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A new method to investigate the energy absorption characteristics of thin-walled metal circular tube using finite element analysis

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ABSTRACT

A numerical study is made to investigate the energy absorbing rule of thin-walled metal circular tube made of three different materials (steel, copper, aluminum) by using response surface methodology (RSM). At the same time, the application prospect of RSM in terms of the research on the energy absorption rule of energy absorption structure can be explored. The test result shows that, the compression process of thin-walled metal circular tube can be divided into three stages: elastic stage, yielding plateau stage, compact stage; To get the greatest value of average plateau force (APF) , a tube with a shorter height and thicker wall should be adopted; To get the greatest length energy absorption (LEA), a tube with thicker wall should be adopted and the ratio of its height and diameter should be as big as possible; To get the greatest specific energy absorption (SEA), a tube with a thicker wall should be adopted and the ratio between its height and diameter should be as big as possible. Thus, it can be seen that, RSM is an advanced experiment design method, and it can be widely used in the research on the energy absorption characteristics of thin-walled metal circular tube and has a promising application prospect in the development of new energy absorbing material and structure.

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1. Introduction

As a structure of high strength-to-weight ratio, high energy absorbing efficiency and low cost, thin metal tube structure [1] is widely used in the Collision kinetic energy dissipation system of ships, motor vehicles, aerospace and many other fields. When it is under impact loading, thin metal tube has a stable gradual damaging pattern. The crushing load fluctuates around the average compressive load, not resulting the out balance of the whole structure. And the impact energy is orderly absorbed through the plastic deformation (plastic bending, plastic twisting and plastic buckling) of thin-walled metal circular tube structure itself. The energy the thin metal structure stored by axial deformation is nearly a magnitude more than that restored by horizontal deformation. Thin-walled structure can absorb a lot of energy under axial impact, and has drawn wide attention from the international academe.

According to structure forms, thin metal structures can be divided into circular tube, square tube, hat shaped structure, conical tube, square taper tube, corrugated plate and so on. At present, rectangle, square and circular section, as they are easy to make, are widely applied in energy absorbing system. The square tube has stable buckling forms, mainly including symmetrical and progressive buckling. However, its specific energy absorption is low [2,3]. Sufficient experiments and theories show that round tube has comparatively higher specific energy absorption. So, circular thin metal structure has a vaster developing prospect and will get more attention.

The energy absorbing properties of circular thin metal structure is closely related to load, geometric parameter, the quality of the material [4–9]. Under impact loading, thin-walled metal circular tube shows the complex plastic dynamic buckling behavior. In the compression process, wrinkle and interactions among the intralaminar part will appear, this is a kind of strongly nonlinear problems, so it is difficult to obtain the analytic solution of the structural response. Hence, in the process of practical engineering application, the above problems were studied using the numerical method, and te finite element method based on dynamic explicit integral is the most effective method currently. Research on the dynamic response and energy absorbing properties of thin-walled metal circular tube can contribute to the research on new energy absorbing material.

Many scholars [10–12] have used the finite element method to study the energy absorption characteristics of thin-walled metal

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circular tube. Marsolek [6] used the finite element analysis software to analyze the energy absorption characteristics under the non axisymmetric cylindrical shell buckling mode; Jiang Jin-hui, Wang Zi-Li [13] studied the dynamic mechanical properties response and energy absorption characteristics of the circular tube under different size by using the nonlinear finite element technology. But these studies have the following characteristics: "single factor variation method" is used, which leads to the lack of systematic researches; the interaction and the influence of quadratic term are ignored, which will reduce the model precision.

Response surface methodology (RSM) [14–17] is a kind of advanced new experimental design method. The purpose lies in: take the initiative to design the factors (i.e., design parameters) level (i.e., the values of design parameters) of experiment and test, then the quantitative functional relationship between the factors and response (index) can be obtained. The interaction and the influence of quadratic term are introduced to the model, so the application of RSM can broke the constraint of "single factor variation method". Moreover, compared with the traditional "single factor variation method", model based on RSM can reveal the essence of the phenomenon at the extreme.

