Detail Design Evaluation of Extruded Sections on a Body-in-White Concept Model

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Abstract

Topology optimization allows for the design of structures with an optimum distribution of material for a given set of load cases. In the past, it has been shown that topology optimization can be implemented for a design space representing a body-in-white vehicle structure undergoing multiple load requirements. Using a Hybrid Cellular Automata algorithm along with a scaled energy weighting approach, both the objective of maximizing stiffness as well as maximizing compliance can be considered concurrently for multiple load cases. This methodology using LS-TaSC™ generates the optimum load paths for the design space subjected to the defined load cases. However, designers are often interested in applying local manufacturing constraints, such as extrusion constraints, on specific portions of the larger design space. This can be achieved by defining multiple design spaces and placing constraints as needed to represent these known manufacturing constraints. In this case, a full body-in-white design space is defined using multiple connected design spaces with an extrusion constraint applied to the side sill structure. The load paths are then generated for the overall requirements of the body-in-white. The results obtained from the initial topology optimization are used to extract the outer boundary of the extruded side sill. These results generate a base model design space to perform a localized topology optimization for the side sill. To successfully solve for the optimal cross-section design of the side sill, this local design space is significantly refined from the original design space definition and subjected to load cases specific to this extruded section. This subsequent topology optimization then solves for the detailed structure of the side sill component. The results from the second stage are interpreted as a shell representation in order to perform a size optimization on the extruded structure. Such a three-staged optimization process enables the designer to obtain design recommendations that originates from a global design domain and finally helps develop a detailed local design.

1. Introduction

Computer-aided design and computer-aided engineering are commonplace tools used by engineers to generate and analyze concept designs. Topology optimization has become increasingly useful to generate efficient designs that meet specified load requirements while achieving design targets such as light-weighting of the structure. When large complex structures such as a vehicle body-in-white are considered for topology optimization, several load cases must be considered simultaneously for the structure. These load cases can often have conflicting objectives such as minimum compliance for normal operational load cases as opposed to the maximization of energy absorbed during extreme events such as a crash. These conflicting load requirements have been managed using a Scaled Energy Weighting Hybrid Cellular Automata method so that a balanced design is generated which meets the various needs of a complex structure [1].

In addition to multiple load requirements, manufacturing constraints will also have a strong influence on the design. In order to facilitate manufacturability of the design developed using a topology optimization analysis, suitable manufacturing constraints are required. The addition of manufacturing constraints at the conceptual design phase generates a feasible concept and limits the range of solutions obtained from the topology optimization. There are several processes for manufacturing parts of structures that would require optimization constraints. Among the most common manufacturing processes are casting, milling, turning, extrusion, and rolling [2].

This paper proposes a methodology which can incorporate known manufacturing constraints of substructures in a larger design space. This is achieved by defining multiple design spaces and applying manufacturing constraints to those structures that are known to require these constraint definitions. This will result in a general optimization result for these substructures which will require an additional topology optimization stage with a more refined mesh to fully resolve this local structure. Once this more refined structure is obtained, the structure can be interpreted as a shell representation so that a size optimization of the extruded structure can be performed. This three-stage optimization process can be used to generate design recommendations based on topology results originating from a global design space and further developed with local, detailed optimization problems.

2. Optimization Methods

The work presented here is based on the Scaled Energy Weighting extension of the Hybrid Cellular Automata topology optimization algorithm [1]. This allows the consideration of multiple load cases with conflicting optimization objectives of minimum compliance and maximum energy absorption. Additionally, extrusion constraints are applied to select areas of the design domain in order to develop a feasible design concept. LSTaSC affords the user the option to apply constraints to selected areas of the design space and was, therefore, the optimization tool selected for this study [2]. This section also briefly describes the proposed methodology for three-stage optimization.

2.1 SEW – HCA

Portions of this section are taken from the authors' paper "Design Space Dependent Preferences of Multi-Disciplinary Body-in-White Concept Optimization" [3].

In topology optimization, the target is to find the optimal material distribution within a two or three-dimensional design space or design domain Ω. Each finite element of the discretized design domain is an optimization variable, i.e. the optimization assigns a density variable that controls the material properties within the element. The SEW-HCA applies a power law approach according to the well-known SIMP approach:

$$E_i(\rho_i) = \rho_i^p E_0 \tag{1}$$

where ρ_i is the density of element i, E_0 is the Young's modulus of the full material and p is a penalization exponent and there are $i = 1 \dots N$ elements. In typical mathematical optimization approaches the densities are iteratively updated based on the gradients of the objective function. We utilize the heuristic Hybrid Cellular Automata approach due to its capability to address certain types of crashworthiness topology optimization problems. The assumption of the HCA optimizer is to target a uniform distribution of a field variable, by iteratively performing a control-based update of the variables according to:

$$\rho_i^{new} = \rho_i + K_p(S_i - S^*) \tag{2}$$

where K_P is a control parameter, S_i is the field variables of the element, and S^* is a set-point for the field variables, which is adapted in each iteration so that a desired volume constraint holds. For the kind of problem addressed by SEW-HCA the field variables are usually the strain or internal energy densities of the elements. In case of multiple load cases, the field variables are combined before the update by a preference-based ting as proposed in [8]:

$$S_i = \sum_{l=1}^{L} w_l S_{il} = \sum_{l=1}^{L} \rho_l \frac{1}{S_l} S_{il} \tag{3}$$

with the number of load cases L, a weight wl for each load case and the field variable Sil associated with element i for load case l. The SEW-HCA approach refactors the weight wl in a user-defined preference factor pl and a scaling factor sl. This refactoring enables to separate the task of scaling each of the load cases to the same level from the task of expressing how important the load case is for the user, hence the preference factor.

Results of previous work, where typically the compliance subject to static loads or the energy absorption subject to crash loads are optimized by SEW-HCA, good results were obtained with choosing the scaling factor according to [8]:

$$s_l = \frac{W_l^{(full)}}{W_{min}^{(full)}} \tag{4}$$

where $W_l^{(full)} = \Sigma^N_{i=1} S_{il}^{(full)} v_i$ is the work of the structure obtained from the analysis of the load cases within the initial iteration of the topology optimization.

