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DESIGN AND ANALYSIS OF A TYPICAL INTER-TANK STRUCTURE OF A LAUNCH VEHICLE USING INTEGRALLY STIFFENED CONSTRUCTION

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ABSTRACT

In launch vehicle structures design, importance is given to lightweight with high load bearing capacity design, so the factor of safety is kept low compared with ground-based structures and at the same time maintaining high reliability. This demands very accurate analysis of structural elements for launch vehicle. The main criteria are lightweight, ease of fabrication, lower cost and at the same time meeting the strength and stiffness requirements. The commonly used launch vehicle structure is the closely stiffened structure in which the structure consists of 90 or 120 no’s of stringers riveted onto a 1.2mm thick skin and a few number of bulkheads. In this type of structures, thin shell can buckle or cripple at a load much lower than the buckling strength of stringers. In order to overcome this, integrally stiffened structures such as isogrid structures is chosen. Isogrid is the name given to integrally, grid stiffened shell and structures in which the grids form an equilateral triangle pattern. The isogrid structure can withstand both compressive and bending loads and also offers lower weight and higher structural efficiency. A typical inter tank structure that was preliminary designed using closely stiffened shell structure has been identified for study. This is a cylindrical structure having a diameter of 4.0m and a height of 2.75m which should safely withstand the loads expected on it during different phases of flight. It should safely carry the accessories needed for the next stage separation. A detailed design analysis of this particular launch vehicle structure using integrally stiffened construction is done both theoretically and also the results are verified by using FEA packages. The scope of study is to make a detailed design through FE analysis.

General Terms

Finite element analysis, tank structure, shell element, integrally stiffened construction

KEYWORDS: Inter-Tank Structure, Isogrid, Integrally Stiffened, Buckling Analysis

INTRODUCTION

The interstage is an inevitable structure for the launch vehicle. The interstage structures interconnect two stages of a launch vehicle. The inter stage structure is located in between the liquid and solid propellant tanks of first stage of launch vehicle. It is a cylindrical structure having a diameter of 4000m and a height of 2750mm. The height of the structure was chosen so as to accommodate the dome profile of the two propellant tanks with which it interfaces. The interstage structure interfaces with the two tanks at the fore and after end through flanged bolted joint. The interstage structure houses the module, feed lines for the propellants etc. within the structure and 4 retro rockets on the outside surface.

The typical inter-stage has to interface with propellant tank at its after end and another structure at its forward end, consists of stringer and bulkhead/rings cylindrical shell with rings on each end. The structure has to house the avionic packages mounted on deck plate. Cutouts have to be provided for accessing the packages and for taking out the pressurization lines. The typical interstage structure is designed for the ultimate load conditions both tensile and compressive without any failure, which are found to be most critical. The main failure mode for these structures is buckling because of the nature of load and type of shell.

INTEGRALLY STIFFENED CONSTRUCTION

The word “integrally stiffened” is applied to construction in which the skin and skin-stiffening elements are made out of one part. In launch vehicles, integrally stiffened sections have proved particularly effective as a lightweight, high strength construction. There are several techniques for making integrally stiffened structure. It can be machined from plate or billet or it may be forged, rolled as a sheet product or extruded or cast or a combination of these processes may be used. Section discontinuities encountered in the region of cutouts can be produced more easily from machined plate. It requires least man-hours for fabrication and leads to less turn-around time. The advantages of integrally stiffened structure over closely stiffened panels are

- Reduction of amount of sealing material for pressurized shell structures.
- Increase in allowable stiffener compression loads by elimination of attached flanges.
- Increased joint efficiencies under tension loads through the use of integral doublers.
- Improved performance in the thermal protection through smoother exterior surfaces.
- Repeatability in production and reduced lead time for frequent launches

Isogrid Structures

Isogrid structure is a lattice of ribs forming pockets of contiguous repetitive equilateral triangular pattern are milled out of thick plate. The triangular ribs behave entirely as an isotropic material. The isogrid structure has the advantage to withstand both compressive and bending loads. Therefore either skin or lattice can be locally stiffened to handle local loads or discontinuities from cutouts. This choice offers more design flexibility than available with rectangular stiffening system of waffle structures.

