

Uncertainty Optimization of Thin-walled Beam Crashworthiness Based on Approximate Model with Step Encryption Technology

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ABSTRACT

Crashworthiness is one of the most important performances of vehicles, and the front rails are the main crash energy absorption parts during the frontal crashing process. In this paper, the front rail was simplified to a thin-walled beam with a cross section of single-hat which was made of steel and aluminum. And the two boards of it were connected by riveting without rivets. In order to optimize its crashworthiness, the thickness (t), radius (R) and the rivet spacing (d) were selected as three design variables, and its specific energy absorption was the objective while the average impact force was the constraint. Considering the error of manufacturing and measurements, the parameters σ_s and E_t of the steel were selected as the uncertainty variables to improve the design reliability. The algorithm IP-GA and the approximate model-RBF (Radial Basis Function) were applied in this nonlinear uncertainty optimization. In order to improve the accuracy of the RBF model, a new step-encryption technology was proposed, in which the encryption points will be added to the current sample points according to the results of each iteration. As a result, when the uncertainty level was 5%, the optimal design vector $[t, R, d]$ was $[1.75\text{mm}, 3.25\text{mm}, 29.48\text{mm}]$, and the possible interval of the specific energy absorption was $[841\text{J/kg}, 1028\text{J/kg}]$ while the possible interval of constraint was $[49.12\text{KN}, 71.39\text{KN}]$. And the optimum was verified with the exact solver. Therefore, this study can provide important references for the crashworthiness design of the front rails.

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INTRODUCTION

Improving the vehicle crashworthiness has been one of the hotspots in the development of automobile technology. The front rails are the main energy absorption parts which should absorb more impact energy by deformation to reduce the injury to passengers. Therefore, optimizing the crashworthiness of them has very promising engineering application potentials.

The material properties, structural designs, connecting methods, and the distribution of connection points have a great influence on energy absorption of the front rail in the front crashing process [1]. Considering that the front rail structure is similar to a thin-walled beam with a simple section, the improvement of its crashworthiness can be achieved by optimizing the latter's structure, the results of which can provide important references in the initial design stage. In order to make it absorb the impact energy as much as possible, its structure should be optimized in a limited design space reasonably, such as using materials with better mechanical properties, optimizing its sectional shape and the thickness of its boards, arranging the connection points reasonably and so on. Mahmood and Paluszny studied the relationships between the buckling half-wavelengths of rectangular thin-wall beam and its sectional parameters including the height (d), width (b) and thickness (t). As a result, when the cross-section of the front rail meet the aspect ratio $d/b > 0.67$ and the width-thickness ratio $t/b > 0.016$, the rail can produce a stable axial crushing mode and the energy-absorbed effect would be better [2].

Xiang Y et al combined the response surface model with enumerating method to optimize the weld spots spacing of the front rail in the axial crashing, which proved that the weld spots spacing had a significant influence on its crashworthiness [3].

Mechanical properties of the connection also play an important role in the performances of crashworthiness. In recent years, riveting without rivets has many advantages with respect to the traditional connection methods (welding, adhesives and bolting, etc.), for example, it is easier to achieve the automated production with low cost and has higher fatigue strength than welding [4, 5]. To the most important, it can realize the connection of dissimilar materials which makes it widely be applied in the connections of automotive sheet metal parts.

In this paper, the front rail of vehicles was simplified to a thin-walled beam with cross section of single-hat, the two boards of which were connected by riveting without rivets. It was taken as the study object both in the simulation and experiment. And that the element SPR2 can characterize the mechanical properties of the rivet joints in the simulation was verified by the axial crashing experiment.

As to realize the optimization of the crashworthiness of the front rail, many previous studies have been conducted while most of them were about the deterministic optimization. Chase et al optimized the design of the front and rear rails in high deformation with the method

of deterministic optimization and improved their crashworthiness successfully [6]. Deb A et al made a multi-objective optimization on front structure of a vehicle in which the second-order response surface model and Genetic Algorithm were applied [7].

