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A Case Study: Size Optimization of Core Frame of Oil Filled Power Transformer

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Abstract: *A transformer is a vital component in any industry. If the transformer fails, the electric supply fails. So it is very necessary that the transformer must work without anyinterruption. Transformer has many components and all are essential for its smoothworking. So every component in transformer is critical. It is said that the core and winding arecalled the heart of a transformer. The core frame is mounted on top and bottom of thecore and winding assembly. Core frame is made up of mild steel. In transformer, thereare several losses occur which decrease the efficiency of transformer. `Stray loss' is oneof the major loss which affects badly on performance of transformer. This stray lossoccurs due to the presence of mild steel in transformer. So if the weight of the core frameis reduced by optimization, it will have large impact on the reduction of stray lossesand improvement of transformer efficiency. Thus, the case of the optimization ofcore frame to reduce the weight of mild steel used has been taken. For the solution towards this case, one particular model of transformerassembly has been taken and using CAE tools, the size of the core frame structure hasbeen reduced by the size optimization.*

Keywords: *Core Frame, Optimization, Oil Filled Transformer, Transformer, CAE Tools, HyperMesh.*

I. INTRODUCTION

REFERENCE: VOLTAMP TRANSFORMERS LIMITED, VADODARA

Figure 1. Core Frame and Winding

The main function of this frame is to provide clamping to the core. It is providedat top and bottom of the core in pair as shown in white colour in above image. It ismade up of a Mild Steel (Grade E250 as per IS 2062-2006).As the high voltage current is flowing in core, stray losses will be induced due tothe mild steel. The more mild steel, the losses will be more. So, if the weight of frameis reduced, the losses will be less.
The optimization of the core frame for the reduction in weight of material used in itsconstruction is to be carried out to improve the functionality of a transformer.

II. LITERATURE REVIEW

Author S.S.Rao explained various optimization techniques for solving problem of optimization in engineering practice in his book titled “Engineering Optimization - Theory and Practice”[1]. This is a very good book of optimization. In this book detailed procedure of classical optimization techniques are explained.

Various classical optimization techniques are given which are very useful to solve optimization problems having different conditions. Lagrange Multiplier technique to solve the problem of multiple design variables with equality constraints is very accurate technique. This technique may be applied on almost every optimization problem and gives satisfactory results.

"Manual on Transformers"[2] contains complete criteria to design the transformer according to various Indian Standards. This book is very useful for transformer design in transformer industry. One can get idea about complete procedure of erection, commissioning and maintenance of transformer.

Similarly the "Transformers"[3] published by BHEL, Bhopal is another good book on transformer. In this book one can get practical knowledge as well as theoretical knowledge about the transformer. In this book one learns about principles of transformer, material used in transformer, electrical accessories used in transformer, cooling arrangement, design procedure, testing, standards used, erection commissioning and maintenance of a transformer.

In IS 2062,2006[4] complete specification of hot rolled low, medium and high tensile structural steel is given. From this various mechanical and chemical properties of steel of various grades used in industry can be referred.

"Standard terminology for power and distribution transformers"[5], standard terminology for power and distribution transformers are given in this standard. This is known as IEEE C57.12.80 - 2010.

"Engineering Mechanics of Solids"[6] is very advanced book of mechanics of solids. Author Popov has described all the aspects very good. One can get idea about solution of various problem related to strength of material.

Many formulas related to designing of various mechanical components used in any industry are given in "Design data hand-book (for mechanical engineers)"[7].

"Westermann tables"[8], this handbook gives us formulas and basic concepts of physics and mechanical engineering, which are very useful for basic understanding for mechanical engineers.

Very good fundamental aspects of machine design are given in "Design of Machine Elements"[9] by author V.B.Bhandari. One can get very useful information about various loadings arrangements and their calculations in this book.

III. OVERVIEW AND METHODOLOGY

The core frame keeps the yoke parts of the core compressed. The top yoke beam keeps the winding in a pressed down condition, while the bottom yoke beam supports thesame winding from the below and carries the core, the windings and inner leads whenthe inner part of the transformer is lifted out of the tank.

The design of the frame is carried out with the following assumptions:

1. The friction between core and frame is not considered.
2. Lifting of the active part is affected through four bollards or suspension girders.

