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Topology Optimization of Pipeline Bracket for Mass Reduction

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Abstract - *Topology optimization is an emerging technique to optimize a structure in terms of size, shape or geometry, based on certain constraints, to better its performance. Brackets are common supports used in pipeline systems. Bulk volume of material in such components does not contribute towards the purpose of withstanding load, which could be removed to reduce the mass and the cost incorporated in material wastage. In this study, a loose- type hanging bracket was optimized for mass by performing numerical analysis, and varying levels of mass reductions were compared for their properties, to choose the most favourable design.*

Key Words: Topology optimization, loose- type hanging bracket, mesh, constraints, static structural analysis, FEA, stress, deformation, factor of safety

1. INTRODUCTION

Pipelines have versatile applications like oil and gas transportation, steam lines, sewage, water transportation, etc. They run for longer distances and require supports like brackets, hangers, anchors, etc. to maintain stability. The primary objective of supports is to guide and support the load of the pipelines. Brackets are one of the most commonly used supports, to constraint the pipe displacement, and support them. Brackets are available in various types like cantilever type, hanging type, etc. depending upon the purpose they serve. Traditional methods of heavy bracket fabrication involve casting and machining, leading to bulk use of material. Numerical analyses on different engineering components and structures reveal that almost 40 - 60 % of their material do not serve the design purpose. Similar studies on pipeline brackets convey the fact that removal of material from regions of negligible stresses, avoid material wastage, while realising same design criteria without any concession in stability and safety. A loose- type hanging bracket was considered in this study, which fully restricts the pipe motion except in the axial direction.

Structural optimization is a technique that designs the structures optimally to suit the exact design needs, and has different approaches such as size, shape, topology, free form, etc. Topology optimization is one of the most used methods, which works on the volume and mass properties of structures and optimizes them by removal of unnecessary materials. Numerical methods could be employed in these pipeline areas to optimize several features of the structures, therefore achieving a material use reduction, and the cost associated. In topology optimization, at a certain element or point in a structure, the density is either one or zero, which corresponds to material removal or existence of that element, respectively. Topology optimization does not place any limitations in the geometry of the model, unlike shape and size optimization.

2. LITERATURE REVIEW

Alzahabi, Basem, et al. [1] performed optimization of a transmission mount bracket for its noise, by improving the stiffness. It focuses on redesigning the component for achieving stiffness enhancement. The proposed design showed a 0.13 kg reduction in mass from incorporation of two holes in the component, while the deduction in lower plate thickness and increase in upper plate thickness, led to enhancement in stiffness of the structure.

Barbieri, Saverio Giulio, et al. [2] employed topology optimization technique to develop a high- performance engine piston, for additive manufacturing. The objective was to replace the conventional aluminium piston, which had low mechanical properties, and was produced by casting or forging, with a steel piston, produced by additive manufacturing. The mass became the optimization parameter and stiffness of significant parts, the constraint.

Park, Hong Seok, et al. [3] developed a concrete pipe moulding machine using topology optimization, with the objective of efficacy to mould the pipe with a novel material, while mass reduction was the parameter under consideration. Analysis results with the aid of density method revealed that 9 % volume reduction and 3 % decrease in displacement was possible for the die in new design.

3. PROBLEM STATEMENT

The bracket under consideration is made of S 235 steel uniformly throughout the geometry and weighs 50.003 kg. A major portion of the bracket was localised and spread around the fasteners as shown in figure. 1, and did not contribute in supporting the load, as those regions are subjected to negligible stress. Owing to the excess material in the bracket, the cost of material builds up in each component produced, which becomes a huge economical factor to be noticed. Hence, it becomes significant to bring down the material usage in these brackets, without any distortion in its stability.

