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Multi-Objective Optimization of Material Layout for Body-In-White using Design of Experiments

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ABSTRACT:

Vehicle mass reduction is a major area of research in the automobile industry. Various techniques like reduced part break up, section reduction, material alternatives and load path design are widely being researched across the world. This paper presents a new technique of identifying materials for the components of minimal part break-up Body-In-White (BIW) in the conceptual phase using design of experiments and multi-objective optimization. Prime focus was on the methodology to effectively consider the materials for the parts without compromising the structural performance of the target components. BIW structural load cases like bending and torsion stiffness were considered to evaluate the structural performance. Material list is used as the design variable and then sampled using design of experiments to undertake multi-objective optimization. As a result, optimal material distribution and mass savings have been achieved for the BIW parts. The optimized design performance is closer to the baseline design. The proposed methodology may be widely adopted by engineers to optimally distribute the materials for the BIW components at various stages of the vehicle design.

KEYWORDS:

Design of experiments; Multi-objective optimization; Body-In-White; Bending stiffness; Torsion stiffness

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1. Introduction

In the automobile industry, the major challenges are energy consumption and protection of the environment. It is therefore necessary to achieve increased fuel economy and emission control with better vehicle architecture. With a reduction of about 5-10% of the vehicle mass, one could expect fuel savings of 4-6% [18]. With reduced mass, the vehicle can accelerate much faster, with more stable and enhanced NVH performance [17]. From safety perspective, the vehicle can have much shorter braking distance since the inertia on the body gets reduced with reduced mass on the vehicle body [16]. Light weight body and better energy management in the vehicle are crucial factors in any vehicle development. Nearly 30-35% of the full vehicle mass is from Body-In-White (BIW). So, the automotive industry focuses a lot on mass reduction opportunities in the BIW right from the conceptual design stage [12, 14, and 16]. The BIW with all its complexity should satisfy all the constraints on multiple disciplines like stiffness, NVH and crash safety [11, 13, and 19].

BIW designs must be able to support the structural loads under various performance conditions. Many numerical researches are being performed across the world on BIW. With the latest technologies, numerical simulations can reduce the BIW mass and product design time frame to a larger extent. Baskin [9] and Christensen [20] have explained their approach to achieve BIW load path using topology optimization and has also highlighted the significance of designing the conceptual BIW for its stiffness as a first step. The approach on optimizing the BIW parts for its thickness using Design of Experiments (DOE) analysis and direct optimization has been performed in earlier studies to compare the optimization approaches by Londhe [2]. Comparison on the methodology of optimization using components made of Aluminium BIW structures and optimum joint stiffness improvement methods have been discussed by Lee [3]. It has been suggested that the pitch of spot weld and part thickness can be used as sensitive parameters. BIW designs with light weight solutions using the carbon fibre composites have been numerically researched by Boeman [14] and believed to achieve the structural performance.

Park [1] has concluded that the Optimal-Latin-Hypercube method is the better choice instead of Latin-Hypercube. Also, it has been highlighted that the prediction error is minimal while using the Optimal-Latin-Hypercube method and has been suggested the same for DOE sampling as well. Liu [12] has explained the methodology of parametric BIW and then trying to reduce its mass. Stochastic optimization approach has been researched to achieve the mass reduction. DOE based optimization using thickness as a design variable and the subsequent structural optimization has been researched by Londhe [2]. Calvo [10] proposed a hybrid cabin that uses metal for front motor component and rear component. The approach uses topology and topographic optimization for thickness by applying equivalent static loads to measure the performance. Based on the literature survey, there is a considerable amount of optimization approach on BIW that has been researched across the world. Most of the researches were performing the conventional topology optimizations and then trying to optimize the thicknesses. However, those researches lack focus on how efficiently the material distribution on the parts of the BIW can be used to innovatively optimize the mass.

