Analysis and Design Optimization of Composite Floor Panel of Mass Transit

Ravi Mallikarjun Teli[1], H.V Lakshminarayana[2], Vijayananda Kaup[3],
1Post Graduate Student, Department of Mechanical Engineering, Dayananda Sagar College of Engineering, Bangalore-560078, India.
2Professor, Department of Mechanical Engineering, Dayananda Sagar College of Engineering, Bangalore-560078, India.
3Professor, Department of Mechanical Engineering, Dayananda Sagar College of Engineering, Bangalore-560078, India.

Abstract— **Fiber reinforced polymer matrix composite materials in laminate configurations has found their applications in front-end bumper beams, under body shields, and other automotive applications. These materials also have potential usage in mass transit vehicles, such as buses. The goals of improved safety, reduced weight, and lower cost are very important to the transportation industry. The present study focuses on the finite element analysis and design optimization of a hat sine wave rib stiffened segment of the floor of a mass transit bus. The focus is on shape optimization of hat sine wave rib structure and composite optimization of hat sine rib stiffened composite floor panel. The software tools used are HyperMesh, Radioss, Optistruct and HyperView. Weight savings up to 30% were realized by optimization process.**

Keywords— Composite floor panel, hat sine wave rib stiffener, glass/polypropylene, shape optimization, composite optimization.

I. INTRODUCTION

Composite materials consisting of stiff and strong fibre (glass, carbon, Kevlar, etc.) reinforcing compatible matrices (polymers, metals, ceramics, etc.) in the form of laminates are engineered materials extensively used in the design and fabrication of automotive, aerospace structures and components. The use of composites in automotive front fenders, inner door panels, roofs, and trunk lids, as well as mass transit systems such as buses, has the potential to save weight compared to the current designs and materials. This weight reduction can lower emissions, enhance fuel economy and lower maintenance costs (tires and brakes) and therefore, contribute to the environmental and economic benefits of mass transit. However, these alternate materials may require significant changes in design and advancement in both materials and processes to meet the stringent safety requirements at a reasonable cost.

Thermoplastic composites typically comprise a commodity matrix such as polypropylene (PP), polyethylene (PE), or polyamide (PA) reinforced with glass, carbon, and/or aramid fibers. Progress in low cost in low-cost thermoplastic materials and fabrication technologies offer new solutions for very lightweight, low-cost composite structures with enhanced damage resistance and sustainable designs. This paper will describe the design and optimization of a woven glass reinforced polypropylene composite bus floor structure, which is one aspect of a larger effort focused on shape and composite optimization of hat sine wave rib stiffened composite floor panel for mass transit applications. Primary considerations for the flooring application were safety, weight savings to reduce fuel consumption, and cost savings to encourage usage in commercial applications.

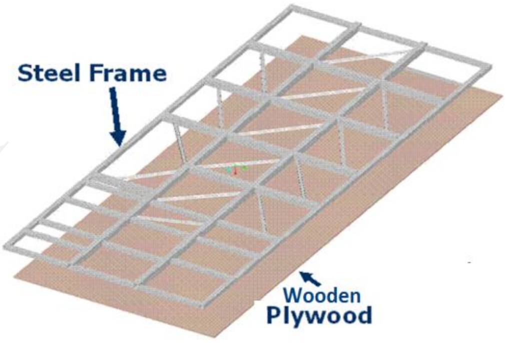


Fig. 1. Major Section of Conventional Floor.

Figure 1 describes the general layout of all steel frame members used on a major portion of the conventional floor along with the plywood floor. In conventional floor structure the whole wooden plywood is placed on the steel frame.

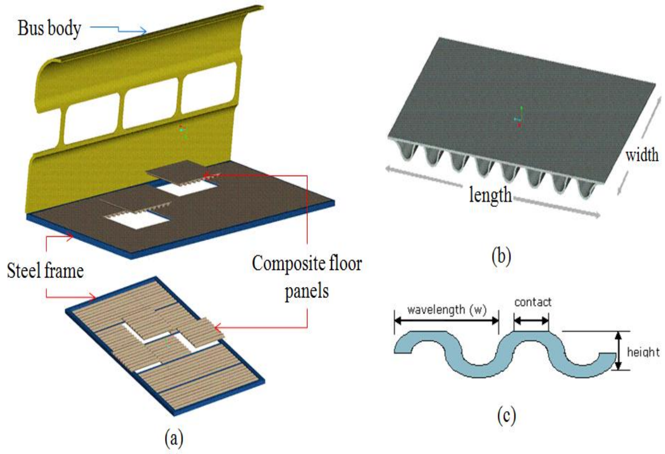


Fig. 2. Composite Unit Cells making up Floor Structure. (a) Proposed floor structure, (b) Composite floor unit cell, and (c) Hat sine wave rib structure.

Figure 2 describes the details of proposed floor structure. Here the whole floor structure is divided into number of unit cells (segments) and they are placed systematically on the steel frame. Each substructure was considered as a unit cell in the present study. Each unit cell has been designed in such a way that plate is stiffened with hat sine wave rib structure.

In recent years Ming Zhou, et.al have developed a comprehensive framework for composite optimization, leading the design from concept to ply-book details. The process consists of three optimization phases. Phase I focuses on generating ply layout concept through Free-Size optimization; Phase II further refines the number of plies for a given ply layup defined by Phase I; Finally, Phase III completes the final design details through Stacking sequence optimization satisfying all manufacturing and performance constraints.

II. LITERATURE REVIEW

The results of efforts made by Klaus F. Gleich and Thomas E. Jackson, Southern Research Institute under FTA (Federal Transit Administration) Project AL-26 7001-01 were directed to the fabrication woven prepreg thermoplastic composite bus flooring subcomponents with demonstration of several contributing technologies [1]. It was prepared for FTA, U.S. Department of Transportation, Washington DC 20590. The primary work was directed at the design, fabrication and testing of a composite bus floor subcomponent. The principal objectives associated with the bus floor project were safety, weight, and cost. The measurements on the mass transit bus floor structure were made at NABI in November 02, 2002. The floor was observed to mainly comprise steel under body frame and plywood flooring. In the study, each substructure was considered as a unit cell. The composite floor component that was designed meets the design requirement of APTA and the weight of the composite unit cell floor was 21.31kg, amounting to about 22% weight savings in comparison to the conventional floor.

