FATIGUE CRACKS OF DEEP THIN-WALLED PLATE GIRDERS

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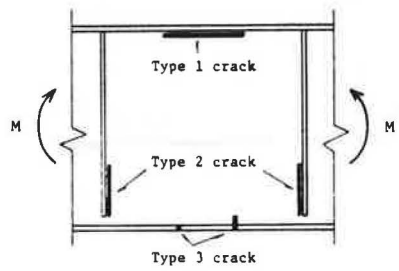
Recently in Japan, fatigue cracks have been observed in bridges, cranes and tanks. Generally, there is a possibility of two types of fatigue cracks inherent in thin-walled plate girders. A crack which is initiated at the toe of fillet welds of compression flange-to-web, is called Type-1 crack. Then, a crack at the toe of fillet welds of vertical stiffener-to-web, is called Type-2 crack. Type-1 and -2 cracks are governing ones in homogeneous and hybrid plate girders, respectively. For the fatigue design of deep thin-walled stiffened plate girders of bridges, the paper presents an extensive study on fatigue strength based on observations at the tests of initiation and propagation of the above -mentioned two fatigue cracks. The outline of girder tests and of coupon-type model tests for Type-2 cracks, and then the outline of girder tests and of plate-type and bar-type model tests for Type-1 cracks, are described and the results are discussed. The mechanism of initiation of Type-1 cracks at the bar-type model tests is discussed from the point of fracture mechanics in connection with unavoidable inherent initial defects due to welding or fabrication. Although the application of the test results to design is discussed, the problem of Type-1 cracks is a matter of structural details subjected to displacement-induced secondary bending stress ranges, and the need of further studies is stated.

As pointed out by Yen (1, 2, 3), Stallmeyer (4), Toprac (5), and the author (6, p. 287, 7, p. IIIA2.2), there is a possibility of the initiation and propagation of three types of inherent fatigue cracks, as seen in Figure 1, at beams or girders subjected to repeated bending. Type-3 cracks are the most ordinary cracks in a tension flange of any kind of beams or girders. On the other hand, Type-1 cracks which occur at toes on the web side of fillet welds to connect a compression flange to the web, are due to the out-of-plane repeated movement of unavoidable initial deflections under repeated in-plane bending, and are the most governing crack at homogeneous thin -walled stiffened girders. Then, Type-2 cracks which occur at toes on the web side of fillet welds to connect a vertical stiffener to the web, will propagate into a tension flange across the web, and are the most critical one at hybrid thin-walled girders.

Figure 1. Pattern of fatigue cracks of thin-walled plate girder under repeated bending.



At the present paper, Type-1 and -2 cracks are dealt with, because they are particular to deep thin-walled plate girders. First of all, the fatigue strength against Type-2 cracks is discussed based on girder tests and model specimen tests. Then, the fatigue strength against Type-1 cracks is investigated on the basis of two kinds of model tests together with the results of the author's previous girder tests. Moreover, a matter of structural details subjected to displacement-induced secondary bending stress ranges is discussed for the design of plate girders against Type-1 cracks.

Type-2 Crack

Girder Tests

At the fatigue tests of hybrid girders by Toprac (9), Type-1 cracks were observed. He suggested that it would be effective to use horizontal stiffeners and or limit the web slenderness ratio less than 200 for the prevention of Type-1 cracks. However, all of the test girders by the author(10) failed due to Type-2 cracks. Type-1 and -3 were also observed, but not critical cracks to cause the failure of the girders. Table 1 shows the results of the fatigue tests of six large-sized stiffened hybrid girders

Table 1. Parameters and test results of hybrid girders.

Test Girder	Aspect Ratio	Web Slenderness Ratio β	Longi. Stiff. Rigidity Ratio γ/γ^*	Tens. Flg. Max. Stress (MPa)	Tens. Flg. Stress Range (MPa)	Stress Ratio R	Type of Crack, No.(×10⁴) of Cycles: Type 1	Type 2	Type 3	Fatigue Life(×10⁴)	Mode of Failure
B4-L1	1.0	413	1	266	207	0.221	46.5	34.1	-----	67.0	Type 2
B4-L7			7	286	226	0.209	----	24.3	-----	26.0	Type 2
B3-L1		310	1	251	115	0.543	----	218.0[b]	218.0	224.0	Type 2
B3-L6			6	356	207	0.402	----	28.0	-----	33.5	Type 2
B2-L0		206	0[a]	308	172	0.439	----	104.0	-----	116.0	Type 2
B2-L5			5	289	158	0.456	----	116.6	-----	123.5	Type 2

Note: 1 MPa = 145 lbf/in.^{2}

[a]No Longitudinal Stiffener. [b]Max. Stress Increased up to 344 MPa after 2×10^6 Cycles.

carried out by the author (10).

The girders were fabricated of HT80 steel in a tension flange, SM58 steel in a compression flange and SS41 steel in a web. HT80, SM58 and SS41 are respectively, a quenched and tempered high-yield high-strength steel, an ordinary high-strength steel and an ordinary mild steel, and have respectively such mechanical properties as min. yielding point and min. tensile strength as 686.0 MPa (99.5 kipf/in.^{2}), 784.0 MPa (113.8 kipf/in.^{2}); 450.8 MPa (65.4 kipf/in.^{2}), 568.4 MPa (82.5 kipf/in.^{2}); 235.2 MPa (34.1 kipf/in.^{2}), 401.8 MPa (58.3 kipf/in.^{2}). Table 1 summarizes the values of parameters to evaluate the test results, those are, web slenderness ratio, relative rigidity ratio of horizontal stiffeners, tensile stress range and min. to max. stress ratio.

