International Journal of Mechanical Engineering and Robotics Research

ISSN 2278 – 0149 www.ijmerr.com
Vol. 2, No. 2, April 2013

Research Paper

DESIGN AND ANALYSIS OF PRESSURE CHAMBERS FOR STRUCTURAL QUALIFICATION TESTING OF THE PAYLOAD FAIRING OF A LAUNCH VEHICLE

Roshbe S Calolsa[1]*, Anish R[1] and Nirmal Ramachandran[2]

*Corresponding Author: **Roshbe S Calolsa,** ✉ roshbecalolsa1988@gmail.com

Payload Fairing (PLF) of a launch vehicle protects the payload from excessive thermal loads, acoustic vibrations, aerodynamic loads and other undesirable environmental influences during the atmospheric ascent phase of the flight. The Payload Fairing (PLF) of LVM3 consists of four segments, the Boat Tail, the Cylinder, the Nose Cone and the Nose Cap. It has a cylinder diameter of 5 m and a semi-cone angle of 200 for the boat-tail and nose cone portions. The overall height of the structure is 10.65 m. In order to save structural mass and minimize fabrication time, the PLF is realized using sandwich construction with carbon/epoxy face sheets and aluminium honeycomb core and assembled with aluminium alloy interface rings at all the segment joints. It is constructed in two halves with the longitudinal joints formed using a Linear Bellow System (LBS). The LBS consists of a linear piston-cylinder riveted structure holding a reinforced rubber bellow in folded condition and accommodates a Mild Detonating Cord (MDC) for pyro separation. For qualification of the structural elements of the payload fairing, a full-scale structural test is to be conducted. This involves simulation of aerodynamic pressure on the nose cap and nose cone areas and shear force application at three levels of bulkhead segment joints. This project brings out the details of the methodology, loads, test set-up and procedure for this test. For this purpose two pressure chambers are used in nose cone and nose cap regions for the simulation of aerodynamic pressures. So this paper includes the Design, Modeling and Finite Element Analysis of these pressure chambers.

Keywords: Nose cone, Nose cap, Pressure, Heat shield, Payload fairing stress, Load, Margin of safety

INTRODUCTION

The Payload Fairing is the most important part in a Launch vehicle. The PLF consists of a Nose Cap, Nose Cone, Heat Sheid or the Cylinder and Boat Tail. The Heat Sheid is the place where we are placing the Satellite. The

[1] Department of Mechanical Engineering, SAINTGITS, Kottukulam Hills, Pathamuttom, Kottayam 686532.

[2] Sci/Eng, INSTEF/SDEG/STR, Pallithura PO, Trivandrum.

Remaining parts of the launch vehicle are mainly the fuel and its engine section which accelerates the Satellite to the outer atmosphere to a specific orbit. So the payload fairing of a launch vehicle protects the payload from excessive thermal loads, acoustic vibrations, aerodynamic loads and other undesirable environmental influences during the atmospheric ascent phase of the flight. The PLF is a sandwich construction. For qualification of the structural elements of the payload fairing, a full-scale structural test is to be conducted. This involves simulation of aerodynamic pressure on the nose cap and nose cone areas. .For this purpose two pressure chambers are used in nose cone and nose cap regions for the simulation of aerodynamic pressures. This chapter describes a brief overview of literature related to the history of different procedures performed for the structural qualification testing of a Payload Fairing and various solution methods. The main structural purposes of the payload fairing are to protect the satellite payload during the ascent phase and to provide an aerodynamic forward surface for the launch vehicle.

Michael (1991), the Ground Test Program for the 14-feet diameter version of New Atlas Payload Fairing is conducted at the Space Power Facility (SPF) operated by NASA/ Lewis Research Centre at the Plum Brook Station near Sandusky, Ohio. This site was chosen because it is the largest vacuum chamber in the world. The interior of the chamber consisted of a metal-walled pressure vessel with a 100-feet diameter circular floor and a 120-feet high, domed ceiling. This was surrounded by a thick concrete-walled containment building. Finite Element Analysis was also performed in Nastran to predict the behaviour of PLF during vehicle flight environments for the comparison of test data with these analytical predictions.

Here, for pressurising the Cone Pressure Chamber, Rocasin Bladder is used. But as a part of modification, Double Walled Cloth is glued to the cone section of the PLF. This modification eliminates the complexity of moulding the rocasin bladder. For moulding rocasin bladder as the shape of the hardware, a mould of same size is made which will be a time consuming procedure. Also the Reaction Beams placing above the top flange of the cap chamber are taken as a single piece for convenience. But during fabrication process due to the ease of handling that huge beams, it is decided to split each reaction beam into two in this thesis and each connecting beam is attached to a reaction beam using a web to web joint. So during design and analysis of the Nose Cap pressure Chamber, this is considered.

