

Experimental research on durability of bonding reinforcement method for distortion-induced fatigue in steel bridges

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ABSTRACT: In order to ensure the service safety, rationally prolong service life and maintenance interval, bonding steel angles reinforcement methodology was used for distortion-induced fatigue cracks at web gaps in steel bridges, featuring introducing no or less damage to the original structure. Full-scale fatigue tests were performed to evaluate the effectiveness and durability of bonding reinforcement. Test specimens were loaded to produce distortion-induced fatigue cracks, and then the girders were strengthened by the bonding reinforcement method. After placed in the laboratory for about three and a half years, the reinforced specimens continued to be subjected to cyclic loads. Test results indicated that the out-of-plane distortion and the stresses at the critical fatigue details sharply decreased, and fatigue cracks did not propagate after bonding strengthening. Therefore, bonding steel angle reinforcement technique has significant potential for controlling distortion-induced fatigue cracks at web gap regions in steel girder bridges effectively, and has good durability.

1 INTRODUCTION

Main girders of multi-girder steel bridges are connected by transverse bracings, which transfer the vehicle load from one main girder to adjacent ones. In the welding connections, vertical stiffeners of main girder are connected to cross braces or cross beams, thus the different main girders can be effectively connected. In order to avoid failures of fatigue details at vertical stiffener and tension flange welds, vertical stiffeners near tension flanges of the girders are cut short usually (Khalil et al. (1998)). Therefore, several-centimeter web gaps are left between the vertical stiffener and the tension flange. The displacements of adjacent main girders are different under the vehicle loads, causing the out-of-plane deformation at web gap regions (Figure 1). Fatigue cracking has serious influence on the service safety and life of steel bridges, and approximately 90% of the fatigue cracks were induced by out-of-plane distortion and secondary stresses (Connor et al. (2006)). And the fatigue damage of the web gaps in steel bridges is a typical fatigue problem induced by out-of-plane distortion.

Many studies have been carried out to investigate the reinforcement performance of the out-of-plane distortion-induced fatigue details at web gaps by field tests, finite element analysis, and experimental studies. Fisher et al. (1990) conducted fatigue tests and found that increasing the web gap length or connecting vertical stiffener with tensile flange can effectively reduce the stress concentration at web gaps. In 2000, the fatigue tests results carried out by Bowman (2000) indicated that bolting T-type steel angles could effectively prevent the occurrence of new fatigue cracks. Connecting a plate between the stiffener and the top flange, and loosening of bolts connecting the cross-bracing to the stiffener proved to be effective in reducing distortion-induced strains and stresses in the web gap regions (Shifferaw et al. (2013)). Andrea et al.

(2001) proposed increasing the thickness of web gaps by bolting a steel angle to the flange and the web, and this method could increase the stiffness of web gaps and effectively reduced deformation and stress in web gap area. Bolting angles with plate and stop-holes reinforcement methods were all effective in preventing the distortion of the web gap region, which drastically reduced the stresses at the critical points. Slot repair was also used to repair the fatigue details, but results showed that this method had introduced higher magnitude fatigue stress in web gaps, which was believed to be the cause of crack re-initiation and propagation found in many repaired details (Zhao et al. 2007). Grondin et al. (2010) found that when the crack length was less than 150mm, the fatigue crack can be prevented by drilling stop-holes at the crack tips and connecting the tension flange and the stiffener by bolting steel angles. In 2013, Hartman et al. (2013) of Kansas University proposed the reinforcement method of connecting stiffeners and webs through bolted steel angles, which can avoid introducing damage to the flanges of the main girders. Experimental research performed by Wang et al. (2018) on cold reinforcement methods (drilling stop-holes, bonding steel angles, etc.) on distortion-induced fatigue cracking at web gap area indicated that drilling stop-holes failed to stop the distortion-induced fatigue cracking effectively. Nevertheless, the reinforcement method using the steel angles to connect the flanges and the stiffeners can effectively reduce the out-of-plane distortion amplitude, thereby reducing the stress range at stiffener-to-web weld toes at the web gaps, and preventing the initiation of new fatigue cracks and the propagation of existing fatigue cracks.

