Fatigue Performance Analysis of U-rib-to-deck Connection with Double-sided Weld in Orthotropic Steel Bridge Deck

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Abstract: In order to explore the influence of weld structure on the fatigue performance of rib-to-deck (RD) connection with double-sided weld in orthotropic steel bridge deck, finite element model of the RD connection with double-sided weld was firstly established. Then, the influences of the weld penetration of outer groove weld, the ratio of weld toes (R), the notch size, the inner fillet weld, etc., on the stress amplitude of weld toes and roots were analysed. Finally, based on the master S-N curve method, the influence of the groove penetration and the ratio R on the fatigue life of the connection was studied. The results show that the groove penetration has insignificant influence on the weld fatigue life. However, the ratio R has great influence on the stress amplitude of weld roots and toes, the fatigue life and the cracking form of the connection. As the ratio R increases, the fatigue life firstly increases and then decreases. Otherwise, the fatigue life is relatively larger when the ratio R is close to 1.0, and fillet weld size of 4 or 6 mm could be applied for the inner fillet weld of the double-sided connection.
***Keywords*:** orthotropic steel bridge deck; rib-to-deck weld connection; finite element analysis; fatigue life evaluation

1. Introduction

Orthotropic steel bridge decks are widely used in modern steel bridges because they are light and have high strengths. But they are prone to fatigue cracking under vehicle loads due to their complex weld structure. Researchers have proposed the U-rib internal welding technique to improve the fatigue life of single-sided groove welds[1]. Although progress has been made around the research of double-sided welded configurations[2,3], relative design theory is still immature, as the fatigue problem of welded structures is affected by structural configurations, weld configurations, welding processes, etc.[4]. In order to further investigate the influence factors of fatigue life of the double-sided rib-to-deck weld, it is also necessary to combine the fatigue life assessment methods to carry out targeted analyses. In view of the limitations of traditional assessment methods such as the hot spot stress method and the nominal stress method[5,6], a method with mesh insensitivity and high accuracy for the fatigue assessment of welded structures, i.e., the master S-N curve method, is introduced[7]. Studies have shown that the master S-N curve method has wide applicability[8,9], can efficiently and accurately assess the fatigue life of various types of welded parts, and the assessment process is relatively simple, providing an effective means for the fatigue assessment of welded structures of orthotropic steel bridge decks.

In this paper, based on the relevant research results[8,10], finite element model of orthotropic steel bridge deck was established. The deck was welded with double U-ribs using double-sided welds. The influence of weld configuration parameters on the stress amplitude was then analysed; Finally, the master S-N curve evalution method was used to further analyse the influence of the outer groove weld penetration and the ratio of the two weld toes on the fatigue life of the RD connection.

2. Finite element modelling and validation

Based on the related fatigue test results[8,10], the finite element analysis model was first established. In the model, the U-rib and the top plate were constructed with double-sided welds[10]. The weld and the steel plate are both constructed with eight-node SOLID45 element, and the fixed constraints are used at the fixing bolts at both ends of the top plate. The load is achieved by applying the surface load in the middle of the model, and the transverse width of the loading surface is 150 mm. The length of the longitudinal direction is 400mm (Figure 1). The weld configuration in the model is shown in Figure 2, where t_c is the fusion depth of the base metal or the previous weld on the cross section of the welded structure; t is the thickness of the U-rib; l_U is the weld toe length of the U rib of the outer weld; l_D is the weld toe length of the top plate of the outer weld; l_C is the size of the cutout; l_{in} is the size of the inner adhering fillet weld. In accordance with the local effect principle of the Saint Venant's principle, the top plate and U-rib weld connection area in the model is divided by a finer mesh (Figure 1).

Then, comparing the displacement and stress values calculated by the model and measured[10], when the stress at the measured point at the weld toe of the top plate was considered, the difference between the measured value and the modelling value is about 5%; for the stress at the measured point at the weld toe of the U-rib, the difference is less than 2%; the difference between the measured displacement and modelling value is less than 5%. Therefore, the finite element model can accurately analyse the stresses and displacements in the connection between the top plate of orthotropic steel bridge deck and the U-rib weld.

