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Stress Analysis and Weight Optimization of a Wing Box Structure Subjected To Flight Loads

Immanuvel D[1], Arulselvan K[2], Maniiarasan P[3], Senthilkumar S[4]
[1]Post Graduate Scholar, Department of Aeronautical Engineering
[2]Professor,Department of Mechatronics Engineering
[3]Professor, Department of Mechanical Engineering
[4]Assistant Professor, Department of Aeronautical Engineering
Nehru Institute of Engineering and Technology, Coimbatore-641105

-----ABSTRACT-----
Optimal proportion of the weight of the vehicle and payload is important in design of an aircraft. It needs to be strong and stiff enough to withstand the exceptional circumstances in which it has to operate. Wing creates the lift required for flight. Spars, ribs and skins are the major structural elements of the wing. 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. Ribs are the structural members which are oriented in the chord wise direction.Ribs carry the shear loads on the wing. Aerodynamic shape of the wing is important in creating the required lift for the aircraft.Ribs also help the wing to maintain its aerodynamic shape under loaded condition. In this paper, a wing box consisting of four ribs and two spars is considered for the analysis. The aerodynamic distributed load on the wing creates shear force, bending moment and torsional moment at wing stations. The wing box is subjected to externally applied shear loads which generates the above mentioned loading actions at various wing stations. A linear stress analysis of the wing box will be carried out for the given shear loads. Several iterations will be carried out for design optimization of the wing box. Different rib design will be considered for the optimization process.An analytical approach will be followed for the optimization. The top skin of the wing box will experience the axial compression during wing bending.

KEYWORDS:*CFD, FSI, fairings, wings*

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I. INTRODUCTION

A wing isa rigid horizontal structure that projects from both sides of an aircraft and supports it in the air.A wing's aerodynamic quality is expressed as its lift-to-drag ratio. The lift a wing generates at a given speed and angle of attack can be one to two orders greater than the total drag on the wing. A high lift-to-drag ratio requires a significantly smaller thrust to propel the wings through the air at sufficient lift.The wing box of an airplane is the structural component from which the wings extend. It is usually limited to the section of the fuselage between the wing roots, although on some aircraft designs, it may be considered to extend further.

II. COMPONENTS OF WING BOX:

The wing box consists of two essential parts. The internal wing structure consists of spars, ribs and stringers, and the external wing structure is the skin.

2.1. Wing Skin

In most aircraft, the wing skinperforms several tasks. It gives it the aerodynamic shape, it carries a share of the loads, it helps to carry torsional loads, it acts as fuel tanks and allows inspection and maintenance.

2.2. Ribs

In an aircraft,ribs are forming elements of the structure of a wing. Usually ribs incorporate the aerofoil shape of the wing, and the skin adopts this shape when stretched over the ribs.The ribs need to support the wing-panels, achieve the desired aerodynamic shape and keep it, provide points for conducting large forces, add strength, prevent buckling, and separate the individual fuel tanks within the wing.

2.3. Spar

In a fixed-wing aircraft, the spar is often the main structural member of the wing, running span-wise at right angles (or thereabouts depending on wing sweep) to the fuselage. The spar carries flight loads and the weight of the wings while on the ground. Spars usually carry shear forces and bending moments.

2.4. Stringer

A stringer is a thin strip of material, to which the skin of the aircraft is fastened. Its primary function is to transfer the bending loads acting on the wings onto the ribs and spar.

III. WINGBOX DESIGN

The designing of the parts and their assembly is done using CATIA V5R20. The parts, after being converted into solid models, are saved in different files with respective file. In order to assemble the parts as an integrated structure of a wing box, we adopt an assembling approach known as the bottom-up assembly approach. While using this approach, parts from various files are inserted into a common file known as the assembly file. The files are assembled in their working position by applying assembly constrains to the individual parts. Figure 1.1 shows the assembly consisting of the skins, stringers and spars.

