Optimization Methodology for an Automotive Hood Substructure (Inner Panel)

D. Costi, E. Torricelli, L. Splendi and M. Pettazzoni

Abstract — **The automotive industry is facing many problem at a present day, but a possible way to overcome these limitations can be a green approach. Besides the most advertised ways of reducing pollutant emission, i.e. changing the fuels, vehicle mass can be reduced to reach the same objective. In this paper, a methodology to reduce the weight of an automotive hood substructure is presented. The methodology consists in a loop of different optimization techniques, i.e. topology, topometry, size and topography, coupled with a constant re-designing of the model. Without breaking the performance targets expected by Ferrari internal regulation, the mass has been reduced respecting manufacturing constrain.**

Index Terms — **Optimization, Topology, Finite Element Method, Torsional and bending stiffness, automotive, car-weight reduction, engine hood.**

I. INTRODUCTION

The automotive market is going towards a green approach at the present time, especially because of marketing purposes. Thus, automotive industries are starting to project and design cars with less environmental impact.

This process is pursued through many different ways. The most known and advertised is for sure the reduction in the consumption of fossil fuels. A different way that could be followed in order to reduce the environmental impact is to decrease the quantity of material used for each a part. This reduction of materials brings many different improvements. First of all, it has direct benefits due to a less use of raw materials and energy for parts production. At a second stage, it has an indirect influence on fuel consumption due to the lower weight of the car (less weight implies less consumption)[1]. Finally it reduces the costs for the firm too.

The purpose of this article is to present the optimization methodology developed with Ferrari S.p.A. in reducing the weight of cars mobile body parts, such as engine hoods, baggage hoods and doors. In particular, this article is focused on a baggage hood of a rear-wheel drive car with rear-central engine.

The target is to design the internal frame part, which is made of aluminum, of the assembled engine hood, keeping the same performances of the car model and reducing, at the same time, the car weight. These performances include different static analysis ruled by Ferrari S.p.A. internal regulation. For example, one mission controls the deformation caused by applied forces such as aerodynamic forces whereas another mission is focused on assuring the correct stiffness to close the hood.

The methodology uses different types of structural optimizations, with the same target and constraints. The objective, in fact, has been set to reduce the mass whereas the constraints were to keep equal performances and equal manufacturability in respect to the reference model.

II. OPTIMIZATION PROCESS

In this article, an optimization process based on different type of structural optimization is presented. The different optimization techniques, which are provided by the Altair Engineering software Optistruct, are used progressively. In particular, the process includes topology, [2] [3], topometry, topography and size optimizations.

This process can be widely found in literature, [4] [5] [6]

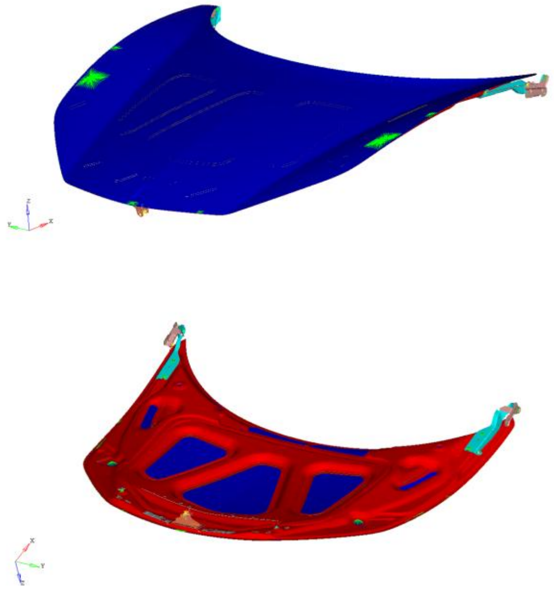

Fig. 1. Ferrari F458 Italia front hood.

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[7], and has been used in a previous work of the authors [8] concerning a different structure, a whole chassis.

The reference model of the study is the front hood internal reinforcement of the Ferrari F458 Italia (Fig. 1).

At first, the previous model has been studied to obtain results in terms of displacements of the node subjected to the different loadsteps. These loadsteps respect internal regulations for numerical and experimental analysis of the component in order to validate the part resistance and strenght. The obtained displacement values represent the constraints for all the optimizations that have been carried out.

