Research Article

Topometry Optimization of Energy Absorbing Structure through Targeting Force-Displacement Method considering Tailor Rolled Blank Process

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Inspired by topometry optimization, this work proposed a new design approach that mixed of targeting force-displacement (TFD) method and tailor rolled blank (TRB) process for thin-walled energy absorption structures, which has vast applied prospects in the aerospace and automotive industries. This method not only overcomes manufacturing difficulty caused by the TFD method based on topometry optimization but also provides a new idea for TRB energy absorption structure. The optimized results can be transferred to the computer aided design environment without additional postprocessing. Firstly, a uniform thickness constraint is introduced to make the designed structure have constant thickness distribution along desired direction; topometry optimization is carried out to use TFD method. Secondly, a method that can automatically divide the design domain is developed. The adjacent elements with smaller thickness differences are merged to form TRB subdomains based on the optimization results of forestep, and the TFD method is used again. Finally, TRB finite element modeling codes is developed. According to the second step, modeling of the transition zone is added to finally form the TRB structure that meets the requirements of manufacturing. This method is used to optimize the crashworthiness of the thin-walled tube under axial and oblique loading. Numerical results demonstrate the effectiveness of this method. Therefore, this method can be used to design high-efficiency energy absorber on aircraft or automobile, such as the strut of aircraft and energy absorption box of automobile.

1. Introduction

Safety is the basic requirement in the design process of the transportation vehicle. The crashworthiness design is an indispensable part of the design process of an aircraft [1, 2], unmanned aerial vehicle [3, 4], and traditional and new energy vehicles [5, 6]. The safety of drivers, passengers, pedestrian, and critical subsystem components [7–14] must be protected in crash events. In recent years, energy absorbing structures with variable thickness [15–17] have attracted extensive attention from researchers all over the world. However, variable thickness design methods considering advanced manufacturing process needs further exploration. Therefore, the development of more efficient energy absorbing structure with variable thickness design methods has important academic value and engineering significance.

Topometry optimization [18], also called free sizing optimization, is proposed to make structure design more flexible. This is owing to each element size can be an independent design in this approach. Topometry optimization can further explore the potential of components while keeping original layout of the structure system, especially in the crashworthiness design of the energy absorbing structure. However, it is difficult that topometry optimization handles impact problems because of the large amount of design variables, fully nonlinearities between objective/constraints function and design variables, and the nature of time-consuming of explicit finite element analysis. Besides, thickness distribution of optimized structure is very complex to cause expensive to manufacturing. Therefore, topometry optimization is only applicable to conceptual design at present.
The TFD method is a heuristic optimization method, the explicit nonlinear finite element analysis code LS-DYNA is used to execute impact simulation, conversion process between nonlinear and linear load is averted contract on the ESL method. Compared to the HCA method, this method does not rely on energy assumption and other inputs from designer. In this method, the analytical relationship between energy and thickness of shell element has been derived. Then, the highly nonlinear crashworthiness problem is rendered into suboptimization problems with analytical form. In each iteration, an explicit finite element analysis is executed and then an optimization subproblem with analytical form is solved. In addition, FD behavior is selected to design objective because it determines the crash force, displacement, and internal energy that the structure should withstand subject to impact load. The desired FD response is achieved; several crashworthiness indicators are improved simultaneously such as peak force, mean force, specific energy absorption, and crash load efficiency. Nowadays, the TFD method is applied to crashworthiness optimization design of automobile front structures [30] and regional airliner’s fuselage section [31] successfully. Although the idea of optimizing the thicknesses of each (shell) finite element of the structure gets good optimization results, this idea led to poor manufacturability of the designed structure.

