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Optimization of Laminated Composite Z-Section Beam

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ABSTRACT
The abstract should summarize the content of the paper. Composites are the relatively new but fast growing field where the researchers are paying their lots of attention. Ever growing market needs always better material and product which is lighter in weight but more strengthen in nature. To justify the current needs this project pays some attention to increase the performance of the composite product by means of some modern optimization techniques. The benefit of material properties and flexibility of selecting material have made composite materials a key preference for structural application. Dissimilar to isotropic materials, the parametric study of laminated composite beams for optimized design is complex due to more number of parameters concerned in designing like lay-up sequence, and layer configuration. Furthermore, the restrictions of FEA methods in designing have created a requirement for an optimum solution for analysis of laminated composite beams structure. The goal of this study focuses on the optimization of composite Z-beam for lowest deflection by a static analysis. Composite materials are extensively being used in aircraft, robotic and automotive industries where the parts are subjected to various loading situations. There is a requirement for the precise prediction of for their static response uniqueness so that they can be designed against the failure because of different types of possible static loads. Here the parameterization of composite is done and then through various parameters like number of ply, ply thickness and ply location etc. the optimization has been done to reduce the weight and other performance criteria's for Z-beam (thin walled composite plate).
Keywords - Composite, weight Optimization, static analysis, leaf spring design, FEA

I. INTRODUCTION

Materials are the essential elements of the entire natural and artificial structures. We can say that, these materialize the structural idea. Technological development is connected with incessant development of existing material properties in addition to the growth of structural material classes and types. Usually, novel materials come out due to the requirement to advance structural effectiveness and performance. Additionally, novel materials themselves as a statute, in turn offer novel chance to expand efficient structures and technology, whereas the concluding confront materials science with novel trouble and tasks. One of the finest expressions of this interconnected method in the growth of materials, technology and structures is connected with the composite materials.

Highly developed composite materials are considered for high definite strength and stiffness and, in permutation with automated manufacturing methods, make it feasible to manufacture composite components with high levels of weight and cost efficiency. The substitute of metal alloys with composite, usually, overcomes the structure's mass by 20–30% [11]. On the other hand, in some unusual cases, the number of which increasingly rises, the permutation of material directional properties with design idea employs these properties, being maintained by the compensation of modern composite expertise, gives a key enhancement in the structural performance. Such competence is established by composite structures of consistent strength in which the load is engaged by uniformly stressed fibers.

Composite materials are greatly used by numerous industrial fields like formula one car, civil or aircraft design. Their attractiveness is due to their outstanding mechanical properties in addition to their accessible freedom to adapt material properties. The majority of practical laminate designs need combinatorial optimizations since the ply orientations are typically constrained to small group of discrete values. Instead of this discretization, composite optimizations frequently have several solutions with comparable efficiency. These types of exertion are one of the most multifaceted and costly to solve. Furthermore, its huge number of design variables contributes to have several local optima. This optimization method is also complex with the accumulation of several structural constraints. In order to ensure various constraints (i.e. maximum strain values), a finite element simulation is typically executed. This simulation is extremely time-consuming and hence its number of executions should be condensed to a minimum.

The objective of this study focuses on the optimization of composite Z-beam for lowest weight by a constraint deformation. Composites are *extensively being used in robotic, aircraft, and automotive industries where the parts are subjected to diverse loading and boundary conditions. There is a requirement for the precise prediction of for their static response characteristics so that they can be designed against the failure due to various types of possible static loads. Here the parameterization of composite is done and then through various parameters like number of ply, ply thickness and ply location etc. the optimization has been done to reduce the weight and other performance criteria's for Z-beam (open section thin walled composite plate).*

II. ASSUMPTIONS

In developing our robust optimization approach, we make the following assumptions:

- The layers are perfectly bonded.
- The each layer material is linearly elastic and has two planes of material symmetry.
- Design variables and/or parameters in optimization problems can be mixed integer.

