Energy Absorption and Lightweight Potential Analysis of the Front Longitudinal Beam

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Abstract. Different high-strength structural steel materials such as DP590, TR590, DP780, QP980, DP980, and MS1180 are tested for frontal impact in this research. The deformation modes and energy absorption characteristics of various materials and thicknesses are studied based on the trolley bump test. Then the average acceleration and the light weight potential under each structure are analyzed and compared. The research provided an optimized direction for the choice of stringer material and thickness.

1. Introduction
The annual number of global road traffic accidents and deaths is in a high level as the cars increase. The number of casualties will continue to grow according to the World Health Organization. Chinese motor vehicles account for only 3% in the world, but the death toll is as high as 7.5%. The safety design of car-collision is necessary [1]. The car frontal collision accidents accounted for 66.9% according to collision accidents statistics. The front longitudinal beam as an important part of the car can absorb energy as high as 30%-5% [2, 3]. So the research on the frontal longitudinal beam is important. At the same time, the lightweight design has been risen to a strategic degree of Chinese social development and energy conservation under the requirement of certain collision strength [4]. Therefore, the research on the energy-absorbing structure that combines strength and light weight is significant.

The existing researches mainly focus on the optimization of some thin-walled structures, ignoring the basic research. In this research, a large number of experiments are carried out on the influence of the material and thickness of the front longitudinal beam. Varies materials and thickness factors of concrete frontal longitudinal beam are firstly studied. The deformation modes of the nine materials’ thickness and their acceleration are then quantified [5-6]. At last, the further simulation, optimization and lightweight design of the front longitudinal beam are based on the tests. The tests also provide the basis for the selection of the structural material and thickness of the front longitudinal beam.

2. Description of the Equivalent collision test

2.1. Equivalent model parameter setting
The energy absorbed by the structure during a collision is usually concerned for a vehicle thin-walled beam. The average collision force is an arithmetic mean of the collision force curve on the compression
displacement. It can reflect thin-walled beam’s overall energy absorption. The average impact force $F_m$ can be used as an indicator to measure the crashworthiness of the structure. Since the maximum collision force can be controlled by triggering structural malformation by inducing grooves, initial defect structures. The interface diagram of the hat beam is shown in Fig. 1. The average impact force of the hat beam during a collision can be approximated as:

$$F_m = 32.89 \frac{M_0 L^{1/3}}{t^{1/3}} = 8.22L^{1/3} \sigma_f t^{5/3}$$

$$L = 2a + 2b + 4$$

$$M_0 = \frac{\sigma_f t^2}{4}$$

The average impact force of a hat-shaped thin-walled beam is proportional to the material strength, the total length of the index times and the material thickness of the index times. Because $\sigma_f$ can be approximated as the average of the yield strength and the tensile strength and it is only related to the material itself. Therefore, it is only necessary to ensure that the total length of the section of the thin-walled beam simplification, the material characteristics, and the material thickness consistent with the real front longitudinal beam. It can be considered that the average impact force of the simplified model in the collision is consistent with the real front longitudinal beam model. This makes it possible to simplify the front longitudinal beam into a thin-walled beam.

Figure 1. Parameter diagram of the hat section

A front longitudinal beam of a certain type of vehicle is selected as the equivalent in the test. The section of the front longitudinal beam is measured and its total length is about 410 mm. Two defect inducing grooves are opened at one of its side to fold the deformation mode into axial.

The folding deformation length of the thin-walled beam structure is consistent with the deformation length of the front longitudinal beam in the real vehicle through the continuous adjustment of the trolley weight. The deformation length of the front longitudinal beam is 320 mm. The quality of the trolley is continuously adjusted. The folding deformation length of the thin-walled beam structure is the same as that in the real vehicle when the weight of the trolley is set to 536kg. So the beam has the same length of deformation.

2.2. Description of the test device and sample selection
The test trolley uses the existing trolley equipment of the automotive laboratory shown in Fig. 2. The design of the trolley meets the requirements of the regulations. The front side is welded with an energy-
absorbing cylinder which size is $410mm \times 80mm \times 80mm$. The total mass of the trolley is 536kg. The main data recording instruments in the collision test include on-board acceleration sensors, vehicle speed photoelectric sensors, and high-speed cameras.

