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Launch Vehicle Topology Optimization using OPTISTRUCT

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Abstract — *Topology optimization is a tool for finding a domain in which material is placed that optimizes a certain objective function subject to constraints. Here topology optimization is attempted on an interstage structure of a heavy launch capability launcher being developed by ISRO. Based on static analysis as well as functional requirements, optimization response and constraints were proposed. Topology optimization method based on density approach is currently employed for the structure with multiple load cases and multiple constraints. Constraints on uniformity of the reaction force are also considered in this model. Finally, based on the reaction forces, a displacement and stress constraint, an optimal layout of the structure is presented. The softwares used are the preprocessor HyperMesh, optimization tool OPTISTRUCT and HyperView which are parts of the software suite HyperWorks from Altair Engineering.*

Keywords- Topology, launcher, Interstage structure, optimization, constraint etc

I. INTRODUCTION

In launch vehicle structures design, the primary requirements are lightweight, meeting the strength and stiffness requirements, high load bearing capacity and ease of fabrication [2]. When designing launch vehicle, it's all about finding the optimal proportion of the weight of the vehicle and payload. It needs to be strong and stiff enough to withstand the exceptional circumstances in which it has to operate. This demands very accurate design and analysis of structural elements for launch vehicle. Compressively loaded cylindrical structures are widely used in launch vehicles as inter stages. To improve the load carrying capability, inter stage structures are stiffened with stringers and bulkheads. In conventional launch vehicles, thrust from strap on boosters are transferred at the bottom, and thus the inter stages are subjected to nearly uniform compressive loads since they are located away from thrust transfer locations**.** There are various types of construction methods which are used for designing launch vehicle structural elements. They are Monocoque, Semi –monocoque, Skin stiffened, Integral stiffened construction etc [1]. These methods are formulated for structures subjected to uniform loads.

In advanced launch vehicles, thrust is transferred at two points which are diametrically opposite and hence the effect of concentrated load transfer in inter stage structures need to be studied. Concentrated axial and radial loads are act on the thrust transfer location where the strap on boosters is joined to the core vehicle. In such cases, above methods are not applicable since the load is transmitted to a given section of the structure. Therefore, some measures should be taken in the structural design to diffuse the concentrated force. In order to optimize the structure for diffusing the concentrated force, the topology optimization method is adopted. This will help to make the structure light as well as stiff by maximum uniformity in load distribution at the interfaces of the designed interstage structure and obtain an optimal stiffness pattern.

Topology Optimization is a mathematical method that optimizes material layout within a given design space, for a given set of loads, boundary conditions and constraints with the goal of maximizing the performance of the system. If the topology of the initial design model is not optimal, the result after shape optimization using this initial topology is only the "optimal design" under this non-optimal topology. Therefore topology optimization, which helps designer to find the optimal topology of the structure, has been a very active research field. Here topology optimization is attempted on an interstage structure of a heavy launch capability launcher being developed by ISRO.

II. RELATED WORKS

Structural optimization is used to recover an optimal solution to a design problem. Three types of structural optimization are the size, shape and topology [3]. Topology optimization has become an effective tool for low weight and performance design, particularly in aeronautics and aerospace engineering. Advances in topology optimization techniques applied in the design of aeronautical and aerospace structures are the design of layout of standard materials for cellular structures, multi-component frame design for aerospace structure systems [4] etc.

III. DESCRIPTION OF STRUCTURE

The interstage is an inevitable structure for a multistage launch vehicle, which connect two successive stages in launch vehicles. It's a cylindrical structure and its height is so chosen to accommodate the dome profile of propellant tanks with which it interfaces and also to accommodate the nozzle of the upper stage. An interstage structure may be designed as a single structure or designed as an assembly of two or three structures – Lower, Middle and Upper interstages. The structure considered for the current study is upper interstage.
The Upper Interstage consists of:

1. Aft end ring : Interfaces with the lower interstage
2. Fore end ring : Interfaces with upper separation truss members
3. Bulk head (4#) : Provides required radial stiffness to the structure
4. Thrust blocks : To receive thrust from strapon boosters

