Effects of the Thickness of Triangular Plates on the Stiffness and Strength of L-type Basic Structures of the Bus Body Frame

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Abstract. In this paper, the effect of the thickness of triangular plates on the stiffness and strength of L-type basic structures of the bus body frame is studied after welding triangular plates at the joint of the L-type structures, for finding out the regularities, so as to provide the theoretical basis for the design of the bus body frame structure joints. The results show that the thickness of triangular plates has little effect on the stiffness of L-type structures, regardless of the bending or torsional conditions; when the right angle side length of the triangular plates is small and the thickness of the triangular plates is less than or equal to the wall thickness of the rods of L-type basic structures, the variation of the triangular plate thickness has a certain effect on the bending strength of L-type structures; the thickness of triangular plates has little effect on the torsional strength of L-type structures. In addition to the bus body joint structure design, this paper also has certain reference significance to the agricultural machinery structure and other engineering structure design.

1. Introduction

Body frame is an important bearing structure of semi-integral bus body and unitary construction bus body. The manufacturers of major bus producing countries adopt the section steel welding process to manufacture the frame of bus. When the bus body frame is loaded, the high stress appears in the body frame structure joints[1,2,3], then the triangle plates are commonly used by the manufacturers to strengthen these weak spots, but in the practice of bus production in our country, the design of triangular plate parameters and position is only based on experience, with some blindness. Therefore, it is of practical significance to discuss the influence law of triangular plate parameters for guiding bus body frame joints design[4].

L-type structure is one of the basic structures of bus body frame, which is commonly used in the door, windward window, side window and the floor frame of bus. In this paper, three typical L-type structures are selected from the frame of the bus body, and two triangular plates are welded at their joint as shown in figure 1, in order to study the influence of the thickness of triangular plates on the stiffness and strength of L-type structures. The purpose of this paper is to provide reference for the design of the joints of bus body frame structure.
2. Research object and method

2.1. L-type structures and triangular plates
In this paper, three typical L-type structures welded by two thin-walled rectangular steel tubes were intercepted at random from the bus body frame structure to calculate and analyze, they are: K structure: 30x30x1.5mm+30x20x1.5mm; M structure: 40x40x2mm+40x30x2mm; N structure: 50x50x2.5mm+50x30x2.5mm. The triangular plates of L-type structures are commonly used isosceles triangle plates. The size of the triangular plates includes four kinds of thickness and six right angle side lengths. The method of choosing thickness is: considering that the thickness difference between the stiffened plate and the reinforced part should not be too big, otherwise not only cracks appear at the edge of the stiffened plate because of stress concentration due to the sudden change of stiffness, but also the welding strength is unfavorable[5]. Therefore, 1 mm, 1.5 mm, 2 mm and 2.5 mm are selected as the thickness of the triangular plates of K structure, and 1.5 mm, 2 mm, 2.5 mm and 3 mm, are selected as the thickness of the triangular plates of M structure and N structure. The method of choosing right angle side length is: through the economical discretization test on the model of L-type structure, 9.5 mm is suitable for mesh length, so the right angle side length of triangular plates is taken as k*9.5 mm, and when k is 2, 3, 4, 5, 6, 7, the right angle side length of triangular plates is 19 mm, 28.5 mm, 38 mm, 47.5 mm, 66.5 mm, respectively.

2.2. Research methods
Ansys finite element analysis software and shell element (shell63) are used to establish the finite element model of the L-type structures. After bus body frame structure is loaded, the internal forces in the rod are axial force, shear force, torque and bending moment. In general, the internal force that has the greatest effect on the body strength is the bending moment. In this paper, bending and torsional conditions are selected for study. As shown in figure 1, one rod end away from the joint is constrained and another end of the other rod away from the joint is applied a unit load (100N). Under bending conditions, bending moment generated at the joint is in the plane of the two-rod structure. Under torsional conditions, torsional moment generated at the joint is in the plane of the two-rod structure.

