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Geometry and Material Effects on Steel Column Performance Under Axial Loads

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تأثيرات الهندسة والمواد على أداء الأعمدة الفولاذية تحت الأحمال المحورية

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Abstract

This study presents a comparative analysis of three structural geometries-rectangular columns, I-shaped beams, and hollow circular tubes—fabricated from ASTM A36 and AISI 4340 steels under axial loading conditions ranging from 50 to 250 kN. Stress capacity, deflection, and strain responses were evaluated to determine the influence of geometry and material selection on structural efficiency. Results indicate that hollow circular tubes exhibit the highest stress capacity, particularly when manufactured from AISI 4340 steel, achieving values up to (1.99 E^{+7}, N/m^2) at 250 KN. However, this advantage is accompanied by increased deflections, raising potential serviceability concerns. I-shaped columns in AISI 4340 provide a balanced performance, combining near maximum stress resistance with reduced deflections (≈ 0.08 m). Rectangular columns consistently underperformed across both materials, underscoring their limited efficiency in high-load applications. The findings highlight the critical role of geometry optimization and material selection in enhancing structural performance, with implications for the design of load-bearing systems in civil and mechanical engineering.

Keywords*:* ASTM A36 steel, AISI 4340 steel, rectangular column, I-beam, hollow circular tube, axial loading, structural efficiency, stress capacity, deflection, strain analysis, geometry optimization.

الملخص

تقدم هذه الدراسة تحليلًا مقارنًا لثلاثة أشكال هندسية إنشائية - أعمدة مستطيلة، وعوارض على شكل حرف I، وأنابيب دائرية مجوفة - مصنعة من فولاذ ASTM A36 و AISI 4340 تحت ظروف تحميل محوري تتراوح من 50 إلى 250 كيلو نيوتن. تم تقييم قدرة تحمل الإجهاد، والانحراف، واستجابات الانفعال لتحديد تأثير الشكل الهندسي واختيار المادة على الكفاءة الإنشائية. تشير النتائج إلى أن الأنابيب الدائرية المجوفة تُظهر أعلى قدرة تحمل للإجهاد، خاصةً عند تصنيعها من فولاذ AISI 4340، حيث تصل قيمها إلى (1.99 × 10^7 نيوتن/م²) عند 250 كيلو نيوتن. ومع ذلك، فإن هذه الميزة مصحوبة بزيادة في الانحرافات، مما يثير مخاوف محتملة بشأن قابلية الخدمة. توفر الأعمدة على شكل حرف I المصنوعة من فولاذ AISI 4340 أداءً متوازنًا، حيث تجمع بين مقاومة إجهاد شبه قصوى وانحرافات منخفضة (≈ 0.08 متر). أظهرت الأعمدة المستطيلة أداءً أقل باستمرار في كلا المادتين، مما يؤكد كفاءتها المحدودة في تطبيقات الأحمال العالية. تسلط النتائج الضوء على الدور الحاسم لتحسين الهندسة واختيار المواد في تعزيز الأداء الهيكلي، مع ما يترتب على ذلك من آثار على تصميم أنظمة تحمل الأحمال في الهندسة المدنية والميكانيكية.

الكلمات المفتاحية: فولاذ ASTM A36، فولاذ AISI 4340، عمود مستطيل، عارضة على شكل حرف I، أنبوب دائري مجوف، تحميل محوري، كفاءة هيكلية، قدرة تحمل الإجهاد، انحراف، تحليل الإجهاد، تحسين الهندسة

Introduction

Structural efficiency in load-bearing members is determined by both material properties and geometric configuration. Conventional steels such as ASTM A36 are widely employed in civil engineering applications due to their ductility, availability, and cost-effectiveness [1]. In

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contrast, high-strength alloys such as AISI 4340 deliver superior mechanical performance under axial and flexural loading, particularly when subjected to heat treatment [2], [7].
Rectangular columns, while simple in design, often demonstrate limited efficiency under high loads because of their lower section modulus and susceptibility to deformation [3]. I-shaped beams are optimized for flexural performance, with flanges resisting bending and webs carrying shear forces [4]. Hollow circular tubes, classified as hollow structural sections (HSS), provide enhanced torsional resistance and uniform stress distribution under axial compression, making them highly effective in resisting buckling [6].

This study builds upon these principles by experimentally comparing the performance of rectangular, I-shaped, and hollow circular geometries fabricated from ASTM A36 and AISI 4340 steels under axial loading conditions ranging from 50 to 250 kN. Stress capacity, deflection, and strain responses are systematically analyzed to determine the relative efficiency of each configuration, thereby offering insights into the combined influence of geometry and material selection on structural performance.