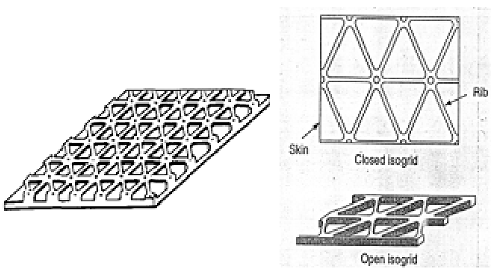

Figure 1: Isogrid Panels

Lattices of rigidly connected ribs, known as grid structures, have many advantages over traditional construction methods, which use panels, sandwich cores and/or expensive frameworks. The introduction of grid structures into industry has been hampered by a lack of understanding of their behavior, especially their behavior in failure space [5]. The plate structures under in-plane compression and shear loads, a critical point exists where an infinitesimal increase in load can cause the plate surface to buckle. Buckling of a plate structure can cause an unacceptable degradation in the aerodynamic profile of a space vehicle.

The isogrid skin panels have applications in offshore structures and presently in airframe. The design and analysis of an interstage structure for launch vehicle isogrid skin panels for an interstage structure is explored in this thesis. These panels will help to replace the presently used skin panels and thus achieve better structure efficiency.

Material Selection

The selection of material is based on the mechanical, chemical, and thermal property requirements of each component of the launch vehicle. The physical and mechanical properties of material are associated with the ability of the material to carry the mechanical forces and loads. The material modulus of elasticity is an important parameter since buckling or deflection characteristics are directly related to it. The structural designer looks for material with high specific strength (UTS/ρ) and high specific stiffness (E/ρ) where UTS is ultimate tensile strength, E is modulus of elasticity and ρ is density of material, along with other desirable characteristics. Other factors like cost, availability, ease of fabrication, and versatility of attachment options are also considered during material selection.

Generally the materials are classified as metals and non-metals. These metallic materials can be ferrous or nonferrous. In this section, properties of a few of the materials are explained briefly with relevance to the ones used in this report.

Aluminum alloys are widely used materials in launch vehicles just as in aircraft/ launch vehicle industry. Although the strength and stiffness of these alloys are not high compared to some other materials, their efficiency parameters are competitive. The aluminum alloys are inexpensive, easily formed, and machined and are readily available. Among the aluminum alloy series, the 2xxx series aluminum alloys are commonly used in launch vehicle.

THEORETICAL BACKGROUND

General Theory of Isogrid

The number of elastic constants required for isotropic materials are always two; the Young's modulus, E and the Poisson's ratio,ν

For isogrid, [1]

$$E = E_o b/h \tag{1}$$

$$\nu = 1/3 \tag{2}$$

where E_o is the Young's modulus of the grid material.

This simple relation makes it possible to use theories of isotropic solutions of generalized shells for isogrid stiffened shells. The plate and shell solutions are generally expressed in terms of the bending and extensional stiffness's, D and K of the shell wall.

Using the assumption that normal to the reference surface remains straight and normal and integrating stresses through the rib grid and skin layers of the wall construction result in the following equations to determine K,the location of the reference neutral surface and D

$$K = \frac{1}{1-\nu 2}\int E(z)dz \tag{3}$$

$$D = \frac{1}{1-\nu 2}\int E(z)\, z^2 dz \tag{4}$$

z is the normal coordinate .In the rib grid layer $E(z)=E_0$ b/h. In the skin layer, $E=E_0$ and it has been assumed that ν =0.3 for the material.

For un-flanged isogrid it is possible to define K and D in terms of the skin thickness t_s, and two dimensional shape factors, α and δ.

