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Weight Optimization of the Vertical Tail in-Board Box Through Stress Analysis Approach

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Abstract : *Vertical tail is a component of the airframe, which is attached to the fuselage at the rear end. It is one of the major components of the airframe. Vertical tail is similar to the wing structure in shape. Rudder attached to the Vertical tail is the control surface, which is used for controlling yawing motion of the aircraft. Deflection of rudder introduces side load on the Vertical tail. Without rudder deflection, there is no aerodynamic load on the Vertical tail. The load due to deflection is the major design load for the Vertical tail. For transport aircraft side gust load is also important from a design point of view.Weight optimization of each component of the airframe is important to achieve the minimum weight for the aircraft. This project includes the weight optimization of the VT in-board box structure through linear static stress analysis approach. VT in-board box consists of two spars and five ribs with top and bottom skin. Finite element method will be used for stress analysis of the component. Loads representative of a medium size transport aircraft will be considered in this study. Iterative analysis process will be adopted to achieve the minimum weight for the structure. Lightening cutouts in the spar and rib webs will be considered based on the stress magnitude and distribution in these components. MSC Patran and MSC Nastran software programs are used for the stress analysis of the structure.*

Keyword: *Component, FEM, In-board box, lightening cutouts, Side load, Transport aircraft, Vertical tail, Weight optimization.*

I. Introduction

Aircraft is a scientific device that requires hundreds of engineers and scientist along with their knowledge and experience, work in a closed group to come up with a successful product. Airframe is the basic structure of the aircraft which carries the load. Aircraft experiences variable loading in services. Aircrafts are generally built-up from the basic components of aircraft are fuselage, tail units, wings, and control surfaces. Each component has one or more specific functions and designer must ensure that it can carry out these functions safely. Even small failure of any of these may lead to a catastrophic disaster which can cause huge destruction of property and lives. When designing an aircraft, it's all about finding the optimal proportion of the weight of the vehicle and payload. The load-bearing members of these main sections, those subjected to major forces, are called the airframe. If all equipment and systems are stripped away then what remains is airframe.

The basic function of an aircraft's structure is to transmit and resist the applied loads; to provide an aerodynamic shape and to protect passengers, payloads etc., from the environmental conditions encountered in flight. Most of the aircrafts have thin shell structures where the outer surface or skin is usually supported by transverse frames and longitudinal stiffening members to enable it to resist compressive, bending and torsional loads without buckling. These structures are known as semi-monocoque, while these thin shells which rely entirely on their skins for their capacity to resist loads are referred to as monocoque.

II. Literature Review

In this competitive environment of aircraft industries it becomes absolutely necessary to improve the efficiency, performance of the aircrafts. And to reduce the operating costs and development considerably, in order to capitalize the market. An important supplement to improve the efficiency and performance can be achieved by decreasing the aircraft weight through weight optimization of aircraft structures. There are many structural components in the aircraft like wing, Fuselage etc. Considering one such component like Vertical tail for the project. Hence to reduce the weight of aircraft (vertical tail) some of the researcher/scientists have done work on this and their brief review is given below

Robert M. Taylor: has maintained a focus on weight minimization that has continued through detail component design. He has applied structural topology, shape, and sizing optimization tools and methods to optimize load paths and sizing of structural components to realize weight savings. In F-35 JSF the author has found weight savings, expedited the maturation of numerous structural components, and made high-quality design decisions by applying finite element-based structural optimization tools. The engineers performed the standard structural analysis and design iterations to get minimum weight over time, optimization is a tool to get there faster if an effective optimization .Furthermore, optimization can provide high- quality structural information to support fact- based design decisions balanced against all requirements **[2].**

Markus Kaufmann et.al, in the paper entitled "Cost/Weight Optimization of Aircraft Structures". In this work, a cost/weight optimization framework for composite structures is proposed. Manufacturing cost, non-destructive testing cost and the lifetime fuel consumption based on the weight of the aircraft, are considered into account, thus using a simplified version of the DOC (Direct Optimization cost) as the objective function. In the appended papers, the cost/weight optimization framework as proposed above is presented. This is done in two steps. **[4]**