Fig. 1 Geometric model of the bracket

4. OBJECTIVES AND METHODOLOGY

The objectives of this study are,

1. To numerically investigate the geometric model of a loose- type hanging bracket, with the structural load conditions and constraints
2. To perform topology optimization on the model for mass reduction and compare different levels of reductions

The existing mass of 50.003 kg is to be reduced by three different amounts -50 %, 60 %, and 70 % reduction. The three most favourable optimizations, closest to these numbers will be the proposed designs.

The methodology of the study is demonstrated in following figure. 2.

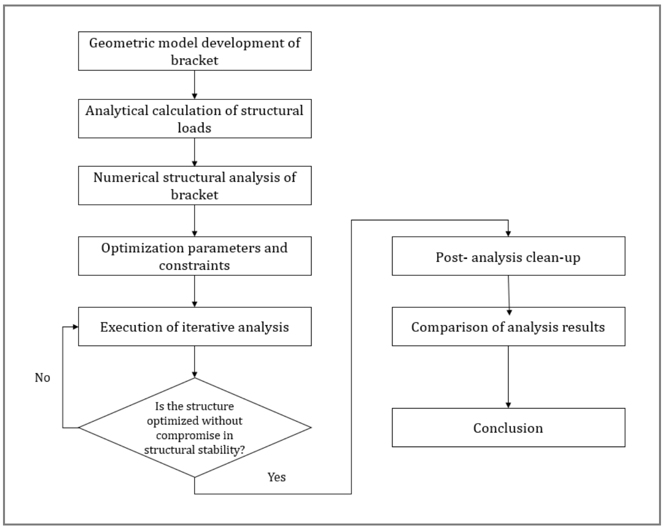


Fig. 2 Methodology

5. ANALYTICAL CALCULATIONS

The properties, loads, and boundary conditions to be incorporated in the numerical analysis are calculated analytically.

5.1 Material properties

The bracket under study was considered to be made of S 235 steel with its properties listed in table. 1. It was designed to support a 4" pipe, which is of the same material.

Table. 1 Properties of bracket and pipe material

Sl. No	Parameter	Value
1	Density (kg/m^3)	7850
2	Young's Modulus (GPa)	200
3	Poisson's ratio	0.3
4	Tensile yield strength (GPa)	0.25
5	Tensile ultimate strength (GPa)	0.46

5.2 Design criteria and load calculations

The specifications of the 4" pipe is listed below, and the conditions are chosen in the worst-case approach. The maximum thickness was assumed for the pipeline, since it contributes the highest load on the support.

Considering the bracket to be an intermediate support,

Outer diameter of pipe, d_o = 114.3 mm

Pipe thickness, t= 17.12 mm

Inner diameter of pipe, d_i = 80.06 mm

Cross- sectional area of pipe, $A = \frac{\pi(d_o^2-d_i^2)}{4} = 5228.84\ mm^2$

Length of pipe on one side of bracket, L = 5 m (or) 5000 mm

Total volume of pipe, V= 2 x L x A = 0.0522 m^3

Total mass of pipe, m = ρ x V = 410.46 kg

Total load on bracket, W = m x g = 4026.64 N

Moment acting on one side of support, $M = \frac{W\ x\ L}{2} = 5033.31$ N m

6. NUMERICAL STATIC STRUCTURAL ANALYSIS

The geometric model of the bracket was developed based on the earlier design specifications to support a 4" pipe, using Autodesk Fusion 360. The clamping portion of bracket was neglected, since it does not affect the results, and it reduces the complexity to solving the geometry. The geometric model of bracket, with analytically calculated loading conditions, material properties, and structural constraints was fed to the numerical analysis feature called 'Static structural analysis' in ANSYS Workbench, a numerical analysis software. This analysis takes the inputs and solves the model for various parameters like stress, deformation, etc. through finite element analysis.

6.1 Geometric model meshing

The incorporation of the model and material properties was followed by meshing, which breaks the model into finite number of elements and treats them individually as a domain during analysis. Smaller the mesh size, or in other words, higher the mesh count, more accurate are the results. The tetrahedron mesh type was used with minimum proximity element size of 0.31 mm and maximum element size of 31.52 mm. The meshed model as shown in figure. 3, had a total of 195,265 nodes and 126,252 elements, which led to convergence of the model, i.e. the analysis results had no significant variation beyond this mesh.

