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Discrete robust optimization algorithm based on Taguchi method for structural crashworthiness design

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ABSTRACT

Hybrid steel–aluminum tailor welded structures have drawn considerable attention and been widely applied in automotive and aerospace industries for their significant advantages in high strength to weight ratios and superior energy absorption characteristics. Structural optimization is considered to be one of the most important means to improve the crashworthiness of tailor welded structures. However, majority of the existing optimization studies to data have not considered uncertainties for simplication. Its associated risk is that a deterministic optimization might deteriorate its optimality and/or violate design constraints when being present in uncertain environment. This study aimed to explore how to maximize the crashworthiness of the hybrid tailor welded structures involving uncertainties. For this purpose, a novel robust optimization algorithm based on successive Taguchi approach for design in discrete space is firstly presented. In the optimization process, the peak force is taken as an objective, while specific energy absorption (SEA) as a constraint. The optimal results show that not only the performance of peak force and specific energy absorption is improved, but also the robustness of these two indicators is also significantly enhanced. The proposed algorithm can also be used to solve other more complicated engineering problems.

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1. Introduction

Lured by the increasing energy and environmental concerns that mankind is facing today, higher desire for light weight and crashworthiness of energy absorbers has been placed a new level in modern automotive industry. The conventional thin-walled structures (Abramowicz, 2003; Alghamdi, 2001; Fan, Lu, & Liu, 2013; Gedikli, 2013; Li, Zheng, Yu, & Guo, 2013; Liu, 2010; Mamalis, Manolakos, Ioannidis, Kostazos, & Dimitriou, 2003; White & Jones, 1999; Yamashita, Gotoh, & Sawairi, 2003; Yang & Qi, 2013; Zhang & Zhang, 2013) mainly use single material and uniform wall thickness. In fact, energy absorbers often bear very complex loading, implying that different regions should have different roles to maximize usage of materials. Obviously, potential of crashworthiness and lightweight of the conventional thin-walled structures has not been fully exploited. In order to address the issue, a relatively novel lightweight technology, namely tailor welded blanks (TWBs), has been presented and widely applied in automotive industry. Tailor welded blanks are semi-finished parts which weld at least two different thicknesses and/or material sheets prior to the final forming process (Merklein, Johannes, Lechner, & Kuppert, 2014). This technology allows saving materials to the maximum extent. In other words, one can use thicker or stronger materials in the critical regions that require to absorb more energy and thinner or weaker/lighter materials in less critical regions to reduce the overall weight while maintaining the same level of energy absorption (Assuncao, Quintino, & Miranda, 2010). To promote the applications of TWB structures in vehicle industry, extensive investigations have been conducted by using experimental (Xu, Sun, Li, & Li, 2013; Xu, Sun, Li, & Li, 2014) and simulation methods (Shi, Lin, Zhu, & Han, 2008).

Although the conventional TWB structures have exhibited significant advantages in light weight and crashworthiness, these TWB structures mentioned above often were welded by the single material, such as advanced high strength steel (AHSS) or aluminum. Actually, AHSS and aluminum have different advantages: AHSS has high strength and stiffness; whilst the aluminum has lightweight and high specific energy absorption. It would be a valuable research how to make a full use of the advantages of AHSS and aluminum in the metallic energy dissipation systems (Schubert, Klassen, Zerner, Walz, & Sepold, 2001). To address this issue, some researchers presented hybrid steel–aluminum TWB

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structures for crashworthiness (Gedikli, 2013; Hosseini-Tehrani & Nikahd, 2006; Zhou, Lan, & Chen, 2011). From their research results, it is easily found that energy absorption and crushing force can be favorably adjusted by choosing different combination of materials and thickness. In summary, the hybrid steel–aluminum TWB structures have better crashworthiness than the conventional mono-material TWB structures. However, it is by no means easy to obtain the optimal match of materials and thickness for hybrid steel–aluminum tailor welded thin-walled structures under impacting load.

Structural optimization represents an effective tool to seek for an optimal design systematically, which helps engineers to attain the optimal crashworthiness of TWB structures (Pan, Zhu, & Zhang, 2010; Song & Park, 2006; Xu et al., 2013). Nevertheless, these abovementioned studies on TWB structures are mainly restricted to deterministic optimization, in which all design variables and parameters involved are assumed to be certain. However, real-life problems inevitably involve some degree of uncertainties in loading conditions, material properties, geometries, manufacturing precision, etc. (Fang, Gao, Sun, Zhang, & Li, 2014; Sun et al., 2011). It must be pointed out that in general, a deterministic optimization tends to push a design towards one or more constraints until these constraints become active, thereby leaving very little or no room for accommodating any modeling and/or manufacturing imperfection (Yang, Akkerman, Anderson, Faruque, & Gu, 2000; Yang & Gu, 2004). Consequently, nondeterministic problems in reality solved by deterministic optimization algorithms could lead to unreliable design. To address this issue, some nondeterministic optimization algorithms have been presented and successfully applied in structural crashworthiness design (Koch, Yang, & Gu, 2004; Youn & Choi, 2004). Other nondeterministic optimization for structural crashworthiness can be also found in literature (Du & Chen, 2004; Fang, Gao, Sun, & Li, 2013; Gu, Sun, Li, Mao, & Li, 2013; Li, Luo, & Sun, 2011; Sinha, 2007).