This paper carried out full-scale fatigue tests to investigate the effectiveness and durability of the bonding steel angle reinforcement. The bonding reinforcement technique does not introduce secondary stress into the fatigue sensitive details, and the process of the reinforcement has no negative influence of the fatigue sensitive details of web gaps. Test specimens were loaded to produce distortion-induced fatigue cracks, and then the girders were strengthened by the bonding reinforcement method. The fatigue tests were conducted after reinforcement, then specimens were placed in the laboratory environment for three and a half years, including the effects of temperature, humidity, and aging of the adhesive materials on the fatigue properties of the cold-reinforced joints. This is to simulate the reinforcement positions at the middle main girders of the I-girder steel plate bridges, where hard to be directly affected by rain, snow, and ultraviolet rays. The reinforced specimens continued to be subjected to cyclic loads, in order to analyze the durability degradation, aging of the adhesive layer, and the effect of temperature changes in the four seasons on the performance of the cold-reinforced joints.

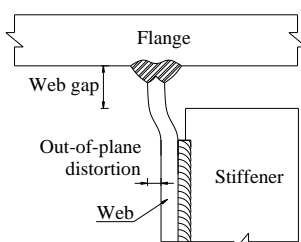


Figure 1. Out-of-plane distortion at web gaps.

2 FATIGUE TEST PROGRAM

2.1 Test program

The full-scale specimens were I-shaped steel girders, consisting of flange, web and stiffener. The specimen was fabricated by the steel grade of Q345 with normal yield stress of

345MPa. The dimensions of the test specimens were determined according to the actual fatigue performance of web gaps effectively. Finite element analysis results showed that the length of the specimen had negligible effect on out-of-plane distortions and stresses of web gaps (Wang & Cheng 2010). Thus, the length of the specimen was adopted as 600mm, considering fixing and loading condition of fatigue tests. Figure 2 shows the dimensions of the specimen as well as the strain and displacement measuring points. The dimensions of flange, web and vertical stiffener are 600mm × 300mm × 24mm, 870mm × 600mm × 8mm, and 790mm × 120mm × 6mm respectively. Strain gauges were arranged at web gap details where the stresses were high according to finite element analysis results.

