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Parameter Optimization Analysis of out of Plane Fatigue Details of Steel Bridge Web

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Abstract

Based on the trend of the fatigue stress in the small gap area, this paper uses the large-scale finite element software ANSYS to simulate a small steel bridge, and discusses the structural optimization effect of the web height, web thickness, small gap height and other details on the out of plane deformation and fatigue resistance at the web gap.

Keywords

Small gap; Fatigue stress; Out of plane deformation; Finite element analysis.

1. Introduction

The research on steel bridge fatigue at home and abroad is mainly divided into two categories: load fatigue and out of plane deformation fatigue [1]. The former one only needs to calculate the in-plane stress of its steel beam in the fatigue design and analysis, which is a familiar form in the field of fatigue research; the latter one depends on the local out of plane deformation at the details, not directly related to the load.

In the fatigue design of steel bridge before 1970, in order to avoid the transverse weld of tension flange, the transverse connecting plate such as stiffener (diaphragm or beam) is usually used to connect only with the compression flange of main beam, while the tension flange of main beam adopts the form of cutting the connecting plate short or only contacting but not connecting. In this way, there is no direct connection between the stiffener (diaphragm or beam) and the tension flange, resulting in a small unsupported web clearance between the end of the transverse connecting plate and the tension flange of the main beam. Under the action of vehicle load, the load transferred in the transverse connecting member will cause out of plane deformation and fatigue crack at the web gap (as shown in Figure 1). The main reason for this kind of crack is that the out of plane deformation at the small gap of Web produces tensile stress at the end of horizontal weld of Web flange and vertical weld of Web stiffener, and the tensile stress will cause horizontal crack at the end of weld of Web stiffener. With the continuous action of cyclic load, the crack length increases, the direction changes, and finally it is perpendicular to the direction of main tensile stress in the small gap of web. Generally, the out of plane deformation fatigue crack mainly occurs at the end of the transverse stiffener (at the weld toe perpendicular to the web of the main beam), and just starts to expand along the horizontal direction. When the crack tip constraint changes significantly, the stiffness of the end of the transverse stiffener decreases, which eventually leads to the change of the main tensile stress direction of the web, and the crack extends away from the end of the tension flange.

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Fig.1 The crack is caused in web space

After entering the 20th century, with the development of iron and steel industry, manufacturing technology and modern structural mechanics, western countries began to build a large number of steel bridges in various forms to meet the economic development. Due to the high stress concentration at the joint of welded structure, and the influence of out of plane deformation and secondary stress of details is seldom considered, it is these factors that make the fatigue performance of steel bridge structure greatly reduced. In recent years, China has designed and built a large number of world-class steel bridges in various forms, such as Runyang Yangtze River Bridge, Sutong Yangtze River Bridge, Chongqing Chaotianmen Bridge, etc. However, it is not suitable for it. At present, the research on detail fatigue of bridge steel structure under load is not deep enough in our country, and a set of perfect evaluation standards for fatigue detail design of steel bridge has not been formed, especially the emergence of some new structures, new processes and new materials. Engineering designers often do not know how to judge the fatigue performance of new structure details. Although 《The Current Code For Design Of Highway Steel Structure Bridges》 (jtgd64-2015) [2] has improved the fatigue design and calculation method of steel structure and increased the fatigue load model, the classification of fatigue details is still not comprehensive. The fatigue strength design of a large number of new steel bridge members can not be guaranteed, and the residual fatigue life of a large number of existing steel bridges can not be correctly judged, so effective schemes can not be adopted for repair [3]. At present, we have the following problems: ① lack of accurate and effective fatigue test data; ② lack of in-depth study on fatigue load spectrum of steel bridge, and no clear calculation method for fatigue load of steel bridge; ③ lack of understanding on fatigue problems of some complex structural details (such as out of plane deformation of various connection details in longitudinal and transverse beam system, etc.).

