BIW structure development in accordance with passive safety requirements using several optimization methods

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Abstract. The article is focused on the BIW characteristics and behavior optimization in terms of EURONCAP rules. Variable parameters: part’s shape, material, thickness. With multi-disciplinary, topological and topography optimization the most acceptable BIW behavior during virtual crash-tests has been achieved. All design improvements were implemented in accordance with stamping and assembly capabilities, restrictions on the use of each type of material. These requirements are especially important because updated design has been developed for the final stage and supposed to be frozen.

1. Introduction

Approximately 1.35 million people die in road crashes every year [1]. Factors which contribute road crashes can hardly be changed in short-time perspective (e.g. poor road infrastructure and management, unenforced traffic laws, etc.) however the death probability can be decreased by improving the vehicle behavior in road crash [2]. Typical road crash is a head-on collision between two vehicles at relatively high speed [3].

In the full-scale test, the car is driven at 64km/h and with 40 percent overlap into a deformable barrier which represents the oncoming vehicle. The test replicates a crash between two cars of the same weight, both travelling at a speed of 50km/h [3].

In this paper authors consider mass decreasing for sedan vehicle while crash-safety requirements are satisfied (C-NCAP). The peculiarity is that the Customer desired to unify BIW structure for gasoline and electric types of vehicle so during design development the features of the both vehicle types have to be considered. Optimization process includes multi-disciplinary optimization (MDO) for dynamic tests and forces redirection, parametric optimization for NVH parameters improvement and topological optimization for strength and stiffness values increase. Also, local dynamic stiffnesses and frequency response analysis have to be considered during design development [4].

In addition to the frontal-crash test side-crash test has been considered. This test describes a collision on the cross-road which also can be included in road crash statistics.

One more restriction is a percentage of high-strength steel implementation. Replacement normal steel with high-strength is a typical method of certain areas reinforcement [5].

Mainstream technique of vehicle improvement in terms of crash-safety is preventing deformations behind the firewall and keeping the living space size [6]. This goal can be reached by redirecting forces and energies between the loadpaths so that energy could be mainly absorbed in the front part of the vehicle, before the firewall [2].
The main innovation of proposed method is that topology, MDO and multivariate optimization have been consistently simulated on the basis of CML-Bench platform for developing digital twins and for control of digital design, mathematical simulations and computer engineering (developed by the Computer Engineering Center, CompMechLab, St. Petersburg Polytechnic University).

In this research full-scale model of vehicle has been tested and optimized in accordance with customer’s requirements [7].

2. Optimization

All improvements were based on CAE-model provided by customer. First of all, the initial model has been calculated. Expert assessment of the vehicle behavior figured out that shotgun is too high to provide the force distribution properly and the subframe carries over not enough force so that all the force distribution can go through the longitudinal (middle loadpath). But in current case crash-boxes don’t collapse properly, there is no bending in longitudinals and lack of deformations in the front area, all these factors involve energy and deformation transfer to the living space which supposed to be a safe area without significant decrease.

The goal for the design of the front part of the vehicle is to evenly spread forces between three loadpathes: upper (shotgun), middle (longitudinal) and lower (subframe) because it’s the best way to improve the vehicle’s behavior in crash collision (Figure 1).

![Figure 1. even distribution of forces](image)

2.1. Multi-Disciplinary optimization

For the behavior improvement marked parts considered in several optimization types (Figure 2). Front parts of the vehicle play an important role in vehicle behavior during head-on collision. Shape of the longitudinals and inner reinforcements, stampings and inner ribs in crash-boxes define the middle loadpath and determine force distribution and ways of the energy absorption in the lower front part. Middle loadpath has to be balanced in terms of stiffness in such a way that it would be stiff enough to prevent deformations behind the firewall and soft enough to absorb significant part of the energy to avoid energy distribution on the middle and rear vehicle’s parts.

![Figure 2. optimization types](image)
In CAE-engineering there is growing interest in multi-disciplinary optimization method which allows to consider different parameters in one optimization process. This method includes several optimization loops of virtual tests, after each loop variable parts are modified in accordance with specified limits to bring optimized value closer to the target and new iteration of test launches [8], [9]. Current case includes CAE-model for crash and frequency response analysis CAE-model (Figure 3).

