Deploying topology optimization for BIW Performance Optimization

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Abbreviations: ADT: Accelerated durability test,  
BIW: Body in white

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Abstract
Lightweight has been the main focus of the auto industry in recent years. To improve the competitiveness, weight reduction should be achieved without compromising the performance. A process for simultaneously minimizing the weight of an automotive body-in-white and getting the best structural performance is critical task, but topology optimization make it to happen.

Topology optimization is a mathematical approach that optimizes material layout within a given design space, for a given set of loads and boundary conditions such that the resulting layout meets a prescribed set of performance targets. This paper demonstrates how the topology optimization in initial phase of product development cycle is helps to provide good insights of load path in BIW to improve sections and joints to get best structural performance. This paper highlights the optimization process deployed for BIW and its benefits considering all the basic performance parameters like bending stiffness, torsional stiffness and modal characteristics.

Introduction
Developing an efficient vehicle in today’s world means that it meet all performance targets, fuel efficient, lightweight and toughest environmental standards. All these requirements are to be met without compromising customer satisfaction. Optimization tools can help to arrive at a very efficient structural design, which in turn helps improve other related aspects of the vehicle such as fuel efficiency, ride and handling. Although there is no one tool to help achieve all these goals, but utilization of the right optimization tools can certainly draw us close to meet the requirements.

Initial numerical optimization tool was developed in 1950’s by Schmidt for structural optimization applications [1]. Topology Optimization for discrete and continuum structures is explained in reference [2] and automotive body structural applications are explained in references [3-8]. The most important reasons for optimization here are to improve performance and reduce weight. There are a number of different optimization techniques that can be utilized to optimize a structure depending on the required end result. The process of choosing the right technique for a given problem to achieve these goals is always a challenge. This paper attempts to determine how topology can be used to optimize structures such as a body-in-white within the linear domain. Brief descriptions of this method is given in the next section.
It is important to note that the body-in-white is subjected to many loading conditions. In BIW, the opportunity to reduce the weight of structure will be more by satisfying the stiffness and strength requirements.

**Topology optimization**

Topology optimization is used at the concept level of the design process to arrive at a conceptual design proposal that is then fine-tuned for performance and manufacturability. This eliminates time consuming and costly design iterations and hence reduces design development time and overall cost with improved design performance.

The design space can be defined using shell or solid elements, or both. The classical topology optimization setup solving the minimum compliance problem, as well as the dual formulation with multiple constraints are available. Topology optimization has been widely studied and various approaches have been advanced since it was developed by Bendsøe and Kikuchi in 1988 [2]. The basic idea of topology optimization is to seek the best solution of material distribution within a specific given design area. The most widely used topology optimization methods include variable density method, homogenization method, evolutionary structural optimization method etc. [6]. Homogenization method is the simple method used for finding the optimum in the material model with micro-scale voids. Evolutionary structural optimization method is the main approach based on the concept of gradually removing material to find the optimal design. Variable density method is another main approach of structural topology optimization, in which the element densities are the design variables and material properties are assumed to be constant.

In this research variable density method is applied. A hypothetical variable density material, whose density varies between 0 and 1, is introduced to solve the variable density problem. The density of ‘0’ represents that no material is need in this area. The density of ‘1’ indicates that the material density requirement is large in this area. By applying the hypothetical variable density material method, the density of each unit is taken as a design variable and the structure topology optimization problem is successfully transformed into a material distribution optimization problem.

The topology optimization is that the design concepts developed are very crude in nature. Another problem is that the solution of a topology optimization problem can be mesh dependent, if no appropriate measure is taken.

The Approach followed in topology optimization is given below

<table>
<thead>
<tr>
<th>CAD Data for Design Space</th>
<th>Modelling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimization Setup</td>
<td>Results Interpretation</td>
</tr>
<tr>
<td>Design Recommendations</td>
<td>Validate Performance Improvement</td>
</tr>
</tbody>
</table>
Step 1: Generate the CAD data for the design space of any part or system for which optimization need to carry out.