This paper considers the structural stiffness of BIW in the conceptual development phase. The proposed new technique considers materials list as the design variable for the optimization. This methodology can also be applied to all the vehicles even across multiple disciplines. Non-structural load path components were mainly considered as design variables in the interest of time and computational efforts. If there is an availability of a large computational facility, this method can also be extended to other disciplines. Implementation of multi-objective optimization focuses on mass reduction without compromising much on the target stiffness [5, 6, 7, and 8]. Bending and torsion stiffness can be analysed to understand the BIW stiffness [15, 19]. Multi-objective optimization techniques using DOE combined with sensitivity study were implemented to achieve considerable mass savings in the BIW [4]. This technique of optimization could help an engineer save a lot of time and effort throughout the vehicle design process [2]. Changes based on the sensitivity of the design variables were also implemented and simulated to further improve the BIW stiffness [9].

2. Analysis of baseline BIW

The Baseline BIW design has a minimal part break up in the BIW and the aim of the research is to achieve minimal mass design. The Baseline BIW architecture with steel lower body and aluminium upper body has 58 parts [3]. BIW bending and torsion stiffness load cases were considered for the structural performance evaluation [15]. The mass of the baseline BIW is 185.7 kg as shown in Fig. 1. It's bending and torsion stiffness is 6.4 kN/mm and 11.06 kNm/deg respectively as shown in Fig. 2. For any BIW development, the criterion is to satisfy the structural stiffness of the load at an early stage of the design. Structural linear solver has been used to simulate this analysis. Since the interest is to keep the BIW architecture the same and to find out its optimal material distribution, material is the only variable for BIW parts in this paper.