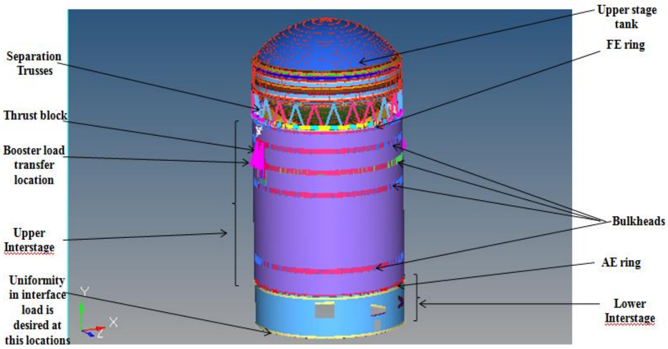

Figure 1. **Interstage Structure with upperstage tank**

Configuration of Model

Interstage Structure is located in between two stages of the launch vehicle. It is a cylindrical structure having a diameter of 4000mm and a height of 4000mm. The structure is constructed using aluminium alloy AA 2014 for which the material properties are given below.

Table 1. Structural Properties of Aluminium Alloy

Material	Young's Modulus E (N/mm^2)	Poisson's Ratio	Density (Kg/m^3)
Al Alloy	**72000**	**0.33**	**2700**

IV. METHOD OF OPTIMIZATION

The goal of topology optimization is to find the best use of material for a structure such that the objective criteria take out a maximum or minimum value subject to given constraints. The first step in setting up the optimization parameters was dividing the Interstage structure into the design space to be optimized and the non-design space to be kept regardless of its structural contribution as shown in 0. FE ring, AE ring, Bulkhead, Thrustblock and a sheet of 1.5mm thickness as outer cover are non design elements and based on functional constraints, size of these elements are finalized.

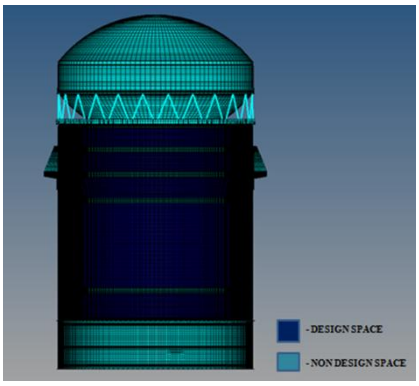

Figure 2. **FE Model showing design and non design space**

Loads and Boundary conditions

There are different types of loads on the structure. These are: Strapons loads (T1 and T2) acting on the thrust block, Compressive load (Fy) at fore end, shear force (Fz) and Bending Moment (Mx) at top flange of the upperstage tank. The bottom end of the structure is fully clamped and all 6 dof are constrained.

Table 2. Load Cases

Load Cases	Strapon loads (kN)		Compressive Load (kN)	Shear Force (kN)	Bending Moment (kNm)
	T1	**T2**	**Fy**	**Fz**	**Mx**
1	400	4000	-1500	-	-
2	160	1450	1000	239	3100

Optimization Parameters

Parameters defined during Topology Optimization Setup are: Objective function, Design Variables & Design Constraints.

Design variable : Density
Design Responses : mass, displacement & reaction force
Objective function : To minimize mass

Constraints :

i. Radial Displacement of FE ring should be less than 20mm (Functional constraint based on stage system specification)
ii. There should be maximum uniformity of reaction forces at aft end.
iii. Stresses should be within allowable limits (With a factor of safety of 1.15 & UTS of 460 MPa, allowable stress = 400 MPa)

Allowable deflection and stress constraints were applied in OptiStruct. Minimum thickness of 2mm was also one of the criterion. Under these objective and constraints, Topology optimization is employed for the interstage structure.

V. RESULTS AND DISCUSSIONS

The topology optimization result using material distribution method is a "density distribution" of the finite elements in the design domain.

Density plot for the model is obtained after topology optimization run. These density values help in finding the redundant locations so as to remove the unnecessary material. The design variable in this method is the material density of each element. The design variable may vary between 0 and 1. Intermediate density is usually penalized to force the design variables to approach 0 or 1. If the material density of an element is close to 0 at the end of topology optimization, the element does not exist in the optimal topology. On the other hand, if the material density of an element is close to 1 at the end of topology optimization, the element exists in the optimal topology.

