Advances in Engineering Software 112 (2017) 192–199

Contents lists available at ScienceDirect

Advances in Engineering Software

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

Research Paper

Crashworthiness design of a steel–aluminum hybrid rail using multi-response objective-oriented sequential optimization

Jianguang Fang[a,d], Na Qiu[b,*], Xiuzhe An[b], Fenfen Xiong[c], Guangyong Sun[d], Qing Li[d]

[a] School of Civil and Environmental Engineering, University of Technology Sydney, Sydney, New South Wales 2007, Australia
[b] School of Automotive Studies, Tongji University, Shanghai, 201804, China
[c] School of Aerospace Engineering, Beijing Institute of Technology, Beijing 100081, China
[d] School of Aerospace, Mechanical and Mechatronic Engineering, The University of Sydney, Sydney, New South Wales 2006, Australia

ARTICLE INFO

Article history:
Received 9 January 2017
Revised 1 May 2017
Accepted 14 May 2017
Available online 19 May 2017

Keywords:
Hybrid structure
Multiresponse objective-oriented sequential sampling
Crashworthiness optimization
Kriging

ABSTRACT

Hybrid structures with different materials have aroused increasing interest for their lightweight potential and excellent performances. This study explored the optimization design of steel–aluminum hybrid structures for the highly nonlinear impact scenario. A metamodel based multi-response objective-oriented sequential optimization was adopted, where Kriging models were updated with sequential training points. It was indicated that the sequential sampling strategy was able to obtain a much higher local accuracy in the neighborhood of the optimum and thus to yield a better optimum, although it did lead to a worse global accuracy over the entire design space. Furthermore, it was observed that the steel–aluminum hybrid structure was capable of decreasing the peak force and simultaneously enhancing the energy absorption, compared to the conventional mono-material structure.

1. Introduction

In recent years, protective structures have aroused extensive attention for impact and blast loadings [1]. S-shaped thin-walled structures have been widely used as a front rail in the automotive engineering to absorb energy during frontal crashes, as depicted in Fig. 1. However, the requirements for load withstanding capacity at different areas are not uniform [2, 3]. To address this issue, hybrid materials, such as steel-aluminum hybrid structure, were investigated to improve passenger safety and weight efficiency. In this regard, Zhou et al. [4] explored the crashworthiness and lightweight design of steel-aluminum structure and they found that steel-aluminum hybrid structures could increase the total absorbed energy by 117.83% and reduce the peak force and total mass by 16% and 7.73%, respectively. Hosseini-Tehrani and Nikahd [5] pointed out that the steel-aluminum S-shaped rail could absorb more energy, produce a lower peak force and offer a lighter weight than the mono material counterpart. However, these above-mentioned studies are limited to the analysis of the crushing performance of the hybrid structure. In practical application, it needs to be further explored how to design the thicknesses and usage ratios of individual materials to excavate the potential of a hybrid structure.

Due to high nonlinearity of the crashworthiness problem, direct coupling the simulation model with an optimization algorithm is rather time-consuming or even prohibited in practice. As an alternative, the surrogate modeling or metamodeling technique is widely adopted in crashworthiness optimization [6]. In this regard, Qi et al. [7] combined the response surface metamodel with multi-objective optimization to improve the energy absorption of thin-walled rails under an oblique impact loading. Khakhali et al. [8] conducted a robust optimization design to maximize the energy-absorbing capacity for S-shaped box beams using polynomial metamodels. Fang et al. [9] conducted the multiobjective optimization of the functionally graded foam-filled tube under the lateral load based upon the multiobjective particle optimization (MOPSO) algorithm and Kriging modeling technique. Xiao et al. [10] investigated the crashworthiness of a novel functionally graded foam-filled bumper beam by utilizing the Kriging model. Qiu et al. [11,12] proposed different multi-cell hexagonal tubes and compared their crashworthiness performance by employing Kriging surrogate model. Gao et al. [13] optimized the energy absorption capacity of foam-filled double ellipse tubes based on the Kriging model. Yamazaki and Han [14] aimed to maximize the crushing energy absorption of cylindrical shells based upon the response surface approximation technique. Hou et al. [15] conducted the crashworthiness optimization of corrugated beam guardrail based

---

[*] Corresponding author.
E-mail addresses: Jianguang.Fang@uts.edu.au (J. Fang), nnaqiu@163.com (N. Qiu).

http://dx.doi.org/10.1016/j.advengsoft.2017.05.013

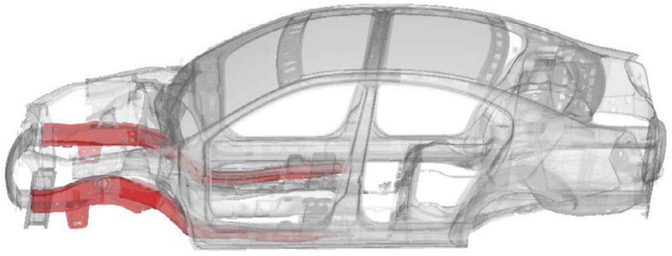

Fig. 1. S-shaped front rail in automotive engineering.

on RBF-MQ surrogate model. Wang et al. [16] developed a metamodeling optimization system and used to improve the crash behavior of the tube structure. Sun et al. optimized the crashworthiness of a novel criss-cross tubes based on the radial basic function surrogate model [17]. Finally, Fang et al. [18] comprehensively reviewed different surrogate models used in the crashworthiness optimization problem.

