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MULTI-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, material alternatives; section reduction and load path design are widely being researched across the world. This paper present the techniques of identifying materials for the component of minimal part break up from BIW (Body in white) in the conceptual phase using design of experiments and multi objective optimization. Main focus was on the methodologies to effectively consider the materials for the parts without changing the standard performance of the target component. BIW structural load cases cases like torsional stiffness and bending stiffness were consider to evaluate the structural performance. Material list is used as the design variables and then sampled using design of experiments to undertake multi objective optimization. As a result, optimal material distribution and mass saving 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 engineer to optimally distribute the material for the BIW components at various stages of the vehicle design.

1. Introduction

In the automobile industry, the major challenges are energy consumption, cost reduction and protection of occupants. 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 saving of fuel of 4-6%[1]. With reduced mass, the vehicle can accelerate much faster, with more stable enhance NVH performance [2]. From safety perspective, the vehicle can have much shorter braking distance since the inertia on the body is reduced with reduced mass of the vehicle body [3]. Lightweight body and better better energy management in the vehicle are crucial factors in any vehicle development. Nearly 30-35% of the vehicle mass is from Body in white (BIW). So, the automotive industry forces a lot on mass reduction opportunities in the BIW right from the conceptual design stage [3, 4 and 5]. The BIW with all its complexity should satisfy all the constraints on multiple disciplines like, stiffness, NVH and crash safety [6, 7, and 8].

BIW design must be able to support the structural load under various performance condition. 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 [10] have explained their approach to achieve BIW load path using optimization and has also highlighted the significant 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 [19]. Comparison on the methodology of optimization using component made of Aluminum BIW structure and optimum joint stiffness improvement method have been discussed by LEE [10].It has been suggested that the pitch of spot weld and part thickness with light weight solution using the carbon fiber composites have been numerically researched by Boeman[5] and believed to achieve the structural performance.

Park [12] 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 [13] 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 researched by Londhe [2]. Calvo[6] 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 the conventional topology optimization and then trying to optimized the thickness. However, those researches lack focus on how efficiently that 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 consider materials list as the design variables for the optimization. This methodology can also be applied to the entire vehicle even across multiple disciplines. Non-structural load path component were mainly considered as a design variables in the interest of time and computational efforts. If there is an availability of large and computational facility. This method can be extended to other disciplines. Implementation of multi-objective optimization focuses on mass reduction without compromising much on the target stiffness [14,15,16, and 17]. Bending and torsion stiffness can be analyzed to understand the BIW stiffness [18,8]. Multi-objective optimization techniques using DOE combined with sensitivity study were implemented to achieveconsiderable mass saving in the BIW [13]. This technique of optimization could help an engineer save a lot of time and effort throughout the vehicle design process[19]. Changes based on the sensitivity of the vehicle were also implemented and simulated to the further improvement the BIW stiffness [9].

2. Analysis of baseline BIW

The baseline BIW has break into the various parts and aim of this research is to reduce the mass. The baseline BIW architecture with steel lower body and aluminum upper body has 58 parts [20]. BIW torsion and bending stiffness load cases were e baseline BIW considered for the structural performance evaluation [15].the mass of the baseline BIW is 185.7 kg as shown in fig.1 its torsion and bending stiffness is 11.06 kN/mm and 6.4 kNm/deg respectively as shown in fig.2 for BIW development, the criterion is to satisfy the structural stiffness of the load at early stage of the design. Structural linear solver is used to simulate this analysis. Since the interest is to keep the BIW architecture same and to find out its optimal material distribution, material is the only variable for BIW parts in this paper.

