Fatigue performance and evaluation of horizontal gusset plate web gap details in steel bridges

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ABSTRACT: Full-scale I-shaped steel girder specimens were designed for distortion-induced fatigue mechanism tests of horizontal gusset plate web gaps in steel bridges. The fatigue cracks at stiffener-to-web welds usually initiated at the web gaps, and propagated along the weld towards the weld ends. The fatigue test results indicate that the stress ratio has a significant impact on the distortion-induced fatigue performance of web gaps. Under the action of high stress ratio, the fatigue crack growth rate and the stress reduction speed increases. And the fatigue strength of the stiffener-to-web welds decreases significantly with the increase of the stress ratio. The fatigue strength of stiffener-to-web welds corresponds to category C of AASHTO Specification and category 125 of Eurocode when the stress ratio is less than 0.3, while it belongs to the category E of AASHTO Specification and category 71 of Eurocode when the stress ratio is between 0.3 and 0.5.

1 INTRODUCTION

Steel structures are widely used in bridge engineering due to their low weight, high strength and fast construction. Due to the increasing traffic load, environmental effects, inadequate early design considerations, and manufacturing defects, steel bridges have some serious fatigue problems in the service stage. Fatigue cracking can cause different degrees of damage in many steel bridges, even collapse (Wang et al. (2015); Wang et al. (2016)).

The fatigue problems of steel bridges can be divided into load-induced fatigue and distortion-induced fatigue. In 2006, a study by American scholars showed that more than 90% of the fatigue cracks that occurred during the service stage of steel bridges were caused by out-of-plane distortion (Connor et al. (2006)). The out-of-plane distortion-induced fatigue of the web gaps in steel plate girder bridges is a typical distortion-induced fatigue problem. The horizontal gusset plate is often set on the main girder when the lateral bracings are connected with the main girders in the steel plate girder bridges. Considering the local stability of the web, the horizontal gusset plate is generally placed at the vertical stiffener, resulting in the intersection of the horizontal gusset plate and the vertical stiffener. In order to avoid fatigue problems caused by the intersection of multiple welds and facilitate processing and installation, the horizontal gusset plates are often cut to bypass the stiffener-to-web joint welds, resulting in the web gaps between the stiffeners and the horizontal gusset plates. Large out-of-plane distortions occur at the web gaps when the horizontal gusset plates are subjected to loads. This results in large out-of-plane distortion-induced fatigue stresses at the stiffener-to-web weld toes, leading to the initiation and propagation of fatigue cracks.

In recent years, scholars have carried out a lot of research on the distortion-induced fatigue problem ofweb gaps in steel bridges (Fraser et al. (2000); Zhao et al. (2007); Bowman et al.

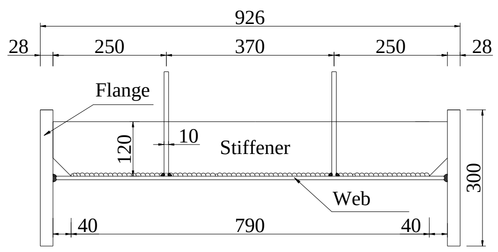
(2012); Hassel et al. (2013)). Fatigue cracks were found at top and bottom web gaps in both positive and negative bending regions, but the fatigue stress of negative bending region is larger than that of the positive bending region (Fisher et al. (1979)). Fraser et al. (2000) found that the cracks induced by the in-plane moment of the main beam and the out-of-plane distortion of the web are combined cracks of Mode I (open) and Mode III (shear) cracks. Zhao et al. (2007) analyzed the web gap fatigue crack induced by the out-of-plane distortion at the connection of the cross beam and the main beam. The results show that the fatigue stress induced by the out-of-plane distortion of the top web gap is higher than that of the bottom web gap. Bowman et al. (2012) used welded I-beam girder specimens to study the reinforcement methods for out-of-plane distortion cracking details, and evaluated the effectiveness of the various reinforcement methods. Hassel et al. (2013) established a large number of three-dimensional finite element models to analyze the effects of different parameters. And results show that stiffness and lateral brace shape have an important effect on web gap stress. Mahmoud et al. (2016) established the finite element model by the extended finite element method (XFEM) to analyze the fatigue mechanism of the out-of-plane distortion details of the web gaps in steel plate girder bridges based on the fracture mechanics theory, and accurately simulated distortion-induced fatigue crack propagation speed and direction. In Chang'an University, full-scale out-of-plane distortion fatigue tests of web gaps in steel bridges were carried out. The effects of web gap length, and web thickness on the out-of-plane distortion-induced stress of web gaps were studied. Additionally, the fatigue strengths of the out-of-plane distortion of the different web gap lengths were determined (Wei. (2014); Wei. (2016)). Wang et al. (2017) investigate fatigue crack initiation and propagation mechanism of typical details of steel bridge web gaps under cyclic loadings with different stress ratios. Test results showed that the details fatigue strength obviously decreases with the increase of the stress ratio.