One lifting point carries 1/3 of the weight of the active part. In order to avoidbending stresses in the top frame during the lifting, the lifting bollard or the suspension girders are located on the centreline of the outer limbs, above the flitch plates.

For obtaining the optimised weight of a upper and lower core frame, size optimization is performed in HyperMesh 9.0A solid model is prepared using SolidEdge ST4. The frame is prepared by welding the plate segments. Hence the plane stress phenomena can be used to analyze the problem. The mid surface of the model has been extracted using HyperMesh 9.0 and the surface mesh has been prepared. The appropriate thickness are assigned to proper components and by applying appropriate boundary conditions, the model is solved using FEA.

IV. TOP FRAME – SIZE OPTIMIZATION

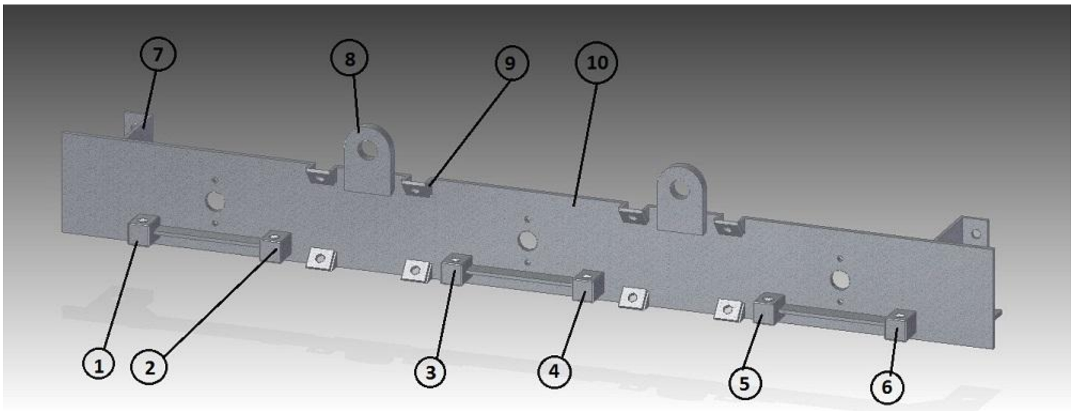

Figure 2. 3D model of Top Frame

Figure 2 shows the 3D model of Top Frame prepared by SolidEdge ST4.This model is then imported to HyperMesh 9.0 and converted to a surface model.Then the meshing is done in HyperMesh.

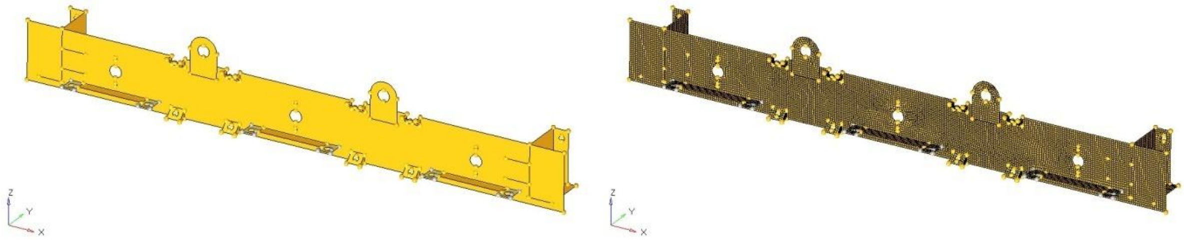

Figure 3. Top Frame – Surface and Meshed Model

Figure 3 shows surface model and meshed model prepared in HyperMesh 9.0.
Meshing is done by manual method.
Mesh Type = quad element
Mesh element size = 10
Total elements = 13357 nos.
Total nodes = 14080 nos.
The top frame has to analyze for two different loading conditions i.e.when the activepart assembly is at resting position and the second condition is when the total assemblyis lifted through lifting lugs. The various loading conditions for the both of the cases areexplained below.