While the surrogate modeling is widely used in crashworthiness optimization, it is generally known that the accuracy of the metamodels largely depends on the number of training points [19]. Thus, it becomes a key issue to gain a satisfactory accuracy using the minimum number of sample points. Conventional one-stage sampling is used to capture the global trend of the real response with less flexibility, as the sampling points cannot be changed during the optimization. As a result, the one-stage sampling will not be able to guarantee a good local accuracy especially at the neighborhood region of the optimum. On the other hand, a more flexible alternative, which is referred to as sequential sampling strategy, can be utilized to refine the previous surrogate model with adding new sample points in an iterative fashion during the optimization [20]. Among various sequential sampling approaches, the objective-oriented sampling is a variant tailored for design optimization which takes the objective design into consideration [21-23]. However, in most of the previous works, objective-oriented sampling only deals with one response which combines objective and constraints. While Chen et al. [24] proposed an effective multi-response and multi-constraint metamodeling technique and introduced uncertainty quantification to take into account the confidence interval because of insufficient samples. Since a series of Boolean operation was utilized, this approach could deal with subspace with arbitrary shapes. In this paper, this sequential sampling strategy is utilized to optimize the steel–aluminum hybrid side rail structure.

The remainder of this paper is structured as follows. Section 2 introduces the finite element modeling for the hybrid steel-aluminum structure and describes the optimization problem for the hybrid structure. Section 3 provides the detailed information about the multiresponse objective-oriented sequential sampling method. Section 4 discusses the optimization results and the effect of sequential sampling technique. Finally, the conclusions are drawn in Section 5.

2. Crashworthiness of a hybrid side rail

2.1. Finite element modeling and experimental validation

The structure studied herein is a thin-walled S-shaped front rail with a rectangle cross-section subjected to an axial impact loading (see in Fig. 2). The model was developed by using explicit nonlinear finite element code LS-DYNA. The Belytschko-Tsay reduced integration shell elements with five integration points through thickness were adopted to model the tube. Stiffness-based hourglass control was used to avoid spurious zero energy deformation modes and reduced integration was utilized to avoid volumetric locking. “Automatic single surface” contact was assigned to the tube to avoid interpenetration.

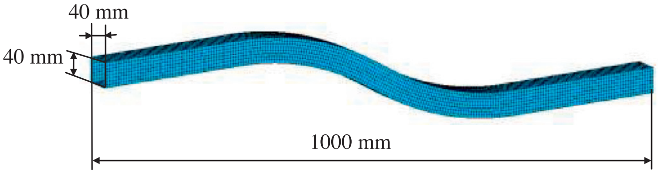

Fig. 2. Shape and cross section for S-shaped structure (thickness = 1.3 mm).

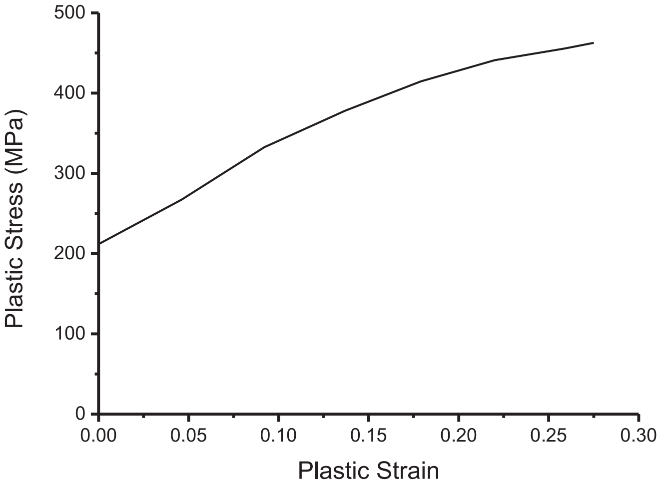

Fig. 3. Strain hardening data for mild steel for base model [25].

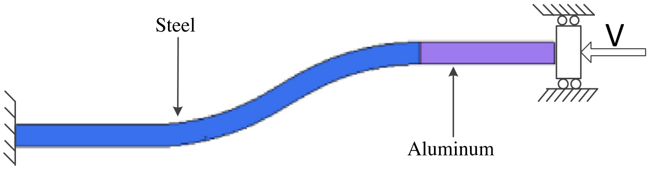

Fig. 4. The boundary condition applied to the hybrid structure.

The baseline design was made of mild steel, with the following properties: density = 7800 kg/m^3, Young’s modulus = 206 GPa, Poisson’s ratio = 0.3. The S-shaped tube was modeled by material model #24 in LS-DYNA, having a piecewise linear elastic-plastic behavior with strain hardening. To accurately describe the hardening characteristic, the relationship between the plastic strain and plastic stress shown in Fig. 3 was used in the FE model.

As pointed out by Pan et al. [26] and Zhao et al. [27], the localized effect of welding properties on the global crashworthiness could be neglected, and thus the welding connection between two parts can be modeled with coincident nodes. The moving end of the tube was connected to the rigid body with the keyword *CONSTRAINED_EXTRA_NODES. The constant velocity of 2000 mm/s was adopted to consider the low-velocity impact as in reference [4]. For the low-velocity impact, strain rate effect of the materials was considered throughout the optimization process below. The load was applied at the center of gravity of this rigid body. The rear end of the tube was fully clamped. The boundary condition applied to the hybrid structure is shown in Fig. 4.

In order to determine the size of elements, a convergence test was conducted to minimize the effect of mesh refinement on the accuracy of the numerical results in terms of the energy absorption and the maximum force. It was found that 5 mm was the optimal mesh size of the tube, as it could reduce computing time without sacrificing the simulation accuracy too much.