III. CONCEPTION DESIGN SYNTHESIS WITH FREE-SIZE OPTIMIZATION

The problem of optimization can be revealed mathematically like this:

Minimize $f(\boldsymbol{x})$

Subject to $g_j(x) - g_j^U \leq 0$, j= 1,........., M

$x_{ik}^L \leq x_{ik} \leq x_{ik}^U$, i = 1,........, NE (1)

Where $f(\boldsymbol{x})$ shows the objective parameter, $g_j(x)$ and g_j^U shows the j-th restraint parameter and its upper limit, correspondingly. M is the entire amount of constraints, NE the amount of elements and Np the amount of super-plies; x_{ik} is the thickness of the i-th super-ply of the k-th element. Through this design stage, responses of global behaviour are measured mutually for objective and constraints. Usually, observance or main displacement responses are used to originate the design problem so that the complete structural stiffness is optimized.

Manufacturing constraints are significant for design of composite and requires to be tackle right from the start of the concept design stage. One significant constraint is that the amount of successive plies of the similar orientation should be restricted to avoid manufacturing failure through the curing method (usual restriction is 3 to 4 successive plies). Through the concept design stage constraining the fraction of all fiber orientation in the complete thickness can make sure that substitute ply orientations are accessible for breaking successive lay-up of a distinct orientation. An extra general design condition is to restrain the entire thickness of the composite laminate. These two kinds of manufacturing constraints can be signifying accurately as follows:

Total thickness:

$T_k^L \leq \sum_{i=1}^{Np} x_{ik} \leq T_k^U$ k = 1,.............., NE

Ply percentage:

$P_j^L \leq \frac{x_{jk}}{\sum_{i=1}^{Np} x_{ik}} \leq P_j^U$ j = 1,..............., NE (2)

The problem in (1) shows the alleged free-size derivation where the thickness of each super-ply is allowed to vary continuously. Though free-size is the ideal natural derivation for composite, Zhou et al. [17] proposed that topology optimization targeting 0/1 thickness allotment can be attained by just concerning a power law penalization of the normalized super-ply thickness.

$x_{ik} = (x_{ik} / x_{ik}^U)^P x_{ik}^U$

Where p is the penalization factor, usually p gets value among 2 and 4. Extra design constraint measured contains assessment of the thickness of two fiber orientations. Such as, for a plate in bending, balancing -45 and +45 orientations assists to reduce twist deformation of the Z-section plate.

IV. PROBLEM FORMULATION

The laminate consists of plies having the same thickness. The objective is to find the optimum design of the laminate to attain the minimum possible laminate thickness with the condition that it does not fail.

Minimization of mass (or Minimize t)

Where t is the thickness of the laminate, m is the number of distinct fiber orientation angles given. The orientation angles, θ_k, and how much plies, n_k, are oriented along each angle are to be estimated in the design procedure. Therefore, the number of design variables is $2m$. The laminate thickness can be shown as

$t = 2\, t_o \sum_{k=1}^{m} n_k$

Where t_o is the thickness of an individual ply and n_k is the number of plies with fiber angle θ_k. The factor ''2'' emerges since the symmetry situation for the laminate regarding to its centre plane. As the plies are prepared of the same material, minimizing thickness leads to the identical optimum formation as the minimization of mass.

We are working on the ply thicknesses and there sequence as the working parameter for the optimization of composite structure. We have taken one problem of Z beam from Petri Kere, 2004 [1], for the composite optimization

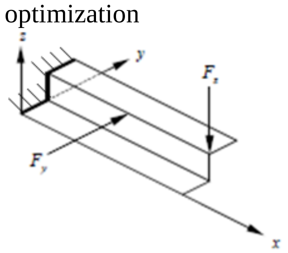


Fig. 1 Z-profile beam.

The beam is composed of layers having the mechanical properties of in plane 20 transversely isotropic AS4 carbon/epoxy ply listed in Table 1. The length of the beam is 1.0 m, the height of the web and the width of the flanges are 0.1 m. The beam is subjected to its own weight and to the design loads F_y = 1290 N at the midlength of the beam and $F_z = -860$ N at the free end of the beam as shown in Fig. 1. The web and the flanges are assumed to have identical lay-up configuration. The material coordinate system is given parallel to the global x-axis. In the design optimization, Tsai-Wu failure criterion is used to predict the failure with $\delta = \delta_F = 0.5 \times 10^{-3}$.

