FATIGUE STRENGTH OF WELDED JOINTS USING STEELS FOR BRIDGE HIGH PERFORMANCE STRUCTURES (SBHS)

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ABSTRACT

In this study, the fatigue performance on the welded joints of the newly developed steel called Steels for Bridge High Performance Structures (simply called SBHS) was investigated. In order to clarify the fatigue crack growth characteristic of the SBHS, the crack propagation tests were performed with compact tension type specimens. Then, the fatigue strengths of out-of-plane gusset welded joints and non-load-carrying cruciform welded joints of the SBHS were investigated. Plate girder specimens, in which gusset plates were attached on their webs, were also fabricated with the SBHS and tested. The fatigue test results revealed that the fatigue performances of the welded joints of the SBHS are almost the same as those of the conventional steel.

Keywords: SBHS, fatigue strength, welded joints.

1. INTRODUCTION

In Japan, Steels for Bridge High Performance Structures, called simply SBHS, have been newly developed (Miki et al. 2003). The SBHS has 10-20% higher yield strength, high weldability and cold formability when compared to the conventional rolled steel for welded structures. These characteristics allow for economical design including weight and work savings. However, since reducing the weight leads to stiffness reductions of members and increasing the magnitude of stress fluctuations due to the live load, it needs to pay more attention to use the SBHS in terms of fatigue.

In this study, the fatigue performance on welded joints of the SBHS was investigated by three kinds of experiments. First, the fatigue crack growth tests were performed with compact tension type specimens to clarify the crack growth characteristic of the SBHS. Then, the fatigue tests were carried out with two joint types; out-of-plane gusset welded joints and non-load-carrying cruciform welded joints. Besides, plate girder type specimens, which have gusset plates on their webs, were fabricated with the SBHS and also tested. In the fatigue tests, the welded joint of which weld toe was improved by the burr grinding or the peening techniques were also used to investigate the

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applicability of the conventional fatigue strength improvement to the SBHS. As a result of these tests, the fatigue performance of the welded joints of the SBHS was confirmed.

2. MECHANICAL PROPERTIES AND CHEMICAL COMPOSITIONS OF STEELS

The mechanical properties and chemical compositions of the steel plates employed in this study are given in **Table 1** and **2**. Two different types of the SBHS, which are called Japanese Industrial Standards (JIS) SBHS500 and SBHS700, were used in the tests. Moreover, JIS SM490Y which is commonly used for bridge structures in Japan was also used for comparison. **Table 3** shows the test matrix in this study.

Table 1: Mechanical properties

Steel type	Yield strength (N/mm^2)	Tensile strength (N/mm^2)	Elongation (%)
SBHS500	570	633	30
SBHS700	823	846	24
SM490Y	450	544	26

Table 2: Chemical compositions

Steel type	C	Si	Mn	P	S	Cu	Ni	Cr	Mo	V	B	P_{CM}
SBHS500	0.02	0.28	1.35	0.013	0.004	0.43	0.24	0.50	0.001	0.002	0.0018	0.16
SBHS700	0.06	0.25	1.37	0.004	0.002	0.98	0.98	0.34	0.30	0.04	0.0003	0.24
SM490Y	0.13	0.30	1.36	0.013	0.001	0.01	0.01	0.04	0.00	0.00	0.0000	0.21

Table 3: Test matrix

Steel type	Fatigue crack growth tests	Fatigue tests with welded joint		Fatigue tests with plate girder
		Out-of-plane gusset joint	Cruciform joint	
SBHS500	○ (2)	○ (3)	○ (4)	×
SBHS700	○ (2)	○ (3)	○ (4)	○ (2)
SM490Y	○ (1)	○ (3)	×	×

* the number of the specimen are in brackets

3. FATIGUE CRACK GROWTH TESTS

3.1. Specimen and experimental procedures

The configuration and dimension of the specimen is shown in **Figure 1**, and the appearance of the test is shown in **Figure 2**. The specimen and testing procedures are compliant with the ASTM E647-08 (ASTM 2008). The stress intensity factor range (ΔK) was calculated according to the following equation.

$$\Delta K = \frac{\Delta P}{B\sqrt{W}} \frac{(2+\alpha)}{(1-\alpha)^{3/2}} \left(0.886 + 4.64\alpha - 13.32\alpha^2 + 14.72\alpha^3 - 5.6\alpha^4\right) \quad (1)$$

where, ΔP is the load range (N), B is the plate thickness (mm), W is the distance from the specimen edge to the loading axis (mm) and $\alpha = a/W$ (a is crack length (mm)).