By definition,

$$\alpha = \frac{bd}{t_s h} \tag{5}$$

$$\delta = \frac{d}{t_s} \tag{6}$$

Where,

b = rib width

d = rib depth

t_s = skin thickness

h = height of grid triangle

then,

$$K = \frac{E_0 t}{1-\nu^2}(1+\alpha) \tag{7}$$

$$D = \frac{E_0 t^2}{12(1-\nu^2)} \frac{\beta}{1+\alpha} \tag{8}$$

$$\beta = [3\alpha(1+\delta)^2 + (1+\alpha)(1+\alpha\delta^2)]^{1/2} \tag{9}$$

The first factor in E_0, t and ν gives the rigidity of the skin material and the second factor gives the amplification due to the grid work. This form of the equation is characteristics for isogrid equation expressed in terms of α and δ.The rib and skin element are combined to produce an equivalent modulus E* such that the structure can be treated like an equivalent monocoque cylindrical structure. For monocoque solutions which are not given in terms of K and D, an equivalent monocoque t* and E* may be determined which then inserted into the monocoque equations will yield the correct isogrid extensional bending rigidities.

$$K = \frac{E_0 t}{1-\nu^2} \tag{10}$$

$$D = \frac{E_0 t^3}{12(1-\nu^2)} \tag{11}$$

Solving for t* and E*,

$$t^* = \sqrt{\frac{12D}{K}} = t\frac{\beta}{1+\alpha} \tag{12}$$

$$E^* = (1-\nu^2)\sqrt{\frac{K^3}{12D}} = E_0 \frac{(1+\beta)^2}{\beta} \tag{13}$$

The optimization principle used assumes that minimum weight occurs when all modes of buckling; i.e., general instability, rib crippling and skin buckling occur at the same time. This optimization principle is popularly known as the "one horse shay" design philosophy of simultaneous collapse of all components. It will also be assumed that buckling and collapse are identical and that the various modes of buckling failure are uncoupled. The analysis will be carried out for the case of the cylinder under axial compression. This is one of the most common applications.

Design Criteria

The Isogrid parameters which ensure simultaneous failure of Isogrid structure are 'General instability', 'Skin Buckling' and 'Rib Crippling'. The expressions are:

General Instability

For a cylinder with L/R ratio ≤ 10 and subjected to combined bending and axial compression, the critical buckling load is given by

$N_{cr}(1) = c_0 E\,(t^2/R)\beta$, where $c_0 = 0.397$ (14)

where,

R = Radius of the Shell

E =Young's modulus of the shell material

On general instability Margin of safety,

$$M.S = \frac{Ncr_1}{Nx} - 1 \quad (15)$$

Skin Buckling

The critical stress for skin buckling is given by

$N_{cr}(2) = c_1 Et(1+\alpha)\, t^2/h^2$, where $c_1 = 10.2$ (16)

On skin buckling Margin of safety,

$$M.S = \frac{Ncr_2}{Nx} - 1 \quad (17)$$

Rib Crippling

The critical stress for rib crippling is given by

$N_{cr}(3) = c_2 Et(1+\alpha) b^2/d^2$, where $c_2 = 0.616$ (18)

On rib crippling Margin of safety,

$$M.S = \frac{Ncr_3}{Nx} - 1 \quad (19)$$

IDEALISATION OF ISOGRID MODEL

Modelling of Isogrid Structure

The preliminary design and analysis of the cylindrical portion is carried out with isogrid construction.Trial model is here to compare between semi-monocoque and idealised structure.

- Thickness of Skin, t = 1.1mm
- Width of rib web, b = 1.7mm

- Depth of web, d = 16.9mm
- Depth of flange, c = 50mm
- Width of flange, w = 17.4mm
- Leg of triangle, a = 116.37988 mm
- Young's Modulus, E = 68670 N/mm^2
- Cylinder area = 12566.37 mm
- Angle of one triangle = 3 degree
- Number of triangles inside the cylinder = 120
- Calculating triangle height = 104.71 mm

In the idealization it is seen that the General Instability and Rib crippling has positive margin of safety where as the Skin crippling has negative margin. This can be improved in future work by increasing the skin thickness by 0.15 mm.

Estimation of Buckling Strength of Isogrid

Buckling strength is estimated in terms of critical edge load. If P and M are the axial load and bending moment, then Applied edge load, Nx for isogrid panel

$$Nx = \frac{P}{2\pi R} + \frac{M}{\pi R^2} \tag{20}$$

where, R is the radius of the cylinder panel.

