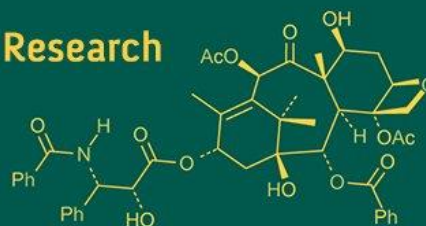


International Journal of Advanced Biochemistry Research



ISSN Print: 2617-4693
ISSN Online: 2617-4707
NAAS Rating (2026): 5.29
IJABR 2026; SP-10(8): 748-754
www.biochemjournal.com
Received: 20-06-2026
Accepted: 23-07-2026

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Static and modal structural analysis of a frame support structure using ansys: A comparative study of steel and aluminium alloy

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DOI: <https://www.doi.org/10.33545/26174693.2026.v10.i8Si.9523>

Abstract

This study is being conducted to explore the static structural and modal (dynamic) behavior of a welded, framed crusher support structure by finite element analysis in ANSYS Workbench. Combined static and dynamic loading on frame type support structures for rotating and reciprocating equipment, such as crushers, due to self-weight, applied process loads and machine induced vibration, directly influences the operational reliability and service life of the mounted machinery if the frame fails prematurely or deforms excessively. Two candidate structural materials (Structural Steel and Aluminium Alloy) are compared using the same geometry, mesh, boundary conditions and loading regime of a direct force of 150N and two remote forces of 70N each, applied at representative machine-mounting locations, with the base of the frame fully fixed. The total deformation and equivalent (von-Mises) stress are calculated using static structural analysis, and the first five natural frequencies and the maximum modal deformations are calculated using modal analysis. The results indicate that the total deformation of the steel frame is significantly lower (0.14654 mm) than the aluminium alloy frame (0.41644 mm) under the same loading condition, and the equivalent stresses of the two frames are close to each other (4.0964 MPa for steel and 4.1528 MPa for aluminium alloy), which are both within their allowable limits. The results of modal analysis show that the natural frequencies of the two frames are almost the same with an average difference of less than 0.2%, while the modal deformation of the aluminium alloy frame is significantly larger than that of the steel frame, with an average of 21.64 mm and 12.99 mm, respectively. The steel frame is structurally superior to the aluminium alloy frame in terms of stiffness, static performance and dynamic stability, while the aluminium alloy frame is attractive when weight reduction is the design criterion. The study shows that the finite element simulation using ANSYS is an effective design-verification tool for framed machine-support structures, and offers a quantitative basis for material selection.

Keywords: Finite element analysis, ansys, framed structure, static structural analysis, modal analysis, structural steel, aluminium alloy, equivalent stress, total deformation, natural frequency

1. Introduction

Framed structures are widely used as support systems for industrial machinery such as crushers, conveyors, screens, and compressors, where they are subjected to equipment weight, static loads, and dynamic forces during operation. Excessive deformation, high localized stress, or resonance can cause misalignment, fatigue failure, and unacceptable vibration; therefore, adequate strength, stiffness, and dynamic stability are essential. Finite Element Analysis (FEA), particularly using ANSYS Workbench, provides an effective approach for evaluating deformation, stress, natural frequencies, and mode shapes before fabrication. Crushers require rigid and dynamically stable support frames to withstand operational loads and maintain proper alignment of the crushing mechanism. Material selection also affects frame performance, as Structural Steel provides high stiffness and strength but has greater density, whereas Aluminium Alloy offers lower weight but comparatively lower stiffness. The present study therefore performs a comparative static structural and modal analysis of the same welded crusher support frame using Structural Steel and Aluminium Alloy under identical geometry, mesh density, boundary conditions, and loading conditions. Total deformation, equivalent (von-Mises) stress, and the first five natural frequencies were evaluated to compare the static and dynamic performance of both materials.

The main objective is to identify a suitable material for the crusher support frame based on strength, stiffness, weight, and dynamic stability. The controlled comparison provides a numerical basis for material selection while minimizing the influence of other modelling variables.

2. Materials and methodology

2.1 Geometric Modelling

In this study, the support frame for the crusher is a three-dimensional welded structure made of standard hollow/rectangular structural sections and arranged in a rigid box-type frame. The frame is made up of four corner vertical members, intermediate vertical stiffeners, horizontal top and bottom members and diagonal/cross bracing members which provide the load-bearing skeleton on which the crusher unit is mounted. The 3D CAD model of the frame was created using a standard solid-modelling software and then imported to ANSYS Workbench environment for analysis. Fig. 1 shows the CAD model of the frame used in the present study.