4.1. At Resting Condition
4.1.1. Boundary Condition

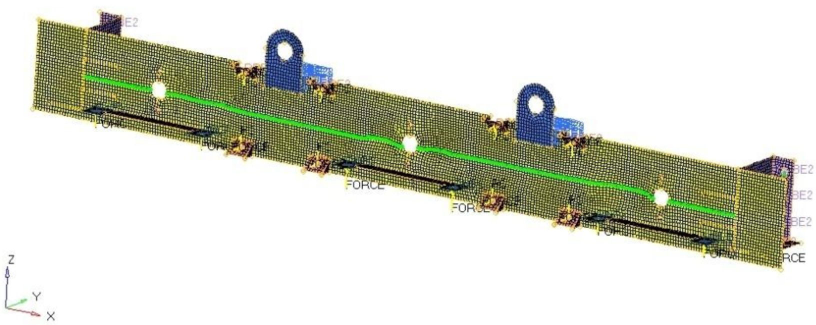

Figure 4. Top Frame – Boundary Condition

The forces acting on top frame are as follows:

The force contracting the yoke acts on the frame main body as a uniformly distributed continuous horizontal load, produced by the mild steel bands by tightening the contracting bolts located outside the yoke. For compressing the yokelaminations, a surface pressure of $p = 1{:}5 \times 10^5 N/m^2 = 0.147 N/mm^2$ is to beapplied to the widest yoke sheet. This compression force has to be reduced to narrowest yoke sheet. Let us denoted p,N/m^2,the pressure specified for the widestyoke sheet of width c, mm and by p1,N/m^2;the pressure acting on narrowestsheet of width c_1,mmand length h,mm.

So it can be written as,

$$p_1 = \frac{c \times h}{c_1 \times h} \times p$$

Here,
c = 495mm
c_1 = 210mm
h = 2395mm
So, p_1 = 0.3465N/mm^2

So the net force acting on the frame main body is,

$$f_1 = 210 \times 2395 \times 0.3465 = 174275N$$

The coil clamping forces are in vertical direction, balanced by the forces arisingin the plates. The coil clamping forces act along the line of clampingelements,whereas the reaction forces arise along the line of flitch plates mounted on thefront surface of the limb.

Now the coil clamping forces are calculated as follows. Coil clamping forces canbe equal to the stabilizing forces arise in the transformer.
So, for this case the stabilizing force is 193400N: Which is given by the electrical designdepartment of the industry.

This force may be shared by both, top frame and bottom frame. By dividing thisforce into two parts, each frame (i.e. top and bottom) has to bear a force of 96700N. The coil is compressed by M36x200mm studs. This force can again divided into threephases of winding. Now each phase experiencing a force of 96700/3 = 32233N. The outer two windings are having 3 nos. of studs, while the centre winding has 2 nos. ofstuds.

Force on each stud of 1st winding = 32233/3 = 10745N
Force on each stud of 2ndwinding = 32233/2 = 16115N
Force on each stud of 3rdwinding = 32233/3 = 10745N.
By considering these forces, the analysis and size optimization is done.

