

A NONLINEAR FINITE ELEMENT INVESTIGATION OF CONTACT-INDUCED STRESS AND DEFORMATION IN TUBULAR WARREN TRUSS STRUCTURES

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ABSTRACT

This study presents a nonlinear finite element analysis (FEA) and geometric optimization of a tubular Warren truss subjected to variable loading conditions using ANSYS Workbench. The investigation focuses on the influence of sectional area ratio ($2A_1/A_2$) and depth-to-thickness ratio (h/t) on structural stiffness, deflection behavior, and stress distribution. A total of twelve three-dimensional truss models were developed using circular hollow sections (CHS) conforming to Tata Structural specifications. The material was modeled with a yield strength of 310 MPa, Young's modulus of 210 GPa, and Poisson's ratio of 0.3. The truss systems were analyzed under uniformly distributed load, single-point load, and two-point load conditions, revealing distinct nonlinear responses. Configurations with $2A_1 > A_2$ and $h < t$ exhibited maximum deflections of 10.821 mm, 10.455 mm, and 15.689 mm, along with corresponding von Mises stresses of 114.37 MPa, 286.77 MPa, and 150.89 MPa, indicating superior stiffness and uniform stress distribution. Conversely, models with $2A_1 < A_2$ and $h > t$ showed increased deflections up to 21.331 mm and stresses reaching 370.04 MPa, signifying reduced rigidity. All stress values remained below the yield limit, confirming structural safety. Finite element results closely matched analytical solutions with deviations below 10%, validating the accuracy of the numerical approach. The optimized configuration demonstrates enhanced load-bearing efficiency, offering a reliable framework for lightweight truss design in bridge and roof applications.



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1. INTRODUCTION

A truss is a structural framework composed of interconnected elements forming triangular units, widely used in bridges, roofs and towers due to its ability to

efficiently distribute loads and enhance stability. In civil engineering practice, truss elements typically utilize cross-sections such as angle, channel, i-sections and tubular (hollow circular or rectangular) sections, selected based on load demands, fabrication ease and design

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requirements. Among these, hollow sections have gained prominence owing to their high strength-to-weight ratio and superior resistance to local and global buckling, particularly under compressive forces. While angle and channel sections are widely adopted for their cost-effectiveness and ease of connection, hollow structural sections demonstrate enhanced torsional rigidity and reduced self-weight, making them ideal for members subjected to both compression and bending (Yang et al., 2018). Truss configurations vary based on geometry and load requirements, with common types including pratt, warren, howe, k, fink, fan, north light, and bowstring trusses (Renton et al., 1969). Each offers unique advantages for instance, pratt and howe trusses are efficient under specific loading patterns, warren trusses ensure uniform load distribution, while configurations like fink and bowstring are favored in roofing and long-span structures for their material efficiency and structural strength. Among various truss configurations, the warren truss is chosen in this study due to its distinct structural advantages. It features a series of equilateral triangles that ensure uniform load distribution, reducing the need for vertical members and minimizing material usage. Compared to pratt or howe trusses, the warren truss exhibits less variation in member forces under symmetric loading, simplifying both structural analysis and fabrication. Its symmetrical design offers effective performance under both compression and tension, making it structurally efficient. Therefore, the present study aims at evaluating the load-carrying capacity and flexural strength of the warren truss under various loading conditions. Building upon this foundation, a review of existing studies is conducted to understand the advancements in the analysis, optimization and design of hollow structural section trusses, emphasizing nonlinear behavior, geometric effects, material optimization and performance evaluation. Chung and Sotelino (2005) numerically investigated tubular steel trusses using nonlinear finite element analysis, reporting that calibrated models predicted buckling loads within $\pm 5\%$ of experimental results and that geometric imperfections altered peak loads by 10–15%. Anwar et al. (2023) analyzed 3d truss bridges under combined gravity and lateral loads using ansys, finding a 25–30% increase in chord forces compared to gravity-only conditions and deflection convergence within 5% across mesh refinements. Renton et al., (1969) compared warren and pratt configurations, concluding that warren trusses required 5–15% less material under symmetric loads. The Bureau of Indian Standards (2022) standardized chs, rhs, and shs dimensions (diameters 21.3–660 mm, thickness 1.6–30 mm, yield strengths up to 350 mpa), ensuring uniformity in hss truss design. Rezaiee et al. (2022) examined geometric nonlinearity, showing that deflection ratios above $1/200$ reduced stiffness by up to 30%. Li et al. (2023) applied metaheuristic optimization to truss systems, achieving 10–20% weight reduction while maintaining deflection limits within $1/250$. Dou et al (2018) demonstrated that post-buckling capacities could reach 1.3 times the elastic limit and that initial

imperfections of 0.1–1% reduced ultimate load by 15%. 9. Keleşoğlu and Ülker (2025) developed a fuzzy optimization approach to design geometrically nonlinear space trusses, enabling efficient handling of uncertainties in loading and structural behavior. Huang & Zhang (2023) established that chs members provided 15–40% higher torsional rigidity and 8–12% lower lateral deflections than rhs members also rsh beam-columns, observing a 15–25% increase in lateral-torsional buckling resistance for $f_y = 700$ mpa steel. Hui et al. (2023) reported that accounting for weld stiffness altered force distribution by 10% and reduced overall roof-truss weight by 20%. Fiore et al. (2016) achieved 18% steel savings through fea-based optimization without exceeding deflection limits of $1/250$. Tousignant and Packer (2018) compared beam and solid models, showing that beam elements predicted global deflections within 5% of full continuum models, with maximum displacements of 10–40 mm. Croccolo et al. (2023) reported that increasing bolt preload from $0.3f_y$ to $0.7f_y$ enhanced joint stiffness by 30%, while thinner end plates reduced capacity by 10%. Yan et al. (2023) found welded joints sustained 150–350 kn axial loads—15% higher than bolted ones but with reduced ductility. Aminifar et al. (2013) presented an augmented genetic algorithm that efficiently optimizes the design of truss structures by minimizing weight while satisfying stress and displacement constraints. Monaco et al. (2025) demonstrated that hybrid hss-plate girder trusses reduced total weight by 5–10% and increased stiffness by 8%. Satria et al. (2025) analyzed a 10 m warren truss bridge, recording axial forces of 80–120 kn and 8 mm mid-span deflection, confirming efficient stress distribution. Ülker & Hayalioğlu (2001) proposed a spreadsheet-based optimization method for space trusses that minimizes structural weight while ensuring member stability through explicit buckling constraints. Kulak et al. (2020) presented the limit-states design framework defining slenderness up to $\lambda = 200$ and safety factors for axial members. Zhang et al. (2023) extended nonlinear design principles to trusses, recommending service deflection ratios of $1/250$ – $1/300$. The revised bis standard (Anwar et al. 2023) reaffirmed yield grades y_{st} 210–355 with minimum elongation $\geq 10\%$, ensuring consistent quality control in tubular structural applications. Collectively, these studies demonstrate substantial advancements in the analysis and optimization of hss trusses through nonlinear finite element methods, optimization algorithms, and experimental validation. High predictive accuracy within $\pm 5\%$ is achieved, with geometric imperfections and load combinations significantly influencing behavior. Optimization approaches yielded 10–20% weight reduction while maintaining deflection limits of $1/250$ – $1/300$, and hybrid truss systems improved stiffness by 5–8% with reduced material usage. However, most studies focused on isolated parameters or simplified static conditions, with limited integration of experimental and computational validation for nonlinear and hybrid truss systems under complex load cases. Toğan and Daloğlu (2006) presented a reliability-based design optimization