TEST LOADS

In order to simulate aerodynamic loads on the nose cap and nose cone segments, external pressure loads (ultimate) as listed below are to be applied (Report No. VSSC/V3/VE/SAS/ PR/07/001).

Nose cap external pressure = 62 kPa.

Nose cone external pressure = 28.13 kPa.

TEST METHODOLOGY

The test involves simulation of aerodynamic pressure on the nose cap and nose cone areas, and shear force application on all the segment joints. The cone pressure chamber shall be supported on a platform during assembly and the cap pressure chamber shall be suspended from the crane (Doc.No: VSSC/INSTEF/DR-gsLVM3/09). Before commencement of the test, the pins at the bottom of the cone pressure chamber reaction lines shall be removed. The hydraulic jacks on the cone-chamber suspension lines shall be actuated to lift the chamber above the support platform. Displacement transducers shall be placed at the base of the cone chamber to ensure that all the four support points are lifted uniformly and tilting of the chamber is avoided. The length of the connecting rods on the reaction lines shall be adjusted and the bottom pins shall be inserted in free condition. The load cells shall be zeroed and structural loading shall commence. The pressure chambers shall be pressurized in steps until the required axial forces are developed (Report No. VSSC/V3/VE/SAS/PR/07/001). Each pressurization step shall be followed by application of shear loads. As pressurization starts, the dead weight of the chambers shall be gradually relieved to balance the axial load generated. After the dead weight is completely relieved, the axial load shall be transferred to the connecting rods that anchor the pressure chambers. The sum of the magnitudes of the readings on the suspension line load cells and the readings on the connecting rod load cells shall indicate the total axial loads generated due to application of external pressure. The pressure applied in each pressure chamber shall also be measured using manometers/pressure pick-up.

DESIGN METHODOLOGY

Nose-Cone Pressure Chamber

The nose-cone pressure chamber consists of a truncated conical shell welded to two end-flanges. Both end-flanges are flat annular plates. For external pressurization of the nose cone region of the PLF, a double walled bladder made of NBRCR coated nylon fabric will be attached to the PLF by Velcro joints (Figure 1). During the structural test, the nose-cone pressure chamber shall be suspended using wire slings around the nose-cone region of the PLF so as act as an enclosure over the double-walled pressure bladder (Report No. VSSC/CSTG/TRD/110/035). The pressure-chamber shall also be anchored to the base of the test rig using four connecting rods. Provision for attaching these connecting rods is provided on the bottom flange of the pressure chamber at four locations equi spaced on the circumference. Compressed air shall be fed into the double-walled pressure bladder through an inlet valve. One wall of the pressure bladder presses against the PLF nose-cone region and transfers the pressure load while the other wall of the bladder presses against the nose-cone pressure chamber (Rahul, 2009). This generates an upward force on the nose-cone pressure chamber. The axial force generated will first balance the dead mass of the nose-cone pressure chamber. After the dead weight is completely relieved, the excess axial load shall be transferred to the connecting rods that anchor the pressure chamber to the test rig. The various steps included here are: Design of the Shell, Bottom Flange, Top Flange, Middle Flanges and the stiffeners.

Nose-Cap Pressure Chamber

The nose-cap pressure chamber consists of a cylindrical shell welded to two end-plates. The top end-plate is a flat solid circular plate while the bottom end-plate is a flat annular plate (Figure 2). A double walled cloth in the shape