2.2 Extrusion

The extrusion process is used to manufacture solid and hollow cross sections along various straight and curved paths as shown in Fig. 1. The extrusion constraint applied to a particular design space maintains a uniform cross-section throughout the length of the specified domain.

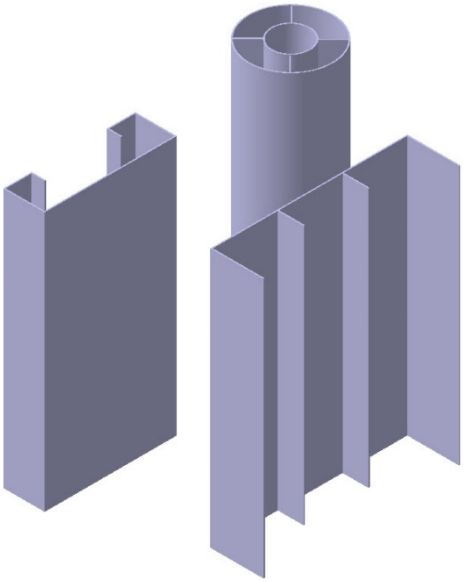

Figure 1: Sample Extruded Parts

The extrusion constraint forces the optimization to generate a constant cross-section along the extrusion direction. The size of each element in the design space is the same; hence the number of elements at any cross-section along the extrusion direction will be the same. An extrusion constraint also implies that all elements in a cross-section and the corresponding variables, are constraint to have the same material density during the optimization. Fig. 2 shows an example of extrusion constraint applied to a bar. The updated optimization simplifies the initial optimization problem since the number of independent variables is reduced.

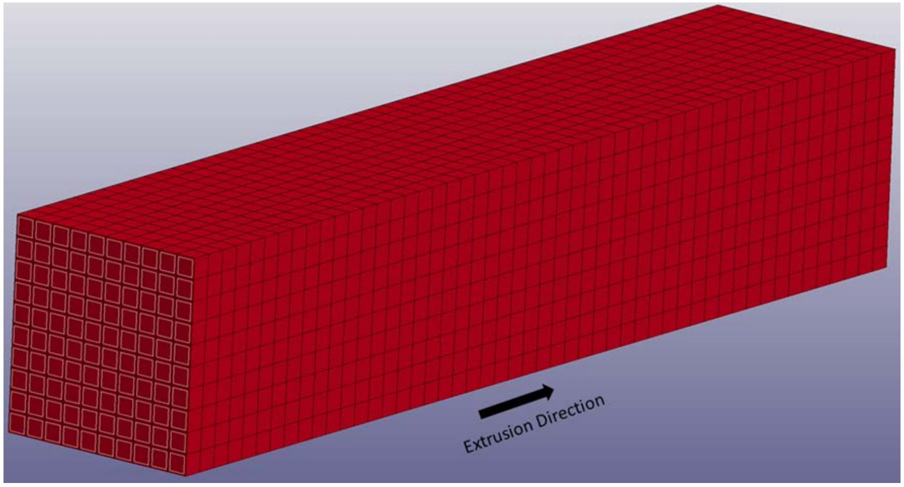

Figure 2: Example FEA Model

2.3 Three-Stage Optimization Methodology

In this paper, a three-stage optimization methodology is proposed as shown in Figure 3. In the first stage, a body-in-white design space is considered with several load cases applied to the structure including static load requirements as well as nonlinear load requirements. The side sill structure is defined as a separate design space so that an extrusion constraint can be applied to this portion of the structure since it is known that an extruded design is desired. The Scaled Energy Weighting Hybrid Cellular Automata method is then used to derive a global body-in-white structure, and the side sill structure is defined as an extrusion in this solution.

The side sill is a component of the cabin structure of the body-in-white and all load cases, including crash, for the cabin structure have an objective of minimum compliance. Globally, the cabin structure must withstand deformation during crash events in order to protect the occupants. Therefore, at this early stage in the design process, load cases are defined such that minimum compliance drives the overall design of the cabin. However, the side sill is also a component that must efficiently absorb energy during side crash events in order to best protect the occupants. Therefore, a local, component level optimization is needed to generate a side sill design that will meet several load requirements.

Since the body-in-white is meshed at a resolution where fine details cannot be captured, a second stage topology optimization considering only the extruded component is defined with an appropriately fine mesh. Specialized loads are applied to this design space in order to resolve the structure completely. The loads considered during this component level topology optimization are based on energy absorption load cases since the structure derived from the global topology optimization is driven by the minimum compliance requirements. In order to construct this local design space, the results from the global optimization are used to define the outer cross-section shape. The inner cross section is then defined as the local design space with a voxel mesh, and nonlinear loads are applied. In this way, an inner cross-section that is driven by nonlinear load cases is derived.

The results from this local, component level optimization are then used to manually interpret a shell representation of the side sill design. The third stage of this methodology is a size optimization driven by both linear and nonlinear load cases. The resulting design is a side sill which efficiently manages both minimum compliance loads as well as energy absorption requirements for crash loads.