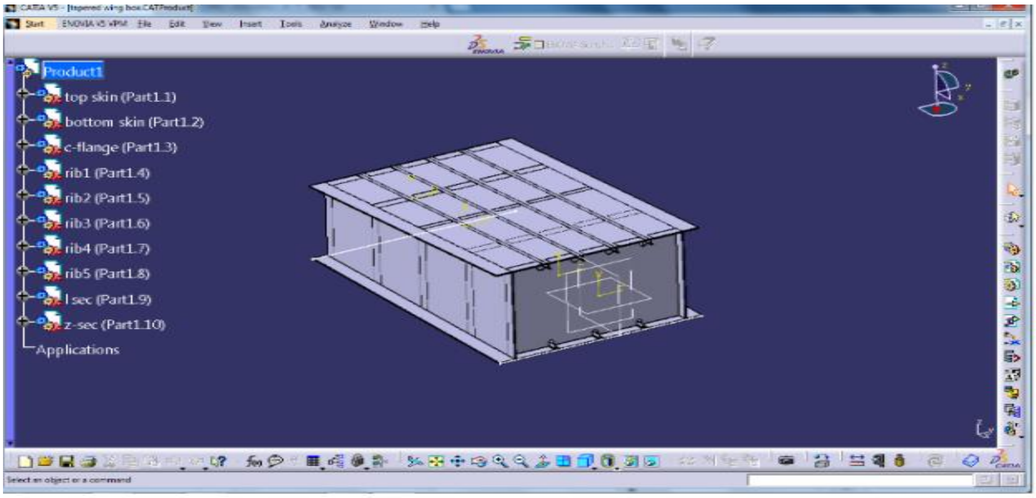

Fig 1.1 Assembled CATIA Model

3.1. Extraction Of Geometry

The wing-box as a whole and the various structural members individually are imported to Patran and their geometry is 'extracted' into groups. The following Fig 1.2 shows all the extracted groups posted as one

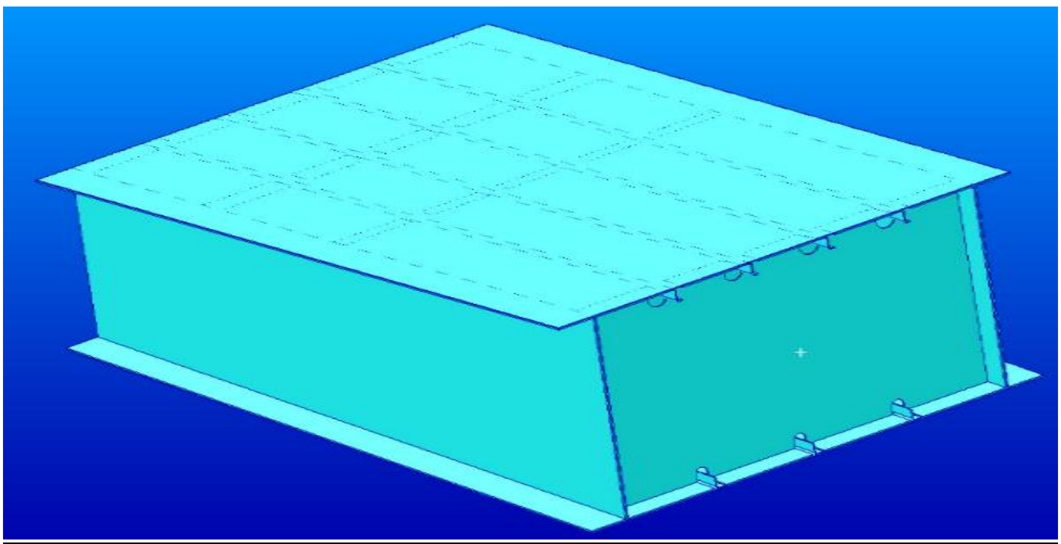

Fig 1.2 Extraction of geomentry

3.1.1.Meshing

Meshing is process of breaking the model into small pieces (finite elements). The network of nodes and elements is called a mesh. The two types of elements extensively used in meshing the wing-box model are Quad and Tria.Certain parameters should be periodically verified in order to prevent failure of elements. For an element, the boundaries, duplicates, normals and connectivity need to be verified. For a Tria element, skew and aspect need to be verified. Aspect, warp, taper and skew for quad element to be verified.The structural members in the extracted groups are individually posted and meshed.Fig 1.3 shows the meshed ribs