Material and methods

Methodology

Finite element analysis (FEA) was conducted using SolidWorks Simulation to evaluate the performance of the three geometries.
Geometry Modeling: Rectangular, I-shaped, and hollow circular tube geometries were created with identical height and comparable cross-sectional area.

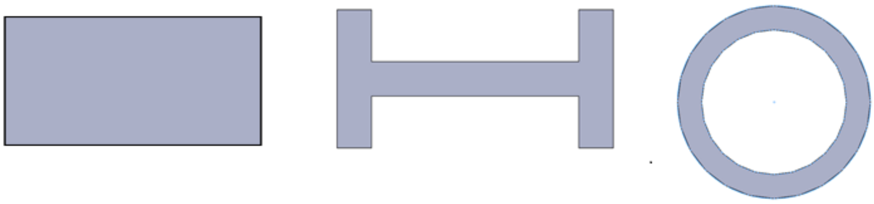
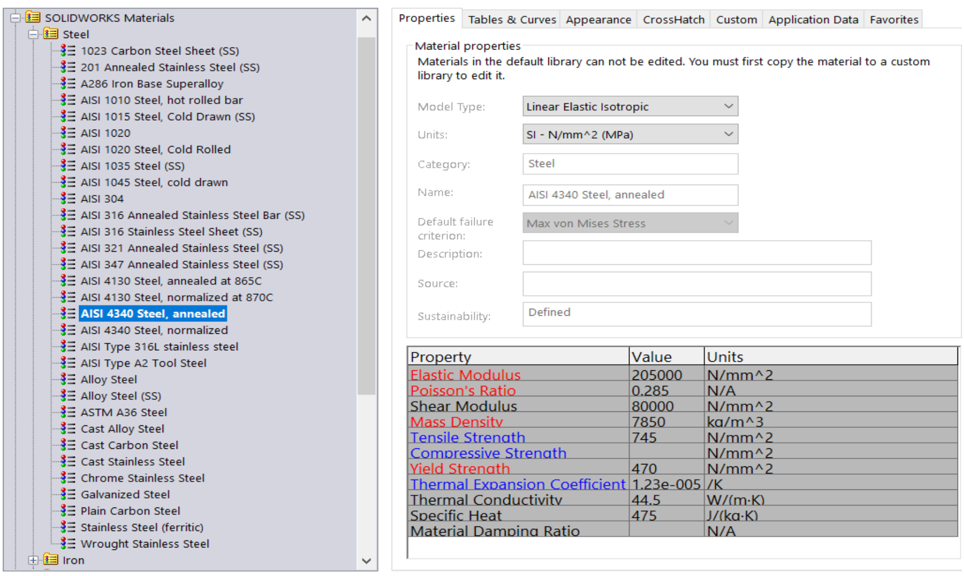


Figure 1 Geometry shapes for all Columns

Material Assignment: ASTM A36 and AISI 4340 properties were assigned from the SolidWorks material library.



Property	Value	Units
Elastic Modulus	205000	N/mm^2
Poisson's Ratio	0.285	N/A
Shear Modulus	80000	N/mm^2
Mass Density	7850	kg/m^3
Tensile Strength	745	N/mm^2
Compressive Strength		N/mm^2
Yield Strength	470	N/mm^2
Thermal Expansion Coefficient	1.23e-005	/K
Thermal Conductivity	44.5	W/(m·K)
Specific Heat	475	J/(kg·K)
Material Damping Ratio		N/A

Figure 2 Solidworks Materials web portal

Meshing Strategy

Tetrahedral meshes were employed due to their ability to conform to complex geometries as shown in the figure 3. Local refinement was introduced at regions of anticipated stress concentration, such as sharp corners, holes, and load application points, to ensure accurate capture of stress gradients. To validate the reliability of the numerical model, convergence testing was performed by analysing results across coarse, medium, and fine mesh densities as shown in the table 1. Mesh independence was confirmed once variations in key outputs (e.g., maximum stress and displacement) between successive refinements became negligible.

Table 1 mesh size comparison

Mesh Size	Total Nodes	Total Elements	Meaning
A (High)	78,922	52,645	Very fine mesh → highest accuracy, but requires more computation time and memory.
B (Medium)	9,891	5,974	Balanced mesh → good compromise between accuracy and efficiency. Often used for parametric studies.
C (Coarse)	2,014	1,083	Very rough mesh → fastest to compute, but may miss localized stress concentrations. Useful for quick checks.