Based on the former studies, the thickness (t) of the lower board made of steel, the rivet spacing (d) and the radius (R) of the upper board made of aluminum were selected as the design variables in this paper. Furthermore, considering the errors of manufacturing and measurement, the parameters σ_s and E_t of the steel were selected as the uncertainty variables to improve the design reliability, of which the uncertainty level was set to 5%. And the specific energy absorption of the beam was the objective while the constraint was the average impact force. Based on the above parameters settings, the nonlinear uncertainty interval optimization was conducted to optimize the crashworthiness, in which the approximate model-RBF and the two-level nested optimization algorithm IP-GA were conducted. In order to improve the accuracy of the RBF model and the efficiency of the optimization, a new step-encryption technology was proposed, in which the encryption points will be added to the current sample points according to the results of each iteration. Finally, the optimum was verified by the exact solver in simulation, which suggested that this optimization has high reliability and adaptability in engineering applications.

THE DESIGN OF THE THIN-WALLED HYBRID BEAM WITH A SECTION OF SINGLE-HAT

Firstly, the front rail was simplified to a thin-walled beam with a cross section of single-hat which was consisted of two boards that were connected by riveting without rivets. The thickness of the upper board made of aluminum 6061T6 is 2mm, while the thickness of the lower flat board made of steel Q235 is 1.5mm. And their material parameters are shown in Table 1. The main structure sizes of the beam were designed as follows: the length of it is 400mm, the closed cross-section is a rectangular of 70mm * 60mm, the flange widths on both sides are 20mm, and the radii of the upper board both at the top and bottom are 4.5mm, as are shown in Figure 1. Considering the convenience of manufacture, the riveting spacing (d) is designed to be 28mm. According to the actual structural characteristics and material parameters, the finite element model (FEM) of the beam was built as shown in (a) and (b) of Figure 2.

Table 1. Material parameters of Aluminum 6061-T6 and Low-carbon steel Q235

Material	Aluminum 6061-T6	Low-carbon steel Q235
Elastic Modulus E (MPa)	7.0×10^4	2.0×10^5
Poisson's ratio γ	0.3	0.27
Yield Strength σ_s (MPa)	275	235
Tangent modulus E_t (MPa)	676	578
Density ρ (kg/mm ³)	2.7×10^{-6}	7.85×10^{-6}

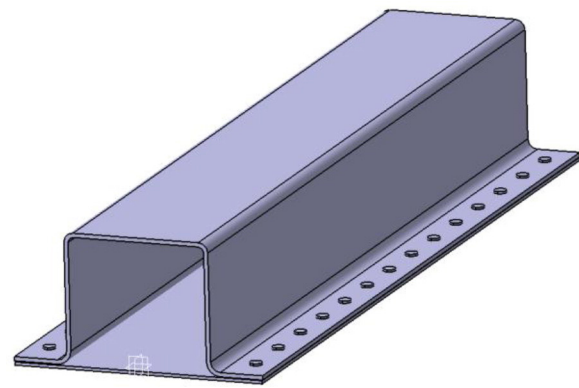
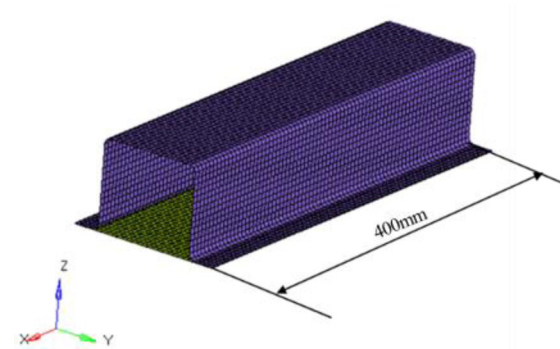
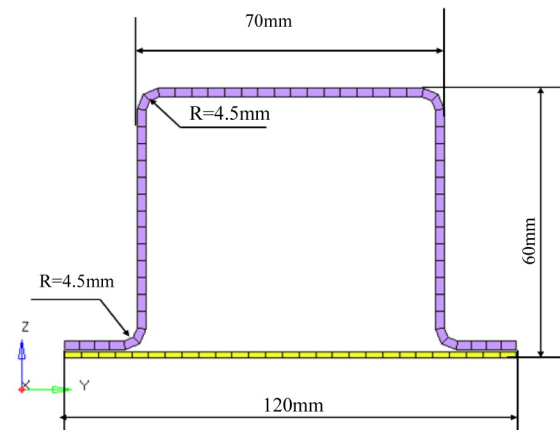


Figure 1. The thin-walled beam with a cross section of single-hat riveted without rivets



a.



b.

Figure 2. Finite Element Model of the thin-walled beam

The FE model of the thin-walled beam was built in the software Hypermesh, and the stress-strain curves in different strain-rates of the steel were input to the material settings considering that the steel was sensitive to the strain-rates. And the special keyword *CONSTRAINED_SPR2 in LS-DYNA was used to define the connection of riveting without rivets which was verified by the axial crushing experiment. The failure parameters of the keyword are shown in Table 2.