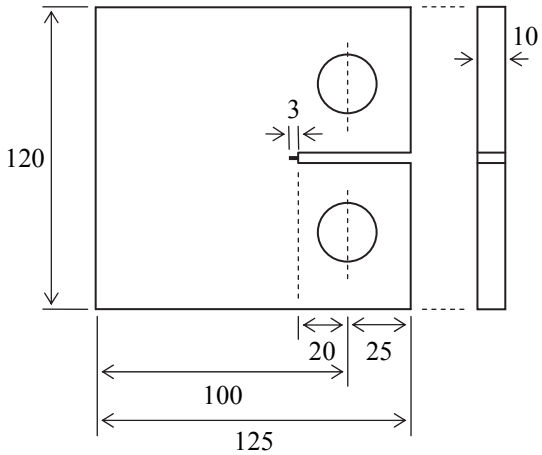


Figure 1: Specimen configuration (unit: mm).

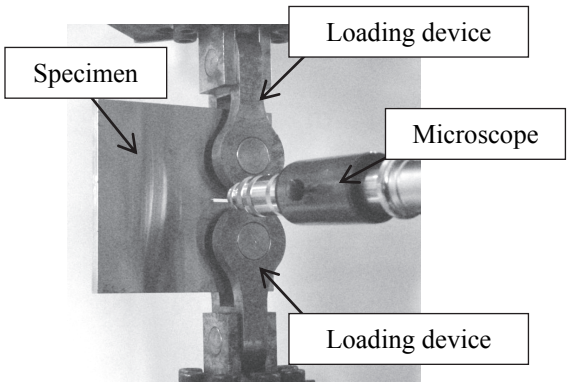


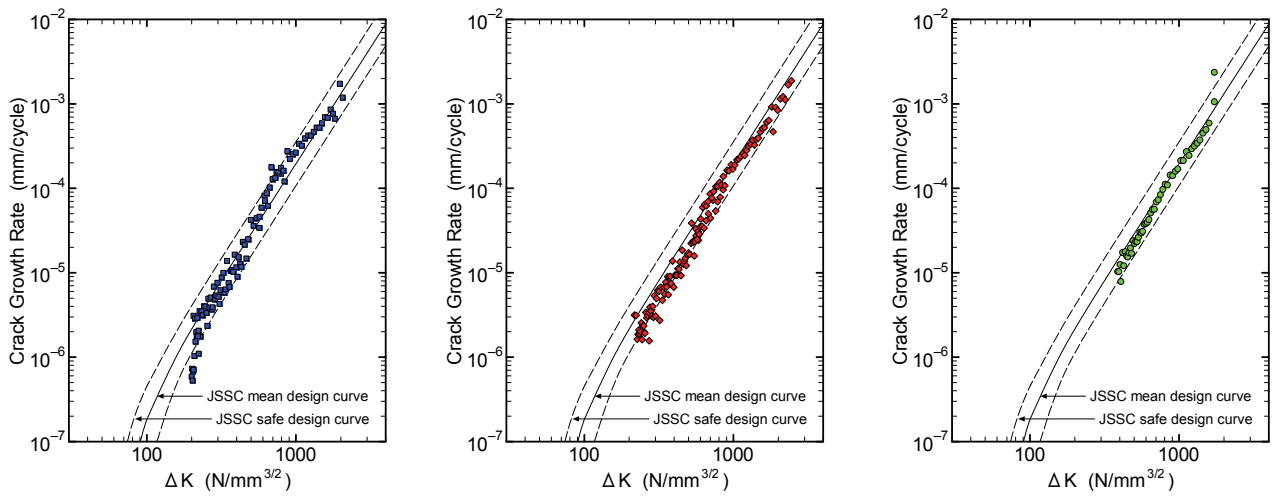
Figure 2: Test condition.