The optimization process starts from a topology optimization applied to a design space: as a consequence, it is necessary to define a suitable preliminary architecture for the structure.

Topology is an optimization technique that assigns a special density to each element. This value can vary between 0 and 1 and multiply the real density of the element material. This special density represents the structural importance of each element for every loadstep: a value of 1 means that the element is fundamental while a zero value implies that the element can be removed without lowering the structural performances.

Thereafter, the results of the topology optimization are re-interpreted in a 3D CAD model of the bonnet substructure.

The inner reinforcement has to be realized with a stamped sheet of aluminum and, for this reason, the solid cross-sections of truss-like structures, which are typical of topology optimization results, have been interpreted as thin-walled cross-sections. This kind of sections are, in fact, more performing in terms of inertia-to-mass ratio.

A layer of non-structural glue has also been added to paste these areas to the upper structure. After the CAD interpretation, a preliminary series of analysis have been carried out to verify the performance of the new model. At a later stage, depending on the results, the design can be changed or is possible to continue with the methodology and switch to other types of optimization.

The next stage consists on a loop of optimizations and CAD changes that improves the design of the model: through optimization is possible, for example, to increase performances that have not been reached yet or to lower the mass if all the missions are accomplished.

In particular, topometry, topography and size optimizations have been used in loop with CAD modifications.

Topometry

This type of optimization is a mathematical technique that optimizes thickness distribution for 2D elements across the structure. Topometry can give indications of which areas should be strengthened with additional reinforcements and which ones can be eliminated from the model to lighten the structure.

Topography

Topography optimization is an advanced form of shape optimization in which a design region for a given part is defined and a pattern of shape variable-based reinforcements within that region is generated using OptiStruct. Simply speaking, this optimization allows to obtain a localized deformation of the sheet creating ribs or indentations, which act as localized reinforcements.

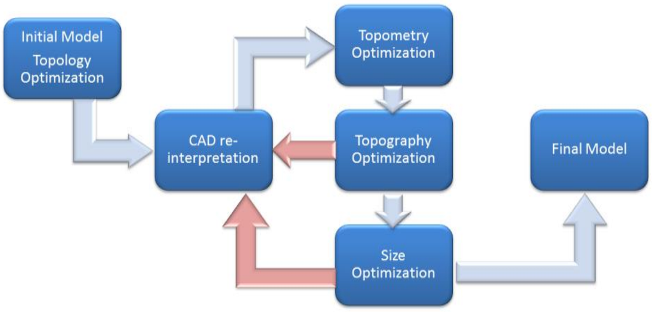

Fig. 2. Design flow of the hood inner panel. It is possible to generate a loop with different type of optimization and CAD re-draw, the output of the last size optimization is the final model. This model has to be verified for final validation.

Size

In size optimization, the properties of structural elements such as shell thickness, beam cross-sectional properties, spring stiffness and mass are modified to solve the optimization problem. Through this type of optimization is possible to define the correct thickness for each introduced components, such as inner panel and internal reinforcement, connected each other with structural rivet or welding.

The design flow is shown in Figure 2. As can be seen, the loop between the improvements and CAD changes is constant after each optimization.

It is fundamental to start from a correct design space to speed up the process. The computational requirements for topology, in fact, are significantly higher than those for the other types of optimization.

III. MODEL SET UP TOPOLOGY OPTIMIZATION

The FEM model of the hood is realized with shell elements. In particular, CQUAD4 and CTRIA3 have been used to represent the inner panel, the external part of hood, the reinforcements and the hinges. In addition, three-dimensional elements (HEXA6 and HEXA8) have been used to model the non-structural glue that connects the bones with the style. Concerning the clinching between the outside of the bonnet and the inner panel elements, rigid elements (RBE2) have been used, whereas CWELD elements model the structural rivets connecting inner panel and reinforcements.

The model presents the distribution of weight shown in Table I (expressed in percentage of the total weight of the structure). As can be seen, about 80% of the total weight is reached by inner panel and external hood style. Since the current analysis is focused only on the inner panel, about only 38% of the total mass is addressed by the present work. As a consequence, a 15-20% maximum achievable reduction in weight has been supposed.

