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Multiobjective crashworthiness optimization of thin-walled structures with functionally graded strength under oblique impact loading

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ABSTRACT

In this paper, the crashworthiness of a new introduced thin-walled structure made of hot stamping high strength steel with functionally graded strength (FGS), i.e. wall strength varying along the axial direction with a specific gradient, is investigated. The FGS columns are comprehensively studied under both axial crushing and oblique impact loading in the nonlinear FE mode LS_DYNA. The numerical simulation result shows that parameters of gradient exponent m and top strength S of FGS columns have a remarkable effect on the crashing behavior indicators such as critical load angle, energy absorption (EA) and peak crash force (PCF). To optimize the crashworthiness of the FGS columns, multi-objective optimization based on surrogate model of Radial Basis Function (RBF) and algorithm of Non-dominated Sorting Genetic Algorithm II (NSGA-II) are performed. To effectively consider the load angle uncertainty effect and obtain a more robust design, four schemes are employed to evaluate the comprehensive crashworthiness with different weight coefficient distributions. The result shows that all the Pareto fronts of FGS columns indicate considerably better crashworthiness compared to that of the counterpart uniform strength (US) columns. The consistent optimization result under different evaluation schemes not only provide guidance for the FGS column design, but also declare a good robustness for Pareto designs obtained by multi-objective optimization design (MOD) optimization. Finally, the obtained Pareto fronts of FGS columns are obviously found to consist of two parts. The first part contains the columns that possess gradient exponent ranging from 0 to 3 with top strength keeping a constant value near 480 MPa. The second part consists of the columns that possess gradient exponent keeping constants close to 0 with the top strength ranging from 700 to 950 MPa. This optimum results is different from that only obtained from pure axial crushing analyze in the previous researches and shows a better reference for engineering practice.

1. Introduction

In recent years, road and vehicle safety becomes increasingly important and has notably heightened legislative requirement by introducing more effective systems to the vehicle, while a growing concern in environment and sustainability has also largely pushed up the lightweight standard to reduce fuel consumption. Thus, various novel configurations of structures have been proposed and further optimized as an energy absorber during crashes, such as the thin-walled structures, multi-cell tubes [1–3], foam-filled structures [4–6], composite structures [7–9], functionally graded structures [10–13] and structures made of tailor-welded blank [14,15] and tailor-rolled blank, which have been widely and deeply investigated in crashworthiness design by using analytical, numerical and experimental methods.

As an energy absorber in crashworthiness applications like trains, cars, ships, airplanes and other high-volume industrial products, the thin-walled structures have been widely used to ensure crash safety due to their lightweight, low cost and high energy absorption (EA), but also exhaustively investigated and designed in order to achieve better crashworthiness performance. Among those, some researchers focused on structures with various cross-sections including circle-[16,17], square-[18], polygonal- hat-shaped [19,20] and multi-cell cross-sections that affect crashing performance. Some other researchers tried to improve the EA of structures by adjusting the thickness or mechanical properties on side walls through different technologies, in order to make full use of the material on structures. For example, Hou et al. [21] optimized the single, double, triple and quadruple cell sectional columns under longitudinal impact loading so as to maximize the specific energy absorption (SEA) and minimize the peak crashing force (PCF). Sun et al. introduced a functionally graded thickness [10,22,23] to the longitudinal direction and cross section of single and multi-cell tubes to obtain better crashworthiness. And results showed that all the

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functionally graded thickness tubes produced more competent Pareto solutions than the conventional uniform thickness counterparts. Even more interesting, a crash-box modeled as a deformable body in full detail was designed and optimized by defining the shapes of the cross-sectional and longitudinal profiles as well as the thickness as the optimization variables, aiming at maximizing its crashworthiness [24].

In addition, along with the development of technologies such as tailor-welded blank, tailor-rolled blank and hot stamping technology for boron steel, researches have also paid great attention to thin-walled structures with graded mechanical properties. Tailor-welded blank technology consists of laser welded sheet metals with different thicknesses and different materials for a single part. Crashworthiness optimization of tailor-welded blank structures [14,15,25,26] often aims to seek the best partition of different materials and thicknesses of each blank for both crash behaviors and lightweight. While the tailor-rolled blank technology varies the blank thickness by a rolling process, which has been demonstrated feasible to be applied in vehicle structures to achieve better functional performance and reduce the mass [27] simultaneously. Employ the hot stamping technology, Ying et al. [28] introduced a thin-walled structure with functionally graded strength (FGS) and demonstrated that the FGS columns could enhance the SEA and lower the PCF concurrently. It is more competent than the traditional uniform strength (US) columns when configured with suitable gradient parameters.