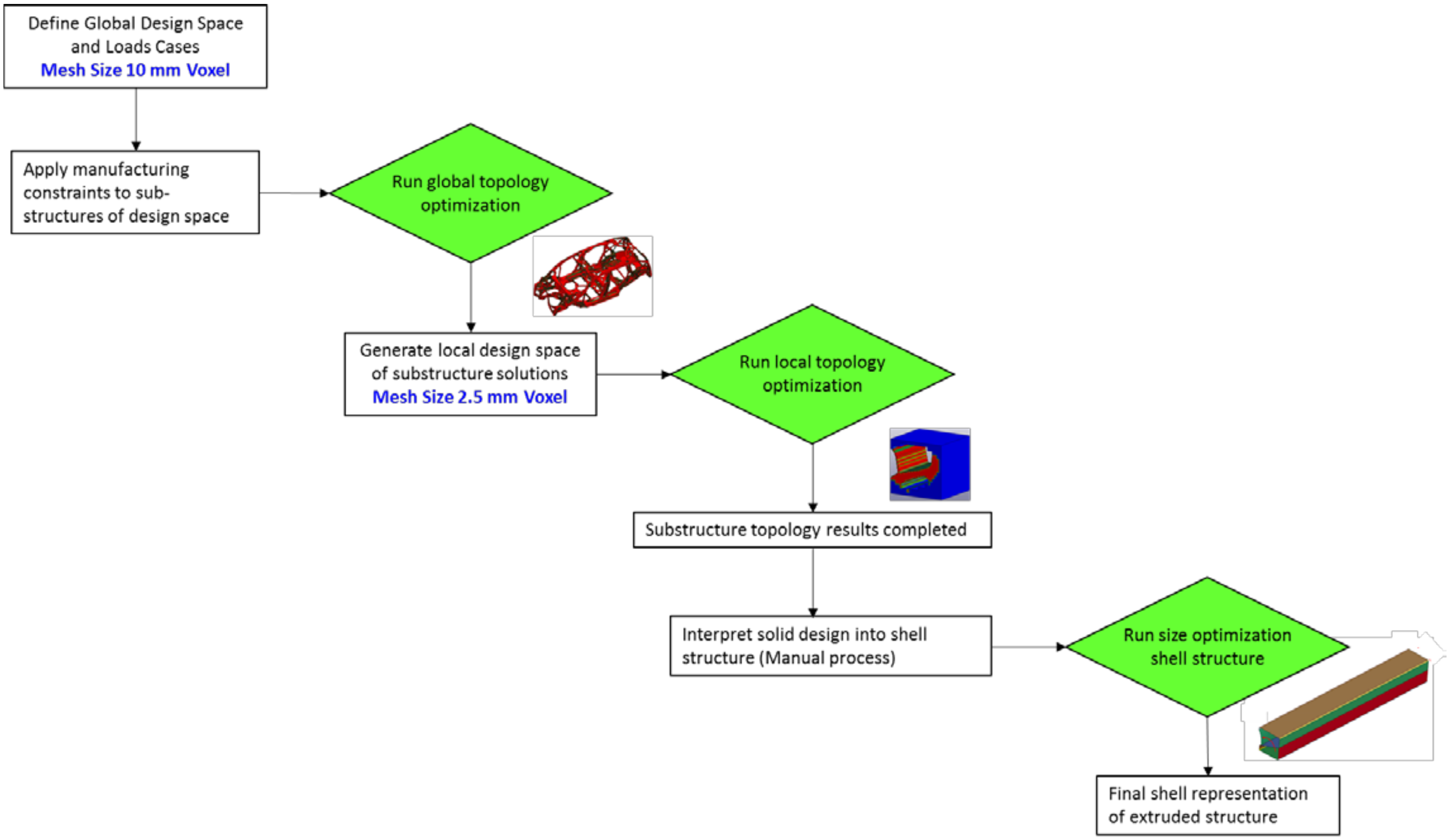

Figure 3: Three-staged Optimization Methodology

3. Case Study on Body-in-White Model

3.1 First Stage Topology Optimization: Body-in-White Design Space

The extrusion constraint was demonstrated on a preselected portion of the Body-in-White (BIW) model which represents the side sill structure. Fig. 4 shows the BIW design space from the early stages of conceptual design. The design space is split in order to create three independent design spaces: side sill on the left and right sides are defined as one design space with an extrusion constraint applied, and the remaining structure is the second design space with no manufacturing constraints defined. Fig. 4 also shows the side sill design space as well as the extrusion constraints that are applied along the longitudinal direction of the vehicle. Symmetry boundary condition is applied to the design spaces.

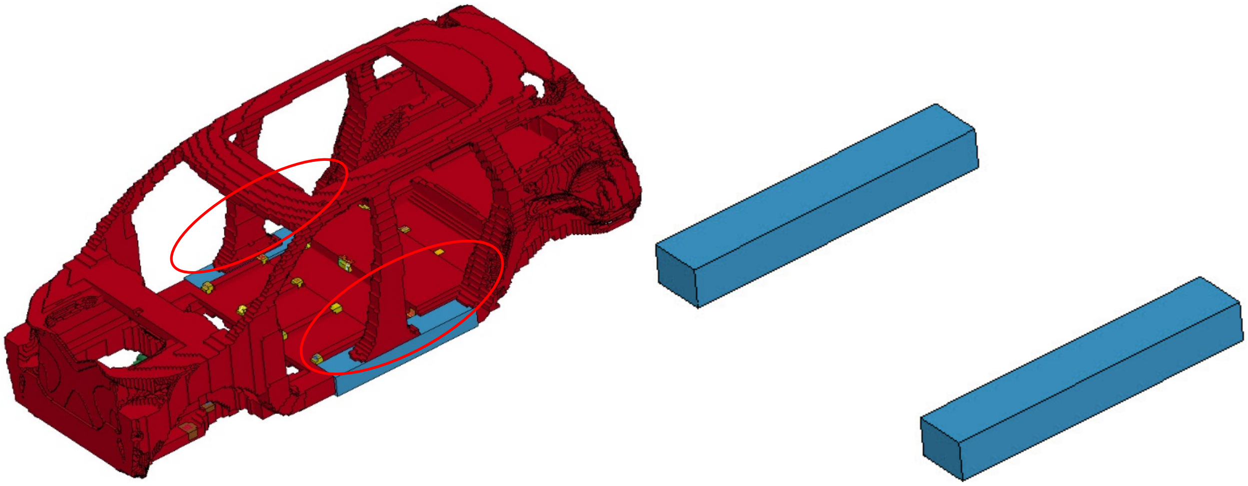

Figure 4: BIW Design Space (red) and Side Sill Design Space (blue)

A total of eleven load cases are applied to the design spaces including two crash load cases and nine static load cases shown in Figure 5 and Figure 6 respectively. In the crash load cases, the initial velocity of the vehicle for the rear crash is 20m/s and on the front is 10m/s. The initial velocities selected for the study suitably deform the design space in a representative manner to simulate a real-world crash scenario. The standard operating conditions are simulated using the nine static load cases which can be categorized as front, seat, and rear load cases. The load cases are similar to the study in [1].