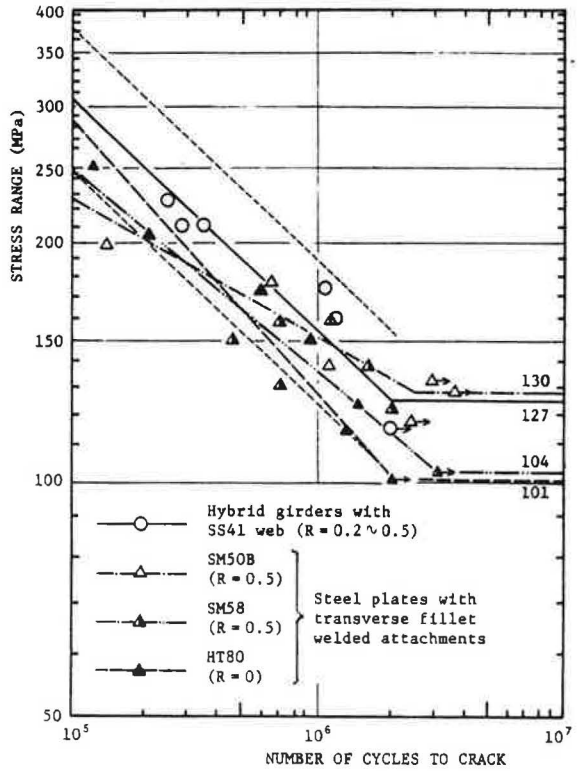
The regression analysis of the test results on the initiation of Type-2 cracks carried out by the author (10) and Toprac (5), gives the fatigue strengths at 2 x 10^6 cycles of 126.4 MPa (18.3 kipf/in.^{2}) in the mean value and of 104.9 MPa (15.2 kipf/in.^{2}) in 95 % confidence limit, both in stress range. Those are 25 % higher than the allowable stress range of 82.3 MPa (11.9 kipf/in.^{2}) in Stress Category C at the AASHTO Specifications (17).

The fatigue strength against Type-2 cracks can be compared to that of a transverse non-load-carrying fillet welded joint (11, 12). Figure 2 shows S-N curves of the results of tests carried out by other investigators on the joint in three kinds of high-strength steels, and of the results of the author's girder tests (10). S-N curves obtained by the former tests do not significantly differ from each other in the grade of steel. Because the scattering of measured values is unavoidable and the difference of stress ratio exists. Moreover, S-N curves of the model specimen tests agree well with S-N curve of the tests of girders with a web in SS41, within the range of fatigue strength of about 100 to 130 Mpa (14.5 to 18.9 kipf/in.^{2}). Consequently, a web in ordinary mild steel is the most economical for Type-2 cracks.

Model Test of Type-2 Crack

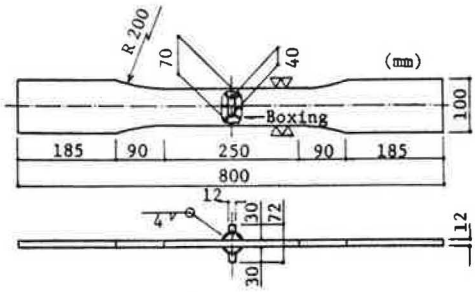
The girder tests described above were not sufficient in numbers to warrant the fatigue strength. Also, the model tests (14) referred to did not exactly simulate the behavior of hybrid plate girders, because the tests were done regardless of a possible maximum strain in the corresponding web. Then, fatigue tests were carried out on axially loaded transverse non-load-carrying fillet welded joints under strain control.

Figure 2. S-N curves for Type-2 crack.



Note: 1 MPa = 145 lbf/in.^{2}

Figure 3. Details of as-welded specimen.



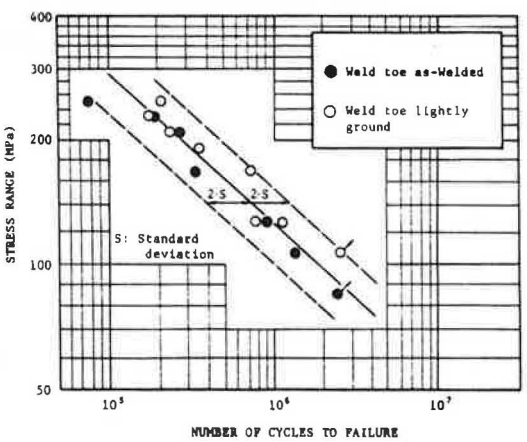
Note: 1 mm = 0.039 in.

Outline of Tests. As shown in Figure 3, the specimens were intended for simulating the boxing part of transverse stiffener-to-web fillet welds in hybrid girders. They were axially loaded under strain control by fixing the out-put of strain gages on the specimen to the maximum strain of 1700 x 10^{-6}, which corresponded to the design working strain of 784.0 MPa (113.8 kipf/in.^{2}) grade high-strength steel in a tension flange of girders.

The specimens were made up of SS41 steel with the specified tensile strength of 401.8 MPa (58.3 kipf/in.2). The tests were divided into two series of as-welded specimens and of specimens lightly ground at the toe of fillet welds to examine the effect of finishing. Such tests were able to simulate the behavior proper to a hybrid girder. Because its web reached a kind of strain-controlled state, after the start of its yielding, due to restraining given by the elastic frame action of the tension flange.

Test Results. S-N diagrams in Figure 4 show the test results in terms of stress range equivalent to strain range at the number of cycles to failure, neglecting the effect of stress ratios. The fatigue strengths of as-welded specimens and of lightly -ground specimens at 2 x 10^6 cycles can be estimated respectively at 93.1 MPa (13.5 kipf/in.^{2}) and 120.9 MPa (14.9 kipf/in.^{2}) as the mean value of stress ranges. The effect of finishing on the fatigue strength is not so remarkable at the present tests. Because the grind operation was not fully performed and consequently some fine notches were not removed.

