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Design and Analysis of Crane Hook with Trapezoidal Cross-Section: A Study on Static Structural and Modal Analysis

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Abstract

In material handling equipment, crane hooks are essential parts that must withstand varying loading conditions. The performance characteristics of crane hooks made of different materials are thoroughly examined in this work. Total deformation and equivalent stress under operating loads are evaluated using Finite Element Analysis (FEA). The research technique includes using industry-standard FEA software packages like ANSYS for finite element meshing and simulation after creating 3D models of crane hooks using SolidWorks Computer Aided Software (CAD) software. To model operational stresses, a variety of loading scenarios that closely resemble real-world circumstances are used, and material parameters like yield strength and modulus of elasticity are taken into account. Through systematic analysis and comparison, this study evaluates the total deformation and equivalent stress distributions across crane hooks with a trapezoidal cross-section with the material assigned AISI 1040, AISI 4140 and Stainless Steel (SS316). The hooks with different materials were loaded at loads of 20 kN, 35 kN and 50 kN to check the effect of load on each material. The influence of material properties and hook geometry on deformation and stress distribution is examined to determine the material better for the application of crane hooks. Also, modal analysis was conducted to determine deformation at a specific frequency. Analysis reveals insights into deformation and stress distribution, helping material selection and design optimisation of hook. Findings contribute to enhancing safety and efficiency in the design process of trapezoidal cross-sectional hooks.

Major Findings: *The primary results reveal that crane hooks featuring trapezoidal cross-sections demonstrate superior load-bearing capabilities and diminished stress concentration, thereby improving durability and operational safety when handling heavy loads.*

Keywords: *ANSYS, Crane Hook, Deformation, FEA, Modal Analysis, Stress*

1.0 Introduction

A crane is a widely used material handling equipment to lift and shift loads[1]. It comprises of boom, hoist and hook, where the load is attached by belts or chains. A Crane hook is an important component, as the load is fastened to it directly and the stress acting on it is maximum[2–4]. Crane hooks with trapezoidal, circular, rectangular and triangular cross-sections are used commonly[5–7]. Crane hooks come in various configurations and designs, each tailored to meet specific operational requirements and load characteristics[8,9]. These encompass single hooks, double hooks and specialised variants such as C-hooks and coil hooks, each exhibiting unique geometries and load-bearing capacities. Additionally, crane hooks may integrate supplementary features

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such as latch mechanisms, swivel attachments and load sensors to enhance operational versatility and safety[10–12].

Typically, iron or steel is used in the construction of crane hooks. Crane hooks with a trapezoidal cross-section find applications in construction, shipbuilding, mining and manufacturing, attributed to their superior load-bearing capacity and minimised stress concentration[13–15]. Low alloy steels are utilised in the construction of heavy-duty crane hooks. However, the raw material is not the only factor that contributes to the hook's capacity to hold heavy loads[14–17]. To create a crane hook that will last for a long time, the steel grade, heat treatment and forging are all equally important. It is essential to have good forging. Because of its superior structural reliability, forging is superior to the other methods of working with metal. It eliminates any defects within the hook, such as gas pockets or cavities, that could potentially have an impact on its long-term performance. As a result, the hook's strength, load-bearing capacity and fatigue resistance are all increased. The stress and loads imposed on crane hooks during lifting operations are complex, comprising a mixture of static and dynamic forces. Static loads emanate from the weight of the lifted object and any associated rigging components, imposing a constant downward force on the hook[18–21]. Conversely, dynamic loads stem from the crane's motion and induced oscillations by load movement, creating transient stress and fatigue effects on the hook structure.