As the hot stamping technology developed, studies have been carried out on how to manufacture the hot stamping structure with graded strengths. Technologies such as the stage cooling by forced air [29], the bypass resistance heating of blank and the tailored tempering process using heated and cooled tools [30–32] have been brought up. Among them, the tailored tempering process is the most popular technology that has been studied by many researchers. Based on this process, parts with graded strengths have been successfully manufactured by R. George [30,33]. And low conductivity tools were proved to be better than that with high conductivity in consideration of the robustness [29]. What's more, a numerical model of the tailored tempering process was developed by B.T. Tang et al. [31]. It can use the commercial FE code Forge™ to accurately predict the part's Vickers hardness distribution and microstructural evolution before it is manufactured, so the temperature distribution on tools can be reverse predicted according to the strength distribution on designed part. Besides, K. Mori et al. [34,35] have developed a hat-shaped tailored die and successfully formed the Advanced High Strength Steel parts with gradient strength distribution using bypass resistance heating technology, too. The above research basis has provided us confidence to design structures with functionally graded strengths (FGS), though, however, very limited studies on crashworthiness design of thin-walled FGS structures have been conducted so far. Along with the development of the tailored hot stamping technology, the optimal FGS columns can be manufactured someday in future.

However, all the above-mentioned studies have focused on the crushing response and energy absorption characteristics of thin-walled structures under pure axial loads. In practical crash event, especially in the context of automobile crashes, energy absorbers such as the side rails rarely experience pure axial, instead, they often deform under a combination of axial and off-axis or oblique loads. Compared to pure axial loading, oblique loading is much more complicated because both axial progressive and global bending deformation would happen, which often leads to unstable reduction in energy absorption. Thus, lots of researches have concentrated on the design and optimization of thin-walled structures regarding oblique loading. According to requirements in the automotive industry, the bumper system should endure a load applied with a load angle of 30° to the longitudinal axis [36]. Investigations on thin-walled columns [37–39] subjected to oblique loading showed that the response of columns could be divided into three stages: axial progressive collapse, global bending collapse and a transition zone, as load angle changes. And a critical load angle that lies within the transition zone can be found for each column. Studies [40,41] on straight columns also found that the crashworthiness indicators, such as EA, peak crashing force (PCF) and mean crashing force (MCF), drop dramatically with an increasing loading angle, especially when the global bending collapse happened.

As a consequence, thin-walled structure, as energy-absorber, needs to not only meet the requirements of structural collapse and deceleration under axial crushing, but also needs to maintain proper crashworthiness under oblique impact loading. In other words, the structures should be intended to minimize PCF, absorb maximum energy, and generate stable folding lobes under oblique impact loading [5,39] as well. So far, the novel developed FGS thin-walled structure has only been investigated based on the axial crushing [28], which has been proved to have superior performance compared to the traditional US columns. However, it is still unknown whether it is able to maintain the superiority when subjected to oblique impact loading under different load angles. Therefore, the purpose of this study is to investigate the crashworthiness of the FGS thin-walled structure under oblique impact and seek out the optimal gradient parameters for FGS columns, aiming to minimize the PCF and maximize the energy absorption capability.

To achieve the above purpose, numerical simulations of FGS columns configured with different gradient exponents and top strength subjected to oblique impact under different angles in range of 0°~40° were carried out in LS_DYNA. To sample the design points, a full factorial design of experiments (DoE) method was employed. When analyze and optimize the crashworthiness performance of FGS columns considering the load angle uncertainty, four evaluate schemes were adopted to calculate the indicator comprehensive EA. In order to search for the best FGS columns with optimal parameters of gradient exponent m and top strength S, the surrogate model of Radial Basis Function (RBF) and algorithm of algorithm of Non-dominated Sorting Genetic Algorithm II (NSGA-II) were implemented in solving multi-objective optimization design (MOD) problems. Based on the simulation and optimization result, factors influencing critical load angle, PCF and EA were analyzed, together with the comparison study between FGS columns and US columns. Results under four different evaluation schemes all demonstrated that the FGS columns were more preferable to US columns.

2. Material and method

2.1. Material and geometry

It is assumed that the thin-walled columns investigated in this paper were made of quenched boron steel 22MnB5 [42], which can obtain different material properties when quenched at different cooling rates [42–45]. According to the constitutive model established by A. Bardelcik [42], a series of material's flow stress curves of USIBOR$^{@}$ 1500P under different Vickers hardness and strain rates can be obtained. They had been adopted by L. Ying [28] and validated to be feasible for numerical simulation of FGS thin-walled structure. The detail process to obtain the flow stress curves are elaborately introduced in literature [28] and the typical true stress-effective plastic strain curves are shown in Fig. 1.

The thin-walled structure is deemed to be made of quenched 22MnB5 steel sheet with functionally graded strength along the longitudinal direction of the wall. The strength gradient can be defined as [11,23]:

$$\sigma_f(y) = \sigma_{f1} + (\sigma_{f2} - \sigma_{f1})\left[\frac{y}{L}\right]^m \tag{1}$$

where σ_{f1} and σ_{f2} are the strengths at the top and bottom ends, respectively, L is the total length of the square column, y is the distance from the top end of the column, and m is the exponent to determine the change pattern of steel strength. When $m = +\infty$, FGS columns turn out