Step 2: Create the Finite element model form the given CAD data. The FE data contains two segments, one is design space and other is non-design space. Design space is the maximum possible volume participating in optimization and non-design space is constrained area, which is not participating in the optimization process.

Step 3: After the FE modelling is done load cases are applied based on performance requirement. Optimization step up of FE model is done in any available optimization software’s like optistruct, Genesis etc. In this paper optistruct software is used for optimization.

Step 4: The very important and critical step of optimization process is interpretation of results. The challenge with post-processing topology optimization results is that the results may have several intermediate density elements or checkerboard patterns which can be interpreted either as solid members or as a void. Dense members indicates requirement of structural members, and voids indicates no requirement of member in that location.

Step 5: The topology optimization results helps the user to understand the load path of structure. The design recommendation are proposed based on topology optimization results by considering the manufacturability of part.

Step 6: The proposed new design based on design recommendation of topology results need to be evaluate for both mass and performance impact.

Optimization formulation

A structural optimization requires an optimization formulation. The basic optimization parameters are design variables, response, design constraint and an objective function.

Design variable:

Design variables are the parameters that are varied to optimize system performance.

Response:

Response are output or effects which are measured for the given inputs. Common types of responses are displacement, stress, mass and compliance. Responses used in this work are weighted compliance and volume fraction of structure.

Objective function:

Optimization formulation can be minimization or maximization. Objective function can be single objective function, which is a functions of single responses and multi-objective functions, which are
the functions of several responses. In this work the objective consider is to minimize the weighted compliance.

Constraints:

Each response might be constrained with an allowed minimum and maximum value. Constraints are used on the response to make sure that they are within the allowed limit. A constraint that always has to be fulfilled is the static equilibrium equation. The displacement measured for the required stiffness target is used as constraint for bending stiffness and torsional stiffness. Volume fraction is used as constrained for ADT analysis.

The basic idea of topology optimization in this paper is find the load path for the structure so that the optimized structure can be used to develop the sections and joinery of BIW. The work is done by taking two response, one is volume fraction and other is weighted compliances of ADT Loadcases. Minimization of volume fraction is taken as the optimization objective in this work.

The minimum and maximum member dimensions used are 50 and 1500 mm respectively for member creation.

CAE Model:

The CAE model is derived from the design space. The given design space is meshed with first order tetrahedral elements whose average element size is 15 mm. There are approximately 2400000 elements are present in CAE model.

The global stiffness (torsional and bending stiffness), ADT and modal characteristics of the BIW has great impact on ride and handling, NVH, vibration, collision and durability performance, hence these load cases are consider for the analysis. In this paper the work is done to find the load path w.r.to each load case and then improve the base design structural performance like bending stiffness, torsional stiffness and ADT with less number of design iterations with minimum weight in very short span of time.

BIW bending stiffness:

In this load case the structure is constrained at spring mounts. The constraints are applied such that it makes the structure stable, but not over-constrained. The load is applied vertically downward direction at center of structure. The loads and boundary conditions are shown in Figure 1.

BIW Torsional stiffness:

Similar to the bending stiffness load case, structure is constrained at spring mounts. The constraints are applied such that it makes the structure stable, but not over-constrained. The rigid is connection between the front shock towers and applied the torque at center of rigid by applying equal but opposite vertical loads at shock towers. The loads and boundary conditions are shown in Figure 2.
ADT:

The loads on BIW are considered as per RWUP (Real world usage pattern). Weight of all the systems which are mounting on BIW like Side doors, engine, front suspension, rear suspension are lumped at their respective CG locations. The Driver weight and passenger weight are lumped at respective locations. The analysis is carried out with inertia relief method.

Load cases consider for ADT are:

1. 2g LH twist load
2. 2g RH twist load
3. 3g Bending load
4. Door Sag equivalent static load
5. Door Slam equivalent static load

The loads of 2g LH twist, 2g RH twist, 3g bending loads are applied at front shock tower and rear bump stop location. The load of side door sag and door slam loads are applied at door latch location on both LH and RH side shown in figure 3.
Results & Discussions

The basic intent of topology optimization in this work is to find the load path so that the joints and sections can be improved to achieve optimum stiffness and modal characteristics with minimum weight.

