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Topology Optimization Approach in a Process of Designing of Composite Shell Structures

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Abstract. Nowadays, engineers and designer are forced to conduct their work quickly and efficiently. That led to introduction and development of many computer-based tools, which aid the process of designing. One of those methods is a topology optimization, which can be used in many branches of industry, such as an automotive or aerospace industry, where many shells and monocoque structures are used, for which this method is very useful. It is an iteration approach that allows obtaining optimal results of material's placement and continuity in a construction, as well as its properties and thickness, in accordance with introduced loads, boundary conditions and needed shape. That allows the designer to obtain needed stiffness and strength of the design, with minimum weight and usage of resources. There are many ways to conduct the topology optimization and one the simplest is considering the material as isotropic and homogenous, which greatly simplifies the calculations and reduces needed time. Nevertheless, the composite structure, especially laminates, should be considered as orthotropic and heterogeneous. The process of topology optimization is shown in the case of preparing the concept solution for lightweight, shell-based support system for an electrical UrbanConcept class vehicle for Shell Eco-Marathon. The description of the outer shape, loads acting on the structure and boundary conditions connected with other subsystems were described, as well as the preparation of the computer model and the process of topology optimization using Altair HyperWorks software. Additionally, the results were presented and a final solution obtained basing on them.

Keywords. Digital manufacturing, Modelling and Simulation, Design of Personalized Products and Services, Complex Systems Engineering

Introduction

One of the goals in the designing process is to obtain an optimal solution. The term "optimal" is generally understood as "the best", but in the engineering point of view, design optimization can be described as a systematic improvement of the initial design by selection of better and better design parameters [1]. The process is iterative and may take a long time, especially in case of more advanced and complicated structures, but also is able to greatly reduce costs of production and maintenance of the product and enhance its overall performance. For years many different optimization tools and

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method were established and for several decades, with a development of computer technology, many numerical solutions were provided. One of those numerical tools is the topology optimization, which is dated back to 1980s. when Bendsøe and Kikuchi introduced their method for designing mechanical structures.[2] For years this method was mostly used for solid elements, as it is based on an introduction of volumes with zero density into the structure [1]. In this paper, the methodology of topology optimization in a case of laminated composite shell structure is presented. Due to the working principle of this kind of optimization, it is not commonly used for shell elements, as it would compromise its performance.[1][3] Nevertheless, later studies introduced specific approach, that can could be used for multilayer shell structure, with adding or removing the material in specific layers. Unfortunately, that approach is enough only for isotropic materials. In case of orthotropic composite plies, the problem of fiber orientation must be taken into consideration as well.[1][4] Developing that approach led to introducing multiple software based on finite element methods, such as OptiStruct, which was used in this paper.[5][6] One of the main optimization solutions for shell structures is the shape optimization, which, cooperating with topology optimization, can provide both optimal shape of the element's mid surface and its thickness.[4] However, in many situations, the outer shape of the structure is restricted by more factors than only mechanical performance. An example of such a factor is an aerodynamic resistance of the vehicle. In this case, the shape cannot be changed and the only optimized feature is the thickness.

Such a situation is presented in this paper, in which the optimization process is a part of designing a supporting structure for an electric vehicle for Shell Eco-marathon. In this competition, the goal is to obtain the most energy-efficient car of all of the participants.[7] Events like that are aimed mostly at innovative solutions, where specific conditions allow the designer to leave the most common solutions and develop new ones.[7][8][9][10] The process presented in this paper is based on several years of experience of Smart Power team from the Silesian University of Technology obtained during development of their previous vehicle for Shell Eco-marathon.[8][9][10]

1. Use Case: Designing of composite shell structure of ultra-efficient electric vehicle

The process of optimization approach in the designing of a composite shell is presented in the case of supporting structure for new Smart Power team's ultra-efficient electric vehicle. This powered by hydrogen fuel cell car is desired to take part in Shell Eco-marathon in UrbanConcept class. It is the totally new project and the new solution, which is based on several years of experience of the team in this field.