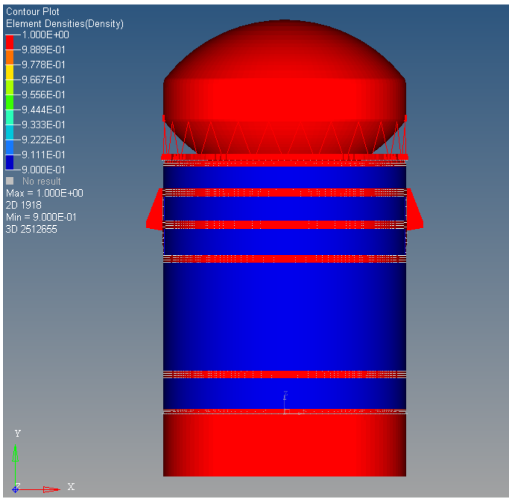

Figure 3. **Component with uniform density**

0 shows structure with uniform density material. Optistruct take this geometry as initial iteration. Optistruct identifies stress distribution pattern throughout the structure and remove the material from that region in successive iterations based

upon set of objectives and constraints. This material removal is given by varying density of each element from 0 to 1. Density pattern after solution convergence is shown in 0.

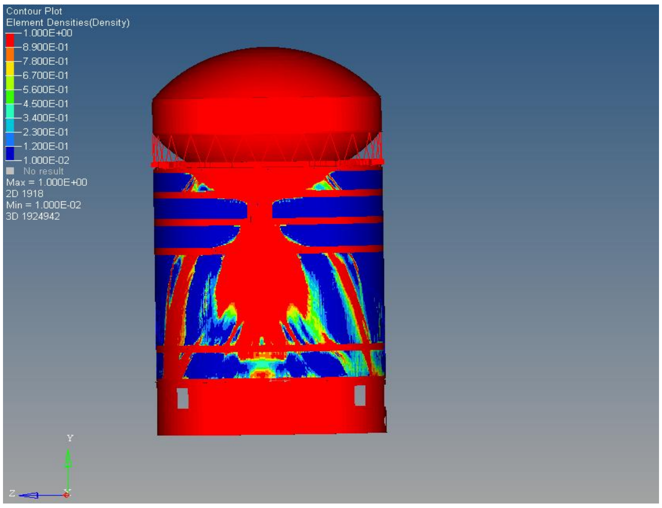

***Figure 4.* Optimization Result**

In 0, a region with lower density indicates that it can be removed without hampering safety of component. The results of each optimization were viewed in Altair HyperView, which displays a contour or iso-map of element densities at each iteration of optimization. OSSmooth was used to extract the geometry of the optimized results at or below the entered element density threshold.

Convergence Histories of Optimization

Convergence histories of optimization process of mass are shown in Fig. 5 and Fig. 6,coverged results at 45th iteration. The initial mass of upper interstage structure is 3498 kg, which includes design space as well as non-design space. After optimization, interstage mass is reduced to 1988 kg.

Mass of design space (interstage) = 2210 kg

Mass of non-design space (interstage) = 1288 kg

Mass of nondesign space (other interface structures) = 1002 kg

Total mass of FE model (including lower Interstage, upper stage tank and separation trusses) =4500 kg

Mass of Optimized geometry =3050 kg

Mass of design space after optimization = 760 kg, which is 65% of original mass.

Hence total mass of interstage structure after optimization is 1288+760 = 2048 kg. Considering 10% additional mass due to fasteners and joints, expected structure mass is 2250 kg

Mass of existing design of the structure is 2800 kg, which indicates that the current optimization has resulted in a mass saving of 550 kg, which is 20% of the existing mass.