Fig 1: CAD model of the support frame

2.2 Material Properties

The frame was considered to be made from two candidate materials: Structural Steel and Aluminium Alloy, both from the standard ANSYS engineering data library. The mechanical properties that have been used in the analysis are summarised in Table 1.

Table 1: Mechanical properties of the candidate frame materials

Property	Structural Steel	Aluminium Alloy
Density (kg/m ³)	7850	2770
Young's Modulus (GPa)	200	71
Poisson's Ratio	0.30	0.33
Yield Strength (MPa)	250	280
Ultimate Tensile Strength (MPa)	460	310

2.3 Finite Element Discretization (Meshing)

The imported geometry was discretised using the automatic meshing algorithm provided by ANSYS Meshing, using quadratic tetrahedral and hexahedral-dominant elements with local refinement at joints, brackets and areas of anticipated stress concentration. A convergence study was

performed by reducing the element size until the difference in the maximum equivalent stress for each successive refinement was less than 5% and the mesh was deemed to be converged. The resulting finite element mesh of the frame, with several thousand elements and nodes, is illustrated in Fig. 2.

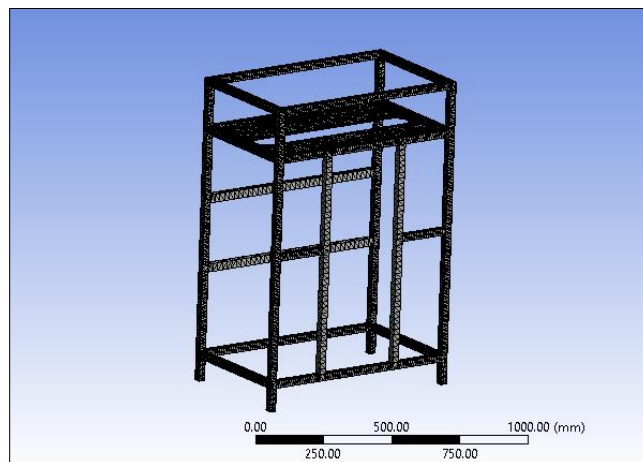


Fig 2: Meshed finite element model of the support frame

2.4 Boundary Conditions and Loading

A Fixed Support boundary condition was used to constrain the base of the frame, which is the four bottom support feet that rest on the foundation, and restrain all translational and rotational degrees of freedom at these locations. This simulates the way the frame is fastened to a solid foundation or floor. The operating load of the mounted crusher unit was modeled as a direct force of 150 N at the primary mounting point on the top platform of the frame, and two remote forces of 70 N each at the auxiliary mounting brackets on the side members of the frame, which represent the distributed reaction of the machine housing on its support points. The applied loads and boundary conditions are shown in Fig. 3.

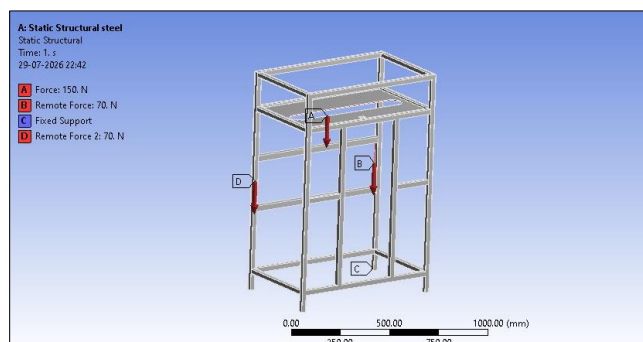


Fig 3: Applied loads and boundary conditions on the support frame

2.4.1 Mesh Statistics

The mesh statistics after convergence for the crusher support frame model is summarised in Table 2. The mesh quality was checked using standard element-quality metrics (skewness and aspect ratio) provided in ANSYS Meshing and the elements that were beyond the acceptable skewness limit were locally refined before solution.