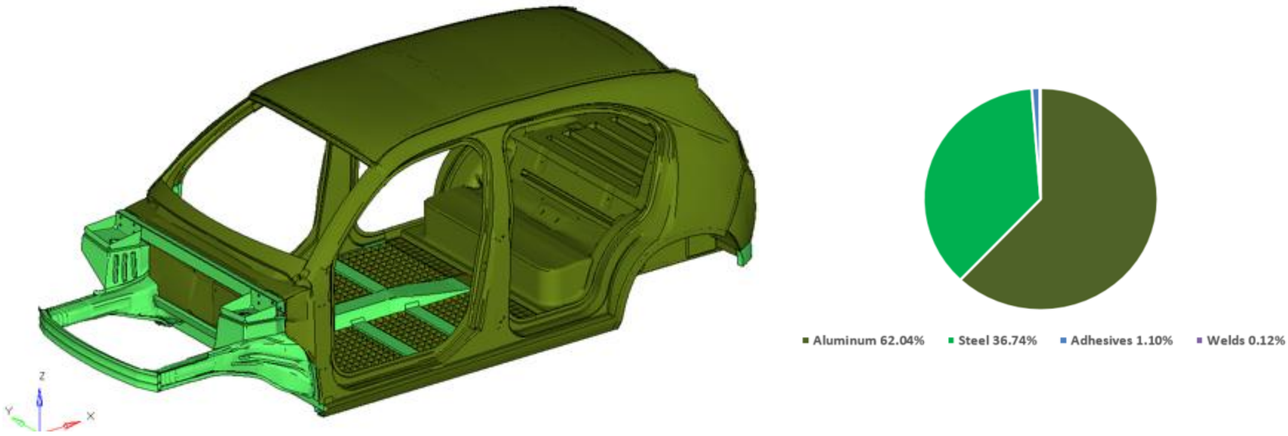

Fig. 1: Baseline BIW material distribution on part basis

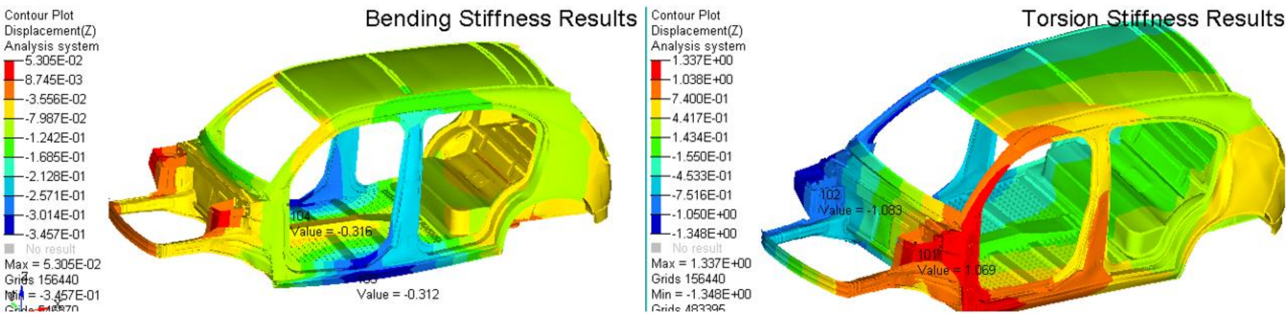

Fig. 2: Stiffness results – Baseline BIW

3. DOE based material sampling

Material variables are considered for the upper body and floor components of BIW as shown in Fig. 3. Major structural components of the material variables amongst the list are defined with combinations of materials like Aluminium and Magnesium. The materials list like PP-GF50, PA66-GF50 and PP-GF50 which are non-structural stiffness members were also used. A total of 26 components were considered for the DOE sampling. Front floor has 6 parts and they were grouped together as a single parameter. Similarly wheel arch, roof rail, B-pillar and rear connecting member components are symmetric about LH and RH, so each of the component pair were considered as a parameter. After identifying all the variables, the DOE has 17 parts with material as variable. The rocker, cross members, tunnels, front rails, hinge pillar and shock tower were considered to be in the non design space. The material variables from Table 1 are provided as an input to the optimization software to generate the DOE sampling [1]. For the baseline BIW, the value of material variable is 1 for all the parts. Optimal Latin Hypercube was used to extract the DOE sampling. There are 17 design variables, so 51 sample designs were extracted. Table 2 summarises the material variables for the first and last two samples. For each of these DOE sample, the BIW model was prepared. All the 51 BIW designs were analysed for bending and torsion load cases. For each of these sampling, the mass, bending and torsion displacement results were extracted.

Table 1: DOE sampling [6] for all variables

Part name	Min. design	Max. design	Variable description
Roof outer	1	3	1 PA66-60% glass filled material
Roof inner	1	3	
Wheel arch	1	3	
Rear floor lower	1	3	2 PA66-50% glass filled material
Rear connecting member	1	3	
Rear floor rear lower	1	3	
Rear floor front	1	3	3 PP-50% glass filled material
Front floor	1	3	
Rear header	1	3	
Roof bow 3	1	2	1 Magnesium
Roof rail	1	2	
B-pillar inner	1	2	
Front dash	1	2	
Rear floor inner reinforcement	1	2	2 Aluminium
Rear header reinforcement	1	2	
Roof bow 1	1	2	
Roof bow 2	1	2	

Table 2: DOE sampling for all design variables

Part name/Variable sampled	Sample number 1	2	50	51
Roof outer	3	3	1	1
Roof inner	1	2	1	1
Wheel arch	2	1	1	2
Rear floor lower	2	1	1	2
Rear connecting member	2	1	3	3
Rear floor rear lower	2	3	1	3
Rear floor front	2	2	1	1
Front floor	2	2	2	1
Rear header	1	2	2	2
Roof bow 3	2	2	2	1
Roof rail	2	1	1	1
B-pillar inner	2	1	1	2
Front dash	1	2	2	2
Rear floor inner reinforcement	1	2	2	3
Rear header reinforcement	2	1	1	2
Roof bow 1	2	3	3	1
Roof bow 2	1	2	2	1
Roof outer	3	3	1	1

Response Surface Model (RSM) is a method of approximation of the responses of the DOE results. All the 51 sets of data points representing the DOE variables and their responses like mass and displacement will formulate the RSM. RSM is used to establish a relationship between the design variables and the responses. From the DOE results, cross validation curves were extracted to verify the DOE accuracy. The actual vs. predicted response has only 3.3%, 2.7% and 5.8% error for mass, bending and torsion displacements respectively as shown in Fig. 4. This percentage of error on the actual response is within the acceptable range. Hence, the actual outputs will be closer to the RSM predictions.

