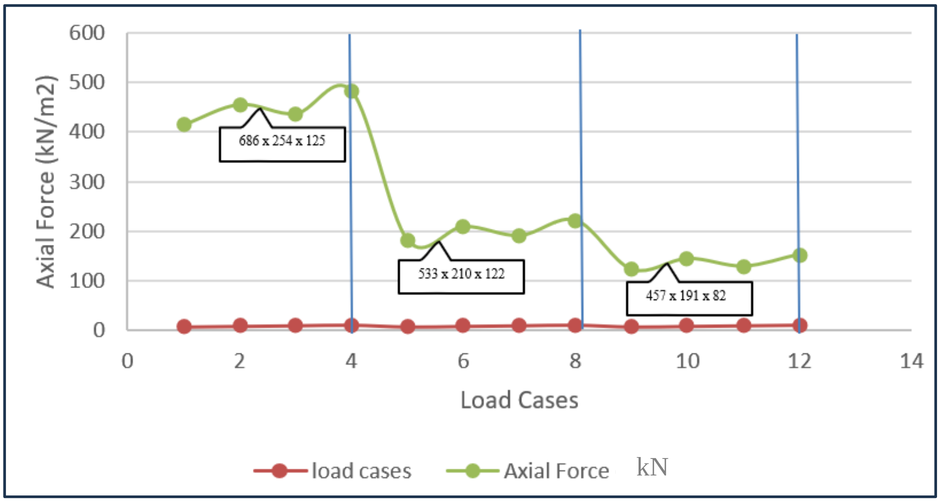


Figure 9. Member forces value

4. Conclusion

In summation, this study represents a significant advancement in the understanding of wind-induced effects on structural steel bridges, providing comprehensive insights into the complex dynamics at play. By rigorously analyzing the structure under wind pressure using Load Combination 2 and evaluating the impact of different steel beam sizes through STAAD Pro, this research has revealed critical nuances in bridge performance under varying environmental conditions. These findings underscore the crucial role of wind load in shaping truss steel bridges, highlighting pathways for optimizing design and construction practices to enhance resilience and longevity.

Moreover, the implications of this study extend beyond academic inquiry, offering practical solutions to real-world engineering challenges. In a rapidly evolving landscape characterized by increasing demands for cost-effective infrastructure solutions, the knowledge generated here holds immense value for practitioners, policymakers, and stakeholders alike. By providing actionable insights into the design and construction of steel bridges, this research equips industry professionals with the tools and strategies needed to effectively navigate the complexities of wind-induced loads.

Looking ahead, the findings from this study serve as a foundation for further exploration and innovation in bridge engineering. By leveraging these insights and embracing emerging technologies and methodologies, future research can continue to push the boundaries of structural design, fostering the development of safer, more resilient, and economically viable infrastructure solutions. As Malaysia and other nations embark on ambitious infrastructure projects to drive economic growth and societal advancement, the lessons learned from this study will undoubtedly play a crucial role in shaping the future of bridge engineering and construction practices.

Future research should explore additional wind load conditions, incorporate experimental validation, and assess alternative structural configurations to further enhance bridge resilience.

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Declaration of Conflicting Interests

All authors declare that they have no conflicts of interest.

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