Because of the effects of welding residual stress and installation stress, large residual tensile stress may exists at the steel bridge web gap details. During the out-of-plane distortion-induced fatigue cracking process, the larger the stress ratio is, the greater the average tensile stress is, the more the crack tip opens. Moreover, the fatigue crack is more prone to propagate when the stress range are same. Therefore, the effect of stress ratio on the fatigue behavior of steel bridge web gaps cannot be neglected. At present, there are some studies on the fatigue properties of out-of-plane distortion of steel bridge web gaps at home and abroad, but there is little research on the effect of stress ratio on the fatigue performance of web gap. In the past, the stress ratio of web gap details under cyclic loading is less than 0.10 (Fisher et al. (1990)), and the variation rule of out-of-plane distortion fatigue performance with stress ratio cannot be given. In this paper, the effect of stress ratio on the fatigue performance of web gap was studied by fatigue tests with stress ratio of 0.1 and 0.5.

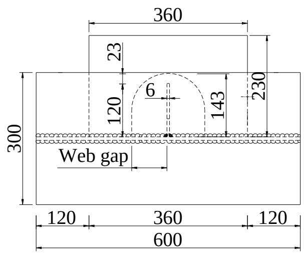
2 EXPRIMENTAL PROGRAM

2.1 Test specimen

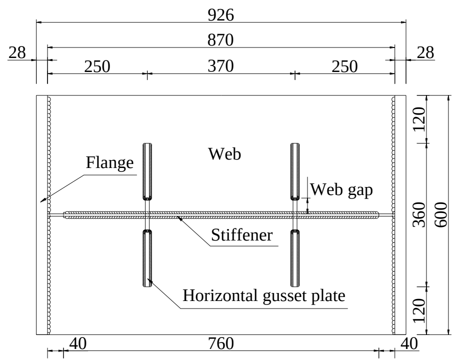
The purpose of the fatigue test is to study the effect of the stress ratio on the out-of-plane distortion fatigue performance of the steel bridge web gap. Full-scale fatigue tests were carried out to determine the fatigue strength of the web gaps of steel bridges. A steel beam section, whose height is 926mm and length is 600mm, was adopted as the specimen. The specimen consists of the flanges, the web, the vertical stiffener and the horizontal gusset plate, and is made of Q345qD steel. Two test specimen S-60-1 and S-60-2 were designed for full-scale fatigue tests, and the dimensions are shown in Figure 1. The stress ratio of specimen S-60-1 and S-60-2 are 0.1 and 0.5 respectively.



(a) Elevation drawing



(b) side elevation drawing



(c) Plan drawing

Figure 1: Full-scale specimens (Unit: mm).

2.2 *Test Setups*

Test loading device is shown in Figure 2. The top and bottom flanges of the specimen were fixed at both ends of the anchor device by 16 high-strength bolts, of which the diameter was 22mm. The actuator of the MTS hydraulic servo fatigue machine applies the load to the loading girder. The loading girder was connected to the vertical stiffener by the steel angles, which applied cyclic loads to the positions where the vertical stiffener and the steel angles were connected, resulting in out-of-plane distortion at the web gaps. Before the cyclic loading, the stress distribution and the out-of-plane distortion were obtained by static tests. The cyclic loading range is determined according to the stress ratio of the tests, then the fatigue cyclic loading was started afterwards. The test was ended when the fatigue crack propagated to affect the stability of the test loading device. Dynamic signal analysis system DH5922 produced by Jiangsu Donghua Test Technology Cooperation was used to collect dynamic data and to monitor the dynamic stress for real time.