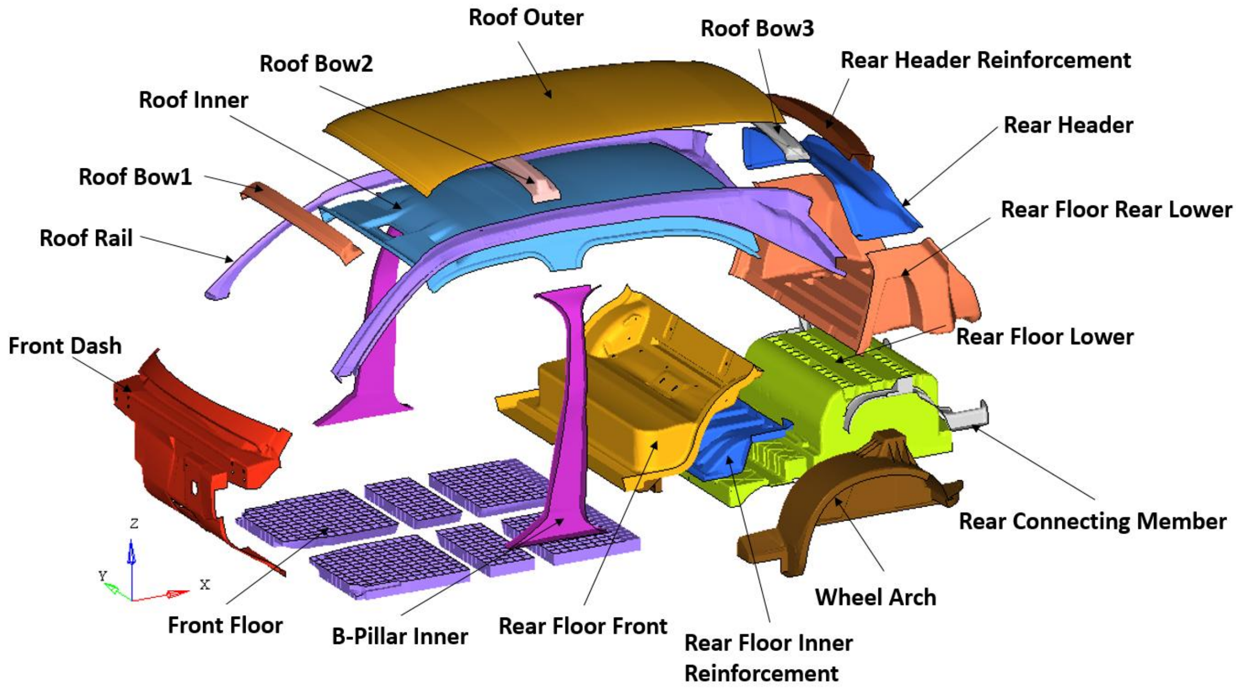

Fig. 3: Upper body parts considered for material DOE

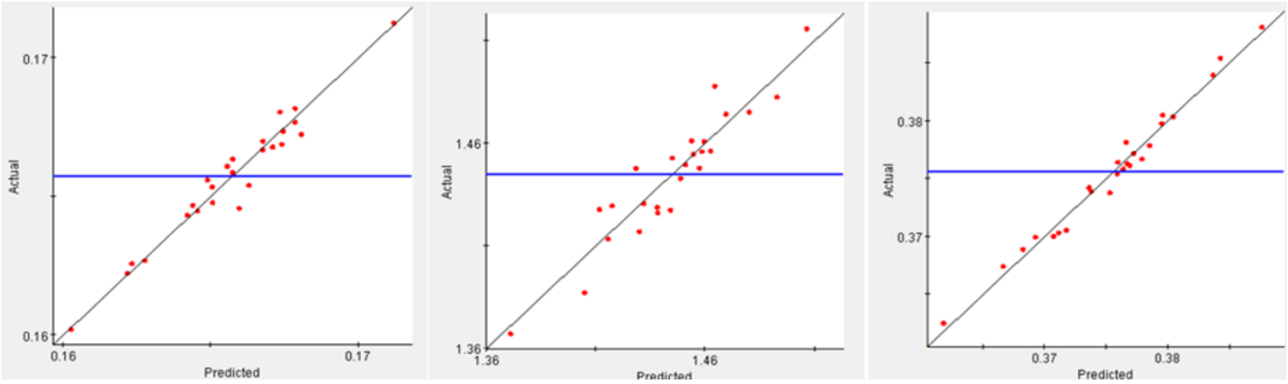

Fig. 4: DOE results cross validation for mass (left), torsion displacement (middle) and bending displacement (right)