TABLE I
DISTRIBUTION OF MASS BY COMPONENT

Component	Mass [a]
External Hood	40.21%
Anterior Reinforcement	4.02%
Inner Panel	38.19%
Hook Lock	1.43%
Hook Lock Reinforcement	0.31%
Mobile hinges	4.02%
Fixed hinges	6.56%
Hinges reinforcement	2.86%
Non-Structural Glue	2.39%
Total Mass	100.00%

[a] Results are in percentage in respect to the total mass of the reference model.

After the calculation performed to obtain the design constraints, the model has been prepared for topological optimization. This model is similar to the basic model. The geometry of the hinges, the look hook and style of the car, in fact, have been maintained. Only one change has been introduced by removing all the internal bracing and the inner panel. These parts have been replaced with a volume of solid elements (CTETRA4), which is made of aluminum and occupies the entire room allowed in the luggage compartment. The 3D elements are linked to the style through a layer of non-structural adhesive modeled with another type of solid elements, i.e. HEXA6 and HEXA8. Both solid elements in aluminum and glue are the design space of topology optimization. The glue has been introduced to test the importance of the link between hood and inner panel. A manufacturing constrain has also been set on the design space: the direction of molding has been set perpendicular to the plane of car style.

The constraints of the optimization are the displacement of the nodes placed under the load during the 6 loadsteps described below, simulating the experimental tests necessary to validate the product.

The six different loadsteps to test and validate the hood are:

- *Torsional*, the typical torsional stiffness of every structure;
- *Bending*, the typical bending stiffness of every structure;
- *Flaps bending*, deformation of the hood caused by the aerodynamic forces when the car is moving;
- *Closure with hand standard*, simulate the closure of the hood when it is grabbed in standard position;
- *Closure with hand Central*, similar to the closure with hand standard, with the only difference that the hood is held on the middle;
- *Closure with hand lateral*, another variation of *closure with hand standard*, but in this case the hold is on the side of the hood.

Each loadstep has its own loads and constraints, which are consistent with company internal regulations. Loadsteps can be easily added to the methodology: for example, is under investigation a load that simulates the weight of a person resting on the hood, such as a model during a motor show.

The objective of the optimizations is the minimization of the mass of the structure.

IV. OPTIMIZATION RESULTS

At the end of the topological optimization the results contain the density that the optimization software has assigned to every single element. As shown in figure 3a, this distribution can also be filtered visualizing only those densities that are above a certain one. It is also possible to observe in the picture that the optimization software, as usually, creates beams through the force lines of the structure.

The target is to redesign the structure in order to make it manufacturable using a stamped sheet and, afterward, a pierced one. The redesigned sheet is confronted with the result of the topological optimization, like shown in figure 3b.

The mass obtained from the topological optimization is the best possible distribution of density throughout the design space and it is 24 percentage points below the starting mass. The results confirm that is possible to obtain mass values lower than the one of the previous model. This value can be considered as the inferior asymptote of the function mass target because represents the best possible density distribution, which is absolutely unrealistic, purely numeric and not realizable.

V. MODEL SET UP FOR OTHER OPTIMIZATION

After re-designing the backbone as close as possible as the results of topological optimization, it is necessary to prepare a new Finite Element Model starting by the CAD design. This model has the same characteristics of the starting model concerning the type of elements.

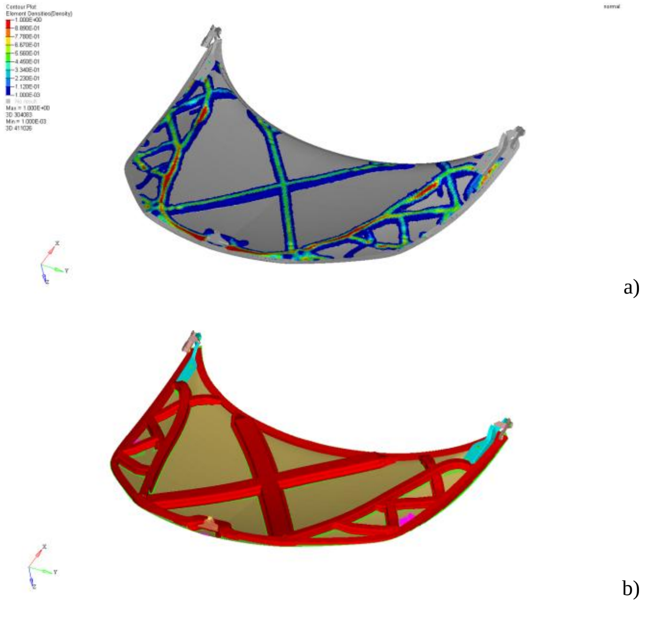

Fig. 3. a) density distribution after topology optimization, the 3D elements displayed have a density above 0.1.
b) Re-interpretation of the optimization result. New CAD model.