Maximum Compression Load on the structure = 1752kN

N_x for isogrid panel (Load/mm)= 139.419N/mm

ANALYSIS ON INTERSTAGE STRUCTURE USING FINITE ELEMENT PACKAGE

About the Software

NASTRAN is developed by NASA scientists and researchers, and is trusted to design mission critical systems in every industry. It is widely used in aerospace and automobile industries. It has wide range of elements in its library to completely model a complex assembly. It also have a large number of solution options. It can be used efficiently to solve complex structural models having a large numbers of elements. The NASA Structural Analysis (NASTRAN) software has been widely used to verify the isotropic property of isogrid, show the variation in deflections and detail stress levels depending on loading versus the orientation of isogrid and to determine the general instability buckling allowable for isogrid tank structures.NASTRAN buckling analysis is based on the elastic and differential stiffnesses of the structure analyzed. The elastic properties of a structure are generally dependent on shear AG/K, torsion JG, bending EI, and axial AE stiffness characteristics. The differential stiffness is based on the static loading, displacement, and geometry of the structure. The approach is essentially based on using Lagrange's equations of motion on a structural system with a finite number of degrees of freedom.

Configuration of the Model

The Intertank structure is located between the solid propellant and liquid propellant tanks of the launch vehicle. It is a cylindrical structure having a diameter of 4000 mm and a height of 2750mm. The height of the structure was chosen so as to accommodate the dome profile of the two propellant tank with which it interfaces. The cutouts provided in the structure are for mounting various electrical/mechanical attachments.

Diameter of the model = 4000mm

Height of the model = 2750mm

Loads and Boundary Conditions

The structure experiences axial compressive load, tensile load as well as bending moment. The loads thus acting on the structure was calculated after considering a load factor of 1.25 which is the Ultimate load or the Equivalent axial load.

Table 1: Load Conditions

Location	AF (kN)	BM (kN.m)	EAL (kN)	AF (kN)	BM (kN.m)	EAL (kN)
FE	**1352**	**1972**	**3324**	-1719	---	-1719
AE	1330	1186	2516	**-1752**	**---**	**-1752**

Description of Finite Element Model

Interstage Structure is in cylindrical shape having diameter of 4m and a height of 2.75m. Structure is subjected to uniformly distribute compressive load. The bottom end of the shell is fully clamped and the compressive force is applied through the rigid ring attached to the top end of the shell.The material and properties used for modelling is aluminium alloy. Consider buckling of the shell with cutouts subjected to an axial compression.

First the structure is modelled without any cutouts in it. Totally nine cut-outs are provided in this structure for various purposes (feed line exit, access door, wire tunnel, access door etc) out of which seven square cut-outs and two rectangular cut-outs.

The designed isogrid cylindrical structure is modelled in Patran 2008r2/2010 for analysis by using mid plane construction.. Using shell elements, the ribs are modelled using CQUAD4 elements, while skin is modelled using CTRIA3 elements. The structure is finally stiffened by using rings above and below the cut-outs using CBEAM elements. The CQUAD4 and CTRIA3 family of elements are the most commonly used 2-D elements. These elements differ principally in their shape, number of connected grid points, and number of internal stress recovery points. Each element type can be used to model membranes, plates, and thick or thin shells. Their properties, which are defined using PSHELL entry, are identical. The important distinction among the elements is accuracy that is achieved in different applications.

Number of Elements **:** 54948

Number of Nodes **:** 33843

Number of CQUAD4 Elements **:** 18263

Number of CTRIA3 Elements **:** 34832

Number of CBEAM Elements **:** 1853

Interstage Structure with Cutouts

Cutouts are provided in the structure to assemble and access mechanical modules/systems, actuators and electronic components while assembly. The cutouts in the structure constitute one of the most troublesome problems confronting the aircraft/launch vehicle designer because the stress concentrations caused by cutouts are localized and a number of solutions can be obtained by analyzing the behavior under load. Totally nine cut outs are provided in this structure for assembly and mechanical/electrical operation for launch, which are listed in Table 2. The figure 2 shows the proposed cut out locations.

