Cost Optimization in Composite Structures

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1. Abstract

Cost optimization is a driving force in all fields of industry, with every manufacturer competing to provide a cost-effective solution to the end customer. Designers and developers are aiming to make their products lighter for both economic and environmental reasons. A weight-reduction of the product could lead to a reduction in stiffness, thus giving a negative effect to the product's handling if an optimization technique is not used.

A car seat's structure must be stiff enough so it does not deform when the driver drives the car in a tough terrain, and provide safety and protection to the driver in the case of an accident. The challenge is to remain, or even improve, stiffness, while reducing the structural weight and cost. Many car seat developers have chosen to stiffen the body by using composite materials, such as carbon fibers, thus keeping the weight of the seat at minimum levels. How to position and dimension these materials optimally is individual for each car's seat structure and the way of doing it has until today been done by comparison between results taken from real life experiments and tests such as driver's behavior, various drop tests and data taken through structural analysis tests and intuition of experienced designers.

New tools, like topology optimization and cost optimization, are rarely introduced in the design process of new products. The designers are constantly under a tight time schedule and performing optimization on every part often seems to be too time consuming. Another contributing reason is the widespread lack of knowledge and experience in the area.

This paper will try to address how to perform an early stage design of components with emphasis on cost optimization and without consuming too much of a construction designer's precious time. Cost optimization could be very useful for a designer but also for CAE engineers in order to help keep design and production requirements inside budget limitations.

The main objective of this paper is to generate a proposal for a car seat design, based on free size optimization and cost optimization using Altair OptiStruct™ commercial engineering software. How to use this tool as a natural part of the design process will also be shown.

Index Terms: composite, cost, laminate, optimization

2. Structural Optimization and Cost Optimization

Cost optimization is used to achieve an optimum solution to a design problem that meets both structural and cost constraints. Before solving an optimization problem in general, a formulation has to be made and a model for calculation created.

There are three main types of structural optimization: topology, shape and size. All three may have purpose in a design phase and how to combine or chose between them depends on what is desirable to achieve. For the structural optimization of the composite structure of the car seat, a new, clever algorithm is being used called "free size optimization" that consists of a concept design synthesis, a design fine tuning, and a stacking sequence optimization.

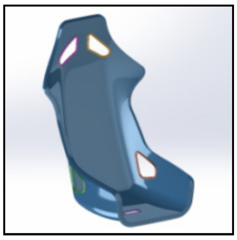


Fig 1: Mitsubishi Lancer EVO driver's bucket racing seat

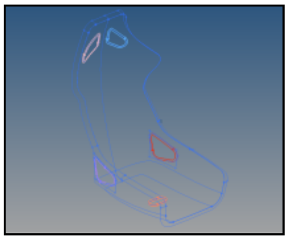


Fig 2: Model with component identification

The free size optimization is applied in order to analyze the model and provide a feasible design that implements various design constraints such as displacement and allowable stress, along with providing a comparison with the cost optimization procedure to be implemented.

3. FE-Model

The model that has been used in this study is a bucket racing car seat. The initial model is the internal frame body of the seat that, in this case, contributes to the durability and stiffness of the seat. The model can be seen in **Fig. 1.** Clearly one can see the general shape of the seat having openings for the five-point safety belt. The seat needs to be stiff in order to provide a firm support for the body, enabling the driver to have good control over the steering of the car to be able to resist an accident and providing safety in a crash situation.

4. Setting-up the Model for Analysis

The software identifies the design components that are included. Clearly one can see the seat and the points for the safety belt passing through it. The component that is under consideration is only the body of the seat, and the rest of the components need to be ignored for the optimization process (**Fig. 2**). Meshing is going to be applied only on the body component. In order for the model to have a good mesh quality, some clean up in the geometry needs to be done so that the elements have a coherent distribution over the faces of the component and not to interact with design details that can lead to a malformation of the pattern.

4.1 Meshing

With an integrated process, OptiStruct software checks the element quality and verifies if any elements have been formed outside of the specified criteria.