Uday K. Vaidya, et. al. (2004), designed and manufactured the segment of the floor of a mass transit bus using glass/PP woven tape forms developed through a hot-melt impregnation process [2]. A combination of analysis software including Pro/Engineer, Hyper Mesh, and ANSYS 7.0 were used for the design and analysis. Weight savings up to 40% were realized using glass/PP woven tape thermoplastic composites as compared to the conventional metal/ plywood design. A concept floor segment was designed, analyzed, manufactured, and tested, complying with the APTA standards. The hat-sine stiffened ribs provide flexibility for routing of wires, embedding of sensors or foams in addition to providing a large surface area for the adhesive bonding as well as fasteners. The thermoplastic composite design was lighter than the steel/plywood counterpart, with projected weight saving of 41% for the entire midsection of the floor. In addition, the high cost of maintenance, corrosion, and deterioration issues encountered in the traditional steel/plywood design is eliminated while using a glass/PP thermoplastic composite. The study demonstrated a full-cycle design and the development of a mass transit floor segment using thermoplastic composite material forms. From a standpoint of the design for manufacture, the stiff thermoplastic glass PP woven tape materials can be effectively used to produce structural components with flat geometry and gradual radii/curvatures.

Thermoplastic Composite Bridge Superstructures was designed by Dr. Nasim Uddin and Abdul Moeed Abro and Dr. Uday Vaidya (2007) [3]. The design concept was presented by utilizing high performance thermoplastic material (i.e. Glass/Polypropylene) along with an efficient low cost manufacturing process and fabrication technique. The design was based on detailed finite element analyses and limited experiments to investigate the stiffness and strength of the structural system. To demonstrate the design concept, two bridge deck systems with different spans were modeled and compared with two current thermoset composite bridge systems. The proposed design concepts for both decks present a unique approach for structurally efficient and low cost bridge deck systems. In all deck design cases, the stiffness was the main governing factor controlling the design. Once the stiffness requirement had been satisfied, the strength of the structure proved to be sufficient. Thus an efficient deck shape should be designed around stiffness criteria and not on strength. In both deck systems (single lane and double lane) a single outer shell (top flat face) with sine ribs provided the most efficient and economical section. Design was compared with two published composite bridge concepts proposed by Dumaloa et al. (1996) and Aref (2000). Although the design has a higher self weight which results in a higher dead to live load ratio than the alternative designs, design could result in a better low cost deck section based on the manufacturing and material cost comparisons. E-Glass/PP is much less expensive than S-glass and the manufacturing process associated with it yields cost effective results under higher production rates. Thus the actual comparison between bridge deck designs should be based on the construction cost of the bridge deck systems.

Anton Olason, Daniel Tidman (2010), investigated how and when structural optimization should be applied in the design process [4]. The tools used are HyperMesh, Optistruct and HyperView which are parts of the software suite HyperWorks from Altair Engineering. The trial cases have been performed as limited design projects where structures were improved or designed by using different types of optimization. The most common objective has been to reduce mass with mechanical properties as a constraint. This has been used to develop a sensible methodology together with guidelines for practical matters such as parameter values and recommended options. It has been found that there are essentially two stages of the design process where structural optimization can be applied.

Ming Zhou, Raphael Fleury, and Martin Kemp (2011), provided an overview of a comprehensive process for the design optimization of composite structures [5]. They showed that optimization technology is well suited to exploit the potential composite materials offer. Free-size optimization for composites allows a true concept level design synthesis of plies. A new PLY and STACK based modeling technique that simplifies the laminate representation and facilitates the ply bundle sizing optimization followed by the ply stacking optimization make the process unique. An aircraft wing case study was shown to demonstrate the optimization process. Then a detailed description of the application within a real world aircraft design environment at Bombardier Aerospace was given. It is particularly notable that customer specific design constraints on panel strength and manufacturing straints stability are incorporated through external responses.

III. PROBLEM STATEMENT

Figure 3 displays a laminated composite floor stiffened panel. The 1079.5mm × 762mm rectangular plate with thickness 6.35mm consist of 6 layers which are stacked in a sequence of [0°/45°/90°/-90°/-45°/0°]. Each ply is glass fiber reinforced polypropylene resin matrix composite. The hat sine wave rib stiffener of wave length 127mm and height 63.5mm is also fabricated using same material and ply orientation and are co-cured. Stiffener is having 38.1mm of contact length.

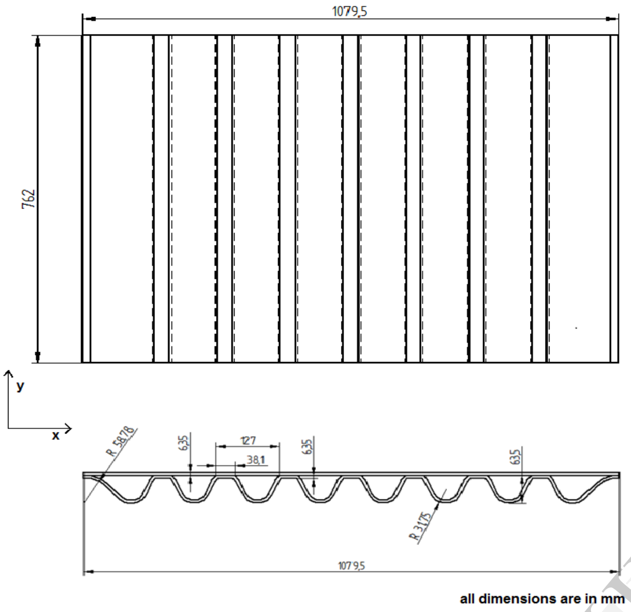


Fig. 3. Geometric details of hat stiffened composite floor segment.

Since the floor segments are simply rest on steel frame like tiles, the support conditions are identified in Figure 4. The above plate surface of the floor segment is subjected to uniformly distributed pressure.

The main objective of the project is to perform static analysis of the composite floor panel with the said boundary condition to obtain stress and displacement contours. Then optimization is done to reduce the weight of the floor panel. Optimization is carried out in two steps: (i) shape optimization is carried out to get optimized shape of the stiffener under given loading and boundary conditions, and (ii) composite optimization is done to get optimal thickness of each ply and optimal stacking sequence of the floor panel. The finite element method in general and commercial FEA software implemented on a desktop computer in particular offers a unified approach.

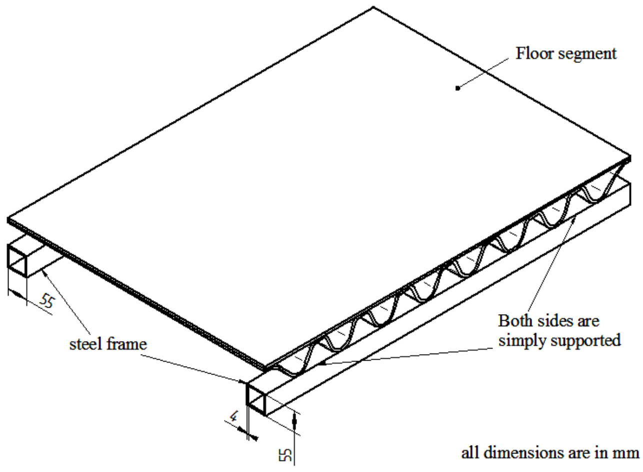


Fig. 5. Floor panel with support conditions.

