Design, Analysis and Testing of Wing Spar for Optimum Weight

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***Abstract*— Aircraft is a complex mechanical structure with flying capability. The structure of an airframe represents one of the finest examples of a minimum weight design in the field of structural engineering. Surprisingly such an efficient design is achieved by the use of simple "strength-of-material" approach. Aircraft has two major components, which are fuselage and wing. For a wing of an aircraft the primary load carrying ability is required in bending. A typical aluminium material 6082-T6 is chosen for the design. A four-Seater aircraft wing spar design is considered in the current study. Wings of the aircraft are normally attached to the fuselage at the root of the wing. This makes the wing spar beam to behave almost like a cantilever beam. Minimum two spars are considered in the wing design. In a conventional beam design approach one will end up in heavy weight for the spar of the wing. In the current project the spar is considered as a beam with discrete loads at different stations. The design is carried out as per the external bending moment at each station. A finite element approach is used to calculate the stresses developed at each station for a given bending moment. Several stress analysis iterations are carried out for design optimization of the spar beam. Linear static analysis is used for the stress analysis. The spar beam is designed to yield at the design limit load. Weight optimization of the spar will be carried out by introducing lightening cut-outs in the web region. The results from the conventional design approach and the optimized design are compared. Weight saving through the design optimization is calculated. Spar will be a built-up structure. A scale-down model of the spar will be fabricated using aluminium alloy 6082-T6 material. Static testing of the spar will be carried out to validate the design and stress analysis results.**

***Keywords*— Design, Aircraft wing, Design optimization, Finite Element Analysis, Static testing.**

I. INTRODUCTION

In a fixed-wing aircraft, the spar is usually the most support of the wing, running span wise at right angles to the body. The spar carries flight loads and also the weight of the wings whereas on the bottom so it is important to make it to withstand the twisting load because that causes the failure if the material soon. Alternative structural and forming members like ribs are also connected to the spar or spars, with stressed skin construction conjointly sharing the loads wherever it is used have to withstand almost all types of loading action like bending, torsion, tensile and compression. There is also quite one spar during a wing or none in any respect. The wing spar provides the bulk of the load support and dynamic load integrity of cantilever monoplanes, usually mention the strength of the wing 'D' box itself. Together, these two structural elements or components put together offer the wing rigidity required to alter the aircraft to fly safely. The spar carries flight loads and the weight of the wings while on the ground. Other structures such as ribs may also be attached to spars. There may be more than one spar in a wing. However, where a single spar carries the majority of forces on it, is known as main spar. As a rule, a wing has two spars. One spar is sometimes settled close to the front of the wing, and therefore the alternative regarding common fraction of the gap toward the wing's edge. No matter kind, the spar is that the most significant a part of the wing.

II. DESIGN, ANALYSIS AND FABRICATION

2.1 Design of Wing Spar

This chapter focuses on the detailed design of Spar. The spar may be considered as the important component of an aircraft wing, since it carries 80% of the total load on the wing. Since the Spar geometry and its features are influencing all other wing components, we begin the detailed design process by Spar design. The primary function of a Spar is to carry the bending load acting on the wing. A Spar is a beam which extends from wing root to tip carrying the compressive, shear and tensile loads. In the current project, the spar is considered as a beam with discrete loads at different stations. The design is carried out as per the external bending moment at each station. The design calculations includes selection of materials; estimation of geometrical characteristics. Spar is designed for the existing aircraft and its configuration. The reference aircraft has the following specifications:

- Aircraft: PIPER PA28-161 WARRIOR II
- Cantilever low wing monoplane
- Wing span: 10.67m
- Aerofoil series: NACA 65-415 at root and NACA 65- 415 at the tip
- Wing chord at tip: 1.07m
- Wing chord at root: 1.60m
- All of weight of aircraft: 1106 kg

2.2 Material Selection

A Spar generally consists of an aluminium sheet Spar webs and caps which is welded or riveted to the top or bottom of the sheet to prevent buckling on application of loads.

