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Improvements in Vehicle Stiffness by Adding Internal Reinforcements

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ABSTRACT:

The world's climatic conditions rises and there is a demand for environment friendly vehicle designs. The automobile industry strives hard to ensure low carbon emissions. This refers to the mass reduction and fuel consumption. This paper investigates to achieve the overall Body-in-white (BIW) bending and torsion stiffness performance using Topology optimization and light weight internal reinforcements. The potential opportunity of achieving light weight structure using the efficient way of defining the internal reinforcements has been investigated. BIW at the conceptual design phase has been considered for the research. Topology optimization was performed considering the roof rail and the rocker as the design space with an approach of achieving the improved torsion and bending stiffness performance. The optimized bulk head design locations have improved the BIW stiffness performance with minimal mass increase in the BIW. This method can be widely used at various stages of the BIW design to identify the weaker sections and then design the load path using internal reinforcements effectively. The optimized internal reinforcements has achieved higher torsion and bending performance with minimal mass addition

KEYWORDS:

Design of experiments; Optimization; Body-in-White stiffness; Multi objective; Bending; Torsion, Bulk heads

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1. Introduction

The latest automotive technology calls for a better performance with minimal cost. Nearly 10% of mass saving on BIW mass can lead to considerable amount of saving on fuel consumption. Light weight vehicle designs can accelerate quickly with stability and better driving characteristics. Large scale production and low prices makes the automobile manufacturers to mainly focus on the cost control on the vehicles. BIW mass contribution will be major in the full vehicle mass with all the subsystems. The numerical research for optimization on the existing design and concept designs can improve the chances of minimizing mass of the design. Traditional techniques with dependency on experience and experiment used to have many trial and error iterations. During mass optimization, it is necessary to ensure that the performance targets are maintained. In many practical scenarios, after achieving low mass there may be some drop in performance. Engineers make aggressive attempts to improve the performance with minimal mass increase.

BIW structure should withstand complex load conditions during the operation of the vehicle under various disciplines like bending/torsion stiffness, NVH and crash. Research to improve the BIW structure performance are being carried out across different parts of the globe with a focus of cost effectiveness with a light weight body [1]. Numerical research is quick method of predicting the vehicle performance before testing and to make iterations for improving the performance of the design [2-4]. Liu [5] has proposed an efficient BIW weight reduction approach with consideration of complex safety and stiffness performances. A parametric BIW FE model was first constructed, followed by building surrogate models for the responses of interest. Stochastic design optimization was then performed to reduce the weight of BIW and ensure the robustness and reliability of the optimal design. A BIW vehicle design example was employed to demonstrate the proposed methodology in details.

Topology optimization of elastic structures to achieve reduced mass meeting compliance targets has been discussed [6]. But this approach was limited to only topology element density contours. The gauge sensitivity on the D-pillar region and locally gauges optimization has been investigated by Guan Zhou [7]. The technique of locally organizing the elements and then optimizing the thickness need to be validated at the full model level. Author [8] has researched the technique of identifying the optimal material mapping in the BIW and achieved reduced mass BIW meeting the performance targets. Baskin D. [9] and Christensen [10] have achieved BIW load path by topology optimization and they have highlighted topology optimization [11,12], joint stiffness [13] and its importance in concept phase. Donald [14] has developed a process for simultaneously optimizing the mechanical performance and minimizing the weight of an automotive body-in-white. The process began with an appropriate load path definition using optimized topology. Load paths were then converted to sheet metal, and initial critical cross sections were sized and shaped based on packaging, engineering judgment, and stress and stiffness approximations.

An approach of optimizing the thickness of the BIW parts using design of experiments has been detailed by Londhe [15]. Similarly a meta model concept was investigated for crash analysis [16, 17]. BIW designs using the carbon fibre composites have been numerically investigated by Boeman [18] and seem to achieve the improved structural performance. Jeong-Soo [19] has investigated the advantage of using Optimal-Latin-Hypercube method due to its capability to predict minimized error as a better option than Latin-Hypercube. Calvo [20] has investigated numerically on the BIW and attempted to propose hybrid cabin for front motor component and rear component. The methodology uses topology optimization and topographic optimization for reducing the thickness by applying static loads equivalent to measure the architecture performance. Literature survey shows that there is a lot of investigations performed on the BIW to reduce mass and improve performance. Conventional topology optimizations [21-23] and thickness optimizations has been widely researched. However, the combinations of topology optimization and use of series of light weight internal reinforcements to enhance the performance still has lot of opportunities.

