"Weight Optimization of Arms & Hinges of a Combat Vehicle using Finite Element Analysis"

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Abstract— **In automobile domain, It is always demanding to reduce weight of any component/assembly without compromising its performance parameters. This research study presents methodology and case studies for structural weight optimization of hinges & arms of ramp door assembly of a combat vehicle using finite element analysis (FEA). Weight reduction of hinges and arms of existing ramp door assembly is achieved by optimal material distribution using density method of topology optimization technique as well as it discusses topology optimization parameters to reduce weight of the existing components without compromising required stiffness and strength requirements. With defining minimum compliance and mass as objective functions, the study highlights problem formulation by defining design and non-design volume for topology optimization using solid isotropic material with penalization (SIMP) technique. As an outcome, optimal material design of hinge and arm is achieved that is converted into feasible light weight design considering manufacturing constraints. These light weight designs are validated for their structural strength using FEA. Existing and optimised designs are compared for weight, stiffness and strength parameters.**

Keywords - **Weight Reduction, Topology optimization, Structural Stiffness & Strength, Finite Element Analysis, Design Volume**

I. INTRODUCTION

It is always desired to reduce weight of a combat vehicle as shown in figure:1, intending various advantages in terms of vehicle performance like ride, handling, fuel consumption, amphibious performance, etc. The present study highlights weight reduction of existing components of ramp door assembly by exploring topology optimization technique using finite element analysis. Initially, hinges and arms of the ramp door assembly are selected for the weight reduction task.

Fig. 1 Wheeled Armoured Platform 8x8 vehicle

Fig. 2 Ramp Door Assembly

A ramp door assembly as shown in figure:2 of a wheeled combat vehicle is one of the critical system which functions as a foldable door that enables easy entry/exit of troops by providing a ramp with adequate stepping height. The ramp door assembly consists of a ramp door, hinges, arms, locks, link rods, guide assembly, etc, which is operated by hydraulic system.

This study represents the structural topology optimization technique for achieving light weight design of existing hinge and arm as shown in figure: 3 & 4 respectively. Weight saving is targeted without compromising performance parameters defining problem formulation for topology optimization using solid isotropic material with penalization (SIMP) technique clubbed with finite element solvers. Optimised material distribution of hinge and arm is calculated by defining minimum mass as objective along with material density as design variable by specifying design and non design volume within available space. As an outcome of the study, optimal material distribution profiles of hinge and arm are proposed which are converted into feasible designs considering manufacturing aspects.

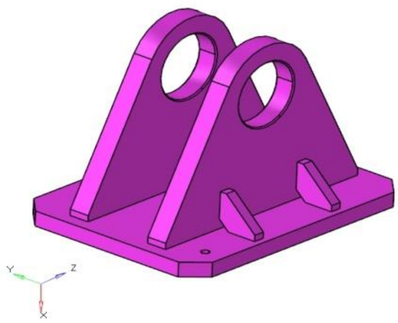


Fig. 3 Solid Modeling of Existing Hinge

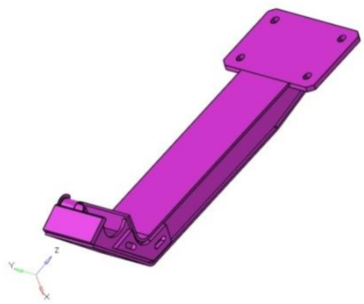


Figure 4 Solid Modeling of Arms

The SIMP method was originally developed by fictitious material model[1] defined with density variables are penalised with a basic power and reproduced onto material stiffness [2]. Recent techniques and advancement in topology optimization are surveyed [3]-[4]. Continuum structure is considered as porous unit cells defining equivalent material constitutive behaviors e.g. elastic stiffness tensor of each unit cell are formulated with homogenisation. Topological solution is achieved by modifying the corresponding size variables of each unit cell iteratively by [5] Convergence properties of the density based SIMP method is discussed [6]-[7]. Stepwise procedure for defining and solving topology optimization problem using FEA is presented [8] Currently, many commercial organizations have implemented the topology optimization algorithms which are interfaced with FE software to develop the structural optimization modules. e.g, Optistruct by Altair, TOSCA, MSC Nastran, ABAQUS, ANSYS, etc.