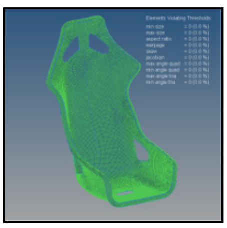


Fig 3: Elements violating thresholds

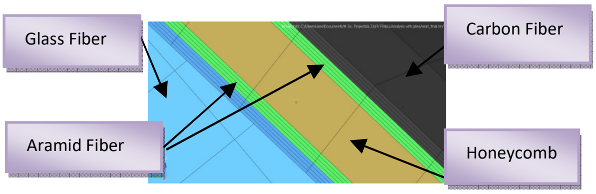


Fig 4: Composition of the laminate according to material

From the quality index shown in **Fig 3,** one can see that all elements fulfill the required parameters. In the case described, element formation has been automatically created according to specific criteria. The process during formation is keeping minimum size and maximum size of the elements between specific parameters, whereas other criteria such as aspect ratio, warpage, skew and Jacobian determinant are being considered. However, the meshing software can also create mesh based on user preferences following an interactive process with element distribution handled by the user. The above-mentioned process can create elements that do not comply with specific criteria and, due to free formation their quality index exceeds the normal limit. In this case, OptiStruct provides the ability to clean up those failed elements using various procedures.

4.2 Material Creation

For the specific model, a composite sandwich laminate is to be the manufacturing material comprising plies of carbon fiber, aramid fiber, paper honeycomb and glass fiber with the stated orientation, thickness and stacking sequence. First each material and material properties need to be created before being assigned to specific plies.

The model in our case consists of four materials divided over seventeen (17) plies to give a sandwich composite laminate with a structural layout that can be seen in **Fig. 4.** The assembly of the laminate according to material composition can be seen in **Table I.**

4.3 Defining Plies, Ply Properties and Total Laminate Stack

A total of 17 plies are to be created with their properties shown in **Table II.**

4.4 Apply Loads and Boundary Conditions - Single Point Constraints (SPC)

In order to apply the loading conditions and support of the model, pressure loads are going to be set at positions simulating the driver's weight. The seat will also be constrained by the bottom part as if it were positioned inside the car. Three loading conditions are going to be set for the back of the seat, the bottom part and the side of the seat. Four load collectors are going to be created, one hosting the SPCs and the other three the pressure forces applied on each position on the seat.

The pressure loads are a combination of mass of the driver, gravitational force applied to that mass and surface where the load is applied. Three sets of elements are being created to act as a reference point for the application of the pressure loads.

Table I: Composition of the laminate according to material

Material	Material Id	Color	Definition	Thickness T (mm)	Angle
Glass Fiber	1		GF	0,2	0,45,-45,90
Honeycomb	2		HC	5	0
Carbon Fiber	3		CF	0,2	0,45,-45,90
Aramid Fiber	4		AR	0,2	0,45,-45,90

Table II: Composition of the laminate according to plies

Material	Ply Id	Color	Definition	Thickness T (mm)	Angle
Glass Fiber	1		GF 1	0,2	0
Glass Fiber	2		GF 2	0,2	45
Glass Fiber	3		GF 3	0,2	-45
Glass Fiber	4		GF 4	0,2	90
Aramid Fiber	5		AR 1	0,2	0
Aramid Fiber	6		AR 2	0,2	45
Aramid Fiber	7		AR 3	0,2	-45
Aramid Fiber	8		AR 4	0,2	90
Paper Honeycomb	9		HC	5	0
Aramid Fiber	10		AR 5	0,2	90
Aramid Fiber	11		AR 6	0,2	-45
Aramid Fiber	12		AR 7	0,2	45
Aramid Fiber	13		AR 8	0,2	0
Carbon Fiber	14		CF 1	0,2	90
Carbon Fiber	15		CF 2	0,2	-45
Carbon Fiber	16		CF 3	0,2	45
Carbon Fiber	17		CF 4	0,2	0

Table III: Pressure Loads

Element Set	Applied on seat	Acceleration (x g)	Mass of Driver (kg)	Area (mm^2)	Pressure (N/mm^2 or MPa)
Pressure Seat	Seat	2	85	134737,966	0,012377358
Pressure Back	Back	1,5	85	157571,447	0,007937828
Pressure Side	Side	1	85	100290,216	0,00831437

The area is being calculated by OptiStruct to provide data for engineering calculations done by the user. **Table III** gives a summary of the pressures applied. The side load is applied on one side only due to the fact that the model is going to be optimized keeping a plane of symmetry that will lead to a symmetric pattern of the ply formation. In order to constrain the seat to the structure of the car, four single point constraints are going to be instigated.

