Invited Paper

DISTORTION-INDUCED FATIGUE CRACKING AT WEB-GAP OF WELDED I-BEAMS

Hung The Dinh,[1] Akhrawat Lenwari,[2] Teerapong Senjuntichai,[3*] and Toshiro Hayashikawa[4]

[1] Department of Civil Engineering, Faculty of Engineering,
Chulalongkorn University, Bangkok, Thailand, e-mail: dinhthehung13@hcmut.edu.vn

[2] Department of Civil Engineering, Faculty of Engineering,
Chulalongkorn University, Bangkok, Thailand, e-mail: Akhrawat.L@chula.ac.th

[3] Department of Civil Engineering, Faculty of Engineering,
Chulalongkorn University, Bangkok, Thailand, e-mail: Teerapong.S@eng.chula.ac.th

[4] Graduate School of Engineering, Hokkaido University, Hokkaido Japan, e-mail:
toshiroh@eng.hokudai.ac.jp

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Abstract

Distortion-induced fatigue cracking has occurred in many types of steel bridge structures, especially welded structures where high local stresses exist. This research experimentally investigates the fatigue cracking behaviors around the web gap of welded I-beam. A total of nine specimens in three series of experiments were tested under constant cyclic loading to observe the cracking behaviors that include crack initiation, crack propagation, and final failure. The test results show that the crack initiates along the weld toe and grows upward to the lower stress field with lower strain energy, whereas the second crack occurs inside the "weak zone" depending on the critical stress or spot available in the area. This second crack is critical as it leads to the beam failure.

Keywords: Constant amplitude cyclic loading, Crack propagation, Crack surface, Distortion-induced fatigue cracking, Fracture failure, Web-gap

Introduction

Distortion-induced fatigue cracking is commonly found in I-beams with web-gap of steel bridges. This is the main reason for failures in a lot of steel bridges having web-gap left close to top or bottom flange. Beginning with the effort to prevent failures occurred in steel bridges originating from welds between connection stiffeners and girder tension flanges, common practice used to provide no positive attachment between connection stiffeners and girder flanges. Lack of connection creates a weak web gap region susceptible to out-of-plane distortions and fatigue.

Unlike load-induced fatigue, the out-of-plane distortion-induced stresses are not quantified in the AASHTO design code. Unless an appropriate finite element analysis or field testing is conducted, secondary stresses would not be determinable because the connection at the stiffener to girder flange and web intersection is under complex structural interactions, and the local geometry and relative stiffness of this detail are varied in each bridge. Previous experimental studies have been conducted to investigate the fatigue behavior and repair performance of the connection details subjected to out-of-plane distortion. Laboratory data by Fisher et al. [1] shows that un-stiffened web gaps can have fatigue resistance equivalent to an AASHTO Category C detail. All field tests performed by Koob et al. [2], Fisher et al. [3], and Stallings et al. [4] reveal that the web gap stresses are higher than the fatigue limit for out-of-plane displacements for only about a tenth of a millimeter. Various repair strategies were also studied and summarized by Zhao and

Roddis [5]. Three most commonly used retrofit approaches are: (1) drilling stop holes at the crack ends; (2) attaching the connection stiffener to girder flange; and (3) removing part of the connection stiffener to reduce the abrupt stiffness change at the web gap. Although AASHTO LRFD Bridge Design Specifications[6] require positive attachment between transverse stiffeners and girder flanges, the web gap with fixed length relative to girder thickness is usually recommended by the designers.

Previous studies concentrated on stress analysis at the web-gap under truck loading as well as retrofit methods. Experiments were also performed on full scale testing with different criteria on beam failure, e.g. using fixed critical deflection or fixed value of crack length. However, the failure due to distortion-induced fatigue crack at the web-gap is still not fully understood. This research investigates the behavior of the distortion-induced fatigue crack at the web-gap of welded I-beams under constant amplitude cyclic loading. The experimental program was carried out to observe the initial cracks, crack paths, and beam failure. The data is recorded and then analyzed to understand the behavior of distortion-induced fatigue crack. The results from this experimental study are useful to prevent cracks in I-beams of steel bridges, which could extend the fatigue life of steel bridges.

Experimental Program

The purpose of the experimental program is to investigate the behavior of distortion-induced fatigue cracks of web-gap in I-beams of steel bridge. In bridge structures, the stiffener is attached to web of the I-beam leaving web-gap close to the top or bottom flange. Due to different deflections between two adjacent girders, the distortion-induced effect occurs, which twists girders at the connection. In addition, the web-gap is also subjected to bending moment. The combination of relative deflection and bending moment results in the fatigue cracking at the web-gap. The test program was set up to simulate the combination of in-plane and out-of-plane moment effects on the web-gap.

Figure 1 shows the test setup, which includes a support beam on a steel platform with a thickness of 20 cm. The pin supports were laid on the support beam and connected by bolts. The distance between two pin supports is adjustable. A supporter placing on the steel plate with fix distance to the testing beam was connected to stiffeners by four bolts. The supporter was located at the half distance between the two girders, and supplied the support point to the stiffener. Because the support beam and the supporter were both fixed to steel plate, the relative deflection between the testing beam and the support beam would be identical to the deflection between the testing beam and the supporter.