On this model, a preliminary analysis of the new structure of reinforcement has been carried out: keeping the same thickness of the previous model is possible to make a comparison.

The table of results shows a decrease in performance of the model, but it is also possible to observe that there is a sharp reduction of the mass. For this reason, it is necessary to use the other types of optimization described above. At first, several topometric optimizations have been carried out modifying the *design variables* in terms of thickness, having zero or the value of base thickness as lower bound and several values of maximum thickness. Through this type of optimization is possible to obtain some suggestions on how to re-design the most critical areas for the stiffness of the structure. Thus, appropriate reinforcements can be introduced and useless material can be removed to further reduce weight.

After the topometry optimization, the inner panel drawing can be changed slightly to increase the stiffness or is even possible to design new parts, such as local reinforcement, which can be connected by structural rivets. Structural rivets assures a good connection without an expensive process and with a small mass increase. This loop of optimizations and re-design can be repeated several times, until a satisfactory layout has been reached.

At this point, a size optimization can be carried out. Size optimization, in fact, can assign to each component, which is newly designed for the assembly of bonnet, an optimal thickness, respecting all the constraints of the project and lowering the mass.

The results in terms of thickness variation are shown in the Figure 4.

The last step consist in topography optimization, which allows the deformation of the mesh and the consequent creation reinforcing ribs in areas with low stiffness. This type of optimization is not intended to reduce the mass, but can increase the stiffness of the considered structure without changing the mass.

The three optimizations used in this part of the methodology and the consequent re-drawing can be used in a loop design to refine the solution. At the end, a final model is designed with performance higher than the constrain or, at least, equal, but lighter than before.

At this point, after defining the layout of the substructure and the additional reinforcement, and the thickness of the components, another topometry optimization has been set, using maximum thickness of each component as upper limit and zero for the lower value. This calculation allows us to eliminate the parts that are not necessary, bringing the result to the limit of numerical approach.

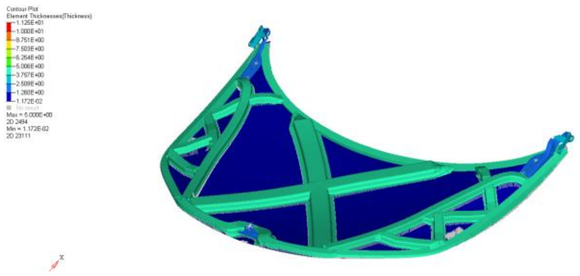

Fig. 4. Size optimization results: thickness distribution.

TABLE II
STIFFNESS OF THE MODEL IN EACH LOADCASE

Loadstep	Initial Model[a]	Final Model[a]
Torsion	100.00%	99.78%
Bending	100.00%	102.45%
Flap’s Bending	100.00%	101.21%
Closure hand STD	100.00%	101.23%
Closure hand Central	100.00%	105.47%
Closure hand Lateral	100.00%	110.88%
Total Mass	**100.00%**	**87.56%**

[a] Results are in percentage in respect to the reference model with constant section

Basically this optimization can be seen as a 2D elements topological optimization, assigning a thickness proportional to their importance; unnecessary items can be eliminated.

VI. FINAL MODEL VERIFICATION AND CONCLUSION

Once the run are finished, the best model, which respects the constrains and has the smallest mass, can be passed to the designer. The designer has to redesign the frame and the braces following the correct criteria of manufacturability for those objects.

After the design stage the behavior of the model has to be verified. The table II shows a perfect behavior of the model in all the loading cases required by the numerical validation and a sensible mass reduction, equal to 12.44%.

Finally it is possible to realize the prototype of the structure and experimentally verify it to have a complete validation. At the end, the model can be manufactured: mounting it on cars, can assure remarkable benefits in terms of weight without damaging the performances.

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