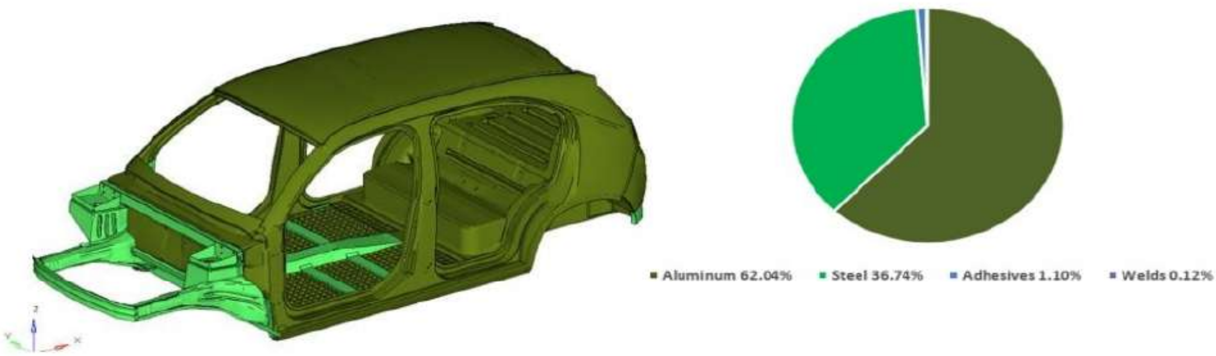


Fig.1: BaselineBIWmaterialdistributiononpartbasis

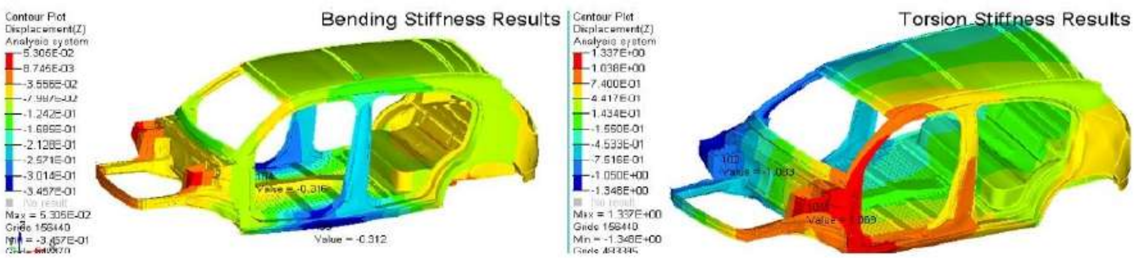


Fig. 2:Stiffnessresults–BaselineBIW

3. DOE based material sampling

Fig.3 shows the material for BIW, major structural component of the material variables are aluminium and magnesium. The materials like PPGF50, PA66-GF50 and PP-GF50 are nonstructural stiffness member were also used. Front floor has 6 parts and they were grouped together as a single parameter. Similarly wheel arch, roof rail, B pillar and rear connecting components are symmetric about LH and RH, so each of the component pair were consider as parameter. After identifying allvariables. The rocker, cross member, front rails, and tunnel hinge pillar and shock tower were considered to be in the non design space. From table 1 tha material variables are provided as an input to the optimization software to generate the DOE sampling [12]. For the baseline BIW, 1 is the value of material variables for all the parts.OptimalLatin hypercube was used to extract the DOE sampling. There were 17 design variables, so 51 sample design are extracted. The material variables for the first and last two samples is summarized in table 2. For each of these DOE sample, the BIW model was prepared. All the 51 BIW design were analyzed for torsion and bending load case. Each sampling, bending, torsion and mass displacement results were extracted.

Table 1: DOE sampling [6]for all variables

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

Table 2: DOE sampling for all design variables

Part name	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	1	2	3
Rear header reinforcement	2	3	1	2
Roof bow 1	1	2	3	1
Roof bow 2	3	3	1	1

Response surface model (RSM) method is used for approximation of the responses of the DOE results. All the 51 sets of data points representing the DOE variables and their responses like displacement & mass 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%, 5.8% and 2.7% error for mass, torsion and bending displacements respectively as shown in fign.4. this percentage of error on the actual outputs will be closer to the RSM predictions.