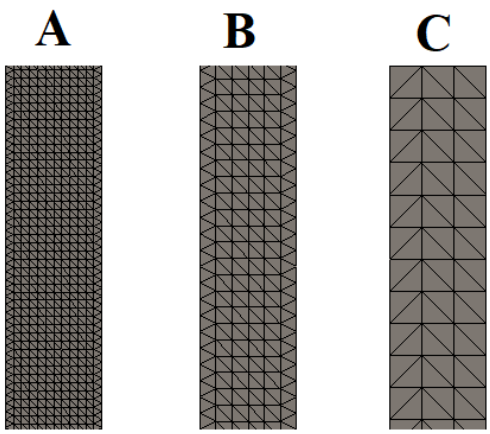


Figure 3 mesh size comparison

Boundary Conditions:

In the numerical simulations, boundary conditions were applied uniformly across all column geometries, including hollow circular tubes, I-shaped sections, and rectangular columns, as illustrated in Figure 4. Each column was modeled with one end fully restrained to represent a fixed support, while incremental axial compressive loads ranging from 50 kN to 250 kN were applied at the opposite free end. This loading configuration was designed to replicate progressive increases in compressive force and to enable a systematic evaluation of structural response under varying levels of axial stress. To investigate the influence of material properties, two steel grades were incorporated into the analysis. ASTM A36 steel, a widely used carbon structural steel known for its moderate strength and ductility, was adopted as the baseline material representative of conventional construction practice. In contrast, AISI 4340 steel, a high-strength alloy steel distinguished by its superior toughness and load-bearing capacity, was employed to provide a comparative benchmark under identical loading and boundary conditions. This consistent modeling framework ensured that variations in mechanical response could be attributed directly to differences in column geometry and material properties, rather than to inconsistencies in boundary constraints or loading protocols.

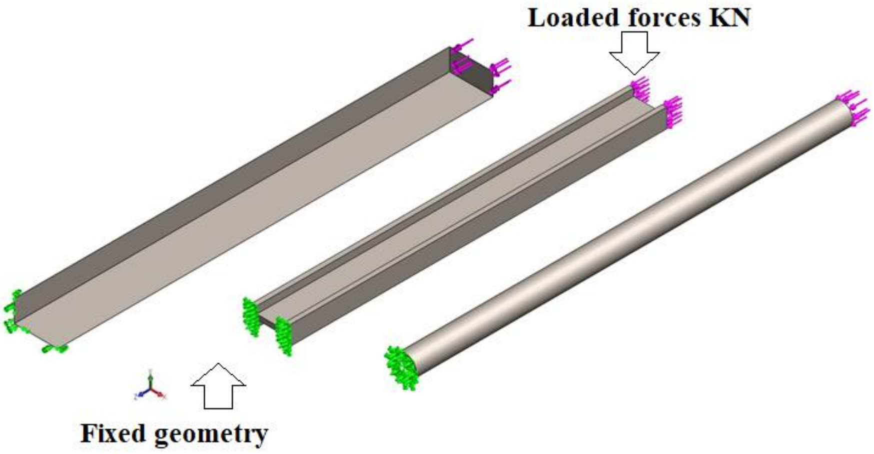


Figure 4 fixed and loaded geometry positions

- **Simulation:** Stress, deflection, and strain responses were recorded and compared across geometries and materials.

Results and discussion

Figure 5 presents the variation of von Mises stress with applied axial force for different column geometries and steel grades. In all cases, the stress increases proportionally with the applied load, confirming the expected linear relationship between force and stress. The influence of column geometry is evident: rectangular columns consistently exhibit the lowest stress values under identical loading conditions, while I-shaped columns show intermediate stress levels due to their improved stiffness and load distribution. Hollow circular tubes, however, generate the highest von Mises stress ratios, with values reaching approximately (2 E 10^{-7} N/m^2) indicating localized stress concentrations despite their superior axial load-carrying capacity. Across all geometries, AISI 4340 steel demonstrates higher strength compared to ASTM A36, yet the geometric trends remain consistent for both materials. These results highlight the combined importance of material selection and geometric configuration in determining the structural performance of columns under compressive loading.