IV. MATERIAL PROPERIES

The material properties of the glass fiber reinforced polypropylene used for stiffened panel is as shown in the Table 1.

TABLE I. MATERIAL PROPERTIES

Material	Glass/PP Laminate
Young's modulus in longitudinal direction, E_1	23GPa
Young's modulus in Transverse direction, E_2	23GPa
Poisson's ratio, υ_{12}	0.11
In-plane shear modulus, G_{12}	1.807GPa
Transverse shear modulus for shear in 1-Z plane, G_1,Z	0.75GPa
Transverse shear modulus for shear in 2-Z plane, G_2,Z	0.75GPa
Mass density, RHO	1.768×10^{-6} kg/m^3
Longitudinal tensile strength, X_t	0.45GPa
Longitudinal compressive strength, X_c	0.25GPa
Transverse tensile strength, Y_t	0.45GPa
Transverse compressive strength, Y_c	0.25GPa
Shear strength, S_c	0.032GPa

V. OBJECTIVES

The overall aim is Finite Element Modeling for static analysis and optimization of hat sine wave rib stiffened composite floor panel. Finite Element Modeling is defined here as the analysts' choice of material models, finite elements, meshes, constraint equations, analysis procedures, governing matrix equations and their solution methods, specific pre- and post-processing options available in chosen commercial Finite Element Analysis software for static analysis and optimization of hat sine wave rib stiffened composite floor panel. The Finite Element Model is developed using HyperMesh, Radioss, Optistruct and HyperView which are parts of the software suite HyperWorks 11.0 from Altair Engineering.

The following are the specific objectives:

- Geometric modeling of composite floor panel.
- Finite element (FE) modeling and static analysis of glass fiber reinforced polypropylene composite floor panel subjected to uniformly distributed pressure load.
- Shape optimization of the hat sine wave rib stiffener to get optimal shape.
- Composite optimization of the hat wave rib stiffened panel to get optimal thickness of each ply and optimal shuffling sequence.

VI. METHOD AND METHODOLOGY

The finite element method is a numerical analysis technique used by engineers, scientists and mathematicians to obtain solutions to the differential equations that describes or approximately describes a wide variety of physical (and non-physical) problems. Physical problems range in diversity from solid, fluid and solid mechanics, to electromagnetism or dynamics. Hence FEA is being considered a part of the design process spanning across industries or domains, be it automotive, aerospace, medical, civil and electrical etc.

Finite Element Method (FEM) in general and commercial Finite Element Analysis (FEA) software in particular implemented on a desktop computer offers a universal procedure for engineering analysis. In the following sections linear finite elements for continua and structures specifically formulated for static analysis and optimization, an overview of linear finite element analysis software and the specific capability of HyperWorks 11.0 used in the present study are presented.

VII. STATIC ANALYSIS

The present study is aimed at determining the displacement and stress contours of hat sine wave rib stiffened composite floor panel shown in Figure 3. The geometric modeling of the hat sine wave rib stiffened composite floor panel is done in Solid Edge v19 with thickness 6.35 mm and plate of 1079.5 × 762mm size. Model is meshed suitably using 4-noded quadrilateral shell elements in HYPERMESH as shown in the Figure 5. The contact region between the face panel and the hat-sine-stiffened ribs was developed the merging the common nodes.

Meshing Details

- Number of elements – 5624
- Number of nodes – 5226

Both the stiffener and plate of thickness 6.35mm consists of 6 layers which are stacked in sequence of [$0^o/45^o/90^o/-90^o/-45^o/0^o$]. Each ply thickness is 1.0583mm. Figure 6 shows the composite layers with different color indicating different orientation.

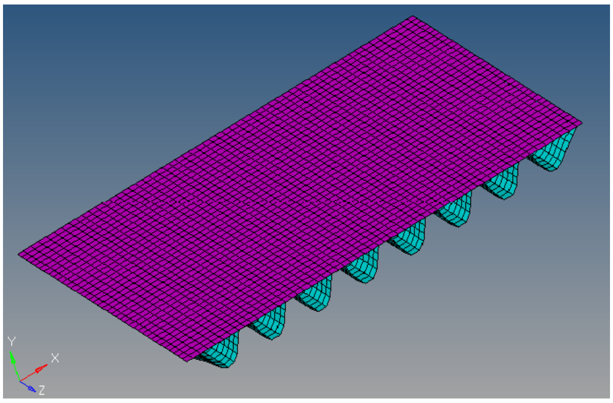


Fig. 5. Discretized model of hat sine rib stiffened panel.

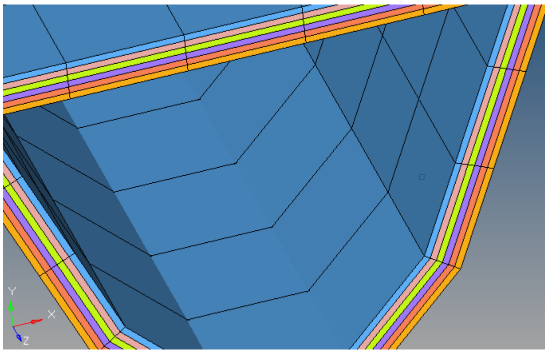


Fig. 6. Composite layers with different color indicating different orientation.

The floor structure is subjected to static / pressure loads, out of plane bending loads and in-plane compression loads. By considering the occurrence of dominant front shear and vertical bending modes during dynamic loading of a bus structure, we estimated that the applied load varies from a upper limit of 17.2kPa to a lower limit of 4.86kPa. The upper limit of this range accounts for the maximum total weight of the vehicle, the weight at which the bus can be safely and reliably operated is about 13636kg, while 17.2kPa accounts for loads including dynamic effects (such as vibration, out-of-plane bending and shear). The lower limit takes into account the 2.5 times the gross load (weight due to people) to which the unit cell will be subjected.

Figure 7 provide the results contours of the displacement and Figure 8 provides the results contours of stresses. The composite floor panel subjected to 17.2kPa gives 4.959mm deflection and maximum composite stress is 88.82 MPa. From Figure 9, the initial mass of the composite floor panel after static analysis is 23.6684 kg.

