Effects of Loading Direction and Triangular Plates on Load Bearing Performance of Spatial Three-rod Structures of Bus Body Skeleton

Deng T S¹, Chen M N²
¹Applied Science and Technology College, Quanzhou Normal University, Quanzhou, Fujian, 362000, China
²Mechanical and Electrical engineering College, FAFU, Fuzhou, Fujian, 350002, China

Abstract. The spatial three-rod structure is one of the basic bus body skeleton structures. Based on the finite element method and the experimental analysis, the influence of the loading direction which is parallel and perpendicular to the main rod on load bearing performance of the three-rod structures is compared, and two cases of spatial three-rod structures welded by one triangular plate and two triangular plates under two kinds of loading directions are calculated and analyzed, respectively. The results show that the maximum displacement at the free end and the maximum Von Mises stress of the structures when the loading direction is perpendicular to the main rod are respectively 3.5 times as much as those when parallel to the main rod. Only when the loading direction is perpendicular to the main rod, can welding triangular plates improve significantly the stiffness and strength of the structures, and the stiffness and strength of the structures can be significantly enhanced by welding only one triangular plate. 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
Bus body skeleton is an important bearing structure of monocoque body and semi-monocoque body. At present, with the rapid development of the market demand for the variety of bus products, the main bus manufacturers in China adopt the welding process of section steel to manufacture bus body skeleton. Bus body skeleton welded from section steel can be regarded as a skeletal structures [1,2]. When bus body skeleton bears the load, the high stress appears in the body skeleton structure joints [3], that is, the joints becomes the weak points of the body skeleton. These weaknesses are often found in the upper corner of the passenger door post, the upper and lower corner of the window post, and the skeleton of the baggage compartment. Welding triangle plate is a common measure to improve the stiffness and strength of body skeleton structures. However, in the practice of passenger car production in China, the parameters and position design of triangle plates are only based on experience, with some blindness. Therefore, it is of practical significance to analyze the load bearing performance of the basic body skeleton structures and to discuss the influence of triangle plates on the stiffness and strength of the basic body skeleton structures.

Spatial three-rod structures are basic structures of bus body skeleton. They are commonly used in luggage bin and skeleton of monocoque bus. In this paper, three typical spatial three-rod structures are selected from the bus body skeleton, and the load-bearing performance is compared under two loading
directions parallel to the main rod and perpendicular to the main rod, the influence of loading direction and triangular plates on the stiffness and strength of spatial three-rod structures is summarized by calculating, analyzing and experiments.

2. Research object and method

2.1. Spatial three-rod structures, loading directions and triangular plates

In this paper, three typical spatial three-rod structures were intercepted at random in the bus body skeleton structure to calculate and analyze. In order to eliminate the influence of load bearing performance of different cross-section members in the three-rod structures, three spatial three-rod structures welded by three thin-walled rectangular steel tubes with equal section were chosen, they are: Structure U: 40x40x2+40x40x2+40x40x2; Structure V: 30x30x1.5+30x30x1.5+30x30x1.5; Structure W: 50x50x3+50x50x3+50x50x3. As shown in figure 1, each structure consists of a main rod and two supporting rods welded on both sides of the end of the main rod. To facilitate analysis, the length of each rod is unified to 400 mm, the hypotenuse length of all the triangular plates is set to 57 mm, and the thickness of the triangular plate is the same as the wall thickness of the respective structure rod. In view of the fact that when the plane of triangular plate is parallel to the direction of loads, it is best to improve the stiffness and strength of spatial three-rod structures[4]. When the loading direction is perpendicular to the main rod, the structures welded by one triangular plate and two triangular plates are shown in figure 2 and figure 3, respectively. When the loading direction is parallel to the main rod, the structures welded by one triangular plate and two triangular plates are shown in figure 4 and figure 5.

Figure 1. Spatial three-rod structure without triangular plate.

Figure 2. Spatial three-rod structure welded by one triangular plate and loading direction is perpendicular to the main rod.

Figure 3. Spatial three-rod structure welded by two triangular plates and loading direction is perpendicular to the main rod.