4.1.2. FEA Results

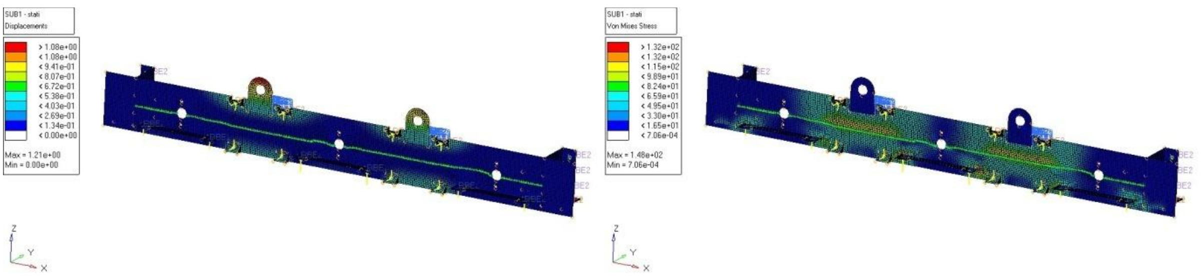

Figure 5. Top Frame – Displacement and VonMises stress before optimization

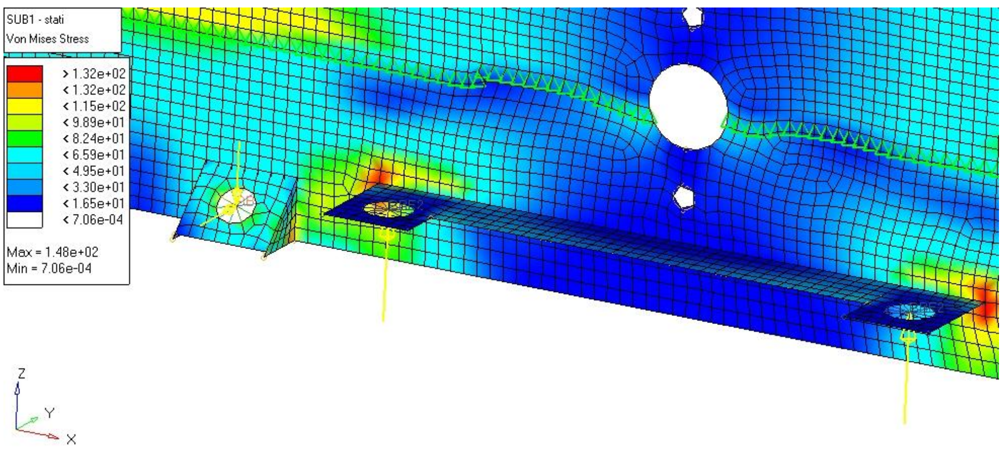

Figure 6. Top Frame – Maximum Von Mises Stress

Displacement = 1.21mm
Von Mises Stress = 148Nmm^{-2}

Mass = 156.8kg

4.2. While Lifting
4.2.1 Boundary Condition

During lifting of the inner part of the transformer, the lifting force acts on the framemain body of top frame through bollards and is transmitted by the flitch plates.

If the points of lifting are on centre line of the outer core limbs, then the bendingstress arising during lifting of the active part can be neglected. If the lifting pointsdo not coincide with the centre line of the outer limbs, then the stress resulting fromthe bending should be taken into account. But in industry, lifting points are alwaysprovided on the centre line of the outer core limbs.

For calculating the lifting force, total weight of the inner parts are taken care of.
Weight of core: 10975kg
Weight of copper: 3915kg
Weight of frame: 410kg (top frame only)
Total weight: 15300kg = 150093N
This weight is acting on 6 nos. of flitch plates while lifting.So the weight on each flitch plate is 150093/6 = 25015N