Most commonly used materials are aluminium alloys. In the current project, the material selected is aluminium 6082-T6 because of its following properties:

- Axial yield strength = 26 kg/mm^2
- Shear yield strength= 18kg/mm^2
- Density = 2700 kg/m^3
- Modulus of elasticity = 70 GPa
- Poisons ratio = 0.33
- Excellent corrosion resistance
- Good welding property

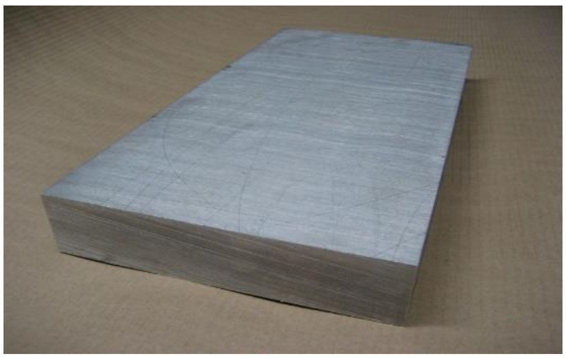


Fig. 1 Aluminium 2024- T3

2.3 Cross sectional shape of spar

The shape of the Spar is decided in the further level of the design process. I-section shape of spar is considered after all the case study of different shapes. Stress and deflection for I-section is less when compared to other sections because moment of inertia for the section is more. Since it is bending, shape of the cross section will have vital role in calculation of stress and deflection of beam.

2.4 Load Estimation

Any aircraft structure will be designed for the particular load given by the aerodynamic experts. In this project the steady level flight is the load case considered to design the spar.

To carry on the design a typical load distribution was obtained by using XFLR software. The inputs given to the software are:

- Aero foil series: NACA 65-415 at root and tip
- Wing area : 15.8m^2
- Wing span: 9.62m (excluding fuselage diameter)
- Maximum speed of the aircraft : 282 km/h
- Wing chord : 1.07m at the tip and 1.60m at the root

New wing was defined by the considering the rib stations to be placed at particular distance according to the standard thumb rule and by giving inputs to the software. The analysis definition properties are free stream speed is 282 km/h and density is 1.225 kg/m^3. By running the analysis for different angle of attack of the wing the load distribution satisfying the load case i.e. steady level flight where lift is equal to the weight of the aircraft (L=W) was obtained at 2.3 degree angle of attack.

Lift distribution obtained at each rib station were considered for the worst case of 3g condition by multiplying lift three times. Lift was assumed to be acting at the centre of pressure (C_p) which is at 20% of the chord length from leading edge.

The front spar is considered to be placed at 15% of chord length from the leading edge and the rear spar is considered to be placed at 50% of chord length from the leading edge. By considering the simply supported beam condition i.e. load acting at C_p and the reaction forces acting at front and rear spar. Solving the simply supported beam conditions the loads acting the front and rear spar was obtained. Loads at the front spar at each station were carried for designing of the spar.

Loads on the spar are acting on the ribs. 17 such rib stations are considered due to wing buckling. The first load acting is at 100 mm from the fixed end and the second load acting is at a spacing of 300 mm from the first rib.

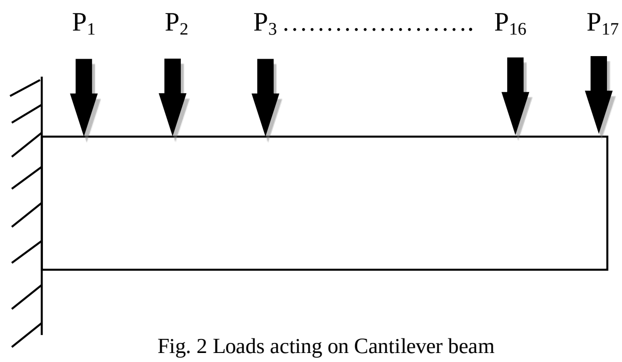


Fig. 2 Loads acting on Cantilever beam

Magnitude of load at each rib sections:

Table 1 Loads acting on each rib station

Sections	Loads(kg)
1	19.38
2	39.27
3	46.35
4	51.30
5	58.18
6	58.34
7	61.06
8	63.46
9	65.61
10	67.54
11	69.28
12	70.89
13	72.32
14	73.62
15	74.84
16	75.86
17	25.14

2.5 Design process

Considering the bending moment acting in that cross section we find out the normal forces acting in the flange of I section. After finding the normal force acting on the flange the areas of flanges will be determined as below calculations shown.