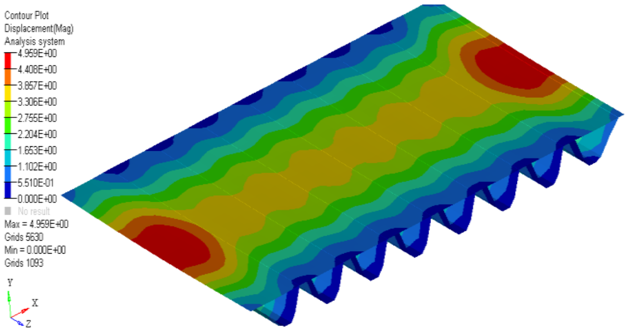


Fig 7. Contours of the displacement

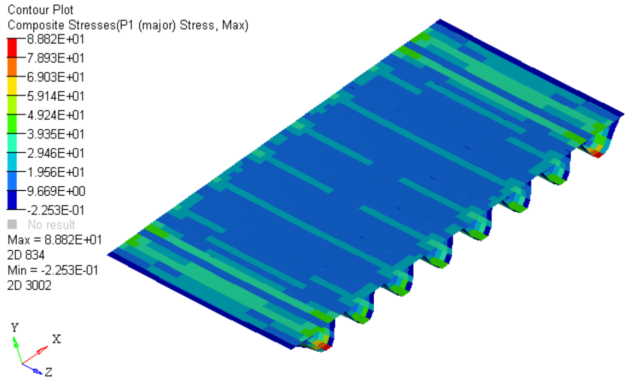
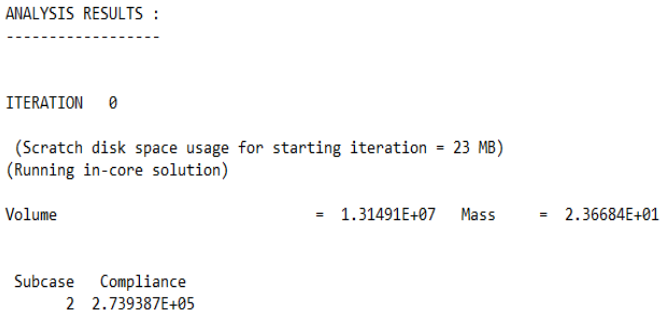


Fig 8. Contours of the composite stresses



```
ANALYSIS RESULTS :
------------------


ITERATION    0

 (Scratch disk space usage for starting iteration = 23 MB)
(Running in-core solution)

Volume                          =  1.31491E+07    Mass     =  2.36684E+01


 Subcase    Compliance
       2  2.739387E+05
```

Fig 9. Static analysis results file.

VIII. STUCTURAL OPTIMIZATION

Optimization is done mainly to reduce the weight of the composite floor panel. Results of shape optimization of hat sine rib structure and three phases of composite optimization of composite floor panel of mass transit are discussed in this chapter.

a) Shape optimization

The main objective of the shape optimization is to minimize mass and to get optimal shape of the hat sine wave rib structure such that stresses induced should not exceed the maximum stress values. Here the only one wave structure of the whole stiffener is considered for shape optimization. The shape optimization is done for same wave length, contact and height of the hat sine wave rib structure. Geometric details of the hat sine wave structure with plate are shown in Figure 3.

Shapes are created by using domains and handles, which are provided by a module in HyperMesh called Hypermorph. Domain is a grouping of elements and nodes that are influenced together during morphing. Handle is control point used to alter the shape of a domain. In Figure 10 yellow spheres are known as handles and red line showing between the mesh lines are known as domains.

Figure 11 and 12 shows two created different shapes. When a shape has been defined with Hypermorph a design variable is easily created from the shape, together with bounds on maximum or minimum magnitude of the shape change.

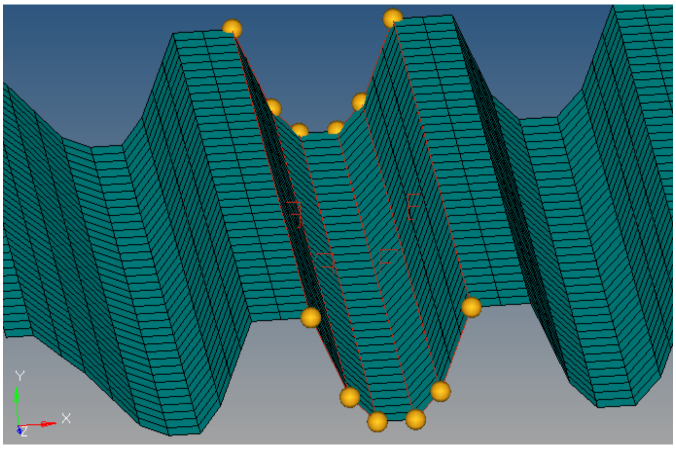


Fig.10. Domains and handles on single sine wave rib structure.

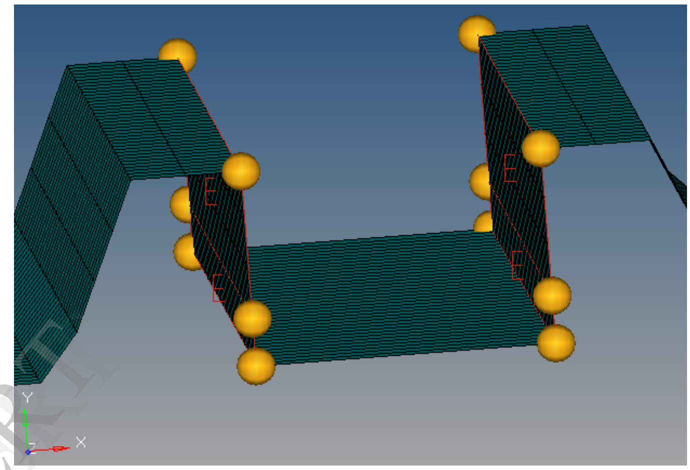


Fig. 11. Rectangular shape created by using domains and handles.

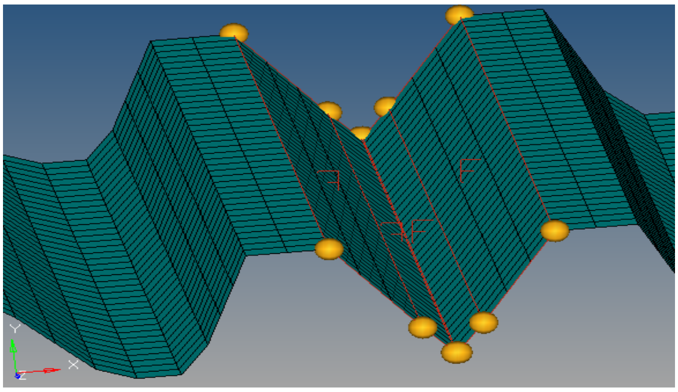


Fig 12. V shape created by using domains and handles.