Figure 4. Fatigue test results.



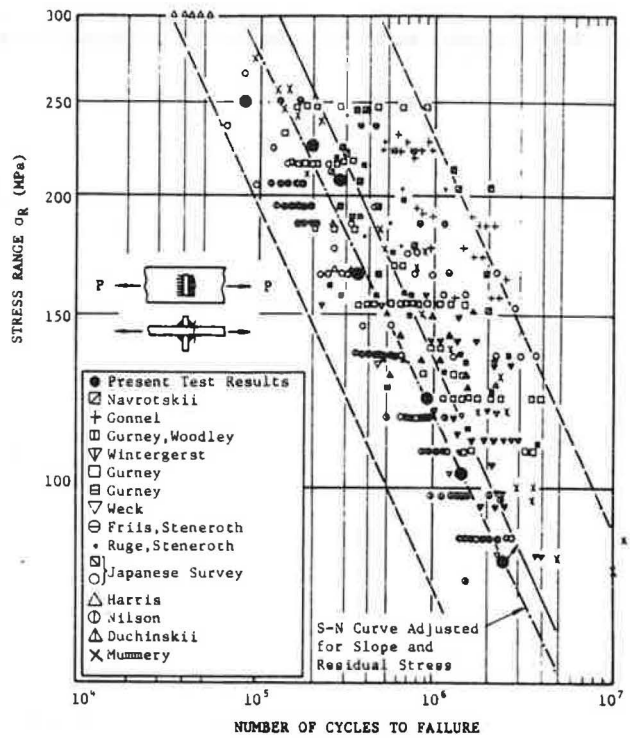
Note: 1 MPa = 145 lbf/in.^{2}

Discussions.

1. Figure 5 shows a comparison of the present test results with the previous fatigue test data on model specimens, under load-controlling, with the same configuration as the present test specimens. Gurney et al. (13, p. 35) gave the latter data as the result of reanalysis of numerous tests. Since the present test results agree well with S-N curves re-analized by Gurney et al., there is no significant difference between load-controlling and strain-controlling.

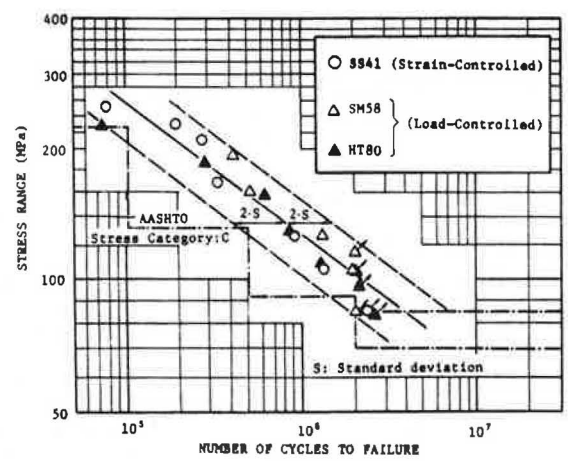
2. Figure 6 shows another comparison of the present test results for the as-welded specimens in SS41 steel with test results in other steels (15). In Figure 6, SM58 and HT80 are high-strength steels with the specified min. tensile strength of 568.4 MPa

Figure 5. S-N curves for transverse non-load -carrying fillet welded joint.



Note: 1 MPa = 145 lbf/in.^{2}

Figure 6. S-N curves for transverse non-load -carrying fillet welded joint in SS41, SM58 and HT80.



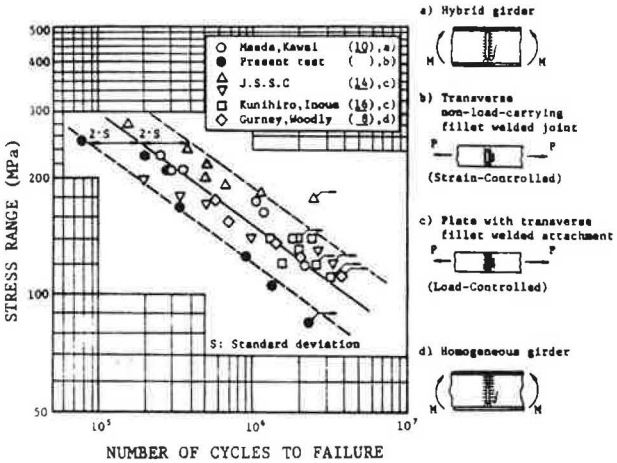
Note: 1 MPa = 145 lbf/in.^{2}

(82.5 kipf/in.^{2}) and 784.0 MPa (113.8 kipf/in.^{2}), respectively. Those specimens were provided with the same configuration as the present test specimens, but their test loads were controlled not by strains, but by loads from zero to tension. Since any significant difference among such results cannot be observed, the fatigue strength of such a welded joint with a large notch effect is almost identical one another, regardless of steel grade, stress ratio and again loading method.

3. Finally, Figure 7 shows the relation between girder tests (8, 10) and some model tests. The model tests results consist of the results of

the present tests and the previous ones in Japan (14, 16) on steel plates with a transverse fillet welded attachment without boxing parts. The present test results under relatively severe loading conditions, can be compared well with lower 95 % confidence limit line of all the quoted results except the present results. This implies that the present test results give conservative fatigue lives for Type-2 cracks in hybrid girders. Also, Figure 6 shows that the allowable fatigue stresses for Stress Category C specified at the AASHTO Specifications (17, p. 87), 1974, are reasonable for Type-2 cracks in hybrid girders.

Figure 7. Comparison of fatigue strength in girder tests with model specimen tests for Type-2 cracks.