![Figure 2. Trolley equipment](image)

Six kinds of high-strength structural steel materials are mainly used in the test and they are shown in Table 1. These materials have a wide range of yield strength and tensile strength, which is beneficial to the comprehensive study of the energy absorption properties under various mechanical properties.

| Numble | number | yield strength (MPa) | Width (mm) |
|--------|--------|----------------------|------------|
| DP590  | 01#    | 340                  | 1.40       |
| DP780  | 02#    | 400                  | 1.38       |
| TR590  | 03#    | 380                  | 1.40       |
| DP980  | 04#    | 550                  | 1.382      |
| MS1180 | 05#    | 950                  | 1.0        |
|QP980   | 06#    | 898                  | 1.22       |

3. Result description of the Trolley crash test

3.1. Deformation mode and acceleration curve

A double beam welding double impact tube collision is conducted at a speed of 38 km/h to strike the rigid wall in the test. The deformation modes and acceleration time curves of thin-walled structures with different materials and thickness are as follows.

Fig. 3a), Fig. 4a), Fig. 3b) and Fig. 4b) show the deformation situations of the DP590 and TR590 specimens and their acceleration curves. The test piece forms a wrinkle deformation under the action of the axial impact force when the test piece collides with the rigid wall. And a series of continuous wrinkle crushing deformation is formed during the whole deformation stage of the test piece. Correspondingly, the acceleration curve forms a plurality of continuous Wave crest.
Figure 3. Comparisons of deformation modes

Figure 4. Comparisons of acceleration curves
Fig. 3c) and Fig. 4c) are the deformation situations and corresponding acceleration curves of the DP780 specimens respectively. It can be seen from the figure that both of them produce better crushing deformation according to the folding order, which belongs to progressive collapse deformation.

Fig. 3d) and Fig. 4d) are the deformation situation of the DP980 specimen and its acceleration curve. It can be seen from the figure that the DP980 produces axial progressive folding at the initial stage of crushing, and has good energy absorption characteristics. The deformation energy per unit length is high due to its high yield strength. Therefore, the number of DP980 wrinkles is small compared with other materials such as TR590 and DP590.

Fig. 3e) and Fig. 4e) are the deformation situations and acceleration curves of the QP980 specimens respectively. The QP980 specimens are relatively thin. Although wrinkle deformation can occur during the collision, the solder joint drop phenomenon is also very serious.

Fig. 3f) and Fig. 4f) are the deformation situation of the MS1180 specimen high-strength steel and its acceleration curve. It can be seen from the figure that the 1180MS specimen has severe tearing during the welding process. Although the martensitic steel has the characteristics of high strength and high hardness, the elongation rate of the martensitic steel low. The plastic deformation occurs only in a small range, and the crushing and wrinkling deformation is mainly caused by plastic deformation.

4. Analysis of the Trolley crash test

4.1. Influence of Material and Thickness on the average acceleration

Materials with the strength level above DP780 has the phenomenon of solder joint tearing and cracking according to the test. The average acceleration of the test piece in the front-end crush test is linearly proportional to UTS, as shown in Fig. 5 through the study of the average acceleration. The acceleration curve has a proportional relationship with UTS. Because the acceleration curve has a close relationship with the generation of wrinkles from the analysis of the test results.

![Figure 5. The relationship between the average acceleration and $UTS \times t^2$.](image)

The different styles of points in the above figure represent different test pieces. The linear relationship between the average accelerations is as the follow by fitting the test data points:

$$\text{Average acceleration} = 8.60857 + 0.00802 \times UTS \times t^2$$  \hspace{1cm} (2)
Figure 6. The average acceleration under Equal Thickness Conditions

The material thickness is unified as 1.4 mm according to formula (2). The test data is used for the material itself 1.4 mm. Fig. 6 shows the average acceleration of the DP780 and its below materials due to the strength higher than DP980 appears solder joint which is not suitable for formula (2). The material which is added with * indicates the average acceleration obtained from the formula. The graph in 6 shows the average acceleration of each material under equal thickness conditions directly. The average acceleration increases with the increase of the strength of the material from the comparison.