3.2. Test results

The test results are shown in **Figure 3**. The crack growth design curves proposed by Japanese Society of Steel Construction (JSSC 2012) are also indicated in the graph (equation (2)).

$$\frac{da}{dN} = C\left(\Delta K^{n} - \Delta K_{th}^{n}\right) \tag{2}$$

where, da/dN is the crack growth rate (mm/cycle), C and n are the material constants and ΔK_{th} is the threshold stress intensity factor range (N/mm$^{3/2}$). The values of C, n and ΔK_{th} are 1.1×10^{-12}, 2.75 and 76 N/mm$^{3/2}$ for the mean design curve, 2.0×10^{-12}, 2.75 and 63 N/mm$^{3/2}$ for the safe design curve, respectively (JSSC 2012).



(a) SBHS500 **(b) SBHS700** **(c) SM490Y**

Figure 3: Crack growth test results.

It can be seen in the graph that the crack growth behaviors are similar regardless of the steel types and that all the results distribute around the design curve in JSSC. It means that the crack growth characteristic of the SBHS is similar to that of the conventional steel and can be evaluated by using the previously proposed crack growth curve.

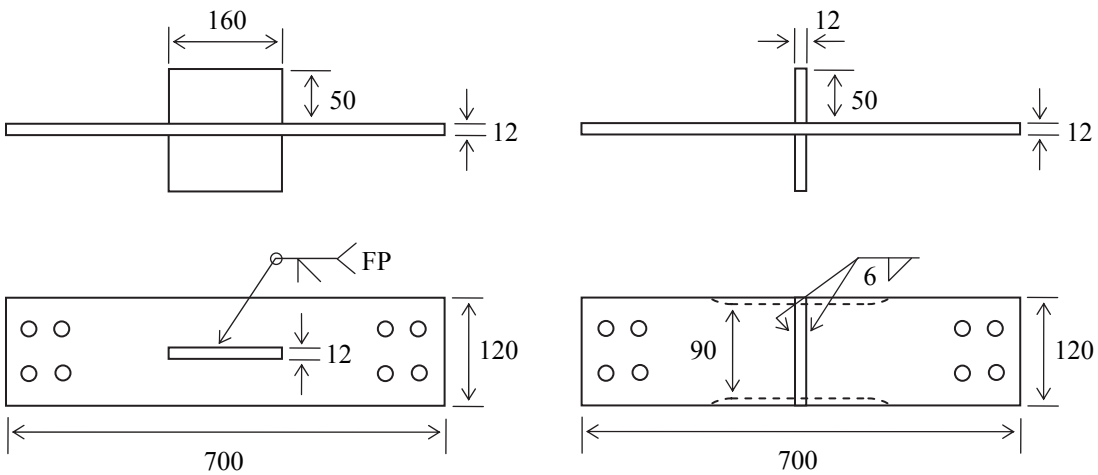
4. FATIGUE TESTS

4.1. Specimens and loading methods

4.1.1. Welded joint type specimen

The configuration and dimension of the specimen is shown in **Figure 4**. Two different joint types were used, which are the out-of-plane gusset joint and the non-load-carrying cruciform joint. The specimens were made of the SBHS and the SM steel. In some out-of-plane gusset joints, the weld toes were finished by the grinding technique. In some cruciform joints, the main plate width was reduced along the broken lines in **Figure 4(b)** because of the loading capacity of the fatigue testing machine. The main plate thickness was 12 mm in all specimens.

The fatigue tests were performed under the constant amplitude load. The nominal stress ranges in the main plate ranged from 67 to 122 N/mm^2 for the out-of-plane gusset joint and from 100 to 180 N/mm^2 for the cruciform joint. The load frequency was changed from 2 to 4.5 Hz depending on the stress magnitude. The stress ratio was set to be almost 0. Beach marks were introduced in some out-of-plane gusset joints to observe the crack propagation behavior.