BM at rib 1:

$BM = P_1 \times L_1 + P_2 \times L_2 + P_3 \times L_3 \dots\dots\dots + P_n \times L_n \dots (1)$

The value of loads P_1 is 25.144 kg, P_2 is 75.863 kg, P_3 is 74.847 kg and so on. And distance with respect to the first rib L_1 is 4710 mm, L_2 is 4500 mm, L_3 is 4200 mm and so on.

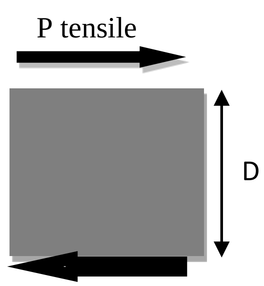
Therefore, BM = 2589594.24 kg-mm

Area of flange:

BM=load x perpendicular distance (D)………..(2)

Substituting the values for BM = 2589594.24 kg-mm and perpendicular distance (D) is 175.47mm.

We get,



$P_{tensile}$ = 14758.045 kg

Since the forces are acting normal to the flange,

We consider stress= P/A to find out area of flange.

$\sigma_{yield\ stress} = \frac{P_{tensile}}{A}$……………………………….(3)

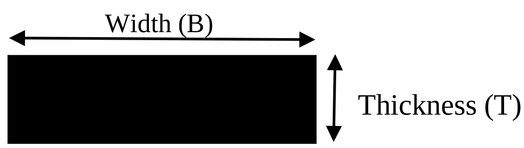
Substituting $\sigma_{yield\ stress}$ = 35 kg/mm^2, we get

A =421.658 mm^2

We know that,

Area=B × t…………………………………………… (4)

Considering the width (B) of the flange to be 60 mm,



We get thickness as:

t = 7.027 mm thickness (t)

Bending stress calculation only for flanges:

$\text{Bending stress}(\sigma_b) = \frac{M}{I} \times y$……………………….(5)

y =distance from neutral axis to the point where stress is calculated = 87.7355 mm

M= Bending moment = 2589594.24 kg-mm

I= Moment of Inertia.

Moment of inertia is given as:

$I = \frac{BD^3}{12} - \frac{Bd^3}{12}$……………………………………….. (6)

Substituting the values of B = 60mm, D=175.471mm, d = 161.417 mm, we get

I =5984862.321mm^4

Therefore, bending stress is:

σ_b = 37.96 kg/mm^2

Area of the web:

Considering the Shear Force (SF) acting in the same cross section, we find out the web cross section area.

$SF = P_1 + P_2 + P_3 + P_4 \dots\dots P_n \dots (7)$

Substituting the values of the loads, we get shear force.

SF = 992.5089874 kg

We know that, Shear yield strength for 2024 is 27 kg/mm^2.

$\sigma_{shear\ yield\ strength} = \frac{SF}{A}$……………………………………(8)

Now substituting for shear yield strength and shear force, we get the area of the web.

A=52.23731513 mm^2

We know the depth of the web is d = 161.417 mm. Therefore, from equation 4.4, we get the thickness of the web as

t = 0.32361 mm

Bending stress with flange and web:

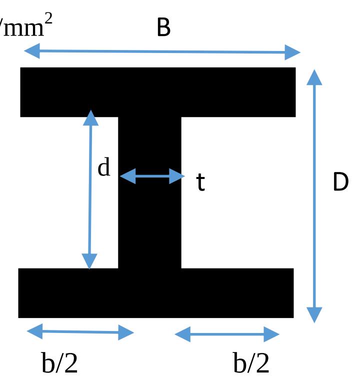
Substituting the values of B, D and d and b = 59.676 mm in equation

$I = \frac{BD^3}{12} - \frac{bd^3}{12}$………………………………………… (9)

We get, I = 6098418.7 mm^4

Now, substituting the values of M, I and y in equation 5, bending stress obtained is

σ_b = 37.255 kg/mm^2



Here it was observed that bending stress in spar of I-section with web is less than that of the bending stress without web due to the increase in moment of inertia. From the bending stress equation, moment of inertia is inversely proportional to the bending stress.