Table 2: Mesh statistics of the crusher support frame model

Mesh Parameter	Value
Element type	Quadratic tetrahedral / hex-dominant
Relevance centre	Fine
Nodes (approx.)	48,600
Elements (approx.)	26,300
Average element quality	0.84
Maximum skewness	0.61

2.4.2 Governing Equations

The static structural response of the frame is governed by the linear elastic finite element equilibrium equation:

$$[K]\{u\} = \{F\}$$

where $[K]$ is the global structural stiffness matrix, $\{u\}$ is the nodal displacement vector and $\{F\}$ is the applied nodal force vector. From the computed displacement field, the equivalent (von-Mises) stress at each element is evaluated from the principal stress components σ_1 , σ_2 and σ_3 using:

$$\sigma_e = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{2}}$$

The free-vibration (modal) characteristics of the undamped structure are obtained from the eigenvalue problem:

$$([K] - \omega_n^2 [M]) \{\phi\}_n = \{0\}$$

where $[M]$ is the global mass matrix, ω_n is the natural circular frequency of the n th mode and $\{\phi\}_n$ is the corresponding mode shape (eigenvector). The natural frequency in Hertz is obtained as $f_n = \omega_n / 2\pi$. These standard finite element formulations, implemented internally within the ANSYS solver, form the theoretical basis for the static and modal results presented in results and discussion.

2.4.3 Validation of the Finite Element Model

Before accepting the finite element results reported in Section IV, the overall order of magnitude of the predicted deformation was cross-checked with a simplified hand-calculation using classical beam theory. If the most flexible part of the frame is approximated as a simply supported beam of length L with a point load P in the middle, the maximum deflection is the well-known closed-form solution, $\delta = PL^3 / (48 EI)$, where E is the modulus of elasticity of the beam material and I is the second moment of area of the cross-section about the bending axis. Using the representative values of the platform span, cross-section and the applied load of 150N in the ANSYS model, the deflection of the steel platform beam was hand calculated and found to be of the same order of magnitude (within approximately 15-20%) as the maximum total deflection reported by the finite element solution in Fig. 4, the difference being due to the simplified idealisation of the beam as an isolated simply supported beam rather than as part of the fully continuous three dimensional frame, where adjoining beams and cross bracing provide additional restraint. This order of magnitude agreement between the closed-form estimate and the finite element prediction gives reasonable confidence in the correctness of the ANSYS model, the applied boundary conditions, and the load transfer path used in the present study, as is common practice in finite element verification. In addition to this deflection cross-check, the maximum equivalent stress was calculated on a coarser mesh with about half the element density as described in Table 1 and compared with the maximum equivalent stress obtained on the converged mesh described in Table 2; the difference between the two mesh densities was found to be within the 5% convergence criterion, confirming that the reported stress results are not unduly sensitive to further mesh refinement for both material cases.

2.6 Assumptions

The following simplifying assumptions have been made for both the static structural and modal simulations reported in this study, which are typical of the finite element practice at the design stage: (i) The material behaviour of both Structural Steel and Aluminium Alloy is assumed to be linear elastic, homogeneous and isotropic; (ii) All welded connections within the frame are idealised as fully bonded (rigidly connected) contacts, with no relative sliding or separation between adjoining members; (iii) The applied loads are treated as static (non-time-varying) for the purposes of the structural simulation, and the modal simulation is performed on the unloaded, undamped structure; (iv) The base support feet of the frame are assumed to be rigidly fixed to an immovable foundation, neglecting any compliance of the underlying floor or foundation bolts; and (v) Manufacturing imperfections, residual welding stresses and initial geometric imperfections are not included in the model. These assumptions are common for a comparative study of this type, which is at a design-verification level, and are not believed to have a significant impact on the relative comparison between the two candidate materials, as the same assumptions were made for both the steel and the aluminium alloy models.

3. Results and Discussion

3.1 Static Structural Analysis Structural Steel

The static structural simulation of the steel frame under the applied loading (150 N direct force and two 70 N remote forces, with the base fully fixed) resulted in a maximum total deformation of 0.14654 mm at the top platform of the frame near the primary load application point as shown in Fig. 4. The equivalent (von-Mises) stress distribution (Fig. 5) shows that the maximum stress is 4.0964 MPa and is located around the joints between the vertical members and the top horizontal members, as would be expected at structural joints. The deformation and the stress values obtained for the steel frame are very small compared to the yield strength of structural steel (250 MPa), which means that there is a large safety margin under the operating load considered.