Table 1 Mechanical properties of the AS4/3501-6 carbon/epoxy ply

AS4/3501-6	**t_{ply} = 0.134 mm**
E_1=139.3 GPa	E_2 = 11.1 GPa
G_{12} = 6.0 GPa	υ_{12} = 0.3
G_{23} = 3.964 GPa	υ_{23} = 0.4
X_t = 1950 MPa	Y_t = 48 MPa
X_c = 1480 MPa	Y_c = 200 MPa
S_{12} = 79 MPa	ρ = 1580 kg/m^3

The Z-section composite model considered here consisting of 10 symmetrical layers, respectively, with ply thickness of 0.134 mm each. The stacking sequence for Z-section laminate is $[90/\pm 50/7(0)]_{SE}$. The plies are made of hyper laminate ply, which are then laminated as a thickness of 2.68mm.

V. FEA ANALYSIS AND OPTIMIZATION

With all the pre-processing steps the model is now set for the static analysis, where the initial results of the static analysis are shown in figures. The maximum deflection of the Z-section composite beam is shown in Fig. 2 as 18mm, the Maximum vonmises 2D&3D stress for the composite structure is shown in Fig. 3 and the Max shear stress generated has been shown in Fig. 4.

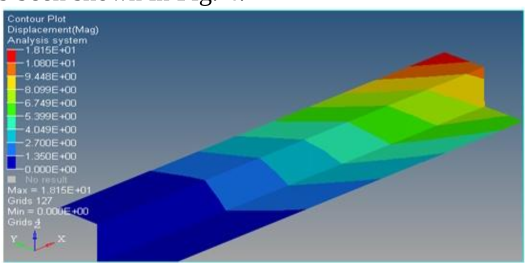


Fig. 2 Maximum Deflection of the Z-section Composite beam

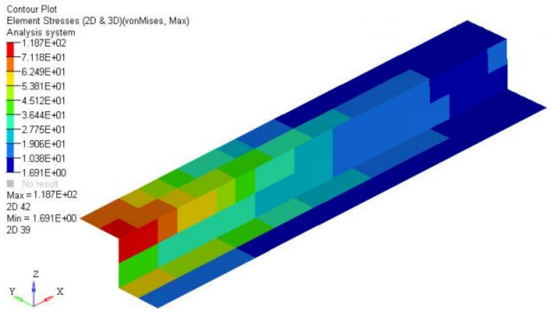


Fig. 3 Element Vonmises stress 2D/3D

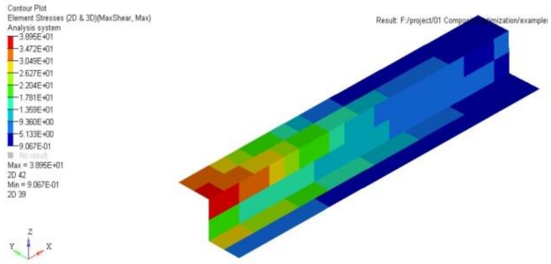
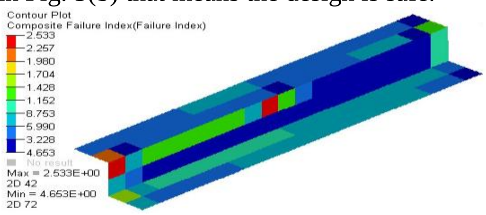
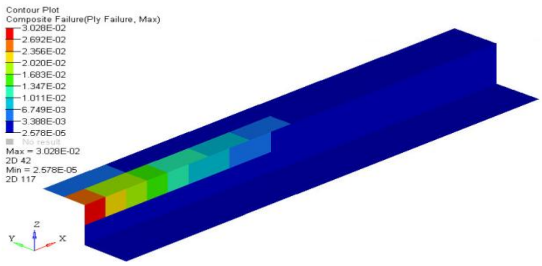


Fig. 4 Maximum Shear stress generated

The composite failure and failure index with maximum ply failure are shown in Fig. 5. As per failure criterion used the failure value should be less than 1, the maximum value is 0.030, which is shown in Fig. 5(b) that means the design is safe.