Figure 1: Cone Pressure Chamber

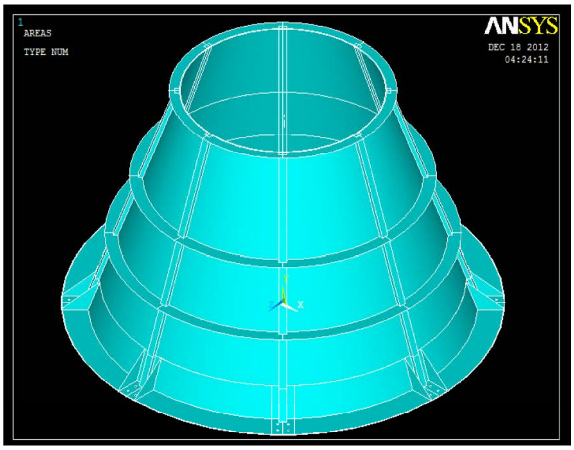
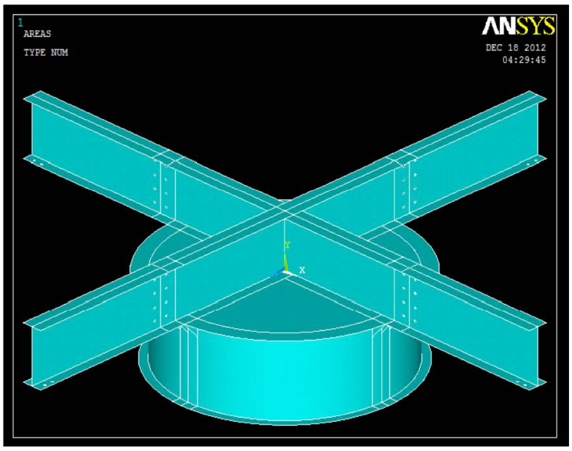


Figure 2: Cap Pressure Chamber



of the PLF nose cap fills the annular space in the nose-cap pressure chamber. On the top end-plate of the chamber, beams are welded. During the structural test, these beams support the chamber such that the double walled bellow just touches the PLF nose cap. Compressed air is fed into the chamber through an inlet valve on the shell. The double walled bellow expands and presses against the PLF nose cap. The pressure load is thus transferred to the PLF. The beams welded on the top end-plate arrest the motion of the pressure chamber (Rahul, 2009).

DESIGN PROCEDURES

Here various parts of the nose cone and nose cap pressure chambers are designed in which the thickness of each part is of prior importance.

Nose Cone Pressure Chamber

Nose Cone Pressure Chamber consists of a Shell, Bottom Flange, Top Flange, Middle Flanges and Stiffeners. So each section will be having different thickness based upon the loading conditions and its dimensions.

Top Flange

$$M_{ra} = K_{M_{ra}} \times qa^2 \qquad ...(1)$$

$$\sigma = \frac{6M_{ra}}{t^2} \qquad ...(2)$$

Bottom Flange

Unit radial bending moment at outer edge,

$$M_{ra} = -wa\left[L_9 - \frac{C_7 L_6}{C_4}\right] \qquad ...(3)$$

where,

w = Load per unit length,

a = Outer radius of the plate. The other factors are,

$$L_9 = \frac{r_o}{a}\left\{\frac{1+\nu}{2}\ln\frac{a}{r_0} + \frac{1-\nu}{4}\left[1-\left(\frac{r_0}{a}\right)^2\right]\right\}$$

$$C_7 = 0.5\left(1-\nu^2\right)\left[\frac{a}{b} - \frac{b}{a}\right]$$

$$L_6 = \frac{r_o}{4a}\left\{\left(\frac{r_0}{a}\right)^2 - 1 + 2\ln\frac{a}{r_0}\right\}$$

$$C_4 = 0.5\left(\left(1+\nu\right)\frac{b}{a}+\left(1-\nu\right)\frac{a}{b}\right)$$

Shell

Maximum Hoop Stress on the Shell

$$\sigma = \frac{pd}{2t\cos\alpha} \quad ...(4)$$

where,

p = Pressure

d = Diameter of shell bottom

α = Cone angle

t = Thickness of the shell

Nose Cap Pressure Chamber

Nose Cap Pressure Chamber consists of a Shell, Top Circular Plate (top flange), Bottom Flange, Bottom Annular Plate, Reaction Beams, Connecting Beams, Beam Joints. So each section should be having different thickness based upon the loading conditions and its dimensions.

Shell

Maximum Hoop Stress on shell taking a stress concentration factor of 2.5 near the hole for the air inlet valve is:

$$\frac{pd \times 2.5}{2t} \quad ...(5)$$

Top Flange

The top flange is a flat solid circular plate of constant thickness. On the top surface of the plate beams are welded at 90° angular locations. These beams arrest the motion of the chamber during pressurization. For a uniformly distributed load q acting over the entire surface of a solid circular 90° sector plate with all the edges simply supported.

$$\left(\sigma_r\right)_{max} = \beta\frac{qa^2}{t^2} \text{ and } \left(\sigma_t\right)_{max} = \beta_1\frac{qa^2}{t^2}$$

$$\text{Maximum Deflection} = \alpha\frac{qa^4}{Et^3} \quad ...(6)$$

β = 0.240, β_1 = 0.216, α = 0.0250, q is the pressure load applied and a is the mean radius of the shell.