The testing machine can supply the cyclic load with combination of top and bottom actuators. Top actuator was fixed during the tests, and it was called the fix actuator. Bottom actuator supplied the cyclic load with frequency control, and it was called the cyclic actuator. The machine can supply loading control or displacement control. In this test, the loading control was used for all specimens.

The operation of the system can be described as follows. When the actuator moves up and down, the system that includes steel plate, support beam, supporter, pin support and testing beam will have the same displacement. The top actuator is fixed and connected to the middle part of testing beam to act as two loading points on the specimen. Testing system will produce the deflection between the specimen and the supporter to simulate the relative deflection between two girders in steel bridges. The constant amplitude cyclic loading parameters for three series of experiments are given in Table 1.

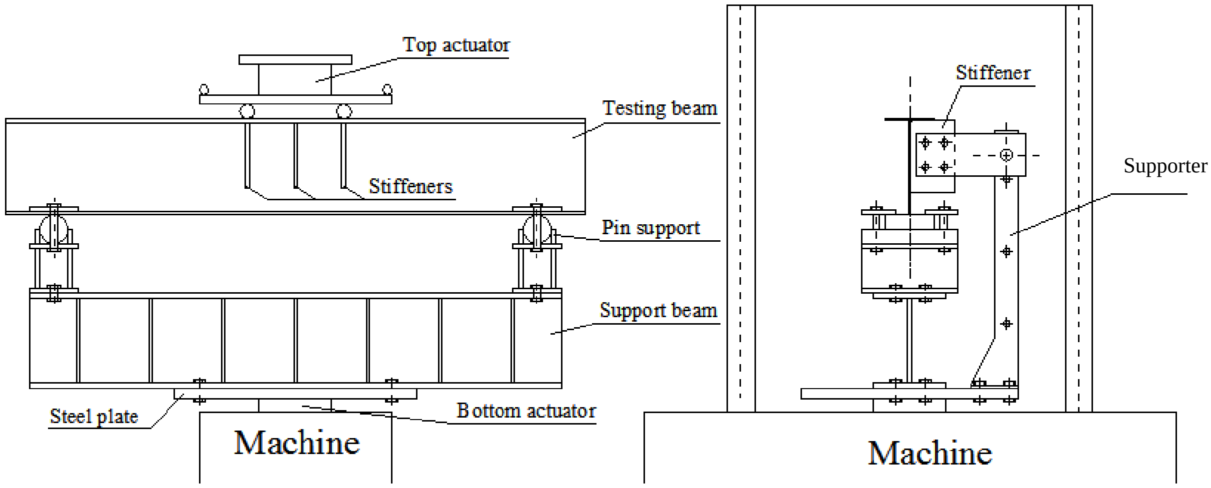


Figure 1.Schematic of testing system

Table 1. Loading Parameters in Experiments

Series of Specimens	Max. load (kg)	Min. load (kg)	Load range (kg)
I	5500	1100	4400
II	4000	800	3200
III	14000	2800	11200

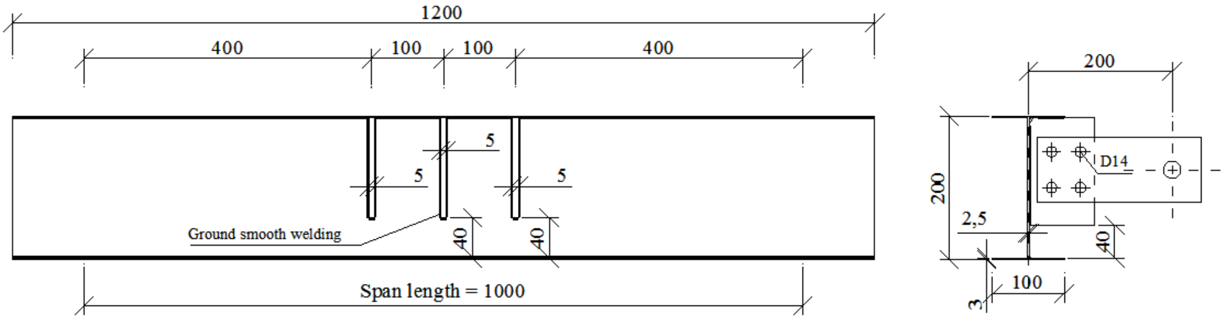
The applied cyclic loads in the experimental program were constant amplitude loading with a frequency of 4 Hz and the stress ratio *($R = \sigma_{min}/\sigma_{max}$)* of 0.2.