III. Methodology

The methodology adapted in the project is as show in the Fig. (3.1) below

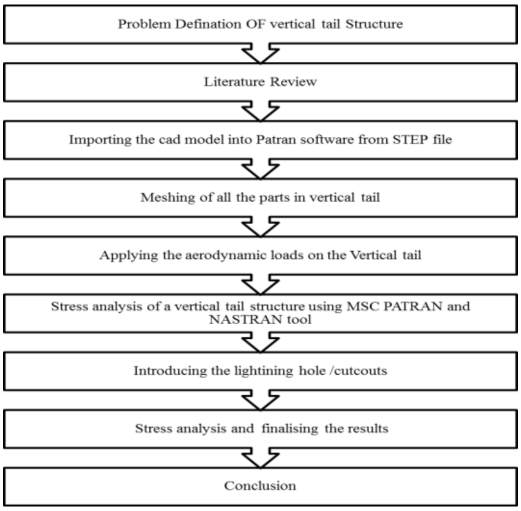


Fig. 3.1 Flow Chart of Methodology

IV. Overview of the Vertical Tail Structure Geometric Model

The vertical stabilizers, vertical stabilizer's, or fins, of aircraft, missiles or bombs are typically found on the aft end of the fuselage are intended to reduce aerodynamic side slip and provide direction stability. The trailing end of the stabilizer is typically movable, which is called as the rudder; this allows the aircraft pilot to control yaw. Often navigational radio or air band transceiver antennas are placed on or inside the vertical tail. Most of the aircrafts are fitted with three jet engines; the vertical stabilizer houses the central engine or engine inlet duct. Fig (4.1) below shows the vertical tail structure of the project which is done in CATIA

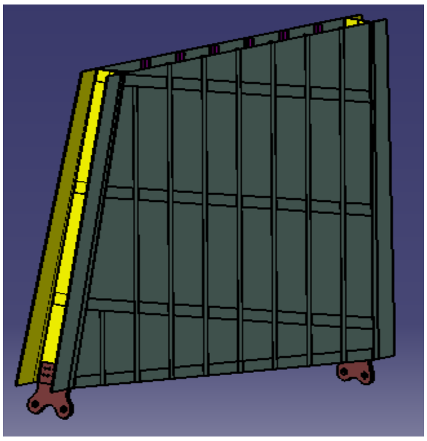


Fig 4.1 Vertical Tail Structure in CATIA

4.1 Parts of the Vertical Tail: The Above vertical tail consist of the following parts

a) Spars: - Spars are member that extend from root to tip. The Fig. 4.2 shows the Spar details

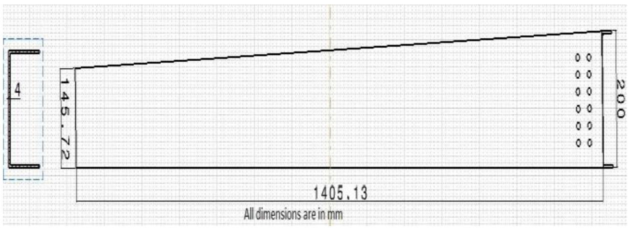


Fig. 4.2 Spar detail section

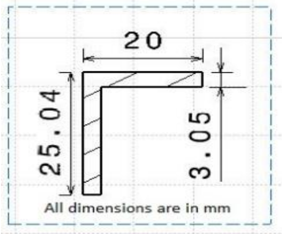


Fig. 4.3 Stiffener section detail

- **b)** **Stringers: -** Stringers are stiffening member attached to skin to avoid Buckling. The Fig. 4.3 shows C/S of stringer used in the vertical tail structure
- **c)** **Ribs: -** Maintain airfoil shape and transfer loads to spar. Fig. (4.4) shows the detailed geometry of Ribs in vertical tail structure. The ribs are also form the main support for the vertical tail structure.
- **d)** **Skin: -** Wing or fuselage or vertical tail skin is mend to carry loads. Small metal strips (stiffeners, stringers, longerons) attached to prevent buckling. Fig. (4.6) shows the skin Dimension which is of 2mm thick. The designing of the parts and their assembly is done using CATIA V5 R20. The parts are converted into solid models and are saved in different files with respective dot STEP files. In order to assemble the parts as an integrated structure of a vertical tail structure, we adopt an assembling approach known as the bottom-up assembly approach.