framework that integrates probabilistic analysis with structural performance criteria to achieve safer and more efficient engineering designs. A notable research gap remains in correlating analytical, numerical and experimental methods to assess moment of resistance, equal area axis and deflection behavior, particularly for warren trusses using tubular steel sections. Hence, in this study, an attempt is made to evaluate the moment of resistance, equal area axis and deflection behavior of a warren truss through numerical simulation using ansys software.

2. GEOMETRY AND CONFIGURATION OF THE WARREN TRUSS

The Warren truss consists of a repetitive arrangement of equilateral or isosceles triangles formed by inclined diagonal members connecting parallel top and bottom chords. This configuration enables efficient axial force distribution with minimal bending moments in the members.

The Tata Structura table is widely used in design as it provides standardized sectional properties of Hollow Structural Steel Sections (CHS, RHS, SHS) in compliance with IS:4923 (Bureau of Indian Standards [BIS], 2018) and the Tata Structura product catalogue (Tata Steel - Tubes SBU, 2023). It ensures accuracy, reliability and efficiency in evaluating sectional parameters, thereby improving structural design optimization, performance and safety. The Warren truss configuration, as shown in Figure 1, is employed to evaluate the moment of resistance, moment of inertia, equal area axis, stress and deflection under different loading conditions. The analysis is performed by considering two cases based on the sectional properties obtained from the Tata Structura table. In the first case, where $2A_1 < A_2$, and in the second case, where $2A_1 > A_2$, the behavior of the truss is examined with respect to the location of the equal area axis denoted as $h < t$ and $h > t$. These conditions, as summarized in Table 1, provide a comparative basis for assessing the structural response and understanding how variations in sectional areas influence the strength and stiffness of the truss system.

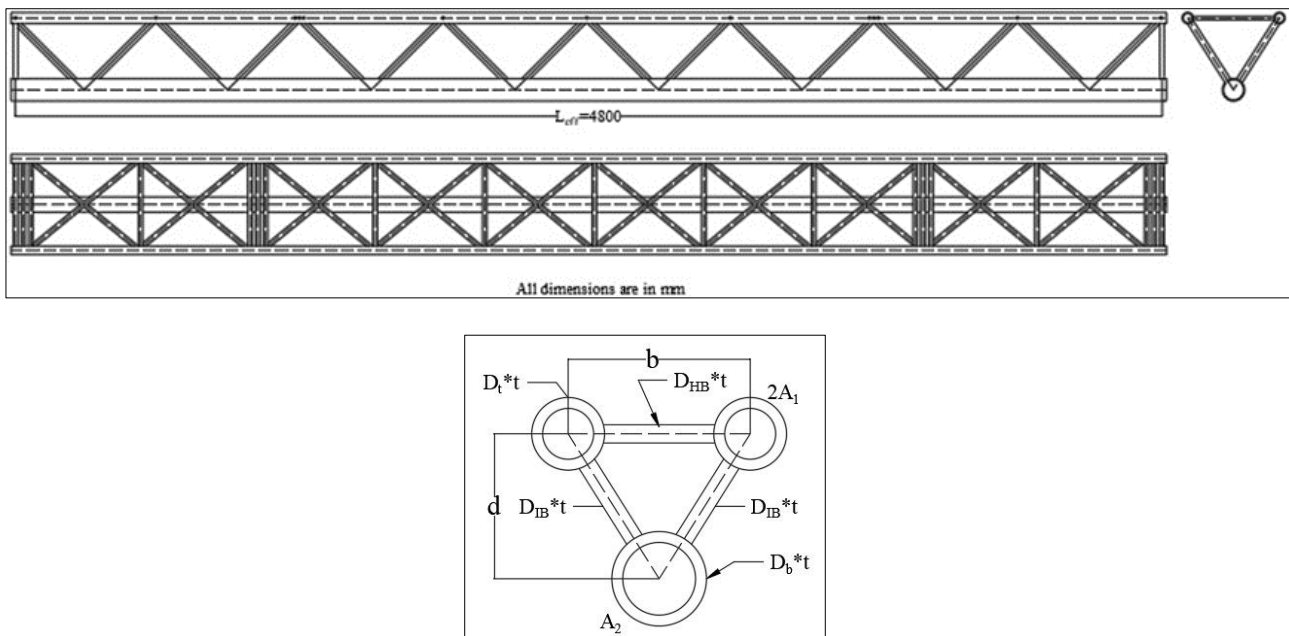


Figure 1. Warren truss configuration and its cross section

Table 1. Different warren truss configurations.

Properties of CHS connections	Location of equal area axis	D_t	t	D_b	t	D_{IB}	t	D_{HB}	t	L_{eff}	d
$2A_1 < A_2$	$h < t$	88.9	3.2	139.7	4.5	76.1	3.2	33.7	2.6	4800	400
		88.9	4	165.1	4.5						
	$h > t$	76.1	3.2	139.7	4.5						
		114.3	3.6	219.1	4.8						
$2A_1 > A_2$	$h < t$	139.7	4.5	273	6						
		76.1	3.2	114.3	3.6						
		114.3	3.6	165.1	4.5						
	$h > t$	139.7	4.5	219.1	4.8						
		139.7	5.4	219.1	4.8						
		165.1	4.5	219.1	4.8						

3. GEOMETRY ESTIMATION OF EQUAL AREA AXIS, MOMENT OF RESISTANCE AND DEFLECTION

Evaluation of EAA, moment of resistance and deflection are fundamental aspects of structural analysis. EAA enables the assessment of section properties, the moment of resistance of the section and deflection quantifies serviceability criteria under the load. Therefore, it is essential to determine these parameters accurately to ensure structural safety and performance.