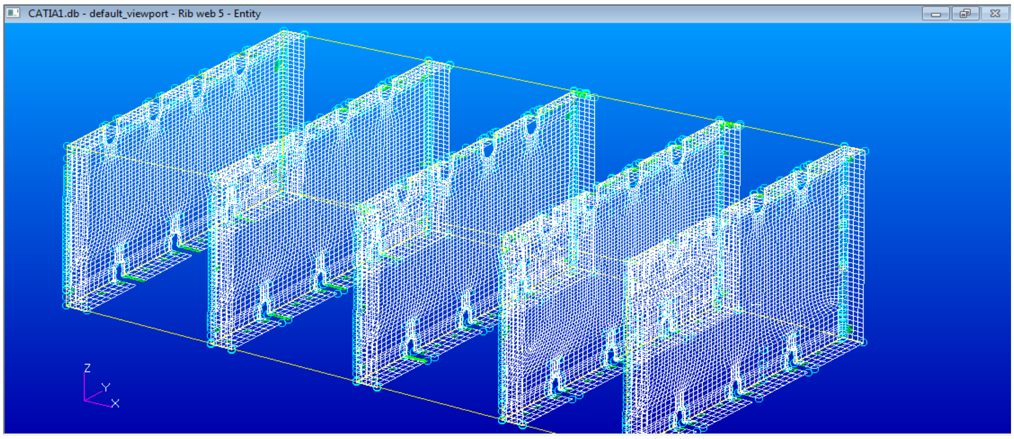

Fig 1.3 Meshed ribs

In order to prevent the presence of any free nodes during the meshing procedure,it is necessary to ensure connectivity in each of the elements used. This is checked using the boundary check.There is also a need to ensure connectivity between elements of various parts when they are assembled.

3.1.2. Property Specification

The wing box structure is a Shell element in 2D. Hence we need to define the inherent properties of the shell element by posting the individual parts and selecting them

Table 1.1 Material properties

No	Part Name	Material	Thickness	Plate Offset
1	Bottom skin	Al	2	1
2	L stringer (Horizontal)	Al	4	2
3	L stringer (Vertical)	Al	2	1
4	Rib Bottom Flanges	Al	5	2.5
5	Rib Side Flanges	Al	6	0
6	Rib Top Flanges	Al	5	-2.5
7	Rib Webs	Al	3	1.5
8	Spar Bottom Flanges	Al	5	2.5
9	Spar Top Flanges	Al	5	-2.5
10	Spar Web	Al	3	1.5
11	Top Skin	Al	2	-1
12	Z Stringer Bottom Flange	Al	2	1
13	Z Stringer Top Flange	Al	4	-2
14	Z Stringer Web	Al	2	-1

3.1.3 Load Calculation

The considered section of the wing is enclosed within the planes AA and BB. The total span of the wing from root to tip is 7500 mm. The span of the wing box section is 1400 mm which is shown in fig 1.4

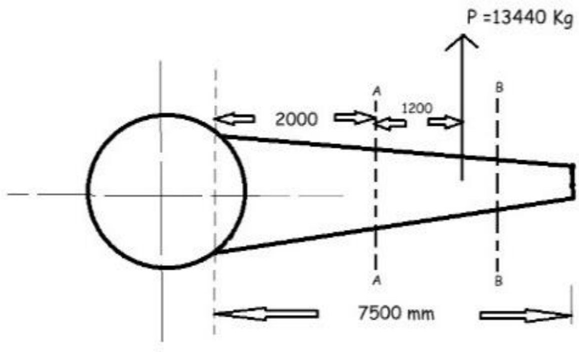

Fig 1.4 Wing box section

Weight of the aircraft considered = 7000 k
Design load factor = 3.2 'g'
Factor of safety consideredin design of aircraft = 1.5
Therefore Total design load on the aircraft = 33600 kg-f
Total lift load on the aircraft is distributed as 80 % and 20 % on wing and fuselage respectively.
Total load acting on the wings = 26880 kg-f
The load acting on each wing = 13440 kg-f
Total span of each wing = 7500 mm

The resultant load is acting at a distance 3200 mm from the wing root. The resultant load is at a distance of 1200 mm from the root end (A-A) of the wing box considered for the analysis.Therefore, we calculate the bending moment due to this resultant load at the root end of the wing box (A-A).