To solve the manufacturing problem of the optimized structures using the TFD method while maintaining the advantages of this method, some new advanced thickness variations manufacturing processes can be considered such as tailor rolled blank (TRB). TRB technique is a novel configuration with continuous thickness variations to maximize usage of material. The desired thickness profile in rolling direction is achieved by adjusting the roll gap during the rolling process, and the smooth thickness transition between the thick and thin can be produced [32]. Thereby, the TRB structures have no stress peaks, show good surface quality due to continuous thickness variations, and exhibit potential in the design of light weight structures. At present, the TRB structure for energy absorption has been widely concerned. Chuang et.al [33] developed a process, which integrates both advantages of the TRB technique and multidisciplinary design optimization methodology for vehicle structure design. Sun et.al [34] and Zhang et.al [35] explored the influence of the thickness difference of adjacent zones and length of transition zone on the crashworthiness of TRB top-hat structures consisting of a thick, a thin, and a transition zone. But the values of these design parameters are determined by the designer, the obtained structures may not be optimal. Yang et.al [36] optimized the automobile B-pillar using nondominated sorting genetic algorithm based on surrogate model. The result shows that the weight of B-pillar can be reduced by over 30%, while its crashworthiness is guaranteed. However, this research ignores transition zone of the B-pillar with TRB concept. Duan et.al [37] improved load bear and energy absorption ability of the TRB with top-hat section under bend loading by integrating response surface method and nondominated sorting genetic algorithm. However, method like these are few optimization variables, and does not use explicit dynamic analysis in the optimization process, which greatly affect the optimization results of TRB structure. Sun et.al [38] obtained optimal thickness distribution of TRB structure in desired direction by adding
thickness constraint during optimization process. The research shows that manufacturing difficulty caused by using optimization can be overcome by constraining the thickness distribution along desired direction. To sum up, the existing design methods of TRB structure cannot be directly applied to guide production.

**Table 1: Crashworthiness parameters.**

| Crashworthiness parameters | Maximum force (kN) | Mean force (kN) | CLE | SEA (kJ/kg) |
|----------------------------|--------------------|-----------------|-----|------------|
| Definition                 | The highest force on above-mentioned the FD curve, $F_{\text{max}}$ | The average of force during the crash process, $F_{\text{mean}}$ | The ratio of maximum force to mean force, to assessed the uniformity of the FD curve | Energy absorption capability per unit mass of the structure |
| Calculate method           | /                  | $F_{\text{mean}} = \int_{d_0}^{d_f} \frac{F_{\text{dd}}}{d_f-d_0}$ | $\text{CFE} = \frac{F_{\text{mean}}}{F_{\text{max}}} \times 100\%$ | $M$ is the total mass of the structures. The higher the SEA, the better the lightweight design potential of the structures. |
| Further explanation        | /                  | $F$ is force response of the crash process, $d_0$ and $d_f$ represents the initial and final displacement of the crash process. | Ideal value is 100%, that is, the crash load is a constant value during the collision. | $\text{SEA} = \frac{\int_{d_0}^{d_f} F_{\text{dd}}}{M}$ |

**Figure 3: Optimization technology roadmap based on TRBs.**

In this paper, an optimization strategy is proposed by integrating the TFD method and the advantages of TRB technique. According to the manufacturing requirements of TRB structures, thickness constraint is added to the TFD method. Firstly, a uniform thickness constraint is introduced to make the designed structure have constant thickness distribution along desired direction; topometry optimization is carried out to use TFD method. Secondly, based on the optimization results of forestep, the adjacent elements with smaller thickness differences are merged to form TRB subdomains, and the TFD method is used again. Finally, on the basis of the second step, modeling of the transition zone is added to finally form the TRB structure that meets the requirements of manufacturing. This optimization strategy is used to optimize the crashworthiness of the square thin-walled tube under axial and oblique loading. The results show that the actual FD response of optimized tube is close to desired FD response, solving manufacturing difficulty caused by using optimization while some advantages of the TFD method are maintained.
The structures of this paper are as follows: Section 2 describes the problem statement and the TFD method. Section 3 presents the proposed optimization method in detail. Section 4 shows the numerical examples and the optimization results. Section 5 summarizes the work of this paper and discusses future work.

2. TFD Method and Crashworthiness Criteria

2.1. Problem Statement. This paper aims at solving the manufacturing difficulty caused by using the TFD method while the advantages of this method are maintained. FD behavior is selected to design objection because it determines the crash force, displacement, and internal energy that the structure should withstand subject to impact load.