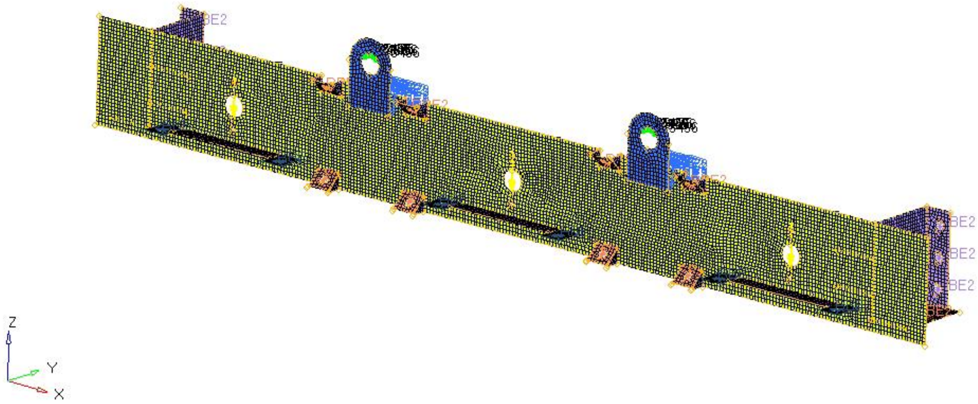

Figure 7. Top Frame while lifting – Boundary Condition

4.2.2. FEA Results

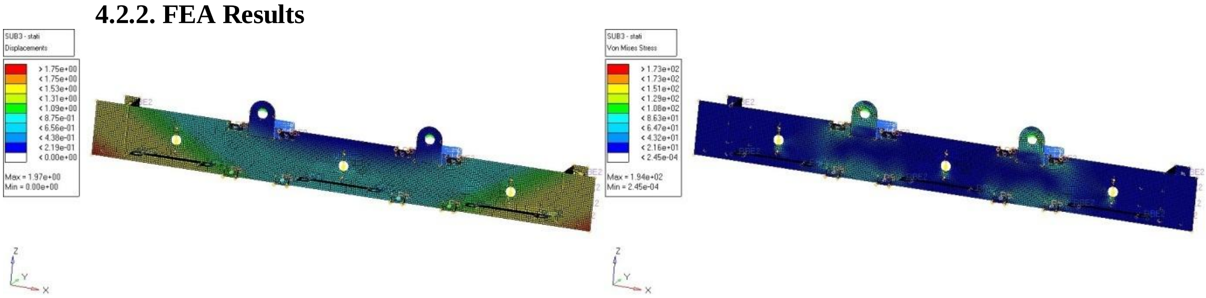

Figure 8. Top Frame while lifting – Displacement and Von Mises Stress before optimization

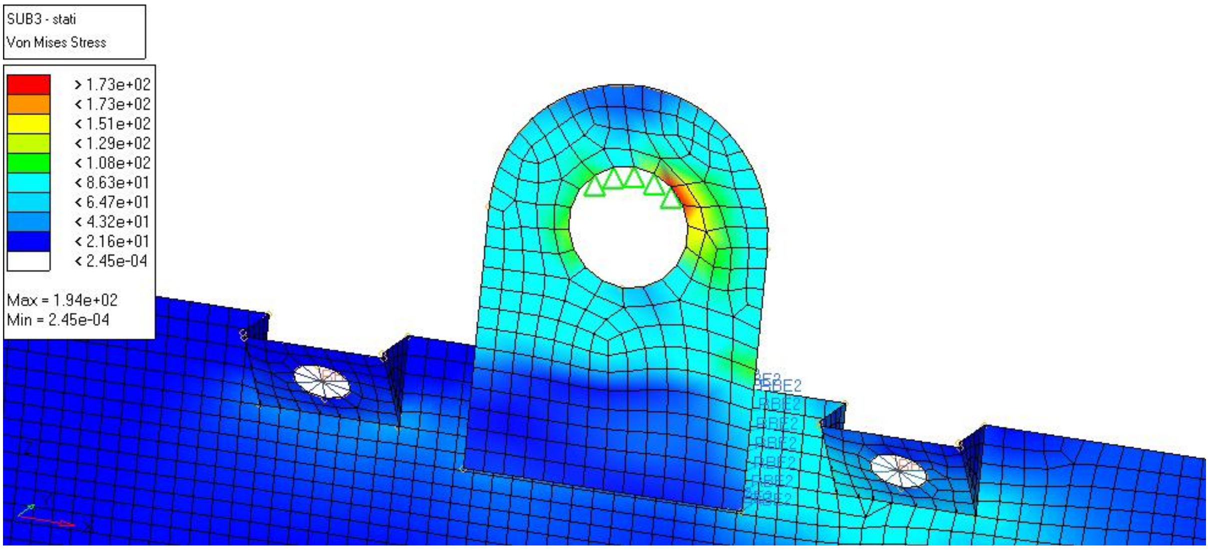

Figure 9. Top Frame while lifting – Maximum Von Mises Stress

Displacement = 1.97mm
Von Mises Stress = 194N/mm^2
Mass = 156.8kg

4.3. Optimization:

As the components of forces acting on the top frame at resting condition is more, theoptimization is performed on top frame when it is at rest.
Objective Function: To minimize the mass of mild steel used in construction ofcore frame.
Design Variable: Thickness of plates can be varied.
Constraints: VonMises Stress = 160N/mm^2:
Following design iterations are done.

4.3.1. Design Iteration 1

Table 1. Thickness before and after iteration 1

Part no.	Part Name	Initial Thk. (mm)	Modified Thk. (mm)
1	Stud nut 1	65	60
2	Stud nut 2	65	60
3	Stud nut 3	65	60
4	Stud nut 4	65	60
5	Stud nut 5	65	60
6	Stud nut 6	65	60
7	Bolt plate and back plate	12	10
8	Lifting lug	32	36
9	Bolt and back stiffener	10	10
10	Main body	16	12

Table 2. Design Parameters

Sr.no.	Parameter	Initial	Modified	% Variation
1	Mass (kg.)	156.8	130	-17.09
2	Volume (mm^3)	1.985x10^7	1.646x10^7	-17.07
3	Stress (MPa)	148	253	70.95
4	Displacement (mm)	1.21	2.85	135.53

