COMPARATIVE STUDY OF MONOCOQUE AND SEMI-MONOCOQUE FLIGHT VEHICLE STRUCTURES UNDER STRUCTURAL AND THERMO-STRUCTURAL LOADS

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ABSTRACT

Analysis of monocoque and semi-monocoque cylindrical flight vehicle structures by using finite element method has been carried out. Shell elements are used for idealizing skin portions and end rings and beam elements are used for idealizing stiffeners. The behaviour of these structures is compared in terms of mass, deformation, stress and buckling under structural and thermo-structural loads to study the effect of number of longitudinal stiffeners. The study shows that semi-monocoque structures give higher factor of safety and buckling load factor when only structural loads (axial force and bending moment) are acting on them and the same structure give lesser factor of safety and buckling load factor when thermal loads (temperatures) and structural loads (axial force and bending moment) are acting on them in a combined manner. It is concluded that monocoque structures are best suitable under thermo-structural load environments.

Keywords: monocoque, semi-monocoque, cylindrical flight vehicle structures, thermo-structural loads.

INTRODUCTION

The basic structural element of any flight vehicle is the thin walled tube called skin. There are many methods to strengthen this skin. One of the generally used methods is reinforcing the skin with longitudinal members called stiffeners. These members can be attached with rivets, welded or machined integrally with the skin. The skin structure that is stiffened by number of reinforcing elements is called semi-monocoque structure (stiffened skin or reinforced skin structures). The unstiffened skin structures are called monocoque structures. Semi-monocoque cylindrical structures are generally used in flight vehicles to get the benefit of higher strength to weight ratio. A structure composed of stiffeners in two directions (longitudinal and circumferential) may be more efficient than one having in single direction. But here the investigation is restricted to structure composed of stiffeners in one direction only i.e. longitudinal direction. Generally, the flight vehicle structures will experience structural loads (axial force and bending moment) and thermal loads (temperature) during the course of trajectory. Structural loads and thermal loads acting on the flight vehicle structure are derived from the load and kinetic heating analyses respectively. The structure has to be designed in order that it will withstand both structural and thermal loads and perform its intended functions.

The flight vehicle section consists of three parts: 1. Skin portion 2. End rings 3. Stiffeners (in case of semi-monocoque structures) and the configuration of monocoque and semi-monocoque sections are shown in Figures 1(a) and 1(b). Skin and end rings without longitudinal stiffeners, with 4 stiffeners, with 8 stiffeners and with 12 stiffeners have been considered independently for the structural and thermo-structural analyses using Finite Element Analysis package ANSYS.

B. Gangadhara Prusty [1] describes the analysis of composite stiffened panels by the method of finite elements. This investigation is made to study the various aspects of laminated composite shells with open and closed shaped stiffeners and it gives an overview regarding the selection of stiffener sections in engineering designs. The paper published by Bernard Budiansky [2] presents the optimization studies made to assess the potential utility of light metal foams as weight-saving components of two kinds of compression structures: columns and flat compression panels. The imperfection sensitivity of optimized thin-walled columns and stiffened panels tend to make failures catastrophic when they occur, whereas foam-core columns and sandwich panels can be expected to undergo more graceful collapse. The paper published by G.Sinha *et al*., [3] reported the static, free, forced and random response analyses of shell panels of varying thicknesses stiffened by beams of varying depths which have found widespread applications in a variety of engineering structures.

The work done by Agarwal *et al*., [4] presents optimum designs for unstiffened, hat-stringer-stiffened and honeycomb sandwiched cylinders under axial compression. It was found from their study that stiffener cross-section deformation, which are usually ignored in smeared stiffener theory, result in a reduction of buckling load by 30% for graphite-epoxy hat stiffened cylinder. Benjamin F. Ruffner [5] made an investigation to determine the possibility of using the photo elastic method for the stress analysis of bulkhead in monocoque structures and the method is found to be accurate. Priyadarsini. R.S. *et al*., [6] carried out the Numerical and Experimental Study of Buckling of Advanced Fiber Composite Cylinders under displacement and load controlled static and dynamic axial compression. The work done by Ferhun C. Caner *et al*., [7] made a study about the size effect on strength of laminate-foam sandwich plates using Finite element analysis with interface fracture which reveals that small-size specimens with notches just under the top skin develop plastic zones in the foam core near the edges of the loading plate, and

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that small-size specimens with notches just above the bottom skin develop distributed quasi brittle fracture in the foam core under tension.