The maximum displacement of the free end (abbreviated as $D_{\text{max}}$) under unit load and the maximum Von Mises stress of the L-type structures (abbreviated as $S_{\text{max}}$) are calculated, to study the effects of thickness of triangular plates with different right angle side lengths on $D_{\text{max}}$ and $S_{\text{max}}$. The stiffness variation of the structures is evaluated by the displacement reduction coefficient $\alpha$, and the strength variation of the structures is evaluated by the stress reduction coefficient $\beta$. The formulas are defined as follows:

$$\alpha = \left| \frac{D_{\text{max with triangular plates}} - D_{\text{max without triangular plate}}}{D_{\text{max without triangular plate}}} \right| \times 100\%$$  

$$\beta = \left| \frac{S_{\text{max with triangular plates}} - S_{\text{max without triangular plate}}}{S_{\text{max without triangular plate}}} \right| \times 100\%$$

3. Results and analysis
3.1. Effects of triangular plate thickness on the coefficient of displacement reduction $\alpha$ and the coefficient of stress reduction $\beta$ of L-type structures

The effects of the thickness of triangular plates with different right angle side lengths of K, M, N structures on the coefficient of displacement reduction $\alpha$ and the coefficient of stress reduction $\beta$ are calculated, under bending and torsional conditions. There are 144 computational models of K, M, N structures, including four thicknesses triangular plates, six right angle side lengths of triangular plates, and K, M, N structures without triangular plates. The results are shown in table 1–table6.

Table 1. The effects of the thickness of triangular plates with different right angle side lengths on the coefficient of displacement reduction $\alpha$ of K structure.

| conditions            | bending condition | Torsional condition |
|-----------------------|-------------------|---------------------|
| length (mm)           | 1                 | 1.5                 | 2                 | 2.5               | 1                 | 1.5               | 2                 | 2.5               |
| $\alpha$ (%) thickness (mm) |                   |                     |                   |                   |                   |                   |                   |                   |
| 19                    | 9.37              | 10.56               | 11.19             | 11.59             | 4.33              | 5.29              | 6.10              | 6.76              |
| 28.5                  | 13.88             | 15.11               | 15.81             | 16.21             | 6.83              | 8.08              | 9.07              | 9.87              |
| 38                    | 17.80             | 19.00               | 19.69             | 20.13             | 9.32              | 10.74             | 11.84             | 12.74             |
| 47.5                  | 21.36             | 22.55               | 23.25             | 23.71             | 11.74             | 13.29             | 14.50             | 16.50             |
| 57                    | 24.68             | 25.87               | 26.57             | 27.03             | 14.08             | 15.70             | 16.98             | 19.04             |
| 66.5                  | 27.83             | 29.03               | 29.72             | 30.19             | 16.28             | 17.97             | 19.29             | 20.37             |

Table 2. The effects of the thickness of triangular plates with different right angle side lengths on the coefficient of displacement reduction $\alpha$ of M structure.

| conditions            | bending condition | Torsional condition |
|-----------------------|-------------------|---------------------|
| length (mm)           | 1.5               | 2                   | 2.5               | 3                 | 1.5               | 2                   | 2.5               | 3                 |
| $\alpha$ (%) thickness (mm) |                   |                     |                   |                   |                   |                     |                   |                   |
| 19                    | 8.13              | 9.05                | 9.62              | 9.97              | 3.84              | 4.63                | 4.98              | 5.43              |
| 28.5                  | 12.37             | 13.29               | 13.97             | 14.43             | 5.98              | 7.03                | 7.42              | 8.02              |
| 38                    | 16.27             | 17.18               | 17.87             | 18.33             | 8.12              | 9.37                | 9.82              | 10.46             |
| 47.5                  | 19.70             | 20.73               | 21.42             | 21.76             | 10.21             | 11.61               | 12.16             | 12.86             |
| 57                    | 22.91             | 23.94               | 24.63             | 25.09             | 12.31             | 13.80               | 14.35             | 15.20             |
| 66.5                  | 26.00             | 27.03               | 27.72             | 28.18             | 14.35             | 15.89               | 16.54             | 17.39             |

Table 3. The effects of the thickness of triangular plates with different right angle side lengths on the coefficient of displacement reduction $\alpha$ of N structure.

| conditions            | bending condition | Torsional condition |
|-----------------------|-------------------|---------------------|
| length (mm)           | 1.5               | 2                   | 2.5               | 3                 | 1.5               | 2                   | 2.5               | 3                 |
| $\alpha$ (%) thickness (mm) |                   |                     |                   |                   |                   |                     |                   |                   |
| 19                    | 9.63              | 10.79               | 11.75             | 12.33             | 3.32              | 4.02                | 4.52              | 4.92              |
| 28.5                  | 14.84             | 16.38               | 17.34             | 17.92             | 5.33              | 6.13                | 6.83              | 7.34              |
| 38                    | 19.65             | 21.19               | 22.16             | 22.74             | 7.34              | 8.24                | 9.05              | 9.75              |
Table 4. The effects of the thickness of triangular plates with different right angle side lengths on the coefficient of stress reduction $\beta$ of K structure.