Note: 1 MPa = 145 lbf/in.^{2}

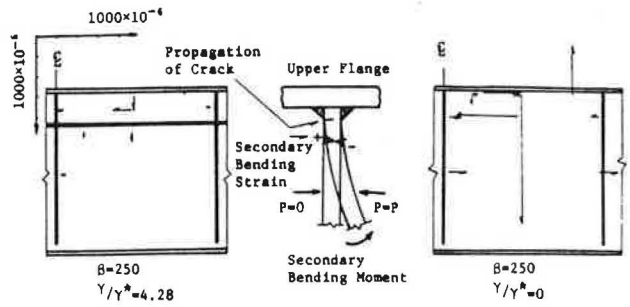
Type-1 Crack

Previous Girder Tests

At the Colloquium of IABSE on "Design of Plate and Box Girders for Ultimate Strength" in 1971, the author published a paper (6). In this paper, the author discussed on the results of flexural fatigue tests of six large-sized welded homogeneous plate girders subjected to repeated bending. The following facts were pointed out:

1. The maximum initial web deflections of 0.3 to 1.6 times the web thickness influenced greatly on the initiation of Type-1 cracks due to secondary bending moment, as seen in Figure 8, caused by lateral web movement under cyclic in-plane loading. Moreover, Type-1 cracks were observed in the case of transversely-stiffened plate girders with a web slenderness ratio larger than 200.
2. The test showed that it would be possible to prevent Type-1 cracks by providing with longitudinal stiffeners and also a smaller web aspect ratio. Rigidities of longitudinal stiffeners of the test girders were selected to 3.83 to 5.30 in terms of the relative flexural rigidity ratio. With a greater rigidity of longitudinal stiffeners, a larger ultimate strength could be achieved and an effective control against Type-1 crack could be expected.
3. In conclusion, the initiation and propagation of Type-1 cracks are influenced by web slenderness ratio, web aspect ratio, initial web deflections and if longitudinal stiffeners are provided with, their rigidity.

Figure 8. Initiation of Type-1 cracks and secondary bending at web boundary.

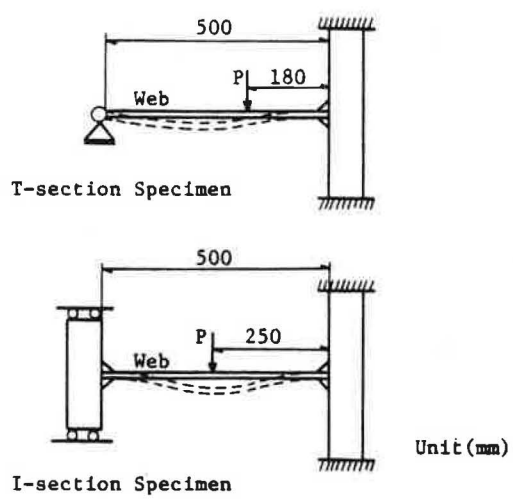


These girder tests, however, did not give sufficient informations of fatigue strength in the moment of initiation of the crack. Even a model specimen test to simulate the initiation and propagation of Type-1 cracks has hardly been reported, because of the complicated condition of cracking, except the values given by girder tests at Lehigh University. The author carried out two kinds of model specimen tests to obtain the fatigue strength against Type-1 cracks. The first plate-type test was intended for the investigation of initiation and propagation of cracks on a web surface along the toe line of fillet welds parallel to girder length. The second bar-type test which is still in progress, is to study on the initiation of cracks propagated through the web thickness.

Plate-Type Specimen Tests (18)

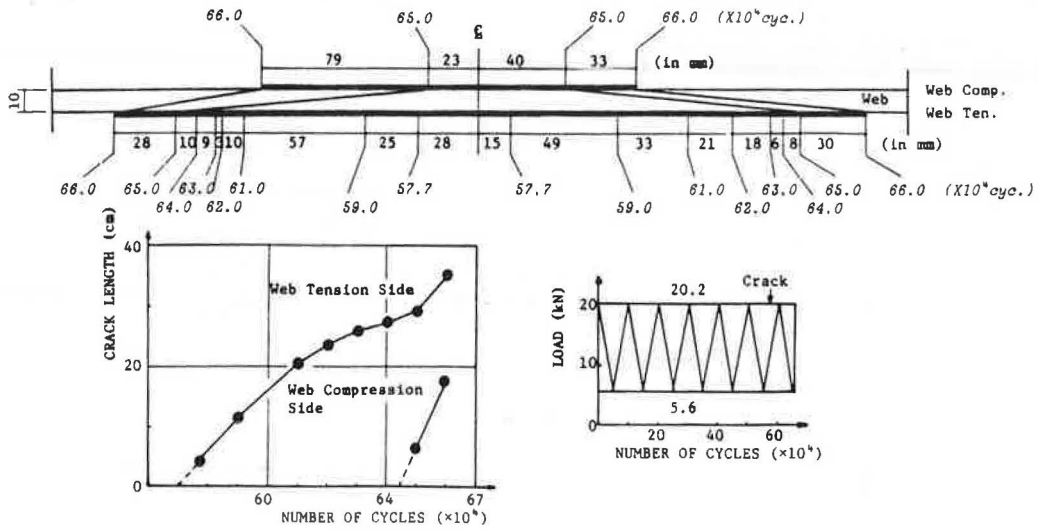
Fatigue tests of two kinds of plate-type specimens in SS41 steel were carried out, as seen in Figure 9, to simulate the fatigue of a web panel enclosed by a compression flange and a horizontal stiffener of a stiffened plate girder. The section of plate specimens was T-shape or I-shape, respectively modelling a less rigid horizontal stiffener or a greatly rigid stiffener. Because at the former specimen, a plate was hinged at the end of web of

Figure 9. Plate-type fatigue test specimens.



Note: 1 mm = 0.039 in.