Details of Specimens

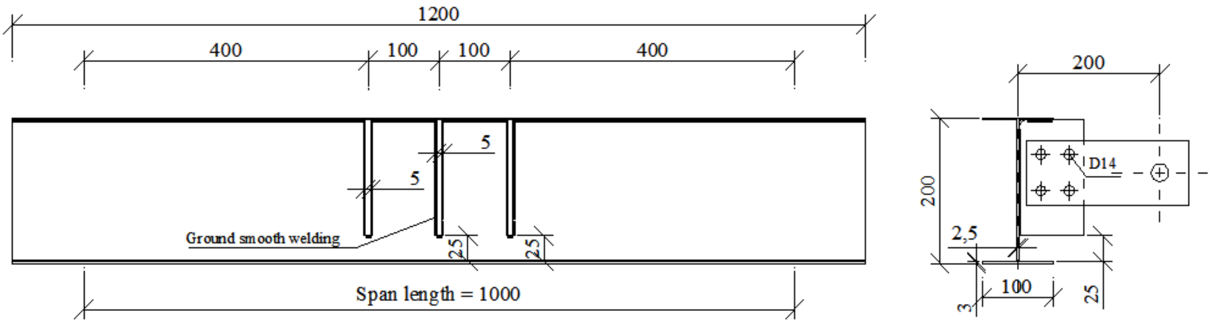
Welded beams were used in the experiments instead of hot-rolled beams since available hot-rolled I-beams cannot represent the scale of real steel bridge given by AASHTO requirements (for the flange thickness to the web thickness ratio). Thicknesses of each component are given as follows:

- Thickness of flange: 3 mm.
- Thickness of web: 2.5 mm.
- Thickness of stiffener: 5 mm.

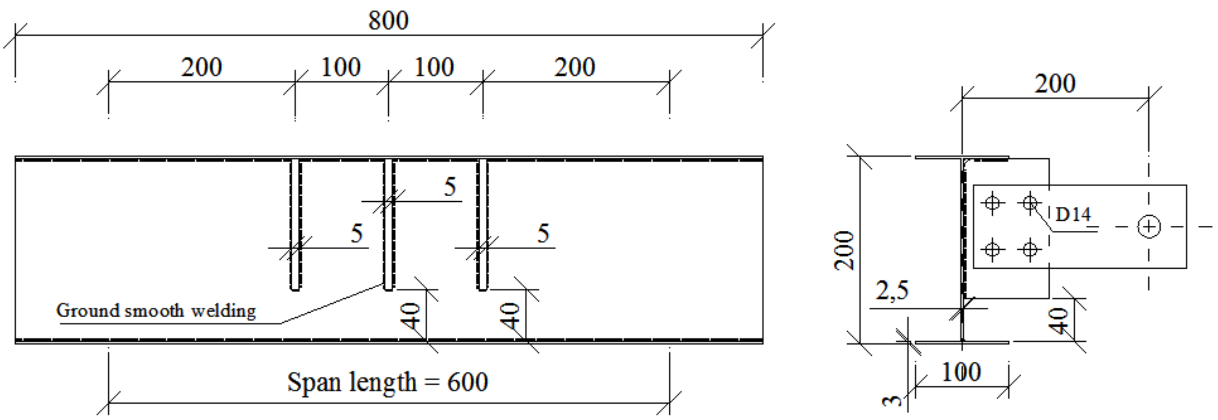
Figure 2 shows the dimensions of three series of specimens. Stiffener is located at themiddle of the testing specimen and connected to the web by ground-smooth welding. Ground-smooth welding is also required in other places such as the weld between flanges and the two girders. Eliminating residual stress is an important task because the thicknesses of flange and web are too thin for assembling by normal welding. If the procedure of welding is not strictly applied and the welds are not ground-smooth, there could be unexpected concentrated stresses that would disturb the stress field around the welds.



(a) Series I



(b) Series II



(c) Series III

Figure 2. Dimensions of three series of specimens

The steel grade is TIS1227 SM400 steel (Thai Industrial Standard) with the properties similar to those of A36 steel. Test results shows that the yield strength of steel is about 3,200 kg/cm^2, and the modulus of elasticity is 2.19 x 10^6 kg/cm^2.

Test Procedure

The test procedure can be summarized as follows: (1) calibration of the testing machine; (2) set-up of data logger (computer) as well as LVDT; (3) constant amplitude loading through P_{max} and P_{min} of given frequency and stress ratio; and (4) regular monitoring of crack initiation and crack propagation until the specimen fails.

Typical Beam Failure

Failure of nine specimens could be categorized into three types. In most specimens, the cracks initiating from the web gap go upward slowly into low stress fields, and do not directly cause the failure of specimens, but these cracks will significantly affect the failure.

Specimen Failure Due to New Crack in “Weak Zone” (Type A)

After crack initiates at the web gap due to the critical zone that is influenced by out-of-plane stress, the crack continues to propagate into lower stress zone. When the stress is low enough, the crack no longer propagates. A “weak zone” area is established between the two crack tips. A new crack occurs in this area, mostly in the middle of the beam and close to the position of the first crack. The second crack then occurs and moves to the bottom flange resulting in the beam failure. Some specimens show welding defects with cracks occurring along the welding, but this type of crack does not directly cause the beam failure. This behavior is found in specimens 1, 6, 8, and 9. The illustration of this type of failure is shown in Figure 3.