| conditions | bending condition | Torsional condition |
|------------|-------------------|---------------------|
| length (mm) | 1 | 1.5 | 2 | 2.5 | 1 | 1.5 | 2 | 2.5 |
| $\beta$ (%) | 24.35 | 40.21 | 47.17 | 48.57 | 26.81 | 28.50 | 29.88 | 31.05 |
| thickness (mm) | 19 | 28.5 | 38 | 47.5 | 57 | 66.5 |

| conditions | bending condition | Torsional condition |
|------------|-------------------|---------------------|
| length (mm) | 1.5 | 2 | 2.5 | 3 | 1.5 | 2 | 2.5 | 3 |
| $\beta$ (%) | 28.02 | 42.26 | 44.04 | 45.00 | 28.06 | 30.14 | 31.09 | 32.05 |
| thickness (mm) | 19 | 28.5 | 38 | 47.5 | 57 | 66.5 |

Table 5. The effects of the thickness of triangular plates with different right angle side lengths on the coefficient of stress reduction $\beta$ of M structure.

| conditions | bending condition | Torsional condition |
|------------|-------------------|---------------------|
| length (mm) | 1.5 | 2 | 2.5 | 3 | 1.5 | 2 | 2.5 | 3 |
| $\beta$ (%) | 23.46 | 32.46 | 40.26 | 44.69 | 26.19 | 29.42 | 31.43 | 32.90 |
| thickness (mm) | 19 | 28.5 | 38 | 47.5 | 57 | 66.5 |

Table 6. The effects of the thickness of triangular plates with different right angle side lengths on the coefficient of stress reduction $\beta$ of N structure.

| conditions | bending condition | Torsional condition |
|------------|-------------------|---------------------|
| length (mm) | 1.5 | 2 | 2.5 | 3 | 1.5 | 2 | 2.5 | 3 |
| $\beta$ (%) | 23.46 | 32.46 | 40.26 | 44.69 | 26.19 | 29.42 | 31.43 | 32.90 |
| thickness (mm) | 19 | 28.5 | 38 | 47.5 | 57 | 66.5 |
It can be seen from table 1 ~ table 3 that: for K structure, when the minimum thickness of triangular plates 1 mm is compared with the maximum thickness of triangular plates 2.5mm, the absolute value of the difference of the coefficient of displacement reduction $\alpha$ under bending condition is less than 3%, and the absolute value of the difference of the coefficient of displacement reduction $\alpha$ under torsional condition is less than 5%. For M structure and N structure, when the minimum thickness of triangular plates 1.5 mm is compared with the maximum thickness of triangular plates 3 mm, the absolute value of the difference of the coefficient of displacement reduction $\alpha$ under bending and torsional conditions are all less than 4%. That is, the thickness of triangular plates has little effect on the coefficient of displacement reduction $\alpha$ of L-type structures, regardless of the bending or torsional conditions.

It can be seen from table 4 ~ table 6 that:
(1) Under bending conditions:
For K structure, the minimum absolute value of the difference of stress reduction coefficient $\beta$ between minimum thickness of triangular plates 1 mm and 1.5 mm thickness equal to wall thickness of the rods of L-type structures is 7.81%, and the maximum is 15.86%. The minimum absolute value of the difference of stress reduction coefficient $\beta$ between the thickness of triangular plates 1.5 mm and the maximum thickness 2.5 mm is 0.25%, and the maximum is 8.36%.

For M structure, the minimum absolute value of the difference of stress reduction coefficient $\beta$ between minimum thickness of triangular plates 1.5 mm and 2 mm thickness equal to wall thickness of the rods of L-type structures is 6.54%, and the maximum is 14.24%. The minimum absolute value of the difference of stress reduction coefficient $\beta$ between the thickness of triangular plates 2 mm and the maximum thickness 3 mm is 2.74%, and the maximum is 6.90%.

For N structure, the minimum absolute value of the difference of stress reduction coefficient $\beta$ between minimum thickness of triangular plates 1.5 mm and 2.5 mm thickness equal to wall thickness of the rods of L-type structures is 7.99%, and the maximum is 16.8%. The minimum absolute value of the difference of stress reduction coefficient $\beta$ between the thickness of triangular plates 2.5 mm and the maximum thickness 3 mm is 1.09%, and the maximum is 4.43%.