Figure 10. Propagation of Type-1 crack.

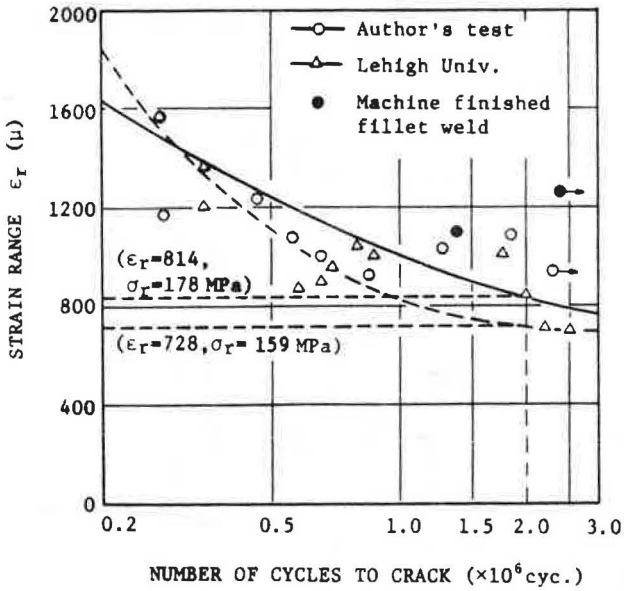


Note: 1 cm = 0.39 in. 1 mm = 0.039 in. 1 kN = 0.255 kip.

T-section and fixed to the flange at the other end, while at the latter specimen, a web plate of I-section is fixed to the both flanges. Deflections of the specimens under an applied concentrated load simulated the web deflections of an actual plate girder. Figure 10 illustrates the initiation and propagation of a fatigue crack observed at a T-section.

Figure 11 shows the test results in terms of the number of cycles at the crack initiation estimated from crack discovery and of the local strain range at the toe of fillet welds estimated by combined finite element analysis and strain measurement. The possibility of about 30 % increase of fatigue strength is expected by machine-finishing at the toe. The regression analysis shows that the fatigue strength at 2 x 10^6 cycles of the fillet weld is 814 x 10^{-6} in strain range or 178.4 MPa (25.9 kipf/in.^{2}) in stress range. Available values from the fatigue test of large-sized plate girders conducted by Yen and then modified by Ostapenko at Lehigh University (19, p. 49) are also given in Figure 11. There is considerable scattering among the test vakues to be attributed to inherent inevitable fine defects at the toe surface of fillet welds.

Figure 11. Test results for Type-1 cracks at Osaka University and Lehigh University.

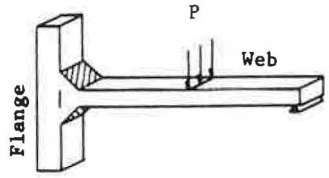


Note: 1 MPa = 145 lbf/in.^{2}

Bar-Type Specimen Tests

To investigate the mechanism of initiation of Type-1 cracks in the direction of web thickness, a series of fatigue tests for specimens of a Tee type fillet welded joint, as seen in Figure 12, was carried out. At the test, the steel of the specimens was 22 mm (0.866 in.) thick in SS41 of the yielding point of 235.2 MPa (34.1 kipf/in.^{2}) and the tensile strength of 401.8 MPa (58.3 kipf/in.^{2}). A repeated load was applied to the web plate of T-joint with 300 cycles per minute, so as to simulate the back and forth movement of the web plate due to its initial deflections of an original plate girder.

Figure 12. Profile of Bar-Type specimen.



As expected, a crack was initiated at either toe of fillet welds and propagated in the direction of the web thickness. The speed of propagation was measured with crack gauges spaced by 0.2 mm (0.008 in.). Furthermore, to examine how the fatigue strength against Type-1 cracks could be increased by finishing the surface of toes of fillet welds, B-series test, in addition to A-series test of as -welded specimens, was conducted with the test spe-

cimens of Tee type joint, in which the toes were finished with a circle radius of 2.0 mm (0.08 in.). Applied nominal stress ranges in a web section are shown in Table 2.

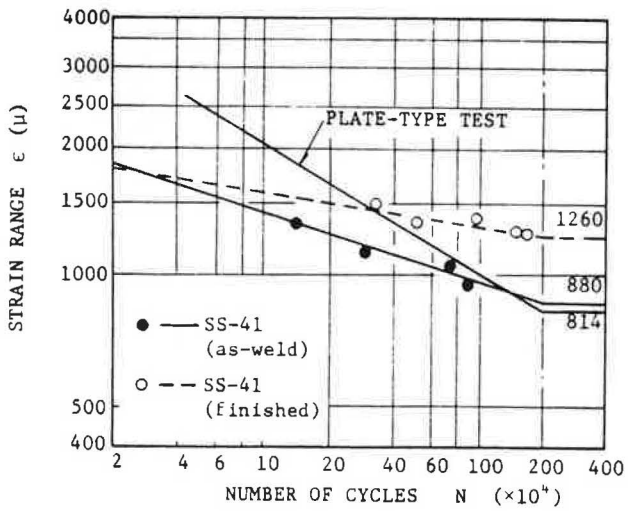
Table 2. Applied nominal stress ranges (Mpa).

Specimen	A-1	A-2	A-3	A-4	B-1	B-2	B-3	B-4	B-5
Stress Range	297	238	199	189	309	268	284	270	252

Note: 1 MPa = 145 kipf/in.^{2}

It was quite difficult to paste strain gauges on the toe of a fillet weld because of sudden sectional change at the toe. Then, in addition to strain gauges pasted on the web surface of the Tee section at the loading point, strain gauges were pasted on the web surface at a distance of 10 mm (0.4 in.) from the edge of the toe. Strains at the toe edge were estimated from the measured values of strains at those two points.