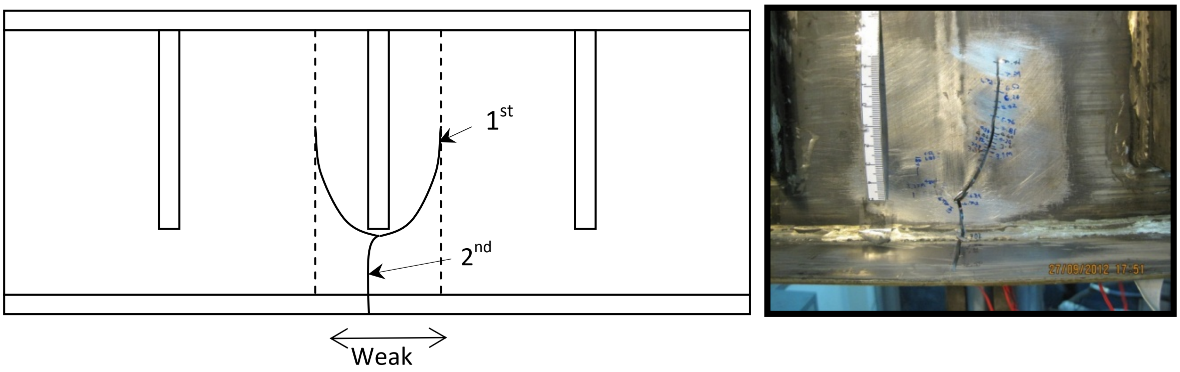


Figure 3. Specimen failure due to new crack in “weak zone”

Specimen Failure Due to New Crack Outside “Weak Zone” (Type B)

In specimens 2, 5 and 7, the first crack occurs at the weld toe and propagates to lower stress zone. Due to small energy in this zone, the crack stops for a long time. The second crack also occurs under the welding and begins from the line of the first crack, propagates towards the bottom flange but does not directly cause the beam failure. A new crack occurs at the welding of bottom flange and web, which is outside the weak zone. The third crack tends to move into two directions at the same time: one end goes upward into the web and connects to the end of the first crack; whereas the other end moves across the bottom flange resulting in the specimen failure due to the breaking of the bottom flange. This type of failure is shown in Figure 4.

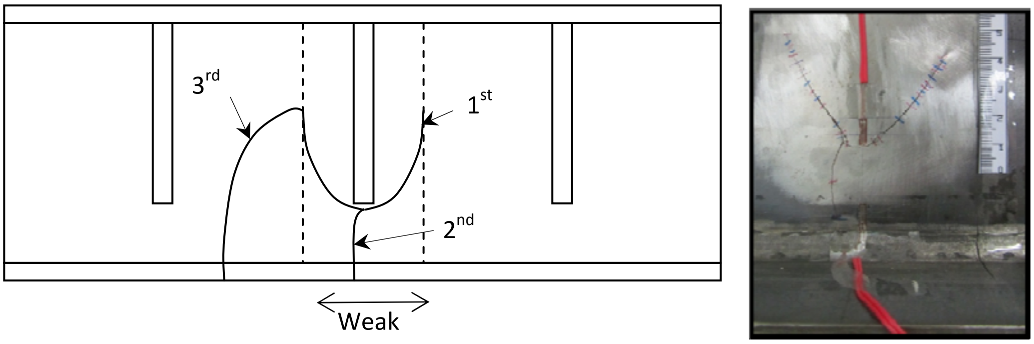


Figure 4. Specimen failure due to new crack occurring outside “weak zone”

Specimen Failure Due to Crack Going Downward (Type C)

In specimens 3 and 4, the cracks initiate at the end of weld toe, and go into different sides. One crack tip goes upward to lower stress zone. The other crack goes downward to the bottom flange and causes the specimen failure as shown in Figure 5.

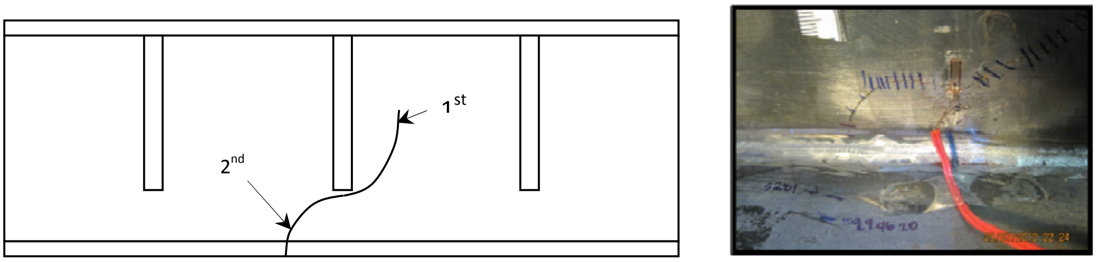


Figure 5. Specimen failures due to initial crack going downward

Fatigue Crack Initiation and Propagation

Based on the experimental results, the failure of beam under combination of distortion-induced and bending moment is classified into three types. If the quality of welds connecting web to bottom flange is good, the third crack will not occur and the second crack is the main reason of the failure of specimens. In other words, the type B failure becomes that of the type A.