![Figure 3. CAE-model](image)

Front part numbers match for both models, thickness of each part set as variable parameter in optimization task. For current task Response Surface Optimization Method can be used. This method is based on the development of a mathematical model approximating the response of the objective function within the range of design variables [11]. Then optimization algorithm uses this surface. About 22 variants have been considered in each iteration, the best one has been chosen. At the end of each iteration variable limits were clarified and the range of possible variable values decreased.

So, parts thicknesses were optimization variables. Mass decreasing is a mainstream optimization goal. In current case optimization constrains were: frequency, b-pillar acceleration, steering column displacement, acceleration pedal displacement, brake pedal displacement, door frame deformation. Virtual crash-test (ODB), frequency response analysis, local dynamic stiffness analysis for the front longitudinals are presented in each iteration. For computational time saving ODB model was reduced to front part while rear part was replaced with mass (Figure 4).

![Figure 4. Virtual crash-test (ODB)](image)

As result left B-pillar acceleration value reaches target due to next improvements: thickness of longitudinal and its reinforcement increased and material has been replaced with more durable to provide energy absorption increase and forces redistribution; thickness of a-pillar’s reinforcements increased to minimize a-pillar intrusion, keep living space and decrease door frame deformation; rocker’s thicknesses have been increased to improve behavior during side crash-test and keep frequency response values acceptable (Figure 5, Figure 6).
To clarify the shape of crashbox reduced task has been calculated with dynamic optimization method [6]. Here only crashbox and frontbeam on the driver’s side are left, the other side has been replaced with symmetrical condition, the rest of the vehicle has been replaced with mass and inertia characteristics. Front crash-test has been calculated in optimization process. This optimization supposed to help with the investigation of the best shape and inner structure of crashbox and frontbeam [10].

Optimization goal in this case is energy absorbing increasing. Inner crashbox and frontbeam ribs position and thickness and stampings distribution are design variables for current optimization. As a constrain dashboard intrusion has been considered, it is a fine marker of the energy absorption efficiency (Figure 7).
2.2. Topology optimization

Topology optimization aimed to help with determination of extra material areas and define where the holes can be created. This method allows to decrease mass of the BIW and keep stiffness values and frequency response analysis values in target. In current case optimization constrain were mass and the first frequency value, while compliance minimization was an objective. Variable parts of the BIW are shown on the figure below (Figure 8).

During topology optimization areas with extra material have been identified. Blue areas define not necessary material areas, in red areas all current material should be kept (Figure 9).
2.3. Parametrical optimization

One more significant marker of BIW structure quality is global stiffness, certain level of stiffness characteristics for the whole BIW helps with acceptable behavior during crash-test achievement. Global stiffness increase provides proper behavior for the rear and middle parts of the vehicle. Parametrical optimization helps with thickness redistribution for chosen parts (Figure 10).

Optimization objective is mass minimization. Global stiffness target values set as constrains, thickness of chosen parts is optimization variable. As result most of involved parts thickness decreased by 0.2 mm while global stiffness values are still in target. Mass decreased by 20 kg (~4% of BIW’s mass).

2.4. Multivariant optimization

The next step is multivariant optimization. This process takes into account production restrictions and expert assessment which can hardly be considered in previous optimization methods. Front parts have been redesigned and reinforcements redistributed during several loops of multivariant optimization. After each iteration expert assessment of the vehicle behavior helps to figure out which of proposed changes have to be implemented into design. Multivariant optimization in current case aimed to improve vehicle behavior during side crash. This test consists of the vehicle and mobile barrier, crash collision speed 50 kmph.

Huge influence on the deformation and force distribution in side crash-test has b-pillar area. Initiate creasing in the bottom part of b-pillar is a mainstream practice to minimize risks during side-crash collision.