This optimization problem involves two FD responses of the structure: the target response $F^*(d)$ and the actual response $F(d)$ (See Figure 1). This is done by adjusting the thickness of structures so that the error between $F^*(d)$ and $F(d)$ is minimized. This is

$$
\text{find } t \in \mathbb{R}^N \\
\text{minimize } C(t) = \int_{d_0}^{d_f} \frac{(F(d) - F^*(d))^2}{d_f - d_0} \; dd \\
\text{subject to } t_{\min} \leq t \leq t_{\max} 
$$

(1)

where $t$ is the vector of element thickness values, $d_0$ and $d_f$ represent the initial and final displacement of the displacement span of the crash simulation, and $t_{\min}$ and $t_{\max}$ are the lower and upper bounds, respectively.

Due to the discrete nature of the numerical analysis, the objective function is transformed a discrete summation form. Therefore, $m$ equidistant design points are defined in the displacement interval. Thus, the objective function can
be restated as

\[
\text{find } t \in \mathbb{R}^N \\
\text{minimize } C(d, t) = \frac{1}{m} \sum_{j=1}^{m} [F(d_j, t) - F^*(d_j)]^2, \\
\text{subject to } t_{\min} \leq t \leq t_{\max}
\]

2.2. TFD Method

2.2.1. Overview of the TFD Method. In the TFD method, the optimization problem is transformed into a series of subproblems. Each iteration consists of one explicit dynamic simulation and the solution of one subproblem. The coordinate displacement and element energy response with respect to time in the impact process can be obtained by explicit dynamic analysis. In the iterative suboptimization, the analytical relationship between the crash force and thicknesses of all shell elements of the structure is established. Design variables are updated by solving the iterative suboptimization. The basic principle is shown in Figure 2.

2.2.2. Suboptimization Problems. The mathematical optimization model of iterative suboptimization problems is as follows:

\[
\text{find } t \in \mathbb{R}^N \\
\text{minimize } C(d, t) = \frac{1}{m} \sum_{j=1}^{m} \left[ \sum_{k=1}^{N} R_{Ek}(\{d_j\}) \left( \frac{\partial F}{\partial d_j} \right) \right]^2 - F^*(d_j) \\
\text{subject to } t_{\min} \leq t \leq t_{\max} \\
\left| \frac{\partial F}{\partial d_j} - F^*(d_j) \right| \leq \alpha, \epsilon = 1, 2, 3, \ldots, N
\]

(3)

where $R_{Ek}$ and $R_{EI}$ represent the derivatives of kinetic energy and internal energy with respect to the displacement, respectively. The parameter $\alpha$ is the move limit. In our previous work [30], a conclusion is drawn that the move limit is recommended to be between 0.05 and 0.15 to ensure the
effectiveness of the algorithm. Therefore, the value of $\alpha$ is 0.1 in this paper. In this paper, considering the process requirements of TRB structures, the upper and the lower bounds of the shell element thickness are 3.0 mm and 0.5 mm. The derivation process of the equation (3) is detailed in reference [19].

2.2.3. Convergence Criterion. Since the large scale of the design variables, highly nonlinearity of the impact problem, and high level of numerical noise, the objective function may not find global optimal solution after a large number of iterations. But a local optimal solution satisfying design requirement can be available. The optimization process is terminated when

$$\min \left\{ C_{k-N_c+1}, C_{k-N_c+2}, \ldots, C_k \right\} > C_{k-N_c},$$

where $N_c$ is an integer called convergence number, and $k \geq N_c$ is the iteration number. In other words, the convergence condition is satisfied when the objective function does not decrease for more than $N_c$ consecutive iterations. Due to the numerical noise in explicit dynamic analysis and the property of time consuming of full-size vehicle simulation, the value of the convergence number is chosen as $N_c = 10$.

2.3. Crashworthiness Criteria. In order to evaluate the crashworthiness performance of the structure, the crash indicators such as maximum force, mean force, crash load efficiency (CLE), and specific energy absorption (SEA) are introduced, and their calculation method are described based on FD curve during crash process in Table 1.

