Linear Static and Shear Buckling Analysis of Spar Panels

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DOI: 10.29322/IJSRP.9.03.2019.p8740
http://dx.doi.org/10.29322/IJSRP.9.03.2019.p8740

Abstract- Optimal proportion of the weight of the vehicle and payload is important in design of an aircraft. Wing creates the lift required for flight. Spars are the structural members which run through the wing root at the fuselage to the wing tip. Spars carry the major wing bending loads. During the take-off, the bottom layer of the wing is subjected to tensile force and top layer is to compression. This leads the spars to buckle. Hence the spars must be strong enough to sustain the buckling load. If the thickness of the spar is increased, the efficiency of the aircraft decreases. Several iterations are done by decreasing the thickness of the spar. Static stresses and buckling load factors are found out for these iterations and weight optimization of the spar is achieved.

Index Terms- Wing box, Spar, Design, Stress Analysis, Design Optimization, Buckling.

I. INTRODUCTION

The aerospace industries are flourishing in the current era with different technologies in the market. A machine or a vehicle which travels through the air is called as an aircraft. The aircraft gains the support from the surrounding air, which is required for the flight in the air. The aircraft flies against the gravitational force of earth. To achieve this aircraft uses the dynamic and static lift of an airfoil. The aircraft wing is one of the most critical components of an aircraft not only from an aerodynamics point of view but also from a structural point of view. The aircraft wing is designed in such a way that it is able to provide the requisite lift while minimizing the drag. Drag is critical from the aerodynamics point of view because it directly affects the performance of the aircraft like fuel efficiency and range [1]. Not only does the wing provide the necessary lift during flight, the aircraft wing is also designed structurally to carry the entire weight of the aircraft. The aircraft wing has more than one role. It not only carries the fuel required for the flight but is also used to provide storage bays where, the aircraft landing gears can be mounted and stowed during take-offs. This means that the aircraft wing has to be sufficiently strong from the structural perspective to carry the weight of these engines, fuel inside the wing box and internal components. Along with its high strength the wing is required to have light weight.

A. Wing Box

Wing box is a small section of entire wing from which the wing extends. Wing box distributes or transfers all type of loads which it experiences to the other section of the wing. In the wing box structure all the axial loads are taken by the stringers and shear loads are carried by the spars. Even though the wing is tapered along its entire length, for the simplicity wing box is assumed to be having rectangular shape. In the present work, the wing box which is considered for the analysis has two tapered spars, seven stringers, seven ribs and two skin panels [3]. The construction of an aircraft wing is shown in figure 1.

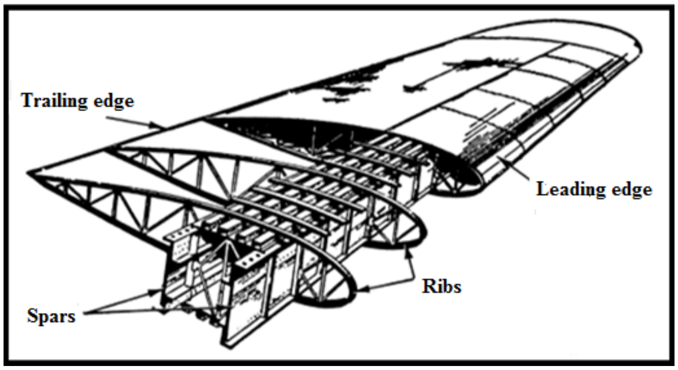

Figure 1: The construction of an aircraft wing

Spars are the main structural members of the wing. They extend from the fuselage to the tip of the wing. All the load carried by the wing is taken up by the spars. The spars are designed to have great bending strength. Ribs give the wing section its shape, and they transmit the air load from the wing covering to the spars [2].