Figure 13. Strain range versus number of cycles.



Test Results. Figure 13 shows the test results of fatigue lives expressed in terms of strain range versus number of cycles. Two lines are obtained by the regression analysis of strains observed at the time when a crack propagated over approximately 11 mm (0.433 in.) which was half the web thickness. The fatigue strength at 2 x 10^6 cycles is 168.6 MPa (24.5 kipf/in.^{2}) in stress range or 880 μ (micron) in strain range for as-welded specimens, and is 242.1 MPa (35.1 kipf/in.^{2}) or 1260 μ for finished specimens. A considerable increase of fatigue strength is given by machine-finishing at the toe.

In Figure 13, strain range versus number of cycles for the plate-type tests obtained in Figure 11 is also shown. When a girder is subjected to a certain strain range at its toe of fillet welds in a compression flange-to-web joint, Type-1 crack will start in the direction of web thickness with smaller numbers of cycles than the ones given by Bar-Type tests in Figure 13. Because the curve in Figure 13 was determined by the propagation to about 11 mm (0.43 in.) growth. The growth rate of the crack in this direction is 1 x 10^{-5} to 2 x 10^{-4} mm/cycle (4 x 10^{-6} to 8 x 10^{-6} in./cycle) and is much slower than that of the crack in the direction of the toe line on the web plate.

Before the crack penetrates the web thickness, it will propagate along the toe line on the web surface with the number of cycles on the curve for Bar-type tests. The growth rate of the crack in this direction is 6 x 10^{-4} to 4 x 10^{-3} mm/cycle (2.4 x 10^{-5} to 1.6 x 10^{-4} in./cycle) and much faster than that in the direction of web thickness. Then, after the crack has propagated to a certain length along the toe line, it will penetrate into the back side of the web.

Thus, the crack grows three-dimentionally and Bar-type fatigue curve and Plate-type fatigue curve may not be compared under the same conditions. Further study is required. The initiation and propagation to a certain length do not mean the failure of the girder. As far as the present available informations are concerned, the fatigue curve of Bar-type tests may be considered a design criterion for fatigue. Then, the fatigue strength at 2 x 10^6 cyclea may be regarded about 800 μ in strain range and about 167 MPa (24 kipf/in.^{2}) in stress range.

Application of Fracture Mechanics. The stress intensity factor, K, for single edge-cracked bending in a plate is in general given by

$$K = \sigma_0 \sqrt{\pi a} \cdot F(a/W) \tag{1}$$

where σ_0 = the extreme flexural fiber stress, a = the crack length, W = the plate thickness and $F(a/W)$ = the flaw shape parameter. Since the shape of crack tip at the toe of a fillet weld is circular and the shape at the toe point is peculiar, the stress distribution along the crack interface is so complicated that the equation of $F(a/W)$ has not been derived for the present specimens. By applying stress extrapolation with a finite element method to the variation of K value due to the growth of crack length a, the following fourth-order polynomial equation of $F(a/W)$ can be obtained

$$F(a/W) = 2.40 - 7.90(a/W) + 30.10(a/W)^2 - 54.79(a/W)^3 + 46.38(a/W)^4,$$

$$0 \leq a/W < 0.7 .$$

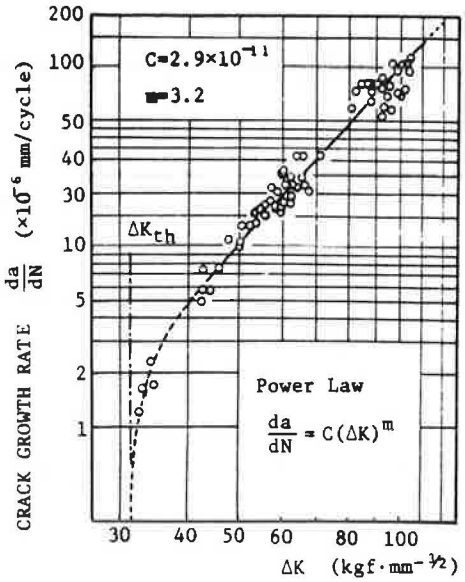
Next, if the measured rate of crack growth is assumed to be expressed as a power of the range of stress intensity, ΔK, as given by Paris (20, p. 70), the crack advance per cycle, da/dN, is shown by

$$da/dN = C \cdot (\Delta K)^m \tag{2}$$

where C and m are the material constants in crack propagation. By plotting test values of da/dN and calculated values of ΔK for arbitrary load range on da/dN versus ΔK diagram, C and m are obtained as 2.9 x 10^{-11} and 3.2 , respectively as shown in Figure 14. N-equation in Figure 15 shows that the integration of da/dN gives the number, N, of cycles required for the crack growth from a_0 to a_l. N-equation is calculated numerically from a_0 to a_l with

a_0 = an unknown initial crack length,
a_l = a certain final crack length within 11 mm (0.43 in.), and
N = the number of cycles corresponding to a

Figure 14. *(da/dN) - K* curve.