B-pillar reinforcement strain is one of the most important markers, so focus of the multivariant optimization is on b-pillar strain decrease and crease in the bottom of the b-pillar provision. There are several methods to improve b-pillar behavior: modification of rocker, b-pillar reinforcements and roof...
rail parts, spotweld points rearrangement. In current case the best results in terms of side crash have been achieved due to the following proposals:
- divide b-pillar reinforcement into two parts
- increase p-pillar reinforcement bead height
- replace b-pillar reinforcement material with high strength steel
- inner rocker reinforcement shape and thickness change
- b-pillar to roof rail overlap
- spotweld points rearranged in roof rail area
All the proposals implementation helped to achieve significant improvement of the vehicle behavior. Overlap to b-pillar and strengthen with spotweld points in the roof rail area allow to avoid local buckling; bead height increase and division b-pillar reinforcement into two parts connected with spotwelds helped with decreasing b-pillar intrusion on the passenger’s head level; rocker reinforcements modification and lower part in the b-pillar reinforcement increase helped to organize strong b-pillar to rocker joint and have controlled deformation in the bottom area.
The result structure is shown on the picture below (Figure 11)

Figure 11. Multivariant optimization

3. NVH
Important part of vehicle’s design development is tracking other key parameters during BIW optimization in terms of crash safety. Previously only frequencies and global stiffness have been considered in optimization process. NVH (Noise, Vibration, and Harshness) performance is significant for quality level of the vehicle. During the driving of a car, the main sources of vibration noise include: vibration noise generated by engine excitation, vibration noise generated by the interaction of automobile tires and the road surface, and vibration noise generated by friction between the air flow and the vehicle body. After the various vibration noises are superimposed, they are transmitted to the entire body, causing the vibration of the body structure, radiating the noise to the interior of the vehicle, and making the passengers in the vehicle feel uncomfortable [12]. During vibrations transfer it is important to avoid resonance, so frequency values of the BIW, engine, closures, package and all other units have to be far enough apart. Mainstream practice is BIW frequency values and global stiffness increase, which has been considered in parametrical optimization and MDO method. High values of these parameters will help with further NVH performance improvement such as IPI (Inertance point interface), LDS (Local dynamic stiffness), VTF (Vibration transfer function), NTF (Noise transfer function).
IPI (Inertance point interface) and LDS (Local dynamic stiffness) performance shows vehicle response for harmonic load applied to each interface point. Displacement and acceleration are evaluated and stiffness value can be estimated in comparison with target value.
VTF (Vibration transfer function) aimed to evaluate vibration response from sources of noise to parts the driver has contact with (steering wheel, seat mounting points).
NTF (Noise transfer function) characterizes which part of the noise can reach the driver’s ear. Vibrations from engine, road and airflow is transferred through the BIW and closure panels and create pressure fluctuations which generate noise inside the vehicle living space.
All the proposals provided during global stiffness and frequency response optimization helped to improve IPI and LDS performance. NTF performance problem has been solved with applying extra
damping material layer. VTF and NTF performance is very important in terms of comfort for the driver and passengers.

Calculations of the NVH performance were based on the trim-body model. All vehicle units except BIW were replaced with masses in the mass center of corresponding unit. As result four improved variants of the BIW structure have been considered. The main proposal allowed to reduce 8 kg while mass reduction was from 20 to 27 kg in alternative proposals. Some compromises in terms of crash and NVH performance took place for the alternative proposals and the Customer could set priority level for each requirement. Changed parts for each proposal marked on the picture below (Figure 12). Red color – parts changed in the main proposal, green and red – parts changed in the first alternative proposal, blue, green and red – parts changed in the second alternative proposal, all colored parts – changes in the third alternative proposal.

Figure 12. Calculations of the NVH

4. Conclusion
During optimization process vehicle mass has been reduces by 12 kg, crash-safety requirements have been satisfied (C-NCAP) and frequency response values kept in target. Shapes of parts have been changed during multivariant optimization, thickness and material redistribution provided by MDO and topology optimization. Improvements implementation took into account the ease of stamping, manufacturing cost and capabilities. Most of design proposals have been realized in the final vehicle design.

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