(a)Failure Index



(b) Composite failure

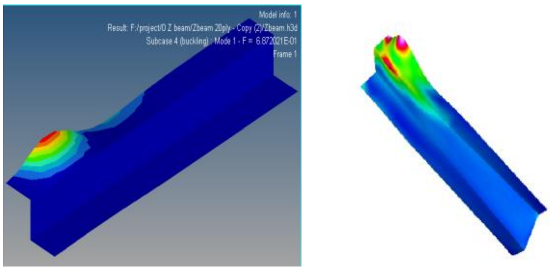
Fig. 5 Composite failure Index and composite failure of Z-section beam

The initial mass of the Z-section composite beam is 1.280 kg, which is shown in Fig. 6.

area =	300000.000
volume =	804000.000
total mass =	1286.400

Fig. 6 Initial mass of the Z-section composite beam

To validate the result, we have referred the reference paper by Petri Kere [1], which has given the result for the Z-Section composite beam.



(a) Present result (b) Result from ref. [1]

Fig. 7 Result of buckling analysis

Table 2 Validation of results

	Lay-up	Failure Index	Buckling Factor	Max. Deflection
PetriKere Ref [1]	[90/50/-50/7(0)]$_{\text{SE}}$	2.581	0.707	18.18mm
Present Analysis	[90/50/-50/7(0)]$_{\text{SE}}$	2.533	0.687	18.15mm

As per the above table it is clear that the analysis has been done is in good amount with the reference paper. So we can proceed with these setting for the further analysis and optimization.

5.1 STAGE I: FREE SIZE OPTIMIZATION

The main objective of the thesis is to reduce the mass of the Z-section composite structure. So the problem is formulated as

Minimize Mass

Subjected to Max. Displacement ≤ 15mm (constraint)

Design Variables -

0.1mm ≤ Laminate thickness ≤ 5mm

Ply thickness (for 20 ply) ≤ 0.5mm

Ply Balance due the symmetric ply – (50° to -50°)

Responses –

1. Mass 2. Max. Displacement

The iteration zero that is the initial status has been shown in Fig. 8.

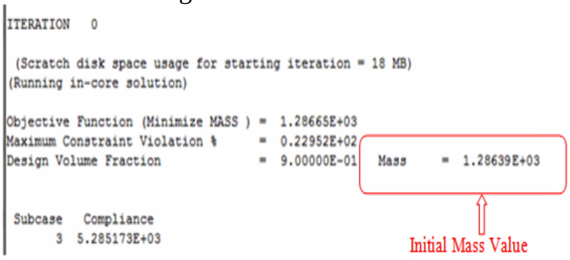


Fig. 8 Initial analysis result

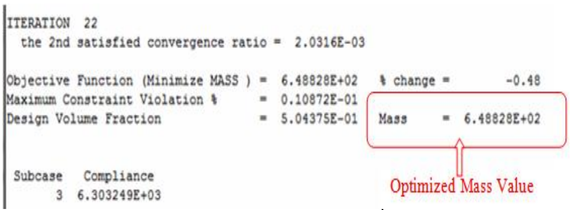


Fig. 9 Converged solution after 22th iteration phaseI

Now let we check the initial ply thickness, orientation thickness and element thickness before optimization, which is shown in Fig. 10.

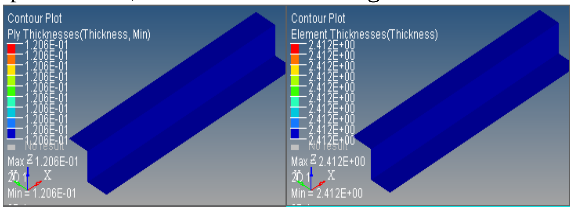


Fig. 10 Initial Element Thickness and Ply Thicknesses

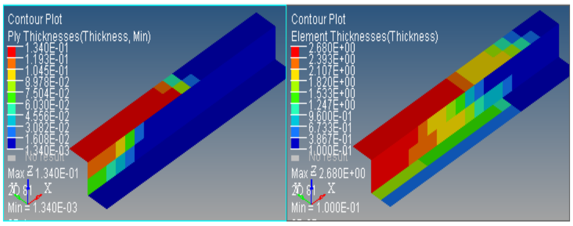


Fig. 11 Optimized Element Thicknesses and Ply Thicknesses

Then let us check the each ply thickness details, these are shown in Fig. 12.

