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Design and Analysis of Composite Truss Structure for Space Borne Payloads

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Abstract: Structure of space borne payload serves as load carrying member and is responsible to meet functional and stability requirement of various sensitive instruments. These structures need to survive launch loads and in orbit thermal expansions. When spacecraft is launched, it undergo excessive vibration and inertia forces. Hence designed mechanical structure should be stiff enough and natural frequency of the overall structure should not match with excitation frequency to avoid resonance. In this research work, structure configuration has been developed for payload. Most of the structure components are designed to be made of composite materials to minimize weight. Payload integration module is made from honeycomb sandwich panels and truss is made from carbon fiber reinforced polymer (CFRP) struts and metallic end fittings. Design considerations for laminate layup sequence has been discussed. Target Natural frequency of 50 Hz has been achieved. Structure for a space borne payload is deigned and analyzed in FEA tools.
Keywords: Mechanical structure, space borne payloads, composite, truss structure, FEA

I. INTRODUCTION

Space borne payloads are instruments or systems which are placed in spacecraft orbiting earth or other planet for remotes sensing and communication applications. These space operating systems undergo excessive loading conditions and temperature fluctuations while launching and in orbit operations. Hence materials used in space borne payloads should be able to withstand high stresses along with having thermal stability and light weight[1][2]. Imaging satellites are used to capture images of planets as well as earth for various applications. To capture clear images satellites must have minimum deflection of structural components and clean surfaces of optical reflectors.

Along with light weight metals, composite materials are now a days used in most space structures. Integration of metallic and composite materials can be done by various joining methods like mechanical fastening, adhesive bonding, welding etc.[3]. Among these methods adhesive bonding is most accepted method due to ease of application and low cost. Due to vacuum and high temperatures in space, materials tend to exhibit outgassing. Dissolved volatile contents present in polymer and adhesive materials tends to get evaporated and it may get deposited on reflector surfaces of mirrors. If it happens then it affects quality of captured data by optical sensors. Hence materials selected for space structure need to be qualified for space application. Outgassing limits for space qualification is such that total mass loss (TML) should be less than 1% and collected volatile condensable materials (CVCM) need to be less than 0.1% [4].

In certain applications where plate like structural members have buckling problem then honeycomb sandwich panels are used instead. Sandwich panels give high stiffness under compressive loading in axial direction of cells and facilitate fastening of instruments. Inserts are to be potted in honeycomb panel with adhesive to attach fasteners. Honeycomb sandwich structure consist of porous core sandwiched between metallic or composite face sheets. Face sheets are bonded with core by film adhesives[5]. Pressure is applied on face sheet by mechanical press or vacuum bagging. To achieve full strength, sandwich panel is then cured at either room temperature for around 7 days or at temperature around 80-120°C for one hour.

II. PRIMARY DESIGN OF STRUCTURE

Overall mechanical structure of space borne payload consist of two parts. One is payload integration module (PIM) and another is support truss structure. A payload integration module is a box type structure which encloses all the optical and electronic instruments. Support truss structure provide rigid and light weight connection of different modules of satellite. Triangulated configuration gives maximum rigidity and widely used in support structures of satellites[1][6]. Based on dimensions and layout configuration of optical and electronic instruments, floor space of around 1 m^2 is required for baseplate and height of at least 270 mm is required in PIM structure.

III. DYNAMIC DESIGN CONCEPT

Dynamic analysis is concerned with response of the structure under influence of external excitation. When spacecraft is launched from earth, the propulsion forces, acoustic and shock loads of space craft strongly interact with low to medium density dynamic characteristic of launch vehicle and will introduce mechanical vibrations throughout launch vehicle and spacecraft. The mechanical dynamic loads can be divided into two groups. One is low frequency sinusoidal vibration in domain of 2 Hz to 100 Hz. Another group is random vibrations in the range of 20 Hz to 2000 Hz[7]. Random vibrations can occur due to acoustic loads and boundary layer turbulences. Generally random vibration occur for very short period of time and hence essentially does not cause failure even if range of random vibration is more than first mode of natural frequency of structure.

Dynamic analysis also consist of checking mode shapes and damping characteristics along with values of natural frequency[8]. Mode shapes of oscillation can help to identify areas of components of the structure which have lower stiffness and need to be redesigned to achieve higher natural frequency of the overall structure. Damping characteristics can be ignored because damping in case of spacecraft structure is very low. For our application target frequency for overall structure is 50 Hz.

IV. MATERIAL SELECTION

For truss structure to be used in space application major considerations are stiffness, thermal stability and weight. Based on these considerations, Fiber reinforced polymer (FRP) composites are now a days very popular for these applications. Comparison of metallic materials with FRP are given below.