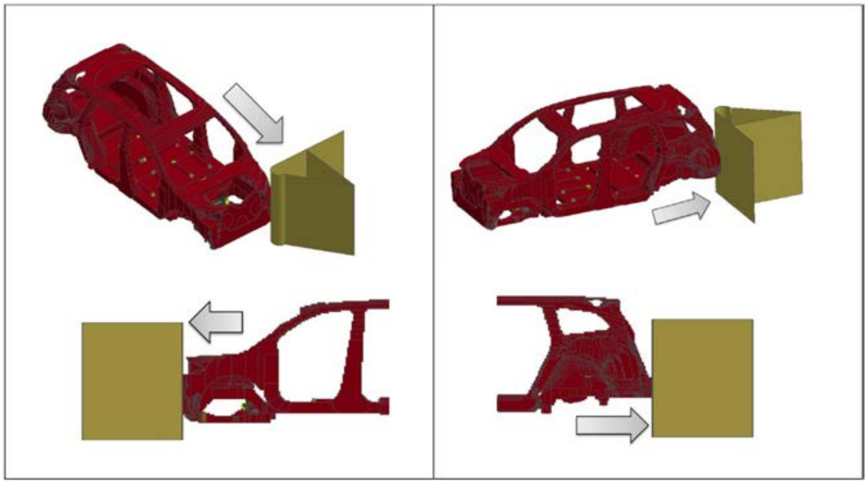

Figure 5: Front (left) and Rear (right) Crash Load Cases

The finite element model is developed in the LS-DYNA® [4] keyword format. The static load cases are analyzed using the implicit solver while the crash load cases are analyzed using the explicit solver in LS-DYNA. The total number of solid elements is 1446184 with an edge length of 10mm. The material model used in the analysis is a piecewise linear elastic-plastic material.

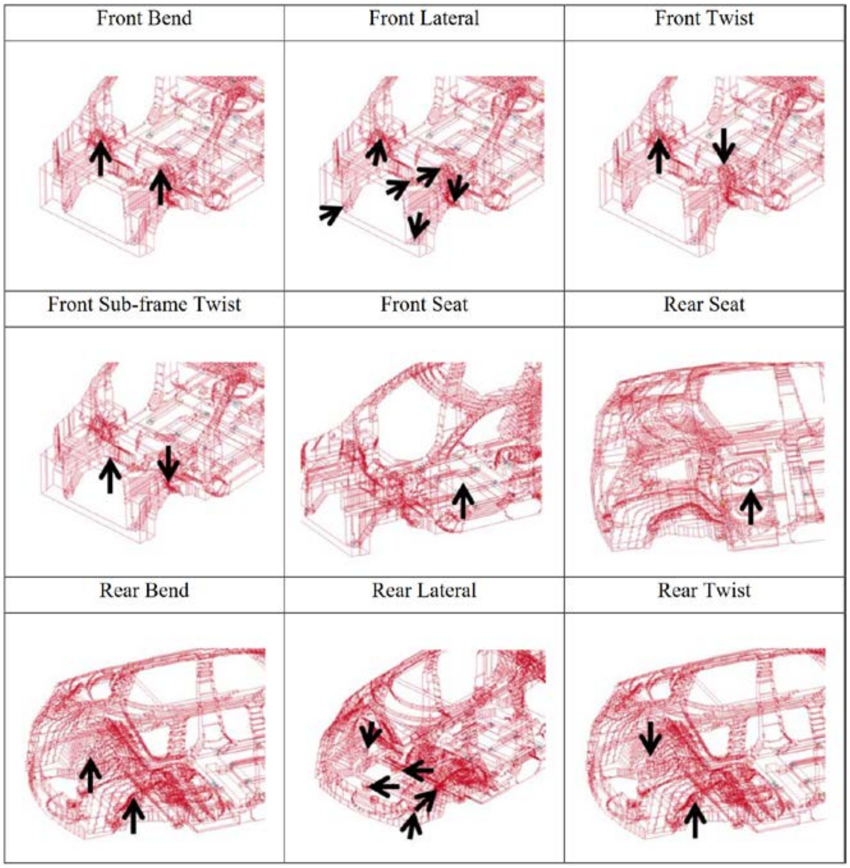

Figure 6: Nine Static Load Cases

The SEW-HCA method was used to assign preferences on the load cases. The preference (*p)* for the crash and static load cases are as follows:

$$p_{crash} = p_{1,2} = 0.5/2 = 0.25$$

$$p_{static} = p_{3,4,5,6,7,8,9,10,11} = 0.5/9 = 0.056$$

A target mass fraction of 0.3 is set along with a move limit of 0.1. As was stated in [5], a mass fraction of 30% is considerably higher than a typical mass of a vehicle body structure as this is a solid representation of the design. However, the result of this optimization study can now be used as starting point for additional design activity [6]. Fig. 7 shows the results from the first optimization run (on the BIW structure) with extrusion constraint on the side sill design space.