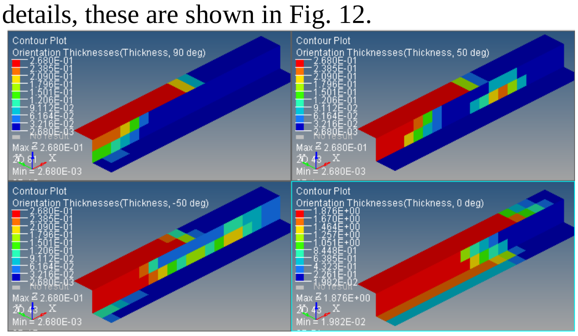


Fig. 12 Ply orientation thickness details

As shown in figure the plies are not having the constant thickness due to their orientation they support the load in their unique way which required the variable thickness as per the load and boundary condition applied. The figure shows the 4 ply details; due to the plies having same orientation are having similar ply thickness so other ply details are not shown here. In the figure above the red portion shows that there we require more thickness then the blue areas (least thickness) shown in fig.12.

5.2 STAGE II: DESIGN FINE TUNING USING PLY-BUNDLE SIZING OPTIMIZATION

The free size optimization illustrated in segment one guides to a constant distribution of thickness for every fiber orientation. The thickness field is supposed to interpret into outline of ply-bundles with every bundle showing multiple plies of similar layout and orientation. The ply-bundle outline can be basically taken by confining diverse level-groups of the thickness field of every fiber orientation. It has been establish from application knowledge that 4ply-bunches for every fiber orientation gives an excellent balance among true depiction for the thickness field and the difficulty of the ply tailoring. Subsequently ply-bundles of diverse fiber orientations are stacked as one alternately to produce a laminate of more even orientation lay-up.
The optimization problem remains the one shown in Eq. (l) and (2). Though, the design parameters are distinct thicknesses at unit ply thickness increments. As well at this design phase every detailed performance constraints with ply failure are supposed to consider.

Having recognized the best possible ply shapes and patch settings, the subsequent move is to modify this design for thicknesses. Stage 2 engaged locating the best thicknesses of every ply bundle. An option of executing the optimization with the thicknesses as continuous or discrete variables is accessible. A manufacturable ply thickness minimum condition can be established, thus executing a discrete optimization and permitting for the designed best ply bundle thicknesses to be a numerous of the minimum ply thickness value. This aids in estimating the entire number of plies necessary per fiber orientation.

This stage is a design modification phase and extra performance criterion can be included into the problem generation to make certain that the optimized design gathers the essential design needs. In this situation, an extra load case was included to compute the natural frequency of the fairing in assembled circumstances. The optimization configuration was also customized to factor in these extra performance goals, between others.

After the phase II, the plies are then further modified according to the manufacturable value. So for the manufacturing value we provide 0.01mm as the increment value for the ply thickness increment or approximation. The previously specified other constraints are implemented along with the manufacturing constraint. This time we are performing the ply thickness shuffling.

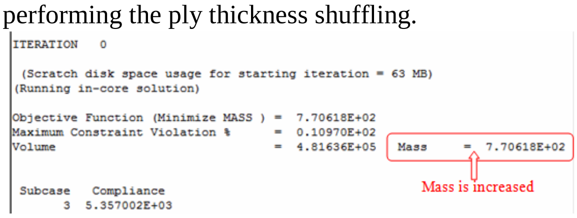


Fig. 13 Before phase II optimization the mass value

As shown in figure when we apply the manufacturing constraint then the mass is increase as compare to result of phase we, due to approximation value of manufacturing constraint. The result after the phase II optimization is shown in Fig. 14.

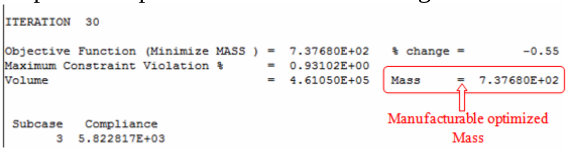


Fig. 14 Phase II optimized result

The thickness contours for the various ply orientations are shown in fig.15.