B. Buckling

Most of the mechanical components undergo sudden failure, mainly because of two things; either due to the failure of the material or due to the instability of the structure and it is often referred as buckling. Unstable situation of any component is termed as buckling. Buckling does not depend up on the strength of the material. Buckling strength of any structure or member is largely effected by the stiffness of that structure or member. Euler formula, developed by the 18th century Swiss Mathematician Euler defines critical buckling load as:

$$P_{cr} = (\pi^2 EI) / L^2 \qquad \text{--------(1)}$$

Where,

P_{cr} = critical buckling load
E = Elastic modulus
I = Moment of inertia
L = Length

II. PROBLEM DESCRIPTION

During the flight of an aircraft, wings create more amount of lift which is necessary thing for flight and also they experience maximum bending moment. Due to this bending action bottom portions of the wings are under the tension and top portions are under the compression which is as shown in the figure 2. This bending moment gets transferred to the rib structures which in-turn gets transferred to the spar web as concentrated shear loads. These shear loads causes bending of the spars, which are the major loading on the spars. There is a chance of shear buckling of the spar webs due this bending action. Which further causes the failure of the spars and hence the wing [4]. Hence, in this paper we are going to carry out the linear static analysis and shear buckling analysis of the spar to know whether the spar is capable of taking the applied load without buckling followed by the weight optimization of the spar to improve the design and to achieve the optimal proportion of the weight of the spar.

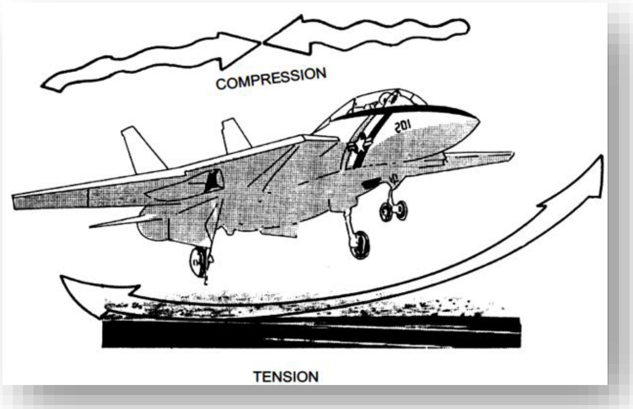

Figure 2: Bending action occurring during flight

III. PROPOSED WORK

A. Modelling

In the present work modelling process of the wing box is done through the Creo Elements / Pro 5.0 software. This model is a combination of 2 tapered C-section spars, seven rectangular ribs and seven stringers and the two skins which are located at the top and the bottom portion of the model at right angles to the ribs. The Creo model of wing box is as shown in figure 3.

B. Finite Element Analysis

The CAD model is extracted using NX NASTRAN software, it is a pre-processor and a post-processor. This model is then meshed using suitable elements and the necessary boundary conditions and loads are applied.

Boundary Condition: One end (larger) is constrained and load is applied at the other end.

Load calculation of the wing box:
Maximum T-O weight = 11,990 kg
Wing span = 19.78 m
Maximum diameter of the fuselage = 2.28 m
We know that,
Wing span = length of two wings + max diameter of fuselage
Therefore,
Length of two wings = 19.78 – 2.28 = 17.5 m
Length of each wing = 17.5 / 2
= 8.75 m

Coming to the actual load distribution calculation,
Max T-O weight of the aircraft = 11,990 kg

For equilibrium, this weight should be equal to the total lift load acting on the entire wing span.

80% of the total lift load is carried by the wing and remaining 20% is taken by the fuselage.

Therefore,
Total load acting on the wings = 9,592 kg
Total load acting on one wing = 4,796 kg

Section of the wing box (portion of the wing which is covered between planes XX & YY) which we considered for the analysis and the location of the resultant load on the wing are as shown in the figure 4.