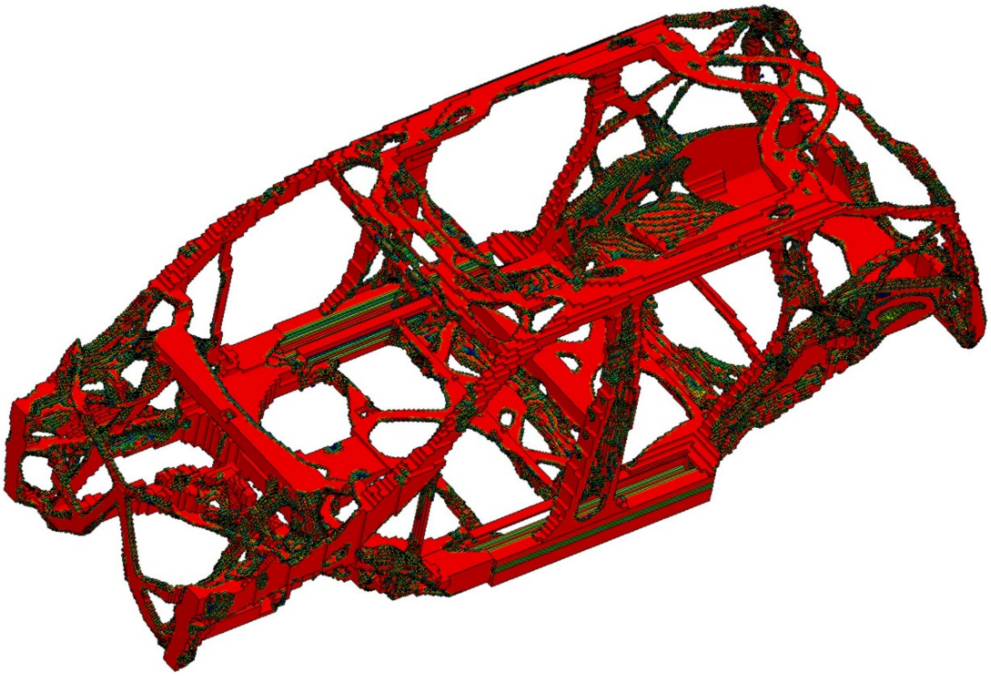

Figure 7: Topology Optimization Stage 1 Result

Fig. 7 shows the results obtained for the side sill design space (extracted from the BIW), from the first stage of optimization performed on BIW structure. The design for the side sill is primarily driven by the standard operating conditions (static loads) applied on the cabin. The objective here is to solve for minimum compliance/maximum stiffness; hence the material gets pushed outward as shown in Fig. 8.

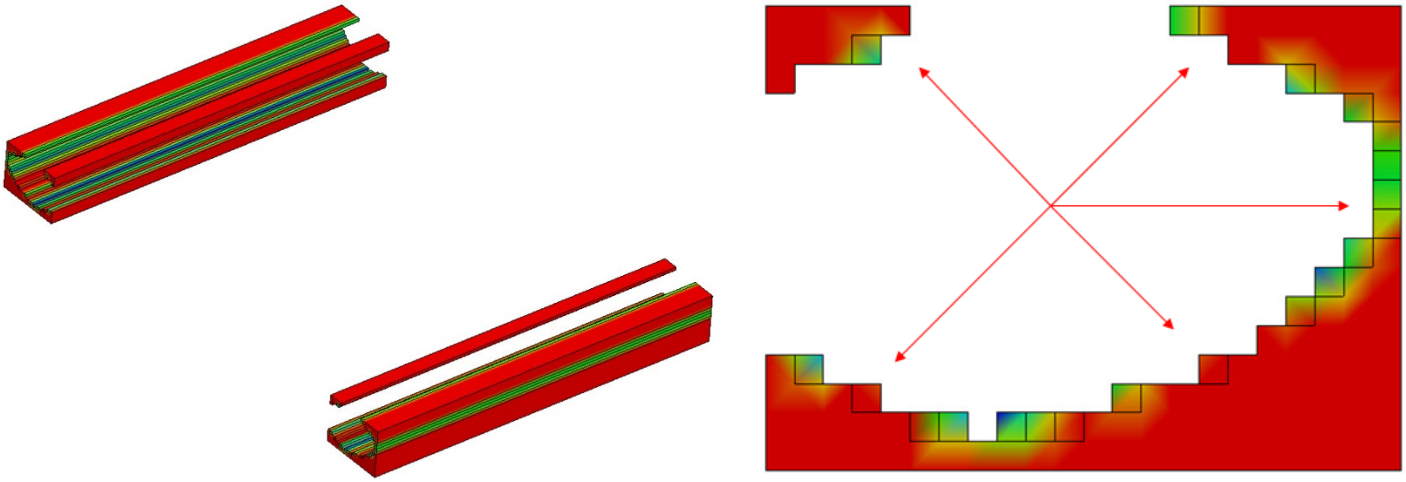

Figure 8: Results of the Side Sill after the 1st Stage of Topology Optimization.

3.2 Second Stage Topology Optimization: Side Sill Local Topology Optimization

The outer boundary for the side sill is extracted to create a reduced design space from the result of the first stage of optimization, and re-meshed in order to create a finer mesh for more accurate results as shown in Fig. 9. This extracted design is modified along the top edge of the side sill in order to connect the two spaces as seen in Fig. 8. The additional step of creating a finer mesh is possible since the size of the side sill design space is much smaller than the BIW considered in the first stage. The result for the cabin of the vehicle which includes the side sill is primarily for the standard operating conditions (static load cases), a localized topology optimization is performed on the stand-alone design space with two crash load cases, to obtain a detailed design. An extrusion constraint is again applied to the side sill design space to maintain uniform cross-section through the length of the extrusion. The model along with the crash loads are shown in Fig. 10.