Since the yield strength of the considered aluminium 2024-T3 is 35 kg/mm^2, the bending stress is further reduced by increasing the moment of inertia. This is done by changing the dimensions of flanges or web of the I-section. Since the depth of I-section is fixed, thickness and width of the flanges and thickness of the web can be changed.

One such iteration is carried out to make the stress to 35 kg/mm^2 by changing the thickness of web. For web thickness = 0.3236 mm stress obtained is 37.255 kg/mm^2,if the load is continuously applied on a structure, web buckles before it reaches the value of bending stress. So to overcome the buckling phenomenon, Shear buckling concept is introduced.

Shear buckling concept plays an important role.

If buckling factor =1 the section buckles or may not buckle.

>1 the section does not buckle.

< 1 the section buckles.

The buckling factor at thickness 0.3236 mm is 0.009. Some iterations are carried out to increase the buckling factor greater than 1. At thickness 1.6 mm, the buckling factor is 1.12. So the web does not buckle and is safe.

Determining buckling factor is as follows:

$$\tau_{cr} = \pi^2 \times k_s \times \frac{E}{12\times(1-\mu^2)} \times \left(\frac{t}{b_2}\right)^2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

Where,

$K_s = a/b_2$ = 6.6 (Bruhns book) a= distance between ribs b_2=smallest length of web

E =Young's Modulus = 7000 kg/mm^2

μ = poissons ratio = 0.33

t = thickness of the web = 1.6 mm

Substituting these equations in the above equation, we get

τ_{cr} = 4.314

To find critical load P_{cr}:

$$\tau_{cr} = \frac{P_{cr}}{A} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (11)$$

$$A = t \times b_1 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (12)$$

Where,b_1= depth of longest web = 161.417 mm, t = 1.6 mm

Therefore, area A = 258.267 mm^2

Substituting in equation 11, we get

P_{cr} = 1114.164 kg

$P_{applied}$ in the fixed section obtained is 992.508 kg.

$$\text{Buckling factor} = \frac{P_{cr}}{P_{app}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (13)$$

Therefore, buckling factor = 1.12

Bending stress and final dimension of 1st section:

Now, we have M = 2589594.24 kg-mm, y = 87.7355 mm,

Since the thickness of web is changed due to buckling factor, the moment of inertia at a given section will alter.

Thickness (t) = 1.6 mm and b = 58.4 mm

Substituting these values in equation 9, we get moment of inertia,

I = 6545634.619 mm^4

Therefore, from equation 5, Bending stress

σ_b= 34.71 kg/ mm^2

The final dimension of the I-section at rib station 1 is shown below:

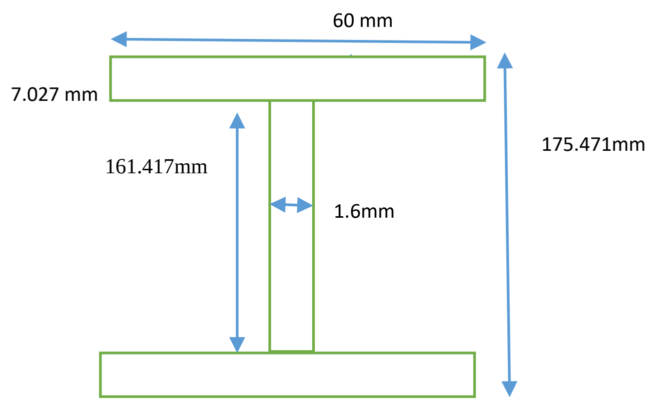


Fig. 3 Final dimension of 1st I – section (Al 2024)

The dimension of the I-section at the 1st rib section was finalised and similarly same procedure was carried out to find the dimensions at remaining sections.