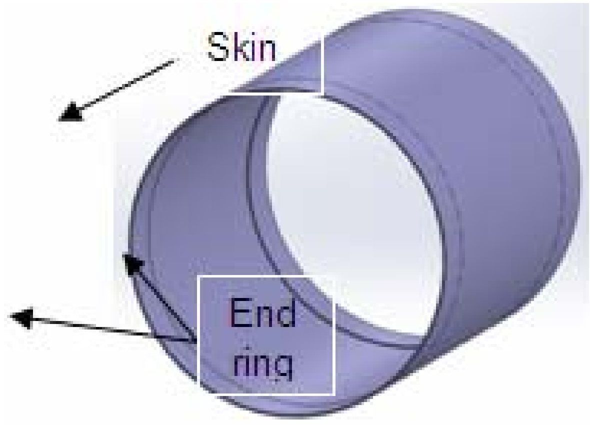


Figure-1(a). Monocoque structure (unstiffened)

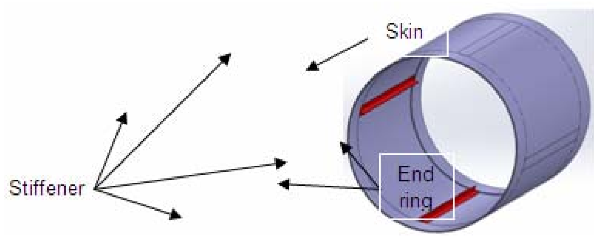


Figure-1(b). Semi-monocoque structure (with 4 stiffeners).

2. DESIGN AND ANALYSIS

The flight vehicle section with outer diameter of 750mm and total length of 1000mm is considered for the study. The skin portion has 750mm length and different thicknesses are considered for analysis. The end rings are on both side of the skin portion with 125mm length each and 6mm thickness. The 'T' shaped longitudinal stiffener has 750mm length and 3mm thickness and the other geometric details of sections and stiffeners are shown in Figures 2(a) and 2(b), respectively. All the dimensions given in Figures 2(a) and 2(b) are in mm.

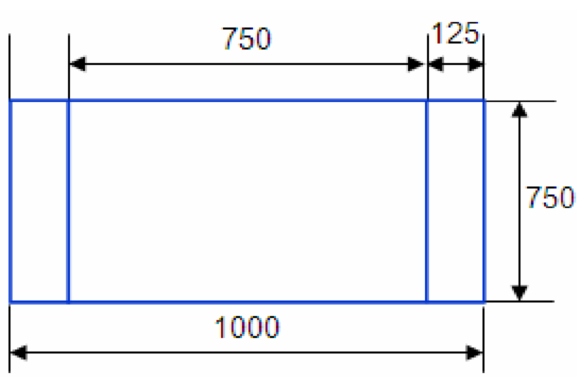


Figure-2(a). Geometric details of section.

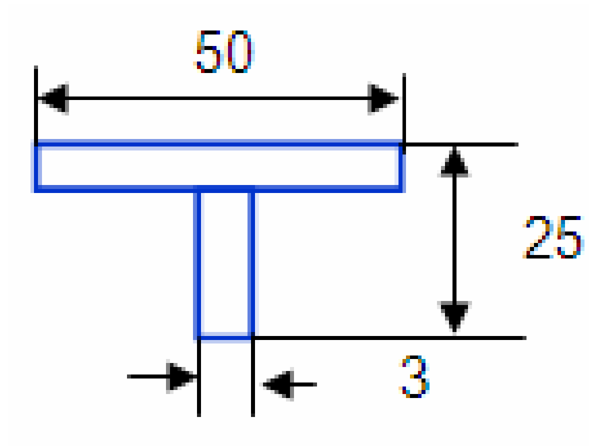


Figure-2(b). Geometric details of stiffener.