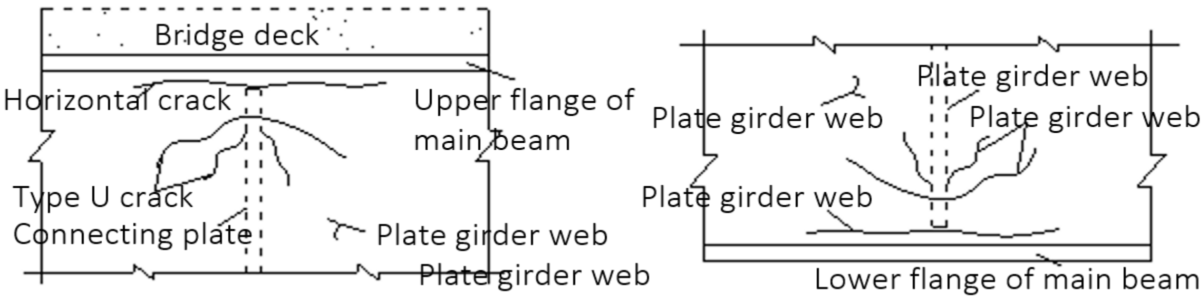

Fig. 2 Diagram of fatigue crack caused by out-of-plane deformation

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In 1981, Fisher and yuceoglu analyzed the fatigue cracks of 142 steel bridges in the United States and Canada, and found that the large initial defects and out of plane deformation at the small gap are the direct causes of most of the fatigue cracks. But in the actual bridge structure, the out of plane deformation of small gap is inevitable. In 1982, China Academy of Railway Sciences investigated the cracking of 50 welded steel bridges on the eight main railway lines in China. It was found that the number of fatigue cracks caused by out of plane deformation (as shown in Figure 2) accounted for more than 65% of the total number of cracks found, and the fatigue cracks were mainly of the following two types: one was at the end of fillet weld between web and connecting plate, the crack shape was U-shaped; the other was between web and flange The cracks are horizontal at the toe of the fillet weld. The fatigue cracking of welded steel bridges in Europe, Japan and other countries has similar characteristics. It has become an important topic to find out the causes of fatigue cracks caused by out of plane deformation and to study the treatment and optimization measures. However, the cracks found are usually in the details of complicated stress, so it is difficult to reproduce the same fatigue cracks in the form of experiments. Therefore, it is of great significance to summarize and analyze the details that are easy to produce fatigue damage and optimize and improve the detail structure in design.

Therefore, in this paper, the finite element analysis method is used to analyze the fatigue performance of the details of the end connection (as shown in Figure 3) of the steel plate beam (or transverse joint) L_g connection plate, and to study the value of the small gap distance (also known as web gap) in out of plane deformation, and the impact $\Delta\sigma$ on the cyclic stress. In order to reduce the bending stress of the main beam web due to out of plane deformation and improve the performance of anti fatigue strength, optimize and improve the detail structure prone to fatigue damage, reduce the restraint strength of the main beam at the welding position, and adapt to the rotation of the beam end.