Type C failure occurs whenever the welds around the end of stiffener are not symmetrical resulting in concentrated stresses at the spot of welds. In this case, the problem could occur during the fabrication of the specimens. The welds around the stiffener may not be ground-smooth, or there are some scratches on the surface of the web. In summary, the progress for crack initiation and propagation is listed as follows.

- Crack initiates as the shape of weld toe, and it grows upward to the lower stress field.
- The shape of crack depends on the in-plane to the out-of-plane stress ratio.
- The crack propagates until it reaches the zone that the stress field is so small that the energy could not generate a new crack.
- Another crack occurring inside the “weak zone” area depending on the critical stress or spot if it does exist in this area. This crack can cause the specimen failure.

The crack propagation can be classified into three stages as follows.

Stage 1: The first crack occurs on the tension side as semi-elliptical crack and grows to the compression side of the web. The shape of crack is formed as the shape of welding at the end of stiffener. After reaching the other side, the crack becomes through-thickness crack with two crack tips as shown in figure 6. This stage lasts less than the first 10% of the fatigue life of specimens.

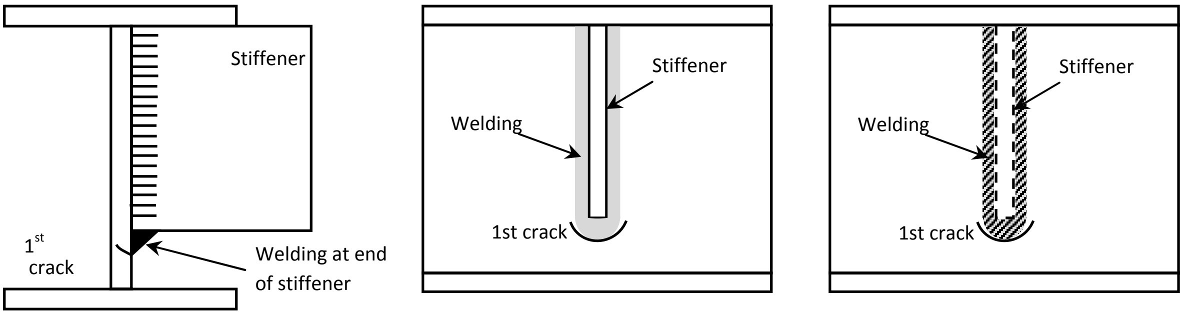


Figure 6. Crack propagation in stage 1

Stage 2: The first crack grows on both tension and compression faces approximately at the same speed leaving paralleled scratches on the crack plane. The shape of the crack path is shown in figure 7. The crack gradually reaches lower stress zone. This stage takes about 70% of the fatigue life. The first crack propagates under the combination of mode I and mode III.

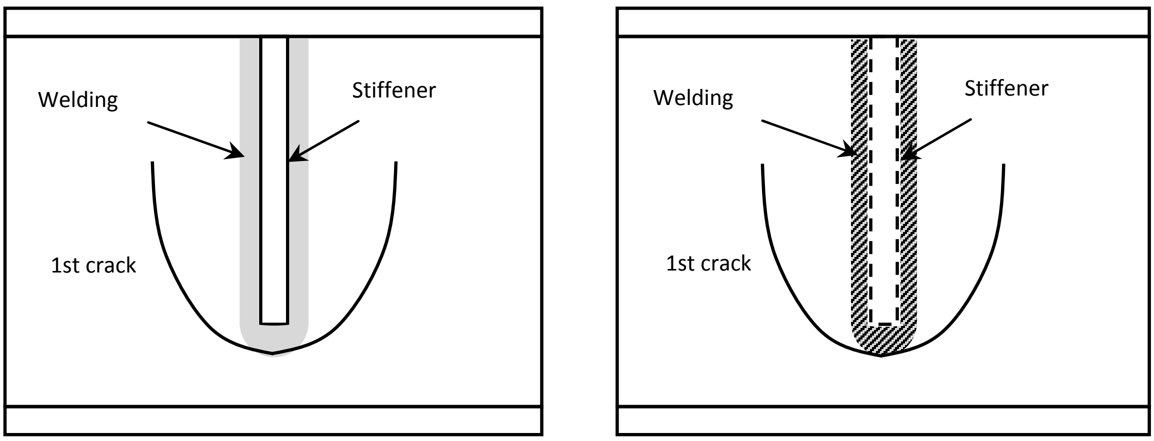


Figure 7. Crack propagation in stage 2

Stage 3: While the first crack grows slowly in low stress zone, the second crack begins from the line of the first crack and grows downward to the bottom flange as shown in figure 8. The second crack occurs due to the spots or scratches of the first crack line as well as the critical tension stress under the bending moment effect. It is observed that the second crack is the main reason of the beam failure. The stage 3 represents the last 20% of the fatigue life of specimen. The second crack occurs due to the effect of mode I.