A general structural optimization problem can be described by an objective function (ƒ) that could either be maximised or minimised as (1.1)

$$\begin{cases} \min x & f\,(x,\ y\,(x)) \\ Subjected\ to & \begin{cases} design\ Constrain\ on\ x \\ state\ Constrain\ on\ y(x) \\ equilibrium\ constrain \end{cases} \end{cases} \qquad (1.1)$$

Typically, volume or compliance (reciprocal of stiffness) is chosen as an objective function. design variable (x) represents density as state variable, (y) represents structural response that may be displacement or stress. The state variable depends on design variable y(x). The overall objective function is set to minimise or maximise the state, subjected to design variables and constrains to get feasible optimal solution. The objective function can also be formulated as combination of several objectives as (1.2).

$$\min x\ f(f_1(x,y), f_2(x,y), (x) \ldots, f_n(x,y)) \qquad (1.2)$$

A state function g(y) represents the state variable. e.g. displacement in particular direction. This state function considered as a constrain to optimization objective, which is defined as $g(y) \leq 0$.E.g. defining g(y) for any nodal displacement as g (u(x)). Then the nodal displacement is solved as 1.3 to get the state function.

$$u(x) = K(x)^{-1}\, F(x) \qquad (1.3)$$

Where Krepresents global stiffness matrix and Frepresents global force vector. Finally, the optimization objective can be defined as (1.4).

$$\begin{cases} \min x & f(x) \\ Subjected\ to & g(u(x)) \leq 0 \end{cases} \qquad (1.4)$$

The above equation is solved by computing derivatives of f and g with respect to x. For structural optimization problem, $x$represents geometry data. Based the defined geometrical data, the optimization can be classified as size, shape or topology optimization

Computation of optimal material distribution is the method where the design or referenced domain (Φ) is discretized into void and solid elements by a FE discretization. In mathematical terms we compute an optimal subset Φ_m pertaining to Φ. The design variable x can be presented by density vectorρ. The local stiffness tensor Ecan be formulated by incorporating ρ. (1.5)

$$E(\rho) = \rho(E)^0 \qquad (1.5)$$

$$\rho_e = \begin{cases} 1 & if\ e \in \Phi_m \\ 0 & if\ e \in \Phi/\Phi_m \end{cases}$$

And a volume constraint,

$$\int \rho\, d\Phi = \mathrm{Vol}\,(\Phi_m) \leq V \qquad (1.6)$$

V is the volume of initial design domain. Here, the gradient based optimization solution method is considered in which (1.6) is formulated as a continuous function such that density function can be defined between 1 and 0. The most common structural topology optimization method is the SIMP. The density function is then written as (1.7)

$$E = \rho^p E^0 , \tag{1.7}$$

$$Where,\ \rho \in [\rho_{\min}, 1]\ \mathrm{p} > 1$$

$$\mathrm{p} = \text{ penalizing factor}$$

The p , penalizes all elements having intermediate densities to get the value of either1 or 0,$\rho_{\min}$represents lower density value limit to avoid singularities. E.g for any material having Poisson ratio $\upsilon = 0.3$, it is suggested to use $p \geq 3$.Typically, compliance and volume are defined as topology optimization problem. To minimize compliance is defined as equivalent strain energy of any FE solution (2.8)

$$C(\rho) = (f)^T u \tag{1.8}$$

$$\text{Where,}\quad f = K(\rho)u$$

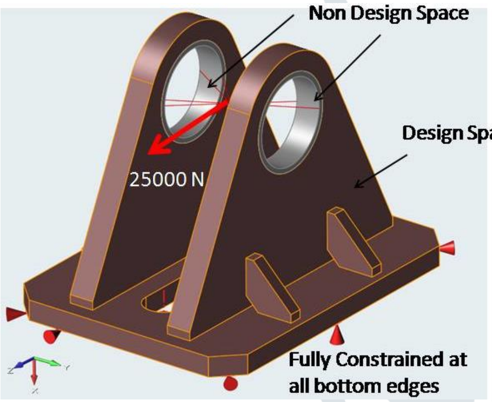
$$K(\rho) = \sum_{e=1}^{n} \rho_e^p \mathrm{K}_e^0$$

K_e^0represents elemental stiffness matrix. Volume constrain is also added to prevent the solution, ending up with total design volume to achieve minimum compliance. Though adequate theoretical data is existing towards topology optimization methods, practical solutions with topology optimization of an Arms and Hinges kind of structure are seldom available.