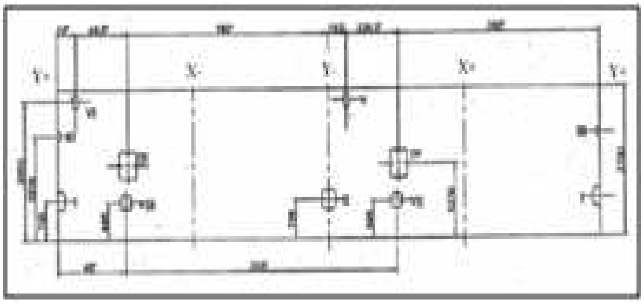

Figure 2: Proposed Cut out Layout on Typical Interstage Structure

The deviations in the cut out layout have been due to the element topology. In order to attain the exact cut out layout along with accurate dimensions it is required to use a more complicated element orientation. Stress concentration occurs around any cut out in loaded structure. To alleviate this effect, one has to adopt various schemes of reinforcement. A cost effective way to alleviate the detrimental effects of a cutout opening is to affix appropriate reinforcements around the opening region, so as to restore the original strength and stiffness of the member. The overall objective of this study is to develop functional, effective and economical reinforcement schemes for Inter-stage structure having cutout openings. So that the original design of the structure need not be changed.

Table 2: Cutout Location on ITS

Cutout No	Angle from X- to Y-(in Degrees)		Size (HxW) (in mm)		Height from AE(mm)	
	Req	Achvd	Req	Achvd	Req	Achvd
I, II	0,180	-1.52, 178.48	350x330	350x314	725	735
III	0	0	150x148	116x209	1910	1899
IV	226.5	225	500x400	581x414	1370	1316
V, VI	192,12	192,12	250x130	232x208	2550	2538
VII, VIII	225,45	225,45	250x250	232x208	695	676
IX	46.5	45	500x400	581x414	1370	1316

Iterations on Designed Isogrid Fe Model

The iterations were performed on the idealised isogrid model as various schemes. The isogrid structure which was idealised was considered for buckling analysis and static analysis. In order to study the effect of reinforcement around the cut out region several iterations are performed. The iterations in this case are done by providing varying reinforcement around the cut out region. The three adjacent pockets of the cut out region are considered for reinforcement and they are analysed for buckling as well as static analysis cases. The thickness of the various regions of the isogrid model without reinforcement is shown below in Table 3.

Table 3: Thickness in FE Model

Sl No	Region	Thickness
1	Fore end-Aft end	12
2	Flange region	10
3	Near Fore end-Aft end skin	1.8
4	Near Fore end -Aft end rib	2
5	Isogrid-portion skin	1.1
6	Isogrid portion rib	1.6

Table 4: Reinforcement Pattern for Various Schemes

Location	Skin Thickness	Rib Thickness
1st pocket reinforcement	2.0	3.2
2nd pocket reinforcement	1.8	2.8
3rd pocket reinforcement	1.6	2.4

Iteration Schemes

In this particular scheme the pocket region closest to the cutout portion alone is reinforced. The pattern that is preferred is hexagonal for reinforcing the model. The thickness of the reinforced skin = 2.0mm and the thickness of the reinforced rib = 3.2mm.

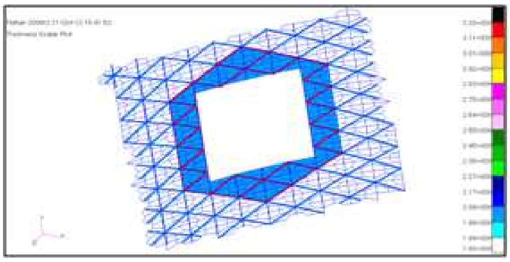

Figure 3: Reinforcement Pattern for Scheme a

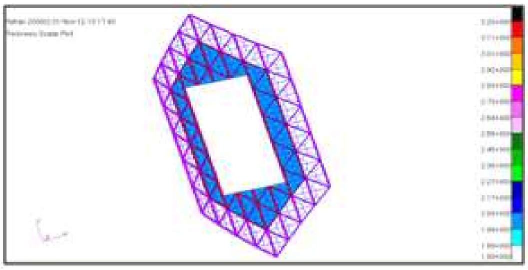

Figure 4: Reinforcement Pattern for Scheme b

In this scheme the two pocket regions adjacent to the cutout are reinforced. The pattern chosen for reinforcement in this particular case is also hexagonal. The reinforcent in the first pocket is the same as in Scheme a. For the second pocket region, the reinforced skin thickness = 1.8mm and the reinforced rib thickness is 2.8mm.