1.1. Requirements for the structure

As the designed composite shell is a part of the vehicle for competition, it must fulfill all of the requirements that are stated in the rules and regulations of Shell Eco-marathon. Those are mostly related to its dimensions, that is total height between 1000 and 1200 mm, total width, without rearview mirrors, between 1200 and 1300 mm and total length between 2200 and 3500 mm, driver's safety, whose compartment must be fully covered and separated from the ground, as well as the energy compartment. Apart from those, the regulations describe the necessary subsystems and elements, with which the supporting structure must cooperate. One of the main reasons for new design development is a demand for doors on both sides of the vehicle from 2019, instead of only one. Apart from the rules of the competition, additional requirements considering the overall performance of the designed structure were stated. The main objective was to minimize the total mass of the structure, with maintaining necessary stiffness to provide safety and comfort of the driver during competition. Prior to optimization process, several general concepts of supporting structure were considered and a unibody monocoque structure was selected (Figure 1).

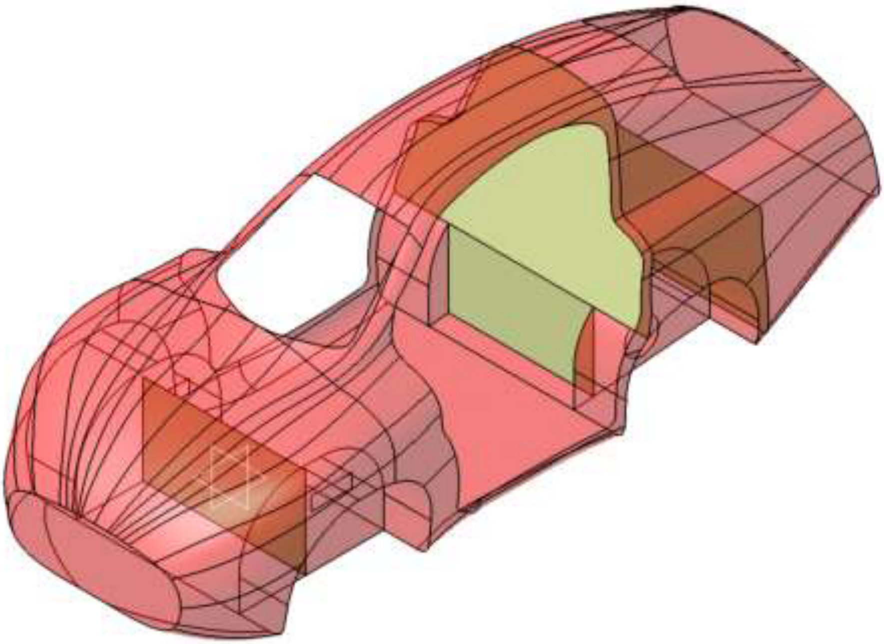

Figure 1. The CAD model of the optimized shell,

1.2. Load structure and load cases

To perform satisfying optimization of the structure, the load structure and load cases must have been properly identified.[11] In the given case, the forces can be divided into three groups. The first one is the group of loads connected to the weights of all of the subsystem, that is braking and steering systems, acceleration pedal, driver and their seat, energy supply, drive unit and the wheels with suspension. The second group consists of forces introduced during performance or maintenance of the vehicle. These are braking and acceleration pedal pressure, resting on a steering column, towing forces, and torque from the motor. The last group consists of forces necessary due to regulations, that is a force applied to the roof, which cannot deform it and a force applied to the harness. In further analysis, all of the forces were multiplied by 1,5, which is a usual procedure in the team.