Figure 4 shows the results of bending stiffness load case. Results shows that requirement of crossmember between the LH and RH long member below the floor.

Figure 5 shows the results of torsional stiffness load case. Results shows the requirement of cross member connection between the front two shock tower and head lamp panel in front side, beading pattern on the shock tower for high stiffness and cross member connection between the long rail and seat back rest in rear side of vehicle to improve the torsional stiffness.

Figure 6 shows the results of ADT load case, result shows the few similar section and joints as seen in bending stiffness and torsional stiffness load cases, which are discussed in the Figure 4, Figure 5 for front and rear side of vehicle. Apart from that it shows the requirement of cross member connection required between B-pillar bottom and D-pillar top, similarly strengthen Joinery connecting D Pillar and rear longitudinal rail with BSI to play key role in torsional stiffness and ADT. It also shows the structure need good section or reinforcement at both A-pillar and B-pillar location for better strength for side door sag and side door slam load cases.
Base design modification based on optimization results:

Based on the topology results of all load cases, the suggested design modifications are incorporated in base model. The stiffness and modal performance are evaluated for optimized design to see the improvement over the base design results. The Figure 7 shows the design changes done for base model rear end and other modification not shown because of confidentiality.

![Base design](image1)
![Optimized design](image2)

**Figure 7: Base design and optimized design**

The optimized design of Figure 7 shows that BSI is connected to long rail continuously till the end. And also shows the proper connection between BSI and BSO. The optimized design of chassis is like integral member of BIW as per optimization results. Connection between D-pillar top and B-pillar is done by changing the section of BSI, this will play key role in torsional stiffness and structural durability. The design modification given based on observation of optimization results showed in Figure 3 to 6 and changes are incorporated in the base design, all the modifications are not shown here because of confidentiality.

The normalized mass, torsion stiffness, bending stiffness and modal characteristics are compared between the base design and optimized design in below table.

<table>
<thead>
<tr>
<th>Table 1: Normalized structural Performance comparison of base design and optimized design</th>
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<tbody>
<tr>
<td>Parameter</td>
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<tr>
<td>Mass</td>
</tr>
<tr>
<td>Bending stiffness</td>
</tr>
<tr>
<td>Torsional stiffness</td>
</tr>
<tr>
<td>First bending frequency</td>
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<tr>
<td>First torsional frequency</td>
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</tbody>
</table>

The bending stiffness of optimized design is 3.9 times of base design, similarly torsional stiffness of optimized design is 4.1 times of base design. The first bending and torsional frequencies are 1.2 times of base design, this results achieved without any additional mass to the base design mass with less number of design iteration.
Benefits Summary

The topology optimization helps in optimizing the structure by identifying the load path and thus reduce the number of iterations to achieve required BIW structure performance. Hence, this process helps to reduce the product development cycle and fast to market.

Challenges

1. One challenge with post-processing topology optimization results is that the results may have several intermediate density elements or checkerboard patterns which can be interpreted either as solid members or as a void. If these semi-dense elements are interpreted as thin members, the final design is difficult to manufacture.

2. Another problem is that the solution of a topology optimization problem can be mesh dependent, if no appropriate measure is taken. The mesh size will be recommended is 10 mm and mesh should be first order.

Future Plans

Topology optimization is first step toward the unconventional optimization. Later MDO can be carried out for optimized the sections, gauge thickness and topography for bead optimization to improve the stiffness.

Conclusions

Topology optimization helps to identify the load path of the BIW structure, which can be used to improve the joinery and sections of BIW at an early stage of program. This will reduce the number of iterations to be carried out to reach matured BIW structure. The results also shows the magnitude of improvement possible in the modal and stiffness performance with minimum mass addition. This paper also suggest that the topology optimization should be part of design cycle to get best performance with minimum weight and time.

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