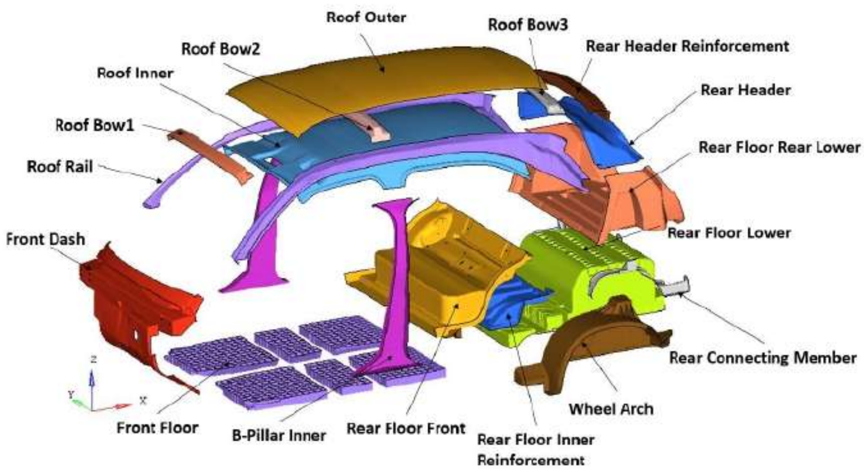


Fig. 3: Upperbodypartsconsideredformaterial DOE

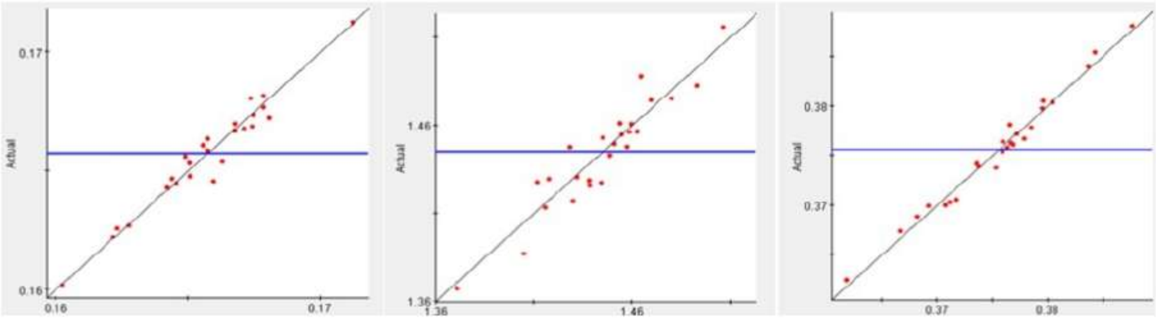
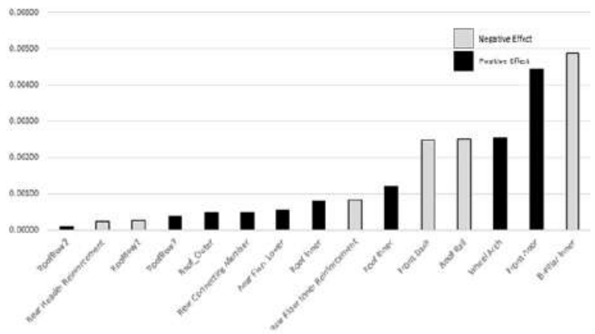


Fig. 4: DOE results cross validation for mass (left), torsion displacement (middle) and bending displacement (right)

4. Results and discussion

4.1Sensitivity of material variables on bending and torsion stiffness

Fig.5 shows the sensitivity of the variables with respect to the bending stiffness analysis. The component like rear floor, front 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 & front dash will not be much effective in meeting the objective. So even if their material strength increases 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, roof rail, Bpillar inner and rear floor inner reinforcement were showing a negative effect on the torsion stiffness performance of the BIW. The material update for rear floor, wheel arch, roof inner, rear floor front, front floor, roof outer and rear header can effectively increases the BIW torsion stiffness. Some of the components like front roof bows has very low sensitivity on the torsion stiffness.