Fig. 3 Meshed model of the bracket

6.2 Structural boundary conditions

Post meshing, the loading and boundary conditions of the bracket structure are applied on the model. Figure. 4 shows the overall boundary conditions of the bracket model. The three bolting cylindrical surfaces are constrained with cylindrical support with freedom in tangential direction, i.e. rotation about its axis. The two overhangs support the pipeline of 402.64 N/m load. Thus, the 5 m pipes on either side of the supports contribute to a downward load of 2013.32 N, and a hogging moment of 5033.31 N m. The self-weight of the bracket was negligible compared to the load applied, hence it is ignored.

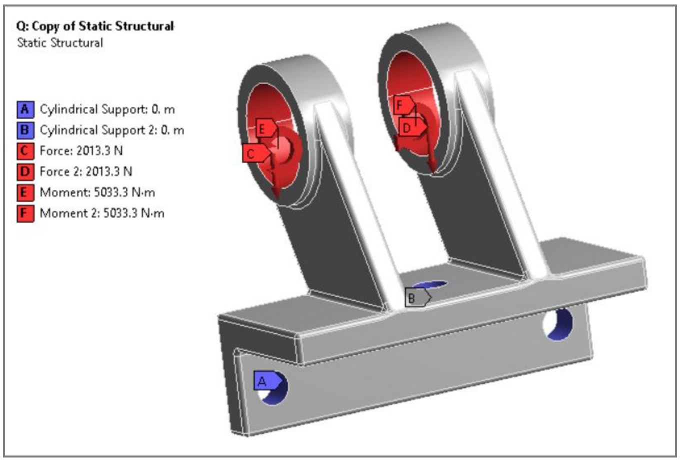


Fig. 4 Structural boundary conditions

6.3 Structural analysis results

With the meshing and boundary conditions applied, the structural analysis was solved to obtain the total deformation and equivalent (von- Mises) stress, and are shown in following figures.

The deformation plot in figure. 5 shows a maximum deformation of 0.48 mm at the top of support, less than 0.2 mm at rib, and almost 0 mm at the vicinity of bolting. This explains the rigidity of the structure with deformation to very little extent.

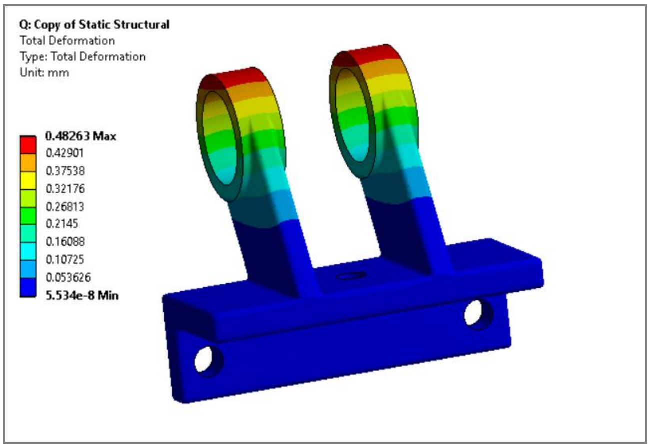


Fig. 5 Total deformation plot of bracket

The von- Mises stress results as shown in figure. 6 report a maximum stress of 89.65 MPa in the rib portion. Majority of rib and guide portions were subjected to stresses ranging from 30 to 60 MPa, while a huge bulk of region surrounding the fasteners was subjected to highly negligible stress, due to which the material in this region does not serve the purpose of withstanding the stress. The factor of safety (FOS) of the structure was found as,

$$\text{Factor of safety, FOS} = \frac{material\ yield\ strength}{maximum\ stress} = 2.79$$

The safety factor of the structure is good enough to prove its structural stability.