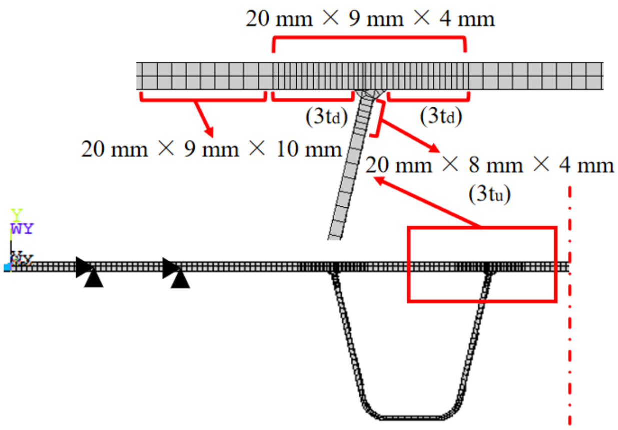

Figure 1. Half-Finite element model and part meshing

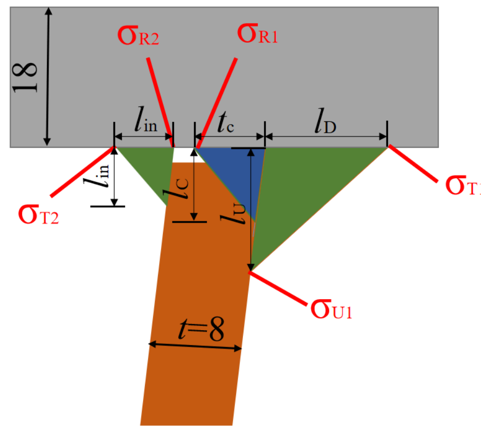

Figure 2. Welding seam construction diagram (mm)

3. Analysis of structural parameters

The structural parameters of the outer groove weld and the inner fillet weld including the outer groove weld penetration α_c, the ratio R of the two toes of the outer groove weld, the sizes l_C and l_{in} were analysed. Here, $\alpha_c = t_c/t\times100\%$, $R= l_D/l_U$. According to the test results in literature [10] and also considering the fact that fatigue cracks of conventional single-sided welds often appear at the top plate root and toe of the outer weld, the toe of the U-rib weld, and the top plate root and toe of the fillet weld, the stress amplitude of the outer groove weld at the top plate toe $\Delta\sigma_{T1}$, the stress amplitude of the outer groove weld at the toe of the U-rib weld $\Delta\sigma_{U1}$, and the stress amplitude of the outer groove weld at the root of the U-rib weld $\Delta\sigma_{R1}$, the stress amplitude $\Delta\sigma_{T2}$ at the toe of the top plate of the inner fillet weld and the stress amplitude $\Delta\sigma_{R2}$ at the root of the inner fillet weld, were all analysed.

Table 1. Effect of the groove penetration αc

α_c(%)	$\Delta\sigma_{T1}$ (MPa)	$\Delta\sigma_{U1}$ (MPa)	$\Delta\sigma_{R1}$ (MPa)	$\Delta\sigma_{T2}$ (MPa)	$\Delta\sigma_{R2}$ (MPa)	N ($\times10^4$)
0	127.90	41.24	60.86	107.72	53.35	303.47
10	128.25	44.62	59.90	108.17	54.03	\
20	128.30	44.51	58.12	108.31	52.58	\
30	128.35	44.45	56.65	108.47	51.48	\
40	128.41	44.41	55.50	108.53	50.84	303.02
50	128.45	42.47	54.30	108.60	50.42	302.90
60	128.50	44.38	51.11	108.67	51.11	\
70	128.54	44.39	50.05	108.74	51.06	302.62
80	128.67	44.50	56.51	108.57	56.52	302.57
90	128.65	44.48	51.76	108.81	51.76	302.34
100	128.43	44.60	\	109.80	\	302.45

Firstly, the dimensions of each weld configuration were determined based on the experimental model, i.e., lC = 6 mm, lin = 6 mm, lD=8 mm and lU =8 mm. The effect of penetration αc on the stress amplitudes mentioned above are reported in Table 1. Then, the outer groove weld penetration αc is selected to be 80%, and the influence of ratio R, size lC and lin on the aforementioned calculated stress amplitudes is analysed respectively. The calculated results are reported in Table 2.