(a) Out-of-plane gusset joint **(b) Cruciform joint**

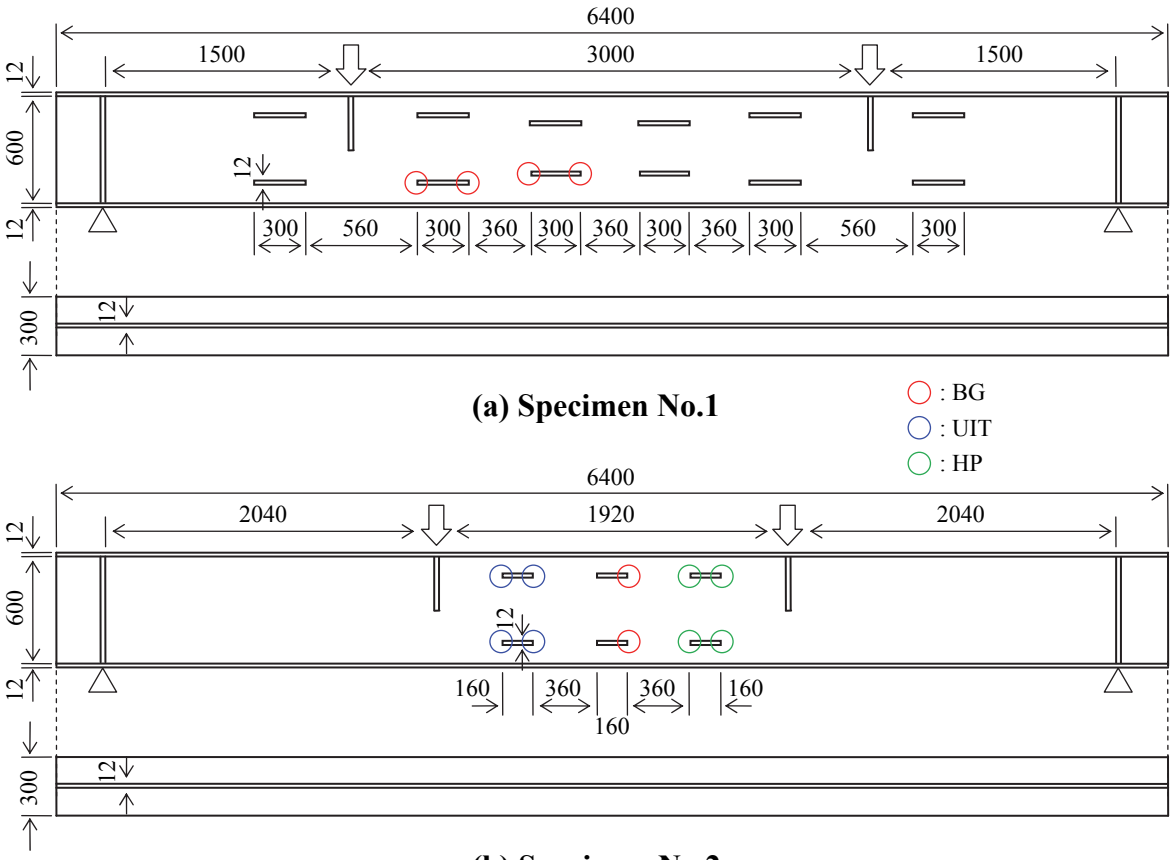
Figure 4: Welded joint type specimens (unit: mm).

4.1.2. Plate girder type specimen

Figure 5 shows the plate girder type specimen. Two types of the specimens were fabricated with SBHS700. Gusset plates were attached on the web in the same welding method as the joint specimen. The main difference between two specimens is the dimension of the gusset plate, which

is 300×70×12 mm in specimen No.1 and 160×70×12 mm in specimen No.2. The fatigue strength improvements such as the burr grinding (called BG: JSSC 2012) and the peening (ultrasonic impact treatment, called UIT: Tominaga et al. 2008, hammer peening, called HP: Ishikawa et al. 2011) were applied to some weld toe. The plate thickness of the web was 12 mm in both specimens.

The load was applied by four-point bending condition. The nominal stress range in specimen No.1 was from 73 to 109 N/mm^2 depending on the gusset locations, while it was constant of 100 N/mm^2 in specimen No.2. The stress ratio was 0.03 in specimen No.1, and 0.1 in specimen No.2. After the crack occurred from the weld toe and propagated to 40 to 50 mm in surface length, the stop-holes were cut at the crack tip and tighten by high strength bolts to retard the crack growth. The loading was continued until about 1.5 million cycles.