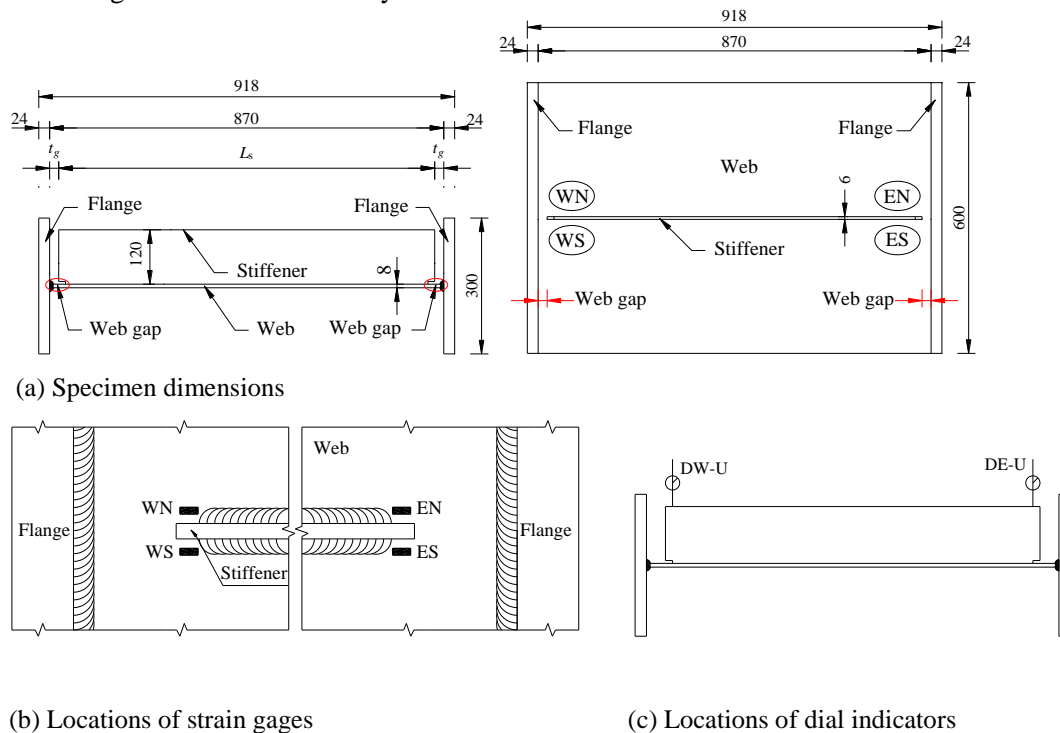


Figure 2. Test specimen (Unit: mm).

Figure 3 shows the test setups. A 100kN capacity MTS servo hydraulic actuator is adopted to apply cyclic load. Cyclic loads were applied by the hydraulic actuator to the stiffener, simulating the actual acting lateral forces on the stiffener in steel girder bridge through the loading beam (Wang et al. (2014)). And the flanges of the specimens were bolted to the anchors. Consequently, the cyclic loads applied on the connection of vertical stiffener and the steel angles, causing the out-of-plane distortion in web gaps.

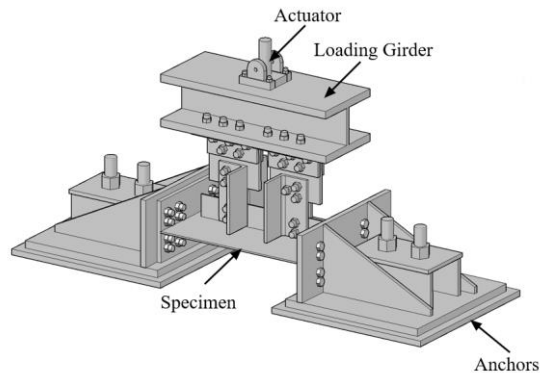


Figure 3. Test setups of fatigue tests.

The loading range of the specimen was determined to control the initial out-of-plane distortion between 0.2mm and 0.4mm. The crack length, out-of-plane distortion, and stress levels were recorded every 100,000 cycles in static tests. During the fatigue tests, the out-of-plane distortions and stresses in web gaps of the test specimen were monitored with a dynamic data acquisition system. Fatigue tests end when the propagation of fatigue cracks affected the stability of test setups.

2.2 Bonding steel angle reinforcement procedure

Adhesive has been widely used in other areas, and also have been studied for using in civil engineering. The structural adhesive used in retrofitting is Araldite AV/HV 111 Normal A/B. Firstly, the area where the adhesive was gelatinized should be polished, as shown in the Fig. 7(a). Then, the adhesives were mixed (Figure 7(b)) before they are gelatinized on the steel angles and the specimens. Finally, the steel angles were bonded to the stiffeners and the flanges of specimens. Fatigue tests continued after the mixed adhesive was fully solidified.



(a) Polish the steel angles

(b) Prepare the adhesive

(c) Finish retrofitting

Figure 4. Flowchart of reinforcement.

3 FATIGUE TEST RESULTS

Fatigue tests of two full-scale specimens were carried out before and after bonding steel angles. Before the reinforcement, fatigue tests were carried out on the specimens for fatigue pre-cracking. After the fatigue cracks initiated and propagated, the steel angles were bonded at web gaps to prevent the propagation of fatigue cracks. Next, the fatigue tests continued to verify the

effectiveness of such reinforcement method. For the purpose of investigating the durability of bonding strengthening, the specimens were placed in the laboratory for three and a half years, and then the specimens were applied with cyclic loads again. Table 1 shows the number of cycles and the cyclic loading range before and after the reinforcement of two specimens. In Table 1, WN, WS, EN, ES represent for the stiffener-to-web weld toe fatigue details of northwest, southwest, northeast, and southeast side respectively, as shown in Figure 2 (a).