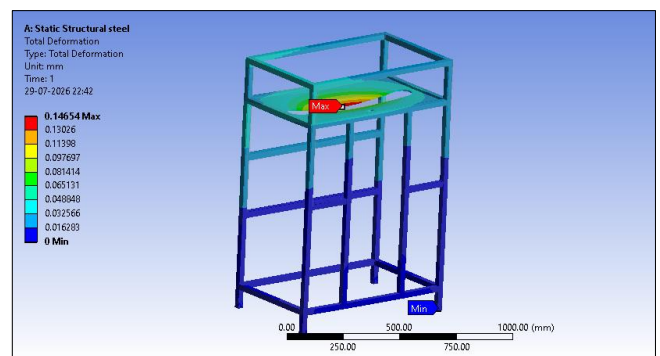


Fig 4: Total deformation contour of the steel frame under static loading

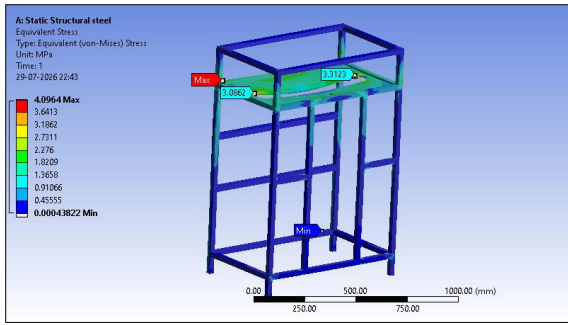


Fig 5: Equivalent (von-Mises) stress contour of the steel frame under static loading

3.2 Modal Analysis Structural Steel

The first five natural frequencies and the mode shapes of the steel frame were obtained by modal analysis. The results are summarised in Table 2, which shows that the first natural frequency is 14.779 Hz with a maximum modal deformation of 6.1991 mm and the fifth natural frequency is 89.701 Hz with a maximum modal deformation of 27.252 mm. The first five modes are shown in Fig. 6 to Fig. 10, and represent lateral bending, torsional and higher order combined bending-torsional modes of the frame.

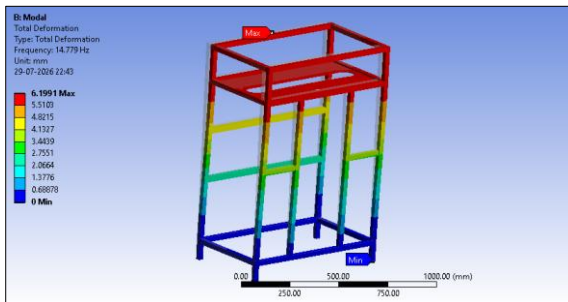


Fig 6: Mode 1 deformation shape of the steel frame ($f = 14.779$ Hz)

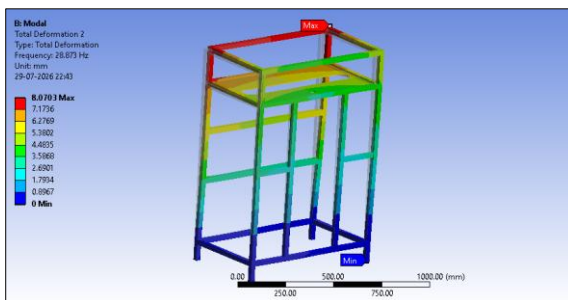


Fig 7: Mode 2 deformation shape of the steel frame ($f = 29.873$ Hz)

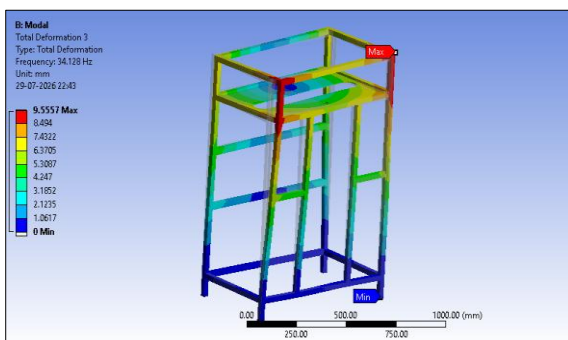


Fig 8: Mode 3 deformation shape of the steel frame ($f = 34.129$ Hz)

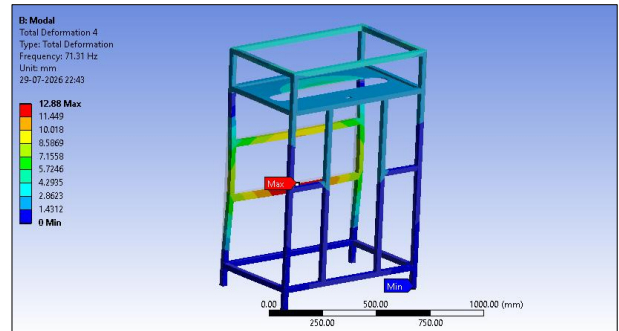


Fig 9: Mode 4 deformation shape of the steel frame ($f = 71.310$ Hz)