3.1 Equal Area Axis

The EAA for different CHS configurations specified in Table 1 are determined using the following relations based on the criteria $h < t$ and $h > t$ and whether the axis passing through the top chord or bottom chord.

$$A = R^2 \cos^{-1}\left(\frac{R-h}{R}\right) - (R-h)\sqrt{2Rh-h^2} \quad (1)$$

$$A = \left\{ R^2 \cos^{-1}\left(\frac{R-h}{R}\right) - (R-h)\sqrt{2Rh-h^2} \right\} - \left\{ (R-t)^2 \cos^{-1}\left(\frac{R-h}{R-t}\right) - (R-t)\sqrt{2(R-t)(h-t) - (h-t)^2} \right\} \quad (2)$$

3.2 Moment of Resistance

The moment of resistance defines the sections maximum capacity to withstand bending without failure. The values of y_1 , y_2 , and y_3 , as represented in Figure 2, are used to calculate the moment of resistance as specified in Equations in 5 & 6. Since, the warren truss braces are inclined at 45° moment of resistance can be directly calculated using these equations. However, if the braces are oriented at a different angle, it becomes essential to determine the exact orientation angle before proceeding with the calculation.

$$\theta = 2 \sin^{-1} \frac{\sqrt{2Rh-h^2}}{R} \quad \check{y} = \left(\frac{4R (\sin \frac{\theta}{2})^3}{3(\theta - \sin \theta)} \right) \quad (3)$$

$$\theta = 2\pi - 2 \sin^{-1} \frac{\sqrt{2Rh-h^2}}{R}; \quad \check{y} = \left(\frac{\frac{R^2}{2}(\theta - \sin \theta) + 4R \left(\frac{(\sin \frac{\theta}{2})^3}{3(\theta - \sin \theta)} \right)}{\frac{R^2}{2}(\theta - \sin \theta) - \pi(R-t)^2} \right) \quad (4)$$

$$M_r = C_1 * y_1 + C_2 * y_2 + T * y_3 \quad (2A_1 < A_2) \quad (5)$$

$$M_r = C * y_1 + T_1 * y_2 + T_2 * y_3 \quad (2A_1 > A_2) \quad (6)$$

Where;

$$C_1 = F_{ysc} * 2A_1;$$

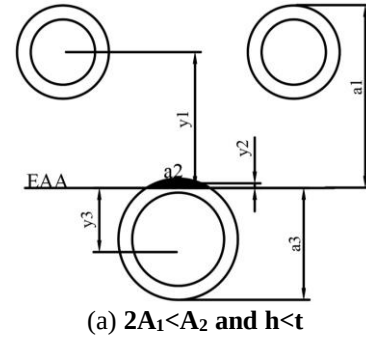
$$C_2 = F_{ysc} * A_{seg}$$

$$C = F_{ysc} * (2A_1 - A_{seg})$$

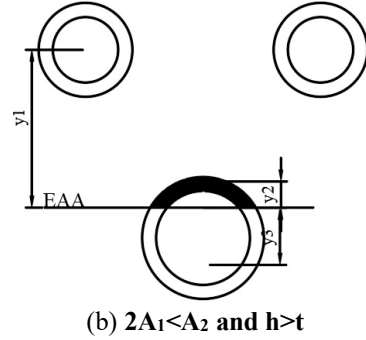
$$T = F_{yst} * (A_2 - A_{seg})$$

$$T_1 = F_{yst} * A_{seg};$$

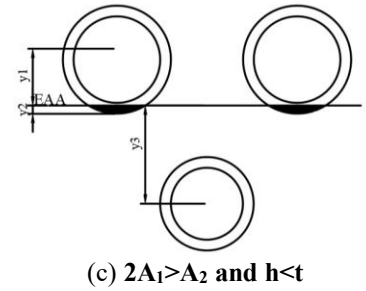
$$C = F_{ysc} * (2A_1 - A_{seg})$$



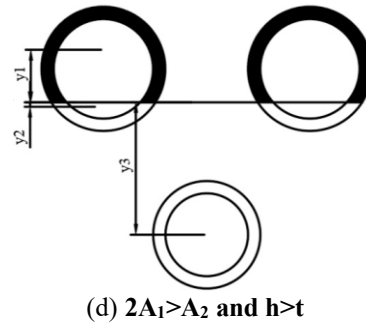
(a) $2A_1 < A_2$ and $h < t$



(b) $2A_1 < A_2$ and $h > t$



(c) $2A_1 > A_2$ and $h < t$



(d) $2A_1 > A_2$ and $h > t$

Figure 2. Centroidal distance of chords from equal area axes (EAA)

3.3. Deflection

The Deflection refers to displacement of the structural member subjected to loading. It is evaluated under various conditions, including uniformly distributed loads (UDL), single-point load and two-point load, to ensure compliance with serviceability criteria. The total weight of the truss is computed by summing the contributions of its individual members expressed as:

$$\text{Total Dead load } (W_{DL}) = \omega((2 L_t L_b) \text{Chords} + (L_i + L_h) \text{Braces}) \quad (7)$$

This formulation accounts for the combined self-weight of the top chord, bottom chord, inclined braces, and horizontal braces, each evaluated with respect to their lengths and the corresponding weight per unit length (ω), as specified for the different cross-sections listed in Table 1.

$$\delta = \frac{5*wl^4}{384*EI} \quad \text{for UDL} \quad (8)$$

$$\delta = \frac{wl^3}{48EI} \quad \text{for Single Point Load} \quad (9)$$

$$\delta = \frac{wa*(3L^2-4a^2)}{24*EI} \quad \text{for Two Point Load} \quad (10)$$

Due to the large volume of data involved in the analysis, dedicated computational tools are developed using Excel and Java programming. The Excel-based program streamlines calculations, minimizes manual errors, and enables flexible handling and visualization of large datasets. Whereas, the Java program enhances computational efficiency, scalability, and automation, making it suitable for processing complex datasets and integrating advanced algorithms. Together, these tools provide accuracy, reliability, and adaptability for structural analysis and related applications. Hence, in this research work, the Java programming language and Excel software are employed.

3.4. Computational Approach for the Evaluation of Warren Truss Parameters

The equations specified in the previous sections are implemented using both Excel spreadsheets and Java programming to determine the moment of resistance and deflection of the truss. These computational results are subsequently compared with the theoretical calculations in order to validate the accuracy and reliability of the numerical approach.