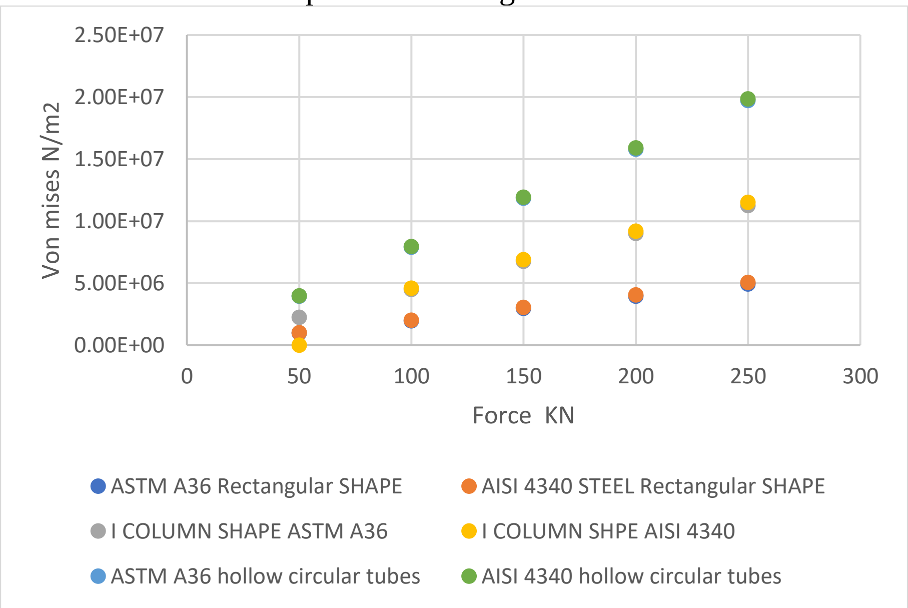


Figure 5 Von mises vs loads KN

Figure 6 illustrates the variation of displacement with applied axial force for different column geometries and steel grades. In all cases, displacement increases proportionally with the applied load, confirming the expected linear relationship between force and deformation. The effect of geometry is evident: rectangular columns consistently show the lowest displacement values under identical loading conditions, while I-shaped sections exhibit intermediate levels due to their improved stiffness and load distribution. Hollow circular tubes produce the highest displacement, reaching approximately (7.07 e10^{-2}mm), reflecting their reduced stiffness despite superior load-carrying capacity. Across all geometries, AISI 4340 steel demonstrates greater displacement compared to ASTM A36, although the geometric trends remain consistent for both materials. These findings emphasize the combined influence of material properties and column geometry on deformation behaviour under compressive loading.

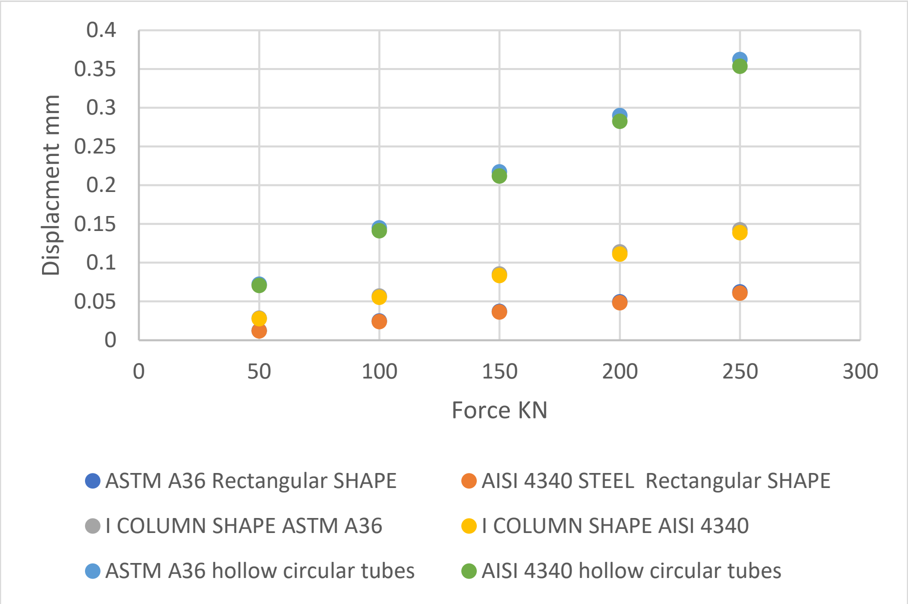


Figure 6 Displacement vs Loads

Figure 7 illustrates the variation of strain with applied axial force for different column geometries and steel grades. In all cases, strain increases proportionally with the applied load, confirming the expected linear relationship between force and deformation. The influence of geometry is evident: rectangular columns consistently exhibit the lowest strain values under identical loading conditions, while I-shaped sections show intermediate levels due to their improved stiffness and load distribution. Hollow circular tubes produce the highest strain, reaching approximately 8E-5, reflecting their reduced stiffness despite their ability to sustain higher loads. Across all geometries, AISI 4340 steel demonstrates greater strain compared to ASTM A36, although the geometric trends remain consistent for both materials. These findings highlight the combined role of material properties and column geometry in governing deformation behavior under compressive loading.