II TOPOLOGY OPTIMIZATION OF HINGE & ARM- CASE STUDY

A. Topology Optimization Parameters & Boundary Conditions

Main components of hinge and arm of ramp door assembly are shown in figure:5. The weight of existing hinge and arm is 5.8 kg and 10.89 kg respectively. Initially critical load cases are decided out of various loading and boundary conditions for defining topology optimization. The hinge is directly connected with connecting rod of hydraulic system. Based on the cylinder force as shown in the figure: 6, it is observed that maximum of 25000 N force in horizontal direction is acting at the pin joint when the ramp door is in horizontal condition. Accordingly boundary conditions for the critical load case is applied as shown in figure:5. Similarly boundary conditions for arm is defined for critical load case.



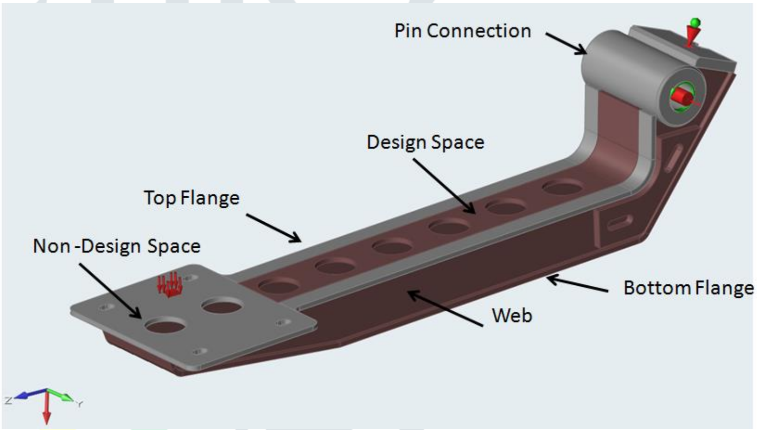


Fig. 5 Boundary conditions along with Design & Non Design space

Material properties for hinge and arm is mentioned in table:1. Design and non-design space for hinge and arm is shown in figure:5 respectively. Various topology optimization parameters are mentioned in table: II for the current case study.

Table : I MATERIAL PROPERTIES

Sr. N	Material Property	Value
1	Modulus of Elasticity (N/mm^2)	200000
2	Density (Kg/m^3)	7850
3	Poisson's Ratio	0.29
4	Yield Strength (N/mm^2)	1450

Table : II TOPOLOGY OPTIMIZATION PARAMETERS

Sr. N	Parameters	Value/Data
1	Objective function	Minimise mass
2	Design variable	Element density
3	Thickness constraint	19 mm minimum
4	Load case	Static load case

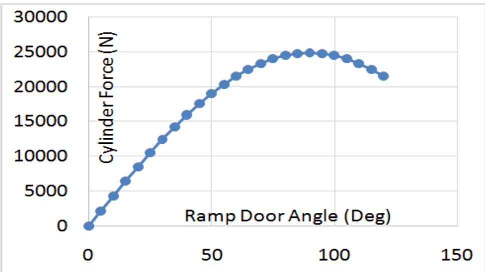


Fig: 6 Cylinder force Vs Ramp door Angle

B. Topology Optimization Results & Discussion

The optimization problem for critical boundary conditions as mentioned above are defined and solved for optimal material density plots. Optimal material density plots for hinge & Arms are plotted in figure:7.

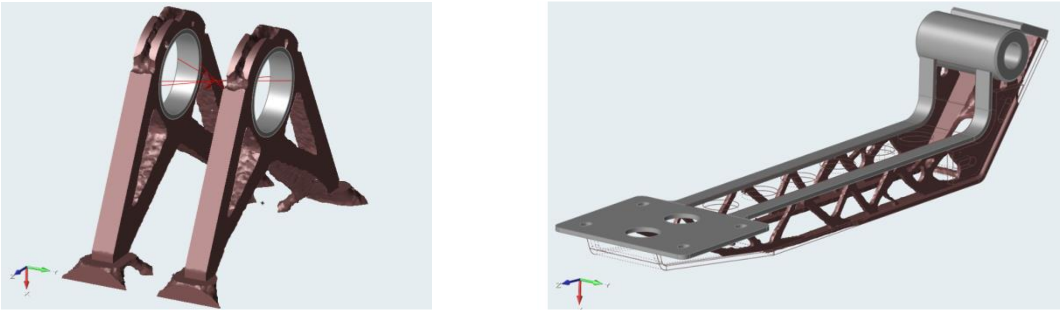


Fig: 7 Optimal Material Density Plot for Hinge & Arm

The material density plots are converted into feasible designs considering manufacturing constraints. The light weight feasible designs are shown in figure: 8.