The specific energy absorption (SEA) is a critical parameter. The energy absorber should dissipate the maximum possible amount of energy per unit mass, in order to allow for a lightweight design.

3. The Targeting Force-Displacement Method considering Tailor Rolled Blank Process

3.1. Overview of the Proposed Optimization Method. The optimization strategy includes the following steps: Firstly, a uniform thickness constraint is introduced to make the designed structure have constant thickness distribution along desired direction; topometry optimization is carried out to use TFD method. Secondly, based on the optimization results of forestep, the adjacent elements with smaller thickness differences are merged to form TRB subdomains, and the TFD method is used again. Finally, on the basis of the second step, modeling of the transition zone is added to finally form the TRB structure that meets the requirements of manufacturing.

3.2. Framework of the Proposed Optimization Method. The overall optimization procedure (See Figure 3) is given as follows:

Step 1: Establish the finite element model of the structure with uniform thickness.
In the given boundary and loading conditions, the numerical model is established using the nonlinear explicit finite element analysis software LS-DYNA. The structure is modeled by employing 4-node fully integrated shell elements with five integration points across the thickness to avoid hourglass deformation.

Step 1: Find the minimum thickness and the corresponding numbering of this element, and judge whether the thickness of adjacent elements meets the conditions according to the connectivity information of the current element.

\[
\text{find } \left\{ \begin{array}{l} T_{\min} \in R_N \\ T_{E_{adj}} \end{array} \right. \quad , \quad (5)
\]

subject to \( \left| T_{\min} - T_{E_{adj}} \right| \leq \varepsilon \)

where \( R_N \) is the thickness dataset of all shell elements, \( T_{\min} \) is the minimum thickness of the current element, \( T_{E_{adj}} \) is a matrix with the thickness of adjacent elements, \( \varepsilon \) is a control parameter relation to element thickness.

Step 2: Obtain optimal thickness distribution of the structure by using TFD method in the given conditions.

Step 3: Merge adjacent elements with smaller thickness differences to form TRB subdomains.

This method is described in section C (III).

Step 4: Set uniform thicknesses constraint of subdomains and find optimal thickness distribution of the TRB structure without transition zones by using TFD method again.

Step 5: Establish finite element model of TRB structure.

Based on the optimization results of forestep, the finite element model of the optimized structure is automatically transformed to the finite element model of TRB structure by using a finite element modeling technique and output the keyword file. This method is described in section D (III), which mainly includes determining length and location of transition zones, and how to realize continuous thickness variation.

Step 6: Evaluate crashworthiness of TRB structure.

3.3. The Dividing Method of TRB Subdomains. For a specific dataset with \( N \) cell array (\( N \) represents the number of shell element), each cell array consists of the numbering and thickness of a shell element. \( K(K \leq N) \) groups are created, each group represents a cluster, and some requirements can be meet as follows:

(1) Each cluster consists of at least a cell array

(2) Each cell array belongs to only a specific cluster

The steps involved in this dividing method are as follows:

Step 1: Find the minimum thickness and the corresponding numbering of this element, and judge whether the thickness of adjacent elements meets the conditions according to the connectivity information of the current element.

\[
\text{find } \left\{ \begin{array}{l} T_{\min} \in R_N \\ T_{E_{adj}} \end{array} \right. \quad , \quad (5)
\]

subject to \( \left| T_{\min} - T_{E_{adj}} \right| \leq \varepsilon \)

where \( R_N \) is the thickness dataset of all shell elements, \( T_{\min} \) is the minimum thickness of the current element, \( T_{E_{adj}} \) is a matrix with the thickness of adjacent elements, \( \varepsilon \) is a control parameter relation to element thickness.
Step 2: When equation (5) is satisfied, adjacent elements are divided into the same cluster. Continue to find adjacent elements of all elements of the current cluster, and judge whether the thickness of unallocated adjacent elements meets the equation (5). The current cluster is stopped until all unallocated adjacent elements are not satisfied with the equation (5), and go to step 3.

Step 3: Found the minimum thickness of unallocated adjacent elements of current all allocated elements, step 1 and step 2 are repeated for clustering until all elements are allocated.