Figure 4. Spatial three-rod structure welded by one triangular plate and loading direction is parallel to the main rod.
2.2. Research methods

Ansys finite element analysis software and shell element (shell63) are used to establish the finite element model of the spatial three-rod structures. The loading direction parallel to the main rod and perpendicular to the main rod are shown in figure 1 and figure 2 respectively. In the calculation and experiments, the end part of the main rod and the first supporting rod are completely constrained, and the unit load is applied in the free end of the second supporting rod.

In this paper, the variation of stiffness and strength is used to evaluate the load bearing performance of the basic structure of bus body skeleton. First of all, the maximum displacement at the free end of the second supporting rod (abbreviated as $D_{\text{max}}$) and the maximum Von Mises stress of the spatial three-rod structures (abbreviated as $S_{\text{max}}$) under unit load are calculated. In order to observe the effect of welding one and two triangular plates and two different loading directions on the $D_{\text{max}}$ and $S_{\text{max}}$ of the three-rod structures, the stiffness variation of the structure is evaluated by the displacement reduction coefficient $\delta$, and the strength variation of the structures is evaluated by the stress reduction coefficient $\Delta$. The formulas are defined as follows:

$$\delta = \left| \frac{D_{\text{max}} \text{ with triangular plate} - D_{\text{max}} \text{ without triangular plate}}{D_{\text{max}} \text{ without triangular plate}} \right| \times 100\% \quad (1)$$

$$\Delta = \left| \frac{S_{\text{max}} \text{ with triangular plate} - S_{\text{max}} \text{ without triangular plate}}{S_{\text{max}} \text{ without triangular plate}} \right| \times 100\% \quad (2)$$

3. Results and analysis

3.1. Influence of loading direction and triangular plates on stiffness, strength and position of $S_{\text{max}}$ of spatial three-rod structures

The effects of two different loading directions and one triangular plate or two triangular plates on the displacement reduction coefficient $\delta$ and stress reduction coefficient $\Delta$ of the spatial three-rod structures U, V and W are calculated. There are 18 computational models of the spatial three-rod structures U, V and W including four cases: without triangular plate, welded by one triangular plate, welded by two triangular plates and two different loading directions. The results are shown in table 1, table 2 and figure 6-figure 12.
Table 1. $D_{\text{max}}$, $S_{\text{max}}$ and position of $S_{\text{max}}$ of the structures without triangular plate.

| loading directions | structure | parallel to the main rod | perpendicular to the main rod |
|-------------------|-----------|--------------------------|-------------------------------|
|                   |           | $D_{\text{max}}$ (mm)    | $S_{\text{max}}$ (MPa)       | $D_{\text{max}}$ (mm)       | $S_{\text{max}}$ (MPa)       | $D_{\text{max}}$ (mm)       | $S_{\text{max}}$ (MPa)       |
|                   |           | 0.401                    | 35.829                        | 1.181                        | 71.752                        | 0.15                          | 18.719                        |
|                   |           | 0.15                     | 128.088                       | 4.237                        | 268.679                       | 0.496                         | 57.95                         |
| Position of $S_{\text{max}}$ |           | At the right corner point of the connection between the second supporting rod and the main rod, as shown in figure 6. | The same as structure U, as shown in figure 6. | At the upper corner point of the three-rod connection, as shown in figure 7. | The same as structure U, as shown in figure 7. |

Figure 6. Stress cloud diagram of structure U without triangular plate when the loading direction is parallel to the main rod.

Figure 7. Stress cloud diagram of structure V without triangular plate when the loading direction is perpendicular to the main rod.