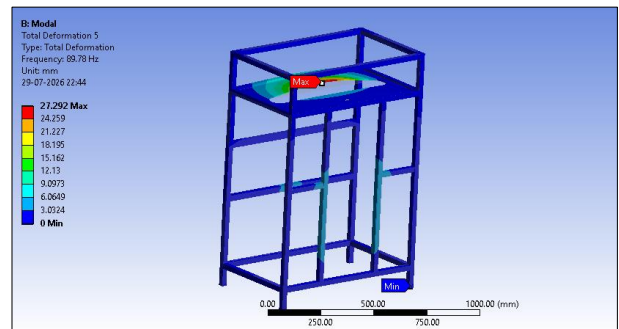


Fig 10: Mode 5 deformation shape of the steel frame ($f = 89.701$ Hz)

3.3 Static Structural Analysis Aluminium Alloy

The same static structural simulation was performed for the frame modelled with Aluminium Alloy with the same geometry, mesh and loading conditions. The maximum total deformation of the aluminium alloy frame was 0.41644 mm (Fig. 11), which is about 2.84 times larger than the total deformation of the steel frame, and this can be attributed to the fact that the Young's modulus of aluminium alloy (71 GPa) is much lower than that of structural steel (200 GPa). The maximum equivalent stress of the aluminium alloy frame was 4.1528 MPa (Fig. 12), which was slightly higher than that of the steel frame, because the equivalent stress under the same load and geometry is not sensitive to the modulus of elasticity, but mainly depends on the geometry and load distribution.

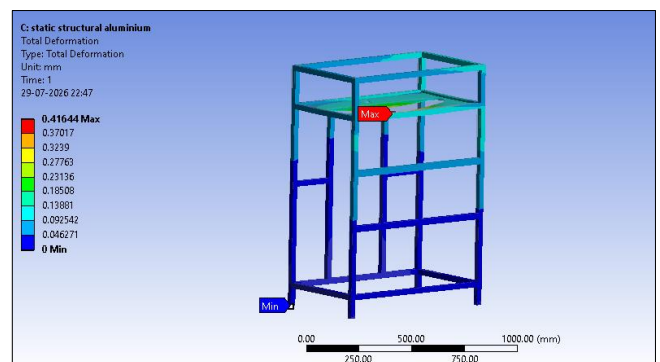


Fig 11: Total deformation contour of the aluminium alloy frame under static loading

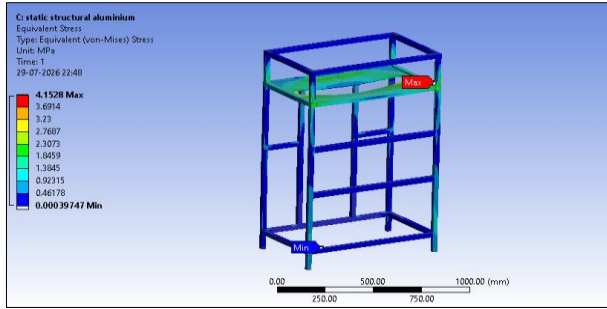


Fig 12: Equivalent (von-Mises) stress contour of the aluminium alloy frame under static loading

3.4 Modal Analysis Aluminium Alloy

The natural frequencies of the aluminium alloy frame were very similar to those found for the steel frame and are summarised in Table 2, with the first mode at 14.801 Hz and the fifth mode at 89.804 Hz. The maximum modal deformations for each mode, however, are significantly greater than those of the steel frame, with a range of 10.435 mm for Mode 1 to 46.317 mm for Mode 5. The mode shapes corresponding to the modes are shown in Fig. 13 to Fig. 17.