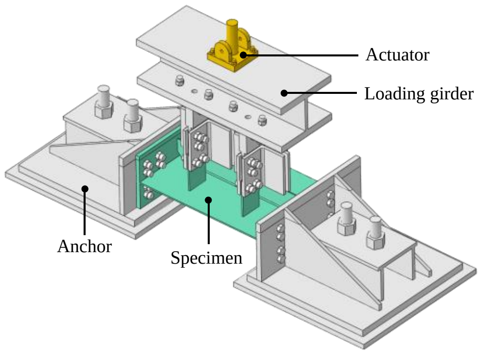
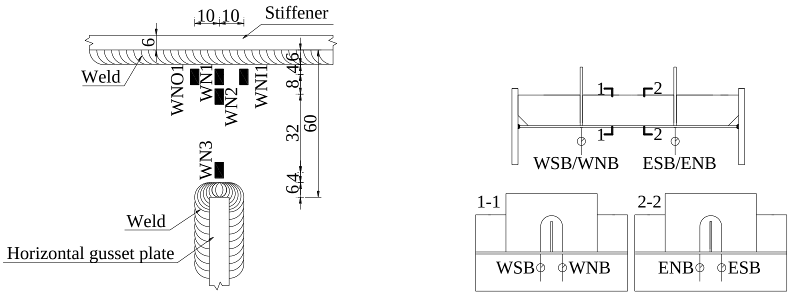


Figure 2: Loading equipment of fatigue tests.

2.3 Measuring Points Arrangement

The measuring points of the tests are arranged as shown in Figure 3. The finite element simulation analysis shows that the fatigue stresses of the stiffener-to-web welds and the horizontal gusset plate-to-web weld ends in web gaps were high. Therefore, during the process of fatigue testing, the fatigue stress of these fatigue-sensitive details should be monitored. Strain measuring points for northwest side web gap were arranged as shown in Figure 3 (a). In Figure 3, W, N and S represent the west, north and south sides of the specimen, respectively. Displacement measuring points were mainly arranged at the web gaps to measure the distortion of the web gaps, as shown in Figure 3 (b), where WSB, WNB, ENB and WSB are the out-of-plane distortion measuring points.



(a) Stress measuring points (b) Out-of-plane distortion measuring points

Figure 3: Measuring points of fatigue tests.

3 FATIGUE TEST RESULTS AND ANALYSIS

3.1 Fatigue test results

During the process of fatigue tests, the dynamic stresses of the fatigue sensitive parts were monitored. Static tests were carried out every 100,000 cycles, and the stresses of measuring points was adopted by strain gauges with TDS602 data acquisition system, to determine the stress distribution of the web gap and the variation of out-of-plane distortion with the increasing of the number of cycles. When the maximum loading was reached, the initiation and propagation of fatigue cracks were observed by magnifying glass. At the end of the test, the out-of-plane distortion fatigue cracks were observed at the web gaps of the specimens. The full-scale fatigue test results show that the fatigue cracks caused by the out-of-plane distortion generally initiated from the intersection of the stiffener-to-web weld toes and the horizontal gusset at the web projection line, and propagated along the stiffener-to-web welds towards two ends. The representative crack is shown in Figure 4.

Figure 4: Typical fatigue cracks at stiffener-to-web weld toes.

The measured stress ratios at the stiffener-to-web weld toes of specimen S-60-1 and S-60-2 were 0.11 and 0.47, respectively. The total number of cycles of the test specimen S-60-1 is 1,600,000, and the cyclic load is -5~-45 kN. The total number of cycles of the test specimen S-60-2 is 1,400,000, and the cyclic load is -37~-77 kN. In the process of cyclic loading, several strain gauges of the specimen were invalidated. Therefore, the fatigue stress analysis was carried out, using the validated strain gauges. The measured parameters of the test specimens were shown in Table 1.