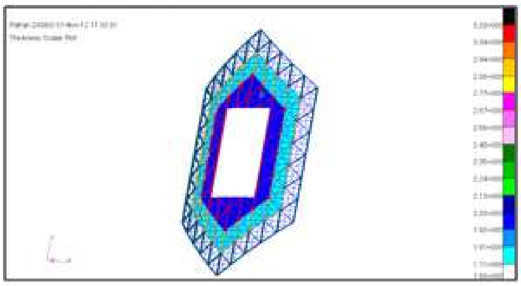

Figure 5: Reinforcement Pattern for Scheme c

In this particular scheme the 1st and 2nd pockets are reinforced according to the patterns discussed in Scheme 3a and Scheme 3b.The 3rd pocket is reinforced with a Skin thickness = 1.6mm and Rib thickness =2.4mm.

RESULTS AND CONCLUSIONS REMARKS

The results of the various schemes have been analysed to check the buckling load factor.

Analysis of Scheme a

The buckling analysis carried out on the reinforcement pattern scheme a produced a buckling load factor =1.4369.The mass of the model was estimated to be 283.775kg. It was also seen that the buckling occurs in cut out 4 and cut out 9.

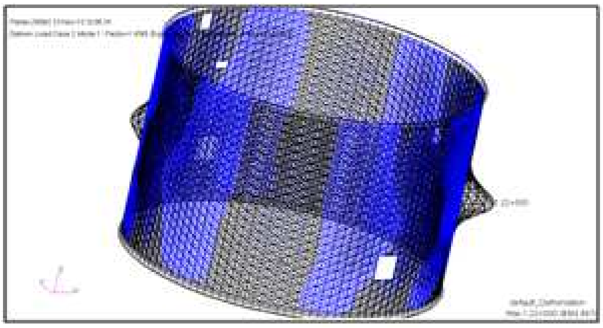

Figure 6: Buckling Analysis Result of Scheme a

Analysis of Scheme b

This is the case where the reinforcement is done around 2 pockets of the cut out region. Buckling analysis done on Scheme b produced the following results.

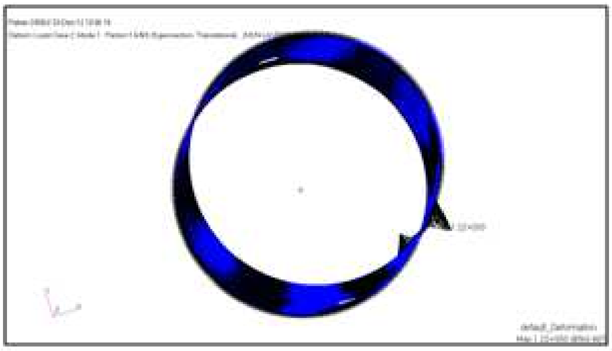

Figure 7: Buckling Analysis Result of Scheme b

The buckling analysis carried out on the reinforcement pattern scheme a produced a buckling load factor =1.6469.The mass of the model was estimated to be 283.887kg. The buckling was identified to have happened near the cut out 4 location.

Analysis of Scheme c

This is the case where reinforcement is done around three pockets of the cut out region. Buckling analysis done on Scheme 3b produced the following results.

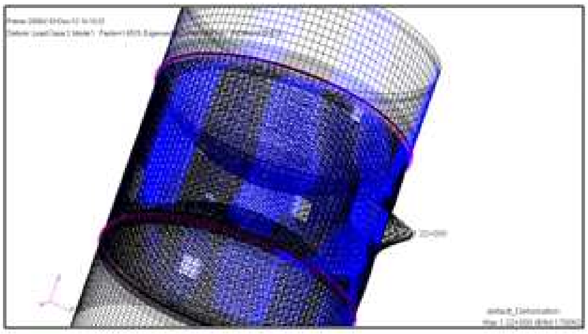

Figure 8: Buckling Analysis Result of Scheme c

The buckling analysis carried out on the reinforcement pattern scheme c produced a buckling load factor =1.6579. The mass of the model was estimated to be 283.968kg.The buckling was identified to have happened near the cut out 4 locations.