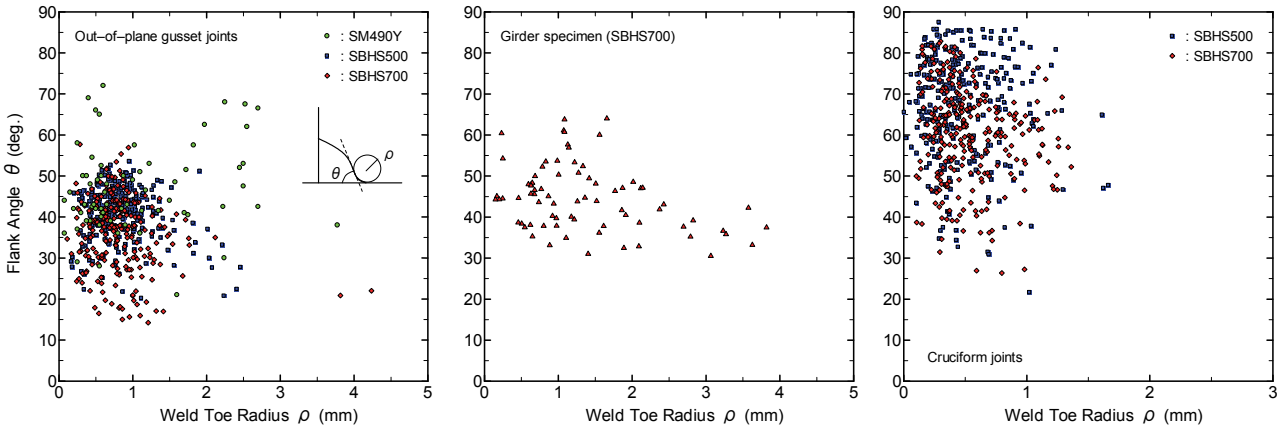


(b) Specimen No.2

Figure 5: Plate girder type specimens (unit: mm).

4.2. Measurements of weld toe geometry

The weld toe geometry of as-welded condition, which is the toe radius ρ and flank angle θ, was measured by the replica method. The measurements are shown in **Figure 6**. Although the measurements vary widely, the toe radius which is one of the influential factors on the fatigue strength distributes in the same range between the SBHS and the SM steel, and between the joint specimen and the girder specimen.

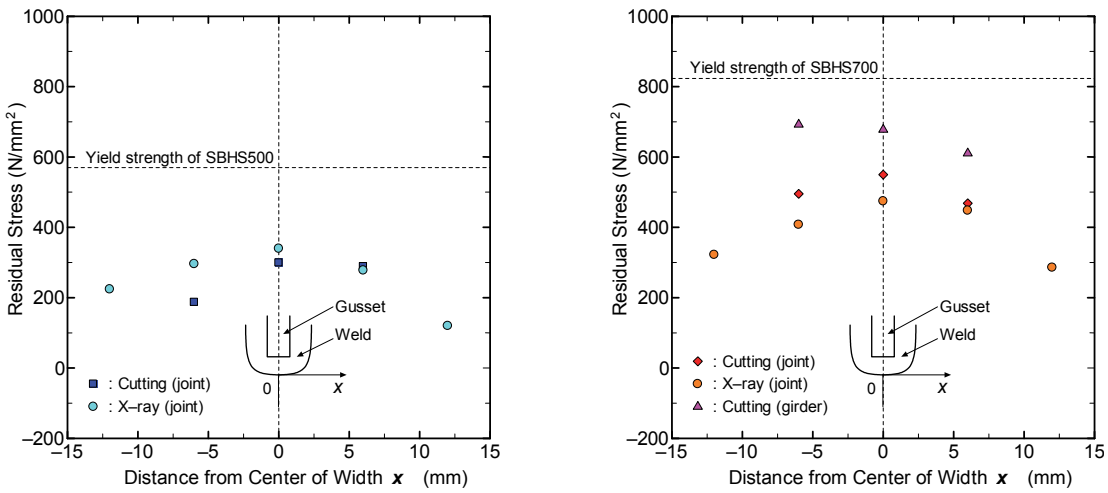


(a) Out-of-plane gusset joints **(b) Girder specimens** **(c) Cruciform joints**

Figure 6: Measurements of weld toe geometry.