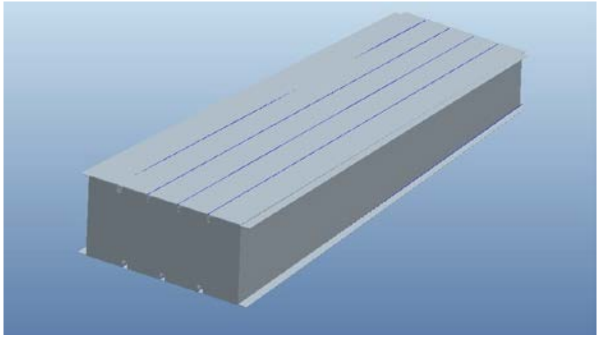

Figure 3: CAD model of a wing box

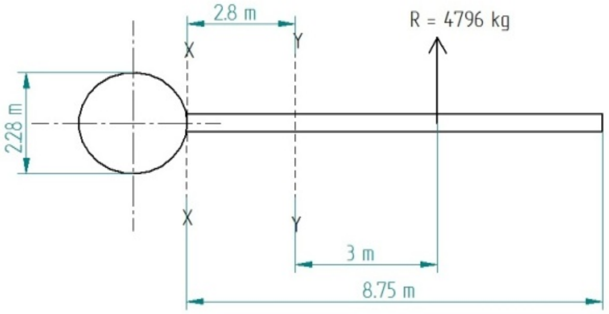

Figure 4: Section of the wing box

The bending moment due to the resultant load at the plane X-X of the wing box = 4796 * 5.8
= 27816.8 kg-m

In order to get a same bending moment at the plane X-X of the wing box we have to apply some load on the other end of the wing box i.e. at the plane Y-Y which is given by
= 27816.8 / 2.8
= 9934.571 kg

Total circumferential length of the plane Y-Y of the wing box = 2700 mm

Therefore, UDL = 9934.571 / 2700
= 3.679 kg / mm

One end of the wing box is fixed and above load is applied to the other end.

Second stage of the Finite Element Analysis (FEA) is solution. Here NX NASTRAN is a solver. Stress analysis is done in this stage. This analysis stage simply solves for the unknown degrees of freedom, as well as reactions and stresses. So the linear static stress analysis of the whole wing box structure is done in this stage [5].

In the post processing stage the results are evaluated and displayed. Global analysis model after assigning material property and applying loads and boundary conditions and solving through NASTRAN are shown in figure 5.

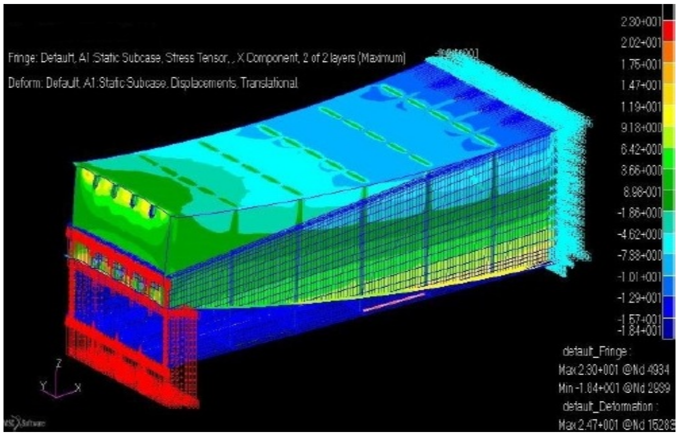

Figure 5: Deformation and stress contour plot of the wing box

From the figure 5 it is observed that, the maximum stress will occur at the root end of the wing box which is equal to 23kg/mm^2 and this value less than 33 kg/mm^2 which is the yield strength of the aluminium 2024 T351 hence the failure does not take place. From this global analysis of the wing box it is possible to know the stress distribution on each spar. Since stress is distributed unevenly in the model, we should take average stress of each individual element around the maximum stress location. The average stress is equal to the 17.07 kg/mm^2. Further this average stress is used for local analysis of front spar.

C. Local Analysis of the Spar Panel

Load acting on the front spar is calculated by using average stress value 17.07 kg/mm^2 around the maximum stress location i.e. at root end of the spar. Load acting on the front spar is calculated as follows:

Moment of Inertia (I_{xx}) = 80805656 mm^4

Bending equation is given by,

M / I = σ / y .... (2)

Where, M = Bending Moment
I = Moment of Inertia
σ = Bending Stress
y = Distance of the fibre from neutral axis

Section Modulus (Z) = I_{xx} / y .... (3)
= 80805656 / 295
= 273917.478mm^3

Bending Moment at the root end of the front spar based on average stress is given by,

Bending Moment=Average stress*Section modulus
= 17.07* 273917.478
= 4675771.35kg-mm

Therefore, load acting at the tip end of the front spar = BM / span length of the front spar
= 4675771.35 / 2800
= 1669.918
= 1670 kg

Total circumferential length of tip end of the spar = 470 mm

Therefore, UDL = 1670 / 470
= 3.553 kg / mm

The root end of the spar panel is fixed and above load is applied at the free end.