At the end of the test before the reinforcement of the specimen S-40-1, fatigue cracks appeared on the northwest side (WN side) and the southwest side (WS side) stiffener-to-web weld toes, and the crack lengths were 13mm and 18mm, respectively. Although the fatigue crack was also found on the southeast side (ES side), which was only 2 mm. The west side web gap was reinforced with an equilateral steel angle of size 140 mm × 140 mm × 14 mm (side width × side width × side thickness). After the reinforced specimen was placed for three and a half years, it was first loaded with a load larger than the previous load range (10kN~45kN) for 2 million times. In order to speed up the test process, load range was adjusted as 10kN~55kN for 3 million cycles.

As for specimen S-20-1, fatigue cracks were observed at the northeast side (EN side) and the southeast side (ES side) stiffener-web weld toes before the reinforcement, and the crack lengths were 22mm and 20mm respectively. The east side web gap was strengthened with equilateral angle steel, whose dimensions are the same with that for specimen S-40-1. After placed in the laboratory for about three and a half years, the reinforced specimen continued to be subjected to cyclic loads. The specimen was first loaded with the previous load range (14kN~42kN) for 2.5 million cycles, then the load range was increased to be 14kN~52kN for 1.3 million cycles.

Table 1. Test results of specimens

Specimen	Web gap length (mm)	Loading range before reinforcement (kN)	Number of cycles before reinforcement ($\times 10^6$)	Crack length (mm)/ WN, WS, EN, ES	Loading range after reinforcement (kN)	Number of cycles after reinforcement ($\times 10^6$)	Loading range after placed in lab for three and a half years (kN)	Number of cycles after placed in lab for three and a half years ($\times 10^6$)
S-40-1	40	10-35	1.6	13, 18, 0, 2	10-35	3.4	10-45/10-55	2.0/3.0
S-20-1	20	14-42	1.26	0, 0, 22, 20	14-42	3.0	14-42/14-52	2.5/1.3

After the reinforcement, the existing fatigue cracks at the web gap stopped propagating, and no new crack was observed at the reinforcement steel angle and the web gap region. It can be seen that bonding angle steels is an effective reinforcement method for distortion-induced fatigue cracking at web gap regions. Moreover, there was no new fatigue crack and no existing fatigue crack grew after three and a half years, indicating that the performance of adhesive layer was acceptable and such strengthening method possessed good durability.

4 OUT-OF-PLANE DISTORTION ANALYSIS

During the process of the fatigue tests, the dial indicators DW-U and DE-U shown in Figure 2 monitored the out-of-plane distortion range at the web gap region. Figure 5 shows the specific out-of-plane distortion curves before and after the reinforcement of the two specimens.

Before and after the reinforcement of the specimen, the change of out-of-plane distortion range at the web gaps was recorded in Table 2 in detail. In the Table 2, the out-of-plane distortion ① is measured in the static test before cyclic loading, when the number of loading cycle is 0. The out-of-plane distortion ② is measured in the static test after fatigue pre-cracking process and before the reinforcement. The out-of-plane distortion ③ and ④ are measured in the static tests after reinforcement before the cyclic loading and for the last time at the end of the tests, respectively. After the specimen was placed in the laboratory for three and a half years, the out-of-plane distortion ⑤ and ⑥ are measured in the static tests before the cyclic loading and for the last time at the end of the tests, respectively.