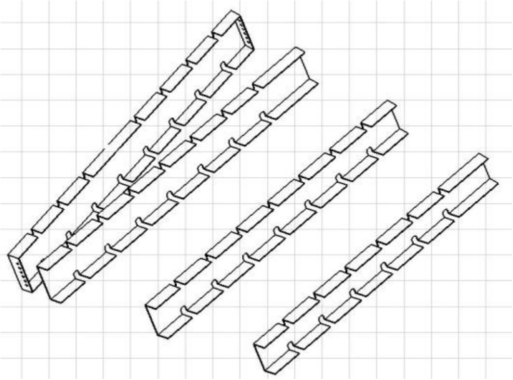


Fig. 4.4 Ribs

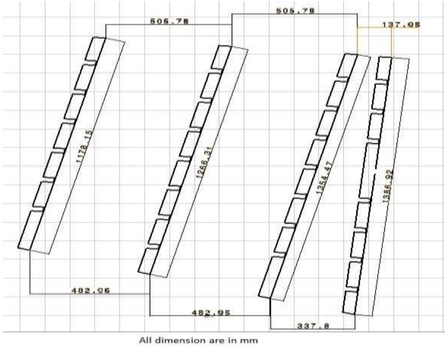


Fig. 4.5 Ribs Geometry

Table 4.1 Geometry Specification of vertical Tail

Structure	Nos	Thickness(mm)
Skin	2	2
Spar	2	4
Rib	4	4
stringer	16	3
Fork	2	16

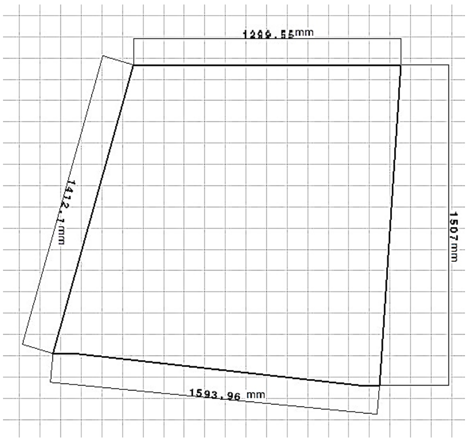


Fig. 4.6 Skin dimension

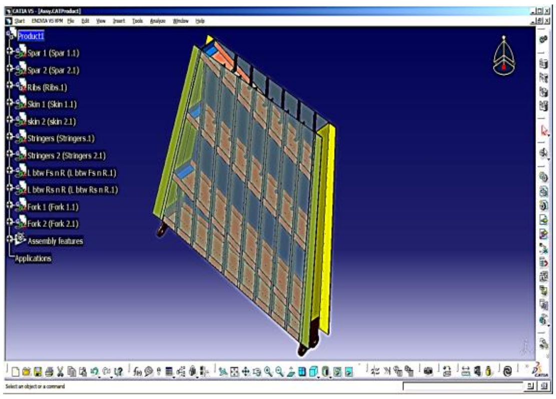


Fig. 4.7 Assembled CATIA model of vertical tail

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 .STEP file. In order to assemble the parts as an integrated structure of a vertical tail structure, 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 parts are assembled in their working position by applying assembly constrains to the individual parts. Fig. (4.7) shows the assembly consisting of the skins, stringers, ribs and spars.

4.2 Importing the model and Geometry Extraction

The vertical tail as a whole and the various structural members individually are imported to Patran from CATIA .STEP file and their geometry is extracted into respective groups.

V. Meshing of Vertical Tail Structure

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 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.

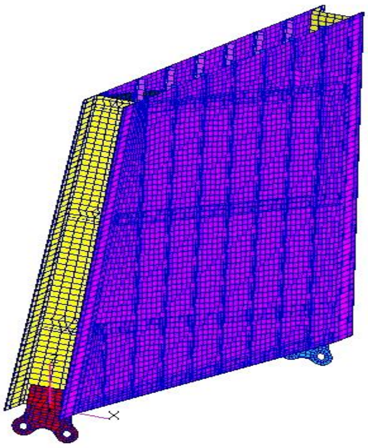


Fig. (5.1) shows the meshed VT

Quad verification summary	
Test	**Total Failed**
Aspect	0
Warp	0
Skew	0
Taper	0
Normal Offset	0

Table 5.1 Quad verification summary

5.1 Material Property

Al 2024-T3 is used in current fuselage structure due to high strength and fatigue resistance properties. The ultimate tensile strength of this material is 483 MPa and yield strength is 345 MPa and it has an elongation of 18%**.** The vertical tail 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 and applying thickness