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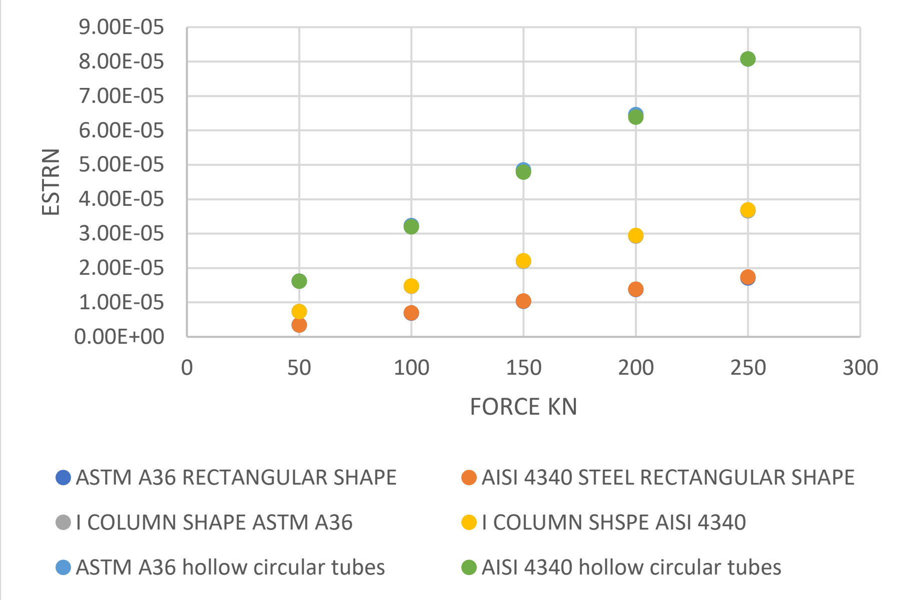

Figure 7 ESTRN Vs Loads

Figure 8 presents the stress and displacement analysis under a 250 kN load for a rectangular column geometry, replicating the conventional shape of a concrete column with identical dimensions. This column has a volume of 0.32 m³, a weight of 24,617.6 N, and a mass of 2,512 kg. In comparison, the geometry shown in Figure 9 has a volume of 0.13 m³, a weight of 10,731 N, and a mass of 1,095.04 kg, representing a reduction of approximately 50% in weight, mass, and volume. Similarly, the hollow circular tube illustrated in Figure 10, with a volume of 0.05498 m³, a weight of 4,229.45 N, and a mass of 431.58 kg, demonstrates a substantial reduction in all three parameters. These reductions highlight the efficiency of alternative geometries, offering significant advantages in terms of cost savings, material optimization, and improved load distribution while maintaining structural performance.