4.3.2. Design Iteration 2

Table 3. Thickness before and after iteration 2

Part no.	Part Name	Initial Thk. (mm)	Modified Thk. (mm)
1	Stud nut 1	60	50
2	Stud nut 2	60	50
3	Stud nut 3	60	50
4	Stud nut 4	60	50
5	Stud nut 5	60	50
6	Stud nut 6	60	50
7	Bolt plate and back plate	10	10
8	Lifting lug	36	40
9	Bolt and back stiffener	10	8
10	Main body	12	16

Table 4. Design Parameters

Sr.no.	Parameter	Initial	Modified	% Variation
1	Mass (kg.)	130	125.4	-3.53
2	Volume (mm^3)	$1.646x10^7$	$1.587x10^7$	-3.58
3	Stress (MPa)	253	256	1.18
4	Displacement (mm)	2.85	2.86	0.35

4.3.3. Design Iteration 3

Table 5. Thickness before and after iteration 3

Part no.	Part Name	Initial Thk. (mm)	Modified Thk. (mm)
1	Stud nut 1	50	40
2	Stud nut 2	50	40
3	Stud nut 3	50	40
4	Stud nut 4	50	40
5	Stud nut 5	50	40
6	Stud nut 6	50	40
7	Bolt plate and back plate	10	10
8	Lifting lug	40	40
9	Bolt and back stiffener	8	8
10	Main body	16	16

Table 6. Design Parameters

Sr.no.	Parameter	Initial	Modified	% Variation
1	Mass (kg.)	125.4	149	18.82
2	Volume (mm^3)	$1.587x10^7$	$1.886x10^7$	18.84
3	Stress (MPa)	256	152	-40.63
4	Displacement (mm)	2.86	1.22	-57.34

4.3.4. Results after optimization: At Rest

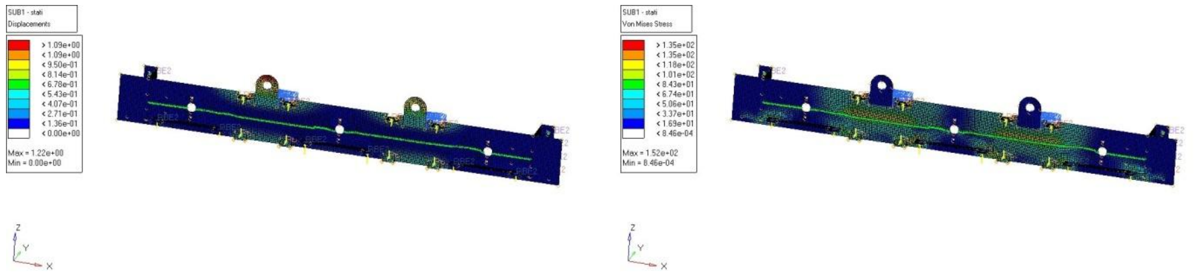

Figure 10. Top Frame – Displacement and Von Mises Stress after optimization (At Rest)

Displacement = 1.22mm
Von Mises Stress = 152Nmm^{-2}
Mass = 149kg

Table 7. Design Parameters

Sr.no.	Parameter	Initial	Modified	% Variation
1	Mass (kg.)	156.8	149	-6.89
2	Volume (mm^3)	1.985x10^7	1.886x10^7	-5.99
3	Stress (MPa)	148	152	2.7
4	Displacement (mm)	1.21	1.22	0.82

4.3.5. Results after optimization: While lifting condition

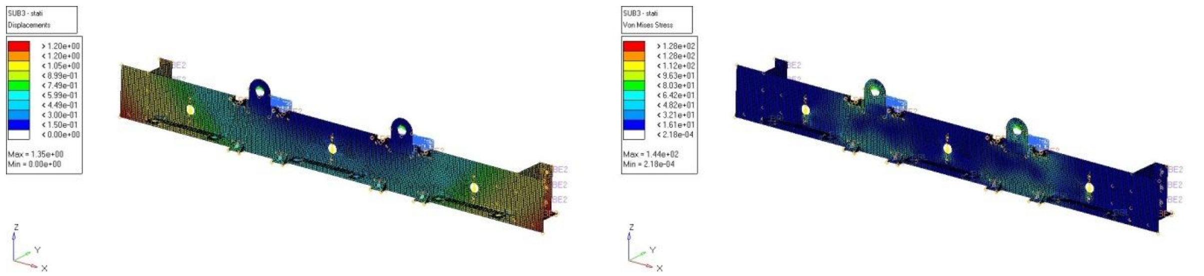

Figure 11. Top Frame – Displacement and Von Mises Stress after optimization (While Lifting)

