Crash optimization of car bodies in the concept stage of vehicle development

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Abstract

In this paper, a shape optimization method is presented for an industrial use in the early stage of car body development with respect to the vehicle's crashworthiness. Crash simulation requires the correct accounting for manufacturing parameters like spotwelds and flanges. Thus, they should be integrated properly in the optimization model. In addition, the industrial context implies that emphasis is put on an optimization strategy, which is efficient with respect to resources and time. To demonstrate the operational field and technical opportunities of this method, a smaller example of a thin-walled beam is chosen first. Based on these results, the method is then extended to an optimization problem for a frontal offset crash (EuroNCAP).

Keywords: Crashworthiness; Car body; Concept stage; Parametric; Shape optimization; Evolutionary algorithms; Manufacturing parameters

1. Introduction

Currently, the automotive industry is influenced by a gradually changing situation; constantly increasing customer and legislator demands are conflicting with shorter innovation cycles. To cope with this, automatic optimization methods are more and more integrated in the standard development process.

State of the art in the field of car body investigation is the optimization of sheet metal thicknesses, e.g. [1]. However, this method has one main disadvantage: the crashworthiness of the vehicle can only be modified in a relatively small range. That is the reason why this kind of parameter-based optimization is mainly used for weight reduction at the end of the vehicle development process, where the topology and shape of the structure is already fixed.

More efficient for the requirements of the automotive development process is an optimization method, which makes use of all design scopes offered by the concept phase, e.g. the modification of cross-sections. But the higher flexibility in design changes renders it more difficult to adjust the model to rather different topologies. With a standard finite element model or current CAD system this is not feasible, cf. [2]. Consequently, a parameter- and geometrical-based shape optimization method is discussed here, which considers the requirements of the automotive development process.

2. Optimization algorithm

In general, stochastic optimization methods are used for crash problems due to their inherent non-linearity; no correct gradients can be evaluated. In the literature, Monte-Carlo search strategies are applied often while more recent studies are using meta modeling methods or evolutionary computation, e.g. [1]. The Monte-Carlo scheme is lacking efficiency: too many simulations are required for optimization. Meta modeling (response surface, regression methods, kriging, etc.) is not generally applicable; in some cases, like frontal impact, the surrogate models fail in representing the real physical phenomena. Therefore, an evolutionary algorithm is used here.

3. Parameter and geometrical-based shape optimization

The explicit time-step scheme, which is used for crash simulation, entails some fundamental restrictions for the optimization model. The time step for an analysis

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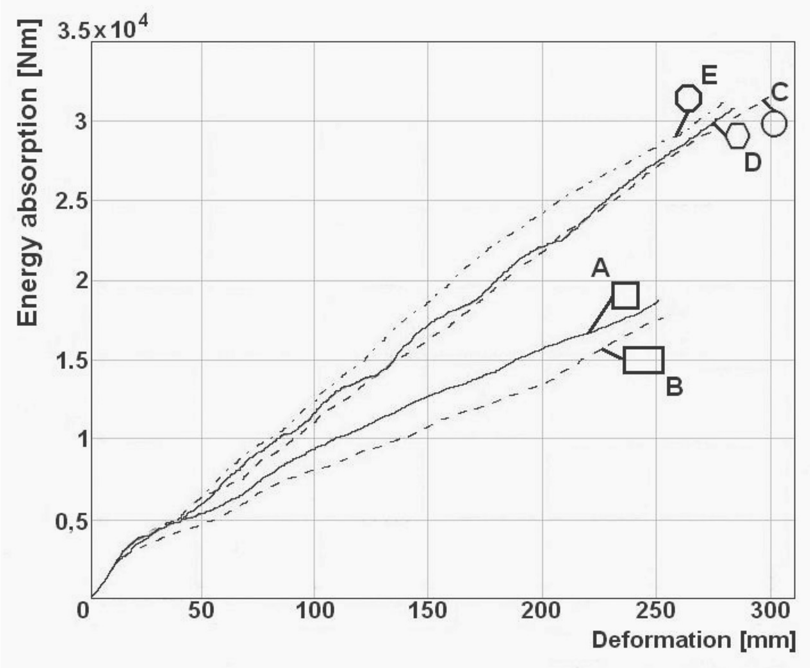

Profile	Shape	Perimeter
A	square	75 + 75 + 75 + 75 = 300
B	rectangle	60 + 90 + 60 + 90 = 300
C	circle	$\pi \cdot 95.5 = 300$
D	hexagon	50 + 50 + 50+ 50+ 50+ 50 = 300
E	octagon	45 + 30 + 45 + 30 + 45+ 30 + 45+ 30 = 300

Fig. 1. Energy absorption of five different profiles with a load of 0 degrees [14].

depends on the smallest edge length of a single element. Thus, to avoid long computational time, a minimal element length should be respected. Furthermore, the mesh must have an acceptable quality (no warped elements, no initial penetrations, etc.) to reproduce the deformation mechanism exactly. In the past, these criteria have rendered a shape optimization too complicated for a complete car body and, hence, few shape optimizations were realized, and only for smaller parts.