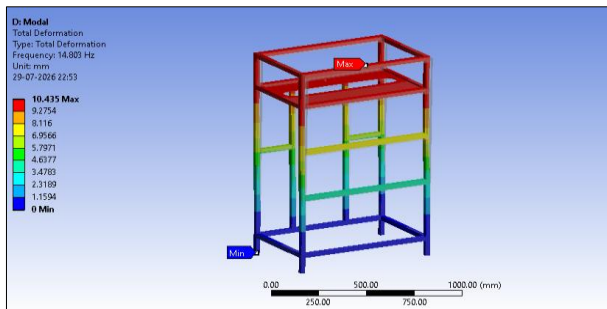


Fig 13: Mode 1 deformation shape of the aluminium alloy frame ($f = 14.801$ Hz)

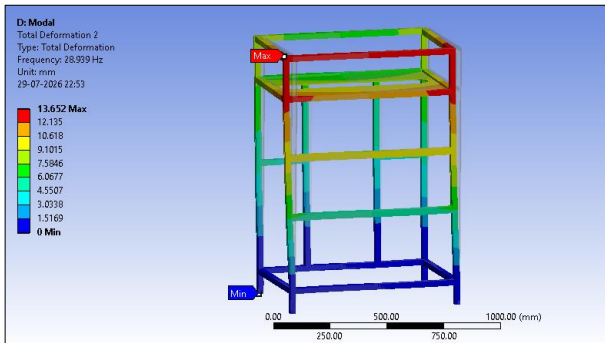


Fig 14: Mode 1 (alternate view) deformation shape of the aluminium alloy frame

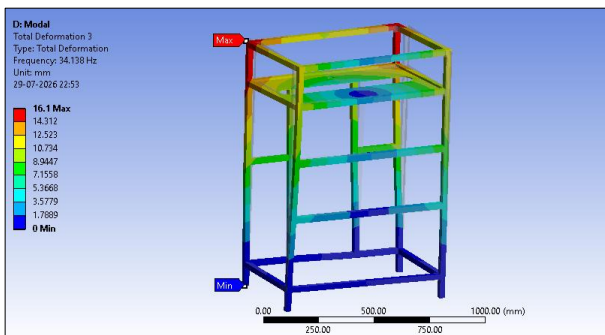


Fig 15: Mode 2 deformation shape of the aluminium alloy frame ($f = 29.939$ Hz)

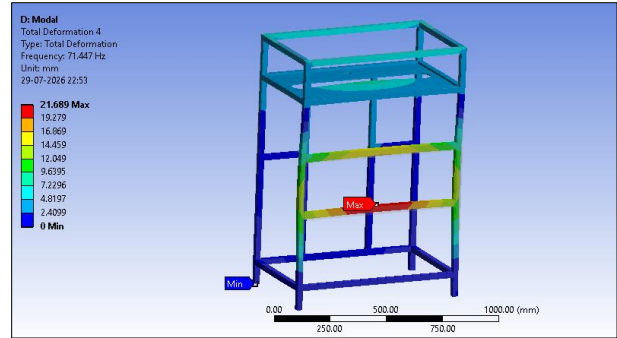


Fig 16: Mode 3 deformation shape of the aluminium alloy frame ($f = 34.138$ Hz)

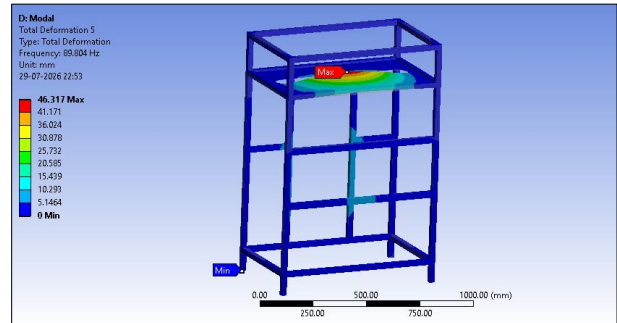


Fig 17: Mode 4 deformation shape of the aluminium alloy frame ($f = 71.447$ Hz)

Table 3: Modal analysis results of the crusher support frame

Mode No.	Freq. Steel (Hz)	Max Def. Steel (mm)	Freq. Al Alloy (Hz)	Max Def. Al Alloy (mm)
1	14.779	6.1991	14.801	10.435
2	29.873	8.0703	29.939	13.652
3	34.129	9.5557	34.138	16.100
4	71.310	12.880	71.447	21.689
5	89.701	27.252	89.804	46.317

3.5 Comparative Discussion

The comparative static structural performance of the two materials is summarised in Table 3. The total deformation of the steel frame is significantly lower than that of the aluminium alloy frame, and the equivalent stress is slightly lower than that of the aluminium alloy frame, which verifies the static stiffness of the steel frame is better. The comparative modal performance is summarised in Table 4, where the average natural frequency of the two materials is less than 0.2% different (47.958 Hz for steel and 48.026 Hz for aluminium alloy), but the average modal deformation of the aluminium alloy frame (21.64 mm) is much higher than that of the steel frame (12.99 mm), which means that the dynamic frequency characteristics of the two frames are similar, while the dynamic stability and vibration resistance of the steel frame are better.