The bending moment at the root end (A-A) of the wing box = 13440 X 1200 = 16128x103 kg-mm

Load to be applied at the other end (B-B) of the wing box = 16128x103/1400 = 11520 kg-f

Load on total circumferential length at the tip end of the wing box = udl * length

Total circumferential length at the tip end of the wing box = 4700 mm

Therefore,UDL = 12649.41/4700 = 2.69 kg/mm

To simulate the analysis, an arbitrary load of 5Kg/mm is applied across the one end of the wing box.The result of application is verified by displaying the shell thickness and modifying it in iterations if required.

3.2 Stress Analysis

After the solving process is completed in NASTRAN, the processed file is selected in PATRAN to access the results. The results will be displayed as shown in fig 1.5

On analysis, the stress concentration at the fixed end of the wing box was found to be maximum.

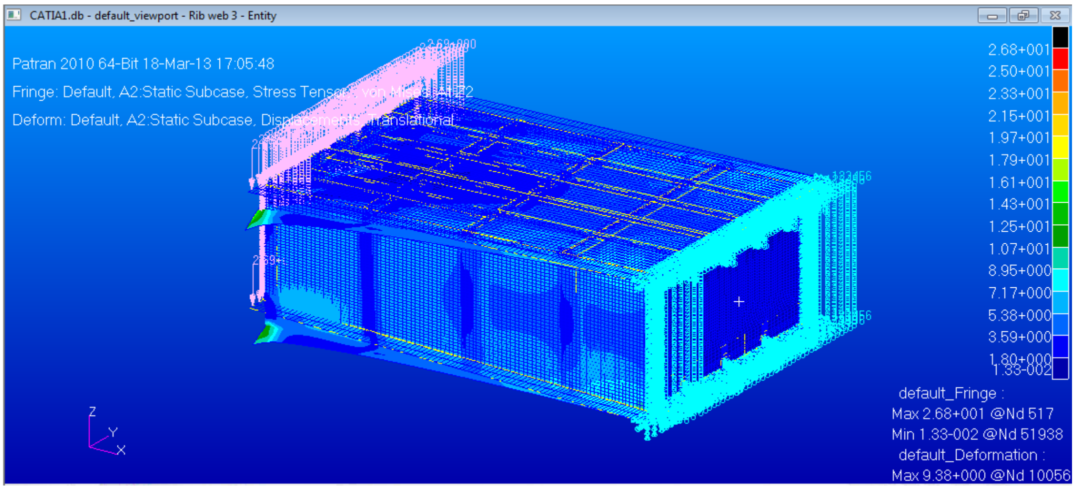

Fig 1.5 Stress analysis in wing-box structure

The areas of low stress concentration (approaching zero) are found in the rib webs. Hence, this analysis shows that the weight optimization of the wing box can be brought about by reduction in area at the low stress concentrated areas, i.e., the rib webs.

Due to these properties of good machinability,surface finish capabilities and a high strength material of adequate workability Al-2024 will be the specified material used for the wing box structure of the aircraft.