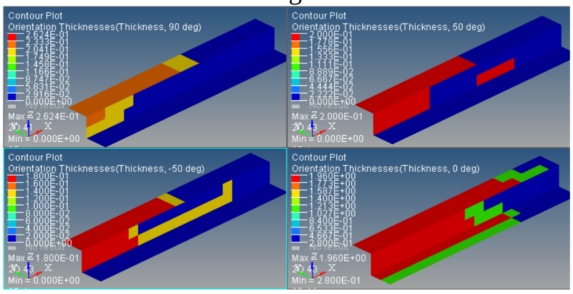


Fig. 15 Ply orientation thickness after Phase II

As per the above figure we can see that the contours are now more clear and crisp and can be manufacturable. After this we should check our displacement constraint also. So the displacement constraint is shown for the 32[th] iteration from the phase II sizing optimization and is given in fig.16.

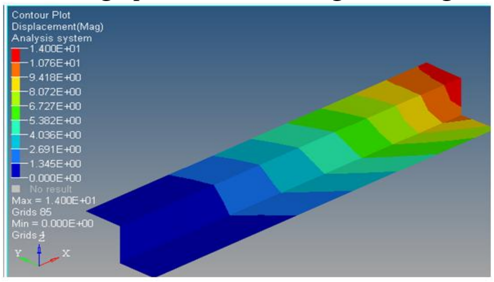


Fig. 16 Total Maximum Displacement after phase II

From the Fig. 16, it is clear that our optimization is good enough where the displacement is restricted up to 14mm, which is less than 15 mm the initial value. We should check the Vonmises Stress also, which is shown in Fig. 17. The stress is increases but is under safe limit.

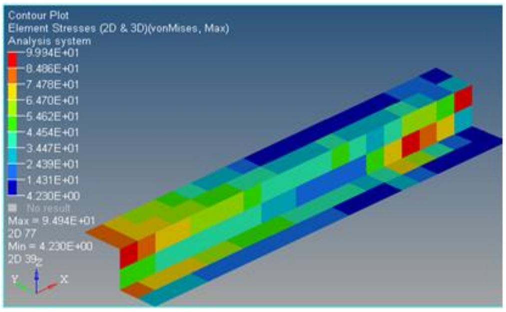


Fig. 17 Composite stress 2D/3D vonmises stress

VI. RESULTS

As presented in above section, we discussed the process detailed in this thesis expands upon two important and advanced optimization techniques, viz. free sizing optimization, and sizing optimization it offers a unique and comprehensive process for the design and optimization of Z-section composite laminate. Free size optimization for composites permits a proper concept level design synthesis of plies. A new PLY based modeling technique that simplifies laminate representation and facilitates the ply bundle sizing optimization make the process unique. The process also allows flexibility in case any alterations are necessary. During the design procedure, manufacturability constraints and behavioural constraints are conserved to arrive at a feasible design and make sure a meaningful method. The stresses and the deflections are at good stage, which means these are at the desired limits. The fig. 18 shows the reduction in mass through the three optimization phases.

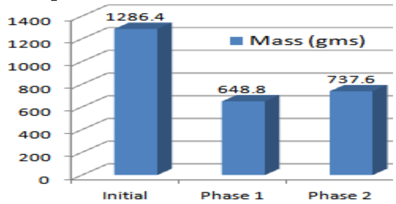


Fig. 18 Mass comparison for the optimization

As per the above figure, the mass has been reduced up to 50% in first phase but that was not manufacturable, so as compare to the initial result the mass has been reduce up to 42%.

VII. CONCLUSION

As presented in previous section, this work presents the results obtained by applying composite optimization to the configuration of composite material of Z-section beam design. The problem is defined by several manufacturing and design constraints (layer symmetry, maximum number of layers). The performance and characteristics of the proposed configurations are evaluated via nonlinear finite element simulation.

The problem of stacking-sequence design of composite laminates for minimum thickness subject to two point load for a given thickness was addressed. It was shown that the use of ply-orientation-identity design constant results in a linear formulation of the problem unlike the use of more traditional ply-thickness design variables that lead to nonlinear formulation. It was also shown that the formulation can accommodate constraints on stiffnesses as well as constraints on the maximum number of contiguous plies of the same angle. Results were presented for both y axis and z-axis loadings. The ply thickness plays a vital role for a composite structure to serve the various responses and mass optimization. The constant thickness of the composite structure may not able to serve the minimum mass and other responses optimistically, so we can say that the composite structure should be of variable thickness.

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