But due to the non-availability of aluminium 2024-T3, forcefully the material had to be changed to aluminium 6082-T6. The thickness of flange and web is 3mm and 2mm respectively in all sections because to reduce the machining cost of sheet metal. The design process of 6082-T6 is carried out as similar to previous procedure.

Area of the flange:

Substituting the values of the bending moment and perpendicular distance in equation 2, we get

$P_{tensile}$ =14757.79kg

We have Yield stress of aluminium 6082 is 26 kg/mm^2

Therefore from equation 3, A = 567.607 mm^2

Considering thickness of the flange to be 3 mm, the width of the flange is calculated.

Hence from equation 4, Width of the flange B = 190 mm.

Bending stress of the flanges:

We have, B = 190 mm, D = 175.471 mm and d = 169.471 mm

Substituting these in equation 6, we get moment of inertia.

$I = 8478535.065 mm^4$

Therefore, bending stress is obtained from equation 5,

$\sigma_b = 26.79 kg/mm^2$

Area of web:

Considering the Shear Force (SF) acting in the same cross section, we find out the web cross section area. Thickness of web is 2 mm as mentioned above.

As considered previously, shear force is 992.5089874 kg.

We have Shear yield strength for aluminum 6082 =18 kg/mm^2

Substituting the above values in equation 8, the area of web obtained is A= 55.1393 mm^2

We know the depth of the web is d =169.471 mm, t = thickness of web.

Equation 4 gives the thickness of web t,

t = 0.325 mm

Bending stress is calculated further for the flanges including the web.

Substituting the values B = 190 mm, D = 175.471 mm, b = 189.675 mm and d = 169.471 mm in equation 9 gives moment of inertia of flanges including web. i.e., I = 8610357.184 mm^4

Bending stress is obtained from equation 5,

$\sigma_b = 26.38 kg/mm^2$

Now we are considering shear buckling concept as mentioned previously.

Substituting t = 0.325 mm, b_2 = 165.82 mm, from equation 10 we get,

$\tau_{cr} = 0.163$

To find Critical load P_{cr}:

From equation 12, we get area of the I-section to be

A = 55.078 mm^2.

And equation 11 gives, P_{cr}= 8.977 kg

$P_{applied}$ on rib section 1 obtained is 992.508 kg.

Substituting the values of P_{cr} and P_{app} in equation 13, gives buckling factor = 0.009

We know that, if buckling factor is less than 1, the section buckles. If buckling factor is greater than 1, the section will not buckle. Here, for thickness = 0.325 mm, BF=0.009. Hence, to increase the buckling factor the thickness of the web should be increased. After several iterations, we got to know that at t = 1.6 mm, the buckling factor is equal to 1. The available thickness of material in market is 2 mm, due to high expense in machining, 2 mm thickness is considered and further calculation is continued.

Moment of inertia after considering web thickness = 2 mm, b = 188 mm. Substitute in equation 9,

Hence, I = 9289748.11 mm^4

Therefore, bending stress from eq.5, we get, σ_b= 24.45 kg/mm^2

Maximum deflection of spar:

Deflection of tapered section(δ) = $\frac{1}{2} \times \frac{BM}{E \times I} \times L \times \frac{2L}{3}$…..(14)

Length of the spar considered is 1500 mm.

Substituting the values in above equation, we get the maximum deflection, δ = 29.99 mm

The obtained total bending stress of I-section is less than 26 kg/mm^2. The finalized dimensions of I-section at rib 1 are as shown below.

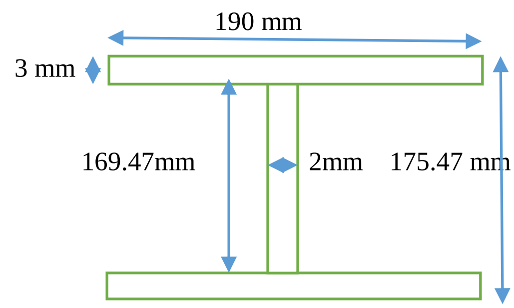


Fig. 4 Dimension of 1st I – section (Al 6082)

Similar iterations are carried out to all the 17 sections over the length of spar and finalized the dimensions of the I-section spar. The finalized dimensions of 17 rib sections are as shown below.