D. Results Discussions

Static analysis stress contour of front spar is as shown in the figure 6. From the figure 6 it observed that maximum stress is 22 kg/mm^2. This value is in good correlation with the global analysis value.

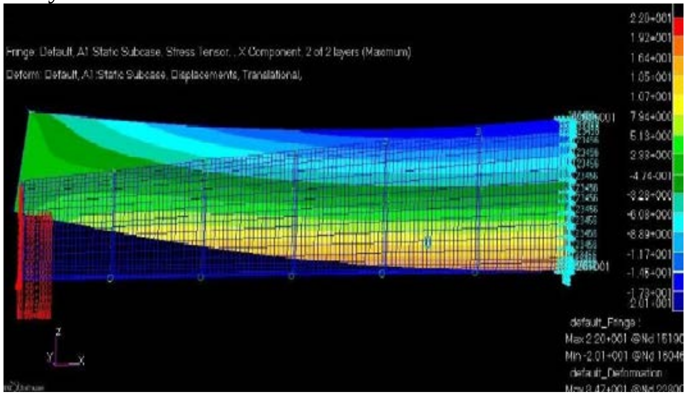

Figure 6: Static analysis stress contour of front spar

E. Buckling Load Factor

The buckling load factor (BLF) is an indicator of the factor of safety against buckling or the ratio of the buckling loads to the currently applied loads which is given in the equation 4. Table I illustrates the interpretation of possible BLF values returned by SW Simulation.

$$BLF = \frac{P_{cr}}{P_{app}} \qquad \text{.................} (4)$$

From the shear buckling analysis of front spar we observed that the buckling factor is more than one. The buckling factors obtained from finite element analysis is 2.0624 as shown in the figure 7. So the structure will not buckle for given load.

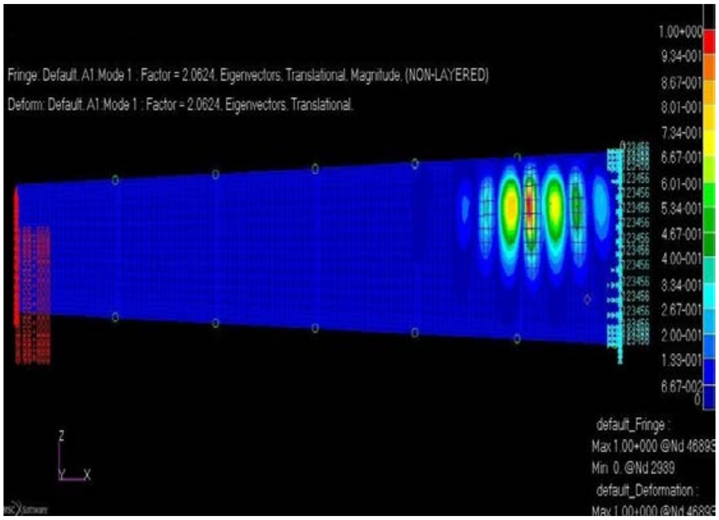

Figure 7: Shear buckling analysis for the spar (with BLF 2.0624)

Table I: Interpretation of the Buckling Load Factor

BLF Value	Buckling Status
>1	Buckling not Predicted
=1	Buckling predicted
<1	Buckling possible
-1<BLF<0	Buckling possible
-1	Buckling possible
<-1	Buckling not Predicted

IV. WEIGHT OPTIMIZATION

From linear static analysis of front spar we observe that the maximum stress is 22 kg/mm^2 and this maximum stress is much lesser than the yield strength of aluminium 2024 T351 which is 33 kg/mm^2. From shear buckling analysis of front spar we obtain the buckling factor as 2.0624 which is more than 1. We know that, thickness of the spar is varying throughout its length with the 3 mm thickness at root end and 2 mm at the tip end of the spar.