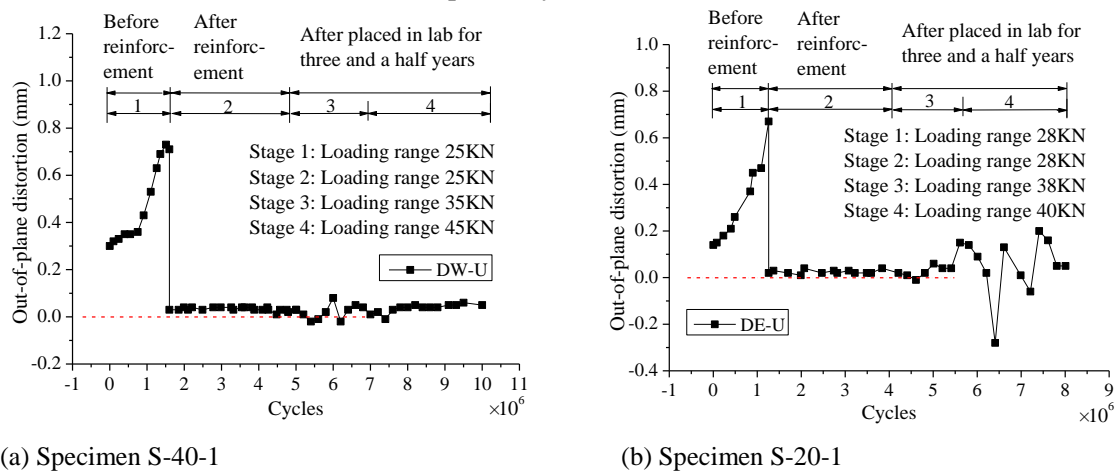


Figure 5. Out-of-plane distortion-number of cycles.

Table 2. Comparing of out-of-plane distortion

Specimen	Out-of-plane distortion (mm)						Comparison	
	①	②	③	④	⑤	⑥	③/②	⑤/②
S-40-1	0.30	0.71	0.03	0.03	0.03	0.05	4.2%	4.2%
S-20-1	0.14	0.67	0.02	0.02	0.02	0.05	3.0%	3.0%

According to Figure 6 and Table 2, the out-of-plane distortion of the web gap after the reinforcement decreased to 3.0%~4.2% of that before the reinforcement. Moreover, bonding steel angle reinforcement can control the out-of-plane deformation of the web gap to a lower level. The reduction of the out-of-plane distortion range indicated that this reinforcement method effectively improved the stiffness and the fatigue performance of the web gap. After three and a half years, the out-of-plane distortion of the web gaps remained as 3.0%~4.2% of that before the reinforcement, proving that bonding strengthening method features good durability.

5 STRESS ANALYSIS

The stresses at the stiffener-to-web weld toes at the web gap regions were measured during the fatigue tests before and after the reinforcement, and could then be used to evaluate the fatigue strength of such fatigue details. Figure 6 shows the stress measurements of the stiffener-to-web weld toes for the specimens.

The measured stresses at the end of the stiffener-to-web weld toes before and after the reinforcement indicated that the bonding steel angle reinforcement decreased the stresses of the stiffener-to-web weld toes to a large degree. After the reinforcement, the stresses of the stiffener-to-web weld toes hardly changed, indicating that there was no fatigue damage accumulated at the web gap after the reinforcement.