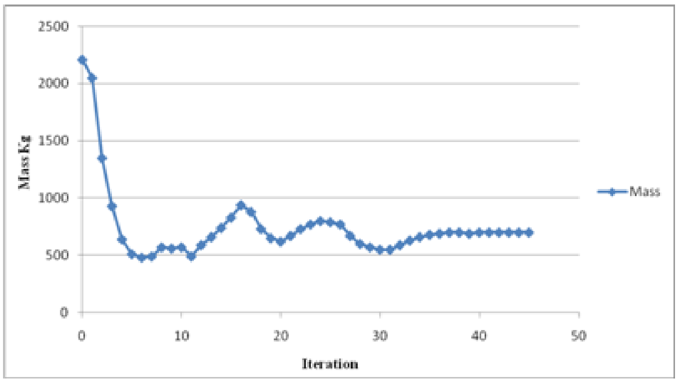

***Figure 5.* .Convergence History of mass of design space**

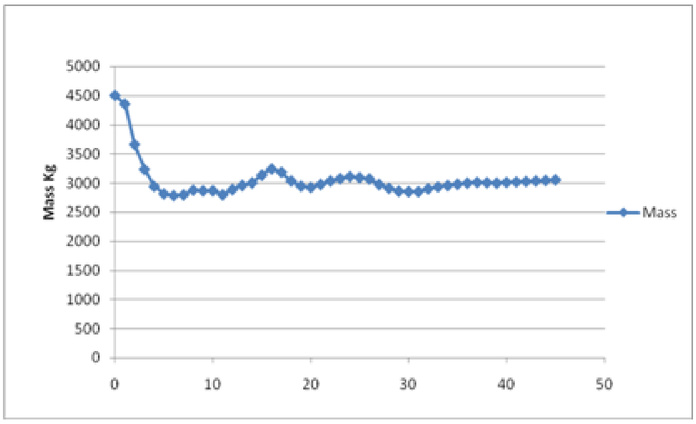

Figure 6. **Convergence History of total mass**

Convergence of displacement is shown in Fig. 7. Displacement is converged towards 45th iteration corresponding to optimized mass. Final displacement is 11.2 mm, against constraint of < 20 mm, which indicates that the displacement constraint has not played a major role in the final optimized geometry. This is due to high radial stiffness of the optimized structure.

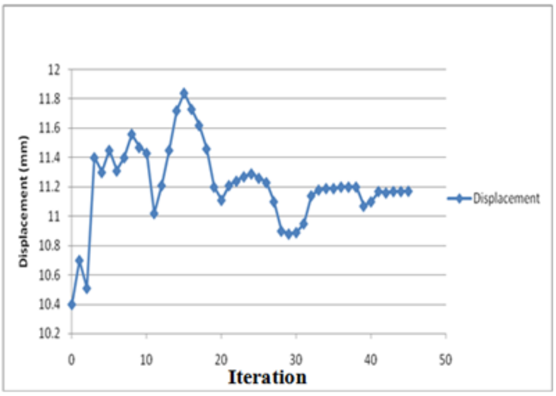

Figure 7. **Convergence History of Displacement**

Convergence history of Reaction force at two representative nodes is as shown in Fig. 8. Initial reaction at node 1 (which represents the max. reaction location) is 80 kN, which is reduced to 72.5 kN towards the end of optimization. It can also be seen that reaction force at other location (node2) increases from 45 kN to 50 kN towards the end of optimization. This indicates that as optimization progress, force distribution results in reduction of peak force.

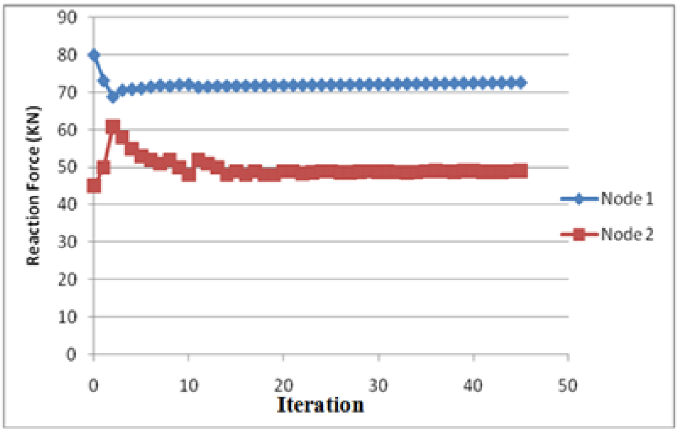

Figure 8. Convergence History of Reaction Forces

VI. CONCLUSION

Topology optimization technique is used to obtain a most favourable shape of the outer shell of an interstage structure subjected to concentrated loads. The study shows a considerable reduction in the weight of the structure compared to existing design. The final optimum design reduced the weight of the structure by 65% when compared to the baseline design while satisfying all required loading scenarios. It is 20% lower compared to existing design with skin and stringer. This can help in increasing the payload capacity of the launch vehicle.

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