4. Results and discussions

4.1. Sensitivity of material variables on bending and torsion stiffness

Fig. 5 shows the sensitivity of the variables with respect to the bending stiffness analysis. The components like front floor, rear floor and wheel arch have high sensitivity with positive effect. These components can be strengthened to improve the overall BIW bending stiffness. The material change from lower strength to higher strength in the B-pillar inner, roof rail and front dash will not be much effective in meeting the objectives. So even if their material strength increases, the stiffness of the overall structure will not improve significantly. Hence, these are the variables with negative effect. The components like roof bow 2, roof bow 1, rear header reinforcement and roof outer have no sensitivity related to the bending stiffness of BIW. Fig. 6 shows the sensitivity of the design variables on the torsion stiffness of the BIW structure. The increase in the material strength for the front dash, roof rail, B-pillar inner and rear floor inner reinforcements were showing a negative effect on the torsion stiffness performance of the BIW. The material update for rear floor lower, wheel arch, roof inner, rear floor front, front floor, roof outer and rear header can effectively increase the BIW torsion stiffness. Some of the components like front roof bows have very low sensitivity on the torsion stiffness.

4.2. Multi-objective optimization for material layout on the BIW

Multi-objective optimization problem was setup with an objective to maximize mass saving and minimize compliance. The constraints in the optimization were set to achieve a minimum of 15% mass saving and displacement constraints were focussed on bending and torsion load case displacements. Optimization runs were performed using the I-sight software and several optimization scenarios were studied to obtain the optimized design. The optimized design generated is implemented in a finite element model. The optimized design, as shown in Fig. 7, has a material distribution of 19.8% Aluminium, 2.4% Magnesium, 41.1% Steel, 27.5% PA66GF60 and 5% of PPGF60. Bending and torsion stiffness analyses were performed on the optimized design. The optimized BIW design has a mass of 156 kg with multi-material distribution for the parts. There is a mass reduction of 16% (29.7 kg) considering the targets for bending and stiffness performance of baseline model. The simulation results for the optimized BIW are shown in Fig. 8. The bending and torsion stiffness of optimized DOE is 5.52 kN and 8.8 kNm/deg respectively. The performance metrics were meeting the stiffness targets for BIW design [14]. There is some drop in the stiffness as compared to the baseline.

