Welding Process Influence on Welding Deformation of Orthotropic Steel Bridge Slab

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Abstract: Orthotropic bridge deck is the main structural form of steel box girder bridge deck. Due to the dense U-rib weld and complex structure, it is easy to produce large deformation during welding. At present, the determination of the amount of deformation is mainly based on the empirical value and the trial and error method. It is of great significance for welding deformation control to study the influence of welding process on welding deformation of orthotropic bridge deck and clarify the influence of welding parameters and welding sequence. Based on Marc software, the finite element thermoelastic analysis method is used to simulate the post-weld residual deformation of orthotropic bridge deck. The influence of welding parameters and welding sequence on welding deformation is analyzed, and the sensitive parameters affecting welding deformation are determined. The optimal combination of welding parameters was developed, and the reasonable sequence of U-rib welding was established, which laid a foundation for welding deformation control of orthotropic bridge deck.

1. Introduction

The heat input during the welding process of the steel plate changes the internal structure of the metal. The welding area shrinks and stretches unevenly due to heating locally and cooling, resulting in welding deformation [1]. At present, the setting of the anti-deformation amount mainly depends on the empirical method, and there is a large subjectivity [2]. Domestic and foreign experts and scholars have carried out preliminary research on welding deformation, and obtained the main factors affecting welding deformation, and optimized the welding process. S.H.Lee [3] based on 3D finite element model and thermoelastic method, using professional welding numerical simulation software SYSWELD to analyze the deformation and stress during MIG welding on automobile muffler, and reduce welding distortion of automobile muffler by adjusting welding sequence the amount. Tian Hao [4] carried out welding deformation simulation based on three typical structures: thin plate butt welding, T-weld welding and double channel steel welded beam with partition plate. Then, based on VC++ and ANSYS software, a system for predicting welding deformation was developed. Zhou Guangtao [5] used Marc software to simulate the welding shape of the top and side of the large crane and optimized the welding sequence.

Based on the large-scale general finite element software Marc, this paper uses the orthogonal experiment method to design the experiment, analyzes the influence of welding parameters on the deformation, determines the main influence parameters and optimization combination, and compares
the deformation under different welding sequences. The rational sequence of U-rib welding is established, which has important engineering significance.

2. Finite Element Analysis of U-rib Welding Deformation

2.1. Model establishment

A single U-rib simplification model was used to analyze the amount of welding deformation. The top plate size is 600mm × 400mm × 16mm, the U rib is 8mm thick, the U rib is 280mm high, and the 50°groove. The established finite element model is shown in Fig. 1. The dense mesh is used near the weld and the mesh is sparse away from the weld zone.

![U-rib finite element model](image)

The steel used in the model is Q345qC, and the material performance parameters are shown in Table 1.

| Temperature / °C | 20  | 200 | 400  | 600  | 1500 |
|------------------|-----|-----|------|------|------|
| Thermal conductivity / (W·m⁻¹·°C⁻¹) | 48  | 47.5| 41.6 | 36   | 35.5 |
| Specific heat capacity / (J·Kg⁻¹·°C⁻¹) | 461 | 533 | 611  | 778  | 780  |
| Linear expansion coefficient / (10⁻⁶·°C⁻¹) | 11.9| 13  | 14.1 | 14.9 | 15   |
| Elastic Modulus / GPa | 212 | 199 | 184  | 164  | 73.75|
| Yield Strength / MPa | 343 | 276 | 167  | 0.5  | 0.35 |

The model selects the double ellipsoid heat source, and the heat source power is set to 5200J, wherein the current is 200A and the voltage is 26V. The effective power coefficient η = 0.8, the width is 8 mm, the depth is 5 mm, the front length is 3 mm, and the rear length is 15 mm.

With a welding speed of 20mm/s and an ambient temperature of 20°C, the welding path is linear and the ends are symmetrically welded at the same time.