Table 1: Material properties of metallic and FRP materials for space application[9]

Sr. No.	Material	Density (kg/m^3)	Modulus (GPa)	Tensile strength (MPa)	CTE (μm/m°C)
1	Glass fiber	2100	45	1020	6.3
2	Aramid fiber	1380	76	1240	-4
3	Boron fiber	2000	210	1240	4.5
4	Carbon fiber	1580	145	1520	-0.9
5	Al6061	2680	68.2	320	23.6
6	Ti6Al4V	4430	114	900	8.8
7	Invar	8000	141	400	1.26

Although FRP materials are superior in mechanical properties but cannot be used for all the structural components because of difficult manufacturing of composite parts. Hence metallic materials has to be used in small and intricate parts. For Struts, carbon fiber reinforced polymer is the most suitable choice. Aluminum alloys, Titanium alloys and Invar are the most widely used metallic materials in space applications.

All the optical and electronic equipments are mounted on base plate of PIM box structure. These mounted instruments acts as lumped and concentrated mass. Hence base plate of PIM structure need to have very high stiffness in direction perpendicular to plate. For this requirement, honeycomb sandwich structure is used in all the panels of PIM box structure. All the brackets and connectors are made of Aluminum alloy to minimize overall weight of structure.

V. CAD MODELLING

Base plate of PIM structure carry all the loads. Hence 40 mm thick honeycomb core is used in base plate and 25.4 mm thick core in all other panels. Face sheets of honeycomb panel is modelled with shell property definition on both surfaces of honeycomb core. Corner brackets and L brackets are designed to integrate honeycomb panels and form closed structure. Cut outs are provided on honeycomb panels for pathway of optical arrays, harnessing, and access for assembly. Truss is designed as shown in figure 1. Materials assigned to all structural components are as shown in table 2.
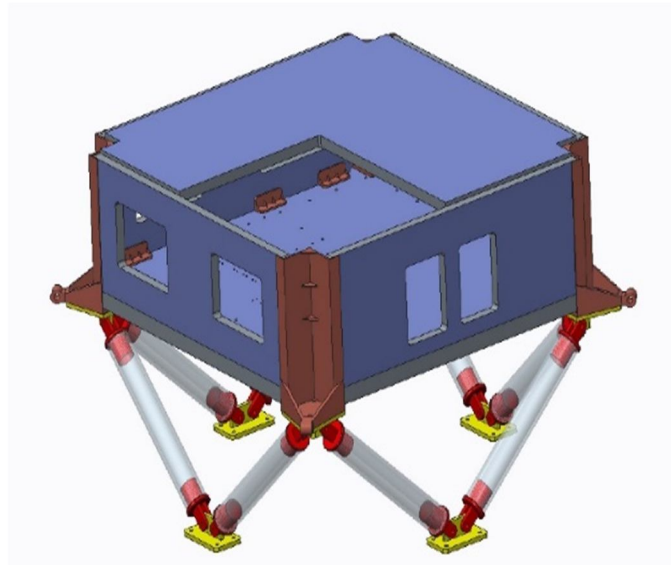
Figure 1: CAD model of primary mechanical structure

Table 2: Materials selected for structural components

Sr. No.	Component	Material
1	PIM structure panels	Al honeycomb core with Al face sheet
2	Brackets	Al6061
3	Connector	Al6061
4	Strut	CFRP

For our application, space qualified high corrosion resistance honeycomb core CRIII-3/16-5056-0.0015-4.4P manufactured by Hexcel corporation is selected. Designation of core defines following parameters[10]:

CRIII – corrosion resistant honeycomb

3/16 – cell size in inches

5056 – Aluminum alloy

0.0015 – foil thickness

4.4 – density in pound per cubic feet

P – Perforated core

Here perforated core is selected to allow gases to escape during curing from cell volumes.

Material property, fiber orientation and lamina thickness are required to define composite properties. Axial direction of tube is considered as reference direction and accordingly quasi-isotropic laminate has been defined.

VI.   LAMINATE DESIGN CONSIDERATION

FRP composite has highest strength and modulus in fiber direction. Hence for ideal truss members where only axial loads are acting, unidirectional orientation is most preferred. But in our application connectors are made stiffer to achieve higher natural frequency of overall structure and hence along with axial load, bending and moment loads are acting on struts. Due to this consideration, laminate for strut is defined to be quasi-isotropic[11]. Quasi-Isotropic term means that individual lamina is transversely isotropic in nature but laminate as a whole behaves like isotropic in in-plane direction.

FRP composites are orthotropic in nature. Study of macro mechanical behavior of FRP suggest that to avoid coupling between extension, shear, bending and torsional stiffness, laminate has to be defined with certain boundary conditions. Coupling effects and their remedies are as shown in table 3.

Table 3: Laminate design considerations[11]

Behavior	Remedy
Bending Extension Coupling	Symmetric laminate
Shear Extension Coupling	Balanced Laminate
Bend Twist Coupling	Increase Number of Lamina, Less number of angle Plies

In our application, laminate is defined to be $[0, 60, -60, -60, 60, 0]_{4s}$. Toray700S fiber is selected with Huntsman XB3542/Aradur5120 resin system[12]. Individual lamina thickness is taken as 0.17 mm which is minimum achievable thickness with selected material and fabric winding process.

Material properties of FRP composite is as follows.

Tensile strength = 2550 MPa

Tensile modulus = 135 GPa

Compressive strength = 1470 MPa

Flexural strength = 1670 MPa

Flexural modulus = 120 GPa

Transverse tensile strength = 69 MPa

Coefficient of thermal expansion = 4.8 μm/m°C

VII. BONDED JOINT DESIGN

Several methods are available for joining metallic parts with CFRP components. Major categories of dissimilar material joining methods are adhesive bonding, mechanical fastening and welding[3]. Among these three methods, adhesive bonding is most feasible and cheapest method of all for joining dissimilar materials in space application.
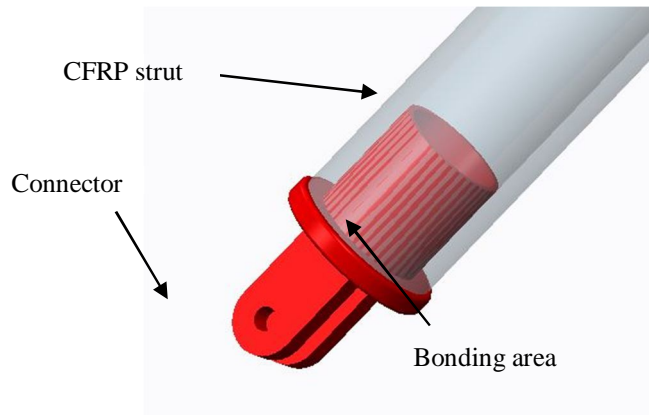

Figure 2: Adhesive bonded joint design

While selecting adhesive for space application environmental factors such as effect of vacuum and drastic temperature variations are need to be considered. Outgassing phenomenon is observed in vacuum. Outgassing is a measure of the level of residual low molecular weight species that can be evolved at elevated temperature. Low molecular weight volatile matter gets vaporized and it may get deposited on optical reflectors such as mirrors. This may cause interference in optical functioning of spectrometers. Adhesive to be used in space must qualify ASTM E595 outgassing standards[4]. Limits for qualifying ASTM E595 is TML should

be less than 1% and CVCM should be less than 0.1% by mass. For structural application epoxy based adhesive is widely used. Hysol EA9309 adhesive is selected based on technical specifications[13].

Shear area for bonded joint A = πdl = 7615 mm^2

Here considering maximum load acting on baseplate of box structure to be 200 kg and in launching conditions maximum acceleration is 15g then axial load acting on one strut is 2325 N. Taking factor of safety of 2 for shear stress calculation,

$$\tau = \frac{F_{axial}}{shear\ area} = \frac{2325\ X\ 2}{7615} = 0.61\ \text{MPa}$$

Shear strength of adhesive at room temperature is 37.2 MPa and at temperature of 82°C shear strength is 6.9 MPa which is far greater than shear stress of 0.61 MPa[13]. Hence bonded joint will be safe.

VIII.   MODAL ANALYSIS

Modal analysis is performed in creo to find first mode of natural frequency. All the optical spectrometers are mounted on base plate and loads acting due to electronics are applied as lumped mass attached to rigid links. As shown in figure first mode is at 56 Hz which is more than target frequency of 50 Hz.
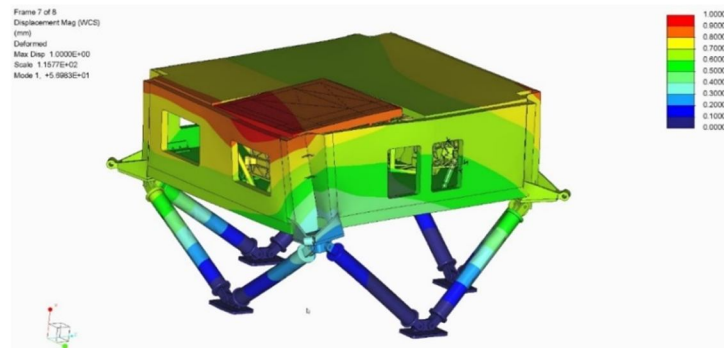