Note: 1 kgf·mm$^{-3/2}$ = 0.2822 kipf·in.$^{-3/2}$

Figure 15. *N* - equation.

$$\frac{da}{dN} = C(\Delta K)^m$$

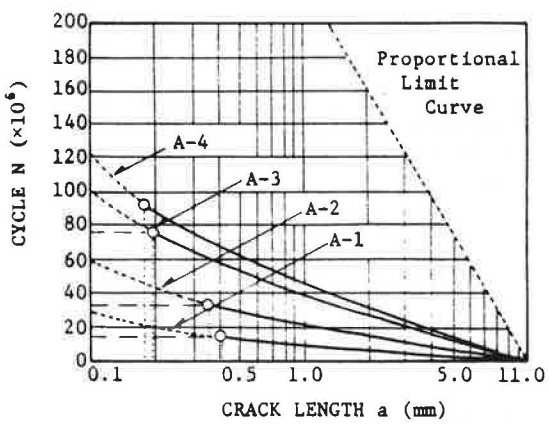
$$dN = \int_{a_0}^{a_1} \frac{1}{C(\Delta K)^m}\, da$$

$$\Delta K = \frac{6 \cdot M(a/W) \cdot \sqrt{a/W}}{W \cdot \sqrt{W} \cdot B} \cdot F(a/W) \cdot \Delta P$$

$$N = \int_{a_0/W}^{a_1/W} \frac{da}{C[6 \cdot B^{1} W^{3/2} \sqrt{a/W} \cdot F(a/W) \cdot M(a/W) \cdot \Delta P]^m}$$

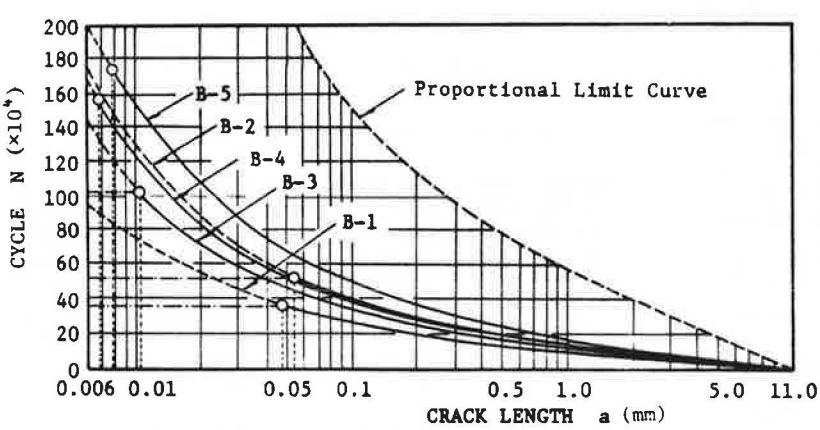
a_0 = initial crack length
a_1 = final crack length
W = web thick
B = web width
M(a/W) = moment

Figure 16. Crack propagation curves (as-welded).



Note: 1 mm = 0.039 in.

Figure 17. Crack propagation curves (finished).



Note: 1 mm = 0.039 in.

certain strain or stress range which is given in Figure 13.

Then, the curves of N versus $a = a_0 - a_l$ are obtained for as-welded specimens A-1 to A-4 and for finished specimens B-1 to B-5, respectively in Figure 16 and Figure 17. The unknown initial crack lengths a_0 are determined as shown by circles in the both figures. Such initial possible cracks are idealized initial cracks equivalent to defects like slug inclusion, undercut, blow hole, notch, etc. In other words, assuming a triger for the initiation of cracks to be such a defect due to welding or fabrication, the fatigue cracking will be interpreted as the propagation of such inherent initial cracks. This is the reason why the test specimens were not provided intentionally with an initial notch. At the application of fracture mechanics, it will be the best way to regard various weld defects as equivalent initial cracks.

In addition to the test of the rate of crack growth, the test to determine the threshold stress intensity factor for fatigue crack propagation, ΔK_{th}, was also conducted. By reducing a load range every crack growth of 0.2 mm (0.008 in.) after a crack had started, the values of ΔK_{th} was obtained

at the time when the crack finally stopped its growth. During the propagation of the crack at the test, the final value of ΔK_{th} was 33 kgf·mm$^{-3/2}$ (9313 lbf·in.$^{-3/2}$) for da/dN of 1.2 x 10^{-6} mm/cycle (0.047 x 10^{-6} in./cycle), as seen in Figure 14, and during the next 1 x 10^6 cycles for ΔK = 28 kgf·mm$^{-3/2}$ (7902 lbf·in.$^{-3/2}$), the crack growth was not observed, and then the test was stopped. Therefore, the value of ΔK_{th} may be approximately 30 kgf·mm$^{-3/2}$ (8466 lbf·in.$^{-3/2}$), below which the Paris equation cannot be applied to any stress range and which will give a limit shown as the proportional limit curve in Figures 16 and 17.

Conclusion.

1. Fatigue strength of Type-1 cracks at 2 x 10^6 cycles will be about 167 MPa (24 kipf/in.^{2}) in stress range in the direction of propagation toward the web thickness.

2. Mechanical-finishing at the toe on the web side of fillet welds will increase the fatigue strength considerably. At the present test, it will be about 40 % higher than the fatigue strength of the as-welded specimens in nominal stresses.

3. The application of fracture mechanics will be enable to evaluate fatigue qualitatively, so that micro initial defects may be evaluated without applying the theory of material science. The application of the Paris equation shows that the initial crack length equivalent to latent defects will be 0.18 to 0.41 mm (0.007 to 0.016 in.) for as-welded specimens (Figure 16) and 0.0068 to 0.053 mm (0.0003 to 0.002 in.) for finished specimens (Figure 17). Such estimation, however, has to be verified by more precise tests.

4. As stated previously, Type-1 cracks will propagate not only in the direction of web thickness, but also in the direction of the toe lines. Furthermore, a study on three-dimensional crack propagation has to be made.

Application to Design

1. As discussed above, the fatigue strength against the initiation of Type-1 cracks along the weld toe line at 2 x 10^6 cycles is 178.4 MPa (25.9 kipf/in.^{2}) and 164.6 MPa (23.9 kipf/in.^{2}), respectively in the plate-type tests for as-welded specimens and in the girder tests at Lehigh University. Also, the fatigue strength against the growth of a crack to half the web thickness is 168.6 MPa (24.5 kipf/in.^{2}) in the bar-type tests for as-welded specimens.