A response is a numerical measure of some aspect on the design variables or an analysis on the model. The response can then be used either as an objective function or as a constraint. The responses that are used in paper are mass and composite stress. Since our main objective is to reduce weight of the composite floor panel, the MASS response is selected as objective function and COMPOSITE STRESS response is selected as constrain function. The upper bound value for constrain is taken as maximum P1 major composite stress i.e. 88.82 MPa as shown in the Figure 9.

This section describes the results in HyperView. For the single sine wave rib structure, the optimized shape is as shown in the Figure 13. The red color indicates large shape change.

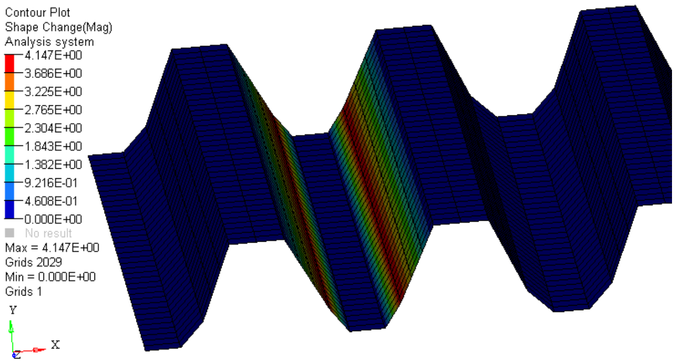


Fig 13. Contour plot of the shape change.

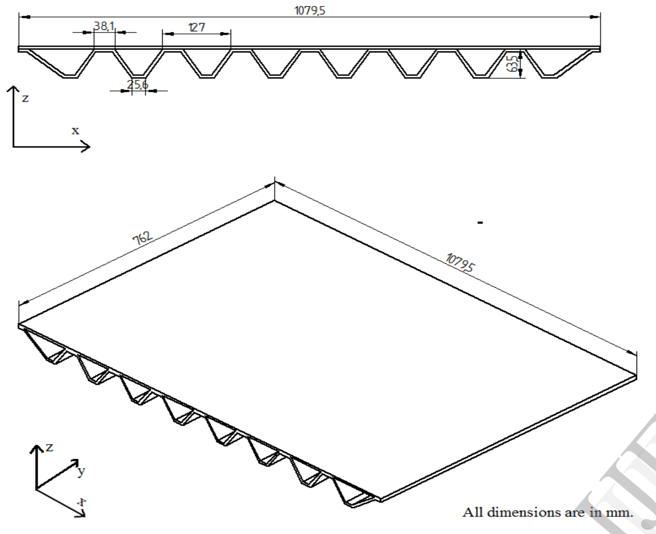


Fig 14. Geometric details of shape optimized composite floor panel

Once shape optimization is done, the whole hat sine rib structure is remodeled and is as shown in the Figure 14. Now again the optimized component is subjected to static analysis with same material, composite ply stacking details, loading and boundary conditions as explained in previous section.

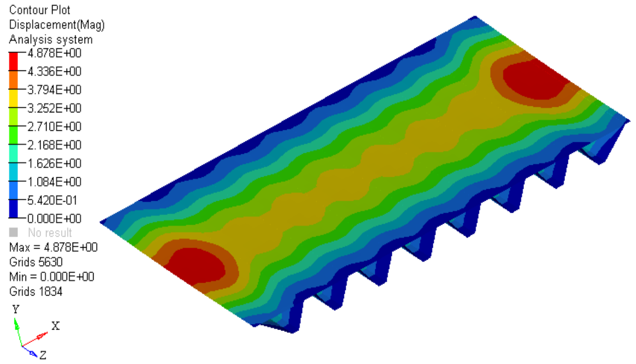


Fig. 15. Contours of the displacement

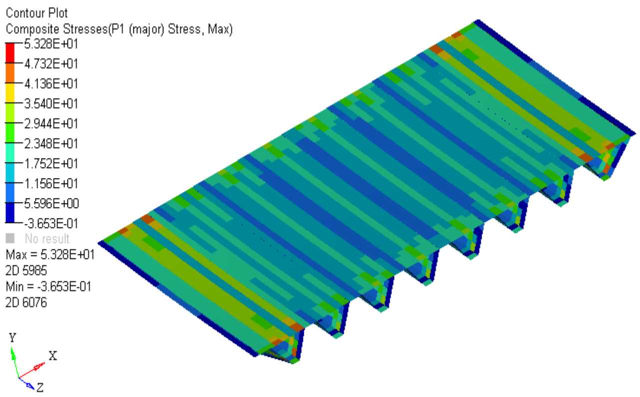
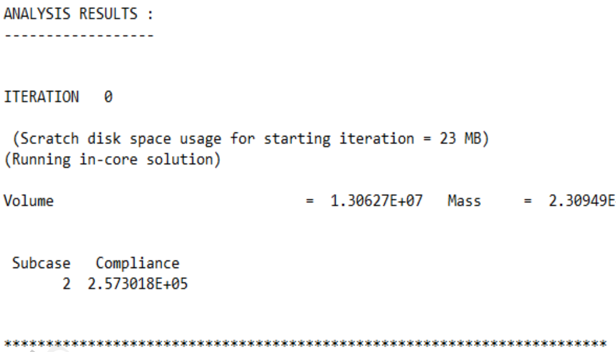


Fig. 16. Contours of the composite stresses



```
ANALYSIS RESULTS :
------------------


ITERATION    0

 (Scratch disk space usage for starting iteration = 23 MB)
(Running in-core solution)

Volume                         =  1.30627E+07   Mass     =  2.30949E+01


 Subcase    Compliance
       2  2.573018E+05


***************************************************************************
```

Fig. 17. Results file of shape optimization

Figure 15 provide the results contours of the displacement and Figure 16 provides the results contours of stresses. The shape optimized composite floor panel subjected to 17.2kPa gives 4.959mm deflection and maximum composite stress is 53.28 MPa. From Figure 17, the mass of the shape optimized composite floor panel is 23.949kg.

b) Composite optimization

There are comprehensive optimization opportunities in Optistruct to achieve improvements on composite models. In general, one have the possibilities to make a free-size optimization, a size-optimization or a ply stacking optimization independent of each other.

Phase I - Free-Size Optimization

Free-sizing optimization is used to generate design concepts, while considering global responses and optional manufacturing constraints.