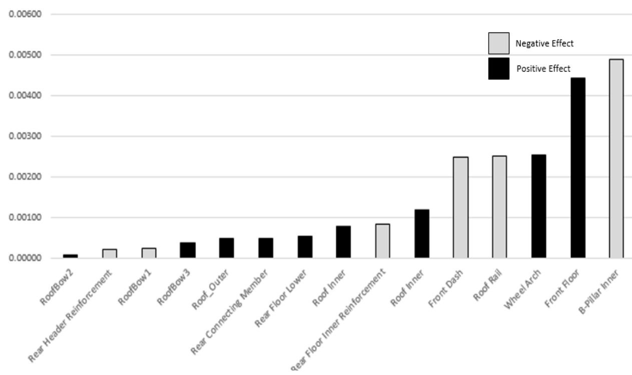

Fig. 5: Sensitivity of the variables for the bending load case

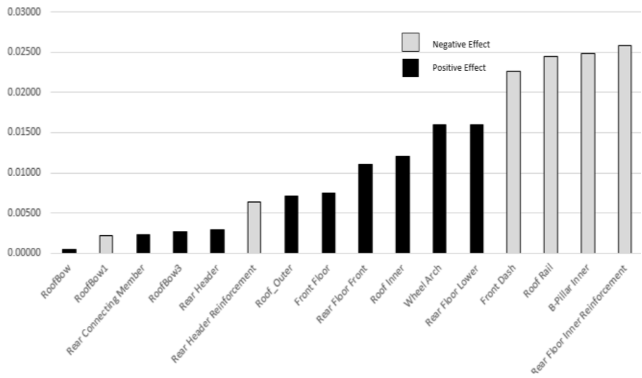

Fig. 6: Sensitivity of the variables for the torsion load case

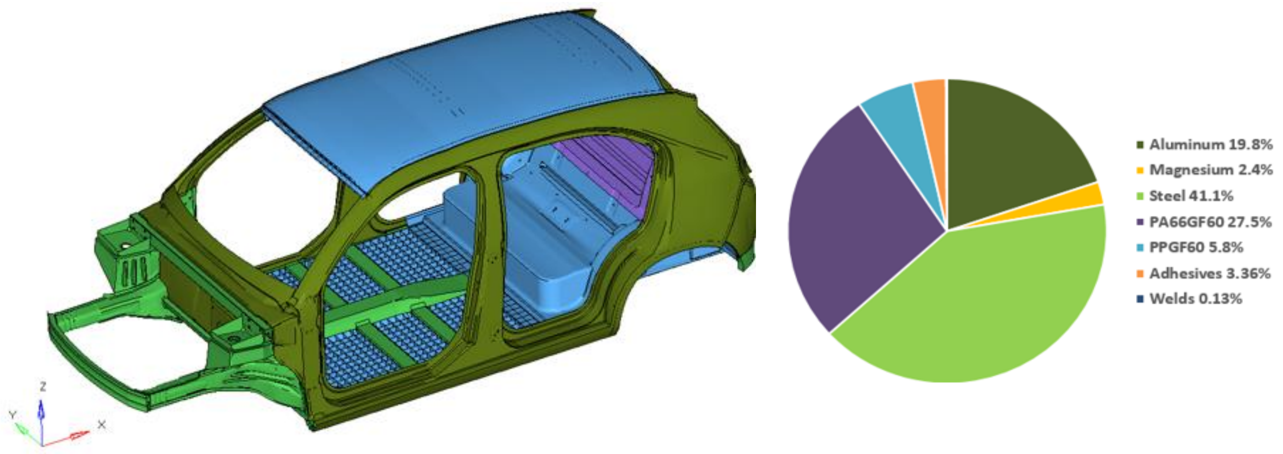

Fig. 7: BIW Design with optimal material layout

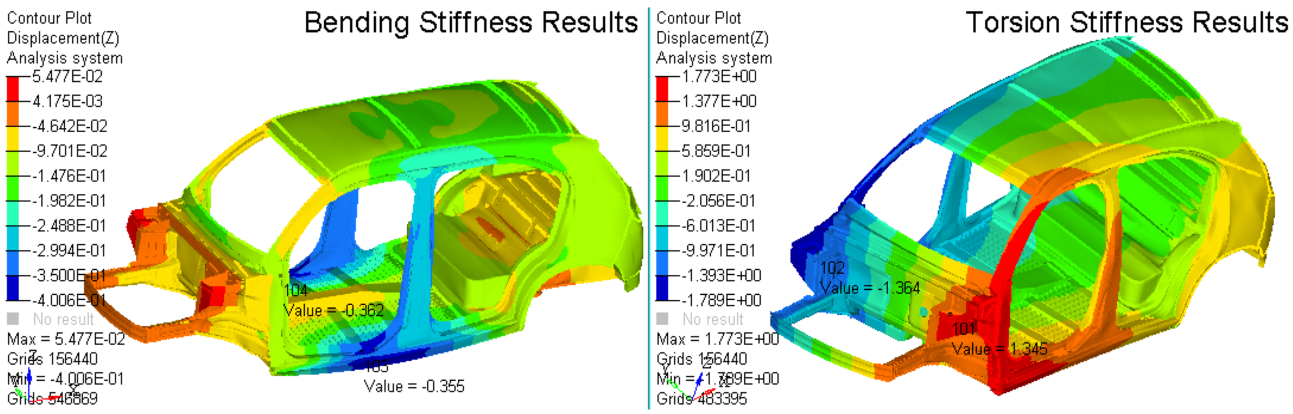

Fig. 8: BIW Stiffness results - DOE optimized material layout

4.3. Sensitivity based BIW engineered solution

Since material is the only design variable and the thickness of the parts remained constant during the DOE based multi-objective optimisation, there is an opportunity to further improve the stiffness of the BIW based on the sensitivity plots. The components like wheel arch, rear floor lower, roof inner, roof outer, rear floor rear lower, front floor and rear floor front were the sensitive parameters in the BIW. The gauge thicknesses for these parts were increased to achieve higher BIW stiffness. The mass summary is shown in the Table 3. Fig. 9 shows the analysis results of the BIW with increased gauges. The improved bending and torsion stiffness is 6.35 kN and 10.44 kNm/deg respectively. The mass of engineered BIW design is 173.42 kg. The structural performance is increased by 15.9% for bending stiffness and 18.6% for torsion stiffness as compared to the DOE optimized design. The finalised BIW design has met the bending stiffness targets of the baseline design. However, the torsion stiffness was 4.9% less than the baseline design. This torsion stiffness drop can be improved with optimum mass by carrying out further joint stiffness analysis and a shape/gauge optimization.