For the optimisation, Benkar *et al.*[22] worked on the crane hook. Using the ANSYS 14 workbench, a solid model was built to examine the stress pattern of the crane hook under loading conditions. Using constant area, he computed the stress pattern for different cross-sectional topologies, including circular, trapezoidal, triangular, and rectangular, and concluded that the area of a rectangular cross-section yields the lowest deformation and stress. Crane hooks are vital load-bearing components often subjected to high stress, risking mechanical failure. Uddanwadiker[23] studied stress patterns under load and researchers created a 3D crane hook model using the Capability Maturity Model (CMM) and CAD software. Stress distribution was validated using a Diffused Light Polariscope on an acrylic model, helping identify critical areas and optimising the hook's design for durability. Narvydas *et al.*[24] used FEA to examine circumferential stress concentration factors with shallow notches of the lifting hooks of the trapezoidal cross-section. The assessment of the strength and durability of machines and structures made extensive use of the stress concentration variables. A chosen generic equation was fitted to the FEA results. This produces formulas that can be used to quickly evaluate stress concentration factors in engineering without the need for finite element models. According to the lifting hook design guidelines, ductile materials must be used to prevent brittle failure. To account for stress triaxiality, they looked into the strain-based failure criteria. Crane hook structural analysis using FEM was presented in detail by Bergaley *et al.*[25]. For FEA, a crane hook was procured from the neighbourhood market. After that, the hook was put through a tension test on the Universal Testing Machine (UTM) machine to identify the hook's yield point and the area under the greatest amount of stress. With dimensions and materials similar to the crane hook that was bought from the market, a model of the hook was created using Computer-Aided Engineering (CAE) software. A theoretical analysis was performed and compared with the obtained results. Then cross-section in which minimum stress-induced for a given load was modified through FEM. Patel *et al.*[26] focus on stress analysis and design improvement of a crane hook. The study involves solid modelling and FEA using SolidWorks and ANSYS workbench. The methodology includes stress calculations for a trapezoidal cross-section hook, comparing analytical and FEA results. Findings suggest stress concentration at inner surfaces and propose design modifications to reduce failure risks. The study aims to enhance the crane hook's performance and safety by optimising its design parameters. Bhagyaraj *et al.*[27] explore the design and analysis of a 25-ton resistant block hook using Alloy 1.2367. SolidWorks and ANSYS workbench are employed for modelling and FEA. Results show stress concentration at inner surfaces, with Von Mises stress and factor of safety discussed. The study aims to enhance hook performance and safety by optimising design parameters, highlighting the importance of material properties and simulation techniques in crane hook analysis. Bhatkar *et al.*[28] focus on the FEA and optimisation of a crane hook using the Taguchi approach. It discusses the importance of designing crane hooks to withstand heavy loads safely, emphasising the use of CAE to enhance the design process. The study involves

CAD modelling, stress analysis, and material selection to determine the most suitable material for manufacturing the crane hook. By employing FEM and Taguchi method, the research aims to minimise stress-induced failures in crane hooks, leading to improved performance and safety in industrial applications. Singh *et al.*[29] present a study into the behaviour of the hook under various grades of stress. By analysing the forged Ramshorn hook with a trapezoidal cross-section, the researchers aim to understand its performance characteristics and deformation patterns. This experimental investigation provides valuable insights into the structural integrity and mechanical properties of the Ramshorn hook, contributing to the broader understanding of material behaviour under different stress conditions.

This study examined the optimal material for crane hooks through the utilisation of FEA. To assess their performance under different loading conditions, an analysis was conducted on 3D models of crane hooks made from different materials (AISI 1040, AISI 4140, and SS316). The study investigated the impact of these materials on the overall deformation and stress distribution in the hooks. The results have the potential to enhance the design of crane hooks, leading to improved safety and efficiency.

2.0 Material and Designing of Crane Hook

2.1 Dimensions of the Crane Hook

Several considerations must be carefully considered when choosing the right size for a crane hook to guarantee efficiency, safety and peak performance. The dimensional terminologies of the trapezoidal crane hook are shown in Figure 1. The selected dimensions for the crane hook are listed in Table 1.