To optimize the crashworthiness of a whole car body, a parameter- and geometrical-based pre-processor was investigated in this work. With this pre-processor it is possible to modify the geometry of a part or a complete car body in an easy way. After finishing all modifications, the finite element mesh is generated automatically and the model is analyzed with a standard crash code. Automatized standard post-processing is closing the optimization loop. The output parameters are then evaluated concerning their fitness and a new generation of design variants is generated. Besides optimizing the shape, the parametric-based pre-processor enables to optimize the spotweld distribution on flanges. The distance between spotwelds is parameterized as well.

4. Crashworthiness of thin-walled beams

The principal structures for energy absorption during a frontal crash are the longitudinal pillars of the car body. Therefore, a lot of research was done in the last decades to predict the crashworthiness of thin-walled structures. Wierzbicki [3,4] and Abramowicz [5] developed in their fundamental scientific investigation the theories for these structures and derived the relationships of the influencing points such as column width, wall thickness and shape geometry on the energy absorption and the different folding modes. Wang [6] and Yuan [7] analyzed the folding modes of circular tubes in 1992. Thin-walled rectangular tubes were explored experimentally by Kim [8]. Groth [9] and Mahmood [10] compared in their researches some

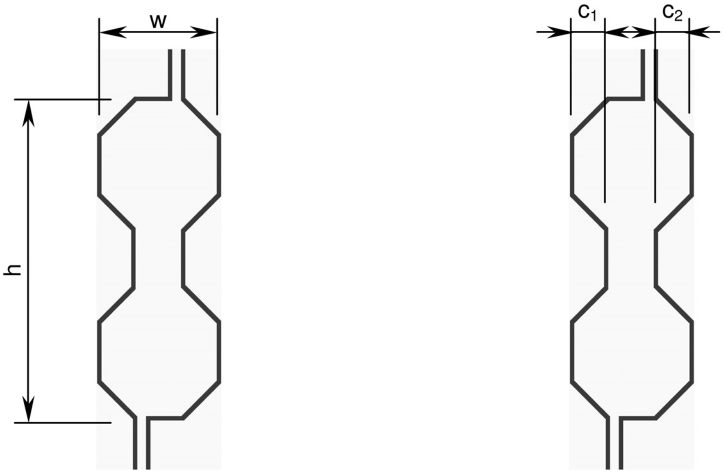

Fig. 2. Design variables for a cross-section of a longitudinal pillar.

different shapes of cross-sections. Nevertheless, for a complete overview of various cross-sections, it is difficult to evaluate results of several publications because important conditions like material, profile dimensions, flanges and the distance between spotwelds [11,12,13] are different.

Summarized, one significant hypothesis can be formulated in general: *the structural efficiency* η, which defines the relationship between the energy absorption and the cross-section surface, *increases with the number of edges and flanges*:

$$\eta := \frac{F_F}{\sigma_f A} = \frac{\text{mean force for folding}}{\text{yield stress} \times \text{cross sectional area}} \qquad (1)$$

This relation is not valid for circular cross-sections as shown in Fig. 1. The mechanical behavior of the circular pillar is comparable to those with hexagonal and octagonal cross-sections.

5. Shape optimization of a thin-walled pillar

Based on the assumptions discussed in the previous section, a parameter-based shape optimization is realized. But before, some additional restrictions coming from the packaging, production process, and crash dynamics have to be respected.

The shape optimization method presented here requires the definition of a basic shape for the cross-section. Figure 1 depicts the theoretical best possible shapes concerning energy absorption. For these types, there is not enough design space left from packaging constraints. Therefore, a basic cross-section is proposed as shown in Fig. 2.

This design combines two octagonal cross-sections for maximal energy absorption and good structural efficiency. The parameters c_1 and c_2 are limited by manufacturing and production parameters. The design variables h and w are modified in a wider range. The crashworthiness of the vehicle is not only defined by energy absorption but also by the intrusion into the passenger cell. For a good rating at a crash test, the intrusions should not exceed a given value. Therefore, the failure modes of the optimized pillar should be as defined in Fig. 3.