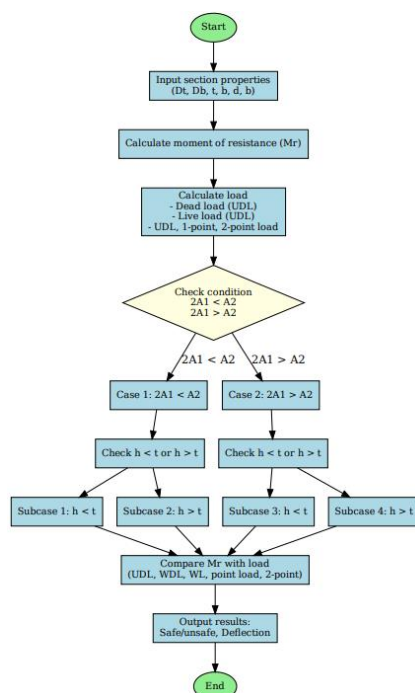


Figure 3. Flowchart for evaluating the moment of resistance and deflection of a Warren truss under variable loads

The flowchart shown in Figure 3 represents the stepwise computational approach for evaluating the moment of resistance and deflection of Warren truss. Section properties are first provided as input to calculate the moment of resistance (M_r). Dead load and live load conditions, including UDL, single and two-point loads, are then determined. A conditional check between $2A_1 < A_2$ and $2A_1 > A_2$ defines the governing case, which is further subdivided by comparing section height with thickness as $h < t$ and $h > t$. For each subcase, the calculated moment of resistance is compared against the applied loads, and the results are reported in terms of structural safety (safe/unsafe) and deflection.

4. MODELING AND FINITE ELEMENT ANALYSIS (FEA) OF WARREN TRUSS

4.1. Modeling of Warren Truss

A three-dimensional (3D) model of a Warren truss is developed using SolidWorks modeling software. The geometric parameters required for the modeling process are obtained from Table 2, which provides detailed specifications, including the diameters of the top chord (D_t), bottom chord (D_b), diagonal braces (D_{IB}), horizontal braces (D_{HB}), as well as the depth of truss (d) and width between the top chords (b), and thickness of the truss sections. Based on these specifications, a total of 12 distinct models are created to represent variations in design. All models are meticulously constructed to reflect the exact dimensions and connectivity of the truss members are saved in the Parasolid format (*.x_t) to ensure compatibility for further analysis and simulations.

Figure 4 shows the 3D model of a truss member, illustrating the top and bottom chords, diagonal and horizontal braces, along with their precise dimensions and connectivity. It provides a clear visualization of the truss structure for further analysis and simulation.

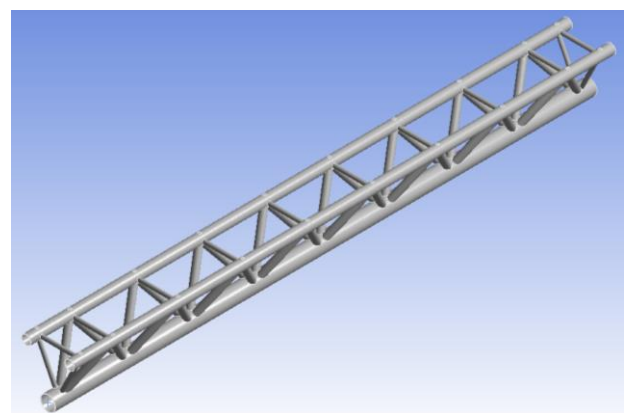


Figure 4. CAD model of the Warren truss structure. Computational

Table 2. Dimensions for CHS truss configurations.

Model No.		D _t *t	D _B *t	D _{IB} *t	D _{HB} *t	d	b
M ₁ 2A ₁ >A ₂ h<t	M ₁₁	114.3*3.6	165.1*4.5	33.7*2.6	76.1*3.2	400	400
	M ₁₂						
	M ₁₃						
M ₂ 2A ₁ <A ₂ h>t	M ₂₁	114.3*3.6	219.1*4.8				
	M ₂₂						
	M ₂₃						
M ₃ 2A ₁ <A ₂ h<t	M ₃₁	88.9* 3.2	139.7*4.5				
	M ₃₂						
	M ₃₃						
M ₄ 2A ₁ >A ₂ h>t	M ₄₁	139.7*5.4	219.1*4.8				
	M ₄₂						
	M ₄₃						

4.2 Finite Element Analysis of Warren Truss

The three-dimensional (3D) models of the Warren truss with different geometric configurations are saved in Parasolid format (.x_t) and subsequently imported into the ANSYS simulation environment for analysis. The appropriate material properties, such as Young's modulus (210 GPa) and Poisson's ratio (0.3), are assigned to each truss model based on the desired structural behavior. To accurately represent the geometry and ensure reliable numerical results, the truss continuum is discretized using tetrahedral elements, which provide better accuracy and computational efficiency for structural analysis. The meshed model, shown in Figure 5, is carefully verified to ensure proper element quality and connectivity before applying the boundary conditions and loading. The meshed model, illustrated in Figure 5, is thoroughly examined to verify element quality, aspect ratio, and connectivity prior to the application of boundary conditions and loading.

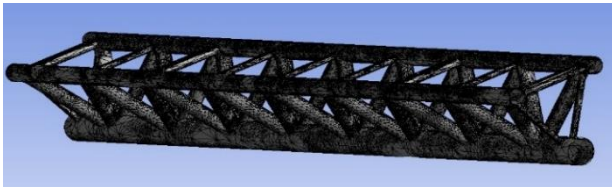


Figure 5. Finite element model of the Warren truss

Based on the moment of resistance calculated using Equations (5) and (6) for the cases $2A_1 < A_2$ and $2A_1 > A_2$ the loads acting on the truss members are determined. The corresponding load values for different configurations are computed using the Equations (11–16) for uniformly distributed load (UDL), single point load, and two-point loads as shown in Figure 6.