IV. RESULTS AND DISCUSSION

4.1 Iteration 1:

Total volume of the wing box = 1.75 E7 cubic metres
Density = 2710 E-9 kg/cubic metres
Initial mass of wing box = density x volume = 47.5 kg

After applying the load on the circumferential length of the wing box, it is solved using NASTRAN and the results are accessed in PATRAN which is shown in figure 1.6

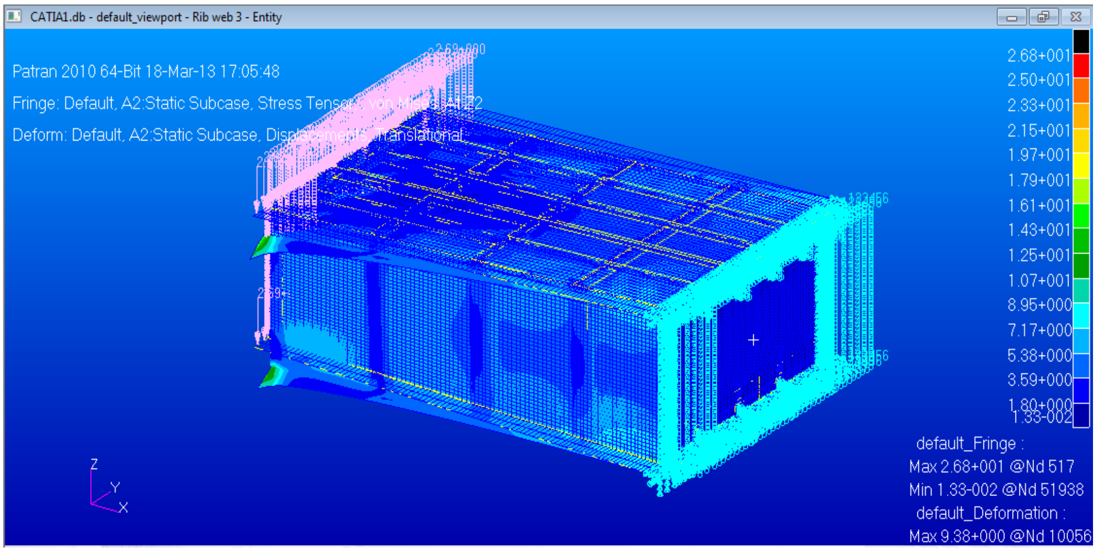

Fig 1.6 Wing-box at iteration 1

The stress concentration in the rib webs approaches zero (deep blue region) which can be seen in fig 1.7. Hence the second iteration will consist of introduction of cut-outs in these regions.

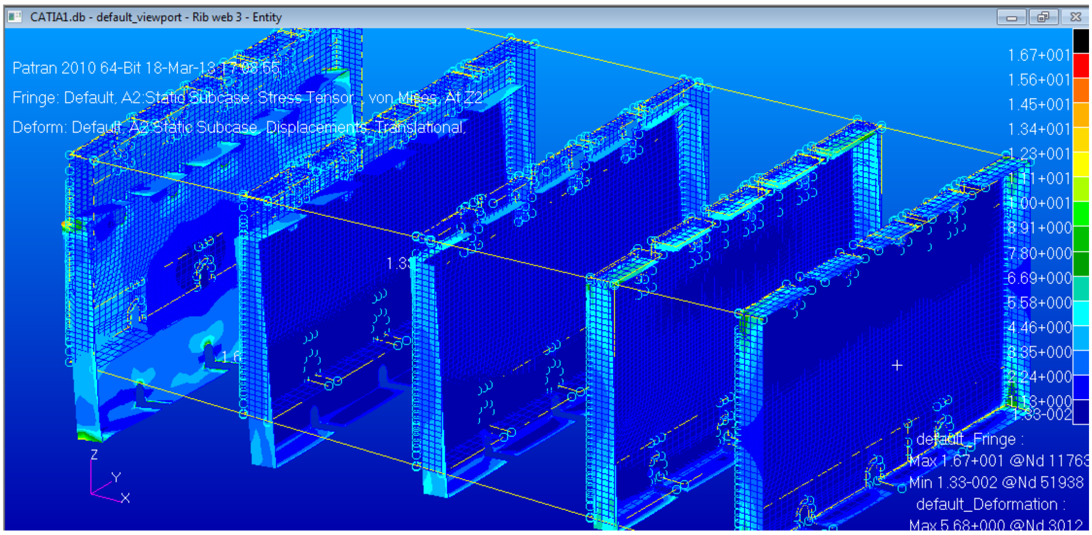

Fig 1.7 Stress Concentrations

4.2Iteration 2:

The stress concentration in the rib webs is found to be minimum (approaching zero).Therefore, we introduce capsule shaped cut-outs in the rib webs.In the second iteration, we introduce two cut-outs in the webs at a distance of L/4 from the rib side flanges and their lengths 1/3rd of the height of the webs.Mass after introduction of cut outs = 47.09 kg After introducing the cut-outs the ribs will be as shown in fig 1.8.