That is, when the right angle side length of the triangular plates is small and the thickness of the triangular plates is less than or equal to the wall thickness of the rods of L-type structures, the variation of the triangular plate thickness has a certain effect on bending strength of L-type structures; when the thickness of triangular plates is greater than the wall thickness of the rods of L-type structures, the thickness variation of 0.5 or 1 mm has little effect on bending strength of L-type structures. In addition, the results also show that the effect of triangular plate thickness on stress reduction coefficient $\beta$ decreases with the increase of right angle side length of triangular plate. Moreover, under the same load, the larger the wall thickness of the rod is, the smaller the right angle side length of the triangular plates is, when the variation of the triangular plate thickness has effect on the stress reduction coefficient $\beta$.

(2) Under torsional conditions:
For K structure, the maximum absolute value of the difference of stress reduction coefficient $\beta$ between minimum thickness of triangular plates 1 mm and the maximum thickness 2.5 mm equal to wall thickness of the rods of L-type structures is 8.7%, and the minimum is only 4.24%. For M structure, the maximum absolute value of the difference of stress reduction coefficient $\beta$ between minimum thickness of triangular plates 1.5 mm and the maximum thickness 3 mm equal to wall thickness of the rods of L-type structures is 4.24%, and the minimum is only 3.07%. For N structure, the maximum absolute value of the difference of stress reduction coefficient $\beta$ between minimum thickness of triangular plates 1.5 mm and the maximum thickness 3 mm equal to wall thickness of the rods of L-type structures is 6.71%, and the minimum is only 2.95%. That is, the thickness of triangular plates has little effect on torsional strength of L-type structures.

To sum up, for a L-type structure consisting of two closed thin-walled rectangular tubes with equal wall thickness, when the thickness of triangular plates is greater or equal to the thickness of thin-walled bars, the continued increase of triangular plate thickness has little effect on the stiffness and strength of
the L-type structure. From this point of view, the thickness of the triangular plates can be the same as the wall thickness of the strengthened rods. This is different from the paper [5], which pointed out that the thickness of stiffeners should be thicker than that of reinforced parts when using stiffeners on open section steel, when introducing the analysis and design of bus body structure.

3.2. Experimental verification

In order to verify the accuracy of the above finite element model and its calculation results, according to the existing test conditions, an experimental structure consisting of three rectangular thin-walled tubes was made. The experimental structure was welded by 50x30x2mm+50x30x2mm+40x30x2mm, and the model is shown in figure 2 (a).

The upper short horizontal rod was fixed at one end and the bottom end of the vertical rod was fixed. Then a unit load was applied to the end of the longer horizontal rod. The displacement measurement and static strain measurement were carried out in the case of no triangle plate and welding triangular plates respectively. The test site and the instrument are shown in figure 2 (b).

![Figure 2. The experimental structure model and the test site](image)

According to the results obtained from the finite element model of the experimental structure, 11 points with big stress and deformation are selected as the test points. Unidirectional strain gauges are used for test points with known principal strain direction, and strain rosette are used for test points with unknown principal strain direction. The measured values of displacement and strain under unit load are obtained by means of step by step loading and multiple metering for each test point. Each test point takes the average of three repeated tests as the final measurement value. By using Hooke's law, the principal stress measurement values of each test point can be calculated.

The calculated and measured values of the experimental structure are compared one by one, and the results show that:

1) The displacement errors of finite element calculation of the experimental structure are all very small, and all of them are below 5%.

2) The stress errors of finite element calculation of the experimental structure are all also small.

The error rate and the relative error rate between the numerical calculation of stress and the test results are all below 10% except for individual test points. Therefore, the accuracy of the finite element calculation results in this paper is verified.

4. Conclusions

In this paper, the effect of the thickness of triangular plates on the stiffness and strength of L-type structures of bus body frame is studied. The results show that:

1) The thickness of triangular plates has little effect on the stiffness of L-type structures, regardless of the bending or torsional conditions.

2) When the right angle side length of triangular plates is small and the thickness of the triangular plates is less than or equal to the wall thickness of the rods of L-type structures, the variation of the triangular plate thickness has a certain effect on bending strength of L-type structure; when the thickness of triangular plates is greater than the wall thickness of the rods of L-type structures, the thickness variation of 0.5 or 1 mm has little effect on bending strength of L-type structures.
(3) The effect of triangular plate thickness on the strength of L-type structures decreases with the increase of right angle side length of triangular plates. Moreover, under the same load, the larger the wall thickness of the rod is, the smaller the right angle side length of the triangular plates is, when the variation of the triangular plate thickness has effect on the strength of L-type structures.

(4) The thickness of triangular plates has little effect on torsional strength of L-type structures.

(5) The thickness of the triangular plates can be the same as the wall thickness of the strengthened rods.

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