5. Optimization Process

5.1 Stage 1 - Concept Design Synthesis - Free Size Optimization

The user can define the ply angles to be used up front. Free size optimization applied to shells works on the concept that the thickness of each designable element is defined as a design variable. Applying this concept to the design of composites implies that the design variables are now the thickness per fiber orientation, per element. OptiStruct will proceed with the optimization by subtracting material from an over dimensioned laminate that the user has created before starting the process, enabling a "fresh" approach directly to optimization criteria. For the initial optimization run, modified thicknesses of the plies from 0.2 mm to 5 mm for all plies and from 5 mm to 15 mm for the honeycomb ply only are applied. Each iteration in the optimization process will calculate the total displacement and total mass of the object's material in the laminate composition and uses these values to reach the objective target. The partial mass of the materials is going to be used in the cost optimization to be conducted after the free size optimization. At the initial stage of the free size optimization, a constraint in the total displacement is set in order to keep the displacement of the seat under 6 mm. Upper and lower bounds are limited to +6 and -6 accordingly in order to prevent deformation to either side of the coordinate axis. Constraints for the partial mass of each material are also created, defining the upper bound limit to a high value for each material. The upper bound limit for the volume responses is set to 10^{20} mm^3 and limit for cost is initially set to 10000 Euro for the racing seat. In order to complete the optimization setup, an objective function is to be created which will at this stage set the target to minimize the total mass of the seat. **Fig. 5** shows the result of the thickness distribution achieved from the free size optimization, post-processed in OptiStruct using a simple averaging method. The regions indicated in red or in colors tending towards red (from the key) can be interpreted as thicker regions, while those in blue or tending towards blue are thinner regions. The contour plot shows the total thickness distribution that includes contributions from each defined super ply orientation, i.e. a thickness contribution from the 0s, +/-45s and 90s.

5.2 Ply Bundles

From a free size optimization, the thickness of a superply is optimized and subsequently subdivided into a user-defined set of “ply bundles”**.** Each ply bundle would have a specific pattern, and the ply bundles for a given orientation would be built up to approximate the thickness distribution of the superply. More ply bundles will result in a final thickness profile of the superply that more closely matches the free size optimization results. On the other hand, more ply bundles increase the number of ply cutout patterns which can increase manufacturing costs. An illustration of the concept of going from a superply to ply bundles to individual plies is shown in **Fig. 6**. For this study, 4 ply bundles per fiber orientation (superply) are defined. These ply bundles represent the shape and location of the plies per fiber orientation. With 4 ply bundles per fiber orientation, this study produced a total of 48 ply bundles (not all 4 bundles for each of the 17 plies of different material and orientation are being formed by the solver). Ply bundles can be seen through element sets.

5.3 Stage 2 - Design Fine Tuning - Ply Bundle Sizing

Phase 2 of this process involves a sizing optimization of the ply bundles generated from phase 1 of the design process. Having established the optimal ply shapes and patch locations, the next step is to fine tune this design for thickness. Phase 2 involves identifying the optimal thickness of each ply bundle. A choice of running the optimization with the thickness as discrete variables or continuous variables is available. *A 0.2 mm minimum manufacturable ply thickness for carbon fiber, Nomex® aramid and glass fiber, and for honeycomb 5 mm is going to be specified (any values can be considered according to manufacturing allowances)*, thereby running a discrete optimization and allowing for the calculated optimal ply bundle thickness to be a multiple of the minimum ply thickness value.