Material used for Skin, End rings and Stiffeners is Aluminium alloy 2014 because of its light weight, high strength to weight ratio, good corrosion resistance, good ductility, ease of fabrication and its availability in various forms. Its mechanical properties with respect to temperatures are given in Table-1. These properties are taken from Metallic Material Properties Development and Standardization (MMPDS) Handbook by Federal Aviation Administration (FAA), USA.

Table-1.

Temp.^{0}C	25	100	150	200	250
E (GPa)	72.2	70	68.3	64.5	59
UTS (MPa)	460	420	376	305	188
0.2% PS, (MPa)	405	379	334	260	154

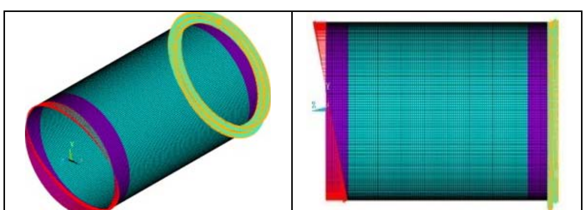
E = Young's Modulus
UTS = Ultimate Tensile Strength
PS = Proof Strength

The Modeling and Finite Element Analysis of the cylindrical Flight vehicle structure have been carried out using ANSYS. The skin portions and the end rings of the cylindrical Flight vehicle structure are modeled as areas according to the dimensions. The eight nodded quadratic shell elements with six degrees of freedom on each node (3 translations along each axis and 3 rotations about the axes) which are well suited for modeling curved geometry are used to idealize the skin portion and end ring of the structure. The thicknesses of skins and end rings are given as real constants. The longitudinal stiffeners are modeled as lines. The two nodded beam elements with six degrees of freedom on each node (3 translations along each axis and 3 rotations about the axes) are used to idealize the longitudinal stiffeners so that the compatibility is maintained. Sectional properties of longitudinal stiffeners are given as real constants. Bending moment is converted into equivalent axial force and is vectorially added with the axial compressive force to be applied. This force set is applied on the front edge of the front end ring of the cylindrical flight vehicle structure. Skin thickness of 1mm was considered initially for the analysis. When it is seen that 1mm was not sufficient to withstand the loads, skin thickness of 1.5mm was considered with different number of stiffeners for both structural and thermo-structural analyses. Finally skin thickness of 2mm without stiffeners was considered for analyses to check and compare the results with other configurations. The temperatures considered for different portions of flight vehicle structures are given in Table-2. The rear edge of the rear end ring is constrained in all the directions (all degrees of freedom are constrained). Stress and buckling analyses have been carried out and found out the mass, deformation, stress and buckling load factor for all the configurations. Mass properties of the structures depend on their geometry and material. Stress and buckling depend on geometry, material, loading conditions and end/support conditions.

Table-2.

Components	Temperature ^{0}C
Skin (1mm thick)	250
Skin (1.5mm thick)	200
Skin (2mm thick)	150
Stiffeners	100
Bulk heads	75

The Flight Vehicle sections without stiffeners, with 4 stiffeners, with 8 stiffeners and with 12 stiffeners have been analyzed under structural loads alone and thermo-structural loads independently. Corresponding material properties with respect to temperatures of the different portions of the flight vehicle sections are considered for thermo-structural analyses. The typical Finite Element Models are shown in Figures 3(a), 3(b), 3(c) and 3(d) for the above said configurations.