Based on possible scenarios, five load cases were distinguished. In a general case, the loads related to the weight of subsystems, apart those from the wheels, the suspension and the motor compartment, were applied. Additionally, all of the loads necessary due to rules of Shell Eco-marathon and performance of the vehicle, excluding towing, were taken into consideration. The model was supported in the mounting points for all of the suspension nodes. In a roll-over case, the whole model was rotated 180 degrees, so it was laying on the roof, where the displacement constraints were placed. All of the static loads, directed toward the roof, were applied. In a towing case, the supports were placed in the suspension and all of the static loads, apart those related to the wheels, suspension, and motor applied. From the temporary loads, the breaking pedal pressing force and the towing force applied to the nose of the body were taken into consideration. In torsion cases, most of the static loads were applied with an addition of torque from the motor and acceleration pedal pressing force. The structure was supported by one suspension in the front and one in the rear, placed diagonally and the load related to the wheels, the suspension and the motor compartment placed on the other sides. The last analyzed load case was the lifting case. As far forces are concerned, all of the static loads were applied, including the driver's weight, in case of lifting the vehicle for a quick pit stop. In that case, the whole vehicle was supported in the four lifting points.

2. Methodology

The process of optimization using finite element methods, that is the topology, free size, size, and laminate sequence optimization can be divided into three main phases, each one followed by the finite element analysis and results' elaboration. The overall process is shown in Figure 2.

Based on requirements for the structure and its general solution concept, the CAD surface model was prepared using CATIA software, which was later exported into HyperWorks software by the usage of .igs file format. In this program, the proper finite element mesh was generated based on imported surfaces. At this stage, very fine mesh structure was not required. Following the meshing process, a single layer shell with a thickness of 4,5 mm and carbon fiber fabric-epoxy resin composite as a material, with mechanical properties according to [12], was applied to all of the surfaces. As the last step of model preparation for first phase of optimization, the loads and load cases, according to the previous part, were applied. The single layer composite was chosen for this step to greatly reduce the time of numerical calculations in phase 1, which do not lead to results compromising.

2.1. Phase 1: Topology optimization

The first step of the optimization process was the topology optimization. Although generally not used in case of shell structures, it may provide the information about which parts of the structure are load-carrying and which are not. To obtain reliable results, the proper parameters of the optimization must be selected.

In the given case the design variable was the shell thickness, which minimal value was set to 0,2 mm, to avoid introduction of zero density areas. The objective function was a minimal total mass of the structure, with a total displacement of the nodes of the roof restrained to 2,5 mm and of every node to 7,5 mm. The selection of allowable displacement is essential, as it constrains the stiffness decrease due to mass reduction. The topology optimization process was conducted for all of the load cases, apart from roll-over case, which would distort the results.