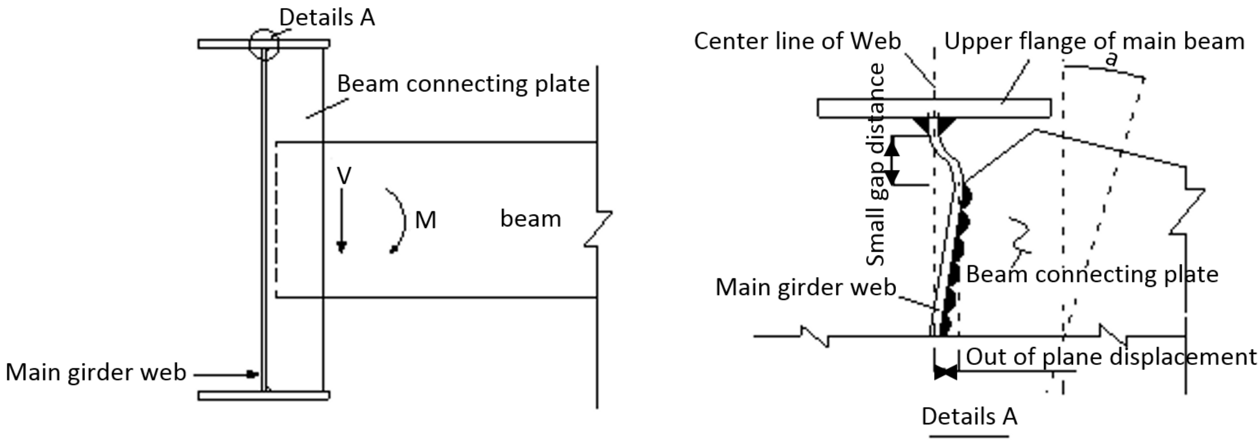

Fig. 3 The steel bridge beam connects the plate end of the plate with the plane fatigue details

2. Finite element model

The main girder of the steel bridge model studied in this paper is two I-shaped steel beams with standard section length of 10 m and spacing of 5.1 M. The material parameters are shown in Table 1 below. The cross section and layout of steel bridge beam are shown in Figure 4 below.

Table 1 Finite element model material characteristics

Material category	Modulus of elasticity（Pa）	Poisson's ratio	density（g/cm^3）
Steel productsQ345	2×10^{11}	0.3	7.9
ConcreteC30	3×10^{10}	0.17	2.5

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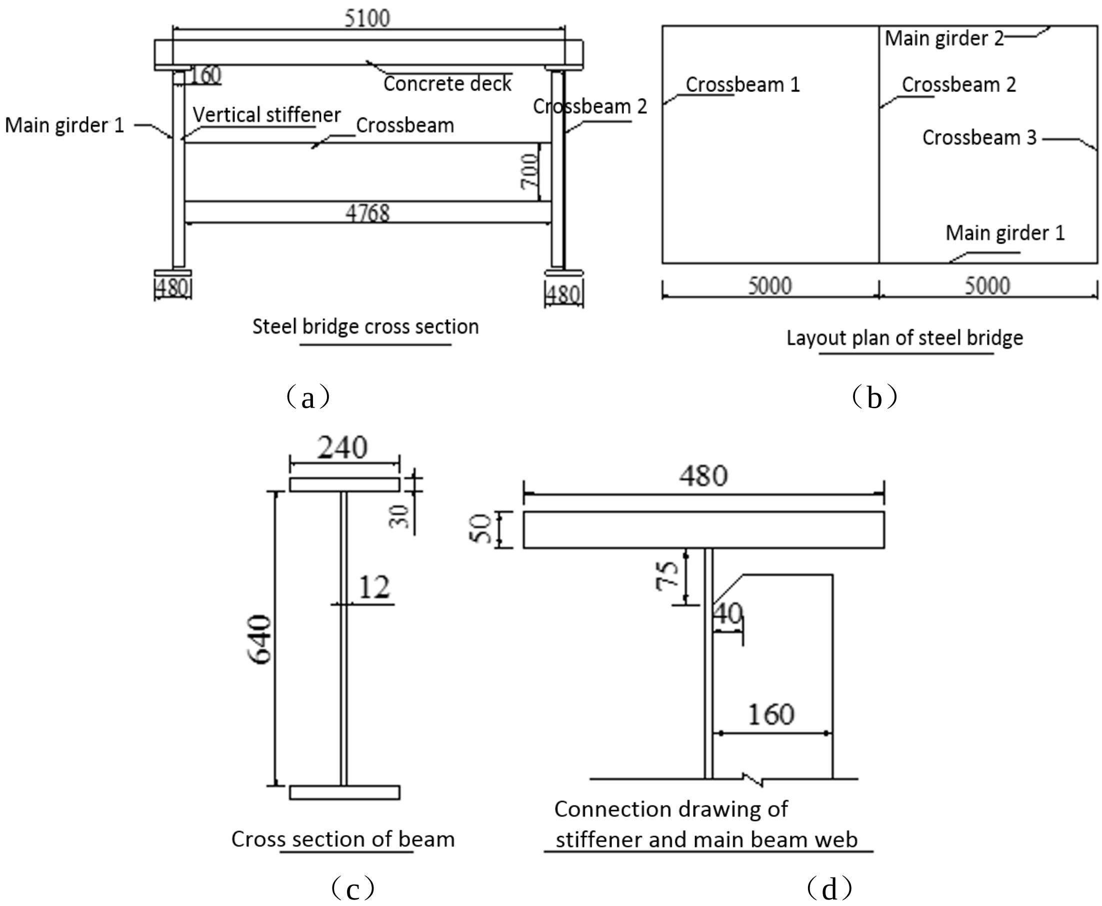