Isometric view | Side view

Figure-3(a). FE model without stiffeners

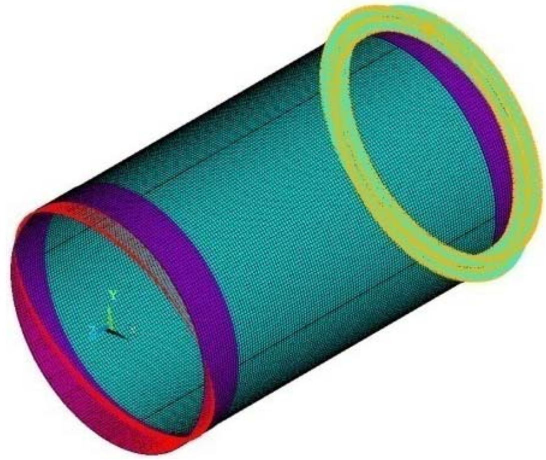


Figure-3(b). FE model with 4 stiffeners.

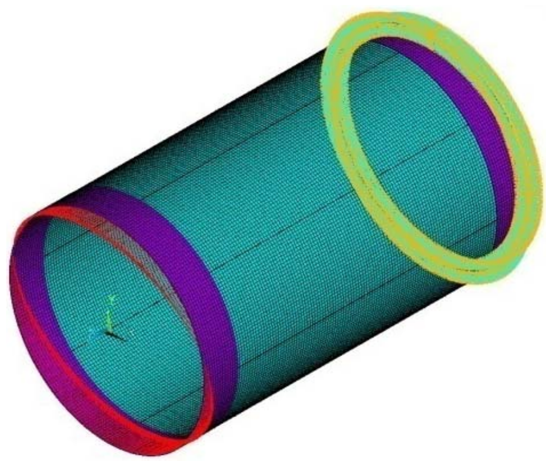


Figure-3(c). FE model with 8 stiffeners.

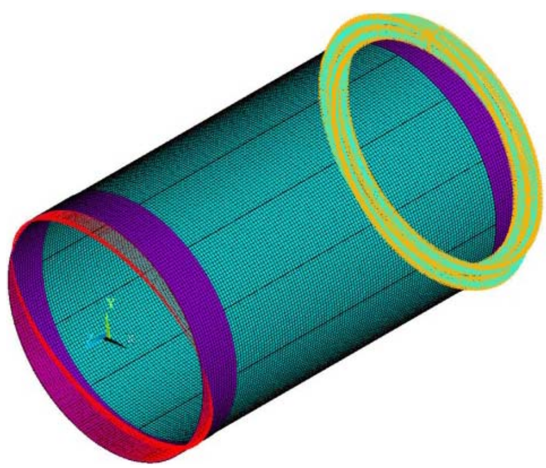


Figure-3(d). FE model with 12 stiffeners.

The flow chart for the finite element analysis is shown on the following Figure-4.

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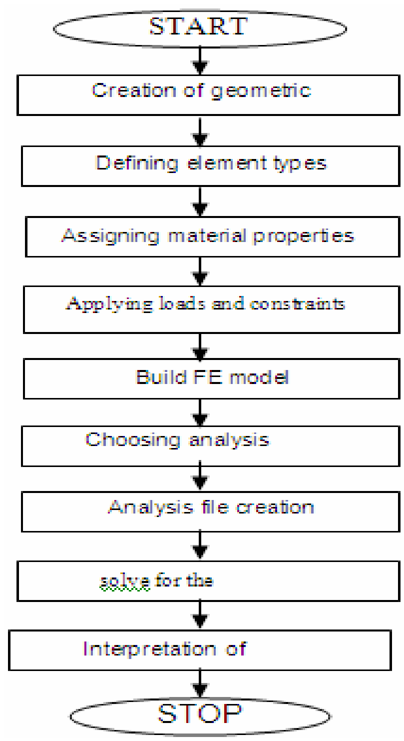

Figure-4. Flow chart for F E A.

Classical Analysis has also been carried out to estimate the deformation, stress and buckling load factors considering both structural and thermal loads for all the configurations using the references [8-10] to verify the FEA results. Same orders of the values have been obtained.