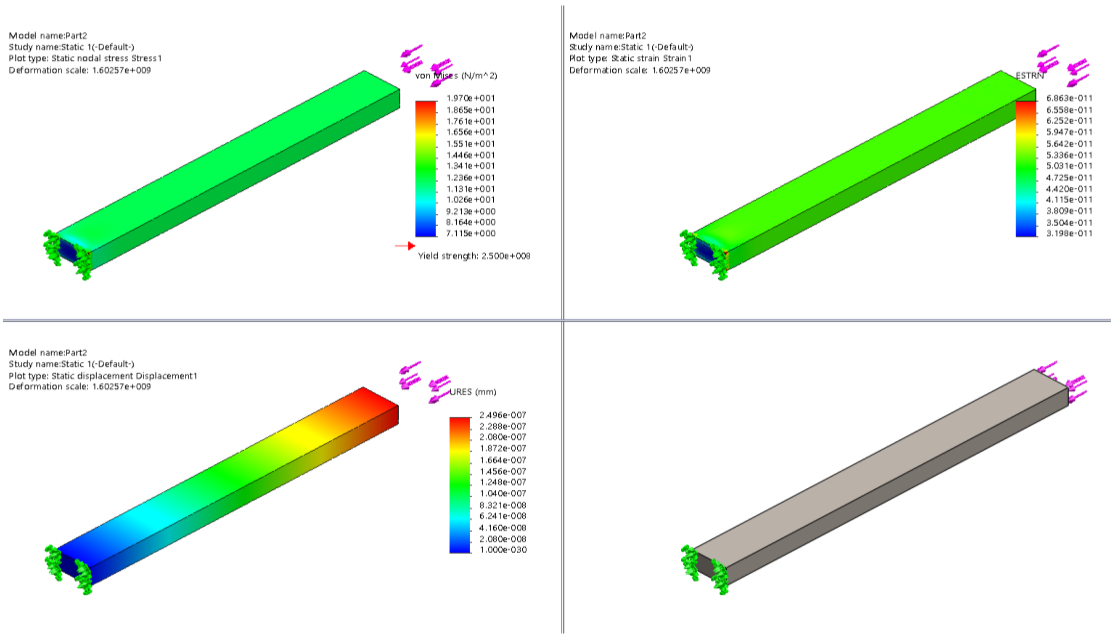

Figure 8 Comparison of Rectangular shape all stress analysis 250KN

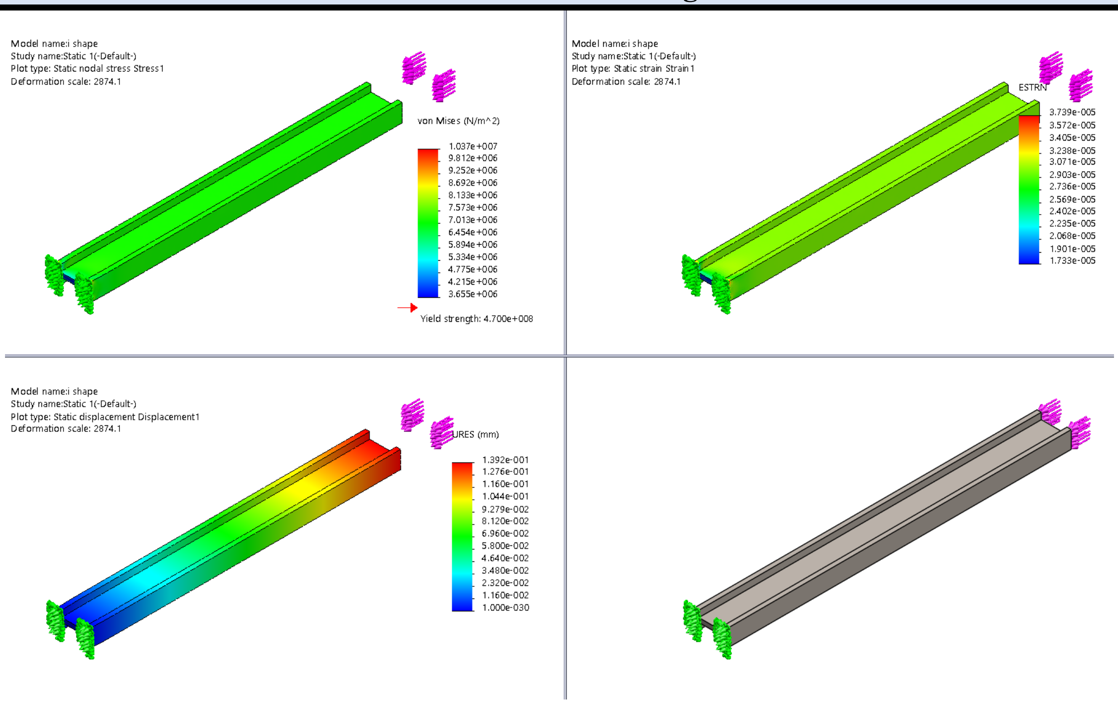

Figure 9 Comparison of I shape all stress analysis 250KN

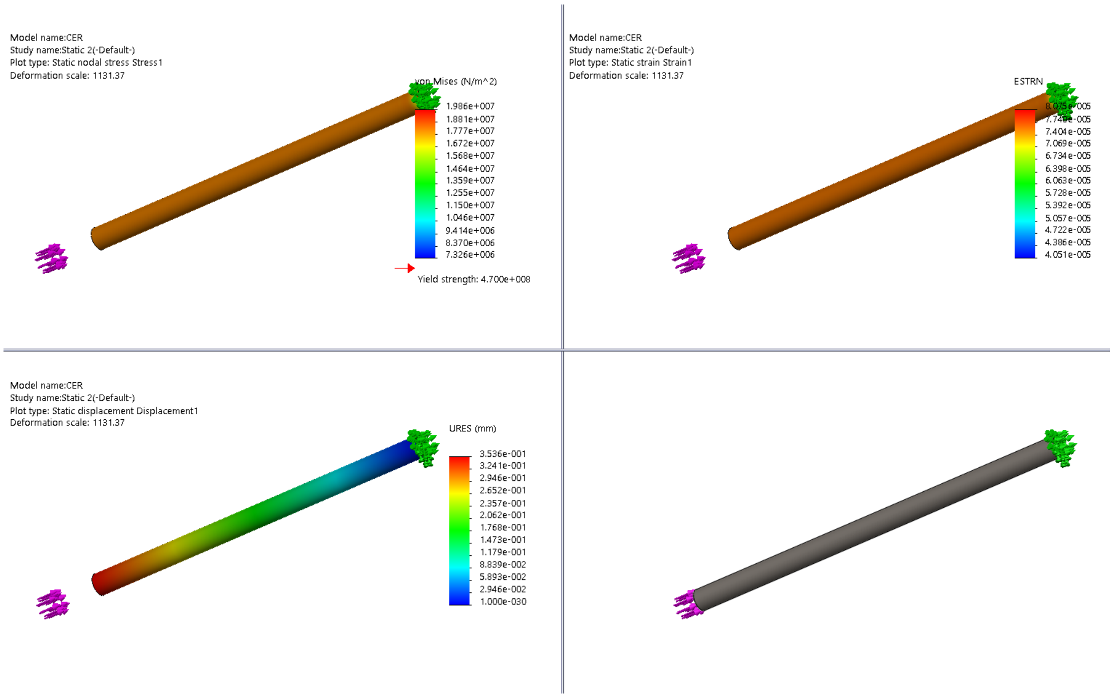

Figure 10 Comparison of Hollow Circular Tubes shape all stress analysis 250KN

Figure 11 compares the volumes of the three column geometries. The hollow circular tube shows the greatest reduction in volume, demonstrating its efficiency in minimizing material usage. The I-shaped section exhibits a moderate decrease in volume relative to the solid rectangular column, balancing strength with material economy. In contrast, the solid rectangular column has the largest volume, reflecting its conventional design but reduced efficiency in terms of material optimization. These comparisons highlight how geometric configuration directly influences structural efficiency and resource utilization.