Fig.4 Cross section and plane layout of steel bridge model

In this paper, ANSYS large-scale finite element software is used to simulate the above steel bridge, mainly using shell 63, beam 188 and solid 45. The concrete bridge deck is mainly used to bear the vehicle load directly and transfer the load to the main beam, so in the rigid connection of the bridge deck and the main beam in ANSYS finite element software, the coupling degree of freedom is used to make its displacement consistent [5] , the finite element model is shown in Figure 5.

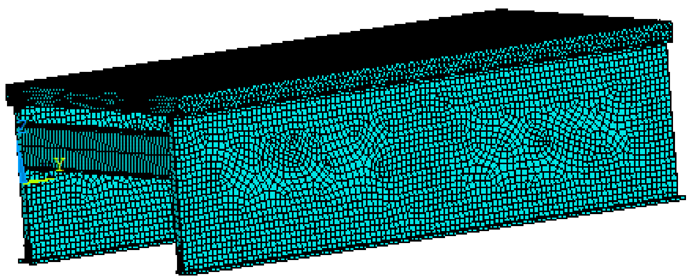

Fig.5 Integral finite element model of steel bridge

In this paper, the fatigue problem of the plane detail of the steel bridge web is mainly concerned with the vibration analysis of the beam under the action of constant moving force at a constant speed, in which the applied load (including restraint and fatigue vehicle axle load) is written into the load step, each load step is 2 s, divided into five load sub steps, and the cyclic sentence is used to load.

3. Optimization analysis

3.1 Influence of web height on external deformation stress

In the model, change the height of the main beam H = 2.1m, 2.3m, 2.7m, 2.9m, etc., and the stress value of point a at the plane detail of the midspan web under condition III is shown in Table 2 below:

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Table 2 Finite element calculation of fatigue stress at the web space at different web height

Web height（m）	Inner force point（MPa）		External force point（MPa）		Lateral displacement（mm）
	Longitudinal stress	Vertical stress	Longitudinal stress	Vertical stress	
2.1	48.980	56.096	-52.044	-83.127	-0.022104
2.3	50.325	57.394	-53.284	-84.769	-0.022385
2.5	51.226	58.373	-54.135	-86.178	-0.022586
2.7	52.161	59.220	-55.034	-87.389	-0.022776
2.9	53.649	60.272	-56.360	-88.903	-0.022923