Table 2. Calculation results

Model	Size (mm)					σ_{T1} (MPa)	σ_{U1} (MPa)	σ_{R1} (MPa)	σ_{T2} (MPa)	σ_{R2} (MPa)
	l_C	L_{in}	l_D	l_U	R					
M1	6	6	6	6	1	129.51	44.48	61.74	107.97	61.75
M2	6	6	6	8	0.75	127.99	44.11	57.73	108.13	57.74
M3	6	6	8	6	1.33	124.87	45.00	92.52	107.05	92.54
M4	6	6	8	8	1	128.67	44.50	56.51	108.57	56.52
M5	6	6	8	10	0.8	126.65	44.25	54.81	106.34	54.82
M6	6	6	10	8	1.25	123.33	43.14	53.45	104.37	53.46
M7	6	6	10	10	1	124.20	44.02	52.64	104.42	52.65
M8	4	6	8	8	1	128.63	44.49	52.09	108.65	52.10
M9	8	6	8	8	1	125.69	43.91	91.12	107.16	91.14
M10	6	0	8	8	1	127.16	46.69	114.60	\	\
M11	6	2	8	8	1	125.50	19.94	87.12	105.95	87.13
M12	6	4	8	8	1	126.10	26.90	65.93	106.22	65.94
M4	6	6	8	8	1	128.67	44.50	56.51	108.57	56.52
M13	6	8	8	8	1	126.98	43.95	49.70	106.32	49.71
M14	6	10	8	8	1	127.39	46.28	46.90	104.10	46.91

From Table 1: (1) The stress amplitude $\Delta\sigma_{T1}$ is the largest, followed by the stress amplitude $\Delta\sigma_{T2}$, and both are significantly larger than those at other weld toes and roots. (2) Changes in the degree of fusion penetration of the outer groove weld have insignificant effect on the stress amplitudes $\Delta\sigma_{T1}$ and $\Delta\sigma_{T2}$ as well as on the stress amplitude $\Delta\sigma_{U1}$; changes in the degree of fusion penetration have the most obvious effect on the stress amplitude $\Delta\sigma_{R1}$, followed by the effect on the root stress amplitude $\Delta\sigma_{R2}$; In general, as the increase of weld penetration, the stress amplitude of the weld root shows a decreasing trend, and the maximum decrease does not exceed 20%. Indicating that a significant increase in the groove weld penetration can improve the fatigue life of the model weld root. (3) When the weld penetration reaches 60% and above, there is a small (not more than 10%) sudden change in the weld root stress. (4) The weld root stress amplitude of the weld toe is relatively small when the weld penetration is 50%, which does not clearly show a favourable effect on the measured fatigue life.