Table 2 Dimension at each rib section

Rib stations	Load (kg)	Total I-section dimension (mm)	
		Width (B)	Depth (D)
R1	19.38	190	175.47
R2	39.27	172	171.82
R3	46.35	154	168.17
R4	51.30	137	164.52
R5	58.18	120	160.86
R6	58.34	104	157.21
R7	61.06	88	153.56
R8	63.46	73	149.91
R9	65.61	60	146.26
R10	67.54	47	142.61
R11	69.28	35	138.96
R12	70.89	23	135.31
R13	72.32	16	131.66
R14	73.62	9	128.01
R15	74.84	4	124.36
R16	75.86	1	120.71

From the above table, it is observed that, the flange width is being reduced from rib location 0 to 17. Since it is difficult to manufacture the flange of smaller dimensions and considering damage tolerance, riveting process, the lower dimension are not considered. Hence a scale-down model of 1.5m is considered for analysis and testing in current study.

The table below shows the dimensions of considered scale down model and according to that dimensions over the length of spar is modelled using CATIA V5 R20.

Table 3 Dimension at rib sections (scale down model)

Rib stations	Load (kg)	Total I-section dimension (mm)	
		Width (B)	Depth (D)
R1	19.38	190	175.47
R2	39.27	172	171.82
R3	46.35	154	168.17
R4	51.30	137	164.52
R5	58.18	120	160.86
R6	58.34	104	157.21

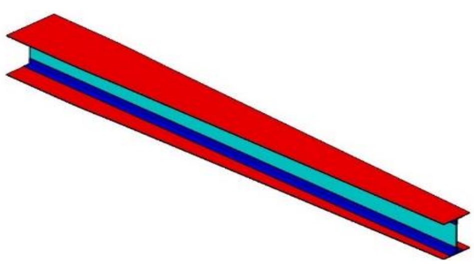


Fig. 5 Spar model

2.6 Stress analysis of the spar

Stress analysis of scale down model of length 1.5m is carried out using Nastran- Patran.3d model has done using CATIA V5 as shown below.

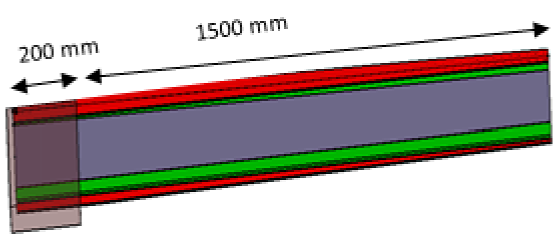


Fig. 6 Load acting on the spar

The length of the build-up model is 1500 mm and extra 200 mm is for test fixture. Load is applied at the free end of the Spar.

As calculated previously, bending moment obtained at rib 1 is 2589594.24 kg-mm

Bending moment = load x perpendicular distance

Perpendicular distance = 1500 (build up for testing)

Load = $\frac{2589594.24}{1500}$= 1726.39 kg

Therefore the load applied is 1727 kg.

The CATIA model is then imported to the PATRAN software. The model is set for default dimensions and extraction of mid surface has been carried out for meshing. A fine and good quality meshing is generated on each part of the structure using MSC PATRAN. Figure 5.2 represents the meshed model of spar. Fine meshing is done for getting better results.

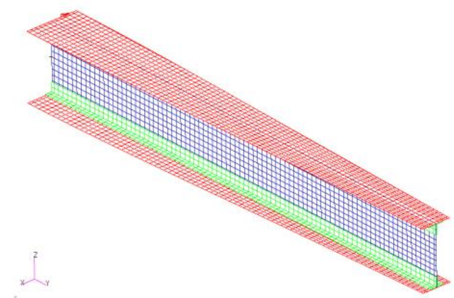


Fig.7 Meshed spar model

The boundary conditions are now applied to the spar model. Since the model considered is a cantilever beam, one end is fixed, ie., all the six degrees of freedom are constrained and at the free end load is applied.