Under constant speed load, a numerical study is made to investigate the energy absorbing characteristics of thin-walled metal circular tube made of three different materials (steel, copper, aluminum) by using RSM. At the same time, the application prospect of RSM in terms of the research on the energy absorption rules of energy absorption structure can be explored.

2. Experiment and methods

2.1. The experiment design

2.1.1. Details of the finite element model

Make the displacement of the bottom panels of the thin-walled metal circular tube 0. Rigid wall with a constant speed of 10 m/s moves from the top to the bottom of the tube. The diameter D of the circular tube is 100 mm, and the variations are height H and thickness S. To realize dimensionless parameterization, the parameters are designed as height diameter ration a=H/D and thickness diameter ratio b=S/D. The material model parameters are shown in Table 1.

A experiment design should be made to analyze the mechanical response and energy absorbing characteristics of thin-walled metal circular tube with different height–diameter ratio (a) and thickness–diameter (b) more effectively, as well as to establish a relationship between energy absorption index and a, b.

2.1.2. Response surface methodology

RSM [18] is an approach to conduct testing, modeling, data analyzing, optimizing and predictive parsing on the research objects, and the main idea of RSM is to use a sequence of designed experiments to obtain an optimal response. Basic process of RSM: firstly, the model of response surface equation should be chosen, secondly, according to least square method, estimate corresponding coefficient of the model, and initial response surface equation can be obtained; make a significant analysis on regression equation and coefficients, and reject the variable whose coefficient is the lest significant based on the significance test, establish the response surface equation after being rejected, then retest until all of the coefficients are significant, so the modified response surface equation is obtained.

Central Composite Circumscribed Design (CCCD) [19] is a specific design method of RSM. In the process of experimental design, adjusting the concrete parameter of CCCD can make design achieve the requirement of orthogonality and rotatability [20]. Rotatable design provides constant prediction variance at all points that are equidistant from the design center, and the level of consistency of predicted variance can be obtained by rotatable design, which can improve the accuracy. The concept of orthogonality is important in design of experiment, and experimental analysis of an orthogonal design is straightforward because each main effect and interaction can be estimated independently, moreover, design orthogonality could fit the objective of reasonable design and work with data more easily. This experiment has adopted the above-mentioned methods, to be called "Orthogonal Rotation Combination Design of RSM (RSM-ORCD)".

Based upon the RSM-ORCD, energy absorption characteristics of thin-walled metal circular tube were tested, and the relationship between energy absorption and design parameters was established.

2.1.3. Test methods

In CCCD, there are five design levels for each factor: $\pm r$, 0, ± 1. The tests generally consist of three kinds of test points. If the quantity of design factors is K, the total tests number (identified as M) can be calculated as formula 2.

$$M = m_k + m_r + m_0 \quad (1)$$

where m_K=2^K, the test points when all factors get two levels, for each factor are two horizontal sites; m_r=$2K$, coordinate points, and r is the distance between pivot point and central point; m_0 is the central point when all factors are at zero level.

In order to satisfy the consistency of variance, design r=1.414 to make the CCCD own rotatability, on the premises of guaranteeing the accuracy. To achieve a reasonable design and data processing, when r=1.414, design m_0=8 to satisfy the requirement of orthogonality. Therefore, When r=1.414, m_0=8, N=16, experimental design meets the rotatability and orthogonality, which can be called response surface orthogonal rotational combination design method.

Based on coding transform principle, the corresponding table of factor and coding is established, as is shown in Table 2.

Experiment scheme are shown in Table 3.

Table 1
Material model parameters.

Material	Steel	Copper	Aluminum
Density (kg/m^3)	7865	8930	2700
Young's modulus (GPa)	200	117	75
Poisson's ratio	0.27	0.35	0.3
Yield strength (GPa)	0.31	0.4	0.08694
Tangent modulus (GPa)	0.763	0.1	0.5

Table 2
The corresponding table of factor and coding.

Coding	Factor			
	a	b	H(mm)=aD	t(mm)=bD
1.414	1.707	0.02207	170.7	2.207
1	1.5	0.02	150	2
0	1	0.015	100	1.5
−1	0.5	0.01	50	1
−1.414	0.293	0.00793	29.3	0.793

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