From Table 2: (1)For the models M1-M7, as the size l_U increases, the changes in the stress amplitudes $\Delta\sigma_{T1}$, $\Delta\sigma_{T2}$, and $\Delta\sigma_{U1}$ are small; the changes of the stress amplitudes $\Delta\sigma_{R1}$, and $\Delta\sigma_{R2}$ are more pronounced; The calculated stress is greatly affected by the ratio *R*. When the weld toe ratio is about 1.0, the stress amplitude of the top plate weld toe is the largest, followed by the U rib weld toe. And the maximum stress amplitude of the weld root does not exceed 50% of the top plate weld toe stress amplitude in general; When the ratio *R* is larger, as exemplified by model M3, the stress amplitude of the weld root of the inner and outer weld seams is significantly increased. This elevation approaches the stress amplitude at the inner weld toe of the top plate, which significantly increases the risk of fatigue cracking of the root and the toe of the inner side weld of the U-ribs. (2) Comparing the results of models M1 and M3, M4 and M6, and M5 and M7, the stress amplitudes $\Delta\sigma_{T1}$, $\Delta\sigma_{T2}$, and $\Delta\sigma_{U1}$ show a small decreasing tendency with the increase of the l_D, and the stress amplitudes $\Delta\sigma_{R1}$ and $\Delta\sigma_{R2}$ decrease to some extent for the other two groups of models, except that the weld root stresses of M3 are significantly increased in comparison with M1. Analysing the results of the models M8, M9 and M4, with the increase of the size l_C, the stress amplitudes $\Delta\sigma_{T1}$, $\Delta\sigma_{T2}$ and $\Delta\sigma_{U1}$ changes insignificantly, and the stress amplitudes $\Delta\sigma_{R1}$ and $\Delta\sigma_{R2}$ increase slightly; When l_C increases to 8 mm equal to l_U, the root stress amplitudes $\Delta\sigma_{R1}$ and $\Delta\sigma_{R2}$ show a more obvious tendency to increase, and the root stress amplitude increase reaches 75%. Therefore, when $l_C \neq l_U$, the notch size has less influence on the stress state of the model; when $l_C = l_U$, the stress amplitude of the weld root increases significantly, which increases the risk of fatigue cracking of the weld root and toe of the inner side weld of the U-rib. (3) For the models M10-M14 and M4, the stress amplitudes $\Delta\sigma_{T1}$ and $\Delta\sigma_{T2}$ changes in significantly with the increase of the size lin; the stress amplitude $\Delta\sigma_{U1}$ firstly shows a significant decrease in the change, and $\Delta\sigma_{U1}$ shows a slight trendency to increase when lin increases to 4mm; the weld root stress amplitudes $\Delta\sigma_{R1}$ and $\Delta\sigma_{R1}$ decrease significantly with the increase of l_{in}.

4. Fatigue life analysis

The structural dimensions of each weld are determined based on literatures [8] and [10], i.e., l_C=6mm, and l_{in}=6mm. Influence of the groove weld penetration αc and the ratio R on the fatigue performance of the double-sided weld connection between the top plate and the U-rib was studied in this section combined with the master S-N curve fatigue evaluation method[11].

4.1 Influence of groove penetration α_c

Based on the previous analysis, the influence of the penetration α_c on the stress amplitude of both the toe and the root is relatively small. The stress amplitudes of the toes and roots are relatively small when α_c=50%, and in combination with penetration limitation of single-sided groove weld (generally 70% to 80%) specified in relative specifications, this section addresses the following penetration, i.e., α_c = 0%, 40%, 50%, 70%, 80%, 90%, and 100%, to analyse the effect. Fatigue life was assessed based on the master S-N curve method[11]. Firstly, the equivalent structural stresses were analysed for double-sided welds with different outer penetrations at the T1, T2 and R1 positions, and then the fatigue life was calculated when the statistical mode was the median value. The equivalent structural stress values and fatigue life assessment values N are also reported in Table 1.

From Table 1, it can be obtained that the penetration has little influence on the structural stresses and fatigue life *N* of the toe of the top plate and the root of the groove weld. Therefore, the influence of penetration α_c on the fatigue life is insignificant. It is consistent with the conclusion that the measured fatigue life of specimens with 0%, 50%, 80% and 100% melt permeability in the test study[10].