3.4. The Finite Element Modeling Techniques of TRB Structures

3.4.1. Determining Length of Transition Zone. To convenient manufacturing while technological requirements of TRB structures (See Figure 4), the ratio of transition zone length and thickness difference between thick and thin shall meet:

$$\frac{l}{\Delta t} \geq 100,$$  \hspace{1cm} (6)

where $l$ is the length of transition zone, $\Delta t$ is the thickness difference between thick and thin.

3.4.2. Determining Location of Transition Zone. As shown in Figure 4, continuous transition zone of optimized structure is ignored. Location of transition zone is determined based on the ration of thick zone and thin zone length. Take the interface between thick zone and thin zone as starting point, and extend the distance to thick zone and thin zone, respectively:

$$l'_{\text{thin}} = \frac{l_{\text{thin}}}{l_{\text{thin}} + l_{\text{thick}}} \times l,$$

$$l'_{\text{thick}} = \frac{l_{\text{thick}}}{l_{\text{thin}} + l_{\text{thick}}} \times l,$$  \hspace{1cm} (7)

where $l'_{\text{thin}}$ is the length of extending to thin zone, $l'_{\text{thick}}$ is the length of extending to thick zone.

Therefore, the thickness of arbitrary nodes on transition zone can be obtained.

3.4.3. Finite Element Modeling Techniques of TRB Structures. Unlike uniform thickness structure, the TRB structure needs to assign different thickness to each node corresponding to the element in the model, so as to truly and reasonably simulate the dynamic impact. To capture accurately the mechanical performance of TRB structure, TRB finite element modeling codes is developed. The finite element model of the optimized structure is automatically transformed into the finite element model of the TRB structure. The steps involved in this technology are as follows:

Step 1: Established the finite element model of uniform thickness structure, and generate the keyword file.

Step 2: Read the connectivity information (elements and nodes information) of all shell elements according to the data regular of keyword *ELEMENT_SHELL and *NODE from the keyword file.

Step 3: Determine the thickness matrix of all nodes according to the obtained transition zone of the optimized structure.

Step 4: Assign different thicknesses to each of the four nodes of the shell element by using the keyword *ELEMENT_SHELL_THICKNESS (See Figure 5) in LS-DYNA according to the nodal coordinate in the desired direction [39].

Step 5: Generate the keyword file of TRB structure.

4. Numerical Examples and Discussion

4.1. Finite Element Model. As shown in Figure 6, a thin-walled square tube is optimized under axial and oblique loading (20°) in this paper. The length of this tube is 1000 mm, the side length of the section is 100 mm, and the initial thickness of the tube is 1.8 mm.

The finite element model is established by commercial software HyperMesh, the explicit nonlinear finite element code LS-DYNA is used to execute explicit dynamic analysis. The thin-walled square tube is discretized by employing 4-node fully integrated shell elements with five integration points across the thickness to avoid hourglass deformation. The mesh size of shell element is $10 \times 10$ mm, so the total number of shell elements is 4000. The one of steel is utilized to the tube, its mechanical properties are summarized in Table 2 and Figure 7. The back end is fully constrained and the front end is subjected to axial impact and oblique impact by a rigid wall.
The rigid wall is discretized by employing solid element, its velocity is 5 m/s, and forward displacement is 700 mm. In order to avoid penetration, the automatic single surface contact is used between the tube and rigid wall, the friction coefficient is set to 0.3 for static and 0.2 for sliding.

Considering the process requirements of TRB structures, the upper and the lower bounds of the shell element thickness are 3.0 mm and 0.5 mm.

### 4.2. Optimization of Thin-Walled Square Tube with Thickness Constraints under Different Load Conditions

The thin-walled square tube is impacted by a rigid wall with a velocity of 5 m/s. The issue is usually overcoming through setting the thickness distribution along desired direction in the manufacturing. Therefore, the thickness constraint of the tube is set to have constant thickness distribution along the circumferential direction.

As shown in Figure 8, the direction of the black arrow is the axial direction of the tube, and the elements thickened in the black wireframe are set to the same thickness value.