This paper presents a new methodology of improving the overall BIW performance with minimal mass increase using the internal reinforcements driven by the topology optimization simulations. The effective method of using topology optimization and light weight internal reinforcements have been focused in the paper. The roof rail and rocker design section space has been used for the optimization research to improve the overall performance. The performance comparison between the initial design and optimized performance design has been carried out to validate the effectiveness of the methodology.

2. Methodology

2.1. Initial BIW design performance summary

The initial BIW design considered for the investigation was having no internal reinforcements. The global stiffness characterization of the conceptual BIW design can be determined by bending and torsion stiffness analysis. The initial design was applied with 1 kN Force on the rocker before the B-Pillar to predict the bending stiffness of the BIW design. For the global torsion stiffness, the static moment was induced by applying the 1 kN force on the front shock towers. Since linear stiffness analysis is being performed on the BIW applied force will have a linear response on the induced response. The mass of the initial BIW was 175.1 kg. Bending and torsion stiffness will define the fundamental structural competency of the vehicle. The bending and torsion stiffness from the simulation are found to be 6.463 kN/mm and 10.918 kNm/deg. respectively The results for the initial design stiffness analysis has been shown in Fig. 1(a) and 1(b).

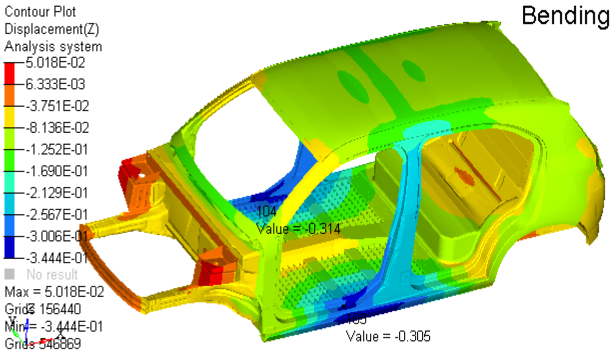

Fig. 1(a): Initial design - bending stiffness analysis results

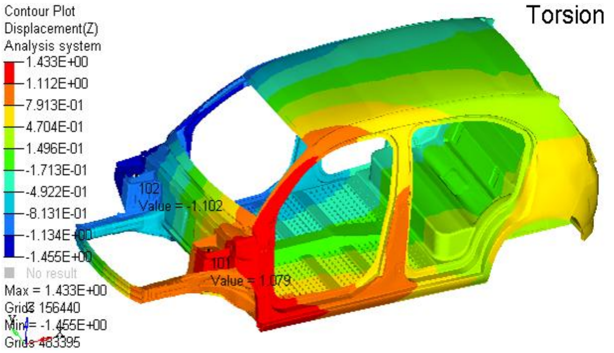

Fig. 1(b): Initial design - torsion stiffness analysis results

2.2. Design space - roof rail and rocker sections

The scope of the topology optimization procedure was to achieve minimum volume on the given design space. So the expectations will be the availability of materials in the efficient load path for the given load cases. The roof rail and the rocker sections volumes have been investigated for the internal reinforcements. The complete volume of the roof rail and rocker were meshed with solid tetrahedral elements. The nodes on the skin of the tetra elements were made node to node merge with the roof rail and rocker mesh to ensure the complete connectivity. The volume mesh for the design space of rocker and roof rail is shown in Fig. 2.

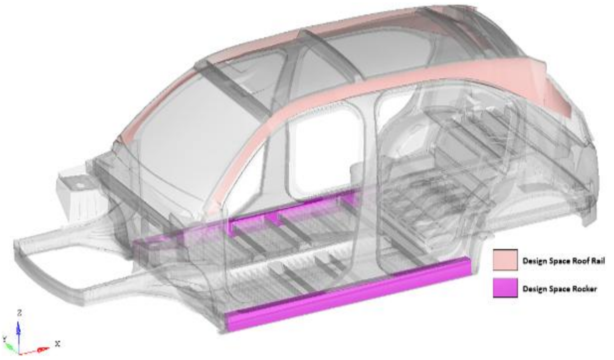

Fig. 2: Roof rail and rocker design space for topology optimization

2.3. Topology optimization on the design space

Topology optimization is the structural optimization for any given design space to restrict material addition only on the load path. Using topology optimization, the optimal location for placing the material can be identified. The success of any optimization setup is dependent on identifying the possible good topology space. Design space is the geometrical space allowed to be considered for the optimization. Design variable in the topology optimization is a discrete value of material or void and every point in the design space is design variable. In theory, this means any structural shape can be achieved within the design space. The element density contours for the roof rail and rocker section volumes are shown in Fig. 3.