$$\text{For UDL } M_r = \frac{W_{LL} \times L^2}{8} + \frac{W_{DL} \times L^2}{8} \quad (11)$$

$$\text{UDL on truss member} = W_{LL}/m \quad (12)$$

$$\text{For 1-point load } M_r = \frac{W_{LL} \times L}{4} + \frac{W_{DL} \times L^2}{8} \quad (13)$$

$$\text{Point load on truss member} = W_{LL} \quad (14)$$

For 2-point load

$$M_r = W_{LL} \times a + \frac{W_{DL} \times L^2}{8} \quad (15)$$

$$\text{2-point load on truss member} = W_{LL} \quad (16)$$

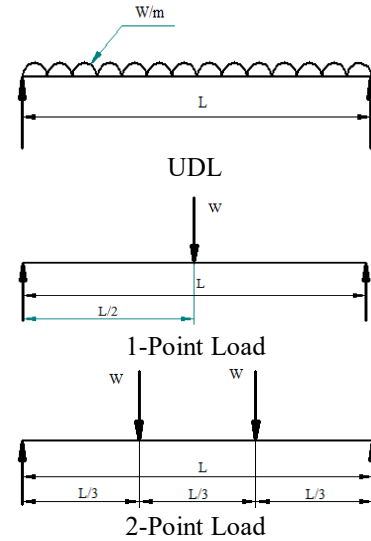


Figure 6. Applied loading configuration for the Warren truss analysis

The calculated loads are applied on the top chords of the Warren truss. In the case of a single point load, the load is applied at the center of the truss span and distributed equally between the two top chords. For the two-point load condition, the loads are applied at a distance of $L/3$ from each end of the truss, representing a symmetric loading configuration. In the case of a uniformly distributed load (UDL), the total load acting on the truss is divided equally between the top chords and applied at eight equally spaced locations along the span to simulate the effect of continuous loading. This loading arrangement ensured uniform stress distribution and accurate representation of real loading conditions in the numerical model.

To ensure realistic structural behavior during numerical simulation, appropriate boundary conditions are applied to the truss models. The support conditions are defined to replicate the actual constraints experienced by the structure under loading. One end of the truss is assigned a fixed support, restricting all translational and rotational degrees of freedom, thereby preventing any movement. The opposite end is provided with a roller support, allowing horizontal displacement while restraining vertical and rotational motion, thus accommodating

thermal expansion and minimizing redundant stresses. These boundary conditions ensured that the structure could deform naturally under applied loads without introducing artificial constraints. Additionally, all connections between the truss members are assumed to be pin-jointed, allowing free rotation at the nodes and facilitating accurate transfer of axial forces.

After defining the geometry, material properties, meshing strategy, and boundary conditions, the models are subjected to structural analysis using the ANSYS Workbench simulation environment. The primary objective of the analysis is to determine the stress distribution, deformation pattern, and load-carrying capacity of the Warren truss under different loading conditions namely, uniformly distributed load (UDL), single point load and two-point loads.

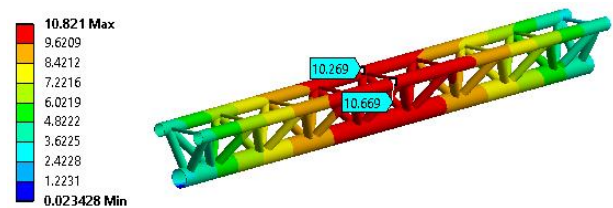
A static structural analysis is performed to evaluate the response of the truss under steady loading conditions. The applied loads are gradually increased to observe the variation in stress and deflection across the members. The finite element solver within ANSYS computed the nodal displacements, reaction forces, and internal stresses for each configuration. Convergence tests are also conducted by refining the mesh density to ensure that the obtained results are both accurate and mesh-independent.

Following the linear static analysis, a nonlinear structural analysis is performed in ANSYS Workbench to account for geometric and material nonlinearities. The same geometric and boundary configurations are retained, while the *Large Deflection* option is enabled to incorporate geometric nonlinearity. Material nonlinearity is introduced using a bilinear isotropic hardening model defined by a yield strength of 310 MPa and the tangent modulus of structural steel. Appropriate contact definitions are applied between the truss members to capture interaction effects. The analysis is executed with automatic time stepping and a refined number of substeps to ensure convergence stability. The solver iteratively computed the response under increasing load increments, yielding realistic results for plastic deformation, stress redistribution, and large displacement behavior of the truss structure.

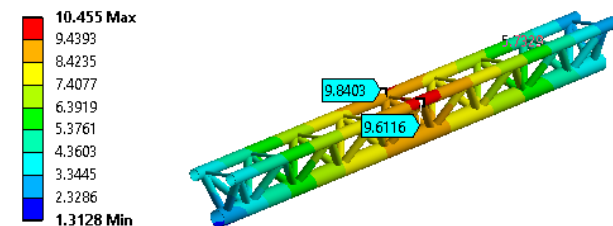
5. RESULTS AND DISCUSSIONS

The nonlinear finite element analysis is performed using automatic time stepping with refined substeps to ensure convergence and numerical stability. The solver iteratively computed the structural response under incremental loading, yielding accurate predictions of plastic deformation, stress redistribution, and large displacement behavior. The following sections present a detailed discussion of the numerical results, focusing on deformation characteristics, stress distribution, and a comparative assessment between the numerical analysis and the analytical model developed using Excel.

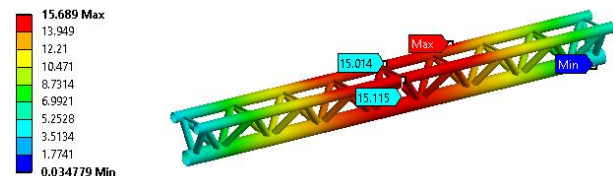
Figure 7 (a–f) presents the nonlinear FEA of the Warren truss under different loading conditions, showing distinct variations in deflection and stress behavior. Under UDL, the truss exhibited a smooth deflection profile with a maximum of 10.821 mm at mid-span. A single-point load produced a localized deflection of 10.455 mm, while two-point loading resulted in twin sagging zones with a deflection of 15.689 mm. The corresponding von Mises stresses are 114.37 MPa, 286.77 MPa, and 150.89 MPa for UDL, single-, and two-point loads, respectively. Overall, the configuration with $2A1 > A2$ and $h < t$ exhibited superior stiffness, reduced deformation, and lower stress concentration, confirming that geometric optimization enhances the truss's global stability and load-bearing efficiency.