Table 1. Test results of specimens

Specimen	Load Range (kN)	Measuring Point	Stress Range (MPa)	Stress Ratio (MPa)	Number of cycles when cracks were detected ($\times10^6$)	Initial Out-of-plane Distortion (mm)
S-60-1	40	WN	167.9	0.11	Not cracked	0.51
		WS	181.5	0.11	0.62	0.55
		EN	135.3	0.11	Not cracked	0.31
		ES	161.3	0.11	1.35	0.37
S-60-2	40	WN	189.5	0.47	0.5	0.46
		WS	171.2	0.46	0.5	0.52
		EN	176.5	0.48	0.6	0.29
		ES	167.1	0.47	0.4	0.33

3.2 Fatigue stress analysis

The stress curves of the measured points of the two specimens with the closest stress amplitude were selected for comparison, as shown in Figure 5. The stress measurement point WS1 side of specimen S-60-1 (stress amplitude was 181.5MPa, stress ratio was 0.11)and the stress measurement point EN1 of spceimen S-60-2 (stress amplitude was 176.5MPa, stress ratio was 0.48) were selected. According to Figure 5, the stress decreasing speed of the stiffener-to-web weld toes accelerated with the increase of the stress ratio.

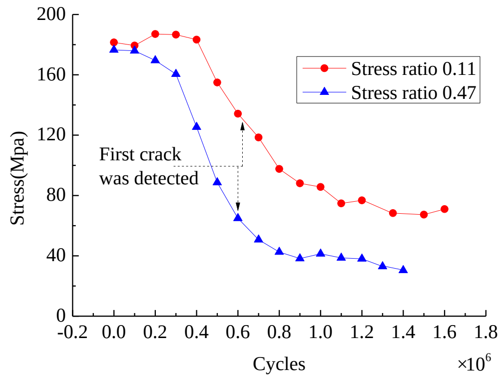
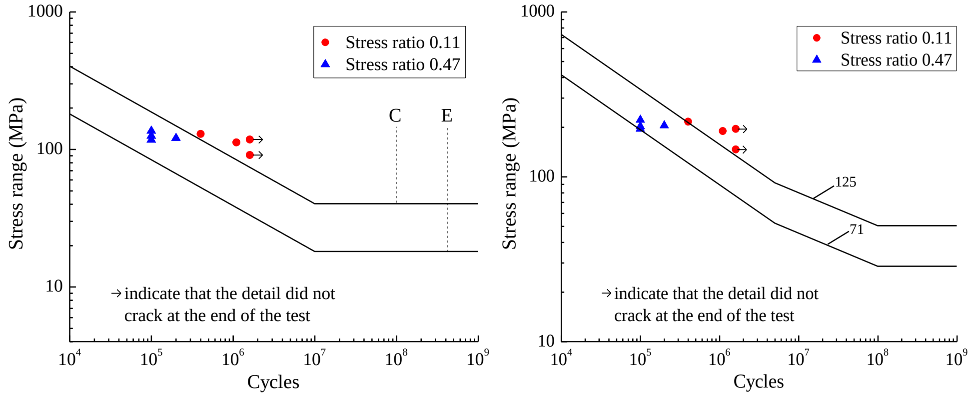


Figure 5: Comparison of stiffener- to-web weld toe stress curves of specimens.

4 FATIGUE STRENGTH OF WEB GAP DETAIL

Under cyclic loading, the stresses of the corresponding measuring points changed significantly when the fatigue cracks propagated. In the process of the test, the stress measuring points were applied at the critical details at the web gaps and the stresses of the stiffener-to-web weld toes were measured. The 60mm web gap specimens were tested under cyclic loading with different stress ratios. The stress range S and the number of loading cycles N of the measured stresses were shown in Figure 6 evaluated with the S-N curves provided by the AASHTO specification and the Eurocode specification (AASHTO 2012; European Committee for Standardization 2005). The stress range of the detail was measured before the fatigue tests, and the number of loading cycles was corresponding to the cycles when the crack was observed.



(a) Results of fatigue strengths in AASHTO (b) Results of fatigue strengths in Eurocode

Figure 6: Fatigue strengths of stiffener-to-web weld toes under different stress ratios.