Topology optimization was performed with the following setup:

1). Objective:

- Minimize mass
- Minimize compliance

2). Constraints:

- Constraints on the range of allowable vertical displacement on the front shock tower mounts (LH and RH) for torsion stiffness load case
- Constraints on the range of allowable vertical displacement on B-pillar rocker region (LH and RH) for the bending stiffness load case.

Topology optimization has been performed using Optistruct solver. Based on the topology optimization, the element density contours of the effective load path as shown in the Fig. 3 has been achieved. The results from the topology optimization highlights the areas of the effective load path with in the design space. These areas are further considered for reinforcement additions.

Fig. 3: Topology optimization results

2.4. *Internal reinforcements design on the roof rail and rocker sections*

The locations with the higher element densities were identified from the topology optimization results as shown in the Fig. 3 and were further used for reinforcement's definition. Bulk heads were commonly used reinforcements in the BIW designs to improve the vehicle performance. Bulkheads were designed as magnesium material with a thickness of 1mm and their masses ranges from 80-100grams depending on the design space in the rocker and roof rail. Linear material properties of the standard magnesium material has been used for analysis. Series of Bulk heads were designed with reference to high density element contour locations from the topology optimization. Fig. 4 shows the positioning of the bulkheads in the rocker and the roof rail regions. Mainly they were populated in the A-pillar, B-pillar and C-pillar joints on the roof rail. Inside the rocker, the optimized reinforcement locations were found to be in the B-pillar lower region extending up to the hinge pillar lower.

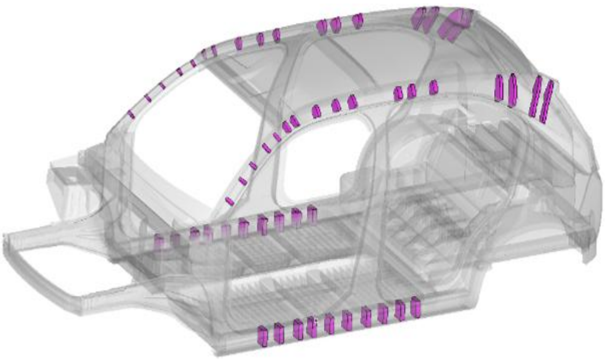

Fig. 4: Internal light weight reinforcement designs

This method of adding small internal reinforcements will improve section integrity and the design can have stiffer response. The stacking of the internal reinforcements in relation to the topology results can achieve some mass savings and performance improvements. Fig. 4 shows the number of internal reinforcements added in the BIW design space. The reinforcements were connected to the BIW using structural adhesives. Light weight internal reinforcements can be more beneficial in terms of mass added to BIW stiffness improvement ratio.

2.5. *Simulation results and discussions on optimized reinforcements design*

Efficient reinforcement technique should be a parallel process during the development of the Car BIW. This is a methodology to add the material systematically in the BIW based on its architecture for the given load conditions and design space. Simulations were performed on the BIW with internal reinforcements defined as per the topology optimization for bending and torsion stiffness load cases. This technique is highly influential on the conceptual body and has been of great knowledge on the load path also to identify the weakness in the BIW structure. FEA results for optimized design are shown in the Figs. 5(a) and 5(b) and their summary results are presented in Table 1 and Table 2. The bending stiffness and torsion stiffness for the optimized reinforcement design are 6.785 kN and 11.46 kNm/deg respectively. This methodology has combined topology optimization with an incredible effective way of creating internal reinforcement in the rocker and roof rail. BIW design with optimized bulkhead locations has a mass of 178.8kg. This shows the methodology of using a series of small internal reinforcements can be highly efficient in achieving higher performance with minimal mass increase. Another significant advantage is the use of existing structure and load cases. Topology optimization and internal reinforcement strategy at early stage of the BIW conceptual design could be helpful in planning the load path and reinforcements in the design concepts, which is more valuable than the detailed design in the conceptual phase. The optimized locations in the rocker clearly highlights the B-Pillar and hinge pillar lower reinforcements were strengthening the design for bending.