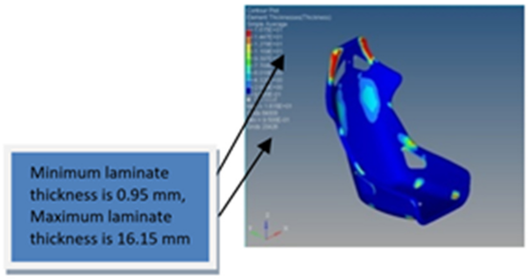


Fig 5: Element Thicknesses

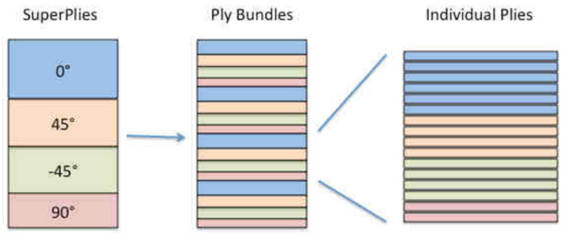


Fig 6: Schematic of "super ply", ply bundles and individual plies

This helps in calculating the total number of plies required per fiber orientation. Additional performance criteria are going to be incorporated into the problem formulation to ensure that the optimized design meets the necessary design requirements. The optimization setup is also modified to factor in an additional performance target, among others:

- Composite Stress

Constraint was defined on stress:

- Stress < 25 MPa

The objective of the problem is going to be kept the same while trying to keep the composite stress in each ply of the laminate in the structure below the constraint limit. Manufacturing constraints previously defined in the free sizing phase are automatically carried over into phase 2, preserving manufacturability across the process. These include:

1. A balance constraint that ensures an equal thickness distribution for the +45s and -45s.

The results are presented in **Fig. 7** which shows the overall thickness distribution map of all 48 ply bundles before the ply bundle sizing optimization stage.

Fig. 8 shows the final ply bundle sizing results where each ply pattern is sized to achieve the overall performance specifications. After the discrete size optimization is complete one can clearly refer to ply thickness results and conclude that:

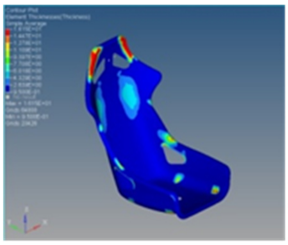


Fig 7: Element thicknesses before ply bundle optimization

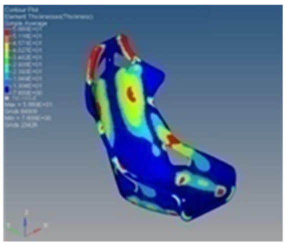


Fig 8: Element thicknesses after ply bundle optimization (discrete sizing optimization)

1) Some of the plies have been calculated to zero thickness and are going to be removed in the next step.
2) The remaining plies are multiples of the manufacturing thickness of each ply.
3) Additional numeration of plies has been created according to manufacturing thickness of plies.

6. Summary and Conclusions

The composite optimization process detailed in this thesis expands upon advanced optimization techniques including:

- **Phase 1 -** free size optimization to determine ply shape
- **Phase 2 -** size optimization to determine ply bundle thickness
- **Phase 3 -** shuffling optimization to determine ply stacking sequence

By stringing these three techniques together, OptiStruct offers a unique and comprehensive process for the design and optimization of composite laminates. Free size optimization for composites enables a true concept-level design synthesis of plies. A new PLY and STACK based modeling technique that simplifies laminate representation and facilitates the ply bundle sizing optimization followed by the ply shuffling optimization make the process unique. The process is automated and integrated within OptiStruct by generating the input data for a subsequent phase automatically from the previous design phase. The process also allows flexibility in case any modifications are required. Throughout the design process, manufacturability constraints and behavioral constraints are preserved to arrive at a feasible design and ensure a meaningful process. Applying this process to the design and optimization of a light-weight car seat met all prescribed design and manufacturing constraints. Incorporating an optimization driven design process can be a major enabler to a more efficient and less costly design process of composite structures.