As shown in Figure 8, the direction of the black arrow is the axial direction of the tube, and the elements thickened in the black wireframe are set to the same thickness value.

#### 4.2.1. Optimization of Thin-Walled Square Tube with Thickness Constraints under Axial Impact

(1) First Optimization by Using TFD Method. Firstly, thickness distribution optimization is performed by using the TFD method to find optimal thickness distribution of the tube based on the thickness constraint along circumferential direction. The iterative progress of the objective function is shown in Figure 9. The best design is found at iteration 6. The optimization is terminated after 16 iterations. The optimal objective function of this optimization is $2.03 \times 10^8$.

### Table 5: Crashworthiness parameters of four configurations of the thin-walled tube.

| Crashworthiness parameters                        | Peak force (kN) | Mean force (kN) | CLE     | SEA (kJ/kg) |
|--------------------------------------------------|-----------------|-----------------|---------|-------------|
| Uniform thickness tube                            | 129.10          | 55.75           | 43.17%  | 6.94        |
| Designed tube with circumferential constraints    | 90.18           | 59.91           | 66.43%  | 7.13        |
| TRB concept tube without transition zone          | 101.70          | 61.27           | 60.22%  | 7.26        |
| TRB tube                                          | 105.50          | 62.15           | 58.90%  | 7.37        |

![Figure 22: Objective function vs. number of iterations.](image)

![Figure 23: The FD curve of the uniform thickness tube and designed tube.](image)

![Figure 24: Thickness distribution of the designed tube.](image)

![Figure 25: Configurations of the TRB concept tube without transition zone.](image)
As shown in Figure 10, the solid blue curve and dashed red curve represents the FD curve of the designed tube and uniform thickness tube (1.8 mm). The FD curve of the designed tube is closer to target curve than initial tube, the peak force is reduced to 90.18 kN from 129.10 kN (decreased by 30.1%), and the mean force is increased to 59.91 kN from 55.75 kN (increased by 7.5%).

The thickness distribution of the designed tube is shown in Figure 11.

(2) Divide Subdomains and Optimize Again by Using the TFD Method. According to finite element model techniques of TRB structures and thickness distribution results of the initial tube mentioned above, the tube can be divided in many different ways depending on different values of control parameter $\varepsilon$.

The tube is divided into eight subdomains while $\varepsilon = 0.25$, these subdomains in detail are shown in Figure 12 and Table 3.

The TFD method is used again to optimize the TRB concept tube without transition zone. The iterative progress of the objective function is shown in Figure 13. The best design is found at iteration 10. The optimization is terminated after 20 iterations. The optimal objective function of this optimization is $1.68 \times 10^6$.

As shown in Figure 14, the solid blue curve and dashed red curve represents the FD curve of the designed tube and uniform thickness tube (1.8 mm). The FD curve of the TRB concept tube without transition zone is closer to target curve than initial tube, the peak force is reduced to 101.70 kN from 129.10 kN (decreased by 21.2%), and the mean force is increased to 61.27 kN from 55.75 kN (increased by 9.9%).

The thickness distribution of the TRB concept tube without transition zone is shown in Figure 15 and Table 4.

(3) Verify the Crashworthiness of the TRB Structure. Due to the length of $L_1$ and $L_2$ being 40 mm and 30 mm, respectively, the thickness difference between the two subdomains is 0.3 mm, manufacturing requirements cannot be met according to location of transition zone mentioned above. Therefore, $L_2$ is not considered, transition zone is established between $L_1$ and $L_3$ directly. The thickness distribution and location of transition zone of TRB tube are shown in Figure 16.