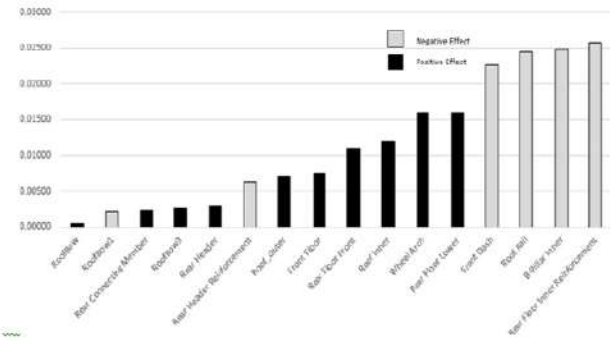


Fig. 5: Sensitivity of the variables for the bending load caseFig. 6: Sensitivity of the variables for the torsion load case

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 focused on bending and torsion load case displacement. Optimization runs were performed using the I-sight software and several optimization scenarios were studied to obtain the optimized design. The optimized generated is implemented in a finite element model. The optimized design As shown in fig.7 has a material distribution of 19.8% Aluminum, 2.45 magnesium, 41.1% Steel, 27.5% PA66GF60 and 5% of PPGF60. Bending and torsion stiffness analysis were performed on the optimized design. The optimized BIW design has a mass of 156 kg with-material distribution for the parts. There is 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 8.8kNm/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.