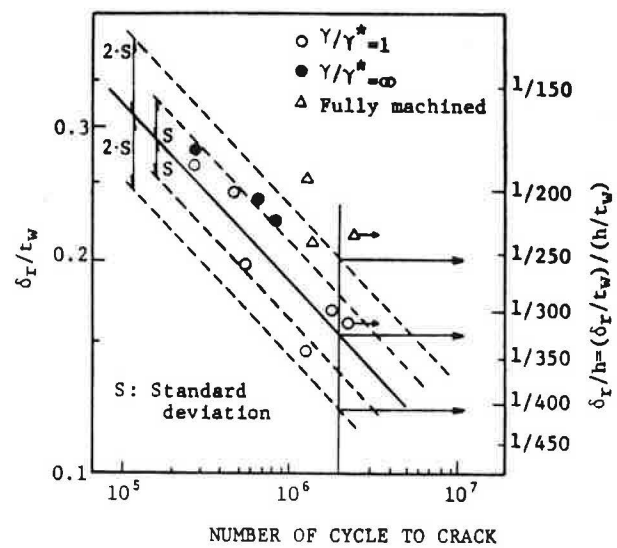
The fatigue strength may be estimated about 167 to 176 MPa (24 to 26 kipf/in.^{2}), but there are some problems to be solved. How much is the fatigue strength for different grade of steel other than SS41 grade steel? Which is the design criterion, the fatigue strength for cracks along the weld line on the web or that for cracks across the web thickness ?

2. The initiation of Type-1 crack is caused by out-of-plane deflections of a web plate due to initial deflections of the web, and the out-of-plane deflections are non-linear with in-plane bending stresses in the web. Therefore, the fatigue strength alone is not sufficient for a practical design purpose. The test results for the plate-type specimens are rearranged in Figure 18 in terms of the maximum web deflection in a compression sub-panel of the web and the fatigue lives. In the figure, the vertical axis on the left side shows the non-dimensional expression of the ratio of out-of-plane deflection range of the web to the web thickness, δ_r/t_w . The vertical axis on the right side gives the ratio, δ_r/h , of δ_r/t_w to the slenderness ratio, $\beta = h/t_w$, where h = the depth of a web sub-panel surrounded by a compression flange, a horizontal stiffener and two vertical stiffeners. From the diagram, the allowable amount of out-of-plane deflection under a live load will be determined for a certain web slenderness ratio.

For example, the value of δ_r/h at 2 x 10^6 cycles can be read as 1/325 as the mean value. Then, if $\beta = h/t_w$ = 50, the out-of-plane web deflection due to live load has to be controlled to about 1/6.5 of the web thickness.

3. In Figure 18, the full-line shows mean values obtained by the regression analysis of the plate-type test values of I-section and of T-section except machine-finished specimens. The most outside broken lines show the range of two times the standard deviation and can be regarded as the upper and lower limits of a scattering band. I-section models equivalent to $\gamma/\gamma^* = \infty$ of horizontal stiffeners, locate near the upper limit of the scattering band, compared with the lower values for T-section models equivalent to $\gamma/\gamma^* = 1.0$. This fact was confirmed at the author's previous girder test.

Figure 18. Out-of-plane deflection of web and fatigue lives of Type-1 crack.



4. Massonnet, Skaloud, Maeda, etc. reported that horizontal stiffeners with a large value of γ/γ^*, for example 3 to 7 recommended by Massonnet, is greatly effective for the increase of ultimate strength of a girder. Even if Type-1 crack was initiated, horizontal stiffeners with large rigidity can delay its propagation. According to Toprac's test (5), Type-1 crack was not observed in girders provided with a horizontal stiffener. Requirement for the number of γ/γ^*, however, has not been clarified. Figure 19 indicates the effect of web slenderness ratio and relative rigidity ratio of horizontal stiffeners on the number of Type-1 cracks observed at the tests at the University of Texas, Lehigh University and Osaka University. Type-5 cracks in the figure is a crack along a vertical stiffener observed for combined bending and shear.

In general, a horizontal stiffener takes great effect on preventing the upper sub-panel of a web from the development of greater web deflections, but

Figure 19. Web slenderness ratio, β , rigidity ratio parameter, γ/γ^*, and number of cracks.

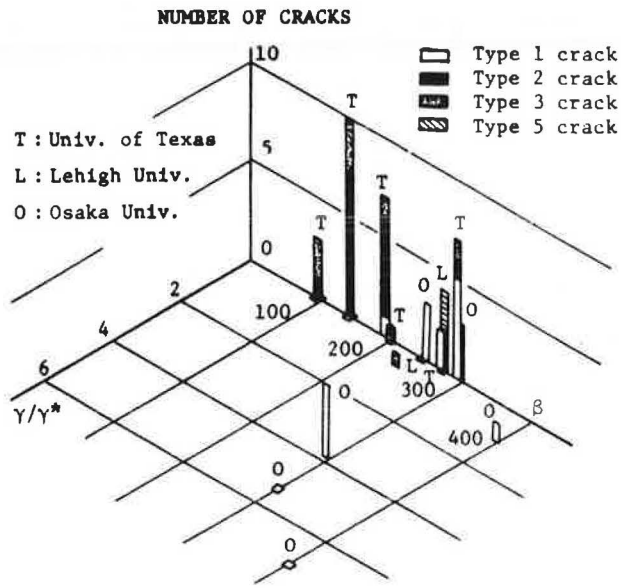


Figure 19 shows that the initiation of Type-1 crack was not observed for $\gamma/\gamma^* < 1.0$ or > 5.0, and also for less than 200 of β . With the intermediate number like $\gamma/\gamma^* = 3.83$ and $\beta = 300$, Type-1 crack was not observed. