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Design and Development of CFRP Tubular Truss Structures

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Abstract— Due to high specific strength and specific stiffness exhibited by composites, they are used to achieve higher payload capabilities in launch vehicle applications. In this paper, a CFRP tubular member is designed and with these members a tubular structure is analysed and developed. Optimization studies were carried out with different layup sequences to find the optimum one. The layup sequence $(0/90/30/0/-30/0/0/0/0/-30/0/30/0/0)_s$ is found to be most desirable and was selected for the composite tubes. The composite tubes were fabricated by hand by rolling the prepreg tapes and were tested in the UTM to find out the failure load under compression and tension. The tested results of strain values were correlated with finite element analysis results. Assembly of composite tubes, brackets and end fittings were done. Linear static analysis was carried out to find the deflection and stresses and was found that they are within permissible limits. Buckling analysis was also done to find the buckling capability of the structure. It was found that the design is safe against buckling.

Index Terms— Boundary conditions, Buckling load, Composite tubes (CFRP), Compression, Distortion energy, Inplane shear stress, Linear static analysis, Octahedral stresses, Tension, Von-mises stress,

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1 INTRODUCTION

TRUSS STRUCTURES composed of many individual struts which are common in launch vehicle and spacecraft to provide stiff, large structures with low mass. Composites are ideally suited for strut applications because they carry predominantly uniaxial loads. This allows the directional properties of fiber-reinforced composites to be exploited, producing a very efficient structure. The advantages of composite use for mass reduction are augmented by the stiffness and stability inherent in composite truss structures. Aluminum or titanium end fittings are generally bonded and bolted to the composite struts for the assembly of CFRP tubes. Human space programs are used to carry men to low earth orbit and return safely to earth after their operation. Human space flight requires launch escape system (LES) in case of any emergency for reentry into the earth. The launch escape system is to be placed above the crew module. There should be sufficient separation between LES and crew module so that the fumes and heat from the rocket will not affect the crew module. Launch escape tower structure serves this purpose which is about 3m long. The tower is made up of composite truss structure and is able to withstand very high temperature with additional thermal coatings.

Chul et al [1] analysed the behaviors of composite circular struts in space environment. The optimal stacking sequence and wall thickness of the composite strut tubes were determined to minimize thermal strains during orbital operation using generic algorithms and finite element analyses. The optimization focuses to minimize the axial strains. The balanced and symmetric stacking sequences are used to minimize the radial and the twisting deformations.

M. M. Shokrieh et al [2] studied about the effect of fiber orientation and cross section of composite tubes on their energy absorption ability in axial dynamic loading. The effect of fiber orientation on the energy absorbed in laminated composite tubes is also studied. Finite-element simulations show that the maximum force and the energy absorbed per unit area of cross section in a circular tube are higher than in a rectangular one, and that a circular tube is also more stable under an axial impact loading. The crushing failure of rectangular tube happened at lower load than that of circular one.

M. Y. Huang et al [3] studied about the hybrid tubes subjected to static and dynamic loading. The effects of composite wall thickness, loading conditions and fiber ply orientation were examined. Increasing the thickness of the composite increases the mean force and the specific energy absorption under both static and dynamic crushing. The ply pattern affects the energy absorption capacity and the failure mode of the metal tube and the composite material property is also significant in determining energy absorption efficiency.

H. Levi et al [4] tested the mechanical performance of thin-walled tubular composite elements under uniaxial loading part (tensile behavior). Elastic and strength properties as well as failure mechanisms were evaluated as related to the wall lay-up configuration. Angle-ply lay-ups of different $(\pm 0)_n$ orientations were compared with tubes having the same thickness but where internal and external 0 plies were replaced by hoop (90) layers. G S Chen et al [5] made an experimental in-

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vestigation was made to study the impact damage tolerance of thin wall composite struts made of both brittle epoxy and toughened epoxy based composite materials. Damage parameters such as barely visible surface damage and internal damage represented by the ultrasonic C-scan, and residual compressive strengths were evaluated against impact energy for two impactor sizes. Puneet saggar [6] made an experimental study of laminated composite tubes under bending. In this paper he evaluates the effect of bending stiffness and bending strength due to stacking sequence, fibre orientation and radius of tube. The strength of composite tube increases as its radius increases. Conversely, the deflection decreases as the tube radius increase.

2. DESIGN OF COMPOSITE TUBES

The composite tube and end fittings are modeled using shell elements. The properties are assigned to the finite element model. The material used for composite tube is Carbon-Epoxy and for end fitting Aluminium is used. The properties of Aluminium and Carbon-Epoxy are shown below in the table 1 and 2

TABLE 1
PROPERTIES OF ALUMINIUM

PROPERTIES	VALUE
Modulus of Elasticity	70000 N/mm^2
Poisson’s ratio	0.3
Shear Modulus	26923 N/mm^2

TABLE 2
MECHANICAL PROPERTIES OF CARBON-EPOXY

PROPERTIES	VALUE
Longitudinal tensile modulus, E_l	294300 N/mm^2
Transverse tensile modulus, E_t	5954.67 N/mm^2
Poissons ratio, υ_{xy}	0.345
Inplane shear modulus	4895.19 N/mm^2
Longitudinal tensile strength	1316 N/mm^2
Longitudinal compressive strength	724.12 N/mm^2
Transverse tensile strength	21.77 N/mm^2
Transverse compressive strength	117.39 N/mm^2
Inplane shear strength	74.7 N/mm^2

The composite tube is made up of 28 layers with thickness 0.1mm each. The layup sequence will be different for these layers. The total thickness of the tube is 2.8mm. The layer sequence given is (0,90,30,0,-30,0,0,0,0,-30,0,30,0,0) symmetric. From the thickness, layup sequence and properties of prepreg, equivalent properties of laminated composite tube is obtained using the PATRAN software and is shown in table 3.

TABLE 3
EQUIVALENT PROPERTIES OF LAMINATED COMPOSITE

PROPERTIES	VALUE
Modulus of Elasticity, E_x	230000 N/mm^2
Modulus of Elasticity, E_y	31200 N/mm^2
Poissons ratio, υ_{xy}	0.522 N/mm^2
Inplane shear modulus	19700 N/mm^2

2.1 Selection of optimum layup sequence

Iterations were done with different layup sequence to obtain the optimum one. The layup orientation selected was balanced and symmetric in order to reduce the inplane bending couplings and inplane shear couplings.

The stresses and deflections were noted for the layup sequence (0,90,30,0,-30,0,0,0,0,-30,0,30,0,0). Then different layup sequences were assigned to composite tube to select the optimum sequence. The sequences assigned were (0,90,45,0,-45,0,0,0,0,-45,0,45,0,0), (0,90,60,0,-60,0,0,0,0,-60,0,60,0,0), (0,90,0,0,0,0,0,0,0,0,0,0,0,0), (0,90,90,0,-90,0,0,0,0,-90,0,90,0,0) and the variations in stresses and deflections were noted.

TABLE 4

STRESSES AND DEFLECTIONS FOR DIFFERENT SEQUENCE

Fibre orientation θ°	Maximum deflection (mm)	Tension (N/mm^2)		Compression (N/mm^2)	
		S_{xx}	S_{yy}	S_{xx}	S_{yy}
±30	1.10	868	288	1120	119
±45	1.16	826	289	1050	107
±60	1.18	1020	289	955	92.5
0	1.09	830	287	1220	129
±90	1.19	768	288	1000	81

From the iterations, layup sequence (0/±30) is the one having more stiffness capability. 0,s alone cannot be provided since they would easily split. The deflection is lowest for layup sequence (0/±30). Hence the layup sequence (0,90,30,0,-

30,0,0,0,0,-30,0,30,0,0) is selected.

2.2 Fabrication & Testing of Composite Tubes

The composite tubes are fabricated by hand by rolling the prepreg tapes in various fibre orientations as per the specified layup sequence. After rolling every 6 layers it is consolidated by machine. After completing all the layers, it is wounded with a covering and filament winding is done. It is then cured at about 170ºC. After curing, filament winding and covering are removed. The tube is then taken out from the mandrel.

The composite tubes fabricated for the truss structure was tested for compression and tension. The testing was done in Universal testing machine. Testing was done to find out the failure load under tension and compression.

2.2.1 Tension Test

The maximum strain developed was 810microstrains and the failure load was at 62kN. The failure was due to debonding of end fitting.

2.2.2 Compression Test

The maximum strain measured was 1289microstrains and the compressive load applied was 85kN.

2.3 Correlate the tested tubes with F.E.analysis result

The strain values find out from the tension and compression were compared with finite element analysis results. The maximum strain when 62kN tensile load was applied was obtained from computerized strain measuring unit and was recorded automatically. The maximum strain developed was 810microstrains.

The same composite tube was modeled and static analysis was done in MSC. Patran by applying 62kN tension. The maximum strain ε_{xx} developed in layer 28 was 812microstrains.

The maximum strain when 85kN compressive load was applied was obtained from computerized strain measuring unit and was recorded automatically. The maximum strain developed was 1289microstrains.

The same composite tube was modeled and static analysis was done in MSC. Patran by applying 85kN compression. The maximum strain ε_{xx} developed in layer 28 was 1340microstrains.

The maximum strains developed by finite element analysis were in the same range as the strain measured experimentally.

3. DESIGN OF TUBULAR TRUSS STRUCTURES

Two types of brackets are needed for the assembly of the tubular truss members. For that brackets are modeled as surface models in CATIA after suitable approximation. The surfaces are divided into different patches so that there will be proper connectivity of elements. The bracketed joint is made up of Aluminium. The brackets are meshed with shell elements and after meshing, continuity is ensured by merging of nodes.

3.1 Application of boundary conditions

After assembling and assigning material properties, boundary conditions are given to the structure. The load is applied on the nodes of upper brackets as point loads. The total nodes on the upper brackets are 560. The actual force that will be coming on the structure is 10 tonnes or 100000N. So on each node a load of 178.57N will be coming. At nodes of bottom brackets displacement boundary condition (U_x, U_y, U_z, R_x, R_y, R_z =0) are given. The figure 1 below shows the loading diagram of the structure.

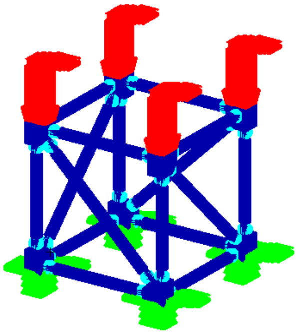

Fig 1. Loading Diagram of the Structure

4. RESULTS

To find out deflections and stresses, linear static analysis is carried out. The maximum shear stresses, Von-mises stresses and octahedral stresses are noted for aluminium brackets and end fittings and checked whether they are within permissible limits. Failure theories are applied to check whether the stresses are within permissible limits. For composite tubes in structure, layer stresses are noted to see the maximum stresses in principal material direction. The maximum deformation from the static analysis is 1.38 mm. The figure 2 shows the deflected profile of the tubular structure.

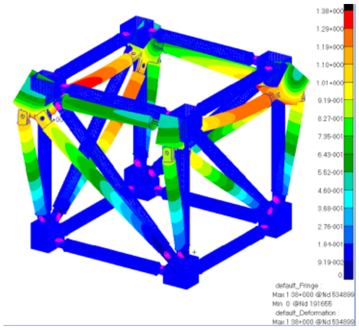

Fig 2. Deflected Profile of Tubular Structure

4.1 Stresses Developed in Brackets and End-fittings

The brackets and end fittings are made of Aluminium. The maximum shear stresses developed is about 211 N/mm² (locally) and this stress occurs for a small region around hole in the projection of vertical tube. But the stress acting globally is less than 30 N/mm². Figure 3 shows the maximum shear stress developed on the structure.

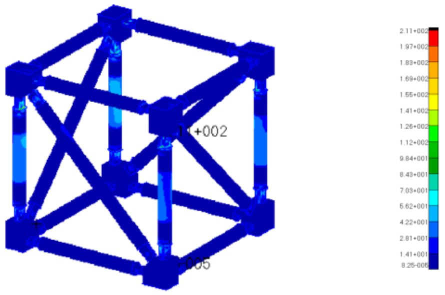

Fig 3. The Maximum Shear Stress Developed on the Structure

According to maximum shear stress failure theory, maximum shear stresses developed should be less than σ_{yp} /2 = 380/2 = 190 N/mm^2.

The maximum Von-mises stress developed is 396 N/mm^2. This stress is acting on a small portion of end fitting. Globally, the maximum Von-mises stress is below 100 N/mm^2. Figure 4 shows the maximum Von-mises stress developed on the tubular structure.

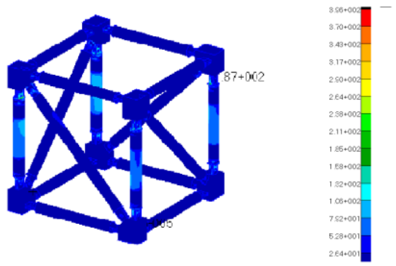

Fig 4. The Maximum Von-mises Stress on the Tubular Structure

According to maximum distortion energy theory of failure, the maximum Von-mises stress developed should be less than σ_{yp} = 380 N/mm^2. So the maximum Von-mises stress developed is within the permissible limits.

Maximum octahedral shear stresses developed is 187 N/mm^2. This is acting in a small portion of end fitting. Globally the stresses are below 60 N/mm^2. Figure 5 shows the maximum octahedral shearing stress developed on the tubular structure.

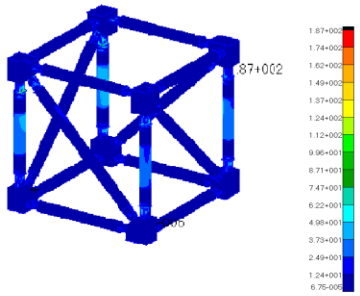

Fig 5. The Maximum Octahedral Shearing Stress on the Tubular Structure

According to octahedral shearing stress theory, the maximum octahedral shearing stress developed should be less than 0.47 σ_{yp} = 178.6 N/mm^2. So the maximum octahedral shearing stress developed is also within the permissible limits.

Since the stresses in the bracket and end fittings are within permissible limits, the design of brackets and end fittings are fixed.

4.2 Stresses in Composite Tubes of Structure

The maximum layer stress in principal material direction 1 in tension (S_{xx}) is 319 N/mm^2 and it's developed on vertical struts.

The maximum layer stress in principal material direction 1 in compression (S_{xx}) is 326 N/mm^2 and its developed on vertical struts.

Figure 6 shows the maximum layer stress S_{xx} in tension in layer number 29 of vertical strut of tubular structure. Figure 7 shows the maximum layer stress S_{xx} in compression in layer number 2 of vertical strut of tubular structure.

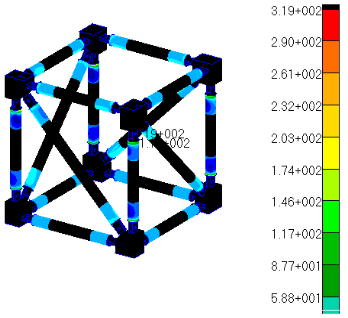

Fig 6. The Maximum Layer Stress S_{xx} in Tension in Layer Number 29 of Vertical Strut

Fig 7. The Maximum Layer Stress S_{xx} in Compression in Layer Number 2 of Vertical Strut

The maximum layer stress in principal material direction 2 in tension (S_{yy}) is 5.7 N/mm^2 and its developed on vertical struts. The maximum layer stress in principal material direction 2 in compression (S_{yy}) is 8.05 N/mm^2 and it's developed on vertical struts. The maximum inplane shear stress developed S_{xy} is 7.82

N/mm^2. Figure 8 shows the maximum layer stress S_{yy} in tension in layer number 28 of vertical strut of tubular structure and figure 9 shows the maximum layer stress in compression (S_{yy}) in layer number 3 of vertical strut and figure 10 shows the maximum inplane shear stress developed S_{xy} in layer number 27.

Fig 8. The Maximum Layer Stress S_{yy} in Tension in Layer Number 28 of Vertical Strut

Fig 9. The Maximum Layer Stress in Compression S_{yy} in Layer number 3 of Vertical Strut

Fig 10. The Maximum Inplane Shear Stress Developed S_{xy} in Layer 27

According to the maximum stress failure theory, each of the stress components should be less than the corresponding failure stresses.

S_{xx}, S_{yy} and S_{xy} should be less than their failure strengths F_x, F_y and F_s.

S_{xx} in tension is 319 N/mm^2 is less than F_x in tension which is 1316 N/mm^2.

S_{xx} in compression is 326 N/mm^2 is less than F_x in compression which is 724.12 N/mm^2.

S_{yy} in tension is 5.7 N/mm^2 is less than F_y in tension which is 21.77 N/mm^2.

S_{yy} in compression is 8.05 N/mm^2 is less than F_y in compression which is 117.39 N/mm^2.

S_{xy} 7.82 N/mm^2 is less than F_s which is 74.7 N/mm^2. Since all the stress components are within permissible limits, layer failure will not occur.

4.3 Buckling analysis

Buckling refers to the loss of stability of a component and is usually independent of material strength. This loss of stability usually occurs within the elastic range of the material. Buckling analysis is carried out to find out the buckling load factors and buckling modes. The total load applied is 100,000N which is the actual load acting on truss structure.

The buckling load = total load applied × buckling load factor. Figure 11 to 13 shows the buckling load factors and buckling modes.

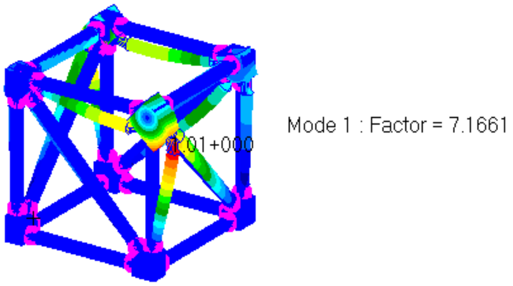

Fig 11. The Buckling Mode 1

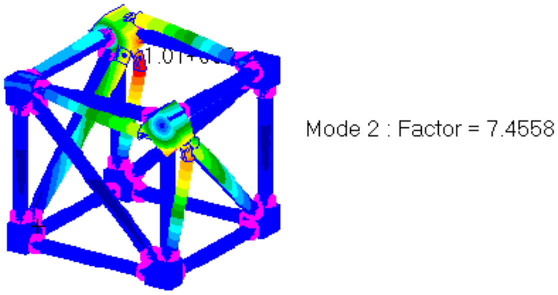

Fig 12. The Buckling Mode 2

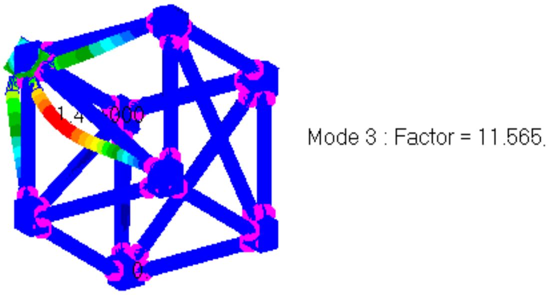

Fig 13. The Buckling Mode 3

The primary buckling load = 100,000 N × 7.1661 = 716.61 kN

The second buckling load = 100,000 N × 7.4558 = 745.58 kN
The third buckling load = 100,000 N × 11.565 = 1156.5 kN

As the buckling load is greater than applied load, hence the tubular structure is safe against buckling.

5. ASSEMBLY OF THE HARDWARE

Assemblies of truss members were done manually. Initially the bracket type 1 is fixed in a position. According to the design length, other bracket (Type 2) was also fixed. Then the vertical tubes, horizontal tubes and brackets were assembled. The whole structure was assembled in the same manner. The original structure consists of bracket type-1, bracket type-2, horizontal tubes, vertical tubes and inclined tubes. But in this assembled view, it doesn't have inclined tubes. These tubes have to be manufactured with the design length and have to add in this structure. The assembly of the composite tubes and brackets are shown in the figure 14 and 15.

Fig 14. Isometric View of Assembled Structure

Fig 15. Assembled Structure without Inclined Tubes

6. CONCLUSIONS

The composite tube with end fittings were modeled in CATIA The tube was fabricated by Prepreg rolling by hand. Then the tube was tested under compression and tension for different loads. This shows that the strain values of tested tubes were found to be in similar order as the static analysis results. This validates the finite element results and the tube has been qualified for the loads acting on tubes. Iterations were carried out with different layup configurations to find out the optimum layup sequence. From the above iterations layup sequence (0/±30) is the one having more stiffness capability. 0,s alone cannot be provided since they would easily split. The deflection is lowest for layup sequence (0/±30). Hence the layup sequence (0,90,30,0,-30,0,0,0,0,-30,0,30,0,0) is selected.

Assembly of the composite tubes with end fittings and brackets were done in software Patran. Linear static analysis was carried out for the tubular truss structures to find out the deformations, stresses etc. Stresses obtained were within the permissible limits by applying failure theories for tubes, brackets and end fittings. The deformations and stresses obtained for tubular truss structure are within the limits. Buckling analysis was also performed to find out the buckling load. The buckling capability of the truss structures is high with respect to the applied load and hence the structure is safe against buckling.

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