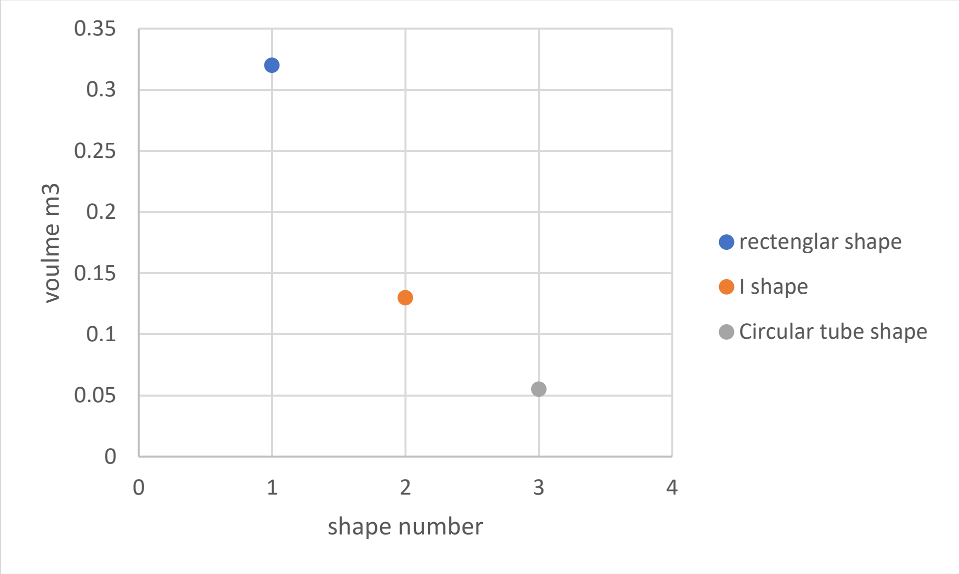

Figure 11 Comparison of the volume three shapes geometry

Figure 12 compares the weights of the three column geometries. The hollow circular tube demonstrates the greatest reduction in weight, highlighting its efficiency in minimizing material usage. The I-shaped section shows a moderate decrease in weight relative to the solid rectangular column, offering a balancé between strength and material economy. In contrast, the solid rectangular column has the highest weight, reflecting its conventional design but reduced efficiency in terms of material optimization. These results emphasize how geometric configuration directly influences structural efficiency, resource utilization, and overall design performance.