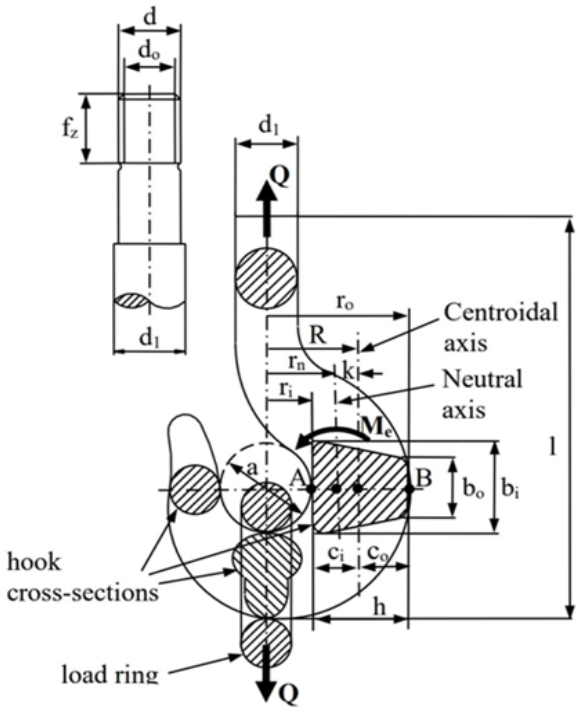


Figure 1. Dimensional terminologies of trapezoidal crane hook[30].

Table 1. Selected dimensions for the crane hook

Parameter	Value
a	70mm
r_i	35mm
r_n	55mm
R	70mm
or	105mm
b_o	25mm
b_i	65mm
d_1	52mm
d	42mm
d_o	36mm
h	70mm

2.2 Material Assignment

The following materials were investigated for the crane

Table 2. Material properties

Parameters	**AISI 1040**	**AISI 4140**	**SS 316**
Density (kg/m^3)	7850	7850	7966
Tensile Yield Strength (MPa)	415	415	290
Tensile Ultimate Strength (MPa)	620	655	580
Young's Modulus (GPa)	210	190	200
Poisson's Ratio	0.28	0.27	0.30

hook to conduct the research: AISI 1040, AISI 4140 and Stainless Steel (SS316). The properties of these materials were explored using the student edition of ANSYS 2023 R3 and listed in Table 2.

2.3 CAD Model

The crane hook's CAD model was initially constructed in SolidWorks 2021 before being imported into ANSYS 2023 R2 to conduct FEA. The CAD geometry of the crane hook is shown in Figure 2.

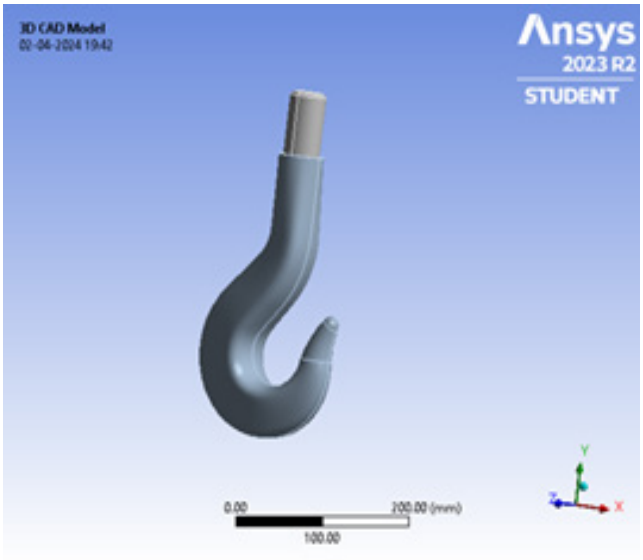


Figure 2. CAD model of crane hook.

2.4 Numerical Approach: Finite Element Analysis

FEA is the application of FEM to model a situation numerically. FEM, which utilises finite elements to decompose a complex system into smaller components, has been implemented in a variety of contexts. To ensure precise and dependable outcomes, it is imperative to correctly determine the number of finite elements and calculation parameters for every given problem. The imported geometry was then assigned material during each analysis for a specific load. The model was meshed where adaptive sizing was not used, instead proximity and curvature were captured with minimum curvature and proximity size of 0.21521mm and element size of 21.521mm. The mesh-generated crane hook is shown in Figure 3.