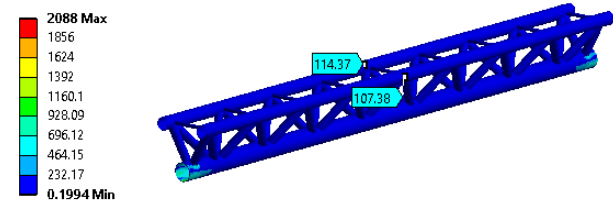
(a): Maximum deflection (UDL)



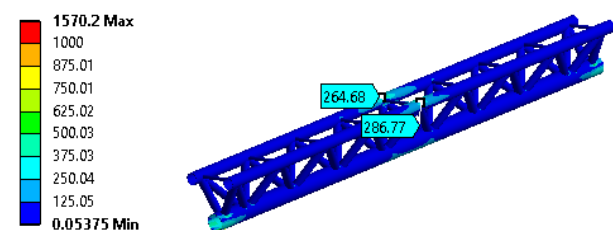
(b): Maximum deflection (Single point Load)



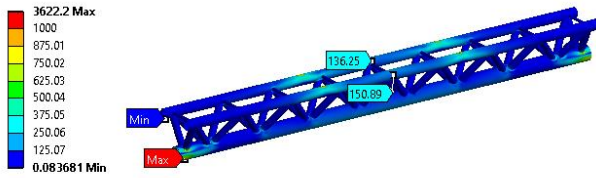
(c): Maximum deflection (Two-point Load)



(d): Von Moises /Equivalent stress (UDL)



(e): Von Moises /Equivalent stress (single point Load)

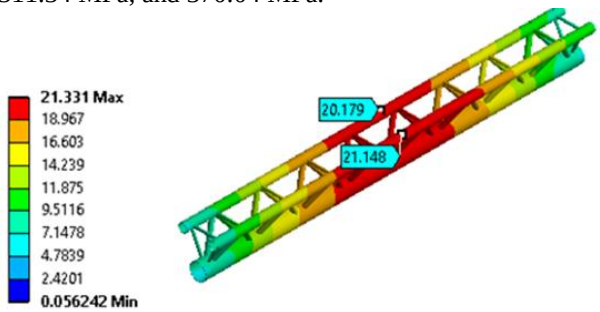


(f): Von Moises /Equivalent stress (Two-point Load)

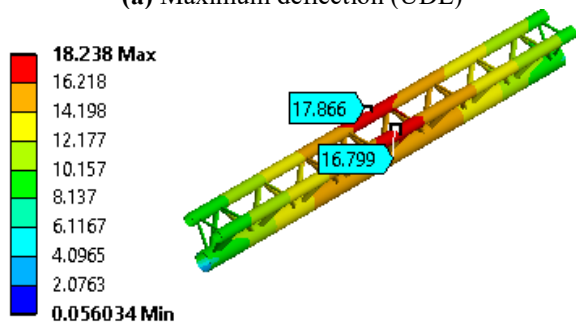
Figure 7 (a-f). Maximum deflection and Von Mises stress in a truss member under different loading when CHS ($2A1 > A2$ and $h < t$)

Furthermore, the von Mises stresses developed in all configurations remained within the yield strength of the material. Theoretical deflections of 13.9 mm, 11.58 mm, and 14.61 mm closely matched the FEA results, with deviations of less than 10%, validating the accuracy and reliability of the numerical analysis.

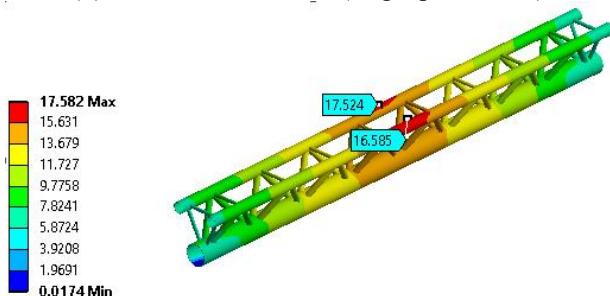
Figure 8 (a-f) presents the nonlinear FEA of the Warren truss with the configuration $2A1 < A2$ and $h > t$, showing distinct variations in deflection and stress behavior compared to the previous case. Under UDL, the truss exhibited a maximum deflection of 21.331 mm at mid-span, while single- and two-point loads produced deflections of 18.238 mm and 17.582 mm, respectively. The corresponding von Mises stresses are 208.62 MPa, 311.34 MPa, and 370.04 MPa.



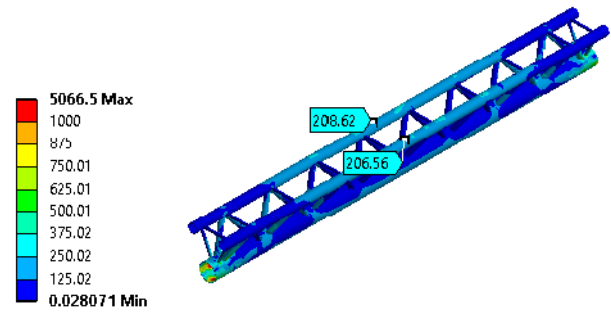
(a) Maximum deflection (UDL)



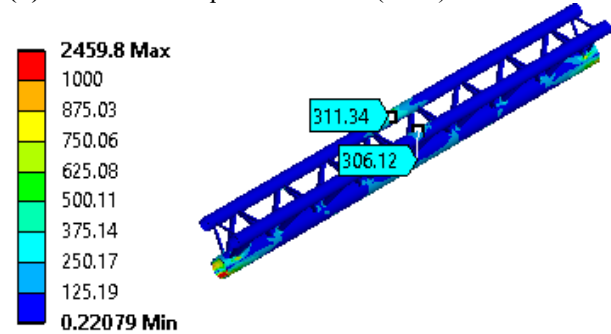
(b) Maximum deflection (single point Load)



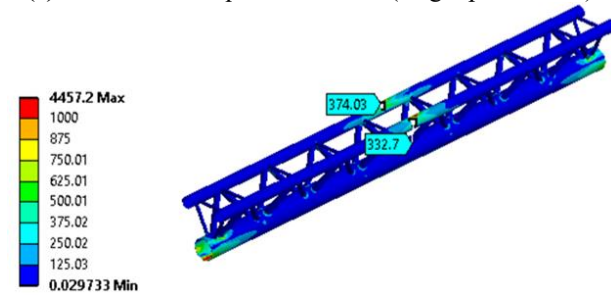
(c) Maximum deflection (Two-point Load)



(d) Von Moises /Equivalent stress (UDL)



(e) Von Moises /Equivalent stress (single point Load)



(f) Von Moises /Equivalent stress (Two-point Load)

Figure 8 (a-f). Maximum deflection and Von Mises stress in a truss member under different loading when CHS ($2A1 < A2$ and $h > t$)

Compared with the $2A1 > A2$ and $h < t$ configuration, this model displayed higher deflections and greater stress concentrations, indicating reduced stiffness. The increased bottom chord area ($A2$) and thicker web height ($h > t$) shifted load distribution toward tensile members, reducing overall structural rigidity. Although stresses remained within the yield strength, the results show a larger top chord section provides better resistance to bending and buckling. Theoretical deflections of 19.38 mm, 16.15 mm, and 20.38 mm align closely with FEA results, with variations below 10%, confirming the accuracy of the simulation and highlighting the geometric influence on truss performance.