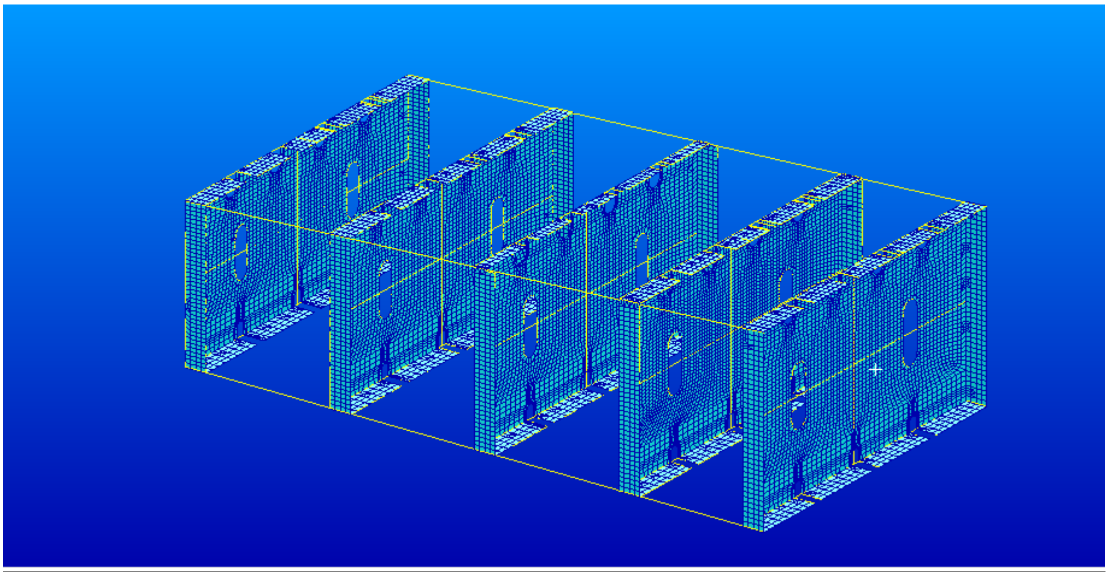

Fig 1.8 Introduction of cut outs

Once the first set of cut-outs are introduced on the rib webs, the entire model is solved again and stress analysis is carried out as shown in fig 1.9.