With these conditions, a shape optimization was performed leading to a design fulfilling the prescribed deformation modes. In the first time phase, the part is deforming with a regular folding mode to maximize the energy absorption and in the second time phase it is collapsing to minimize the intrusion. Compared with the serial pillar the following can be stated: the shape optimization has enlarged the bearable axial force by more than 16% and the width of the part can be reduced about 11%. In total, the optimized beam is lighter and can absorb more energy as the serial pillar.

6. Shape optimization of a vehicle in the concept stage:

In this section, a typical shape optimization problem is formulated for a frontal EuroNCAP crash test where the car hits the deformational barrier with a 40% offset and a speed of 64.4 km/h. These conditions cause massive deformations in front of the passenger cell. Thus, the optimization should maximize the energy absorption of the front area of the car and should minimize the intrusions into the passenger cell. Additionally, the total mass of the system should be minimal.

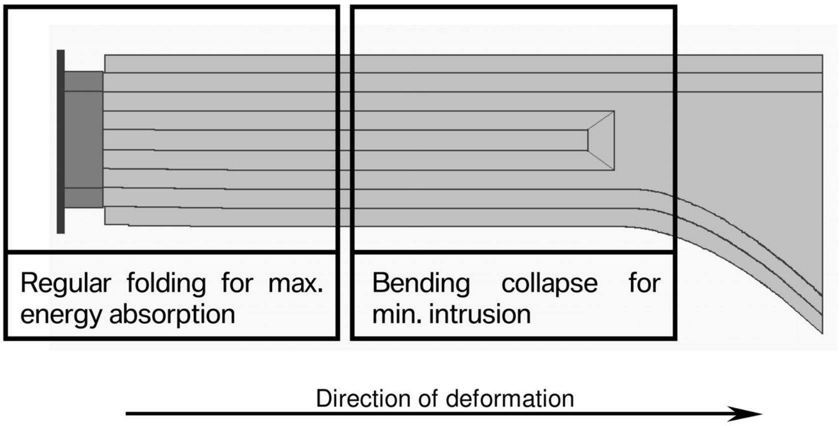

Fig. 3. Principal failure modes of a thin-walled pillar.

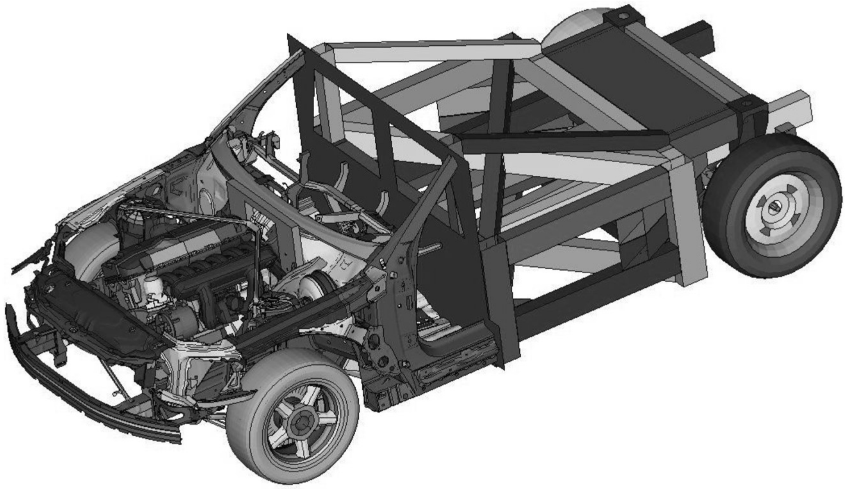

Fig. 4. Simplified FE-model of a car in the concept stage, courtesy of BMW.

In Fig. 4, a reduced car body is shown. This simplified model of a car was made to reduce the computational effort and to maintain the essential physical behavior of the full car. The differences to a full car simulation are in a tolerable range for the concept stage.

As variable parts for this optimization problem, all pillars, crimps, and stiffeners of the car body are defined. In sum, the optimizer can modify over 100 design variables to reach a feasible region.

The shape optimization resulted in a remarkable weight reduction and in an essential limitation of the intrusions into the passenger cell.

7. Conclusion

We have presented a parameter- and geometrical-based shape optimization – combined with an evolutionary algorithm – that makes it possible to optimize a car body with all significant constraints of manufacturing and production. With this method, not only a minimization of the weight is possible but in addition, the deformation mechanism of a car body could be designed. Therefore, this method is a powerful tool for the development process in the concept stage of car body investigation.

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