Bottom Flange

The bottom flange is connected to the shell using an all-round fillet weld of leg size 5 mm on either side of the shell. For the design of the bottom flange, the case of an annular plate with a uniformly distributed load over the entire surface, having its outer edge fixed and inner edge free is considered.

$$\sigma_{max} = \frac{6M}{t^2} = \frac{6 \times K_M qa^2}{t^2} \quad ...(7)$$

Where, K_M is a constant dependent upon the radius ratio b/a

$$\text{Maximum deflection} = \frac{K_Y qa^4}{D} \quad ...(8)$$

where,

D is the plate constant and K_Y is a constant dependant on the radius ratio b/a

For b/a = 0.9, K_Y = 0.00001.

$$D = \frac{Et^3}{12(1-\nu^2)}$$

Beam Joints

$$\text{Torsion Load, } F_T = \frac{Mr_1}{\Sigma r^2} \quad ...(9)$$

The finite element analysis of both the pressure chambers are done using ANSYS 13.0 and the values are obtained which is useful for comparison as shown in Figures 3 and 4.

Figure 3: Finite Element Model Showing Maximum Displacement

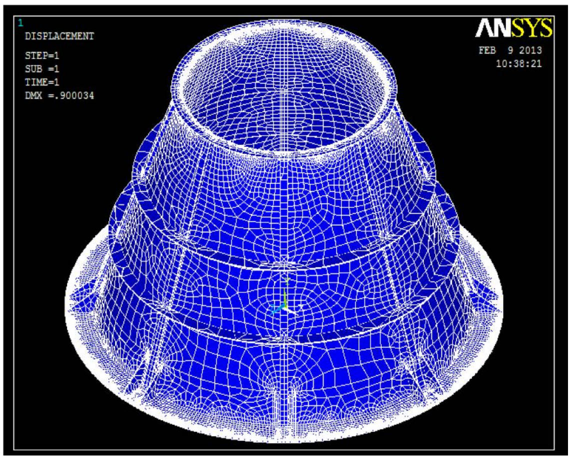
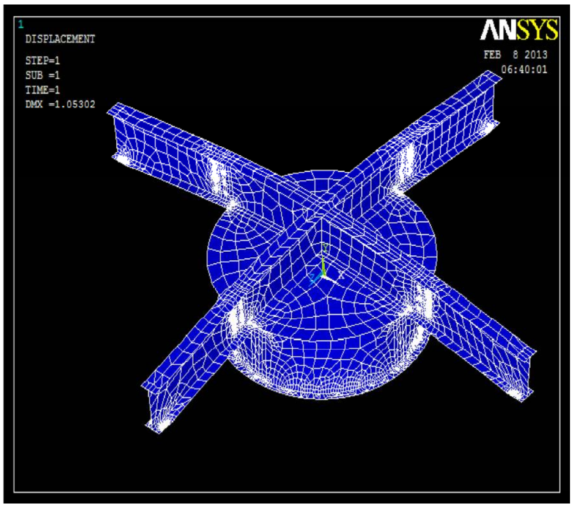


Figure 4: Finite Element Model Showing Maximum Displacement



CONCLUSION

This paper gives a brief summary of the work done and the conclusion derived from the Theoretical and Numerical work. This thesis work focused on design and development of Nose Cone and Nose Cap Pressure Chambers for the structural qualification testing of payload fairing of LVM3 and the analysis of the same using Theoretical means and Finite Element software. This involves simulation of aerodynamic pressure on the nose cap and nose cone areas. The pressurizing methods are different as Nose Cone Pressure Chamber uses double walled cloth while Nose Cap Pressure Chamber uses Rocasin Bladder (Report No. VSSC/V3/VE/SAS/PR/07/001). The test results which are obtained from the theory and analysis of the test setup are compared and approached to the approximate values under some of the assumptions taken during the analysis part. The theoretical estimates of Stress, Strain and Displacement are compared with the Analysis values. The actual deformation behaviour of the test hardware at critical locations are obtained. Validation and Generation in the methodology for design and analysis are also completed.

ACKNOWLEDGEMENT

The analytical work was conducted at INSTEF, VSSC, Trivandrum, the author gratefully acknowledge their support. The author also would like to thank Mr. Nirmal Ramachandran (Scientist/Engineer) for providing expert guidance and advice for the analytical and theoretical work. In addition the author would like to thank the anonymous reviewers for their constructive comments.

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