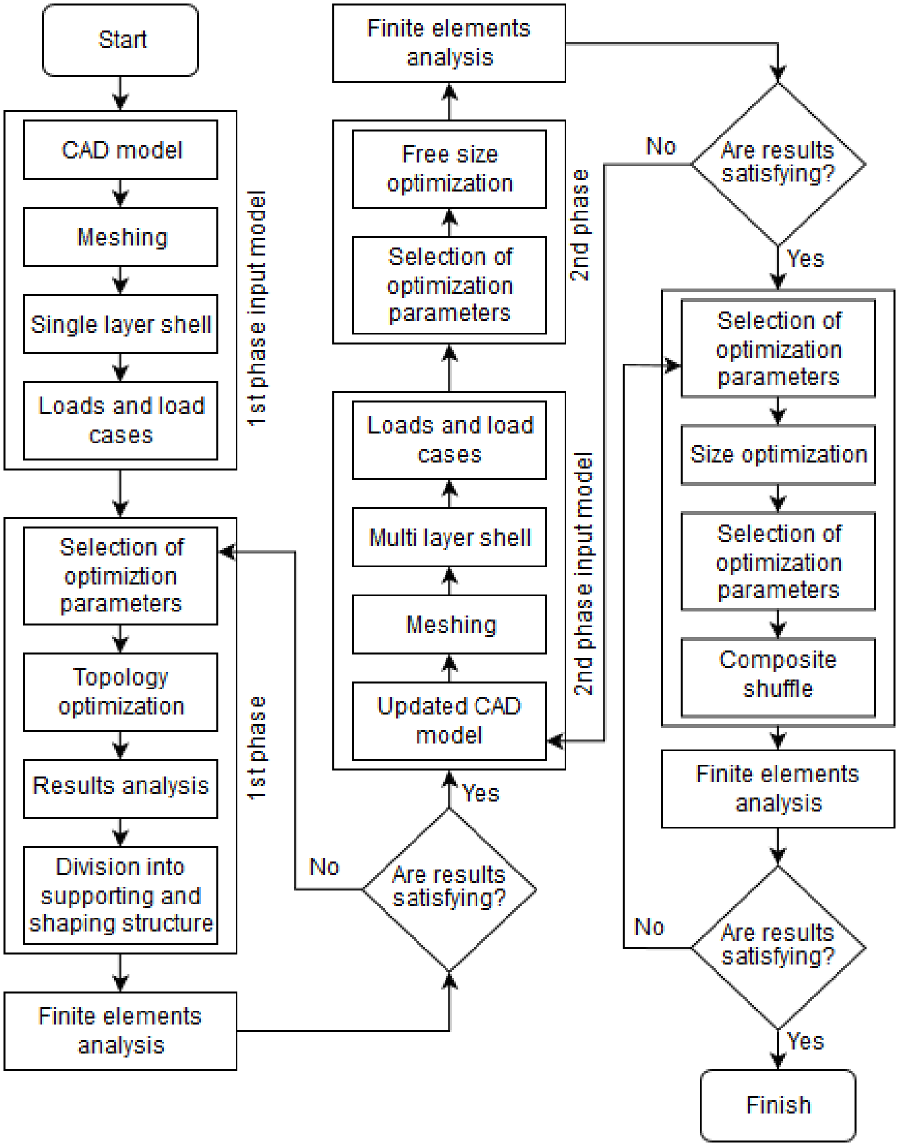

Figure 2. Stages of the process.

Based on the density map obtained in topology optimization process, the division of the shell into load-carrying and shaping elements was conducted. For mesh areas corresponding to the non-load-carrying structure, another shell property with the same material, but a thickness of 2,5 mm, was applied. Later the finite element analysis for all of the load cases was conducted and it was decided whether the obtained results are satisfying or not. In case of unsatisfying results, the changes in optimization parameters must have been made and the whole process repeated. Otherwise, the next phase may have started.

2.2. Phase 2: Free-size optimization

Base on the division of the structure and results from FE analysis after phase 1, the CAD model in CATIA was updated, with additional reinforcements in most crucial parts of the structure. The advanced model of the solution was again exported into HyperWorks, where the surfaces were meshed with a finer mesh than in phase 1. At this stage, two multilayer composite laminates were introduced as the shell materials. For load-carrying areas, the sandwich structure with two-layer carbon fiber fabric-epoxy resin skin and PVC foam core, with material properties according to [13], was applied. Whereas for the shaping elements the laminate of four plies of carbon fiber fabric-epoxy resin composite was applied. As the last step of the model preparation for phase 2 of optimization, loads and load cases were set.

The second phase of shell structure optimization was the free-size optimization process. At this stage, the optimal thicknesses of plies of each orientation were obtained. As in phase 1, the process parameters were essential. In the given case, the total thickness of the laminates was restrained between 1,5 mm and 10 mm and the objective function was again to minimize the mass of the structure. To avoid decreasing the stiffness too much, the 2,5 maximal total displacement restriction was set for the roof, 3 mm for the front former and 8 mm for the whole structure. Again all of the load cases, apart from roll-over one were taken into consideration.

If the program were unable to obtain feasible results, it would be necessary to get back to the CAD model and adjust it by adding reinforcements in critical areas. When the free-size optimization process was complete, the finite element analysis was conducted and the results were evaluated. If they were satisfying, the next step can occur, otherwise, changes in the model or process parameters must be done.

2.3. Phase 3: Size optimization and composite shuffling

After obtaining the FEM model with optimized thicknesses, the last phase of optimization process may occur. It consisted of two stages: the size optimization, where the thickness of each ply resulting from phase 2 was reanalyzed with a consideration of manufacturability. During this process, the thicknesses of several plies may be set to zero, as they were not necessary in that case. The second stage was connected with obtaining optimal plies sequence to achieve the best performance.