Volume of the spar = 4.164 * 10^6 mm^3

Density of spar material = 2.7 * 10^{-6} kg/mm^3

Initial mass of spar = Density * Volume = 11.24 kg

Since spar seems to be an over design, we can reduce the weight of the spar either by making cut outs in the spar web or by varying the thickness of the spar. In this project weight optimization process is carried out by varying the thickness of the spar. Several iterations are done to get an optimal design [6].

A. Iteration – 1

In the first iteration, the thickness of the original spar is reduced by 0.25mm throughout its length i.e. thickness of the spar is varying with 2.75mm at the root and 1.75mm at tip.

Volume of this modified spar (1) = 3.764 * 10^{6}mm^3

Mass of this modified spar (1) = 10.16 kg

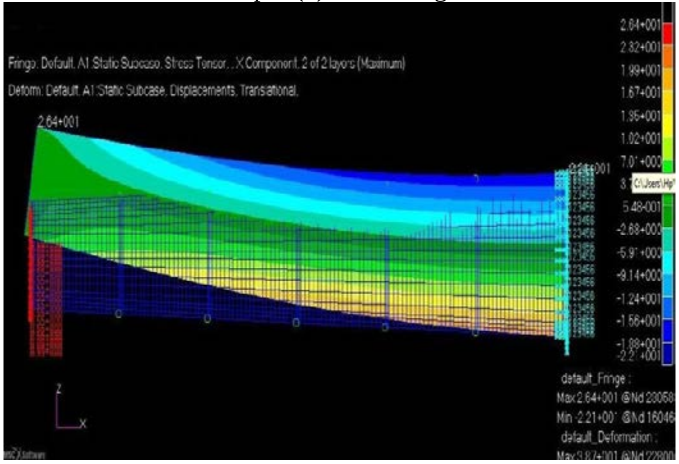

Figure 8: Static analysis stress contour of modified spar (1)

From the figure 8 it is observed that, the maximum stress is equal to 26.4 kg/mm^2 and this value is lesser than 33 kg/mm^2 which is the yield strength of aluminium 2024 T351. Hence the failure does not take place.

From the shear buckling analysis it is observed that the buckling factor is more than one. The buckling factors obtained from finite element analysis is 1.6423 as shown in figure 9. So the structure will not buckle for given load.

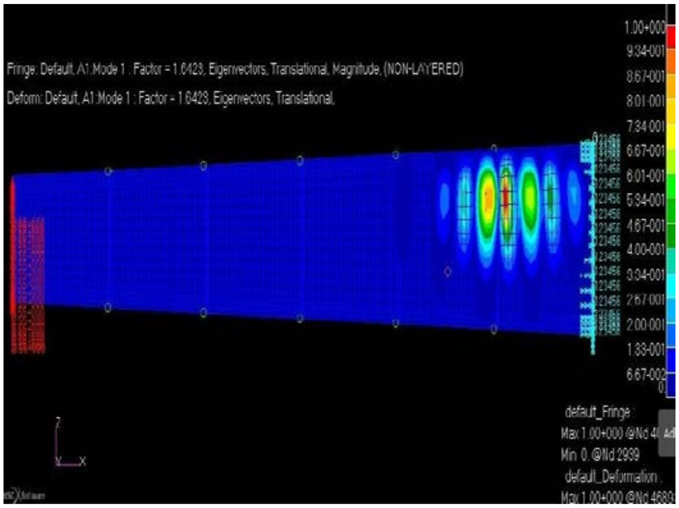

Figure 9: Shear buckling analysis result of modified spar (1) at with BLF (1.6423)

B. Iteration - 2

In the second iteration, the thickness of the original spar is reduced by 0.5mm throughout its length i.e. thickness of the spar is varying with 2.5mm at the root and 1.5mm at tip.