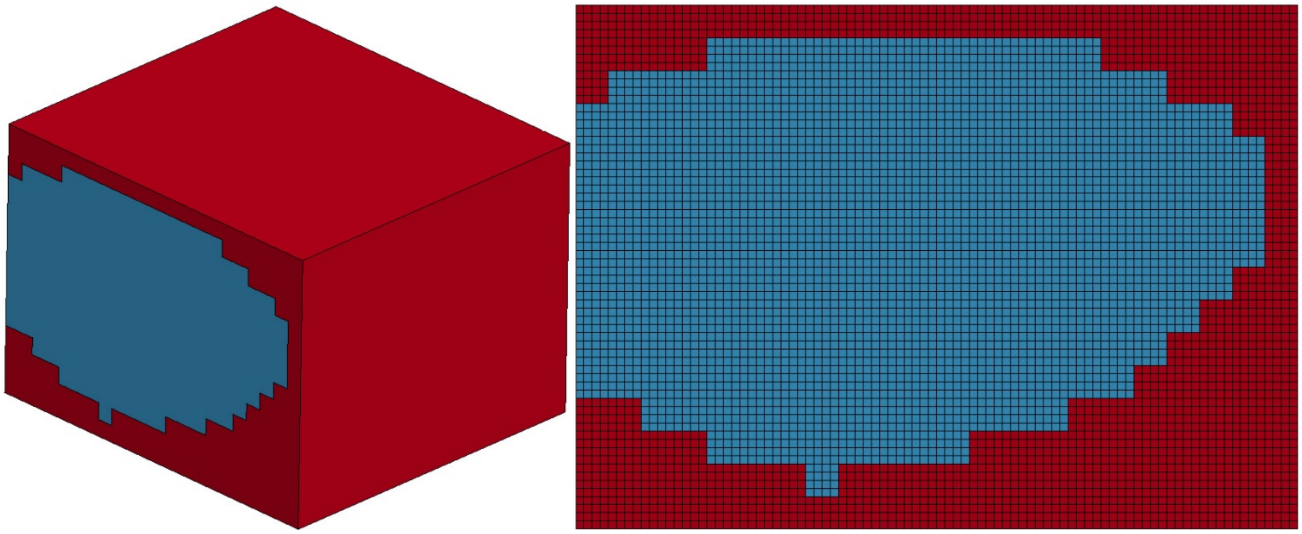

Figure 9: Side Sill Design Space for Second Stage Topology Optimization, where the red, outer design space is the result of the 1st stage and the blue, inner design space will be optimized in the 2nd stage.

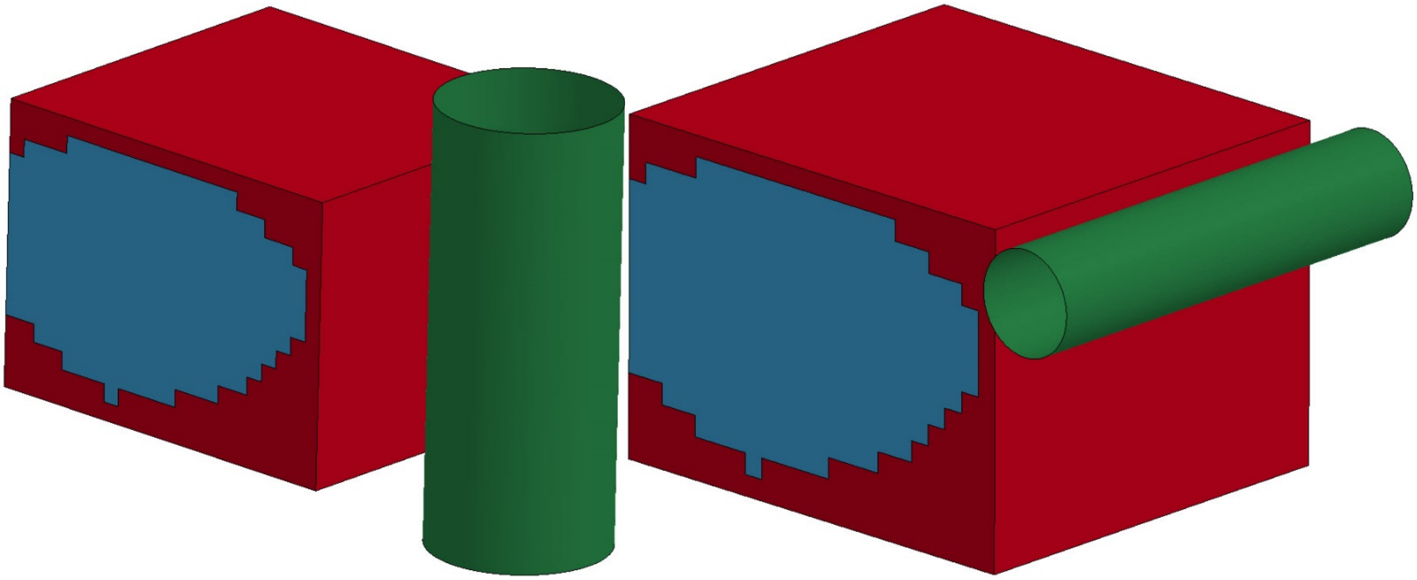

Figure 10: Side Sill Design Space Setup: Loadcase 1 (left), Loadcase 2 (right)

Similar to the first stage of optimization, the SEW-HCA method is used to assign equal preferences to both the load cases. A target mass fraction of 0.3 is set for the topology optimization with a move limit of 0.05. It is important to notice that the move limit in the second stage of optimization is much lower than the first stage. This is due to the fact that the element size is smaller (2.5mm) than in the previous stage of optimization. Optimal parameter values are used based on the findings in [6]. The preference values are as follows:

$$p_{crash} = p_{1,2} = 1/2 = 0.5$$

Since there are only crash loads in this stage of optimization, the analysis is done using the explicit solver. The total number of solid elements is 450560 with an edge length of 2.5mm. The same material model and material properties are used in the analysis. Fig. 11 shows the result of the local topology optimization on the side sill.

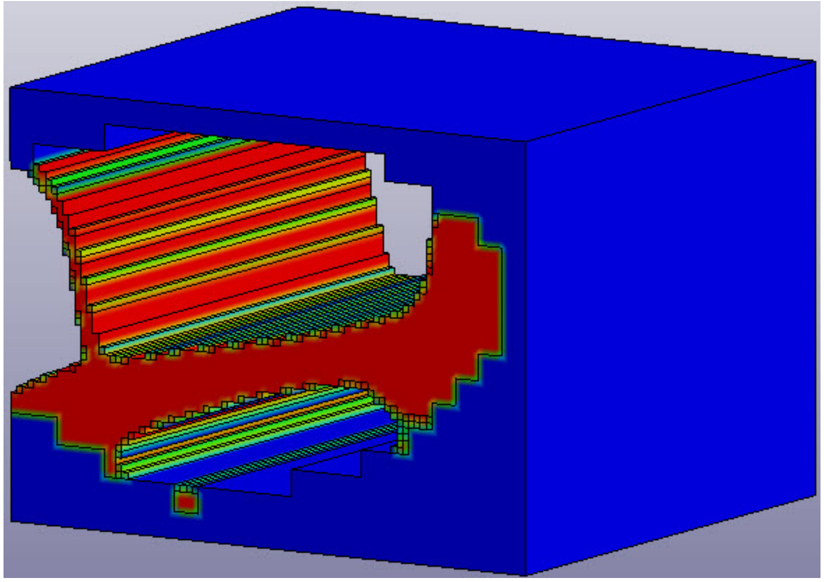

Figure 11: Second Stage Topology Optimization Result

3.3 Size Optimization on Shell Model

Upon completion of the localized topology optimization, the results are extracted and cleaned. This reference structure is then used to interpret a wireframe model for the cross-section of the side sill by contouring the topology results as shown in Fig. 12. This wireframe is then swept along the extrusion direction in order to generate a surface model. The surface model is then converted into a shell model for FEA purposes, as shown in Fig. 13. The new structure model consists of thirteen different thin-walled sections. For each section, a thickness variable is optimized in the 3rd stage shape optimization.