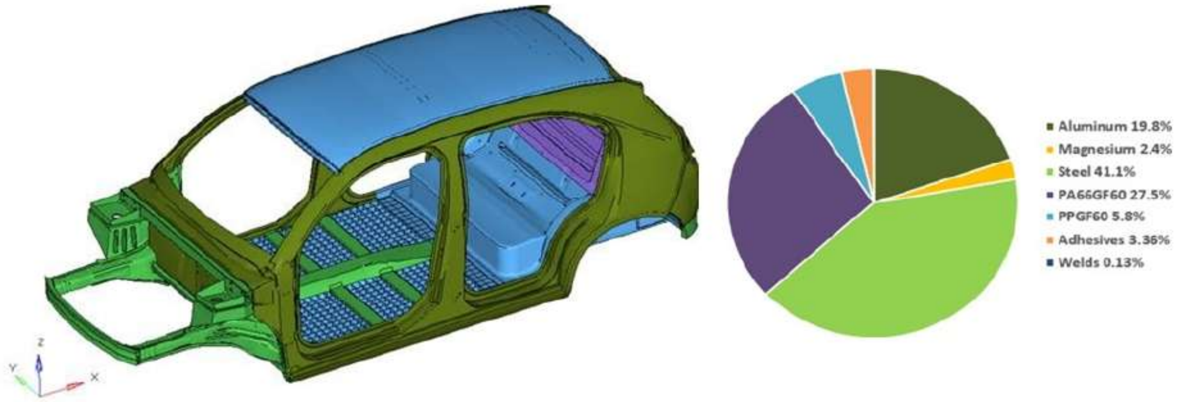


Fig. 7: BIW Design with optimal material layout

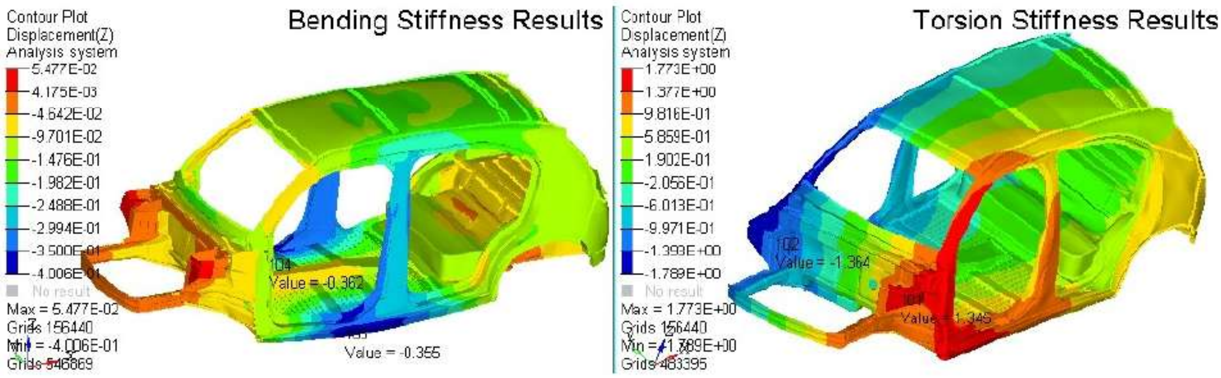


Fig. 8: BIW Stiffness results - DOE optimized material layout

4.3 sensitivity based BIW engineered solution

Since material is the only design variables and the thickness of the parts remained constant during the DOE based multi-objective optimization, there is an opportunity for further improvement in eh stiffness of the BIW based on the sensitivity plots. The components like wheel arch, rear floor lower and front floor were the sensitive parameter in eh BIW. The gauge thickness for these parts are increased to achievehigher BIW stiffness. The mass summary is shown in the Table 3. Fig.9 shows theanalysis results of the BIW with increased gauges. The improvedtorsion and bending stiffness is 10.44kN and 6.35 kNm/deg respectively. The mass 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 finalized 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 joints stiffness analysis and 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	6.85
Roof inner	8.60	5.40	7.10
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	2.56	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

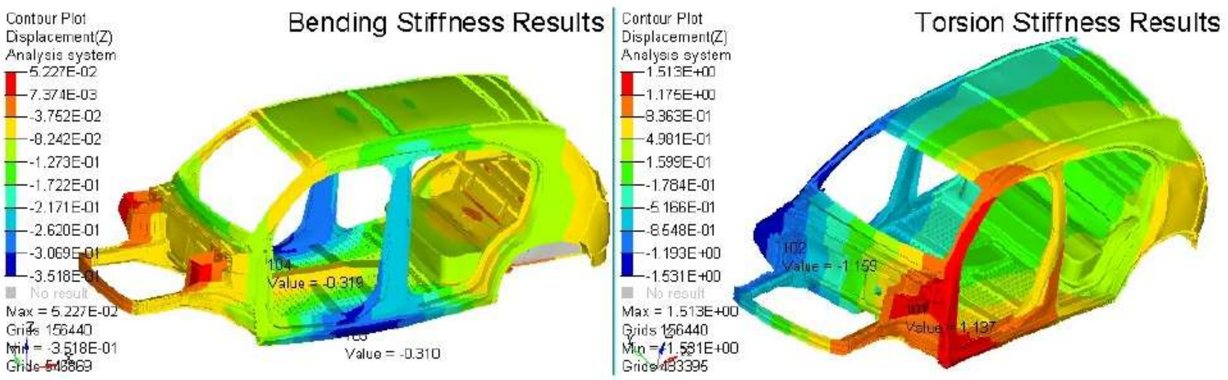


Fig. 9: BIW Stiffness analysis results-Engineered design

5. Conclusion

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 optimization BIW for torsion and bending stiffness was 8.8 kN and 5.52 kNm/deg respectively, eith an initial mass saving of 16%. In the DOE analysis material is the only design variable and component thickness remained unchanged. With this given variables, the DOE results have shown maximum possible structural performance. The effective design variables were identified from the sensitivity chart and their thickness were increased to improve the BIW stiffness. Based on this approach, torsion and bending stiffness values are improved to 6.35 kN and 10.44 kNm/edg. The final optimized design has a mass saving of 12.3 kg and the BIW mass of 173.42kg. the achieved final mass saving is 6.6%. The drop in the torsion stiffness can be improved by considering the joint and topology DOE optimization

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