When a Warren truss with a small depth-to-thickness ratio and thin chord members is subjected to concentrated or uniformly distributed loads, its structural response becomes highly sensitive to local stiffness variations. Under point loading, the concentrated force produces steep stress gradients and localized bending at the loaded node a classic nonlinear behavior observed in slender truss systems when h/t is small and loads are highly localized (Timoshenko &

Gere, 1961). Because the chord thickness is insufficient to resist these bending moments, the stress field exhibits near-singular behavior, with stresses theoretically tending toward infinity at the points of load transfer, consistent with stress-singularity phenomena reported in finite-element analyses (Cook et al., 2002).

Under a uniformly distributed load (UDL), the same behavior appears in milder form; stresses and deformations oscillate along the span due to alternating tension and compression in the diagonals. This oscillatory response arises from member slenderness, leading to minor local buckling and stiffness fluctuations that amplify the deformation waveform. Since the truss depth is small relative to its thickness, the system behaves less like a conventional truss and more like a flexible frame, reducing the efficiency of load distribution and increasing numerical sensitivity in the nonlinear analysis (Zienkiewicz & Taylor, 2000).

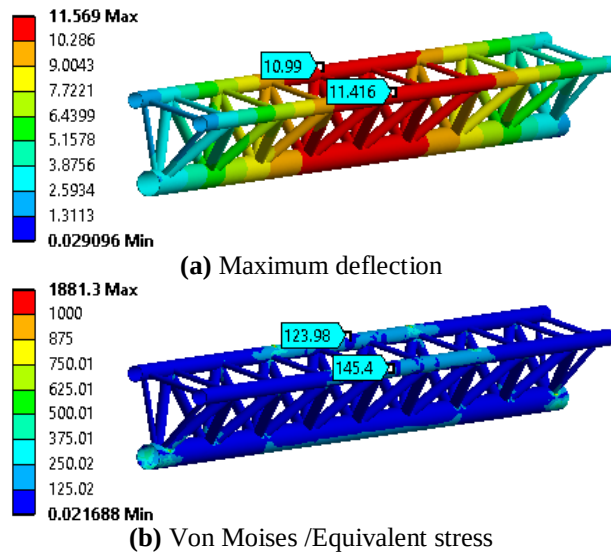
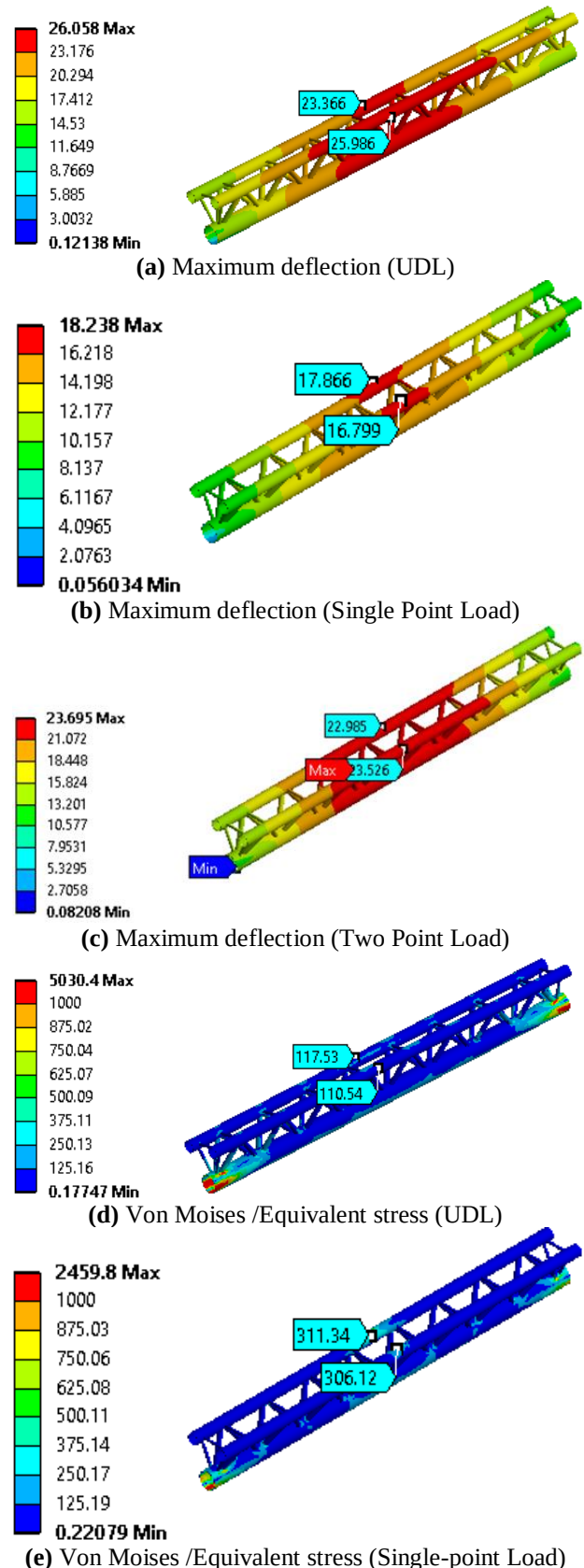


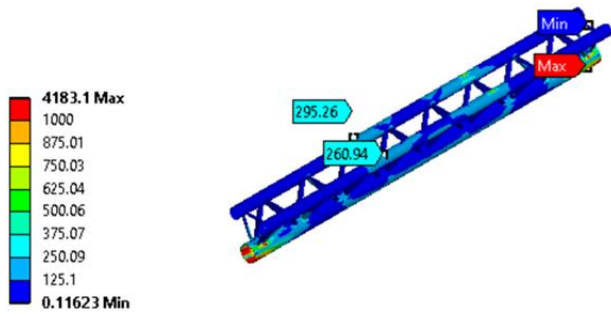
Figure 9 (a-b). Maximum deflection and Von Mises stress in a truss member for Two-point Load when CHS ($2A1 < A2$ and $h < t$)

In contrast, under two-point loading, the load is shared between nodes, producing smoother stress transitions and minimizing local singularities. Figure 9 (a-b) illustrates this stabilized response, showing a maximum deflection of 11.569 mm and a von Mises stress of 145 MPa, both below the material's yield strength. The theoretical deflection of 11.13 mm aligns closely with the FEA results, confirming the model's reliability and demonstrating the stabilizing effect of distributed load paths on overall structural performance.

