International Journal of Mechanical Sciences 88 (2014) 46–54

Contents lists available at ScienceDirect

International Journal of Mechanical Sciences

journal homepage: www.elsevier.com/locate/ijmecsci

A multi-objective surrogate-based optimization of the crashworthiness of a hybrid impact absorber

M. Costas*, J. Díaz, L. Romera, S. Hernández

Structural Mechanics Group, School of Civil Engineering, Universidade da Coruña, Campus de Elviña, 15071 A Coruña, Spain

ARTICLE INFO

Article history:
Received 14 January 2014
Received in revised form
21 May 2014
Accepted 7 July 2014
Available online 15 July 2014

Keywords:
Optimization
Surrogate methods
Crashworthiness
Hybrid parts
Multi-objective
Composites

ABSTRACT

This paper applies surrogate-based multi-objective optimization techniques to a crashworthiness problem in which the impact performance of a frontal crash absorber made of steel and a glass-fiber reinforced polyamide is optimized. Two well known crashworthiness indicators are considered as contrasting objective functions: the Specific Energy Absorption (SEA) and the Load Ratio (LR), whose responses are approximated by multiple types of surrogate models due to their computational cost and their noise levels. These models are quadratic and cubic polynomials, Gaussian process (kriging) and multivariate adaptive regression splines (MARS). The finite element model includes strain-rate sensitive properties, which is verified with experimental data from a drop-tower test. The thickness of the different parts, the geometry of the cross-section and the offsets of the reinforcement parts are chosen as design variables. Pareto solution is obtained after both models are verified. Results show improvements in both functions by almost 50% compared to the original design.

1. Introduction

The combination of different materials in crash-absorbing parts is nowadays a promising research topic with a direct application to the field of road safety. Relatively new materials such as carbon fibers, glass fibers and artificial foams are featuring in this market thanks to their specific strengths and stiffnesses (carbon and glass fibers) and to their stable collapse mechanisms (artificial foams). New designs arise from the multiple possible combinations of these materials and steel or aluminum parts. These metals add a ductile, progressive collapse mechanism to the final design. These new car parts are usually designed to be placed at the end of the front rails of cars, as shown in Fig. 1. The advances in computational finite element analysis codes have allowed not only accurate and affordable simulations of crash events but also the possibility of applying optimization strategies to these new designs. This is not an easy task due to the inherent characteristics of finite element impact simulations, due to the presence of noise in the responses and the high computational cost of each evaluation.

Early studies on the crushing mechanism of metal tubes start with the works by John M. Alexander [1], in which the author proposed an approximate theory to predict the crushing load of thin cylindrical shells made of different metals. Many detailed studies were carried out in the 1980s trying to improve Alexander's solutions [2–6]. The first direct applications of these collapse mechanisms to car crash absorbers appeared in the mid 1990s [7,8]. Regarding composite materials, their first applications to car crashworthiness are dated in the same period, in which an early attempt was made to build car parts with solely composites [9]. Nowadays, a combination of composite material with steel is preferred. The idea of wrapping composite materials around a metal core is one of the most efficient impact energy absorption systems available now. The composite materials selected for this task are usually carbon or glass fiber reinforced polymers [10–12]. Another way to improve the crashworthiness characteristics of steel tubes is filling them with polymer-based or aluminum-based artificial foams, which improves the crushing force levels and reduces the folding distance of the steel sheets, allowing the generation of more energy-dissipating folds. Research on these hybrid elements began with some experimental studies in the late 1980s by Reid et al. [13,14]. Later investigations on this combination by Hanssen et al. in 2000 [15,16] need to be highlighted as well. Foam-filled multi-cell sections have also been deeply studied, highlighting one of the first investigations on this topic by Chen and Wierzbicki [17].

Regarding the field of surrogate-based crashworthiness optimization, the first attempts date from late 1990s, when Yamazaki and Han [18] used an approximate response surface to maximize the crushing energy of square and circular tubes, with the aim of using the minimum number of finite element structural analyses.

---

* Corresponding author. Tel.: +34 981 167 000x1407; fax: +34 981 167 170.
E-mail addresses: miguel.costas@udc.es (M. Costas), jdiaz@udc.es (J. Díaz), lromera@udc.es (L. Romera), hernandez@udc.es (S. Hernández).

http://dx.doi.org/10.1016/j.ijmecsci.2014.07.002
0020-7403/© 2014 Elsevier Ltd. All rights reserved.

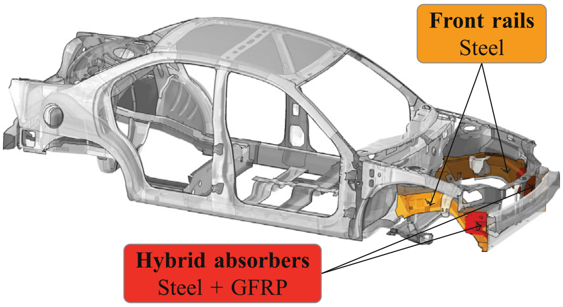

Fig. 1. Location of the hybrid absorbers in a car structure.

