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Shape optimization of bumper beams under high-velocity impact loads

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ABSTRACT

Box-shaped bumper beams mounted on vehicles serve as shock absorbers in a potential crash. In this study, their optimal shape design is investigated. The objective is to maximize the crashworthiness of the beam. The crash phenomenon in standard tests is simulated in which the vehicle hits a deformable barrier with 40% offset by 64 km/h speed. The bumper beam and the brackets supporting the beam are modeled as deformable bodies in full detail. For the rest of the car, a lumped parameter model is developed. The crash event is simulated using explicit finite element method. The design variables are the parameters defining the cross-sectional shape of the beam. The beam is optimized using a hybrid search algorithm combining Genetic and Nelder & Mead algorithms. The results indicate significant improvement in the crashworthiness of the bumper beam currently in-use. Resistance to low-velocity impact is also improved.

1. Introduction

In automotive industry, bumper beams are used as shock absorbing parts. They are attached to the front and rear ends of motor vehicles by means of brackets, which act as crash-boxes by taking the loads mainly in the axial direction. These parts need to be designed to minimize the damage to the vehicle and the risk of injury to the occupants by absorbing the energy stemming from collision. Their effectiveness under such impact loads is called crashworthiness. Better crash performance of the bumper beam reduces the effect of crash transmitted to the other components, and thereby protects them from further damage and saves the occupants from severer injury. As a design requirement, bumper beam-crash box system should absorb at least 15% of the total energy in NCAP crash tests [1]. For low velocity impact tests, on the other hand, they should absorb all the energy excluding the energy absorbed by body panel, bumper cover, reinforcement, radiator support, etc. according to the United Nations Economic Commission for Europe (ECE) Regulation No. 42. Existing bumper-beams are generally box-shaped for increased impact resistance. However, their cross-sectional profile can be modified to further improve their impact performance. This requires, first, a realistic simulation of the behavior of the bumper under crash, and then design optimization.

Although there are many studies on shape optimization of crash-boxes [1–14], the studies on beams subjected to transverse impact loads are relatively few. A number of researchers developed simulation models for bumper beams under impact conditions. Kokkula et al. [15] considered the anisotropy stemming from manufacturing processes and the effect of strain rate in the analysis of bumper beams subjected to transverse impact loads in order to obtain a realistic finite element model. They also validated the numerical model by comparing the results with the experimental data obtained by Kokkula et al. [16]. Liu and Day [17] modeled bumper beams under impact loads both numerically and analytically. In their numerical study, they neglected the frictional effects. They verified their simulation model by comparing the results with impact test data and results of an analytical model. Marzbanrad et al. [18] studied the effects of material, shape, thickness, and impact conditions on bumper-beams subjected to low-velocity impact. The materials considered in their study were aluminum, glass-mat-reinforced thermoplastics (GMT), and high strength sheet molding compound (SMC).

Some other researchers, on the other hand, conducted, besides modeling, design optimization studies to improve the performance of bumpers. Patel et al. [19] carried out topological optimization of straight and curved bumper beams subjected to static and dynamic loads using hybrid cellular automata (HCA). In the case of dynamic loading, curved beams hitting a rigid wall at 5 m/s were considered. The constitutive relation was modeled using piece-wise stress–strain curves. However, the strain rate effect was not

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included in the model. Farkas et al. [20] found an optimal geometry for dual-channel bumper beams hitting rigid barriers at 16 km/h for offset frontal impact and at 15 km/h for pole frontal impact. Cross-sectional profile is defined using straight lines with seven geometric parameters. They created a meta-model and carried out a multi-objective optimization. Their objective was to minimize the weight and at the same time achieve force uniformity. They imposed constraints on the peak force and the largest intrusion in the bumper beam. In another study, Farkas et al. [21] considered the same problem and improved the model by including the effects of parametric uncertainties. Duponcheele and Tilley [22] conducted a topology optimization study using genetic algorithm to maximize the area moment of inertia of a bumper beam; but not considered a crash event. Zhang et al. [23] used a multi-objective formulation for optimum crash performance of rib-reinforced thin-walled hollow square beams under three-point bending drop test with a speed of 36 km/h. They used the feasible direction method as well as the ideal point method. The profile of the reinforcing rib was defined by spline curves with three variables while the outer shape is not varied. Zarei and Kroger [24] optimized the bending behavior of filled and empty hollow beams with rectangular cross section under impact loads using wall thickness and base dimensions as design variables; in other words, they optimized the size not the shape of the beam. They employed response surface methodology to build a meta-model then, using genetic algorithm, they maximized total energy absorption and specific energy absorption. They also conducted three-point bending tests under impact loading to compare the numerical and experimental results. Shin et al. [25] optimized a bumper beam together a plate connected to it with three springs. The objective was to minimize the weight using the thicknesses of these parts and the stiffnesses of the springs as variables. The constraints were pedestrian upper tibia acceleration and intrusion and deflection of the bumper beam. The plate with the springs primarily provided pedestrian protection while the bumper beam minimized the damage. Mullerschon et al. [26] carried out a topology optimization of the bumper beam based on HCA under the conditions of a mass barrier hitting the bumper beam with a velocity of 16 km/h to get uniform strain energy density. Then the resulting design was transformed into a thin-walled structure modeled with shell elements. This part was considered as having four different subsections with different thicknesses. These four thickness parameters were optimized in order to satisfy the maximum force constraint. Kim et al. [27] optimized the topology of frontal back beam reinforcement of a bumper-beam to get uniform strain energy density. They simulated full frontal and corner tests. Using response surface methodology, they created a surrogate model. Then, without changing the overall shape of the bumper beam, they varied the overall dimensions of the reinforcement to minimize the repair cost of the car, they imposed constraints on the intrusion, back beam deflection, back beam height variation.