3. RESULTS AND DISCUSSIONS

From the FEA results of all four configurations for structural loads alone, it is seen that when the number of stiffeners are increased the stresses on the skin have come down, because of which the factors of safety have increased and also the buckling load factor values have increased. When thermal and structural loads are combined, the increase in number of stiffeners lead to decrease in stresses on the skin stiffener junction in addition to skin bulkhead junction and the factors of safety and the buckling load factors have reduced. It is observed that under thermo-structural loads, the use of stiffeners causes localized stresses due to difference in temperature between the skin portions and stiffeners because of different thermal masses. In addition to the above, the increase in temperature leads to reduction in material strength and stiffness properties. Both of these cause the structure to become weak and buckle. The following Figures 5 - 8 show the various representative plots of results for flight vehicle section with 12 stiffeners under thermo-structural loads from Finite Element Analysis.

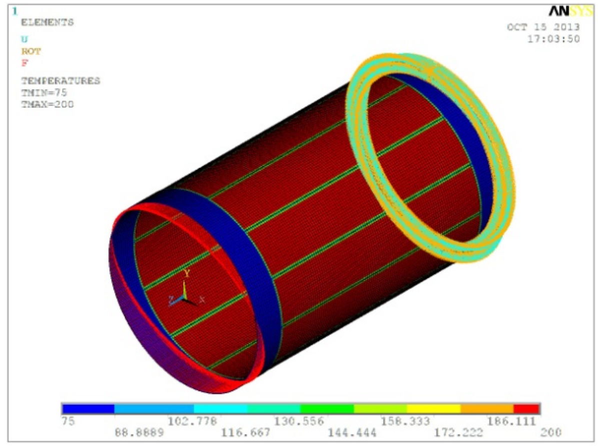

Figure-5. FE model with thermo-structural loads.

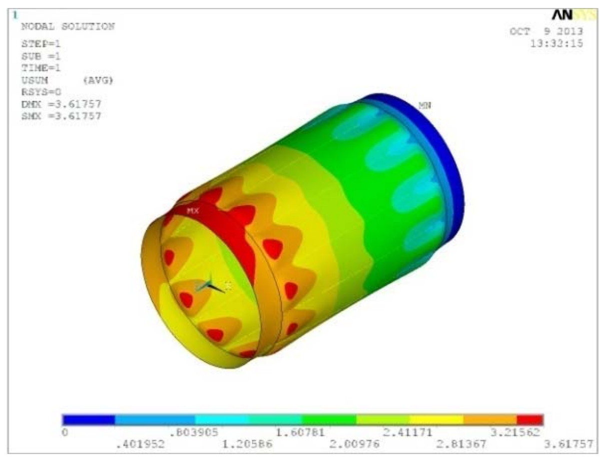

Figure-6. Deformation plot.

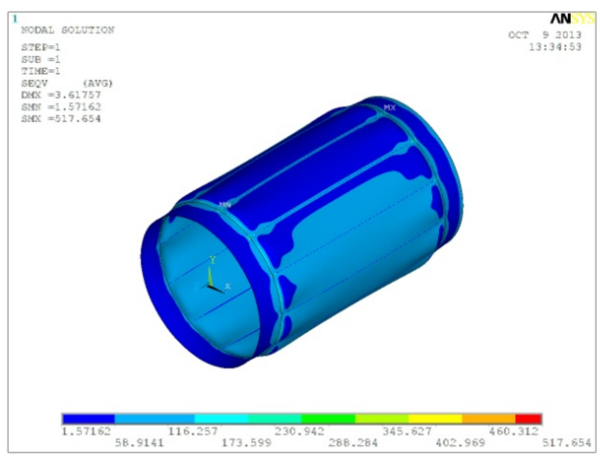

Figure-7. Maximum stress plot.