To avoid very filigree optimization results the minimum member size control is activated with the value 60mm. This induces the optimizer to leave at least three rows of elements (with the present element's edge length of the value 20mm) along the load paths. The total laminate thickness constrained by maximum and minimum thickness values as 1.05833mm and 6.35 mm respectively.

Balancing 45° and -45° plies would eliminate twisting of a plate under bending along the 0 axis. The responses that are used in paper are mass and weighted compliance. Since our main objective is to reduce weight of the composite floor panel, the weighted compliance response is selected as objective function and MASS response is selected as constrain function. The upper bound value for constrain is given as 18kg.

The thickness variation of each ply with a particular fiber orientation for every element, the total laminate thickness can change ‘continuously’ throughout the structure, and at the same time, the optimal composition of the composite laminate at every point (element) is achieved simultaneously. Since the mass constrain is kept 18kg, the compliance of load step and thickness of each ply orientation, total thickness are optimized to the same value.

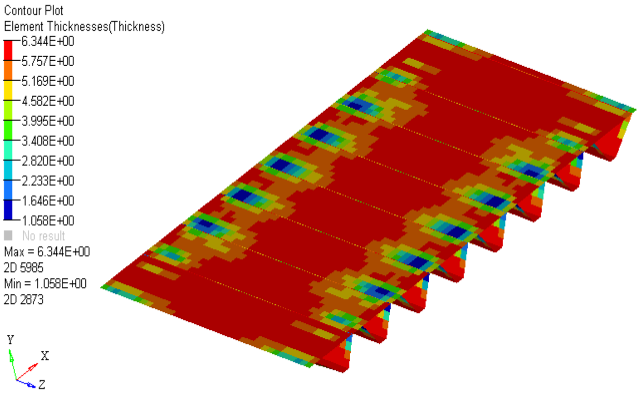


Fig. 18. Thickness distribution of total laminate thickness.

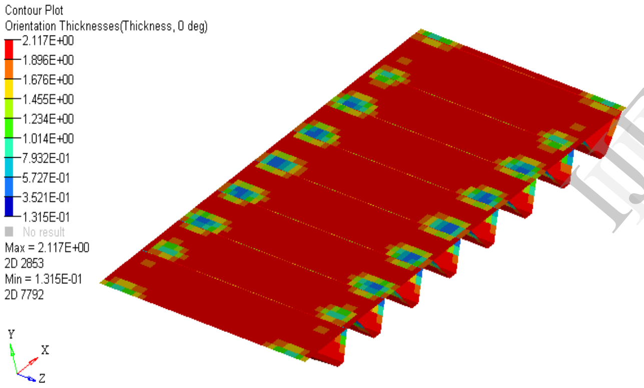


Fig. 19. Thickness distribution of 0^o plies orientation

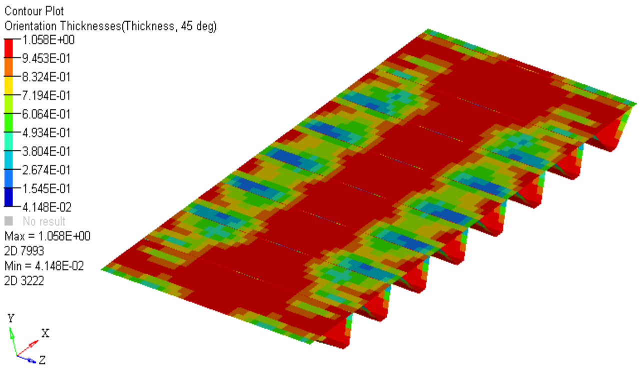


Fig. 20. Thickness distribution of 45^o ply orientation.

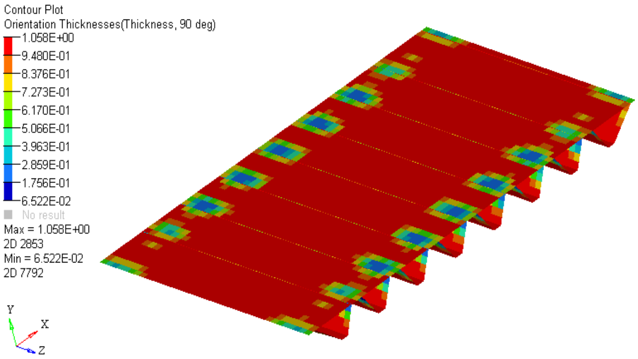
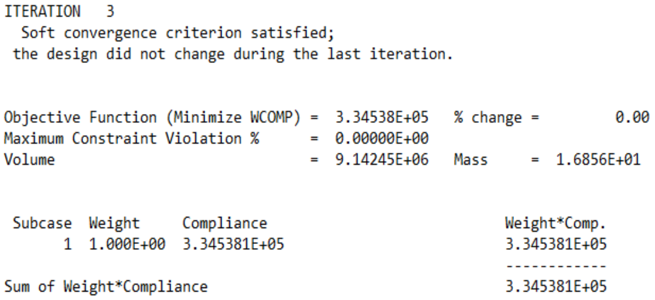


Fig. 21. Thickness distribution of 90^o ply orientation.



```
ITERATION    3
  Soft convergence criterion satisfied;
 the design did not change during the last iteration.


Objective Function (Minimize WCOMP) =  3.34538E+05   % change =         0.00
Maximum Constraint Violation %      =  0.00000E+00
Volume                              =  9.14245E+06   Mass     =  1.6856E+01


 Subcase  Weight     Compliance                                Weight*Comp.
       1  1.000E+00  3.345381E+05                              3.345381E+05
                                                               ------------
Sum of Weight*Compliance                                       3.345381E+05
```

Fig. 22. Output file of free size optimization.

Figure 18 shows the thickness distribution of total laminate thickness of the composite floor panel. Thickness distribution of 0^o, -45^o, -90^o ply orientations will be same as the thickness distribution of 0^o, 45^o, 90^o ply orientations as shown in figure 19 to 21. Mass of the composite floor panel for the last iteration of the solution is as shown in Figure 22.

Phase II - Size optimization

The second phase of the optimization-cycle tracks two goals. On the one hand manufacturing constraints shall be considered; on the other hand in this phase the optimizer shall aim at discrete, manufacturable ply thicknesses.

The newly created design variables for all plies should be edited as preparation for the discrete optimization step by changing the design upper bounds to each with a later manufacturable value of 0.25. Editing the plies happens individually, that means that for every orientation the shapes 2 till 4 are edited because shape 1 includes all previous elements. This is done because, elements of the shapes generated for each ply orientation will not in proper alignment so that it can be manufactured. Hence for every orientation the shapes 2 to 4 are edited in such a way that it can be manufactured easily.