4.2 Influence of the ratio R

According to the above analysis, the ratio *R* has a greater effect on the stress amplitude. By comparing the calculation results of the models M2, M4, and M6 in Table 2, the stress amplitudes $\Delta\sigma_{R1}$ and $\Delta\sigma_{R2}$ decrease as the length l_D increases, while the stress amplitudes $\Delta\sigma_{T1}$, $\Delta\sigma_{T2}$, and $\Delta\sigma_{U1}$ first increase and then decrease. The stress amplitude $\Delta\sigma_{T1}$ at the top plate weld toe is larger than that of the other control points. Then, a model with a penetration of 80%, a notch size of 6mm, an inner fillet weld size of 6mm, and an outer groove weld U-rib weld toe length of 8mm was selected for further analysis. By adjusting the length l_D to change the ratio R, the stress amplitude $\Delta\sigma_{T1}$ at the top plate weld toe where fatigue cracks are most likely to occur was considered. Finally, based on the statistical model of the median master S-N curve method, the fatigue life was also evaluated. The calculated structural stress ΔS_{ST1} [11] and fatigue life assessment of the top plate weld toe are all listed in Table 3. In the table, $\delta_R=(\Delta S_{ST1,R}-\Delta S_{ST1,1})/\Delta S_{ST1,1}\times100\%$, $\delta_{NR}=(N_R-N_R=1)/N_R=1\times100\%$, which are the change percentage of the structural stress and fatigue life of the groove weld toe at different penetration depths compared to the corresponding values when the weld toe ratio is 1.0. Negative and positive values respectively indicate decrease and increase.

Table 3. Effect of outer groove weld

R	l_D (mm)	l_U (mm)	ΔS_{ST1} (MPa)	δ_R (%)	N ($\times10^4$)	δ_{NR} (%)
0.50	4	8	176.19	4.79	267.49	-13.63
0.75	6	8	167.26	-0.52	314.80	1.65
1.00	8	8	168.13	—	309.70	—
1.25	10	8	162.23	-3.51	346.37	11.84
1.50	12	8	204.65	21.72	167.41	-45.94

From Table 3, it can be obtained that: (1) with the ratio R increases, the structural stress ΔSST1 first decreasesed and then increased. Thus the fatigue life N is first increased and then decreased, and the change degree of fatigue life is larger than change percentage of the weld toe structural stress; (2) when the ratio R changes between 0.75 and 1.25, the structural stress of the top plate weld toe changes slowly, and the percentage δR is less than 5.0%; the change of the corresponding weld toe fatigue life is slightly larger, and the δNR is close to 10%, and the fatigue life of the weld is larger when the value of R is in this range; (3) compared with the corresponding structural stress and fatigue life of the model with R=1.0, when R is 0.5, the fatigue life decreases up to 13.63% although the structural stress increases by only 4.79%; when R is increased to 1.5, the structural stress and fatigue life change significantly, and the former increases by 21.72%, resulting in decrease of 45.94%. Therefore, the ratio R has a great influence on the fatigue life N. And the fatigue life of the groove weld is longer when the weld toes of the top plate and the U-rib are close.

5. Conclusion

(1) The stress amplitude ($\Delta\sigma_{T1}$) at the weld toe of the top plate of the orthotropic steel bridge deck with double-sided weld connection is larger compared to the stresses of other fatigue control points, so the double-sided weld connection model

is prone to cracking from the weld toe of the top plate.

(2) The weld penetration of the outer groove weld (α_c) has an insignificant effect on the stress amplitude, the modelled structural stress and fatigue life at the weld toes and roots of the double-sided rib-to-deck connection.

(3) The toe ratio R between the top plate and the U-rib of the groove weld has a large effect on the structural stress and fatigue life of the double-sided weld. When the ratio R increases, the top plate weld toe structural stress firstly reduces and then increases, fatigue life therefore firstly increases and then decreases. When the ratio approaches to 1.0, the stress distribution of the weld toe and root is more reasonable and the fatigue life is longer. Fatigue damage tends to occur in the weld toes of top plate.

(4) When the sizes l_C and l_U are significantly different, the effect of the size l_C on the structural stress and fatigue life of the double-sided weld is relatively smaller; when the size l_C is equals l_U, the weld root stress amplitude increases significantly, which increases the risk of fatigue cracking of the rib-to-deck connection.

(5) The inner fillet weld size of 4mm or 6mm is suggested for the inner fillet weld of the double-sided connection of the orthotropic steel bridge deck.

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