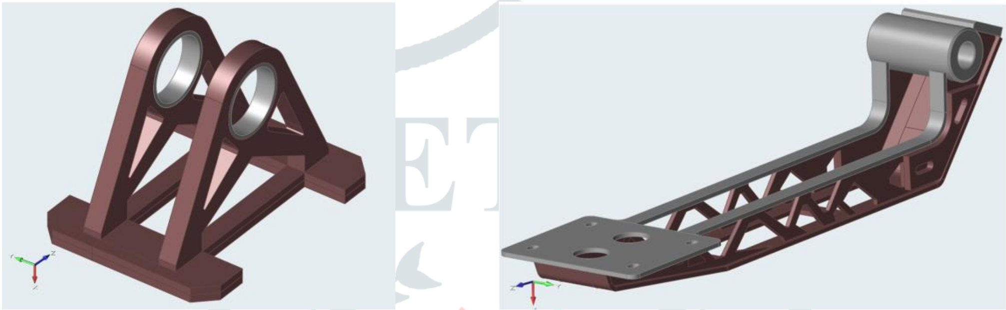


FIG: 8 feasible design of hinge & arm

III. DESIGN VALIDATION & COMPARISON

Existing and optimised designs are validated with linear static FE Analysis for critical loading conditions. Stress (Von mises) results of existing and optimised design of hinge are plotted in figure:9.

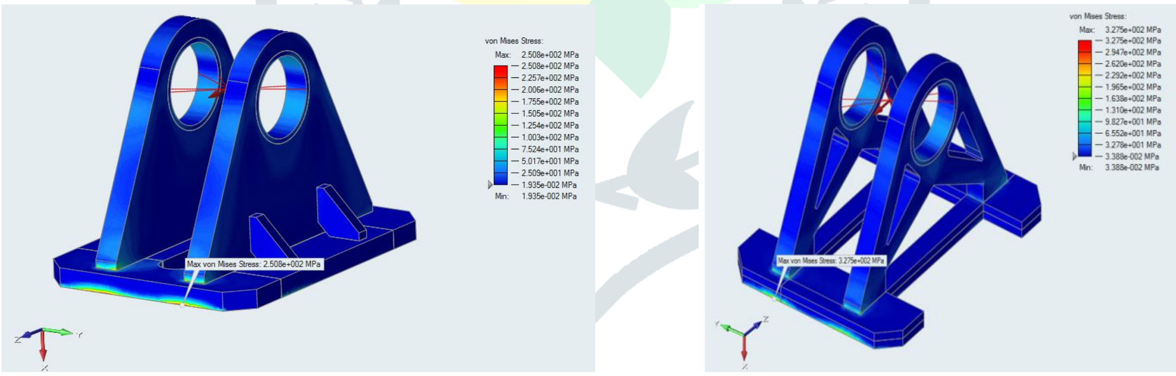


FIG: 9 Stress (von mises) plots for hinge

Maximum deflection results of existing and optimised design of hinge are plotted in figure:10.

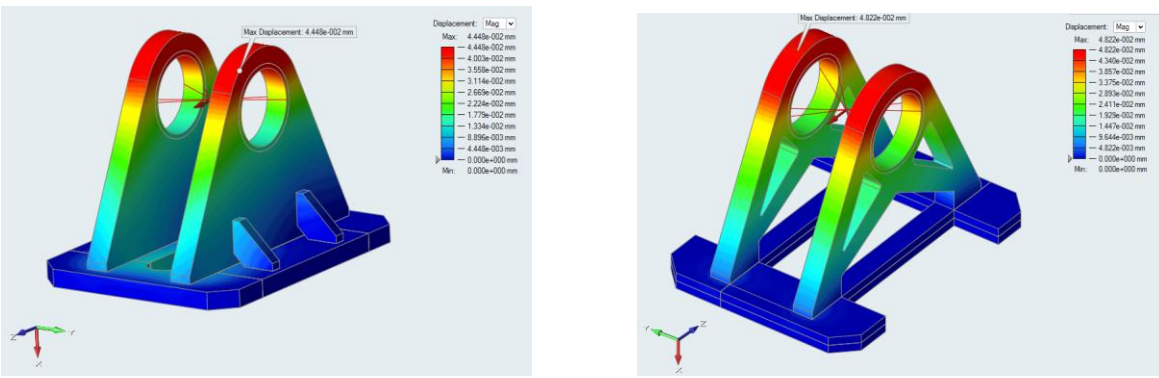


FIG: 10 Deflection plots for hinge

Max stress (Von mises) results of existing and optimised design of arm are plotted in figure:11.