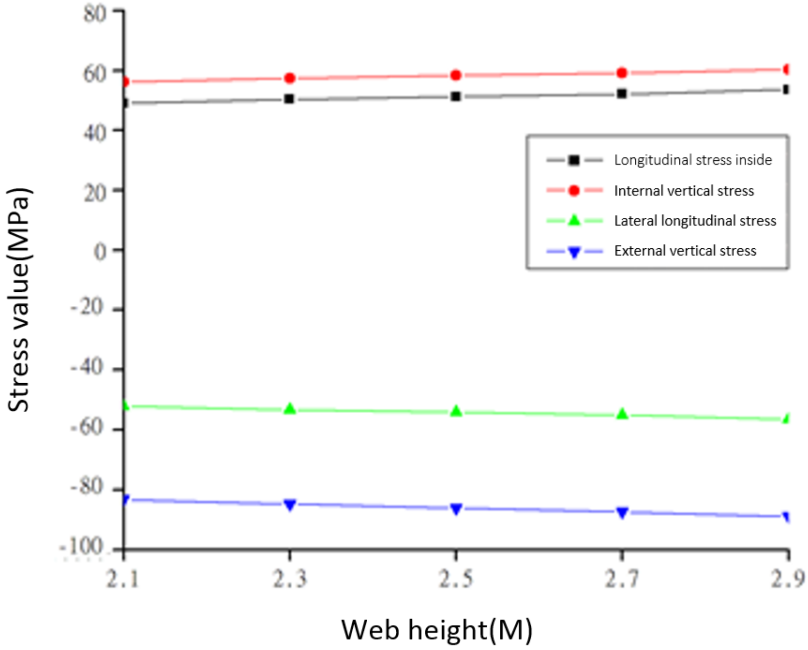

Fig.6 Trend Chart of stress values in the space of Web at different Web height

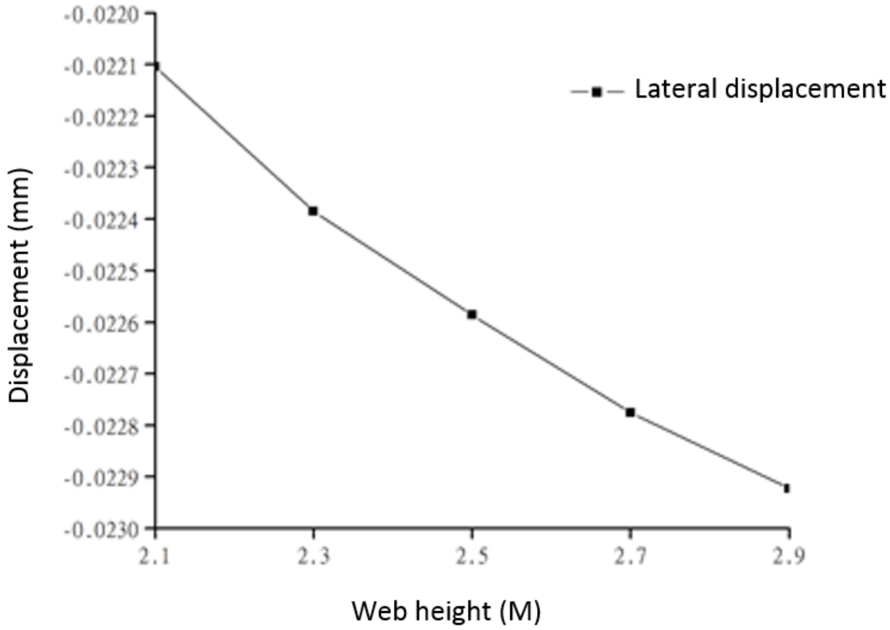

Fig.7 Trend Diagram of Transverse displacement of Web space at different Web height

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It can be seen from Fig. 6 and Fig. 7 that the increase of the web height of the main beam is accompanied by the increase of the lateral displacement and stress value at the high stress point. In the steel bridge model simulated in this paper, the change of the web height of the main beam directly affects the change of the welding length between the web and the stiffener, so when other parameters do not change, the welding length of the web and the stiffener determines the flexibility of the fatigue details, and then affects the out of plane deformation fatigue stress.

3.2 Influence of web thickness on external deformation stress

In the model, change the web thickness of the main beam H = 6mm, 9mm, 15mm, 18mm and so on. Under condition III, the stress value of point a at the plane detail of the midspan web is shown in Table 3 below:

Table 3 Finite element calculation of fatigue stress in web space with different web thickness

Web thickness（mm）	Inner force point		External force point		Lateral displacement
	Longitudinal stress	Vertical stress	Longitudinal stress	Vertical stress	
6	38.164	27.796	-41.198	-84.626	-0.020783
9	47.005	49.517	-50.121	-85.484	-0.021891
12	51.226	58.373	-54.135	-86.178	-0.022586
15	52.184	60.955	-54.851	-84.984	-0.023095
18	50.867	59.965	-53.309	-81.957	-0.023492

(Note: stress unit is MPa, displacement unit is mm)