Later in 2001, Marklund and Nilsson [19] applied linear and quadratic approximations to minimize the mass of a car B-pillar, which was reduced by 25% maintaining the safety conditions. In the same year, Sobieszczanski-Sobieski et al. [20] carried out a size optimization of a full car body finite element model under constraints of noise, vibration and harshness (NVH) and crash using different approximations, and reducing the mass of the car body. In 2003, Jansson et al. [21] successfully applied surrogate models and response surfaces to engineering problems of sheet metal forming and crashworthiness design with a limited number of design variables. Fast improvements in computation capabilities allowed a rapid increase of the problem size and the solution accuracy. In 2007, Hou et al. [22] carried out an optimization of hexagonal metal tubes taking as objective functions the Specific Energy Absorption (SEA) and the peak crushing load by means of a surrogate approach built up from a full-factorial sampling strategy of finite element models. The same authors attempted an optimization of a hybrid foam-filled thin-walled metal structure via surrogate-based meta-modeling in 2009 [23]. Since then, similar investigations on single-material and foam-filled crashworthy parts can be found in the literature, including indentations or grooves on the metal part [24], or based on different tube geometries like circular [25] or square [26] tapered metal tubes, with or without a foam filling. In 2013, the performance of different surrogate models, including robustness or reliability criteria, was evaluated in [27], and vibrations design criteria were also recently taken into consideration [28]. The presence of SEA as an objective function is common in most of the investigations on this topic. Occupant safety is also taken into consideration by means of the peak force or the Load Ratio, which we used in this paper (LR, ratio between the peak and mean crushing forces).

This paper contributes by applying different surrogate-based multi-objective optimization approaches to an original design of a hybrid absorber which is made of a steel tube with an inner glass-fiber reinforced polyamide (GFRP) structure. We have considered SEA and LR as objective functions.

2. Optimization problem and methodology

The objective of this research is to obtain a set of optimum designs addressing two objective functions. These functions are the Specific Energy Absorption (SEA) of the crash absorber and its Load Ratio (LR). Both parameters are obtained from the force–displacement curves produced in finite element simulations. The SEA is one of the most important performance indicators in energy absorption devices, particularly when a weight reduction is pursued. It is defined as the ratio of the absorbed energy E_a to the mass of the specimen m:

$$SEA = \frac{E_a}{m} \tag{1}$$

The value of the absorbed energy is obtained by a direct integration of the force–displacement curve resulted from the test:

$$E_a = \int_0^{\delta} F(z)\, dz, \tag{2}$$

where δ is the total axial crushing distance and $F(z)$ is the value of the crushing force at the crushing length z. The ratio of the initial peak load P_{peak} to the mean load P_m is called Load Ratio (LR). This crush force ratio should be as low as possible, in order to reduce the eventual accelerations peaks suffered by the occupants during a crash:

$$LR = \frac{P_{peak}}{P_m} \tag{3}$$

The mean load P_m can be obtained as the ratio of the absorbed energy to the total displacement of the absorber's head or crushing length δ:

$$P_m = \frac{E_a}{\delta} \tag{4}$$

Prior to the calculation of these indicators, a standard SAE 600 filter [29] is applied to the force–displacement curves resulting from the simulations, which removes high-frequency noise from the curves with a 1000 Hz cutoff frequency. This filter is recommended for vehicle component analysis in the specialized literature [30].

The selection of these two functions for the multi-objective optimization problem is not arbitrary. While SEA can be easily increased by using greater thickness values up to a certain point, this increment in thickness in turn makes the initial peak force much higher, increasing the LR and the eventual injuries suffered by the car occupants. In addition, the axial distance between the top of the steel tube and the GFRP reinforcement (called “offset” in this research) plays also a very important role in the value of both indicators. This is due to the fact that an axial separation between the assembled parts divides the initial peak force in two lower peaks. The total amount of absorbed energy and the SEA can be increased as well by setting these offsets to 0 (reinforcement starts at the same level as the steel tube), but the initial peak grows since the peaks of all materials occur at the same time. Although offsetting the reinforcement leads to a distribution and reduction of the peak forces, in turn SEA is affected in a negative way.

Crashworthiness optimization is usually affected by two well-known problems. The first of them is the large computational cost for this kind of analysis, involving severe plasticity, failure, friction and contact phenomena. Each of these requires a specific formulation which makes the analyses slower. This makes gradient-based optimization procedures almost unaffordable, even if parallelization is used. The second big problem of these analyses is noisy results, which lead to very coarse objective functions in which a gradient-based optimization cannot run properly. This computational noise stems from the schemes used to set up computational models, involving iterative approaches in which the solutions are not completely independent of the number of iterations or the discretization. As an example, Fig. 2 shows the evolution of the SEA of an empty steel tube, similar to the one used in this research when the corner diagonal projection varies from 0 (orthogonal corner) to 50 mm (sheet bends at half the side length). We have found out that this variable has a minor influence on the objective functions by analyzing the correlation matrices, which are obtained from the samplings used to built up the surrogate response surfaces. Besides, the noise levels are high compared to the variations produced on the SEA (see Fig. 2).

Luckily, there is a solution which overcomes both problems: the use of surrogate-based optimization methods. These methods are based on the construction of an inexpensive-to-evaluate function $\hat{f}$