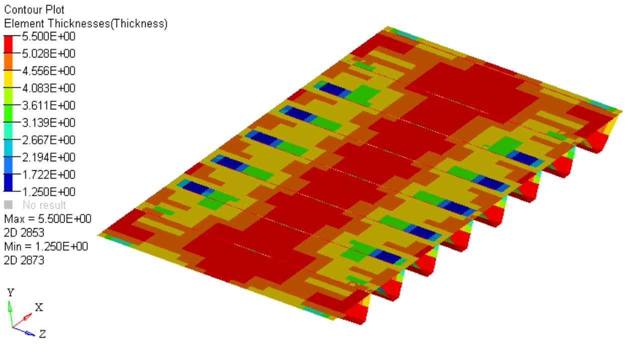


Fig. 23. Thickness distribution of total laminate thickness.

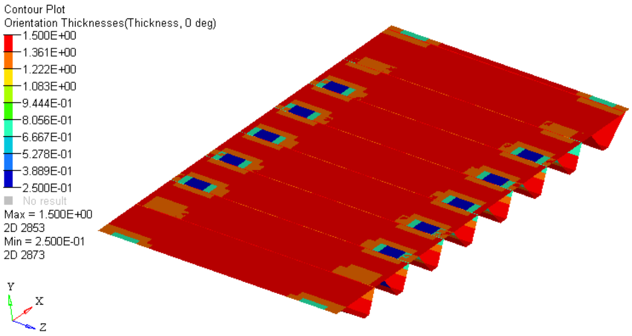


Fig. 24. Thickness distribution of 0^{o} ply orientation.

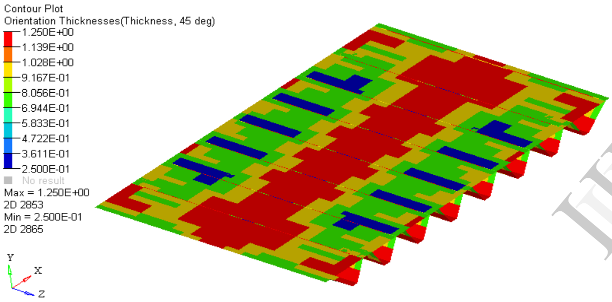


Fig. 25. Thickness distribution of 45^{o} ply orientation.

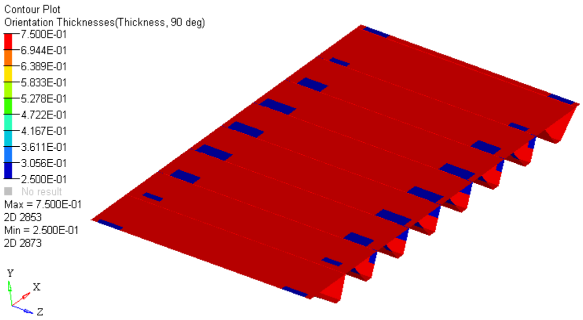
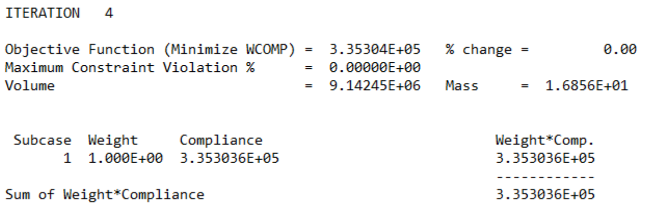


Fig. 26. Thickness distribution of 90^{o} ply orientation.



```
ITERATION   4

Objective Function (Minimize WCOMP) =  3.35304E+05   % change =        0.00
Maximum Constraint Violation %      =  0.00000E+00
Volume                              =  9.14245E+06   Mass     =  1.6856E+01


 Subcase  Weight     Compliance                              Weight*Comp.
       1  1.000E+00  3.353036E+05                            3.353036E+05
                                                             ------------
Sum of Weight*Compliance                                     3.353036E+05
```

Fig. 27. Output file of size optimization.

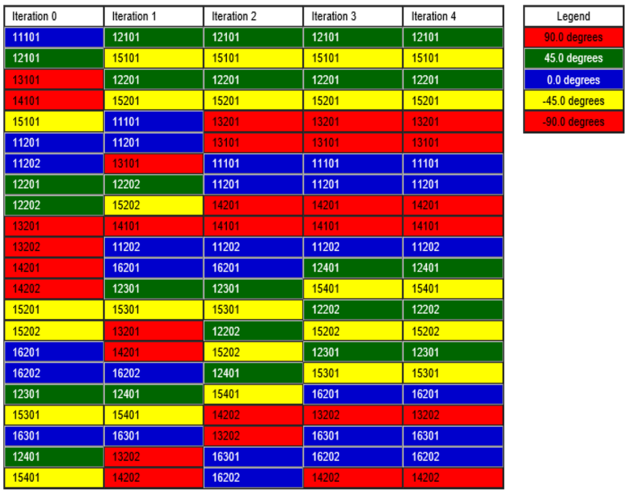
At every point of time during the optimization-cycle the responses can be changed or further responses can be added. Exemplarily now in the sizing step the element stresses shall be added as responses. A new stress-response shall be defined as design constraint with subsequent upper and lower bounds values as -88.82 and 88.82 MPa.

Figure 23 shows the optimized thickness of total laminate thickness of the composite floor panel and is 5.5 mm. Thickness of 0^{o}, -45^{o}, -90^{o} ply orientations will be same as the thickness distribution of 0^{o}, 45^{o}, 90^{o} ply orientations and are 1.5 mm, 1.25, and 0.75 respectively, as shown in Figure 24 to 26. Mass of the composite floor panel for the last iteration of the solution is 16.856 Kg as shown in Figure 27.

Phase III - Ply bundle stacking optimization

This is last optimization phase and is of peculiar interest, because now we order the pre-optimized ply bundles in a new way. The design variable is updated with new name that defines parameters for the generation of composite shuffling design variables.

Exemplarily a pairing of the 45° and the -45° orientations shall be carried out with the same presetting. The MAXSUCC parameter is used as constraint that indicates the stacking sequence should contain no sections with more than a given number of successive plies with the same orientation. With MAXSUCC for the orientations 0°, 45° 90°, -90°, -45° and 0°, it is defined that maximum two of these plies are allowed to follow on each other. COVER constraints specify stacking sequences for the cover layers. With COVER, it is defined that the cover layer shall get 45° and -45° orientations.

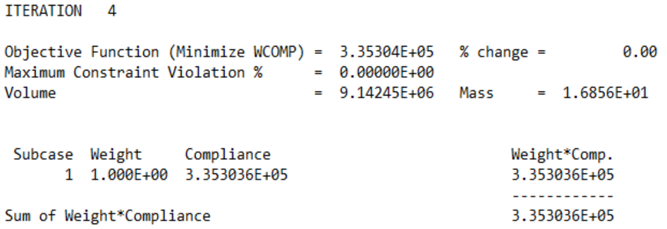


Iteration 0	Iteration 1	Iteration 2	Iteration 3	Iteration 4
11101	12101	12101	12101	12101
12101	15101	15101	15101	15101
13101	12201	12201	12201	12201
14101	15201	15201	15201	15201
15101	11101	13201	13201	13201
11201	11201	13101	13101	13101
11202	13101	11101	11101	11101
12201	12202	11201	11201	11201
12202	15202	14201	14201	14201
13201	14101	14101	14101	14101
13202	11202	11202	11202	11202
14201	16201	16201	12401	12401
14202	12301	12301	15401	15401
15201	15301	15301	12202	12202
15202	13201	12202	15202	15202
16201	14201	15202	12301	12301
16202	16202	12401	15301	15301
12301	12401	15401	16201	16201
15301	15401	14202	13202	13202
16301	16301	13202	16301	16301
12401	13202	16301	16202	16202
15401	14202	16202	14202	14202

Legend
90.0 degrees
45.0 degrees
0.0 degrees
-45.0 degrees
-90.0 degrees

Fig. 28. Shuffle-optimization results.

The optimized stacking sequence given by solver is [$90^o/45^o/0^o/-45^o/-90^o$] as shown in the shuffle optimization result in Figure 28. The reduced mass that is obtained by optimization is 16.856 Kg and is as shown in the Figure 29. Figure 32 shows the plot of mass in Kg vs stages of the optimization. Total mass reduction by all the stages of optimization is about 30%. Figure 30 and 31 shows the displacement and stress contours of composite optimized floor panel and are 6.435 mm and 72.22 MPa respectively.



```
ITERATION    4

Objective Function (Minimize WCOMP) =  3.35304E+05   % change =        0.00
Maximum Constraint Violation %      =  0.00000E+00
Volume                              =  9.14245E+06   Mass     =  1.6856E+01


 Subcase  Weight     Compliance                              Weight*Comp.
       1  1.000E+00  3.353036E+05                            3.353036E+05
                                                             ------------
Sum of Weight*Compliance                                     3.353036E+05
```

Fig. 29. Output file of shuffle optimization.

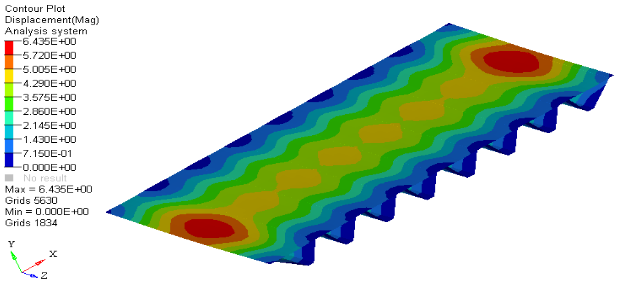


Fig. 30. Displacement contour of composite optimized floor panel

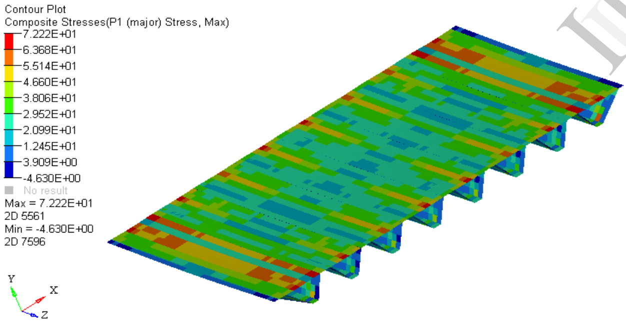


Fig. 31. Stress contour of composite optimized floor panel

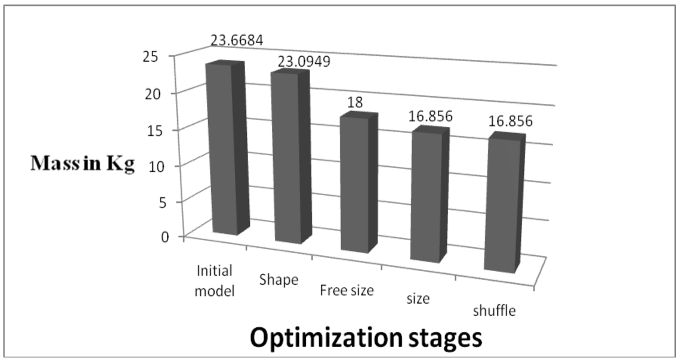


Fig. 32. Plot of mass in kg vs optimization stages

IX. CONCLUSION

Finite Element method (FEM) in general and Altair HyperWorks modules in particular implemented on desktop computers is demonstrated in this study for analysis and design optimization of composite floor panel of mass transit.

The procedure of shape optimization of the hat sine wave rib structure resulted in an optimized shape with slight reduction of weight and at the same time stiffness, strength, and durability requirements are fulfilled.

A unique and comprehensive three phase composite laminate optimization process was implemented for the design and optimization of hat sine wave rib stiffened composite panel resulting in a design with up to 30% of weight reduction.

REFERENCES

[1] Klaus F. Gleich and Thomas E. Jackson, "Center For Composites Manufacturing," Southern Research Institute, Birmingham, FTA-AL-26-7001-01, 2003.

[2] Uday K. Vaidya, Francis Samalot, Selvum Pillay et al., "Design and Manufacture of Woven Reinforced Glass/Polypropylene Composites for Mass Transit Floor Structure," Journal of Composite Materials - J COMPOS MATER 01/2004; 38(21):1949-1971. DOI:10.1177/0021998304048418.

[3] Dr. Nasim Uddin, Abdul Moeed Abro and Dr. Uday Vaidya,"Design and Analysis of Thermoplastic Composite Bridge Superstructures," University Transportation Center for Alabama, University of Alabama, UTCA Report 05228, January 2007.

[4] Anton Olason and Daniel Tidman, "Methodology for Topology and Shape Optimization in the Design Process," Department of Applied Mechanics, Chalmers University Of Technology, ISSN 1652-8557 Sweden, 2010.

[5] Ming Zhou, Raphael Fleury and Warren Dias, "Composite Design Optimization œ from Concept to Ply-Book Details," 8th World Congress on Structural and Multidisciplinary Optimization, California, USA, 2009.

[6] Altair Hyperworks Version 11.0, Users manual. Altair Engineering, Inc., 2011.