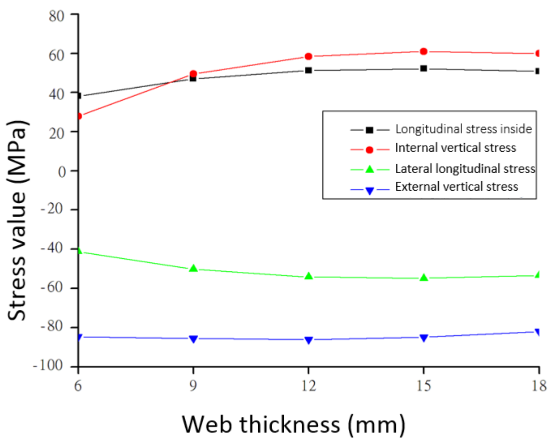

Fig.8 Trend Diagram of stress value in the space of Web with different thickness of Web

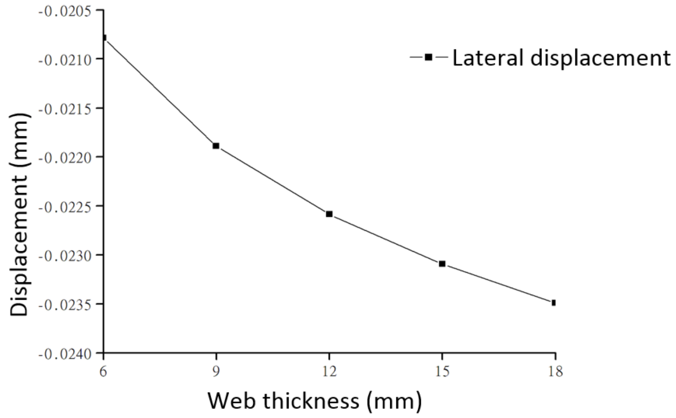

Fig.9 Trend Diagram of Transverse displacement value of Web space with different thickness of Web

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It can be seen from figure 8 and Figure 9 that with the increase of web thickness, the stress value at the connection of web and stiffener rises. When the web thickness h = 6mm, the longitudinal stress at the web gap is greater than the vertical stress, so at this time, the cracks at the web gap are mainly U-shaped cracks, while with the web thickening, the vertical stress at the web gap is dominant, mainly horizontal cracks. The change of web thickness directly leads to the change of girder stiffness and out of plane deformation at web gap, and then affects the value of stress at high stress point. Therefore, when the thickness of web is changed to optimize the fatigue strength of the structure, it should be considered that the U-shaped crack at the web gap has a greater impact on the fatigue strength of the structure than the horizontal crack, so as to avoid the influence of too thin web on the local stability of the main beam.

3.3 The influence of small gap height on the external deformation stress

Under the condition that other parameters do not change, the height of small clearance at the web gap is h = 45mm, 60mm, 75mm, 90mm and 105mm respectively. Under the action of condition III, the stress value of point a at the plane detail of midspan web is shown in Table 4 below:

Table 4 Finite element calculation of fatigue stress at A point at different small space height

Clearance height（mm）	Inner force point		External force point	
	Longitudinal stress	Vertical stress	Longitudinal stress	Vertical stress
45	9.087	12.574	-12.397	-19.394
60	56.571	66.494	-59.501	-95.850
75	51.226	58.373	-54.135	-86.178
90	11.370	17.087	-14.736	-39.019
105	43.442	48.035	-45.666	-75.860

(Note: stress unit is MPa, displacement unit is mm)