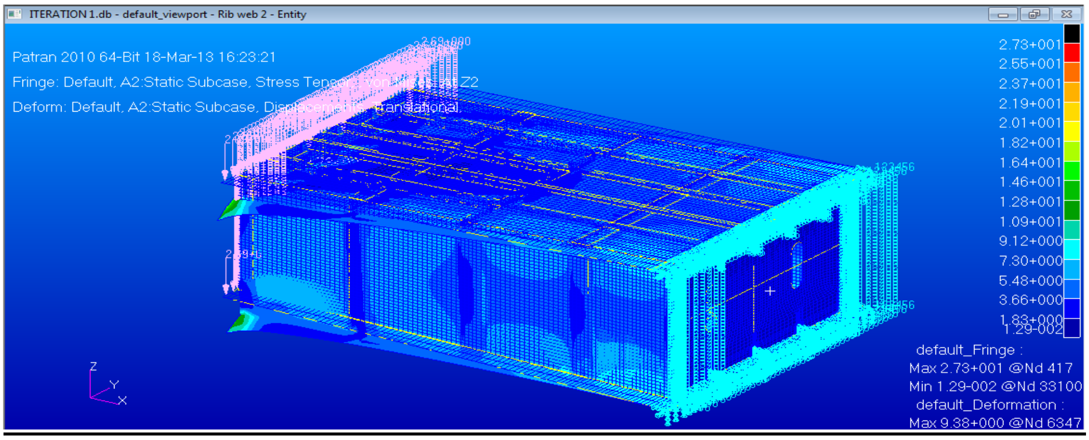

Fig 1.9 Stress analysis in cut outs

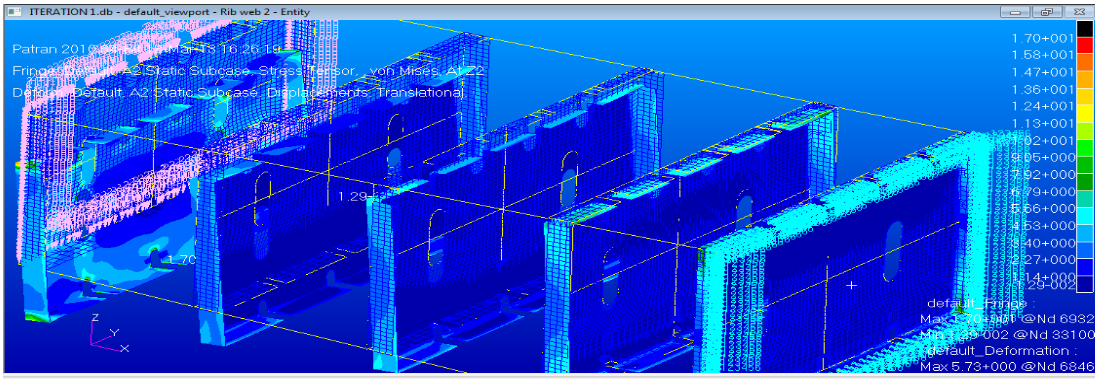

Fig 1.10 Introduction of two cut outs in each rib web

On analysis, after introduction of two cut-outs in each rib web, the stress concentration around the cut-outs is not critical as in fig 1.10. Therefore, the cut-outs can be further enlarged and an additional cut-out can be introduced in between the existing cut-outs.

4.3 Iteration 3: The cut-outs are enlarged to a length ½ of the height of the rib webs.In iteration 3, the introduced cut-outs are further enlarged and an additional cut-out is introduced in the first four rib webs as shown in fig 1.11.

Mass after 3$^{rd.}$ iteration = 45.66 kg.

Volume after 3$^{rd.}$ iteration = 1.68 E7 cubic meters.

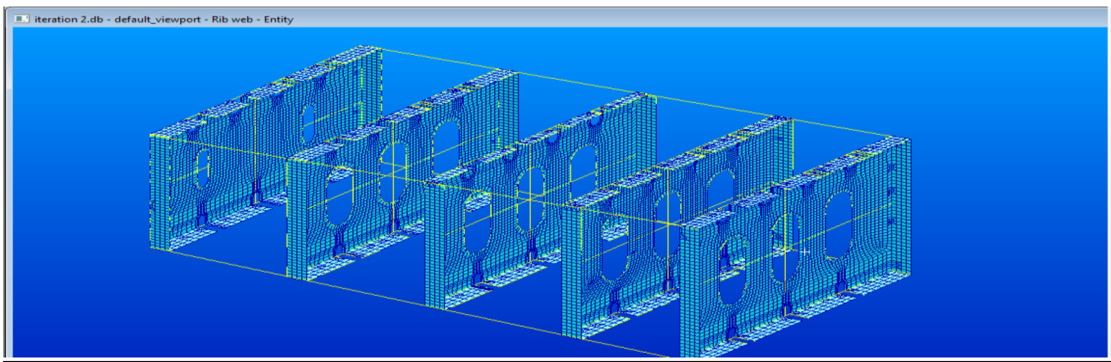

Fig 1.11 Introduction of cut outs in first four ribs

The second set of cut-outs are introduced on the rib webs, the entire model is solved again and stress analysis is carried out as shown in fig 1.12.