Displacement = 1.35mm
Von Mises Stress = 144Nmm^{-2}
Mass = 149kg

Table 8. Design Parameters

Sr.no.	Parameter	Initial	Modified	% Variation
1	Mass (kg.)	156.8	149	-6.89
2	Volume (mm^3)	1.985x10^7	1.886x10^7	-5.99
3	Stress (MPa)	194	144	-26.9
4	Displacement (mm)	1.97	1.35	-31.47

V. BOTTOM FRAME – SIZE OPTIMIZATION

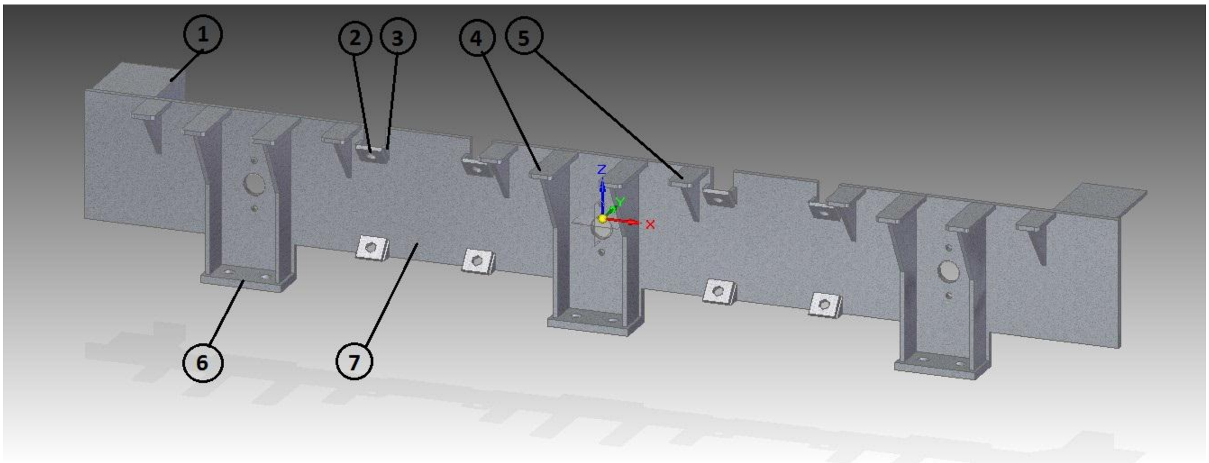

Figure 12. 3D Model of Bottom Frame

Figure 12 shows the 3D model of Bottom Frame prepared by SolidEdge ST4.
This model is then imported to HyperMesh 9.0 and converted to a surface model.Then the meshing is done in HyperMesh 9.0.
Same procedure done for optimizing the size of Bottom Frame as Top Fame and following results are obtained.

Table 9. Design Parameters

Sr.no.	Parameter	Initial	Modified	% Variation
1	Mass (kg.)	206	193.2	-6.21
2	Volume (mm^3)	$2.608x10^7$	$2.446x10^7$	-6.21
3	Stress (MPa)	144	127	-11.81
4	Displacement (mm)	0.721	0.733	1.66

VI. RESULTS AND CONCLUSION

The complete study of electrical aspects for the functionality of the core frame is done.Optimization in the weight of a core frame without affecting its function is carried outsuccessfully by the method of size optimization in HyperMesh 9.0. The initial weight of one half a top frame and bottom frame is 156.8kg and 206kg respectively. Which is reducedto 149kg and 193.2kg for top one half of top frame and bottom frame respectively. Thus the reduction of mass of one half of a top frame is 7.8kg and in one half of bottomframe is 12.8kg

VII. FUTURE SCOPE

In this problem of core frame optimization, various CAE based optimization techniquesi.e. shape optimization and topology optimization can be used to derive at furtheroptimised solution.

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