The final design of the car seat can be seen in **Fig. 9, 10.** In **Figure 11** clearly the requested result, keeping the honeycomb inside the structure has been achieved as can be seen by the material distribution:

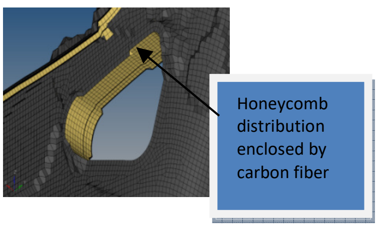


Fig 9: Position of Honeycomb in the structure

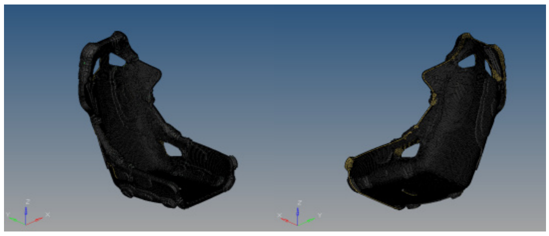


Figure 10: Final design according to property

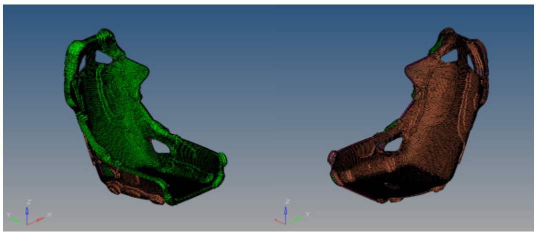


Figure 11: Final design according to material

7. Cost Optimization in the Optimization Software

Using the before mentioned free size optimization procedure and by alternating the optimization objective function, an alternative approach, that of a cost optimization, can be achieved. There can be two different methods used for such calculations. One is the internal procedure integrated within OptiStruct which uses mathematical equations programmed by the user. The second is with the help of a common application of a spreadsheet software used by many companies for financial and numerical calculations. In our case the integrated process is used, although the procedure using a spread sheet software is also going to be demonstrated.

7.1 Modification of the Model for Cost Optimization

According to the materials used, four mass responses are created in the model, one for each material (carbon fiber, aramid, honeycomb and glass fiber). Before moving forward with the procedure, a table of costs for the materials used with the help of a table entry is going to be created.

7.2 Programming a Mathematical Equation using DRESP2 response

The equation to be minimized should have the following statement:

$$f(x)=m1*p1+m2*p2+m3*p3+m4*p4$$

Where m1, m2, m3, m4 are the variables for the different material masses, and p1, p2, p3, p4 the variables for the different costs.

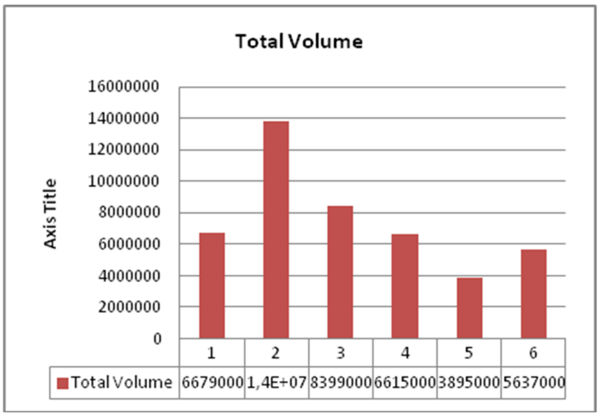
8. Results of Cost Optimization Trials

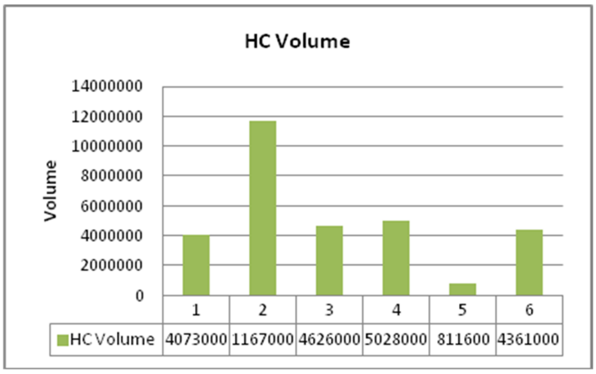
After the cost optimization formulation has been clearly stated, a free size model is then analyzed. The model is run first for total mass optimization to have a comparison and guideline, then further on several formulations are used in combination. The formulations used can be obtained from **Table IV**, where each of the three different stages is modified accordingly.