In the case of size optimization, the displacement and laminate thickness restrictions remained unchanged in comparison to phase 2, the minimal mass objective was also held. Additionally, the minimal and maximal thickness of each ply and minimal manufacture thickness were set. In the given example, the latter was set to 0,5 mm for each ply, the minimal thickness was set to 0 mm and maximal one was set separately, depending on initial thickness. After the size optimization, the composite shuffling process occurred. In that case, the only parameters were maximal two subsequent plies of the same orientation and PVC plies set to act as a core in case of the sandwich structure. After conducting the optimization process, the finite element analysis was done and the results evaluated. If they were unsatisfying, the parameters of the optimization would be changed, otherwise, the whole optimization process was finished.

3. Results overview

The analysed model consisted of 55188 finite elements, with an average size of 15 mm. The calculations were conducted with two different PCs. The first one, with 12 GB of RAM and a CPU 2x2,4 GHz, was insufficient for the free-size optimization, which had to be done using another one, with 8 GB of RAM and a CPU 4x3,2 GHz. The topology optimization took on the first unit about 4 hours and both size optimization and composite shuffling took about 1 hour each. The most time consuming was the free-size optimization, which took about 34 hours. During the process, the following results were obtained. In the case of phase 1, the map of element densities, which acted as the base for structure division is presented. For phases 2 and 3, the resulting total thicknesses of the shell are shown.