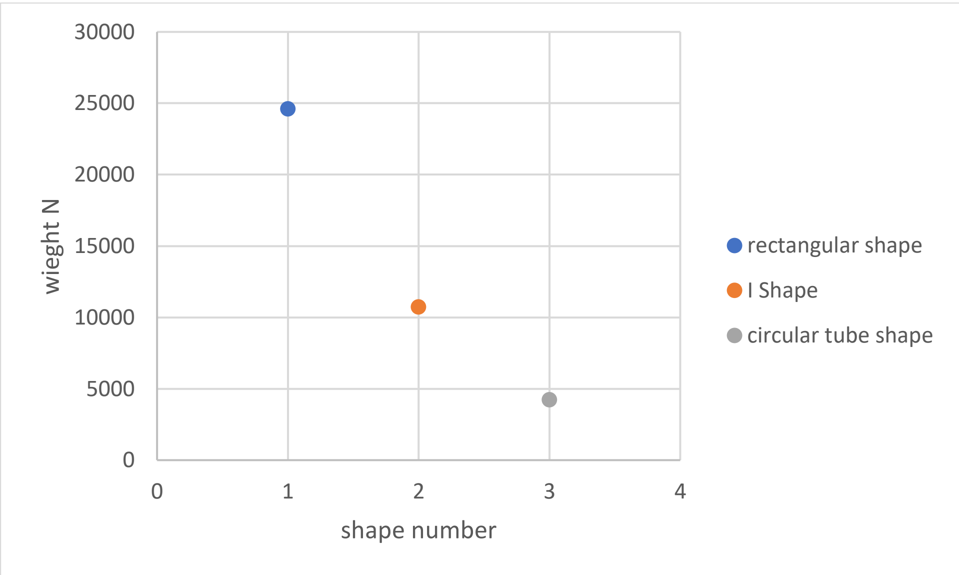

Figure 12 Comparison of the weights three shapes geometry

Figure 13 compares the masses of the three column geometries. The hollow circular tube exhibits the greatest reduction in mass, underscoring its efficiency in minimizing material usage. The I-shaped section shows a moderate decrease in mass relative to the solid rectangular column, offering a balance between strength and material economy. In contrast, the solid rectangular column has the highest mass, reflecting its conventional design but reduced efficiency in terms of material optimization. These findings highlight how geometric configuration directly impacts structural efficiency, resource utilization, and overall design performance.

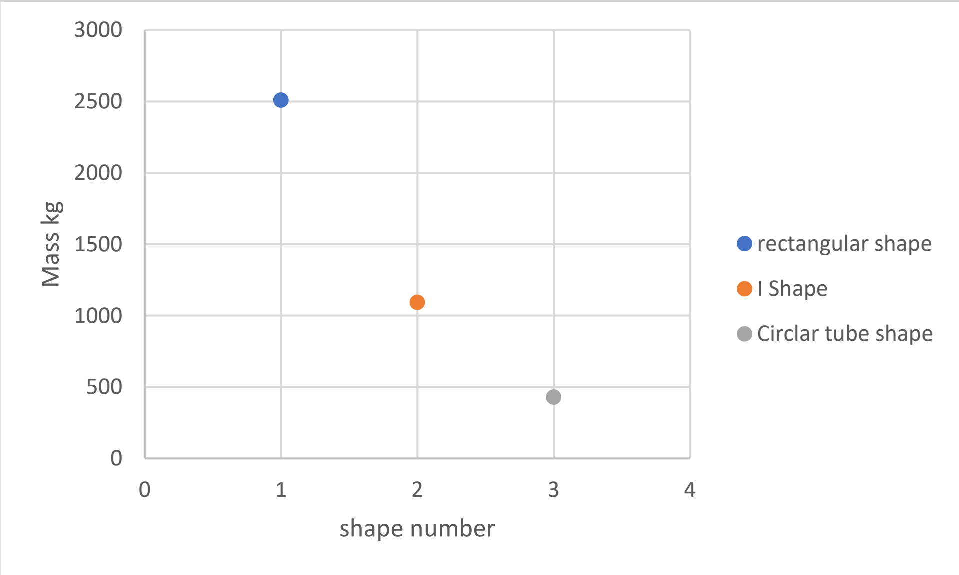

Figure 13 Comparison of the mass three shapes geometry

Conclusion

Structural efficiency is governed primarily by geometry, with material strength serving as an amplifying factor. Hollow circular tubes consistently demonstrated superior stress distribution, reduced displacement, and enhanced buckling resistance, while I-shaped sections provided a balanced compromise between strength and deflection. In contrast, solid rectangular sections underperformed across all loading conditions, highlighting the limitations of conventional geometries in terms of efficiency and material economy.

The hollow circular tube fabricated from AISI 4340 steel emerged as the most efficient configuration, delivering nearly four times the stress capacity of the baseline rectangular ASTM A36 column. This remarkable improvement underscores the critical role of combining geometry optimization with advanced material selection in achieving high structural performance. Beyond stress capacity, the reductions in volume, weight, and mass observed in optimized geometries translate directly into cost savings, improved load distribution, and enhanced sustainability in structural applications.

These findings emphasize that future structural design should not rely solely on material strength but must integrate geometric innovation to maximize efficiency. The comparative analysis demonstrates that hollow and optimized geometries can achieve significant reductions in resource consumption while maintaining or improving mechanical performance. Such strategies are particularly relevant in modern engineering contexts where sustainability, lightweight construction, and cost efficiency are increasingly prioritized.

In summary, geometry optimization coupled with advanced materials such as AISI 4340 steel provides a pathway toward more efficient, economical, and sustainable structural systems. This study highlights the importance of adopting innovative design approaches that balance mechanical performance with resource utilization, offering valuable insights for both academic research and practical engineering applications.

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