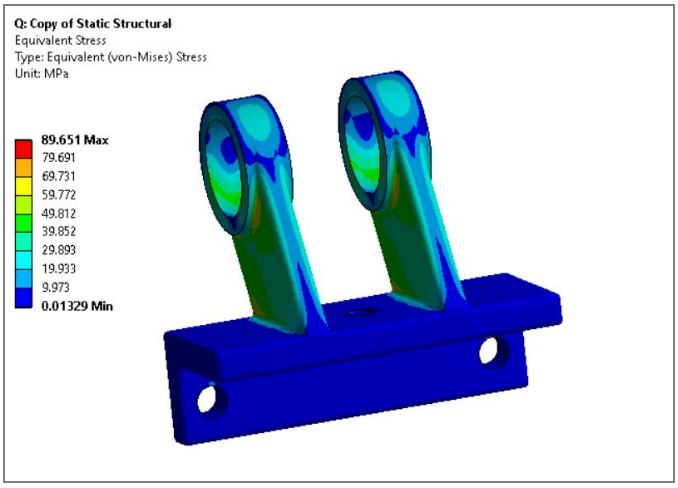


Fig. 6 Equivalent (von- Mises) stress plot of bracket

From the numerical analysis, it could be interpreted that a large volume of material goes unstressed by the loads, and the mass of bracket being 50.003 kg, could be brought down by a great number, thus preventing material wastage. The unstressed material portions are removed from the bracket without any distortion in structural stability, by use of iterative numerical analysis in topology optimization.

7. TOPOLOGY OPTIMIZATION

The results from static structural analysis are connected to the 'Topology optimization' feature in ANSYS, which performs number of iterations on the geometry to optimize material, while adhering to certain constraints. Removal of material near the locations of loads or constraints could lead to failure of the structure, hence those regions are excluded from the material optimization domain. The regions of optimization and exclusion are shown in figure. 7.

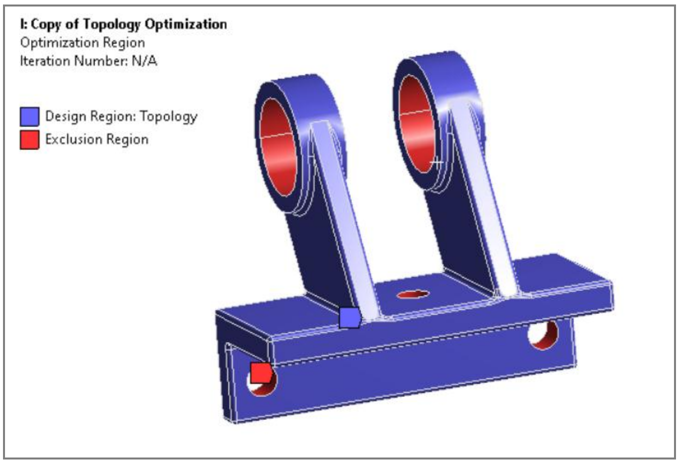


Fig. 7 Regions of optimization and exclusion in bracket

In this study we start the analysis with material removal closest to 50 % and perform the same with mass reduction of 60 % and 70 %. The objective of the optimization was chosen as mass, and the response constraint was chosen as 50 % retainment of mass, and it was solved. ANSYS runs several iterations of material removal and corresponding structural analysis to ensure stability of the bracket and provides the final design.

7.1 Optimization results

The simulation ran for 14, 14, and 19 iterations for the three optimizations. This design had countless sharp edges, and many such intricate surface features, which poses a complication during manufacturing. Hence, the surface texture of the optimized design was modified to bring a feasible design in manufacturing aspect. 'ANSYS SpaceClaim' was used to perform this clean- up modification by auto-fixing the mesh projections, and coating the design surface with a sheet of 1 mm thickness thus smoothening the surface texture.