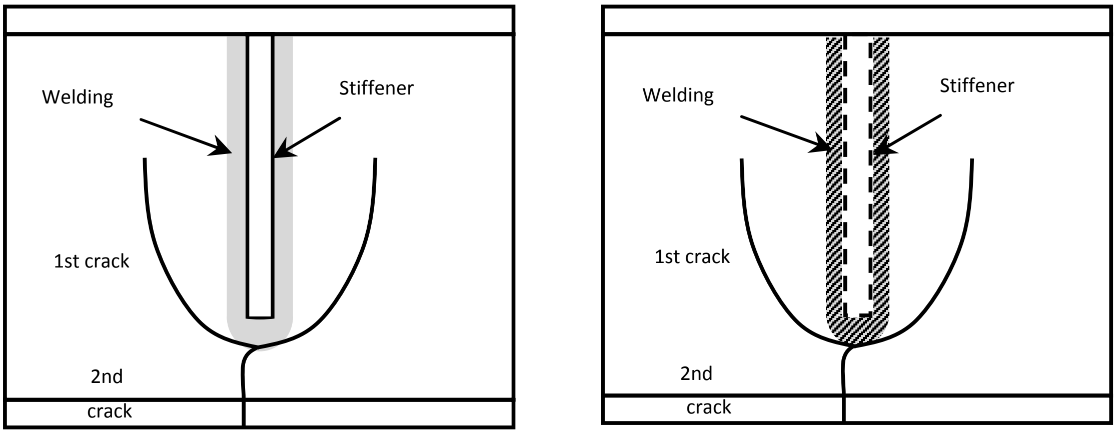


Figure 8. Crack propagation in stage 3

Failure Surface

For a typical beam failure, the first crack occurs and then propagates, and it plays the main role in the overall fatigue life of the beam. The second crack occurs after the first one "stops" (or propagates slowly) for a while, and it is the main reason for the failure of the beam. In other words, the first crack controls the overall fatigue life and creates the critical condition for the initiation of the second crack that leads to the failure of the specimen. It can be concluded that the fatigue life of the beam with distortion-induced fatigue effect mainly depends on the life of the first crack.

There are two main cracks initiated in the test specimens as shown in Figure 9. The first crack propagates upward to the top flange and the surfaces at points A, B, and C (see Figure 9) as shown in Figures 10A, 10B, and 10C respectively. The second crack propagates downward to the bottom flange (point D) and its cracks surfaces are shown in Figure 10D. From the crack surface of the first crack line (see Figures 10A, 10B, and 10C), the crack tip on the tension face propagates a little faster than the one in the compression face in the zone where the crack starts as shown in Figure 10A. When the crack propagates away from the end of stiffener, the crack tips on the tension and compression faces grow at the same speed as well as the same position at point B in Figure 9. It is also observed from the failure surface in Figure 10B that there are parallel scratches occurring on the surface, from tension to compression side. This is the evidence of the fact that the first crack propagates in the same speed for both faces of the web. When the first crack becomes critical (point C in Figure 9), the scratches at the crack surface (see Figure 10C) grow from both sides of web. The first crack becomes critical by the time the second crack breaks the bottom flange of the beam

The second crack starts when the first one reaches the low stress zone. The second crack has a short fatigue life and quickly causes the specimen failure. Beginning from the first crack, the second one propagates downward to the connection of web and bottom flange as shown at point A in Figure 9. When the second crack passes the connection, the point D in Figure 9, it propagates to both sides of the bottom flange and quickly becomes critical as shown in Figure 10D. The second crack propagates in a short time and its surface is rough as shown in Figure 10D.