Table 2. Failure parameters of CONSTRAINED_SPR2

SP2	Value
FN(N)	751
FT(N)	2026
DN(mm)	0.561
DT(mm)	0.379
XIN(mm)	0.526
XIT(mm)	0.347
D(mm)	6

In Table 2, the parameter FN represents the rivet strength in tension (pull-out), the FT represents the rivet strength in pure shear, the DN represents the failure displacement in normal direction, the DT represents the failure displacement in tangential direction, the XIN represents the fraction of failure displacement at maximum normal force, the XIT represents the fraction of failure displacement at maximum tangential force, and the D represents the rivet diameter [8]. The CONSTRAINED_SPR2 model was created by L. Olovsson, Porcaro, Hanssen et al in SIIVILab of Norwegian University. It consists of a failure criterion which is similar to the plastic strain failure criteria used to make the force and torque of the failure rivet joints drop to zero. It is also a constraint model established according to lots of aluminum alloy rivet experiments of rivet joints. By observing the mechanical characteristics of the rivet joints and its failure modes, the completed curve of force-displacement from initial strain to failure was obtained, which was also reflected by reasonable mathematical equations. Thanks to both the connections of riveting with rivets or not are similar to each other, the equations can also be applied to reflect the connection of riveting without rivets.

AXIAL CRUSHING EXPERIMENT AND SIMULATION OF THE THIN-WALLED BEAM

As to the thin-wall beam structure, the deformation mode has the most important influence on the energy-absorbed effect in the crashworthiness. Based on the previous studies, the impact energy was mainly absorbed in two kinds of deformation modes that were the axial folded and bent modes, as are respectively shown in (a) and (b) of Figure 3. The folded deformation has better energy-absorbed effect than the bent deformation which may lead the entire part into the Euler bent deformation mode losing the original energy-absorbed capacity [9]. Therefore, the steady axial folded deformation is one of the most ideal energy-absorbed modes in the crushing process, which was taken as the main assessment indicator of crashworthiness of the thin-walled beam in this paper.

The axial crushing experiment of the beam was conducted in the hammer tower, as is shown in Figure 4. The experiment procedure is as follows:

1. 60mm length in the bottom of the beam was completely fixed by fixtures, and the hammer that weighs 150 kg was located directly above it.
2. Set the impact initial velocity of the hammer to 6 m/s. And a high-speed video was applied to collect the hammer

displacement ranges during the impact process. A force sensor was used to collect the axial impact loads.

3. The results are shown in Figure 5, and the load-displacement curve was obtained based on the data collected, as is shown in Figure 6.

Seen from Figure 5, there was a large fold in the top of the beam, and almost all of the rivet joints failed within the displacement of 20mm, which occurred before the end of the first peak in the curve in Figure 7. This phenomenon indicated that the main energy-absorbed deformation was the first large fold corresponding to the first peak of the curve.

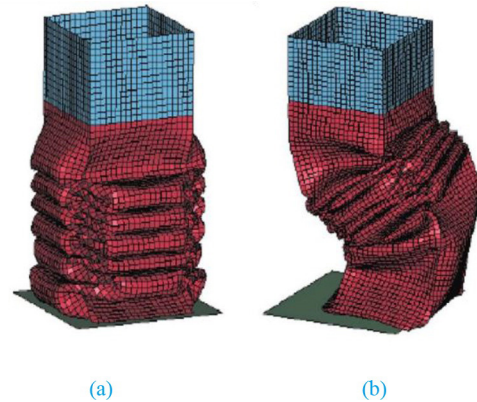


Figure 3. Two kinds of deformation of the thin-walled beams



Figure 4. The hammer tower of the experiment

Based on the FEM built above, the axial crushing of the thin-walled beam was simulated in LS_Dyna solver, before which a rigid wall weighs 150 kg was built in Hypermesh to simulate the impact hammer. All the simulation settings were consistent with the actual experiment above including the loading and boundary conditions. The contact between the rigid wall and beam were set as "CONTACT AUTOMATIC_SURFACE TO SURFACE". Furthermore, there is a clearance of 0.5 mm between the flanges of the two boards in order to avoid the initial penetration causing the abnormal solving termination. The axial average impact force and the energy-absorbed capacity