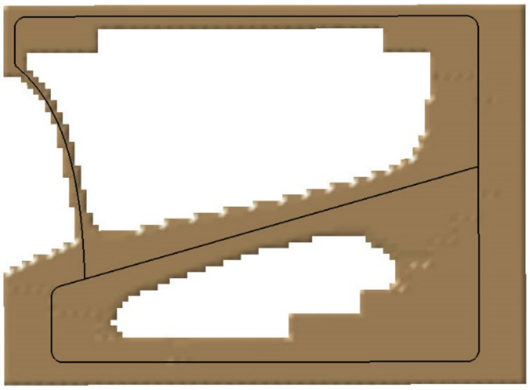

Figure 12: Wireframe Model Contouring the Optimization Result Figure

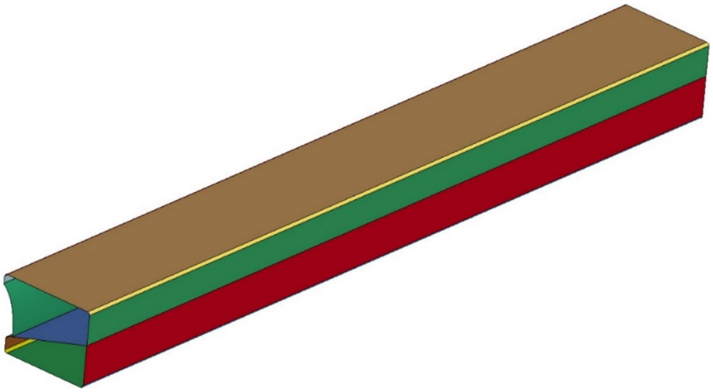

Figure 13: Shell Model of Side Sill

The 3rd stage shape optimization considers a total of three load cases (two static and one dynamic) on the side sill, which is extracted from previous stages, based on their effect on the side sill design. The static load cases are representative of the loads for standard operating conditions in the BIW. The dynamic load represents a side crash. The objective of the optimization is to minimize the mass of the side sill such that the resultant displacement in the static cases and energy absorption for the crash case, maintain the performance of a reference structure. The problem is represented as follows:

$$\begin{aligned} \min.\, mass(m) &= \sum_{i=1}^{13} t_i a_i \rho \\ s.\,t.\!: C_t &\le C_{tbaseline} \\ C_a &\le C_{abaseline} \\ EA_{crash} &\ge EA_{baseline} \end{aligned} \tag{5}$$

where m is the total mass of the side sill, t_i and a_i are the thickness and area of each shell component and ρ is the density;

C_t and $C_{tbaseline}$ are the compliance in the torsion load case, for the new side sill and baseline models respectively;

C_a and $C_{abaseline}$ are the compliance in the axial load case, for the new side sill and baseline models respectively;

EA_{crash} and $EA_{baseline}$ are the energy absorption for the new side sill and baseline models respectively.

The shell model is divided into 13 individual components. Each shell component in the model is optimized with varying thicknesses from 1mm to 5mm. Constraints (lower/upper bounds) are set on the models in all the load cases for the energy absorbed by the side sill for the crash case and resultant displacement for the static cases.

Four Point Bend Test and Results (Dynamic Load Case):

A standard 4-point bend test is shown in Fig. 14a and 14b (for the baseline and new design respectively) and is used to benchmark the shell model of the side sill. The energy absorption (internal energy) in the model is used, for performance comparison.

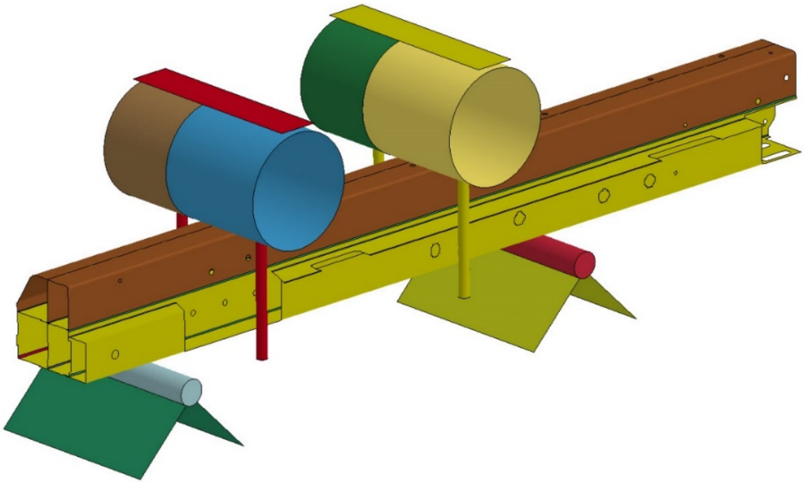

Figure 14a: Side Sill Baseline Model Setup

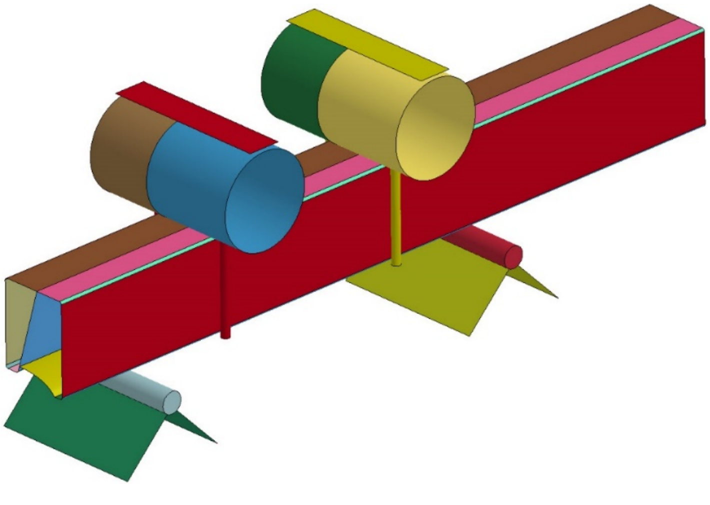

Figure 14b: Side Sill Shell Model Setup

Torsional Bend and Axial Loading Test and Results (Static Load Cases):

The torsional and axial loading tests closely represent the loads acting on the BIW applied during the first stage of optimization. Fig. 15 shows the model setup for the torsional load test for the baseline and the shell model. Equal moments are applied about the extrusion direction, on both ends of the side sill in order to induce a twist.