Table 3: BIW design variable parts mass summary

Part name	Baseline design parts mass kg	DOE optimized design mass kg	Sensitivity based updated design mass kg
Roof outer	8.00	5.04	6.84
Roof inner	8.60	5.4	7.1
Wheel arch	6.23	3.92	5.92
Rear floor lower	11.36	7.1	9.59
Rear connecting member	1.19	0.75	0.75
Rear floor rear lower	6.66	3.85	3.85
Rear floor front	6.58	4.14	5.64
Front floor	20.96	13.1	18.3
Rear header	2.02	1.17	1.17
Roof bow 3	0.56	0.35	0.35
Roof rail	5.21	5.21	5.21
B-pillar inner	2.65	2.65	2.65
Front dash	4.62	4.62	4.62
Rear floor inner reinforcement	3.28	2.06	2.06
Rear header reinforcement	1.21	0.76	0.76
Roof bow 1	0.85	0.53	0.53
Roof bow 2	0.80	0.5	0.5

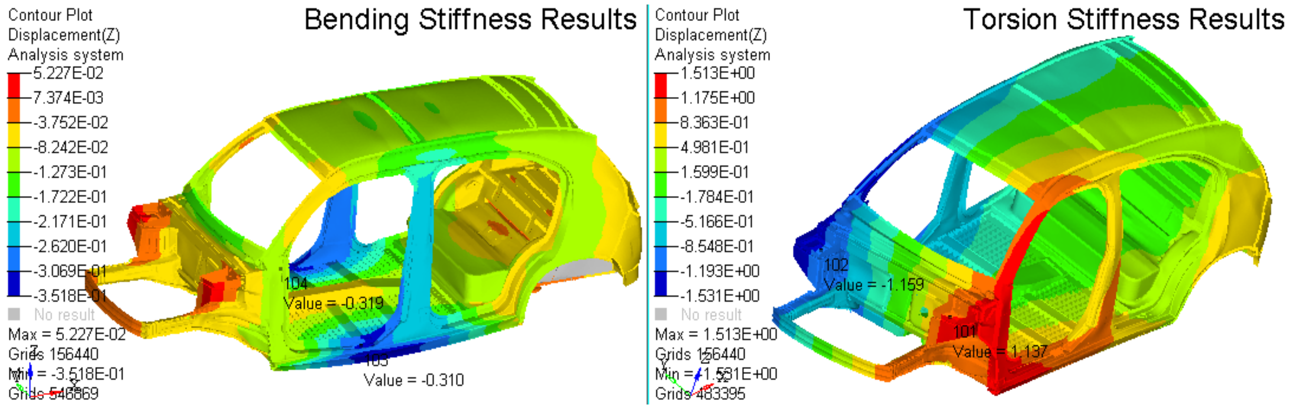

Fig. 9: BIW Stiffness analysis results - Engineered design

5. Conclusions

The DOE based material distribution for BIW has shown significant mass reduction without compromise on the structural stiffness targets. The structural performance of the DOE optimized BIW for bending and torsion stiffness was 5.52 kN and 8.8 kNm/deg respectively, with an initial mass saving of 16%. In the DOE analysis material is the only design variable and component thickness remained undisturbed. With this given variable, the DOE results have shown maximum possible structural performance. The effective design variables were identified from the sensitivity charts and their thickness were increased to improve the BIW stiffness. Based on this approach, torsion and bending stiffness values improved to 6.35 kN and 10.44 kNm/deg. The final optimized design has a mass saving of 12.3 kg and a BIW mass of 173.42 kg. The achieved final mass saving is 6.6%. The drop in the torsion stiffness can be improved by considering the joint stiffness and topology DOE optimization.

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