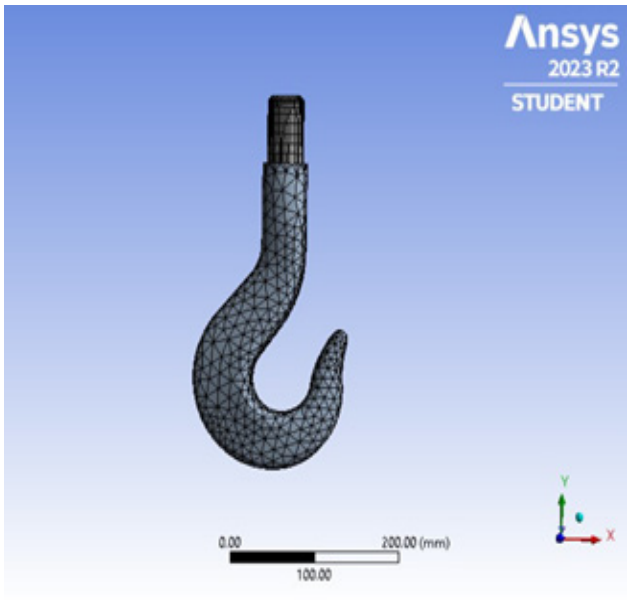


Figure 3. Mesh generated for crane hook.

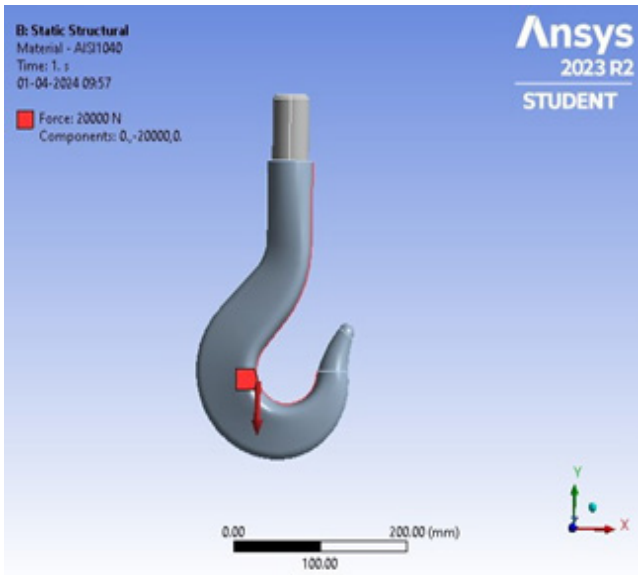


Figure 4. Location of load application.

A total of 11551 nodes were produced, while 5403 elements were generated. Subsequently, boundary conditions were implemented, which involved providing a fixed support to the shank of the hook and applying a vertical force to its eye. Each material-specific hook was subjected to three distinct loads: 20,000N, 35,000N and 50,000N. The location of the load application on the crane hook is shown in Figure 4. In each instance, the Von Mises stress and total deformation were evaluated.

Modal analysis was subsequently performed to compare deformation at a certain frequency.

3.0 Result and Discussion

3.1 Static Structural Analysis

Following the implementation of suitable boundary conditions, a static structural evaluation was performed to assess the performance of the crane hook subjected to a load of 20 kN. The findings presented in Figures 5 and 6 demonstrate the peak von Mises stress and overall deformation that the hook undergoes across different material types. The findings demonstrated that the hook constructed from SS316 stainless steel showed minimal deformation, highlighting its exceptional mechanical stability and resistance to elastic deformation when subjected to the applied load. This indicates that SS316 is a superior material selection for crane hook applications, where limited deformation and elevated strength are essential for ensuring operational safety and durability.

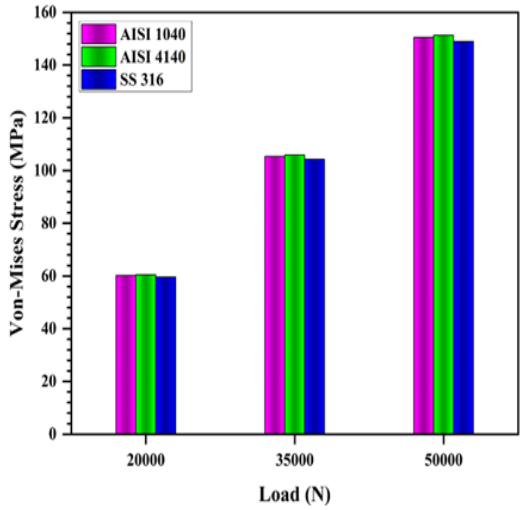


Figure 5. Von-Mises stress vs. load.