2.2. Post-weld deformation analysis

In the center of the weld, four nodes are selected along the welding direction. The temperature change curve is shown in Fig. 2. Node 1 is the welding end and node 4 is the welding end. It can be seen from Fig. 2 that the temperature at the front end of the welding is slightly lower than 1500 °C. As the heat source moves slowly, the temperature also reaches a peak value of 1769 °C. When the heat source moves to the end, the temperature reaches 1803 °C, which is slightly larger than the peak of temperature during the welding process. This is because the rate at which the metal exchanges heat with the air is lower than the rate of exchange inside the metal.
Fig. 2. Temperature curve of each node. Fig. 3. Vertical deformation node coordinates change.

The amount of contraction of each node along the weld direction (Y direction) and perpendicular to the weld direction (X direction) is extracted, and the maximum values are 0.02 mm and 0.09 mm respectively, so that it can be ignored. It can be seen that the post-welding is mainly vertical deflection deformation similar to the ship type, as shown in Fig. 3. The maximum vertical deformation of the plate surface appears in the middle, which is 0.71 mm.

3. Orthogonal test design
Orthogonal test method is a kind of test method that scientifically analyzes and studies the influence of multiple factors. It can infer the comprehensive test results by a limited number of tests. It has uniform dispersion and neat and comparable characteristics, so it is widely used in experimental design and parameter optimization. The range analysis of the test indicators corresponding to each level is often used to determine the primary and secondary status of the factors. The smaller the difference is, the smaller the influence of the corresponding factors is [6].

The welding parameters should be selected in accordance with the welding process requirements in the current national standard steel structure welding specification [7]. The welding process parameters selected in this experiment include: welding heat source power, welding speed, and ambient temperature. From the selection range of parameters, a three-factor four-level test table is proposed, as shown in Table 2 below.

| Level | Test number | Heat source power (P/W) | Welding speed (v/mm·s⁻¹) | Ambient temperature (°C) | Post-weld deformation (mm) |
|-------|-------------|-------------------------|--------------------------|--------------------------|---------------------------|
|       | 1           | 5200                    | 20                       | 5                        | 1.13                       |
|       | 2           | 5200                    | 26                       | 20                       | 0.53                       |
|       | 3           | 5200                    | 30                       | 30                       | 0.25                       |
|       | 4           | 5200                    | 35                       | 40                       | 0.14                       |
|       | 5           | 6615                    | 20                       | 20                       | 1.48                       |
|       | 6           | 6615                    | 26                       | 5                        | 0.90                       |
|       | 7           | 6615                    | 30                       | 40                       | 0.35                       |
|       | 8           | 6615                    | 35                       | 30                       | 0.16                       |
|       | 9           | 7000                    | 20                       | 30                       | 1.50                       |
|       | 10          | 7000                    | 26                       | 40                       | 0.68                       |
|       | 11          | 7000                    | 30                       | 5                        | 0.52                       |
|       | 12          | 7000                    | 35                       | 20                       | 0.24                       |

Table 2. Orthogonal test table.
4. Analysis of test results
In order to determine the primary and secondary sequence and optimization level combination of the influencing factors of each index, then analyze the test index values, and the calculated extreme difference values of test indicators are as shown in Table 3.

Table 3. Extreme difference values in test indicators of various factors.

| Test index | Project     | Factor         | Heat source power | Welding speed | Ambient temperature |
|------------|-------------|----------------|-------------------|---------------|---------------------|
|            |             | k1             | 0.51              | 1.42          | 0.74                |
|            |             | k2             | 0.72              | 0.77          | 0.73                |
|            |             | k3             | 0.74              | 0.46          | 0.71                |
|            |             | k4             | 0.90              | 0.22          | 0.68                |
|            |             | Extreme difference | 0.39            | 1.20          | 0.06                |

4.1. Analysis of influencing factors
The average deformation value under each factor in Table 3 is plotted as a line graph, as shown in Fig. 4.

Fig.4. Effect of various factors on the average deformation.