Table 2. $D_{\text{max}}$, $\delta$, $S_{\text{max}}$, position of $S_{\text{max}}$, and $\Delta$ of the structures welded by one or two triangular plates, when the loading direction is parallel to the main rod.

| structure | number       | $D_{\text{max}}$ (mm) | $\delta$ (%) | $S_{\text{max}}$ (MPa) and Position of $S_{\text{max}}$ | $\Delta$ (%) |
|-----------|--------------|------------------------|--------------|----------------------------------------------------------|--------------|
| U         | one triangular plate | 0.343                  | 14.46        | 22.005, at the upper corner point of the three-rod connection, as shown in figure 8. | 38.58        |
|           | two triangular plates | 0.308                  | 23.19        | 16.396, on the upper side of a triangular plate, as shown in figure 10. | 54.24        |
|           | one triangular plate | 0.992                  | 16.00        | 38.464, the same as structure U welded by one triangular plate. | 46.39        |
|           | two triangular plates | 0.903                  | 23.54        | 30.179, the same as structure U welded by two triangular plates. | 57.94        |
|           | one triangular plate | 0.13                   | 13.33        | 11.973, the same as structure U welded by one triangular plate. | 36.04        |
|           | two triangular plates | 0.116                  | 22.67        | 8.269, the same as structure U welded by two triangular plates. | 55.83        |
Table 3. $D_{\text{max}}, \delta, S_{\text{max}}, \text{position of } S_{\text{max}}, \text{and } \Delta$ of the structures welded by one triangular plate or two triangular plates, when the loading direction is perpendicular to the main rod.

| Structure number | $D_{\text{max}}$ (mm) | $\delta$ (%) | $S_{\text{max}}$ (MPa) and Position of $S_{\text{max}}$ | $\Delta$ (%) |
|-----------------|------------------------|--------------|-----------------------------------------------------|-------------|
| U one triangular plate | 0.466 | 68.93 | 33.977, in the middle of the hypotenuse of the triangular plate, as shown in figure 9. | 73.47 |
| U two triangular plates | 0.349 | 76.73 | 20.379, on the hypotenuse of the triangular plate below, as shown in figure 11. | 84.09 |
| V one triangular plate | 1.157 | 72.69 | 52.158, on the right side of the hypotenuse of the triangular plate, as shown in figure 12. | 80.59 |
| V two triangular plates | 0.944 | 77.72 | 34.479, the same as structure U welded by two triangular plates. | 87.17 |
| W one triangular plate | 0.2 | 59.68 | 19.696, the same as structure V welded by one triangular plate. | 66.01 |
| W two triangular plates | 0.145 | 70.77 | 10.596, the same as structure U welded by two triangular plates. | 81.72 |

Figure 8. Stress cloud diagram of structure U welded by one triangular plate when the loading direction is parallel to the main rod.

Figure 9. Stress cloud diagram of structure U welded by one triangular plate when the loading direction is perpendicular to the main rod.

Figure 10. Stress cloud diagram of structure U welded by two triangular plates when the loading direction is parallel to the main rod.

Figure 11. Stress cloud diagram of structure U welded by two triangular plates when the loading direction is perpendicular to the main rod.
Figure 12. Stress cloud diagram of structure V welded by one triangular plate when the loading direction is perpendicular to the main rod.

It can be seen from table 1 that the influence when the loading direction is perpendicular to the main rod on $D_{\text{max}}$ and $S_{\text{max}}$ of the structure U, V and W are greater than those when the loading direction is parallel to the main rod. The $D_{\text{max}}$ and $S_{\text{max}}$ when the loading direction is perpendicular to the main rod is respectively 3.5 times higher than those when loaded parallel to the main rod direction.

It can be seen from table 2 and table 3 that:

1. The stiffness and strength of the structures U, V and W have been improved by welding one triangular plate or two triangular plates under two different direction loads. When the loading direction is parallel to the main rod of the structures welded by one triangular plate or two triangular plates, the displacement reduction coefficient $\delta$ is over 13.33% and 22.67% respectively, and the stress reduction coefficient $\Delta$ is over 36.04% and 54.24% respectively. When the loading direction is perpendicular to the main rod of the structures welded by one triangular plate or two triangular plates, the displacement reduction coefficient $\delta$ is over 59.68% and 70.77% respectively, and the stress reduction coefficient $\Delta$ is over 66.01% and 81.72% respectively. It can be seen that in the case of the same size of triangular plates the stiffness and strength of the structure is improved to a certain extent only when the loading direction is parallel to the main rod, however the stiffness strength of the structure is obviously increased when the loading direction is perpendicular to the main rod. The effect of welding two triangular plates on the stiffness and strength of the structures is only slightly higher than those of welding one triangular plate. That is, only when the loading direction is perpendicular to the main rod, can welding triangular plates improve significantly the stiffness and strength of the structures, and the stiffness and strength of the structures can be significantly enhanced by welding only one triangular plate.