4.3. Measurements of weld residual stresses

The residual stresses induced by welding were measured by the cutting method and the X-ray diffraction method (sin2Ψ method, spot size: 2mmφ). The measurement was conducted in the out-of-plane gusset joint and the plate girder specimen. The stress component of the longitudinal direction was measured by both methods. The residual stress distributions in the transverse direction are shown in **Figure 7**. The horizontal axis is the distance from the center of the specimen width. The measurements by the cutting method are in well agreements with those by the X-ray method. It can be seen that high tensile residual stresses are induced around the weld, which are almost 50 to 70% of the yield strength of the material in the joint specimen. On the other hand in the girder specimen, it is higher than that in the joint specimen, which is about 75 to 85% of the yield strength.



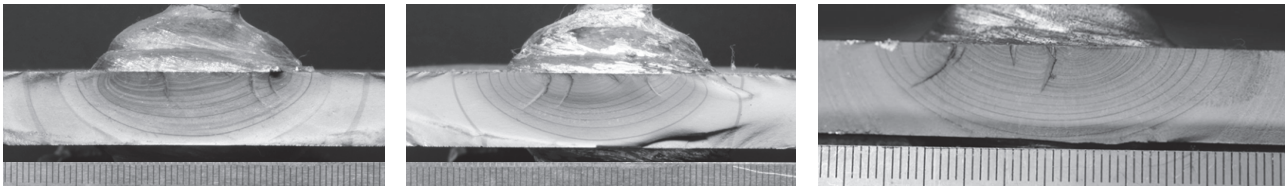
(a) SBHS500 **(b) SBHS700**

Figure 7: Measurements of residual stress.

4.4. Fatigue test results

4.4.1. Fracture surfaces

Examples of the fracture surface of the out-of-plane gusset joint are shown in **Figure 8**. From the beach marks in the fracture surface, the crack length ($2b$) and the crack depth (a) were measured and their relationships (a/t versus $2b/W$, t is the plate thickness and W is the plate width) were plotted in **Figure 9**. The results indicate that the crack propagation patterns are quite similar regardless of the steel types. And it can be found that the crack penetrates the main plate when the crack length reaches approximately 40% of the plate width (in other words, 50 mm in crack length).



(a) SBHS500 (80 N/mm^2) **(b) SBHS700 (80 N/mm^2)** **(c) SM490Y (67 N/mm^2)**

Figure 8: Examples of fracture surfaces.

4.4.2. Fatigue lives

Figure 10 shows the fatigue test results which are the fatigue life versus the nominal stress range. The fatigue life of the joint specimen was defined as the number of cycles to failure, and that of the girder specimen was defined as the number of cycles when the crack reached about 50 mm in surface length. In the graph, the fatigue test results stored in the database (JSSC 2009, Mori et al. 2011) and also the fatigue strength curves in JSSC (JSSC 2012) are represented. The marks with an arrow mean the specimen which did not fail within the test.

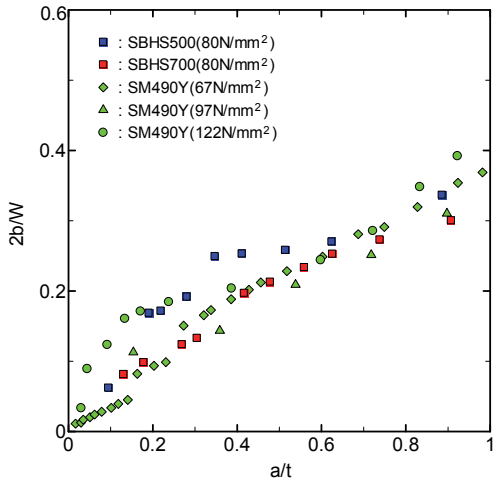
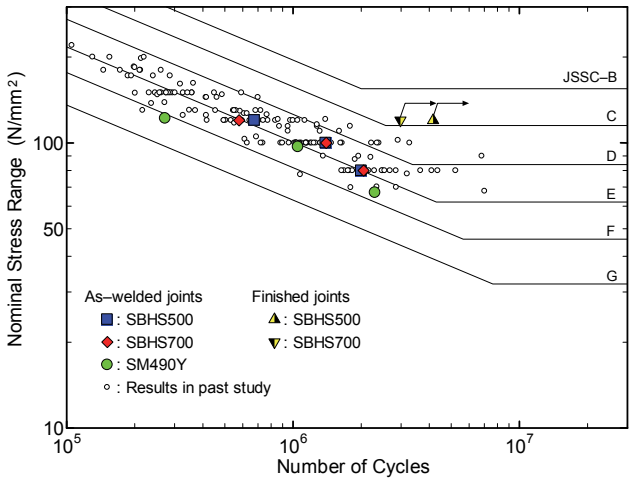