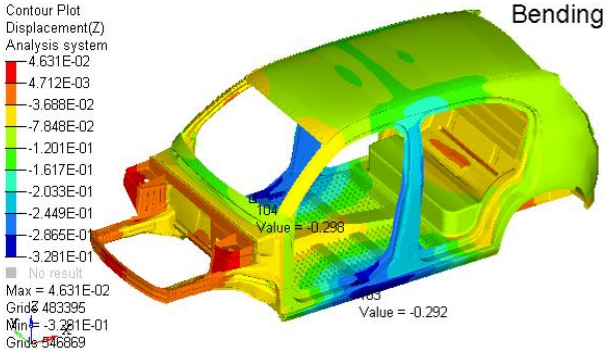

Fig. 5(a): Validation simulations results - bending stiffness

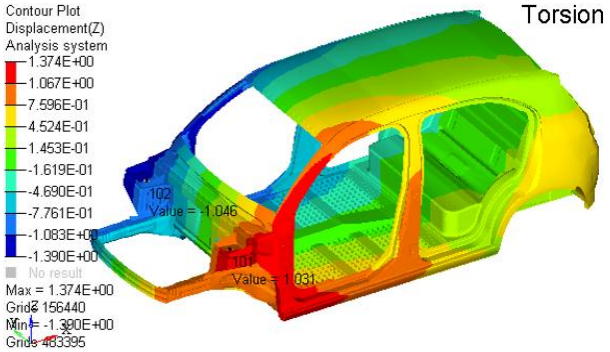

Fig. 5(b): Validation simulations results - torsion stiffness

Table 1: Summary of bending stiffness results

Details	Mass	Bending stiffness	Bending stiffness / mass	% Improvement on bending stiffness / kg
	kg	kN/mm	kN/mm/kg	
Baseline design	175.1	6.463	0.0369	
Optimized design	178.8	6.785	0.0379	2.81%

Table 2: Summary of torsion stiffness results

Details	Mass	Torsion stiffness	Torsion Stiffness / mass	% Improvement on Torsion stiffness / kg
	kg	kN/m/deg	kN/m/deg/kg	
Baseline design	175.1	10.918	0.0624	
Optimized design	178.8	11.465	0.0639	2.40%

The reinforcements lining up the floor cross members have significantly helped to improve the under body strength by adding more lateral stability. The reinforcements in the rocker have improved the bending stiffness significantly. The stiffness improvement in the BIW design can have better performance on acceleration or deceleration of the vehicle. The roof rail internal reinforcements from optimization were mainly stabilizing A-pillar, B-pillar and C-pillar upper joints. C-pillar upper internal reinforcements were strengthening up the design to improve the match boxing and lining up with rear header ensuring lateral load transfer. A-pillar and B-pillar upper region reinforcements in the roof rail were reinforcing all the three major upper joints. The roof rail reinforcements improved the torsion stiffness of the BIW architecture significantly. Torsion stiffness will significantly impact the suspension kinematics, compliance, handling, ride behaviour and steering effects. The current research is BIW structure stiffness based solution under torsion and bending loads.

3. Conclusions

The methodology of using topology optimization, identifying the load path in the given design space and then adding a series of small light weight internal reinforcements have shown considerable improvement in the stiffness of the BIW with a minimal mass increase. Since the roof rail and rocker volumes were considered as the design space for the optimization process, the possible performance improvement in the BIW has been achieved. Based on this method, bending stiffness values improved from 6.463 kN/mm to 6.785 kN/mm and the torsion stiffness increased from 10.918 kNm/deg to 11.465 kNm/deg. With an addition of 2.1% of BIW mass (3.7 kg), the method has achieved a 2.8% increase in the bending stiffness and 2.4% increase in the torsion stiffness. This method has shown the efficient way to improve overall BIW stiffness considering the roof rail and rocker section as design space. This method can be extended further to other possible sections spaces available in the BIW like hinge pillar section, Floor cross members sections, front/rear rail sections etc. Since the effectiveness of the topology optimization alone was focused on this current investigation, further thickness of the reinforcements can also be considered as a variable.

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