There are also studies [28–31] that tried to minimize the risk of injury to pedestrians; but this is achieved generally by optimizing low-stiffness parts in the front of the bumper beam not the bumper beam itself, which is too rigid to have an effect in that respect.

In some of the published studies [15–18], only crash phenomena were modeled. The ones that included optimization of the bumper beam [19–23,25,26] considered the problem under low collision velocities. Only Zarei and Kroger [24] considered high collision velocities (45 km/h) under a three-point bending drop test; but they just conducted a size optimization study. The loading conditions of the bumper beams considered in the previous studies were pole frontal impact [19,23,24] and central frontal impact [25]. Moreover, the past studies mainly focused on size and thickness optimization except for a few topological [19,22] and shape [20,23] optimization studies. There is only one study [21] that modeled 40% offset impact test but with an impact velocity of 16 km/h.

All in all, the previous studies did not fully simulate the standard high-speed test conditions. One may not assume that the optimum shape designs obtained for low impact velocities are also optimum for high velocities. Although, the collision energy is not absorbed solely by the bumper beam at high collision speeds, impact energy absorbing capacity of the bumper beam will have an effect on the overall crashworthiness of the whole vehicle. Satisfaction of the requirements on the crash performance of the bumper beam for low velocity collisions is just sufficient. The effective way of optimally designing bumper beams is to maximize their crashworthiness at high speeds, thus providing the maximum protection for the passengers, while setting a constraint on their low-speed crash performance.

2. Problem statement

The types of obstacles that bumper beams endure during frontal impact are countless. Needless to say, there is an extensive literature about the collision of motor vehicles using numerous impact scenarios like [32–39]. However, they can be categorized into three major divisions: full frontal collision, offset frontal collision, and pole frontal collision. The harshest one among the three scenarios is the pole; however it is also the rarest among them. The second harshest one is the offset impact. The majority of the frontal collisions happens at an offset with varying percentages [40]. In this study, considering the severity and frequency of the three major frontal crash scenarios, the bumper beam is optimized for collisions with a 40% offset in accordance with European New Car Assessment Program (EuroNCAP), IIHS, ANCAP standard tests (See Fig. 1). The objective of this study is to develop a methodology to find the globally optimum shape or near globally optimum shapes for the cross-sectional profile of a hollow bumper beam to maximize its crash performance under the loading conditions in EuroNCAP tests.

3. Approach

3.1. The objective function

A metric is defined that is a measure of the crashworthiness of the bumper beam. Depending on the choice of the metric, different

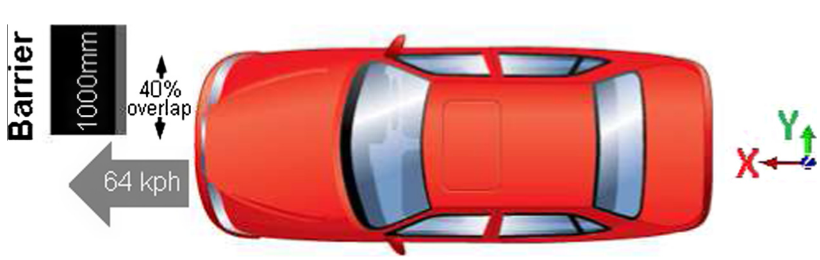

Fig. 1. A scheme for EuroNCAP Frontal offset crash tests [41].