Table 5.2 Material properties of Vertical Tail structure

Sr. No	Part Name	Material	Thickness	Offset
1	Skin	AL	2	1
2	Spar	AL	4	2
3	Rib	AL	4	2
4	Stringer	AL	3	1.5
5	Fork	AL	12	6

5.2 Applying Boundary Conditions

The boundary conditions are given in Table (5.3).The root ends (A & B) are at the fork which are fixed. In practical approach the fork will be hinged to aft fuselage of the aircraft. The top surface of the vertical tail is free end.

Table 5.3 Boundary conditions

	Translation motion			**Rotational motion**		
Position	**U_x**	**U_Y**	**U_Z**	**R_X**	**R_Y**	**R_Z**
Root End A	0	0	0	0	0	0
Root End B	0	0	0	0	0	0
Top surface	-	-	-	-	-	-

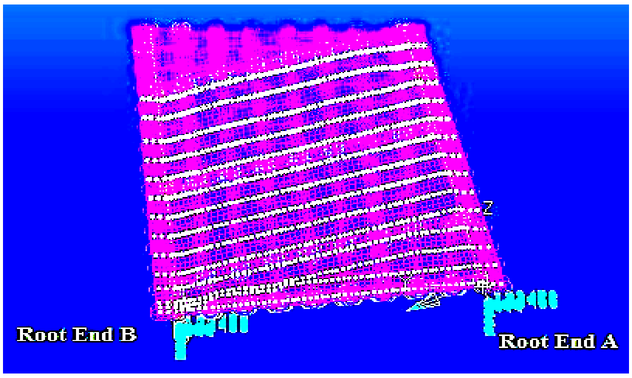
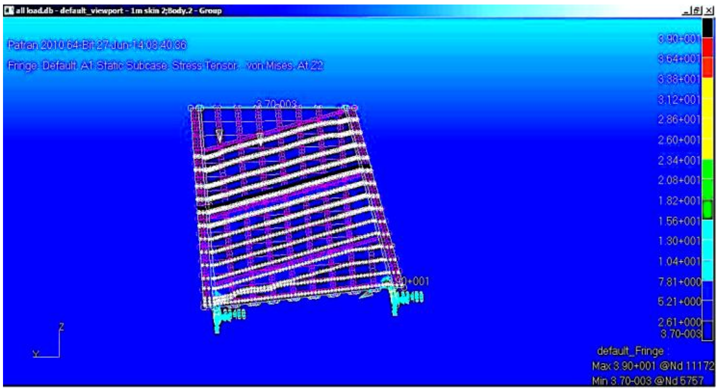


Fig. 5.2 Load Distribution

VI. Result and Discussion

6.1 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. (6.1). On analysis, the stress concentration at the fixed end of the vertical tail was found to be maximum. The FEM geometry in the vertical tail structure is shown in Table (6.1).


all load.db - default_viewport - 1m skin 2;Body.2 - Group

Patran 2010 64-Bit 27-Jun-14 08:40:36

Fringe: Default, A1:Static Subcase, Stress Tensor, , von Mises, At Z2

default_Fringe :
Max 3.90+001 @Nd 11172
Min 3.70-003 @Nd 5757

Fig. 6.1 Stress analysis in Vertical tail structure

Table 6.1 FEM geometry

FEM Geometry	**Nos**	**Units**
Bar	1793	Nos
Tria	171	Nos
Quad	13646	Nos
Mass	57.12	Kg
Volume	20400354	mm^3

Maximum stress in vertical tail structure = 33.9 kg/mm^2 Since this stress is in one element so we need to calculate the average elemental stress

$$\therefore \text{ Average Elemental Stress} = \frac{33.9+32.8+14.8+28.6}{4} = 27.525 \text{ kg/mm}^2$$

As we proceed further we will be doing modification in spar and ribs and their respective stress are as follows