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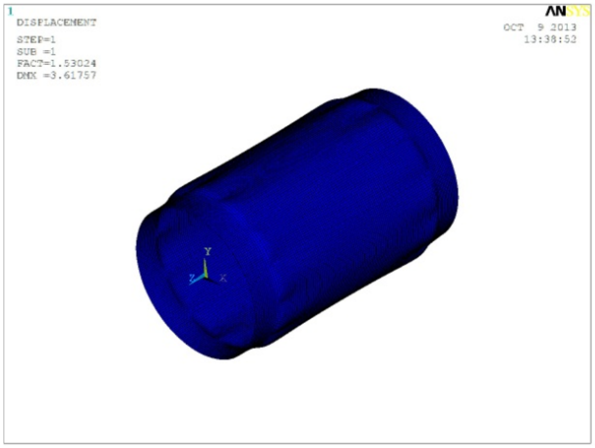

Figure-8. Buckling mode shape plot.

Figure-5 shows the FE model with structural loads (axial force and bending moment) applied on the front end ring of the section, thermal loads (temperature) applied on all the portions of the section and constrained at the rear end ring of the section. Figure-6 shows the deformation plot with maximum deformation of 3.62mm near the front end. Figure-7 shows the Von Mises stress plot with maximum stress of 173.6 MPa near the skin stiffener junctions. Figure-8 shows the buckling mode shape plot with buckling load factor of 1.53 from FE analysis and the final buckling load factor is around 0.77 after considering the knock down factor of 0.50. Similarly, the structural and thermo-structural analyses have been carried out for all the configurations. Figures 9-12 show the comparison plots of results for all the analyses in terms of mass, deformation, stress and buckling load factors.

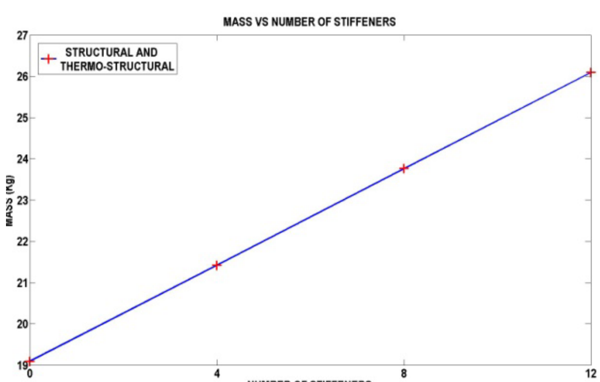

Figure-9. Mass vs. no. of stiffeners.

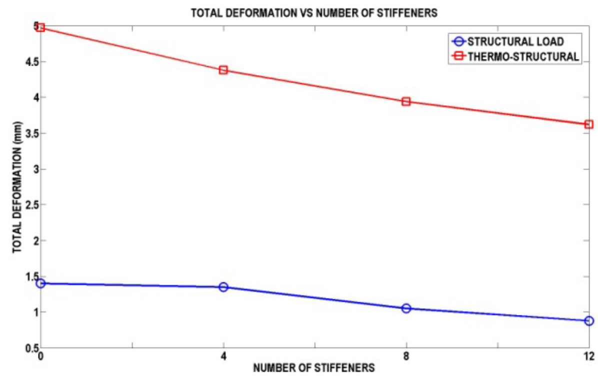

Figure-10. Deformation vs. no. of stiffeners.

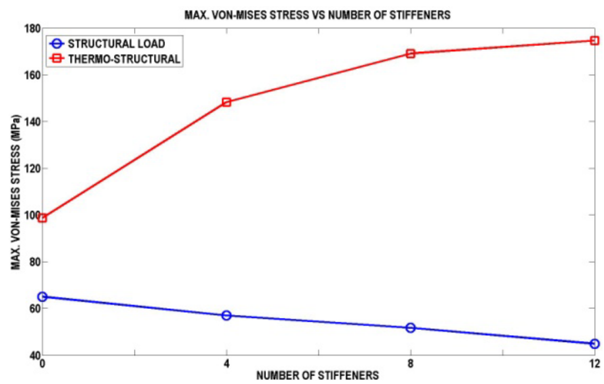

Figure-11. Stress vs. no. of stiffeners.