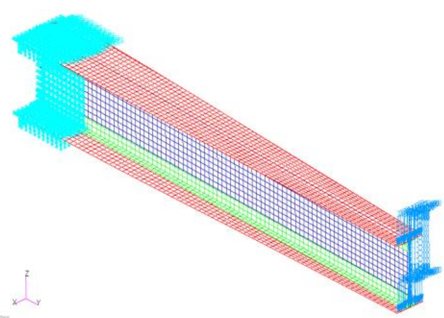


Fig. 8 Boundary conditions

The loads are applied. Due to the application of load, the deflection is observed and also the stress at each section is obtained.

Maximum Deflection = 35.5 mm

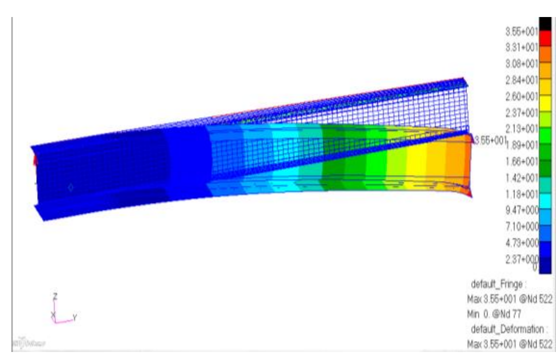


Fig. 9 Deflection of the spar

Maximum stress = 23.8 kg/ mm^2

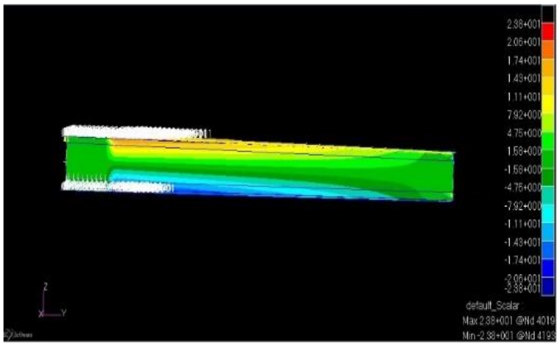


Fig. 10 Maximum stress of the spar

2.7 Fabrication of the wing spar

Metal fabrication is the process of manufacturing metal structures by cutting, bending and assembling processes.

Initially, aluminium 6082-T6 metal sheet of 3mm and 2 mm thickness are purchased. To obtain a structure of I-section, the sheet is first marked to cut according to the required dimensions. Sheet of 3mm thickness is marked according to the dimensions of flange and 2mm thickness sheet is marked according to the dimensions of web.

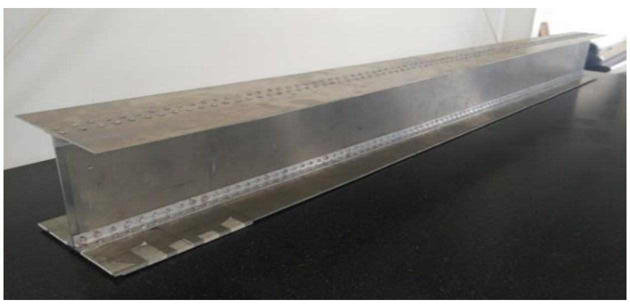


Fig. 11 Fabricated spar model

2.8 Testing Setup

After riveting the spar model, the structure is then introduced for testing. Test rig is required to test the fabricated spar. Spar length of 1700 mm out of which 200 mm is for fixing the model on the setup. The determined load is applied on the free end of the spar, correspondingly the deflection is noted for each interval of load application. Finally, test results which are obtained validates the results of calculated and analysis.

Fig. 12 Test rig with spar

In the scale down model, the calculated bending moment magnitude should be at the fixed end, so the load acting on the spar is calculated by the formula.