Spar1: -

Maximum stress in spar1 = 21.6 kg/mm^2

Average Elemental Stress = $\frac{21.6+10.9+21.2+8.27+7.38}{5}$ = 13.96 kg/mm^2

Spar2: -

Maximum stress in spar2 = 23.2 kg/mm^2

Average Elemental Stress = $\frac{23.2+20.4+21.7+8.4}{4}$ = 18.425 kg/mm^2

Ribs: -

Maximum stress in Ribs = 29.5 kg/mm^2

Average Elemental Stress= $\frac{29.5+16.1+27.5+20.3}{4}$ = 23.35 kg/mm^2

The areas of low stress concentration (approaching zero) are found in the rib and spars. Hence, this analysis shows that the weight optimization of the vertical tail structure can be brought about by reduction in area at the low stress concentrated areas, i.e., the rib webs and spars. Due to these properties of good machinability surface finish capabilities and a high strength material of adequate workability Al-2024t3 will be the specified material used for the vertical t structure of the aircraft. The vertical tail deformation is shown in Fig (6.2)

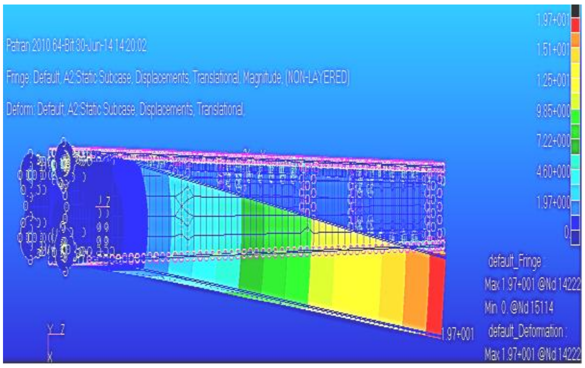


Fig. 6.2 Deformation contour of vertical tail structure

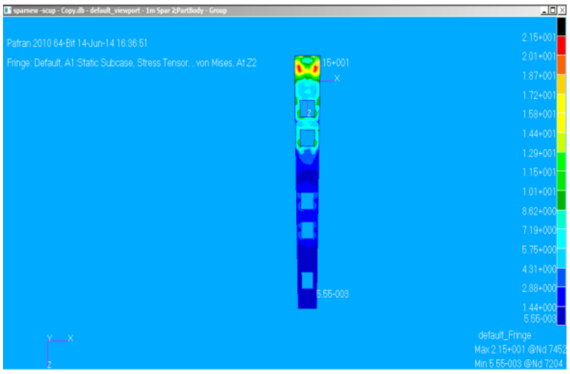


Fig 6.3 stress in modified spar

In fig. (6.2) it is observed that the maximum deformation of the vertical tail structure is found to be 19.7 mm. This maximum vertical tail deformation is found to be at tip of the structure.

6.2 Iteration 1

The Iteration I involves the introduction of cutouts in spars. After applying the same load on the surface of the vertical tail, it is solved using NASTRAN and the Results are accessed in PATRAN. This is shown in Fig 7.3. The detailed cut section is shown in Fig. (6.4)

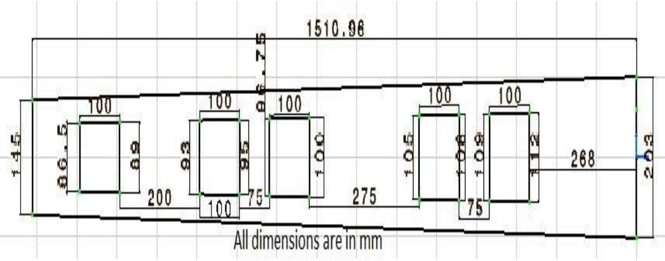


Fig 6.4 lightening cutout detail in spar

Here in the above Fig. (7.4) though the cutouts are sharp edged it is recommended to keep the edges with standard radius of 5mm or as per manufacturing standard. The stresses developed near the cutouts are very less. Hence the detailed analysis is not recommended.