As shown in Figure 17, the solid blue curve, dashed red curve, and solid black curve represent, respectively, the FD curve of the TRB concept tube without transition zone,

| Subdomains | $L_1$ | $L_2$ | $L_3$ | $L_4$ | $L_5$ | $L_6$ |
|------------|-------|-------|-------|-------|-------|-------|
| Length (mm)| 50    | 110   | 230   | 240   | 140   | 230   |

Table 6: Length of the TRB concept tube without transition zone.

| Subdomains | $L_1$ | $L_2$ | $L_3$ | $L_4$ | $L_5$ | $L_6$ |
|------------|-------|-------|-------|-------|-------|-------|
| Thickness (mm) | 1.8 | 2.1 | 1.75 | 1.65 | 1.5 | 1.1 |

Table 7: Thickness distribution of the TRB concept tube without transition zone.
uniform thickness tube (1.8 mm), and TRB tube. Compared with the uniform thickness TWB tube, the peak force of the TRB tube is reduced to 105.5 kN from 129.1 kN (decreased by 18.3%), and the mean force is increased to 62.15 kN from 55.75 kN (increased by 11.5%).

(4) Optimization Results and Discussion. The deformation history of four configurations of the thin-walled tube is shown in Figures 18–21. When the tube undergoes pure axial impact, the progressive buckling is clearly shown the formation of the sequential folds from the front end to back end of the tube. The uniform thickness tube and the designed tube with circumferential constraints have relative uniformity in the shape and size of each fold. For TRB concept tube without transition zone and TRB tube subdomains have obviously local bulking at the front end and relative irregular deformation at the back end, especially TRB tube. In the transition zone at the back
end of TRB tube, there is an obvious trend of the plastic hinge (in black wireframe), which absorbs more energy in the impact process.

The peak force, mean force, crash load efficiency (CLE), and specific energy absorption (SEA) of the four configurations of the thin-walled tube are summarized in Table 5.

As shown in Table 5, the crashworthiness performance of TRB tubes is higher than the uniform thickness tube. Compared to uniform thickness tube, the peak force of the TRB tube is reduced to 105.5 kN from 129.1 kN (decreased by 18.3%), the mean force is increased to 62.15 kN from 55.75 kN (increased by 11.5%), the CLE is increased to 58.90% from 43.17%, and SEA is increased to 7.37 kJ/kg from 6.94 kJ/kg (increased by 6.2%). Compared to other designed tube, the mean fore and SEA of TRB tube is the highest. The highest mean force indicates that more energy is absorbed in the impact process; the highest SEA means that the structure utilization per unit mass is the highest. Therefore, TRB tube has great potential in the lightweight of energy absorbing structure.

4.2.2. Optimization of Thin-Walled Square Tube with Thickness Constraints under Oblique Impact

(1) First Optimization by Using TFD Method. Firstly, thickness distribution optimization is performed by using the TFD method to find optimal thickness distribution of the tube based on the thickness constraint along circumferential direction. The iterative progress of the objective function is shown in Figure 22. The best design is found at
iteration 8. The optimization is terminated after 18 iterations. The optimal objective function of this optimization is $5.88 \times 10^7$.

The FD curve of the designed tube and uniform thickness tube (1.8 mm) are shown in Figure 23. The solid blue curve and dashed red curve represents the FD curve of the designed tube and uniform thickness tube. The FD curve of the designed tube is closer to target curve than initial tube, the peak force is increased to 64.47 kN from 51.05 kN (increased by 26.3%), and the mean force is increased to 35.01 kN from 7.30 kN (increased by 379.6%).

The thickness distribution of the designed tube is shown in Figure 24.

(2) Divide Subdomains and Optimize Again by Using the TFD Method. According to finite element model techniques of TRB structures and thickness distribution results of the initial tube mentioned above, the tube can be divided in many different ways depending on different values of control parameter $\epsilon$.

The tube is separated into six subdomains while $\epsilon = 0.25$, these subdomains in detail are shown in Figure 25 and Table 6. The TFD method is used again to optimize the TRB concept tube without transition zone. The iterative progress of the objective function is shown in Figure 26. The best design is found at iteration 12. The optimization is terminated after 22 iterations. The optimal objective function of this optimization is $5.29 \times 10^7$.

As shown in Figure 27, the solid blue curve and dashed red curve represents the FD curve of the designed tube and uniform thickness tube (1.8 mm). The FD curve of the TRB concept tube without transition zone is closer to target curve than initial tube, the peak force is increased to 59.19 kN from 51.05 kN (increased by 15.9%), and the mean force is increased to 33.77 kN from 7.30 kN (increased by 362.6%).