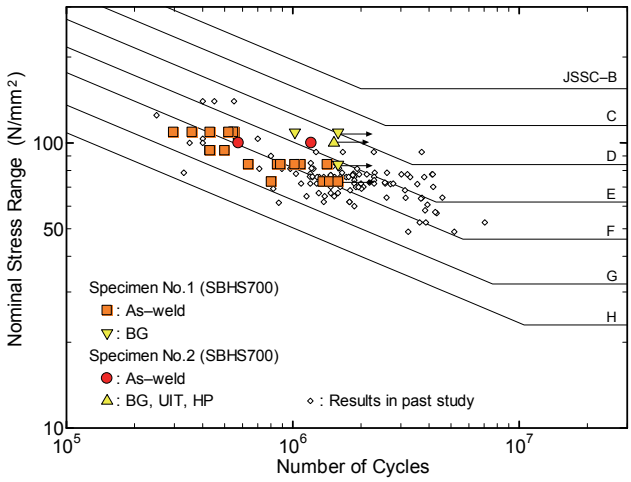
Figure 9: Crack depth versus length.

The test results revealed that there is little difference in the fatigue strength between SBHS500 and SBHS700, and that the fatigue strength of the SBHS is almost the same as that of the SM steel. In the plate girder specimen, it can be seen that the results of specimen No.2 tend to be higher than that of No.1, which implies the effect of the gusset plate size on the fatigue strength.

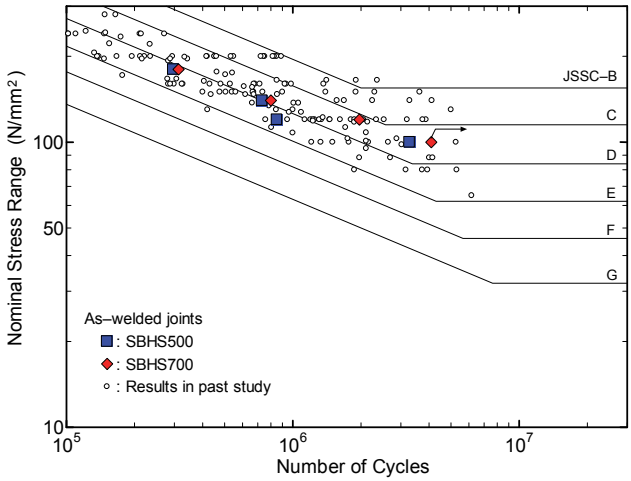
When compared with the test results in the past study, the results in this study locate in the same area, meaning that the conventional fatigue strength curves are applicable to evaluate the fatigue strength of the welded joint of the SBHS. In addition, the fatigue strengths of the SBHS can be improved to at least one class of the fatigue strength curve by the grinding and peening technique, which is also the same tendency in case of the conventional steel.



(a) Out-of-plane gusset joints



(b) Girder specimens



(c) Cruciform joints

Figure 10: Fatigue test results.

5. CONCLUSIONS

The fatigue performance on the welded joints of the SBHS was experimentally investigated. The test results revealed that the SBHS has similar fatigue characteristics compared with the steel commonly used in the steel bridges. It means that the conventional fatigue strength evaluation methods can be applied to the welded joint of the SBHS.

6. ACKNOWLEDGMENTS

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