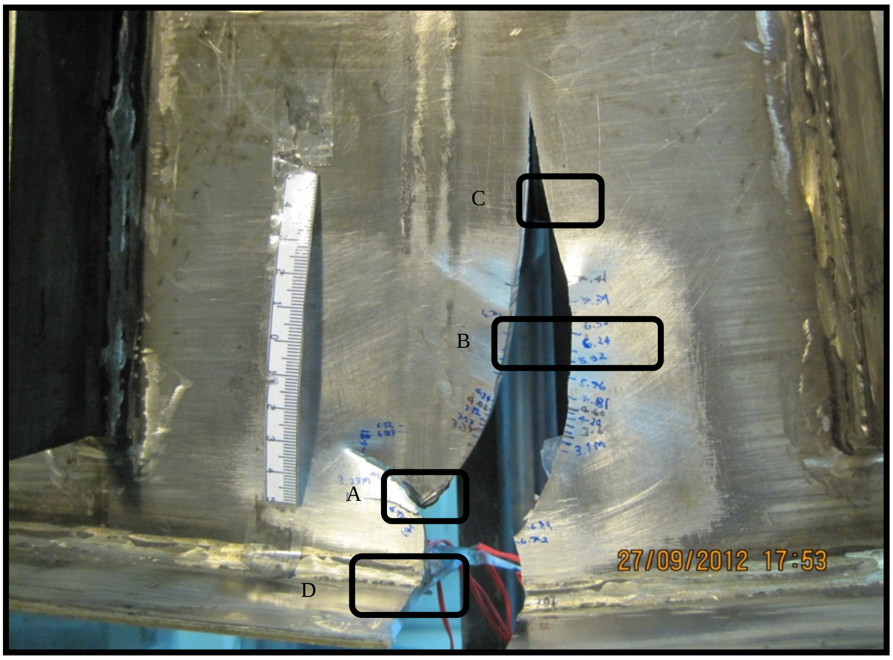
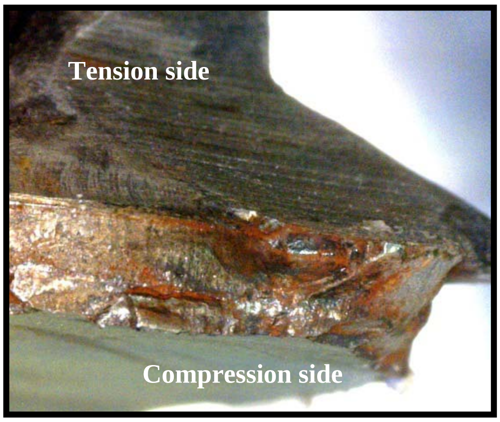
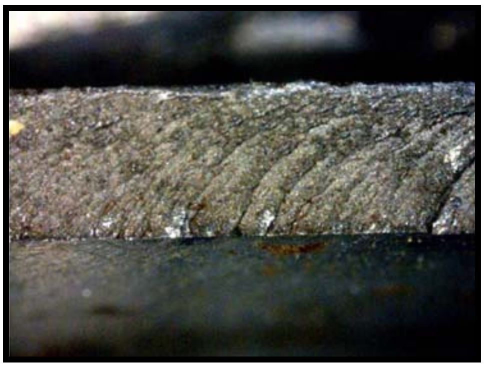


Figure 9. Pictures of the first and second cracks



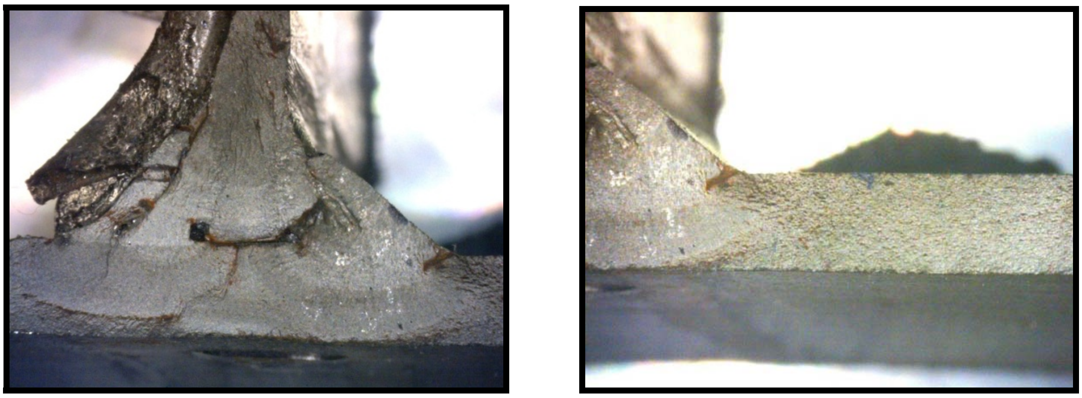
(A)Initiation of the first crack at weld toe



(B) Propagation of the first crack

(C) The critical first crack

Figure 10. Crack surfaces of the first and second cracks



(D) Propagation of the critical second crack to the bottom flange

Figure 10 (continued). Crack surfaces of the first and second cracks

During the test, the crack propagation life was regularly recorded. The crack paths were recorded as the period of time and written directly on specimens to construct the S-N curves. The second stage of crack propagation is identified when the initial crack propagates out of the weld connecting web and stiffener. At this stage, the crack propagates in a stable manner according to the definition from Paris law. The testing machine was stopped after an exact time to record the length and direction of crack growth. An example of recorded fatigue life on test specimens is shown in Figure 11. The recorded data shows the same range of fatigue life and crack length after the same time. When the first crack becomes critical, the number of cycles is shorter, whereas the crack length becomes longer. The crack propagation is too complex to predict the direction due to the complicated stress field around the crack by the time the beam fails. Naturally, the lengths of the first crack at each side of the web are slightly different due to the residual stress in the specimen, and the approximate values of the crack lengths have been used in the data analysis.