The mass reduction closest to 50 % occurred at 46.65 % with final mass of 26.675 kg. The same steps were repeated for 60 % and 70 % reductions, with the response constraint varying in each case. The mass reduction closest to 60 % occurred at 55.84 % with final mass of 22.082 kg, and that closest to 70 % occurred at 65.5 % with final mass of 17.249 kg. This denotes a huge reduction in mass and cost involved during production of these brackets. The optimized designs with a feasible surface texture are shown in figure. 8, figure. 9, and figure. 10.

Fig. 8 Optimized design at 46.65 % mass reduction

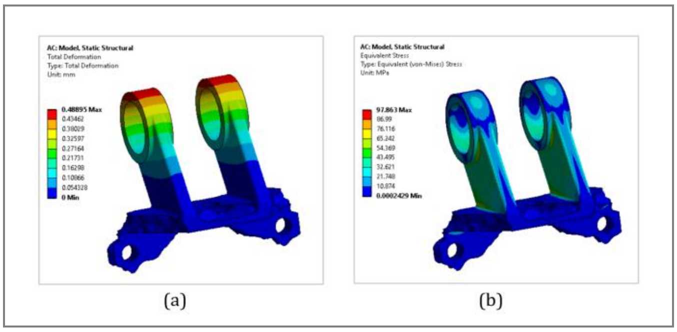
Fig. 9 Optimized design at 55.84 % mass reduction

Fig. 10 Optimized design at 65.5 % mass reduction

The designs showed a major material removal near the bolting locations, and partial removal from the rib, and guide portions. When comparing this with the stress plots, it is obvious that material removal occurred at regions of negligible stress, which indicates that the optimizations do not affect the bracket's stability.

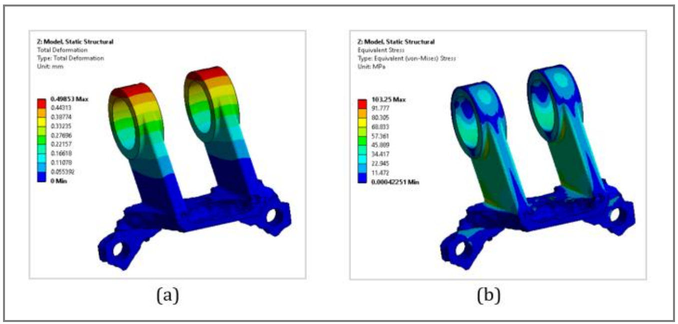
7.2 Validation of optimized models

The models of the bracket, post optimization, should be validated to ensure the stability of the structure. Results from topology optimization are transferred to design validation in the workspace, and loads and constraints applied to the model. This analysis was solved to obtain the total deformation and equivalent (von- Mises) stress, whose plots are shown in figure. 11, figure. 12, and figure. 13, for 46.65 %, 55.84 %, and 65.5 % mass reductions respectively.



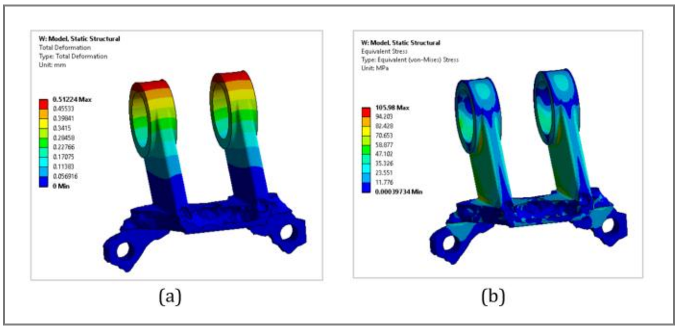
(a) (b)

Fig. 11 Plot at 46.65 % mass reduction for: (a) Total deformation; (b) Equivalent (von- Mises) stress



(a) (b)

Fig. 12 Plot at 55.84 % mass reduction for: (a) Total deformation; (b) Equivalent (von- Mises) stress



(a) (b)

Fig. 13 Plot at 65.5 % mass reduction for: (a) Total deformation; (b) Equivalent (von- Mises) stress

Comparison of these plots with that of the unmodified bracket, showed that the plots of deformation and stress were almost similar in distribution and magnitude, with negligible discrepancies.