Figure 3: Mode shape for first Natural frequency of structure at 56 Hz

IX.   STATIC ANALYSIS

All the loads acting on the base plate are applied as lumped mass as shown in figure 4. Fixed constraint is applied on brackets at the end of struts. Static analysis is performed to check stresses acting on the structural components. Results are as shown in figure 5.
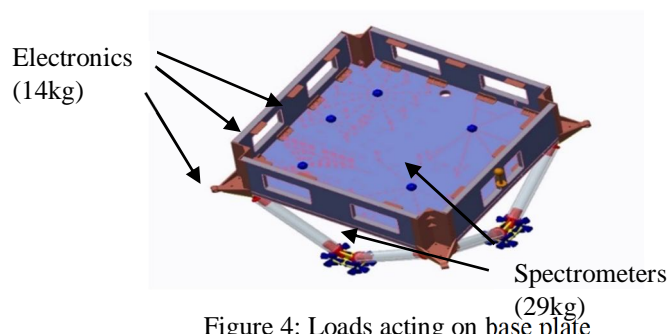

Electronics (14kg)

Spectrometers (29kg)

Figure 4: Loads acting on base plate

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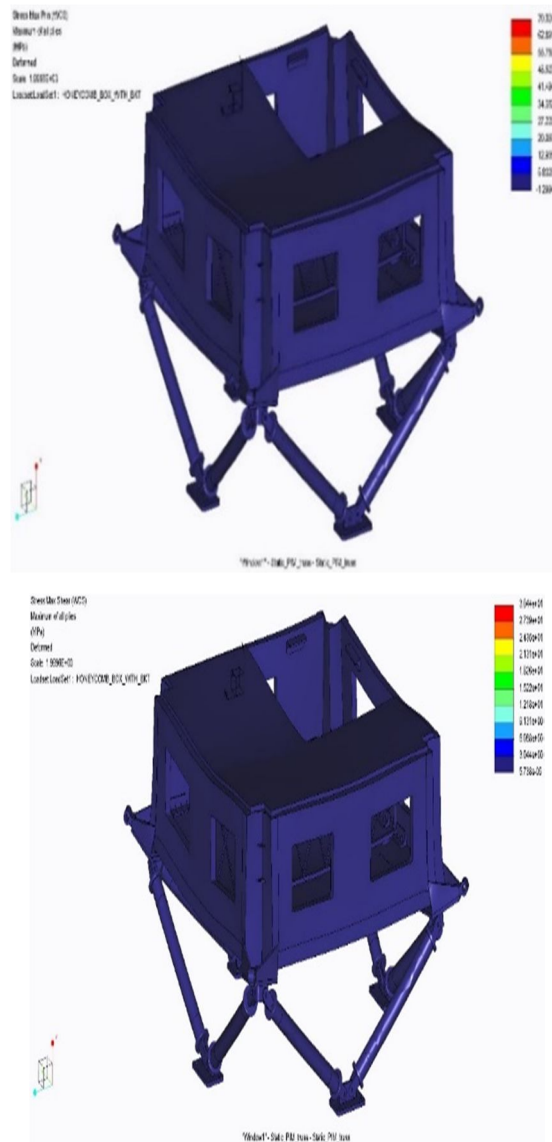*Volume 5 Issue VIII, July 2017- Available at www.ijraset.com*

Figure 5: Static analysis : (a) Von-mises stress (b) max. principal stress (C) max. shear stress

Maximum von-mises stress, maximum principal stress and maximum shear stresses are well below corresponding strengths of selected materials. Maximum von-mises stress is 56 MPa, maximum principal stress is 70 MPa and maximum shear stress is 30 MPa. These maximum stresses are acting at very localized regions and hence not visible as contours in result window

X. CONCLUSION

A summary of design criteria for space borne mechanical structure has been provided. Dynamic design considerations for designing of space borne structure are investigated. Primary design methodology and design considerations for FRP composites and honeycomb sandwich panels are discussed. Adhesive bonded circumferential lap joint is designed to join metallic connector with CFRP strut. CAD model is prepared and FEA is performed to find natural frequency and stresses acting on structural members. Natural frequency of 56 Hz has been achieved for overall structure.

XI. ACKNOWLEDGEMENT

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