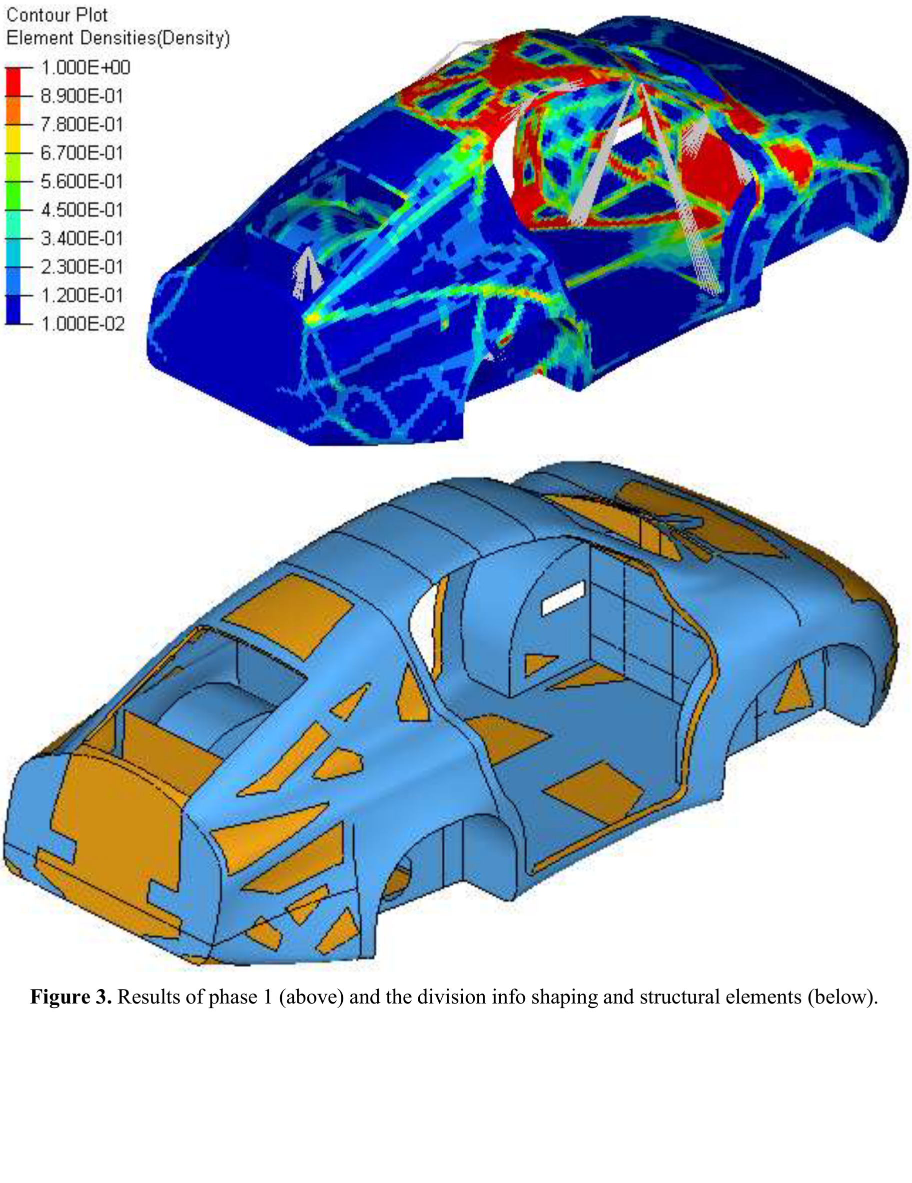

Figure 3. Results of phase 1 (above) and the division info shaping and structural elements (below).

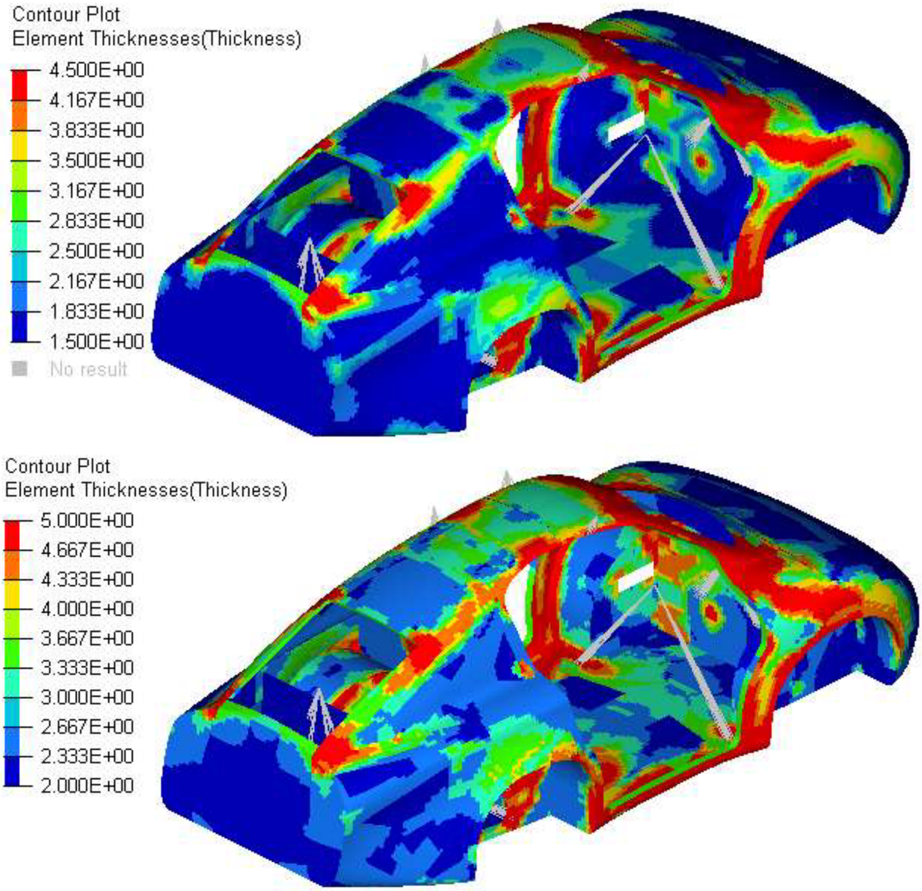

Figure 4. Results of phase 2 (above) and phase 3 (below).