The thickness distribution of the TRB concept tube without transition zone is shown in Figure 28 and Table 7.

(3) Verify the Crashworthiness of the TRB Structure. According to determining method of transition zone location mentioned above, the thickness distribution and location of transition zone of TRB tube are shown in Figure 29.

As shown in Figure 30, the solid blue curve, dashed red curve, and solid black curve represent, respectively, the FD curve of the TRB concept tube without transition zone, uniform thickness TWB tube, and TRB tube. Compared with the uniform thickness TWB tube, the peak force of the TRB tube is increased to 56.09 kN from 51.05 kN (increased by 9.9%), and the mean force is increased to 33.43 kN from 7.30 kN (increased by 357.9%).

(4) Optimization Results and Discussion. The deformation history of four configurations of the thin-walled tube is

\begin{table}[h]
\centering
\caption{Crashworthiness parameters of four configurations of the thin-walled tube.}
\begin{tabular}{|l|c|c|c|}
\hline
Crashworthiness parameters & Peak force (kN) & Mean force (kN) & CLE \% \\ \hline
Uniform thickness tube & 51.05 & 7.30 & 14.3\% \\ \hline
Designed tube with circumferential constraints & 64.47 & 35.01 & 54.3\% \\ \hline
TRB concept tube without transition zone & 59.19 & 33.77 & 57.1\% \\ \hline
TRB tube & 56.09 & 33.43 & 59.6\% \\ \hline
\end{tabular}
\end{table}
shown in Figures 31–34. When the tube undergoes oblique impact, the uniform thickness tube occurred the global bending, which is a deformation mode of low energy absorption. In order to avoid global bending, the algorithm adds more materials to the back end of the structure, which is conducive to promoting progressive buckling that is a deformation mode of high energy absorption. The progressive buckling is clearly shown in the impact process of the other three designed tubes.

The peak force, mean force, crash load efficiency (CLE), and specific energy absorption (SEA) of the four configurations of the thin-walled tube are summarized in Table 8.

Due to the change of deformation mode, the crashworthiness of TRB tube is much better than uniform thickness tube. When the peak force is only increased by 5.04 kN, the mean force is increased to 33.43 kN from 7.30 kN (increased by 357.9%), the CLE is increased to 59.6% from 14.3%, and SEA is increased to 4.79 kJ/kg from 0.91 kJ/kg (increased by 426.4%). Compared to other designed tube, TRB thin-walled beam has lower peak force and higher CLE and SEA. The lowest peak force and highest CLE indicate that impact load more stable in the impact process; The highest SEA means that the structure utilization per unit mass is the highest. Therefore, the optimized TRB tube has important guiding significance for the lightweight design of the structure.

5. Conclusion

An optimization strategy is introduced mixed of the TFD method and the TRB process to design the thin-walled energy absorption structures in this paper. This optimization strategy is used to optimize the crashworthiness of the square thin-walled tube under axial and oblique loading. According to the optimization result and discussion mentioned above, the conclusion can be drawn as follow:

1. The manufacturing difficulty caused by the TFD method is overcome by setting thickness constraints in the desired direction. Meanwhile, the advantages of the method are maintained. Numerical examples verify the effectiveness of the method, the actual FD response of the TRB tube is close to target FD response, several important crashworthiness indicators are improved simultaneously.

2. A new idea is provided for TRB structure design, and the optimized structure can be directly used to guide production. The explicit nonlinear finite element analysis code LS-DYNA is used to execute impact simulation, and fewer computational resources are required in this method. Optimal thickness distribution can be found quickly, and the accuracy of optimization results can be guaranteed. Optimization results show that TRB structure has great potential in the lightweight of energy absorbing structure.

3. This method can be used to design high-efficiency energy absorber on aircraft or automobile, such as the strut of aircraft and energy absorption box of automobile.

In future research, some problems still need to be considered. The next works are as follows:

1. The designed TRB structure will be verified by experiments.
2. Explore the influence of the length of transition zone on TRB structure.
3. The bidirectional thickness variation is considered to further develop the potential of TRB structure.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflict of interest.

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