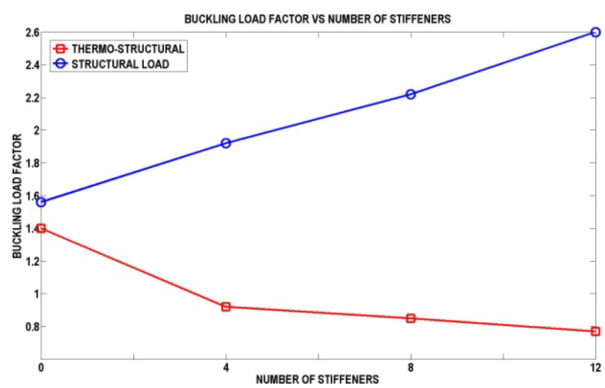

Figure-12. Buckling load factor vs. no. of stiffeners.

Figure-9 shows the effect of number of stiffeners on the total mass of the flight vehicle section. It shows that the mass is increased with the increase in number of stiffeners and the relation is linear. It is same for both structural and thermo-structural load cases. Circular symbol in blue colour represents the structural load alone and square symbol in red colour represents the thermo-structural loads for the Figures 10-12. Figure-10 shows the effect of number of stiffeners on the total deformation of the flight vehicle section. It is seen that the deformation is decreasing with the increase in number of stiffeners for both structural and thermo-structural load cases because the stiffeners are sharing the load in structural load case and stiffeners are resisting the expansion of the sections due to thermal load due to difference in thermal mass and temperature of the skin and stiffeners. Figure-11 shows the variation of the von mises stress with respect to number of stiffeners in the section. For structural load case, the stress is decreasing with the increase in the number of stiffeners whereas for thermo-structural load case, the stress is increasing with the increase in the number of stiffeners. This is due to the difference in temperature at the skin stiffener junctions and skin bulkhead junctions due to difference in thermal mass between them. The variation of stress leads to variation in factor of safety on ultimate tensile strength and yield strength based on the temperatures of the different portions of the flight vehicle section. Figure-12 shows the change in buckling load factor with respect to number of stiffeners of the flight vehicle section. Buckling load factor is increasing with increase in number of stiffeners for structural load case whereas it is decreasing with increase in number of stiffeners for thermo-structural load case. Increase in stresses only causes decrease in buckling load factors as far as the thermo-structural load case is concerned. This buckling mode shape results support the stress results of the section for both structural and thermo-structural load cases. When the section was anlysed with 2mm thickness without stiffeners, it is seen that the deformation is about 3.52mm, the stress is about 87.68 MPa and the buckling load factor is 2.64 (is 5.27 from FEA without considering the knockdown factor). The whole section is weighing about 22.27 Kg which is 14.64% less than the configuration with 1.5mm skin thickness and 12 stiffeners and also has higher safety factor and buckling load factor.

4. CONCLUSIONS

The Flight Vehicle sections without stiffeners, with 4, 8 and 12 stiffeners have been analyzed under structural loads alone and thermo-structural loads combined. Analysis results shows that the mass is increased with the increase in number of stiffeners and the relation is linear for both structural and thermo-structural load cases. From deformation plots, it is seen that the deformation is decreasing with the increase in number of stiffeners for both structural and thermo-structural load cases. It is observed from the stress plots that for structural load case, the stress is decreasing with the increase in the number of stiffeners whereas for thermo-structural load case, the stress is increasing with the increase in the number of stiffeners. The variation of stress leads to variation in factor of safety also. Buckling load factor is increasing with increase in number of stiffeners for structural load case whereas it is decreasing with increase in number of stiffeners for thermo-structural load case. It is observed that under thermo-structural loads, the use of stiffeners causes localized stresses due to difference in temperature between the skin portions and stiffeners because of different thermal masses in addition to the reduction in material strength and stiffness properties which cause the structure to become weak and buckle. Instead of adding the stiffeners, the thickness of the skin of monocoque structures can be increased to slightly higher value without much increase in mass of the structure to solve the problem. It is concluded that monocoque structures are best suitable under thermo-structural load environments and semi- monocoque structures can be used when structural loads are acting alone / dominant than thermal loads.

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