Volume of this modified spar (2) = 3.339 * 10^{6}mm^3

Mass of this modified spar (2) = 9.015 kg

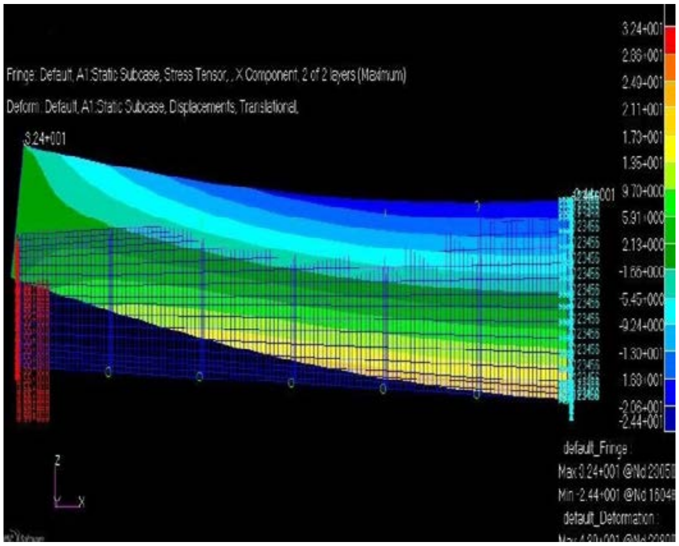

Figure 10: Static analysis stress contour of modified spar (2)

From the figure 10 it is observed that, the maximum stress is equal to 32.4 kg/mm^2 and this value is lesser than 33 kg/mm^2 which is the yield strength of aluminium 2024 T351. Hence the failure does not take place.

From the shear buckling analysis it is observed that the buckling factor is more than one. The buckling factors obtained from finite element analysis is 1.2643 as shown in figure 11. So the structure will not buckle for given load.

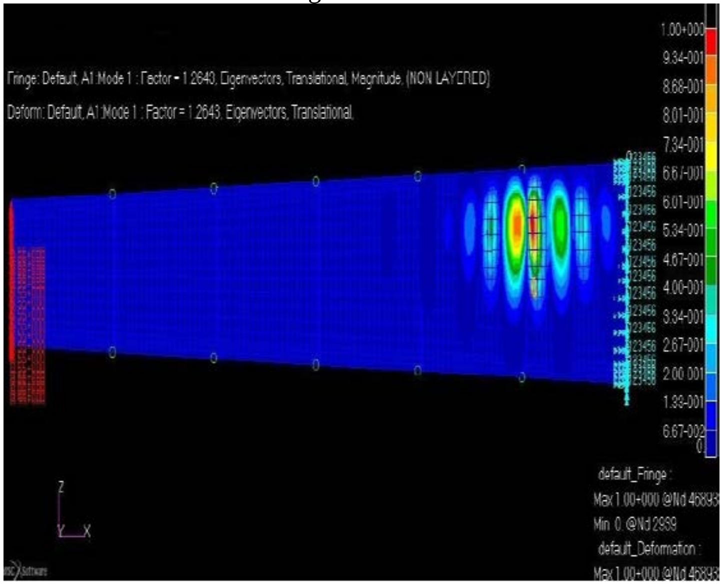

Figure 11: Shear buckling analysis result of modified spar (2) with BLF (1.2643)

C. Iteration – 3

In the third iteration, the thickness of the original spar is reduced by 0.75mm throughout its length i.e. thickness of the spar is varying with 2.25mm at the root and 1.25mm at tip.
Volume of this modified spar (3) = 2.926 * 10^{6}mm^3
Mass of this modified spar (3) = 7.901 kg