It can be seen from the figure that as the welding speed increases, the post-weld deformation gradually decreases and the trend is obvious; after the heat source power increases, the post-weld deformation also increases. This is because the welding speed is increased or the heat source power is increased, the energy of the arc is more concentrated, and the post-weld temperature difference between the weld zone and the base metal is increased. This more intense thermal change causes residual stress and deformation after welding. Also increased further. After the external ambient temperature rises, the deformation after welding will decrease, but it is not obvious.
The order of the extreme difference of each factor is: 1.20 > 0.39 > 0.06. It can be clearly seen from the histogram of Fig. 5. The most influential factor on the deformation after welding is the welding speed, followed by the heat source power, and the influence of the ambient temperature is the least. Therefore, the order of sensitivity of the influencing factors should be: welding speed > heat source power > ambient temperature.

4.2. Optimal parameter combination
The test results were analyzed using a secondary statistical method. When the heat source power is at 1 level, the minimum post-weld deformation is 0.14 mm, corresponding to the fourth set of test schemes, at which time the welding speed and the ambient temperature are at the 4 and 4 levels, respectively. Similarly, the optimal schemes for the 2, 3, and 4 levels, as well as the welding speed and the ambient temperature are also listed in Table 4. Then count the number of occurrences of each level of each factor.

| factor                | Heat source power | Welding speed | Ambient temperature | Heat source power | Welding speed | Ambient temperature | number of occurrences |
|-----------------------|-------------------|---------------|---------------------|-------------------|---------------|---------------------|----------------------|
| level                 | v T P T P v        |               |                     |                   |               |                     |                      |
| 1 level               | 4 4 1 1 4 4 5 0    | 2             | 2                   | 2                 | 2             | 2                   |                      |
| 2 level               | 4 3 1 2 3 4 1 0    | 2             | 2                   | 2                 | 2             | 2                   |                      |
| 3 level               | 4 2 1 3 2 4 1 0    | 2             | 2                   | 2                 | 2             | 2                   |                      |
| 4 level               | 4 1 1 4 1 4 1 1 8  | 8             | 8                   | 8                 | 8             | 8                   |                      |

It can be seen from Table 4 that the heat source power occurs most frequently at the 1 level, the welding speed occurs at the 4 levels most frequently, and the ambient temperature occurs as many times as every level. Therefore, the heat source power P=5200W and the welding speed v=35mm/s are the best parameters. The optimal ambient temperature effect is not significant, and can be combined with the specific conditions.

5. Welding sequence impact analysis
This experiment uses four welding sequence schemes, namely: (a) welding from left to right: ①→②→③→④→⑤→⑥, (b) symmetrical welding from the ends to the middle: ①⑥→②⑤→③④, (c) symmetrical welding from the middle to the ends: ③④→②⑤→①⑥, (d) and six welds at the same time, as shown in Fig.6.
The deformation conditions under different welding sequences are calculated, and the deformation cloud diagram is shown in Fig. 7. After the completion of all four calculations, the maximum vertical deformation after welding is shown in Fig. 8.

It can be seen from the figure that the order of deformation amount after welding is: (a)>(c)>(b)>(d). Among them, the largest deformation is the welding from left to right, the smallest deformation is the simultaneous welding of six welds. This is because the welding is carried out from left to right in sequence, and the angular deformation gradually accumulates, resulting in an increase in vertical flexural deformation. When the six welds are simultaneously welded, the difference in temperature field distribution is small due to the uniform heat input. Then, the vertical deflection deformation is also correspondingly reduced.

6. Conclusion
Through the analysis of welding parameters and welding sequence, the following conclusions are drawn: increasing the welding speed or reducing the heat source power, the deformation after welding will be significantly reduced; the heat source power \( P = 5200 \text{W} \), and the welding speed \( v = 35 \text{mm/s} \) is the most of excellent parameters combination. The increasing of the ambient temperature makes the welding deformation slightly reduced, which can be determined according to the specific conditions. The sensitivity factors of the influencing factors of post-weld deformation are: welding speed \( > \) heat source power \( > \) external environment temperature. Six welds are simultaneously welded and symmetrically welded from the ends to the middle, which can effectively reduce post-weld deformation.

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