In Figure 3, there are the results of the topology optimization of the one layer shell, where the blue areas represent the lower densities of the structure, thus lower stresses occurring there. Analogically, the red areas indicate higher densities and higher stresses. Based on that map, the structure was divided into shaping elements made of carbon laminate, shown as the orange areas in the figure, and load carrying ones made of the sandwich structure represented as the blue areas. The obtained results are symmetric. In Figure 4, the results of phases 2 and 3 are shown. In both cases, the blue color indicates the lower total thickness of the shell and red color represents areas with higher total thickness. In phase 2, the minimal obtained thickness of the shell is equal to 1,5 mm, that is the limit set by the designer and maximal is 4,5 mm. The areas of lower thickness correspond to the shaping elements of the shell and the higher thickness is present in the areas of load concentration, mostly near cut-offs for the doors, the window and the inspection hatch. The overall thickness dispersion obtained during phase 3 is similar, but the range of total one increased to 2 - 5 mm, due to the ply manufacturing constraints. Moreover, the edges of plies became more sharp and visible.

Following the obtained results, additional changes were made to the structure. A layer of 10 mm thick plywood was introduced wherever the concentrated forces are present, with the area of 10 cm^2 for each 10 N of the force. That lead to an increase in the mass of the structure. The comparison of its changes after each phase of the optimization process and the final design (Figure 5).

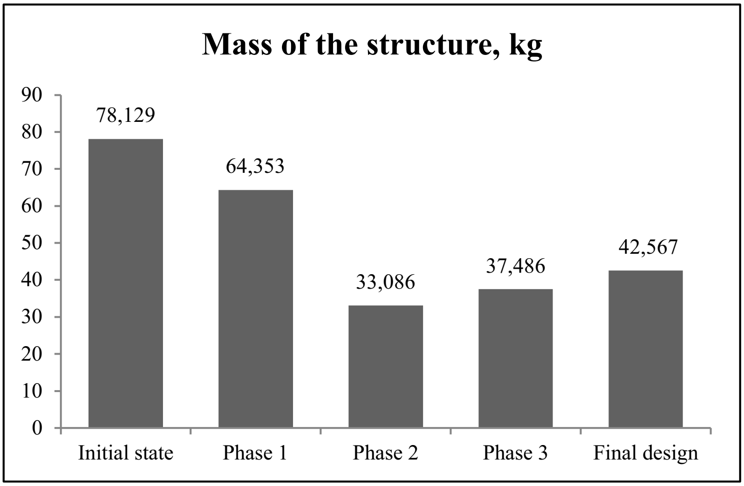

Figure 5. The comparison of the mass of the structure.

4. Conclusions

Numerical optimization processes can greatly help the designer in their work. Even though the basic topology optimization is not usually used in case of shell structures, it was proven that it still can be used for determining the load carrying parts of the shell, and thus may be used for preliminary division of the structure into shaping and supporting elements. That process is useful in a development of general design, which acts as a base for more detailed one. Moreover, it greatly reduces the time necessary for further steps, as the structure is already thinner in areas identified as a nonload-carrying. Unfortunately, due to the software limitations, a model for the topology optimization must be one-layer, which may distort the results to some extent. The usage of a different solver or another setup should enable the multi-layer structure at this step as well, which should improve the results in an expense of increased calculations time. Unfortunately, numerical optimization requires many preparations in the field of finite element method analysis, as a load structure and load cases must be as close to the real situations as possible. That level of complexity causes a long time of calculations. Moreover, to achieve good results in phases 2 and 3, parameters of the optimization should be carefully selected, as they highly impact the obtained structure. As phase 2 is the most time-consuming, it may be impossible to adjust the optimization parameters to a satisfying level, however, the final results would be greatly improved in phase 3, which, much quicker, can be repeated many times with different parameters. As phase 2 provides a very high number of separate plies, a way to identify which are more important, thus should have higher upper thickness boundary in an expense of less important ones, ought to be investigated in the future.

In the presented case, the optimization process led to the mass reduction of over 55%, with maintaining the necessary stiffness of the structure. However, this process should not be treated as the final step of the design process, as the results usually need to be adjusted to a given case. In this example, the additional layers of plywood were added to strengthen the structure in places of concentrated forces, as the thin laminates do not work very well under such conditions.

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