8. RESULTS AND DISCUSSIONS

From the deformation plots of the optimized models, it could be found that the maximum deformations in all three designs do not exceed that of unmodified design highly, with little increase of 6 μm, 16 μm, and 30 μm, while the stress plots reveal a maximum increase of 8.21 MPa, 13.56 MPa, and 16.33 MPa, , in 46.65 %, 55.84 %, and 65.5 % mass reductions respectively. The comparison of maximum deformation and stress, mass, and factor of safety between the unmodified and optimized designs is tabulated in table. 2.

Table.2 Comparison of results in unmodified and optimized bracket designs

Sl. No	Parameter	Unmodified design	Optimized design		
			46.65 % mass reduction	55.84 % mass reduction	65.5 % mass reduction
1	Maximum deformation (μm)	482.63	488.95	498.53	512.24
2	Maximum equivalent stress (MPa)	89.65	97.86	103.25	105.98
3	Mass (kg)	50.003	26.675	22.082	17.249
4	Factor of safety, FOS	2.79	2.55	2.42	2.36

The maximum deformation experiences 1.3 %, 3.29 %, and 6.13 % increase, and maximum stress experiences 9.15 %, 15.17 %, and 18.21 % increase, in 46.65 %, 55.84 %, and 65.5 % mass reductions respectively. Initially, the bracket has a mass of 50.003 kg, which was reduced to less than half, which significantly contributes in saving material and cost. The factor of safety of the unmodified design is 2.79, with the material yield strength being 250 MPa, and maximum stress in the bracket being 89.65 MPa. The factor of safety sees a maximum reduction to 2.36, which does not cause any significant drop in the bracket's stability.

It could be interpreted that, both the parameters-deformation and stress, do not see an appreciable variation from that of unmodified design, which confirms the structural stability of the optimized design. Owing to mass reductions of more than 50 %, a huge economically benefit comes into play.

The results of this study are summarized below.

1. The bracket post optimization has realised maximum of more than 30 kg mass reduction, without any appreciable trade- off in deformation and stress
2. The factor of safety of all optimizations remain above 2, which ensures the bracket's safety while supporting the pipelines
3. The optimized design with 65.5 % mass reduction shows the most favourable properties, with 17.249 kg of mass, without showing a compromise in its structural stability
4. Further mass reductions lead to reduction in factor of safety of the bracket, hence subjecting it to potential failure

This advanced technology sees few forthcomings of which the manufacturing feasibility takes a major part. The optimized design should be processed further to achieve better geometric features so as to ease the manufacturing processes involved in its production. Topology optimization is an emerging technique and isn't widely employed in all industrial scales, which hinders it adoption. Yet, advanced techniques like 3D printing, powder metallurgy, etc. are available to incorporate these optimizations in manufacturing scale to ease and speed the process of manufacturing.

9. CONCLUSION

Topology optimization brings about a great material conservation in manufacturing industries. Material cost takes a major portion in the financial domain; hence it becomes critical to focus on material conservation. Brackets are used in large numbers in pipelines, the optimization of which results in huge economical advantage. The numerical studies on the bracket discussed, shows high mass reduction with almost no performance deterioration. Therefore, it emphasises the use of topology optimization in versatile engineering components to conserve material and improve performance.

10. SCOPE FOR FUTURE WORK

The foremost challenge in this technique is the manufacturing feasibility of the component, which could be met by post- optimization surface modifications, to develop machinable surface geometries, and features. Research and developments are being done in this area for the past few years, which could bring about this feasibility practical. Future trends like additive manufacturing and powder metallurgy methods could also be employed to eliminate this challenge, since the complexity in geometry, or surface of parts do not pose a huge limitation.

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