4.2. Lightweight potential of the High-strength steel

The application of high-strength steel plays an important role in vehicle lightweight and collision safety. Lightweight of high-strength steel is feasible because the reduction of material yield limit and thickness could lead to the insufficient of energy absorptions from formula (2). The relationship between the strength and the weight loss effect of the high-strength steel at DP780 level and below can be obtained, as shown in Fig. 7, from the relationship between the average accelerations summarized above.

Figure 7. The relationship between the strength and the weight loss effect

The calculation procedure for the lightweight effect map of high-strength steel replacement is as follows.

1) Selection and calculation of reference materials
The DP450 is used as the reference material to replace it because the lowest tensile strength product is DP450. At the same time, the average acceleration of 18.5 is selected as the constraint condition according to the test conditions. The DP450 was not subjected to the front-end crush test in this research. The thickness of DP450 is calculated as 18.5g from formula (2) when the test material is DP450. The corresponding reference thickness could be calculated by bringing the average acceleration of 18.5 g and UTS of 450 MPa into formula (2).

\[
\begin{align*}
\text{acc} &= 8.60857 + 0.00802 \times t^2 \\
t &= 1.66\text{mm}
\end{align*}
\]

(3)

2) Calculation of test materials
In order to explain the effect of high-strength steel on vehicle lightweight, the materials selected here come from two aspects: the DP780 grade and its below materials tested and the DP780 grade and below materials selected. Since the strength range of high-strength steel used in the test in this research is limited.

Material X is used as an example in the test. Its tensile strength is \( A \) and the thickness of it is \( t_0 \). The average acceleration in the test is \( acc_0 \). The thickness is \( t \) corresponding to the reference average acceleration \( acc = 18.5 \). The following equations are solved to obtain the thickness corresponding to the reference displacement when the above parameters are respectively brought into the formula (2).

\[
\begin{align*}
\text{acc}_0 &= 8.60857 + 0.00802 \times A \times t_0^2 \\
\text{acc} &= 8.60857 + 0.00802 \times A \times t^2 \\
t &= \sqrt{t_0^2 + \frac{\text{acc} - \text{acc}_0}{0.00802 \times A}}
\end{align*}
\]

(4)

3) Calculation of material selected from product manual
Material Y is chosen as an example from the product manual. Its tensile strength is B. The thickness is \( t \) corresponding to the reference average acceleration \( acc \). The thickness of the displacement \( t \) could be calculated through bringing the above parameters into formula (2).

\[
\begin{align*}
\text{acc} &= 8.60857 + 0.00802 \times B \times t^2 \\
t &= \sqrt{\frac{\text{acc} - 8.60857}{0.00802 \times B}}
\end{align*}
\]

(5)

The thickness of different materials corresponding to the same average acceleration can be obtained through the above calculation. The lightweight capability variation curve of the front side with the increase of the yield strength could be obtained for the relative reference material DP450.

The lightweight capability increases quickly at the beginning and then its change rate slows down as the tensile strength of high-strength steel increasing in Fig. 7. As a result, the cost-effectiveness of material replacement must be considered to find the most suitable material in the replacement of the front longitudinal material.
5. Conclusion
A series of high-strength steel thin-walled beam specimens are tested in the trolley crash test. The energy-absorbing deformation characteristics of various high-strength steels are analyzed in the research. The conclusions of the research are in the below.

(1) DP590 can absorb the collision energy by crushing and wrinkle deformation better and the average acceleration is low. DP780 can achieve better crush deformation mode and proper average acceleration by reducing material thickness. DP980, QP980 and MS1180 specimens have progressive axial folding at the initial stage of crushing, but some solder joints have tearing phenomenon, which is not suitable for front longitudinal beam energy absorbing components.

(2) The lightweight capability increases quickly at the beginning and then its change rate slows down as the tensile strength of high-strength steel increasing. As a result, the cost-effectiveness of material replacement must be considered to find the most suitable material in the replacement of the front longitudinal material.

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6. Definitions/Abbreviations

| Symbol | Definition |
|--------|------------|
| $M_o$  | the plastic limit bending moment per unit |
| $L$    | length |
| $a$    | the width of the section |
| $b$    | the height of the section |
| $f$    | the width of the flange |
| $t$    | the thickness of the material,(mm) |
| $\sigma_f$ | the average flow stress is in MPA |