As for the 60mm web gap specimens, the fatigue strength of the stiffener-to-web weld toes decreased significantly with the increase of the stress ratio. When the stress ratio is less than 0.3, the fatigue strength of stiffener-to-web weld toe details belongs to the category C of AASHTO specification and the category 125 of Eurocode. When the stress ratio is between 0.3 and 0.5, the fatigue strength of such details belongs to the category E of AASHTO specification and the category 71 of Eurocode. It can be seen that the detailed fatigue strength decreases significantly with the increase of the stress ratio.

5 CONCLUSIONS

(1) The full-scale fatigue test results show that the fatigue cracks caused by the out-of-plane distortion generally initiated from the intersection of the stiffener-to-web weld toes and the horizontal gusset at the web projection line, and propagated along the stiffener-to-web welds towards two ends.

(2) The stress ratio has a significant effect on the out-of-plane distortion-induced fatigue performance of the web gaps in steel bridges. The decreasing speed of the fatigue stress of this detail grows with the increase of the stress ratio. The influence of stress ratio should be considered in the distortion-induced fatigue design of web gaps in steel bridges.

(3) With the increase of the stress ratio, the fatigue strength of the stiffener-to-web weld toe reduced. The fatigue strength of stiffener-to-web weld toe details belongs to the category C of AASHTO Specification and the category 125 of Eurocode when the stress ratio is less than 0.3, while it belongs to the category E of AASHTO Specification and the category 71 of Eurocode when the stress ratio is greater than 0.3 and smaller than 0.5.

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7 REFERENCES

AASHTO. 2012. *AASHTO LRFD bridge design specifications*, *5th Edition*. Washington DC.

Bowman, MD, Fu, GK, Zhou, YE. 2012. *Fatigue evaluation of steel bridges, Transportation Research Board*. Washington DC.

Connor, R. J., and J. Fisher, 2006, Identifying effective and ineffective retrofits for distortion fatigue cracking in steel bridges using field instrumentation. *Journal of Bridge Engineering*, 11(6): 745-752.

European Committee for Standardization. 2005. E*urocode 3: Design of steel structures-Part 1-9: Fatigue*. EN 1993-1-9, Brussels, Belgium.

Fisher, J. W., T. Fisher, and C. Kostem, 1979, Displacement induced fatigue cracks. *Engineering Structures*, 1(5): 252-257.

Fisher, JW, Jin, J, Wagner, DC. 1990. *Distortion-induced fatigue cracking in steel bridges, Transportation Research Board*. Washington DC.

Fraser, R. E. K., G. Grondin, and G. Kulak, 2000, Behavior of distortion-induced fatigue cracks in bridge girders, University of Alberta, Edmonton.

Hassel, H. L., C. Bennett, and A. Matamoros, 2013, Parametric analysis of cross-frame layout on distortion-induced fatigue in skewed steel bridges. *Journal of Bridge Engineering*, 18(7): 601-611.

Mahmoud, H. N., P. Miller, 2016, Distortion-Induced Fatigue Crack Growth. *Journal of Bridge Engineering*, 21(2): 04015041.

Wang, C. S., L. Duan, and M. Zhai, 2017, Steel bridge long-term performance research technology framework and research progress. *Advances in Structural Engineering,* 20(1): 1-18.

Wang, C. S., M. Zhai., and L. Duan, 2015, Fatigue Service Life Evaluation of Existing Steel and Concrete Bridges. *Advanced Steel Construction*, 11(3): 305-32.

Wang, C. S., Y. Wang, B. Cui,T. Qu, and Y. Sun, 2017, Experimental Research on the Effect of Stress Ratio on Distortion-induced Fatigue Performance of Steel Bridges. *China Journal of Highway and Transport*, 30(3): 72-81.

Wei, M. C., 2014, The research of the fatigue mechanism and retrofitting methods for distortion-induced fatigue in steel bridges, Chang'an University, Xi'an.

Wei, X. Q., 2016, Numerical fracture mechanics analysis of distortion induced fatigue crack propagation in steel bridges, Chang'an University, Xi'an.

Zhao, Y., and W. Roddis, 2007, Fatigue behavior and retrofit investigation of distortion-induced web gap cracking. *Journal of Bridge Engineering*, 12(6): 737-745.