Load applied on the spar at free end is obtained as follows:

Bending moment = load x length of spar

2589594.24 = P x 1500

Therefore, P = 1727 kg

The deflection at a tip of structure is determined while testing with the application of 1727kg load at the free end. The yield stress value of the material is 26kg/mm^2, which is expected at the load of 1727kg.

Since, the spar needs to be considered for further studies, a conscious decision was taken not to load the spar up to yielding level. Therefore, the testing was stopped at 1000kg peak value and the corresponding results are tabulated below.

Total Weight of spar =7.38kg

III. RESULTS AND DISCUSSION

3.1 Test Results

Table 4 Tabulation

Load(kg)	Deflection(mm)
0	0
100	2.4
200	4.7
300	6.9
400	9.2
500	11.4
600	13.7
700	16
800	18.4
900	20.5
1000	22.35

3.2 validation

Deflection of a spar for 1000kg by considering linear interpolation, the below graphs which shows the interpolation method of deflection versus load we have considered and compared with calculated, analysis and tested results.

3.3 Calculated result comparison

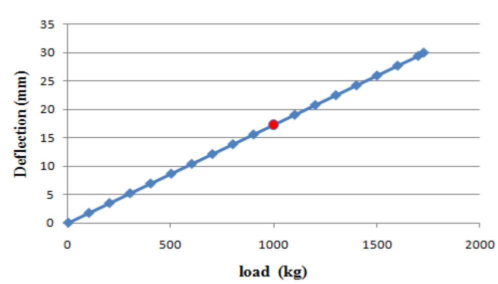


Fig. 13 Calculated results

3.4 Analysis result comparison

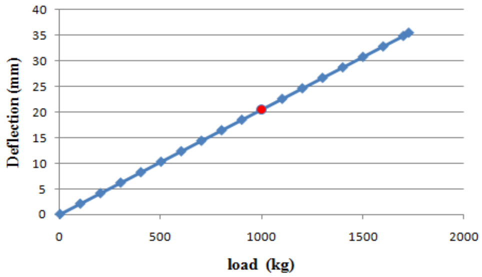


Fig. 14 Analysis results

3.5 Tested result comparison

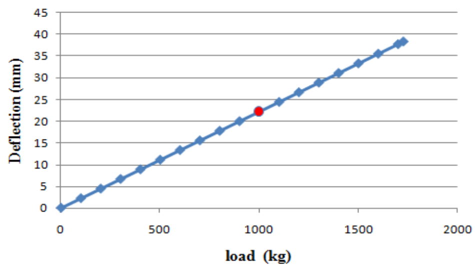


Fig. 15 Tested results

Maximum deflection of a spar:

Calculated result(mm)	Analysis result(mm)	Tested result(mm)
17.37	20.55	22.35

Maximum stress of a spar:

Calculated result(kg/mm^2)	Analysis result(kg/mm^2)
24.45	23.8

IV. CONCLUSION

Wing spar design was carried out by using strength of material approach. Spar is designed for minimum weight. Finite Element Analysis approach was used for stress analysis of the structure. Iterative analysis was carried out to achieve minimum weight for the structure. The maximum stress obtained from the finite element analysis is 23.8 kg/mm^2. The maximum deflection at the tip is 35.5 mm. Steady level lift load condition was considered for the design. Transport category aircraft are generally designed for "3g" condition. The design limit load magnitude corresponding to 3g condition was considered. The spar was fabricated based on the design configuration. Aircraft standard material Aluminium alloy 6082-T6 material is used for the fabrication of the spar. It is a build-up construction. Spar web and flanges are connected by using L- angles which are in turn connected using rivets.

Static testing of the spar is carried out. A test rig was designed and developed. Vertical deflection of the spar was measured at several locations. A good co-relation between stress analysis and test results was observed.

In current study the weight optimization is done through design process, few iteration are carried out by varying the dimensions of spar and model is finalized with the dimensions which has less weight. The finalised structure which is in tapered form.

In further studies, the following can be considered.

- The weight can also be reduced by introducing cut-outs in the web of the spar model
- Fatigue damage calculation for crack initiation
- Damage tolerance design can be carried out.

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