Figure 10 (a-f) presents the nonlinear FEA of the Warren truss with the configuration $2A1 > A2$ and $h > t$, illustrating distinct variations in deflection and stress response compared to the previous models. Under a uniformly distributed load (UDL), the truss exhibited a maximum deflection of 26.058 mm at mid-span, whereas single- and two-point loads produced deflections of 18.238 mm and 23.695 mm, respectively. The corresponding von Mises

stresses are 117.53 MPa, 311.34 MPa, and 295.26 MPa for UDL, single-, and two-point loadings. The theoretical deflections of 22.18 mm, 18.48 mm, and 23.32 mm closely align with the FEA results, with deviations below 10%, validating the accuracy of the simulation.





(f) Von Moises /Equivalent stress (Two-point Load)

Figure 10 (a-f). Maximum deflection and Von Mises stress in a truss member under different loading when CHS ($2A_1 > A_2$ and $h > t$)

The observed increase in deflection under UDL and two-point loading can be attributed to the larger height-to-thickness ratio, which enhances geometric flexibility but reduces overall stiffness. Although the larger top chord area ($2A_1 > A_2$) improves bending resistance, the greater truss depth increases the influence of geometric nonlinearity, resulting in higher mid-span deflection. Additionally, stress redistribution becomes more pronounced due to increased member length and the enhanced contribution of axial forces over bending stiffness.

Under single-point loading, the structure displayed a more concentrated stress field, with local stress peaks reaching 311.34 MPa near the loaded node. This localized behavior arises from combined axial and bending effects in the diagonals, a typical characteristic of nonlinear load paths in truss systems. However, because the stresses remain below the material's yield strength, the structure retains sufficient reserve capacity under all loading cases. The moderate stresses under UDL (117.53 MPa) further confirm efficient load dispersion through the upper chord and diagonals.

A comparative evaluation of all three configurations reveals that both cross-sectional proportion and depth-to-thickness ratio critically influence the nonlinear performance of the Warren truss. The configuration $2A_1 > A_2$, $h < t$ demonstrated the highest stiffness and lowest deflection, confirming superior flexural rigidity due to the increased top chord area and compact geometry. In contrast, the configuration $2A_1 < A_2$, $h > t$ exhibited greater flexibility and higher stress magnitudes, as the larger bottom chord and shallower section reduced compression resistance in the upper chord. The configuration $2A_1 > A_2$, $h > t$ achieved an intermediate response, combining improved bending resistance from the larger top chord with enhanced geometric flexibility from the greater depth.

Overall, the configuration $2A_1 > A_2$, $h > t$ demonstrates a balance between stiffness and ductility exhibiting greater deformation under distributed loads but improved stress uniformity and load transfer efficiency. These findings emphasize that optimizing both sectional area ratio and depth-to-thickness proportion is critical for achieving reliable performance in nonlinear truss systems.

6. CONCLUSION

This study comprehensively analyzed the nonlinear behavior of a Warren truss using finite element analysis (FEA) under different geometric configurations and loading conditions. The results confirm that the cross-sectional area ratio ($2A_1/A_2$) and depth-to-thickness ratio (h/t) significantly affect stiffness, stress distribution, and overall load-bearing efficiency.

For the configuration $2A_1 > A_2$, $h < t$, the truss exhibited the lowest deflections 10.821 mm, 10.455 mm, and 15.689 mm for uniformly distributed, single-point, and two-point loads and the corresponding von Mises stresses are 114.37 MPa, 286.77 MPa, and 150.89 MPa. This setup achieved the greatest stiffness and most uniform stress distribution, confirming high flexural rigidity and efficient load transfer.

For $2A_1 < A_2$, $h > t$, the deflections increased to 21.331 mm, 18.238 mm, and 17.58 mm, with stresses of 208.62 MPa, 311.34 MPa, and 370.04 MPa. The higher deformation and stress magnitudes reveal diminished compression stiffness in the top chord and enhanced stress redistribution caused by geometric flexibility. The configuration $2A_1 > A_2$, $h > t$ yielded intermediate behavior, showing deflections of 26.058 mm, 18.238 mm, and 23.695 mm, and stresses of 117.53 MPa, 311.34 MPa, and 295.26 MPa. Although a larger depth increased mid-span deflection, it improved stress uniformity and delayed local buckling.

The nonlinear response of slender trusses with small h/t ratios aligns with classical findings on geometric instability and stress singularity. Concentrated loads produced steep stress gradients and localized bending near the nodes, while uniformly distributed loads generated oscillatory stress fields due to alternating tension and compression in the diagonals. This oscillatory pattern arises from member slenderness, which amplifies deformation through local stiffness fluctuations. Under two-point loading, smoother stress transitions are observed, with a maximum deflection of 11.569 mm and a von Mises stress of 145 MPa, both below the material's yield strength, confirming structural stability and accurate nonlinear modeling.

Across all configurations, FEA results agreed closely with theoretical predictions, with variations below 10 %, validating the reliability of the simulation. Stresses in all models remained below the 310 MPa yield strength, ensuring safety under service loads. Overall, increasing the top chord area (A_1) and maintaining a moderate h/t ratio significantly improve stiffness, flexural strength, and stability. The configuration $2A_1 > A_2$, $h < t$ proved most efficient, offering optimal nonlinear performance and providing a validated framework for future experimental and hybrid structural optimization.

Nomenclature

D_t	:	Diameter of top chord	CHS	:	Circular Hollow Steel
D_b	:	Diameter of bottom chord	EAA	:	Equal area Axis
D_{HB}	:	Diameter of horizontal braces	M_R	:	Moment of resistance
D_{IB}	:	Diameter of inclined braces	C, C1 & C2	:	Total compression
y_1, y_2 & y_3	:	Distances from centroid to EAA	T, T1 & T2	:	Total Tension
t	:	Thickness of chord	δ	:	Deflection
h	:	Vertical distance from the centre of the circle to the extreme fibre (used in defining geometric conditions like $h < t$ or $h > t$).	L_t & L_b	:	Length of top and bottom chord
A_1	:	Area of each top chord	L_i & L_h	:	Length of inclined and horizontal braces
A_2	:	Area of bottom chord	W_{LL}	:	Live Load
b	:	Width between of top chords	W_{DL}	:	Dead Load
d	:	Depth of truss	E	:	Young's Modulus
			M	:	Moment of Inertia
			L	:	Span
			FEA	:	Finite Element Analysis

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