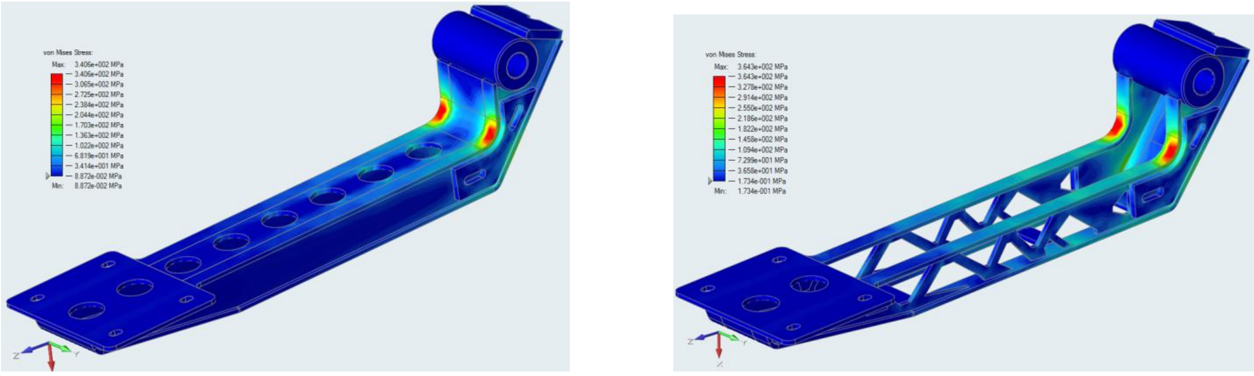


FIG: 11 Stress (von mises) plots for arm

Maximum deflection results of existing and optimised design of arm are plotted in figure:12.

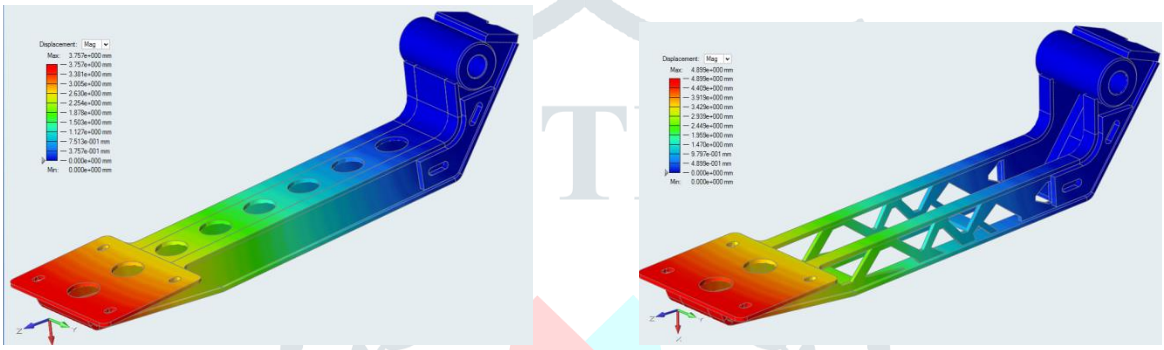


FIG: 12 Stress (von mises) for arm

Comparison of existing and optimised designs in terms of maximum stress and maximum deflection along with weight saving is summarized in table: III.

Table : III : RESULTS COMPARISON

	Max. Deflection		**Max Stress (Von Mises) N/mm²**		**Weight**		**Weight saving (%)**
	Existing Design	Optimised Design	Existing Design	Optimised Design	Existing Design	Optimised Design	
Hinge	0.44 mm	0.48 mm	25.1 N/mm²	32.7 N/mm²	5.80 Kg	3.35 Kg	42
Arm	3.76 mm	4.89 mm	341 N/mm²	364 N/mm²	10.89 Kg	8.47 Kg	22

IV. CONCLUSIONS

Topology optimization technique for reducing weight of an existing design of hinge & arm of a combat vehicle is presented with case study. Various topology optimization parameter along with boundary conditions are discussed to achieve weight reduction of around 42% for hinge and 22% for arm without much compromising of stiffness and strength requirements. Maximum stress & deflection values along with weight saving of existing and improved designs are mentioned in table:III. Optimal material distribution plots as an outcome of the study are plotted and converted to feasible design considering manufacturing constraints. The feasible light weight designs of hinge and arm are validated by linear static FEA for critical loading and boundary conditions. This presented topology optimization technique can be applied to all similar kind of structural components.

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