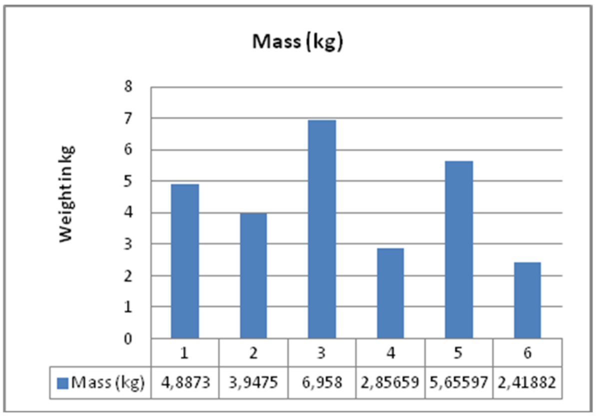
Table IV: Free Size Optimization Formulations

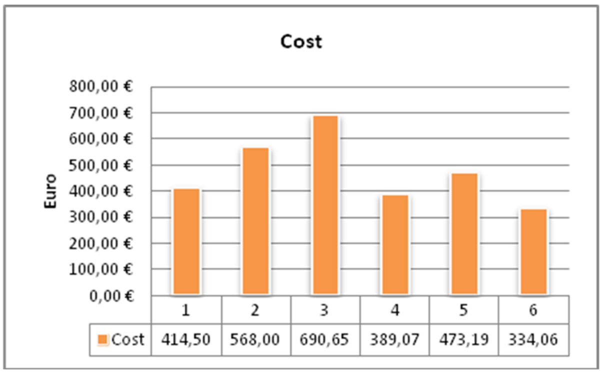
	Free Size	Size	Stack Optimization
Case 1		Original Model	
Case 2	Mass	Mass	Mass
Case 3	Mass	Cost	Cost
Case 4	Cost	Mass	Mass
Case 5	Cost	Cost	Cost
Case 6	Cost	Mass	Mass

Case No 6 is similar to Case No 4, except that in Case No 6 in the second step of the process, where mass is set as an optimization objective, total cost is constrained below the value obtained by Case No 4. This was done to show further directions of the optimization procedure. The results after each step are shown in charts:









8.1 Summary and Conclusions

As we can see from the results, a variety of solutions can be achieved through different approaches. Every solution given is an optimum solution according to the data input used each time by the solver. All solutions depend on the experience of the user in order to moderate the data and constraints of the structure to obtain the desired result. OptiStruct is a certified solver which assures that results obtained by the solver will be as accurate as the data entered by the user.

It has to be taken into consideration that the solver uses different approaches according to the manufacturing constraints defined by the user. In this study, with the mass minimization formulation, the solver created a fewer number of ply bundles than the cost minimization approach where all 4 ply bundles/shapes from each super ply were created as per the default behavior. The approaches described here can equally be applied to other optimization criteria defined by engineers and, as such opens a vast field of future research.

9. Final Conclusions

The concept of cost optimization has a different approach to the free size optimization process targeting mass minimization. By enabling the cost variable to be a response for optimization, based on financial criteria the solver offers a feasible solution but while keeping the original constraints such as displacement and stress inside specific boundaries. The result is a cost-effective solution that on one hand has all the structural benefits of an optimization process, and from the other a cost-effective proposal that can provide a new design perspective that was not considered before. However, if the cost response is being constrained, a predefined budget solution can also be achieved! The processing time depends on the form of the cost variables being added to the simulation. Optimization tools have been a great design help for engineers and designers. Cost optimization has come to add value to that process by providing a budget analysis tool for the initial design stage.

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11. Acknowledgements

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