Table 5: Scheme Comparison

Iteration	BLF	Mass
Scheme a	1.439	283.775
Scheme b	1.6469	283.887
Scheme c	1.6579	283.968

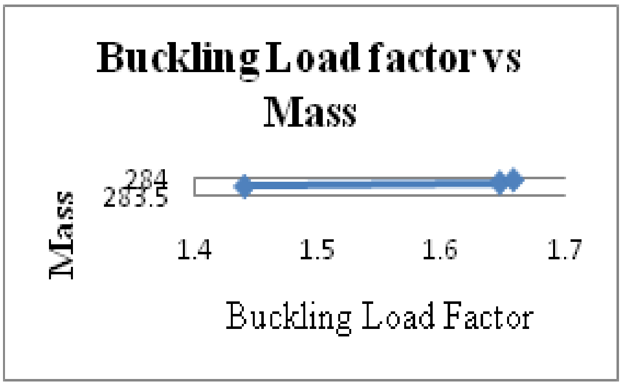

Figure 9: Trend of Buckling Load Factor Vs Mass

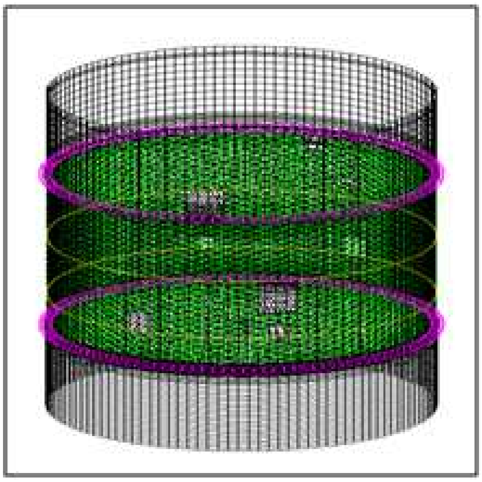

Figure 10: Optimised FE Model

The optimised isogrid model was provided a beam element (CBEAM) in the cut out region for stiffening which is shown in the figure given above. The analysis results obtained for the optimised model are

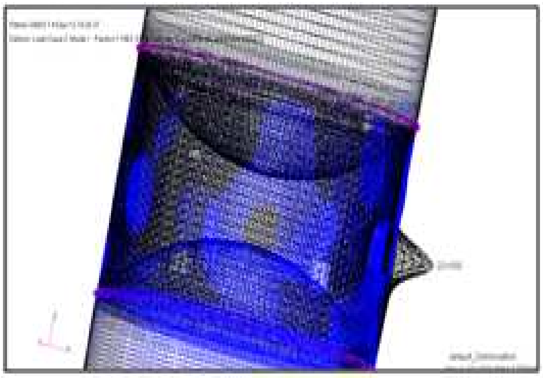

Figure 11: Buckling Analysis Result of Optimised Model

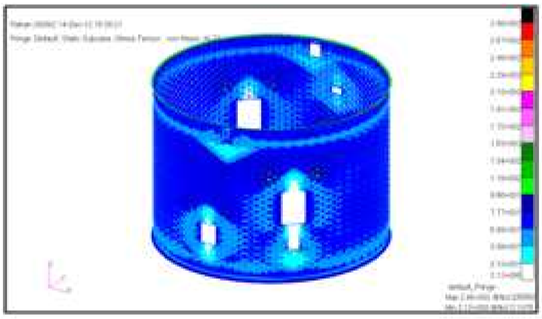

Figure 12: Von Mises Stress Plot of Optimised FE Model

The buckling load factor was found to be 1.7463 and the maximum Von-Mises stress was found to be 286 N/mm^2.

The main findings are

- Finite element modeling is done for a typical intertank structure using integrally stiffened construction replacing closely stiffend construction.
- All the functional and interface requirements as for the original structure are achieved.
- Cutouts are provided in the proposed locations.
- This structure meets the specification requirements for the interstage in the launch vehicle.

Scope for Future Work

- Generating the detailed drawing of the model.
- Holes for fastening of cutout covers need further stiffening, These are to be accounted for future studies

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