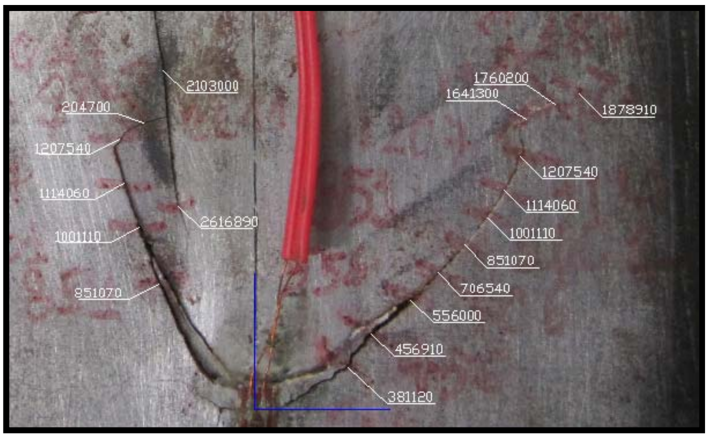


Figure 11. Recorded fatigue life on specimen

Figure 12 shows the S-N data for all specimens. There are nine specimens, which are classified into three series of beam as previously explained. The comparison of S-N curves from all specimens shows the differences between the stress at bottom flange and the number of cycles at the time the specimens failed. In this study, the fatigue life and the beam failure are defined by the complete collapse of the specimen. The three series of specimens reveals three levels of the stress at bottom flange, and of the fatigue life. The S-

N line, which is constructed from this test data and shown in Figure 12, presents a typical fatigue life for this type of web-stiffener connection. It can be obviously seen that the case of distortion-induced fatigue crack in steel I-beams with web-gap belongs to the Category C* according to the definition of AASHTO's S-N curves.

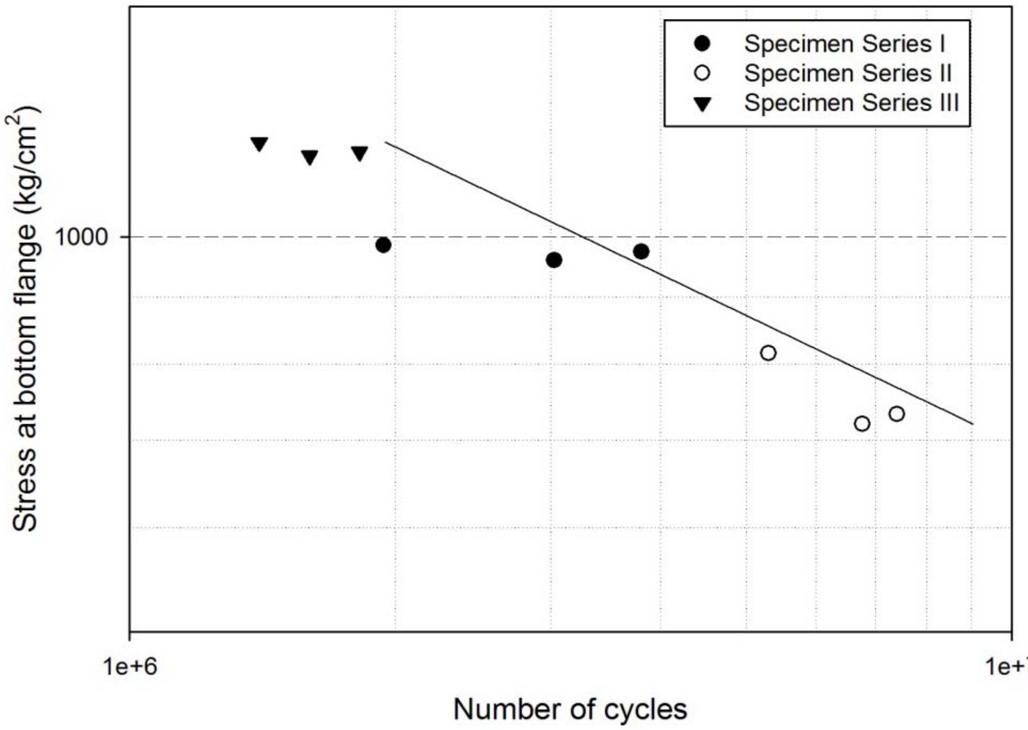


Figure 12. S-N curve from the test data

Conclusions

In this study, a series of tests was conducted to investigate the behavior of distortion-induced fatigue cracks in I-beams of steel bridges. Observations reveal the mechanism of crack initiation, propagation, and failure. The first crack initiates at the web-gap on the tension face, propagates deeper into the web-thickness as a semi-ellipse, and is formed as web-toe. Thereafter, the crack propagates up to the compression face and becomes two crack tips. Crack continues to propagate horizontally and then vertically. This crack propagates as parallel curves from tension face to compression face of the web. When the crack grows close to lower stress zone, it propagates slowly. The second crack initiates from the first crack at the position of web-toe, and propagates downward to bottom flange. The beam fails after a number of cyclic loads because the second crack breaks the bottom flange. These observations reveal that a typical beam failure depends significantly on the second crack initiation. Without the first crack, however, the second one could not initiate and propagate.

The crack path depends on the strain energy in the vicinity of the web-gap. Therefore, the shape of weld is important in distributing the stress around the critical zone. If the shape of the weld-toe consists of many spot points, it will produce many critical stress points on the web. Therefore, the new crack could appear anywhere in those points. The second crack initiates from one of these critical points. Although loading and geometry of the test specimens are symmetrical, unsymmetrical shape of weld causes the crack path to be different in the same specimen series.

Acknowledgement

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