Maximum stress in Vertical tail structure after Spars modification = 34.2 kg/mm^2

Average Elemental Stress = $\frac{33.3+15.3+28.6+34.2}{4}$ = 27.85 kg/mm^2

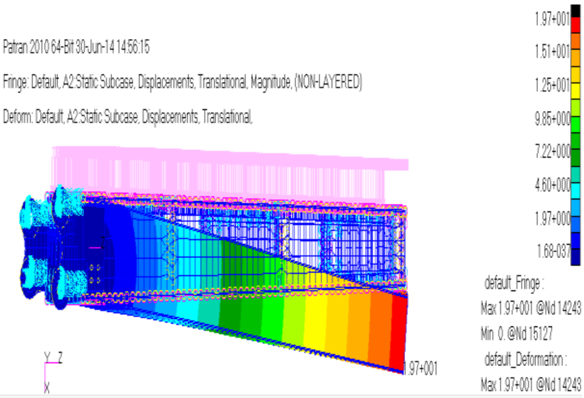


Fig 6.5 Deformation of VT after introducing cutouts in spar

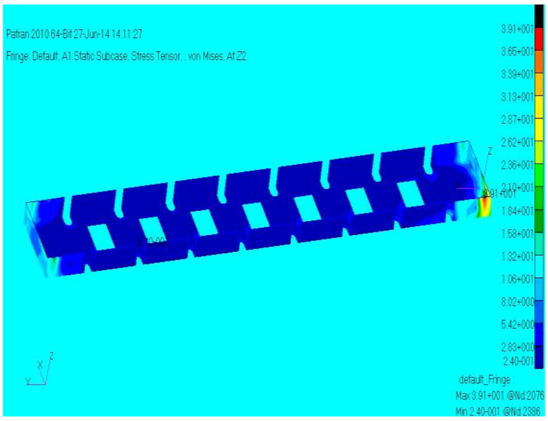


Fig 6.6 Stress in Rib

Stress at Spar 1 = 21.8 kg/mm^2
Stress at spar 2 = 23.0 kg/mm^2
Mass of the vertical tail structure after iteration 1 is =55.46 Kg

The deformation for the vertical tail structure after introducing cutouts in spar is shown in Fig. (6.5). From the Fig. (6.5) it is observed that the deformation is 19.7 mm which is almost similar to the deformation without introduction of cutouts.

6.3 Iteration 2

The second iteration will consist of introduction of cut-outs in Rib regions. The cutouts are shown in Fig. (6.6)
Maximum stress in Vertical tail structure after Ribs modification = 34.3 kg/mm^2
The cutouts in the ribs are of 58mm*58mm and seven sections in one rib.

$$\text{Average Elemental Stress} = \frac{34.3+13.4+28.7+15.3}{4} = 23.7 \text{ kg/mm}^2$$

Table 6.2 Maximum stress induced in structural member at introduction of cutouts

Structural member	**Maximum Stress (N/mm^2)**
Spar1	215.82
Spar2	225.63
Rib 1	23.83
Rib 2	81.71
Rib 3	85.44
Rib 4	294.30

Mass of the vertical tail structure after iteration 2 is =54.93 Kg The deformation for the vertical tail structure after introducing cutouts in spar is shown in Fig. (6.7)

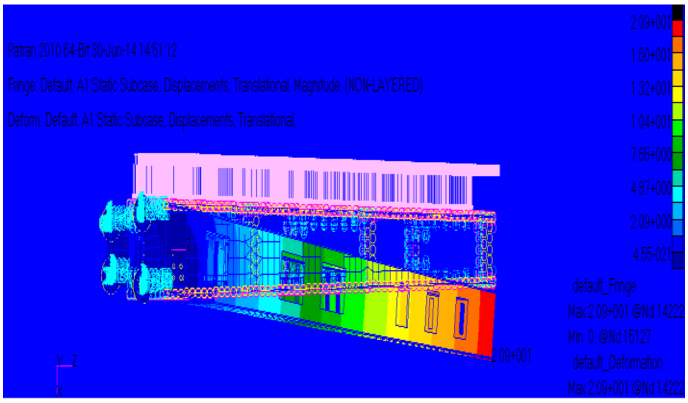


Fig 6.7 Deformation of VT after introducing cutouts in ribs

From the fig. (6.7) it is observed that the deformation of the vertical tail structure after introduction of cutouts in spar and rib is 20.9 mm.

Table 6.3 Summary

Sr. No.	Load cases	Stress (N/mm^2)	Deformation(mm)	Wt (kg)
1.	Vertical tail structure	332.56	19.7	57.12
2.	Iteration 1	335.50	19.7	55.46
3.	Iteration 2	336.48	20.9	54.93

VII. 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 = 57.12 kg and Final mass = 54.93 kg

It is observed that an appreciable difference in the mass of the vertical tail structure. There is a 3.8% decrement in the weight of the vertical tail structure. 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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