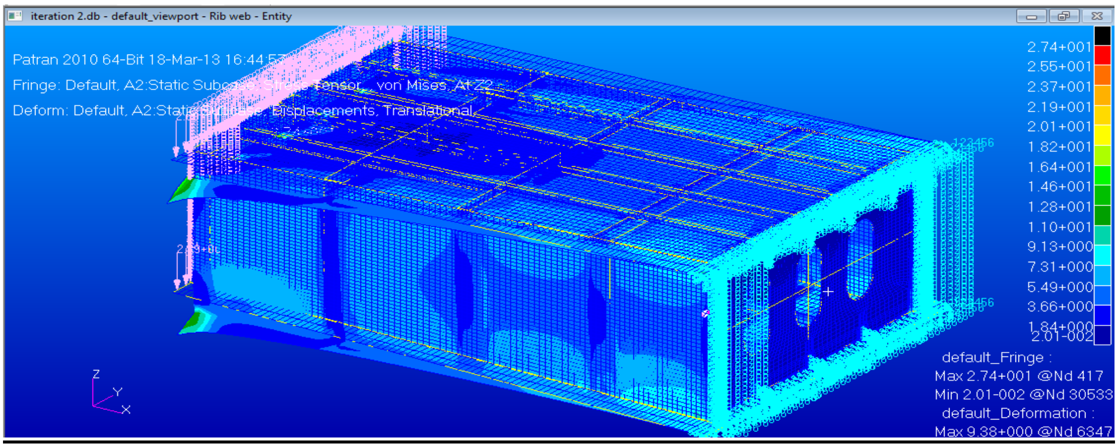

Fig 1.12 Stress analysis in two cut outs

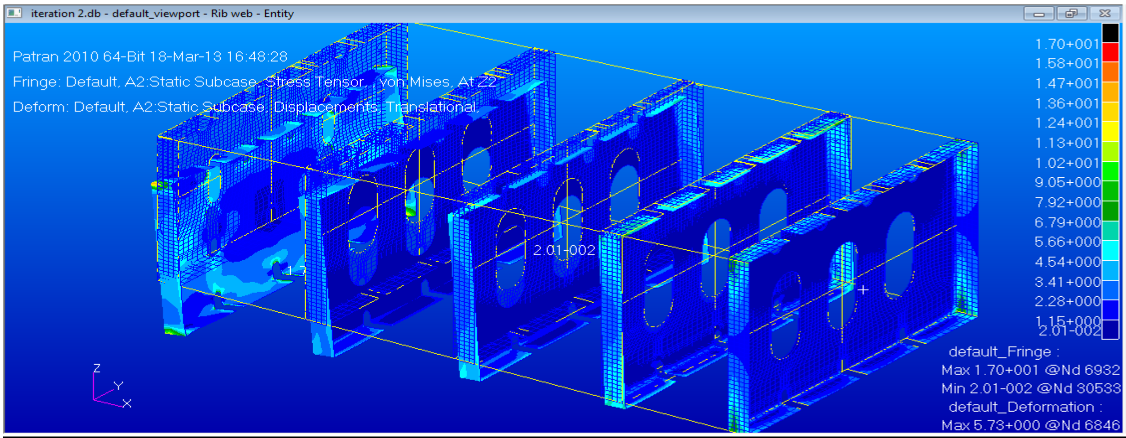

Fig 1.13 Stress analysis in four cut outs

V. SUMMARY AND CONCLUSION

A comparative study of the structural mass is made after the iterations are done. The difference in initial and final mass after the introduction of cut-outs is observed:

Initial mass = 47.5 kg
Final mass = 45.66 kg

We observe an appreciable difference in the mass of the wing box. There is a 3% decrement in the weight of the wing box, and hence the wing. And this is done by maintaining similar rib stiffness to the baseline rib design which also permits the minimization of the effect of design changes.The most significant advantage of the weight reduction is that, there is an overall reduction in the structural weight of the aircraft.Reduced weight induces the tendency to use efficient fuel consumption levels.This results in increased efficiency and improved performance characteristics.

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