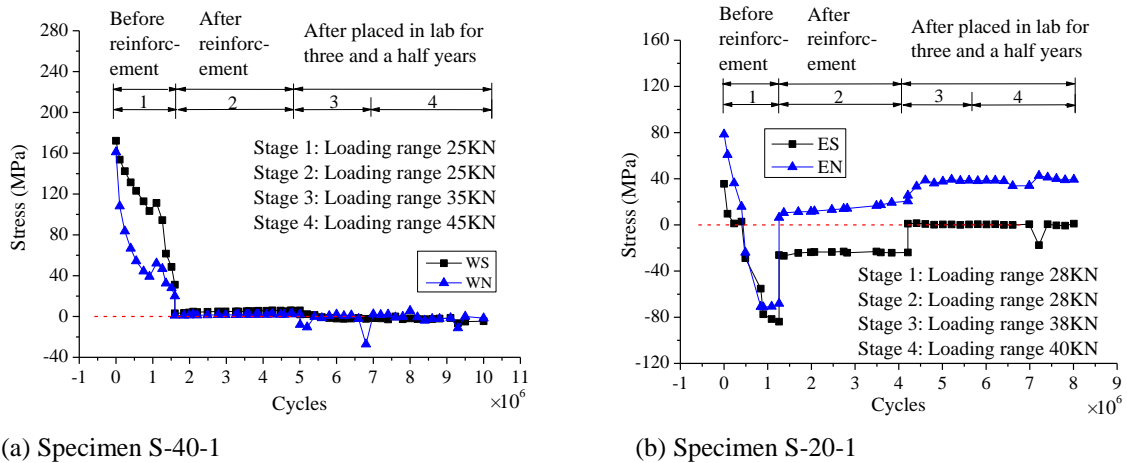


Figure 6. Stresses of stiffener-to-web weld toes.

Before and after the reinforcement of the specimen, the stress ranges of the stiffener-to-web weld toes were recorded in Table 3 in detail. The stress range ①, ②, ③, ④, ⑤, and ⑥ in the Table 3 are recorded at the same cycles with out-of-plane distortion ①, ②, ③, ④, ⑤, and ⑥ in the Table 2, respectively.

Table 3. Comparing of stresses of stiffener-to-web weld toes

Specimen	Measuring points	Stress range (MPa)						Comparison	
		①	②	③	④	⑤	⑥	③/②	⑤/②
S-40-1	WS	172.2	31.1	3.1	6.0	2.1	-4.6	9.9%	6.8%
	WN	161.1	20.0	1.0	2.3	-8	-1.648	5.0%	-40%
S-20-1	ES	32.6	-83.8	-26.2	-23.9	1.03	1.03	31.3%	-1.2%
	EN	78.5	-68.2	6.4	20.6	25.5	39.3	-9.4%	-37.4%

According to Table 3, the stress range of the web gap after the reinforcement decreased to 5.0% ~ 31.3% of that before the reinforcement. After the reinforcement, the stresses of the stiffener-to-web weld toes reduced below 30MPa after reinforcement. Therefore, the bonding steel angle reinforcement significantly improved the stiffness of the web gap region, reduced the stresses of the fatigue details. After three and a half years, the stresses of the stiffener-to-web weld toes were below 40MPa, showing that the durability of bonding steel angle reinforcement method was decent.

6 CONCLUSIONS

Full-scale fatigue tests were carried out to investigate the availability, effectiveness and durability of the bonding steel angle reinforcement. Based on the experimental results, the following conclusions can be drawn:

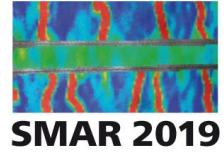
- (1) Bonding steel angle reinforcement improves the stiffness of the web gap region. After the reinforcement, the out-of-plane distortion at the web gap region was reduced to 3.0%~4.2%, and the stresses of the stiffener-to-web weld toes decreased below 30 MPa. After three and a half years, the out-of-plane distortion remained as 3.0%~4.2%, and the stresses were below 40 MPa.
- (2) After the web gap region was reinforced by the bonding steel angles, the existing fatigue cracks at the web gap stopped propagating and there was no new crack initiating at the steel angle and the web gap, and the strengthened side was stable during the fatigue tests. After three and a half years, no new crack was observed and existing cracks did not propagate, and the reinforced side was still stable.
- (3) Bonding steel angles is an effective reinforcement method and has good durability to strengthen fatigue cracking at web gaps. Moreover, such reinforcement form does not need to remove the concrete deck plate, and introduce little damage to the original structure and no secondary stress into the fatigue details in the web gap regions. Furthermore, the reinforcement procedure has no negative influence on the fatigue sensitive details in the web gap region.

7 ACKNOWLEDGEMENTS

The authors acknowledge the financial support provided by National Natural Science Foundation of China (Grant 51578073), the Special Fund for Basic Scientific Research of Central Colleges of the P.R. China, Chang'an University (Grants 310821153501), China National "Ten-Thousand People Program" Technology Innovation Leading Talents Support Project (W03020659).

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