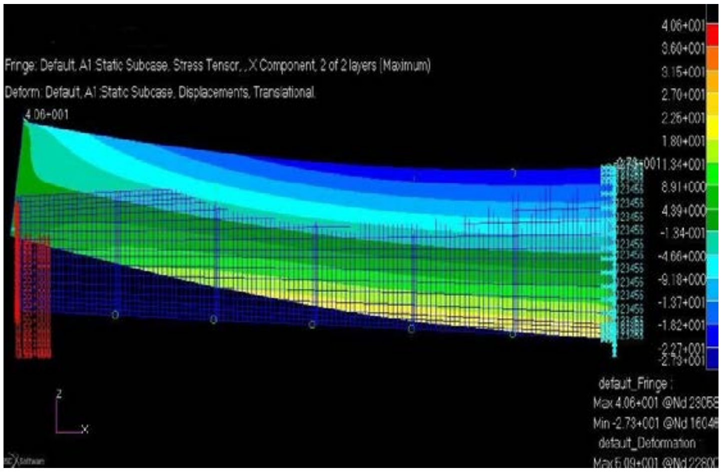

Figure 12: Static analysis stress contour of modified spar (3)

From the figure 12 it is observed that, the maximum stress is equal to 40.6 kg/mm^2 and this value is more than 33 kg/mm^2 which is the yield strength of the aluminium 2024 T351. Hence the spar will fail for given load.

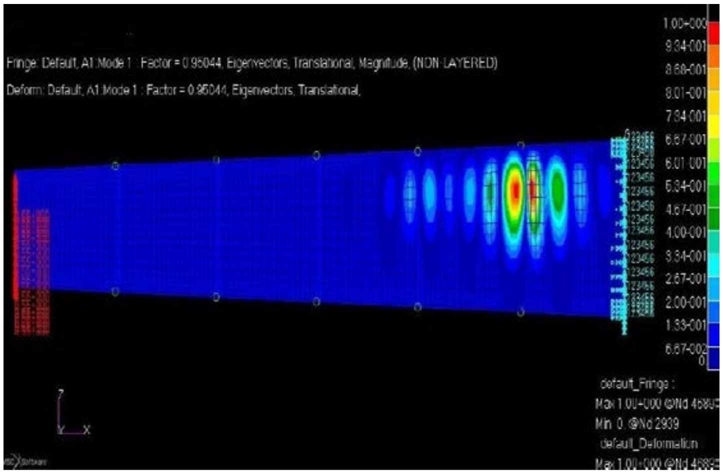

Figure 17: Shear buckling analysis result of modified spar (3) with BF (0.96045)

From the shear buckling analysis it is observed that the buckling factor is less than one. The buckling factors obtained from finite element analysis is 0.96045 as shown in figure 17. So the structure will buckle for given load.

Table II: Summary of results

Iteration Number	Maximum Stress Values (Kg/mm^2)	Deformation Values (mm)	Buckling Factor (BF)
1	26.4	38.7	1.6423
2	32.4	43.9	1.2643
3	40.6	50.9	0.96045

The results obtained from all the iterations are tabulated in the Table II. From the table it is clear that the spar with thickness varying 2.5mm at the root and 1.5mm at the tip gives the better results. So it is considered that the spar with thickness varying 2.5mm at the root and 1.5mm at the tip is the optimized one.

V. CONCLUSION

By observing the maximum stress values and buckling factors from the Table II we can decide that the spar with the thickness varying 2.5 mm at the root and 1.5mm at the tip is the accurate design and its performance is good as compared to the other designs and it is the optimized one.

The mass of the original front spar = 11.24 kg

The mass of the spar after reducing the thickness by 0.5mm throughout its length=9.015kg.

After reducing the thickness of the front spar by 0.5mm throughout its length there is a 2.225 kg reduction in the weight of the spar is observed. Reduction in the weight of the front spar automatically reduces the weight of the wing and hence the entire aircraft. Weight reduction will increase the efficiency of the structure and also its performance gets improved.

ACKNOWLEDGEMENT

We are indebted to **Dr. R Srinivasa Rao Kunte** Principal, and **Prof. Ravichandra K Rangappa,** Head of the Department, for their advice and suggestions at various stages of the work.

Special thanks to the management of SCEM for providing us good study environment and laboratory facilities. Besides we appreciate the support and help rendered by teaching and non-teaching staff of mechanical engineering department.

Lastly, we take this opportunity to offer our regards to all of those who have supported us directly or indirectly in the successful completion of this work.

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