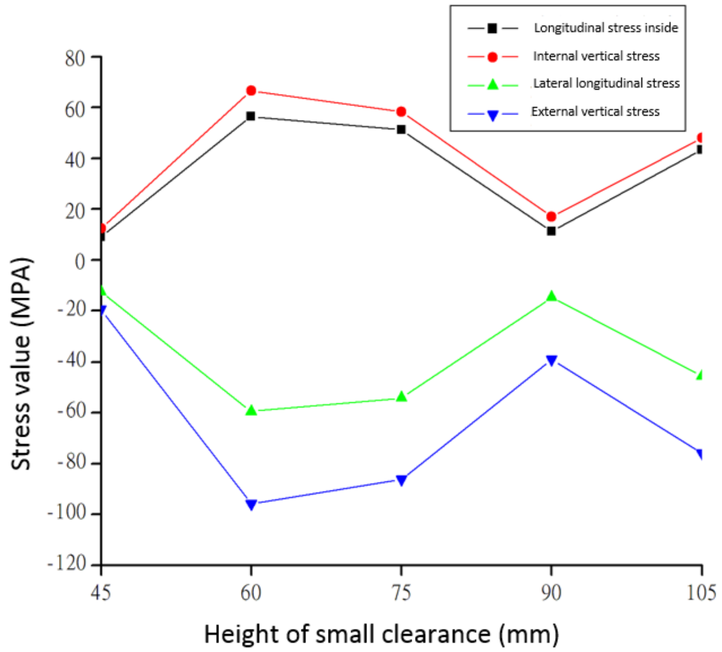

Fig.10 Trend Chart of stress value at Point A at different height of small space

According to the stress change trend in Figure 10 and the finite element calculation results, when the height of small gap H = 45mm and H = 105mm, the stress values of points A-J at the web gap (the stress trend of inner point and outer point is the same, so the stress change of inner point is taken as the research object) are shown in Table 5 below. The stress concentration occurs at points I and j near

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the bridge deck, and the stress change is abnormal compared with other points, This kind of state can easily lead to the loss of stability failure at the web gap, which does not meet the research needs of this paper for the optimization measures at the web out of plane details. Therefore, based on the change of stress values under the three states of void height h = 60mm, 75mm and 90mm, it can be found that with the increase of small gap height, the longitudinal stress and vertical stress at each point of the web gap are decreasing. The conclusion is consistent with the result of article [5]. It is suggested that the height of web gap should be increased as much as possible to increase the web under the condition of meeting the stability requirements of the steel bridge Fatigue strength at out of plane details.

Table 5 Finite element calculation of fatigue stress at web space with small space height of 45mm and 105mm

Node number	H=45mm		H=105mm	
	Longitudinal stress	Vertical stress	Longitudinal stress	Vertical stress
A	9.087	12.574	43.442	48.035
B	2.7299	1.0306	18.294	13.465
C	-2.0336	-3.0207	10.693	8.9116
D	-5.4347	-6.7144	6.2335	5.8173
E	-7.6018	-10.320	2.399	3.3709
F	-8.5902	-13.750	-1.5967	0.96689
G	-7.5677	-15.669	-6.7991	-1.9382
H	-4.0459	-21.827	-15.283	-6.4325
I	-163.850	-453.440	-38.815	-22.012
J	202.440	889.080	353.030	1080.400

4. Conclusion

Through the overall finite element modeling of the steel bridge and the stress analysis of the out of plane details of the main beam web, the optimization measures of the out of plane details of the steel bridge web are studied, and the influence of the web height, web thickness, small gap height and other details on the out of plane deformation fatigue of the web gap is discussed. Since the changed value is smaller than the original value after changing the detail structure of the fatigue detail, it is difficult to clearly show the optimization effect in the figure. Therefore, the stress difference parameter s is introduced to show the optimization degree of the changed structure compared with the original model.

When the web height of the steel bridge model is changed, the finite element analysis shows that the stress at each point of the web gap increases with the web height, showing an upward trend. Along the longitudinal nodes of the main beam, it also rises with the increase of the web height, and this optimization measure has a great influence on the U-shaped crack.

After changing the thickness of the web of the steel bridge model, the finite element analysis shows that the stress at each point of the web gap increases with the thickness of the web, which shows an upward trend. Except that the thickness of the web is 6mm, which is mainly to control the U-shaped crack, other parameters are mainly to control the horizontal crack. With the increase of web thickness,

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the closer to the high stress point, the faster the longitudinal stress and vertical stress rise, the larger the lateral displacement deformation.

When the height of the small gap of the steel bridge model is changed (within the range of 60-90mm), the finite element analysis shows that with the increase of the height of the small gap, the longitudinal stress and the vertical stress at each point of the web gap decrease. With the increase of the height of the small gap, the transverse displacement of each node along the longitudinal direction of the main beam is smaller, and the closer it is to the high stress point, the faster the longitudinal stress and vertical stress decrease. Especially when the height of the gap H = 90mm, the longitudinal stress changes the most, and the mechanical properties change, which indirectly confirms the rationality of the international regulations that the reference height of the small gap is not more than 80mm.

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