However, the traditional nondeterministic optimization algorithms have been focusing on continuous variable problems. In fact, the design of hybrid steel–aluminum TWB structures is indeed a discrete optimization problem. In addition, the responses of hybrid steel–aluminum TWB structures are highly nonlinear, imposing considerable difficulty to establish a proper surrogate model with adequate accuracy (Song, Sun, Li, Gao, & Li, 2013). Therefore, the aim of the paper is to develop a new nondeterministic optimization method for discrete variables without using surrogate.

For the discrete nondeterministic design problem, the Taguchi method has been extensively used to determine the optimal level of each parameters to reduce variations in responses and at the same time improve the mean performance (Badkar, Pandey, & Buvanashekaran, 2011; Sibalija & Majstorovic, 2012). However, the traditional Taguchi method only fits the problems with small variables and levels. The reason is that the number of the experiments of orthogonal array would significantly increase with the increasing of the number of variables and levels, leading to high computational cost. To address the issue, a novel discrete robust optimization algorithm, namely a successive Taguchi approach, is developed for the crashworthiness design of hybrid steel–aluminum tailor welded thin-walled structures.

2. Conventional Taguchi robust design method

Taguchi design method is an important tool for robust design, which is able to find the optimum setting of the control factors to make the product and process conditions insensitive to the causes of variation (Gaitonde, Karnik, & Paulo Davim, 2008). Therefore, the method could produce high-quality products with low development and manufacturing costs. Two major tools used in Taguchi method are the signal-to-noise ratio (SNR) and the orthogonal array.

2.1. Signal-to-noise ratio

In the Taguchi method, the term 'signal' represents the desirable value (mean) for the output characteristic and the term 'noise' represents the undesirable value (standard deviation) for the output characteristic. Therefore, the SNR is the ratio of the mean to the standard deviation. Taguchi uses the SNR to measure the quality characteristic deviating from the desired value. The reason of quality fluctuation is that there are some uncontrollable factors, named as noise factors, which can be classified into external factors (e.g. temperatures and human errors), manufacturing imperfections and product deterioration. Depending on design objective, there are three quality characteristics namely "the-nominal-the-better", "the-smaller-the-better", and "the-larger-the-better" (Nalbant, Gokkaya, & Sur, 2007). Their mathematical expressions are formulated as follows:

Case 1: "Smaller-the-better": aiming to minimize the performance.

$$SNR = -10\log_{10}\left(\frac{\sum_{i=1}^{N} y_i^2}{N}\right) \tag{1}$$

where the y denotes the performance indicator, subscript i experiment number, N number of replicates of experiment 'i'.

Case 2: "Larger-the-better": aiming to maximize the performance.

$$SNR = -10\log_{10}\left(\frac{\sum_{i=1}^{N} 1/y_i^2}{N}\right) \tag{2}$$

Case 3: "Nominal-is-best": aiming to target the predetermined nominal value.

$$\begin{cases} SNR = 10\log_{10}\left[\left(\frac{\bar{y}}{s}\right)^2\right] \\ \bar{y} = \frac{y_1+y_2+y_3\cdots+y_N}{N} \\ s = \frac{\sum_{i=1}^{N}(y_i-\bar{y})^2}{N-1} \end{cases} \tag{3}$$

Regardless of the category of quality characteristic, a greater SNR corresponds to better quality characteristic.

2.2. Orthogonal arrays

To simply describe the principle and progress of orthogonal experimental design, it is assumed there are four design variables of A, B, C and D. Each design variable has three levels. The L_9 orthogonal array is chosen to arrange the experimental plan, as shown in the inner array in Table 1. In order to obtain reliable SNR, each experiment often needs a large number of replicates. Repeated physical tests often obtain different results due to the presence of noise factors. However, in the numerical simulation, repetitive runs often generate the same output responses, which cannot reflect the effect of noise factors. To address this issue, cross product arrays (see Table 1) is used to sample the design space and capture variability, where the noise factors sampled with design of experiments (DoE) such orthogonal arrays as Optimal Latin Hypercube sampling are arranged in an outer array, and the design variables sampled with orthogonal arrays are arranged in an inner array (Sun et al., 2010a). For each controllable factor experiment, a response value is obtained for each noise factor design point. Many response vales can be obtained by repeating the process on all noise experimental points. Based on these results, the SNR could

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