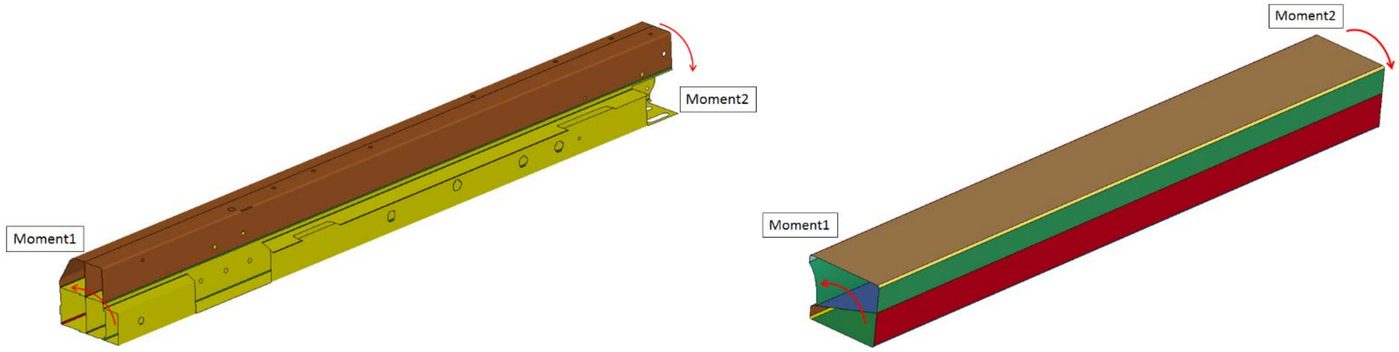

Figure 15: Torsional Bend Test Setup

Fig. 16 shows the model setup for the axial load test for the baseline and the shell model. Forces are applied along the extrusion direction and the other end is fixed in all degrees of freedom.

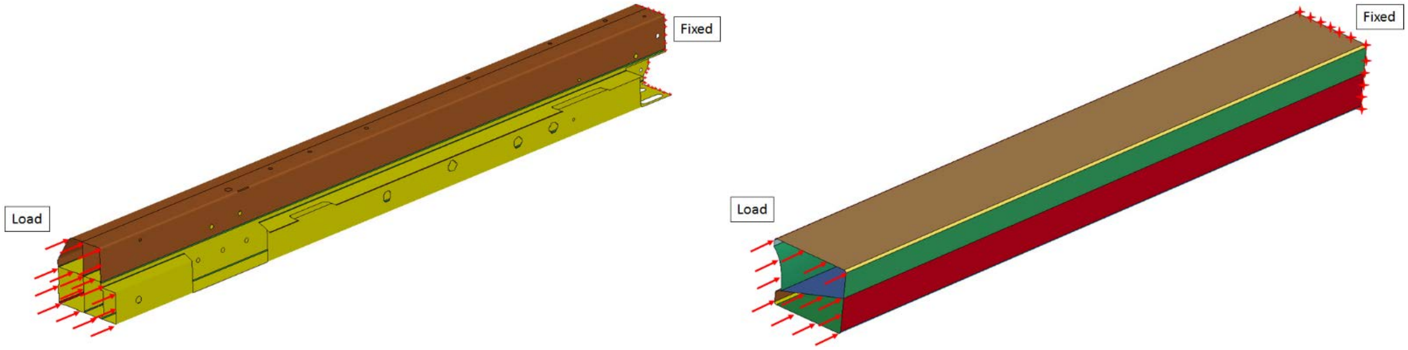

Figure 16: Axial Load Test Setup

Future development of this 3-stage optimization process will include the results of this size optimization. The weighting of the load cases is a concern since over emphasizing load cases with similar objectives, such as the static load cases which represent a normal operation, will decrease the performance of load cases whereas competing objective, i.e., energy absorption is the target. The investigation into the load case weighting is needed to devise the appropriate strategy as this weighting will impact the balance of the design to achieve the various targets for this structure.

4. Conclusion

This paper proposes a three-stage methodology to generate meaningful concept designs for specific vehicle components. The first stage of this methodology is a global topology optimization of the structure. Separate design spaces are defined as needed to account for manufacturing constraints. Several load cases are applied, and these load cases may have conflicting objectives such as minimum compliance and maximization of energy absorption. The Scaled Energy Weighting Hybrid Cellular Automata method allows for a balanced design to be generated which meets the various needs of a complex structure [1]. The second stage uses the results of the first stage to generate a local topology optimization problem. Appropriate load cases are defined and a finer mesh is used so that details of the substructure can be resolved with this optimization. For the case presented in this paper, these load cases were limited to an objective of maximization of energy absorbed as the first stage structure was driven primarily by minimum compliance requirements. This detailed topology result is then interpreted into a thin-walled structure. This is currently a manual process which requires interpreting the solid topology results into a shell representation of the structure. A size optimization can then be executed so that an optimized design is generated which meets the predefined targets.

Using the proposed three-stage optimization process enables the development of a concept design based on an initial design space which is a relatively coarse representation of the structure. By driving the design from this initial coarse representation to a more detailed representation, the optimized structure can be developed with the target load requirements driving the optimization definition. Application of manufacturing constraints results in a more feasible design which can be realized into a manufacturable structure which efficiently meets the design targets.

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