2. When structures U, V and W with one triangular plate or two triangular plates under two different direction loads, the positions of $S_{\text{max}}$ have all been transferred. When the direction of load is parallel to the main rod, the positions of $S_{\text{max}}$ of the structures welded by one triangular plate have all been transferred from the lower right corner point at the connection of the second supporting rod and the main rod, as shown in figure 13 (a), to the upper corner point at the three-rod connection, as shown in figure 13 (b). That is, although there is a transfer, it is still located on the weld at the rod connection. The positions of $S_{\text{max}}$ of the structures welded by two triangular plates have all been shifted to the hypotenuse of the triangular plates, as shown in figure 13 (c). When the loading direction is perpendicular to the main rod, the positions of $S_{\text{max}}$ of the structures welded by one triangular plate or two triangular plates have all been transferred to the hypotenuse of the triangular plates, as shown in figure 13 (d). Therefore, when the loading direction is parallel to the main rod, only welding two triangular plates can the position of $S_{\text{max}}$ of the structures be improved evidently. When the loading direction is perpendicular to the main rod, welding one triangular plate can also evidently improve the position of $S_{\text{max}}$ of the structures.
(3) The displacement reduction coefficient $\delta$ and stress reduction coefficient $\Delta$ of the structures U, V and W welded by one triangular plate are all not as big as those of welded by two triangular plates, but are all more than half of those welded by two triangular plates.

![Figure 13. The position variations of $S_{\text{max}}$ in the structures.](image)

### 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, three structural forms of the structures U, V and W including without triangular plate, with one triangular plate and with two triangular plates are made into test members. The displacement measurement and static strain measurement were carried out when the load was parallel to the main rod. The main rod and one supporting rod had a square steel plate welded at their ends respectively, and they were fixed on the anchor bolt of the test bed through the square steel plates, and the load was applied on the other supporting rod. The test site and the instrument are shown in figure 14.

![Figure 14. The test site](image)

According to the results obtained from the finite element model of the test members, 10 ~ 12 points with big stress and deformation are selected as the test points on each test member. 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. The average value of three repeated tests is taken as the final measurement value at each measuring point. By using Hooke's law, the principal stress measurement values of each test point can be calculated.

The calculated and measured values of the three test members are compared one by one, and the results show that:

1. The displacement errors of finite element calculation of the three test members are all very small, and all of them are below 5.7%.
2. The stress errors of finite element calculation of the three test members are all also small, and the relative error rates of 10% of the measured points are more than 9%, the rest are below 9%.

Therefore, the errors between the measured values and the calculated values of most of the measured points are within the acceptable range, which verifies the finite element calculation results in this paper.
4. Conclusions
In this paper, the effect of welding triangular plates on the stiffness and strength of the spatial three-rod structures of bus body is studied. The results show that:

(1) The influence when the loading direction is perpendicular to the main rod on the stiffness and strength of the spatial three-rod structures is greater than that when parallel to the main rod. $D_{\text{max}}$ at the free end and $S_{\text{max}}$ of the structures when the loading direction is perpendicular to the main rod are respectively 3.5 times as much as those when parallel to the main rod.

(2) Only when the loading direction is perpendicular to the main rod, can welding triangular plates improve significantly the stiffness and strength of the structures, and the stiffness and strength of the structures can be significantly enhanced by welding only one triangular plate.

(3) When the loading direction is parallel to the main rod, only welding two triangular plates can effectively transfer the position of $S_{\text{max}}$ of the spatial three-rod structures. When the loading direction is perpendicular to the main rod, welding only one triangular plate can transfer evidently the position of $S_{\text{max}}$ of the spatial three-rod structures.

(4) Although the stiffness and strength of the spatial three-rod structures by welding one triangular plate are not as big as those by welding two triangular plates, the enhancement effect of the stiffness and strength by welding one triangular plate is more than half of that by welding two triangular plates.

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