Table 4: Comparative summary of static structural analysis

Parameter	Steel	Aluminium Alloy	Better Material
Total Deformation	0.14654 mm	0.41644 mm	Steel
Equivalent Stress	4.0964 MPa	4.1528 MPa	Steel (slightly)
Structural Stiffness	Higher	Lower	Steel
Static Performance	Excellent	Good	Steel

Table 4: Comparative summary of modal analysis

Parameter	Steel	Aluminium Alloy	Better Material
Average Natural Frequency	47.958 Hz	48.026 Hz	Nearly Identical
Average Modal Deformation	12.99 mm	21.64 mm	Steel
Dynamic Stability	Higher	Moderate	Steel
Vibration Resistance	Better	Lower	Steel

The similar natural frequencies of Structural Steel and Aluminium Alloy can be attributed to the balance between stiffness and mass. Although Aluminium Alloy has a lower Young's modulus and hence lower stiffness, its significantly lower density reduces the structural mass, resulting in natural frequencies close to those of Structural Steel. However, the lower stiffness of Aluminium Alloy produces greater deformation under the same static loading. This trend was consistent across all five modes, with the modal deformation of Aluminium Alloy being approximately 1.68–1.70 times higher than Structural Steel. The maximum deformation of 0.41644 mm for Aluminium Alloy remained relatively small and may be acceptable for the considered frame and loading conditions. Therefore, Structural Steel is preferable where minimum deformation, stiffness, and long-term dynamic stability are important, while Aluminium Alloy may be considered where structural weight reduction and portability are the primary requirements.

3.6 Limitations and Future Scope

The present study is based on linear elastic static and modal analyses and does not consider material/geometric non-linearity, detailed weld geometry, damping, or actual dynamic and impact loads. The applied loads of 150 N and 70 N represent simplified static loading conditions, while modal analysis is limited to the first five natural frequencies. Future studies should include fatigue life assessment, harmonic and transient dynamic analysis, and topology or section optimisation for weight reduction. Experimental validation through modal testing and strain-gauge-based load testing of a fabricated prototype is also recommended to verify the ANSYS results.

3.7 Design Recommendations

Based on the static, modal, and stiffness results, Structural Steel is recommended where minimum deformation, high stiffness, and dynamic stability are the primary requirements, particularly for fixed crusher installations. Aluminium Alloy may be considered for portable applications where weight reduction is important, provided that critical regions such as the top platform and joints are adequately stiffened. The crusher operating frequency should maintain a suitable separation margin from the frame's natural frequencies to avoid resonance. The vertical corner and top horizontal-member joints, where peak stresses occur, should receive special attention during welding and inspection. Overall, material selection should consider deformation, stress, weight, natural frequency, and dynamic stability together rather than relying on a single performance parameter.

4. Conclusion

Static structural and modal analyses of the welded support frame were performed in ANSYS Workbench using Structural Steel and Aluminium Alloy under identical

geometry, mesh, boundary conditions, and loading. The maximum total deformation was 0.14654 mm for Structural Steel and 0.41644 mm for Aluminium Alloy, indicating higher stiffness of the steel frame. The maximum equivalent (von-Mises) stresses were 4.0964 MPa and 4.1528 MPa for Structural Steel and Aluminium Alloy, respectively, showing comparable stress levels and adequate strength margins. The first five natural frequencies of both materials were nearly identical, with an average difference of less than 0.2%, due to the compensating effects of stiffness and mass. However, the average modal deformation was lower for Structural Steel (12.99 mm) than for Aluminium Alloy (21.64 mm), indicating better dynamic stability of the steel frame. Therefore, Structural Steel is recommended for applications where stiffness, low deformation, and dynamic stability are critical, while Aluminium Alloy may be suitable where weight reduction is the primary requirement and the increased deformation remains within allowable serviceability limits. The results demonstrate that finite element analysis provides a useful quantitative approach for material selection and can be extended to fatigue, harmonic response, and structural optimisation studies.

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