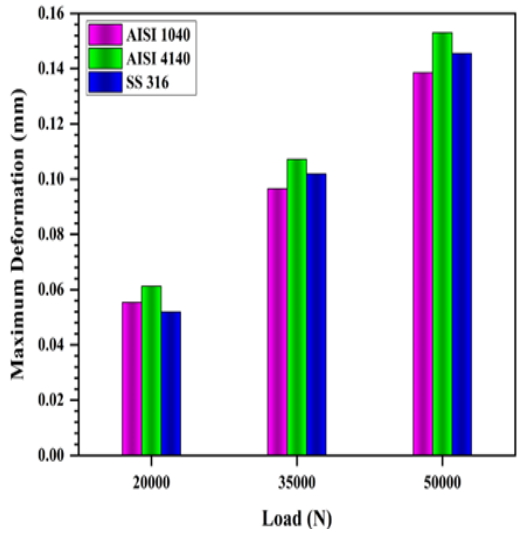


Figure 6. Maximum deformation vs. load.

3.2 Modal Analysis

Modal analysis of the three hooks was performed after the static structural analysis was completed. For every hook, a maximum of five different modes were generated. Figure 7 depicts the fifth mode shape of an AISI 1040 crane hook, Figure 8 depicts the fifth mode shape of an AISI 4140 crane hook and Figure 9 depicts the fifth mode shape of an SS316 crane hook. It has been determined through the modal analysis that the fifth mode shape is where AISI 1040 displays the lowest frequency.

The results obtained from modal analysis (fifth mode shape) of crane hook for three different materials are listed in Table 3. Among the three materials, AISI 4140 exhibits the highest maximum frequency, which is 1.19 × 10-3Hz. Nevertheless, it possesses the greatest magnitude of deformation, reaching a maximum of 20.77mm. SS316 exhibits the second-highest maximum frequency,

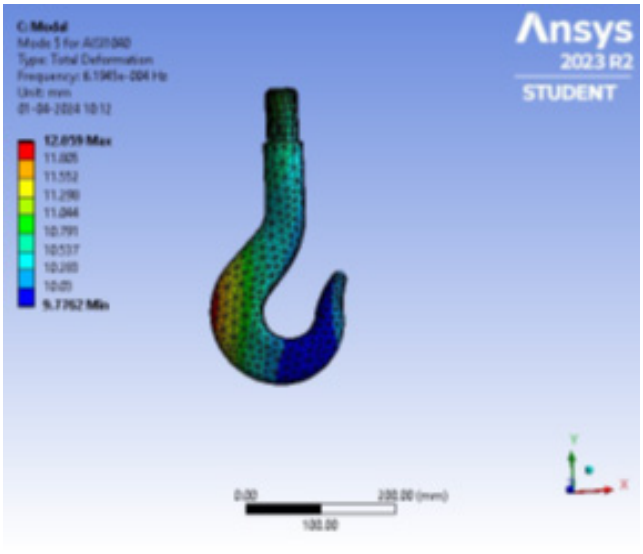


Figure 7. Fifth mode shape of AISI 1040 crane hook.

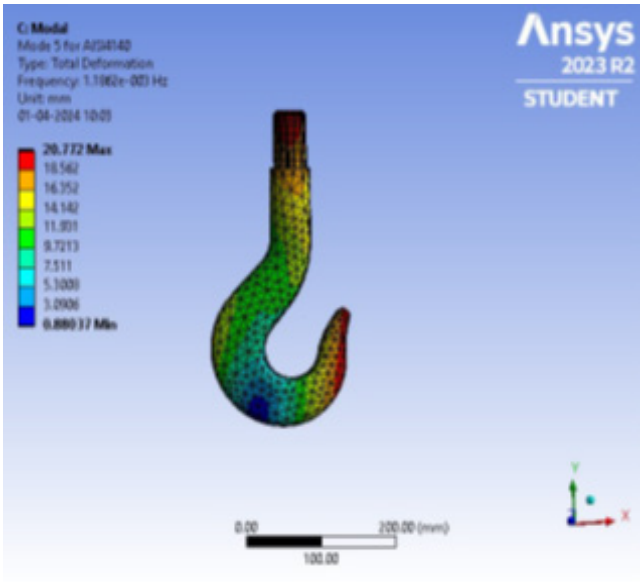


Figure 8. Fifth mode shape of AISI 4140 crane hook.

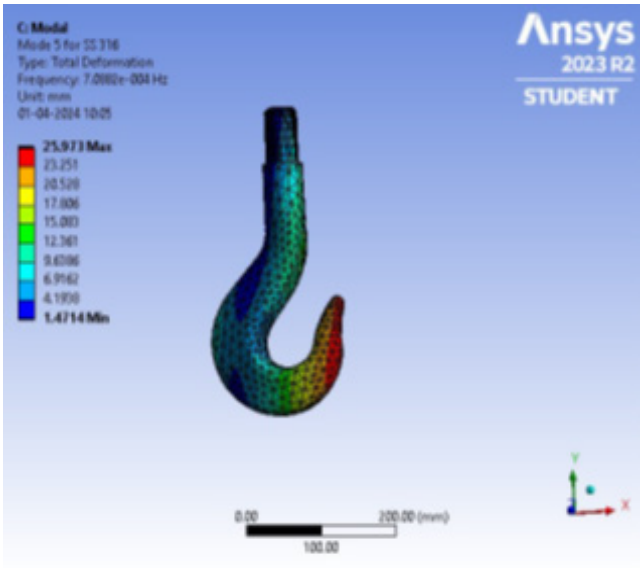


Figure 9. Fifth mode shape of SS316 crane hook.

which is 7.09 × 10-4 Hz, and the highest maximum deformation, measuring 25.97mm. AISI 1040 exhibits a minimum maximum frequency of 6.19 × 10-4Hz and a minimum maximum deformation of 12.06mm. Ultimately, the selection of the hook material will be dependent upon the particular needs and specifications of the given application. If the main consideration is rigidity, then AISI 1040 would be the optimal selection. If the main priority is to maximise strength, then AISI 4140 would be the optimal selection. In instances where

Table 3. Comparison of fifth mode shape results

Fifth Mode Shape	AISI 1040	AISI 4140	SS 316
Maximum Frequency (Hz)	6.19×10^{-4}	1.19×10^{-3}	7.09×10^{-4}
Maximum Deformation (mm)	12.059	20.772	25.973

it is crucial to achieve a balance among rigidity, durability and corrosion resistance, SS316 stainless steel emerges as the optimal choice. The material's exceptional ability to withstand oxidation and corrosion, along with its sufficient mechanical strength, renders it highly suitable for demanding environments where maintaining structural integrity and environmental durability is essential.

4.0 Conclusion

The static structural and modal analyses conducted on the crane hook using different materials, that is, AISI 1040, AISI 4140 and SS 316, yielded insightful findings. In terms of static structural analysis, as the applied load increased from 20,000N to 50,000N, all materials exhibited a proportional increase in maximum Von-Mises stress and maximum deformation. However, the magnitude of these increases varied among the materials, with AISI 4140 generally displaying the highest values followed by SS 316 and AISI 1040. This suggests that AISI 4140 may be more prone to early failure as compared to the other materials under similar loading conditions. Moreover, modal analysis provided valuable insights into the dynamic behaviour of the crane hook. The maximum frequency and deformation observed in the fifth mode shape were significantly influenced by the material properties. AISI 4140 exhibited the highest maximum frequency, indicating its potential to withstand dynamic loads more effectively than AISI 1040 and SS 316. However, it also showed the highest maximum deformation, which warrants further investigation into its structural integrity under dynamic loading scenarios. In summary, the choice of material for the crane hook significantly impacts its structural and dynamic performance. While AISI 4140 demonstrates favourable characteristics in terms of static

strength and frequency response, its susceptibility to deformation under dynamic loads necessitates careful consideration. Future research could delve deeper into optimising material selection and design parameters to enhance the overall performance and reliability of crane hooks in practical applications.

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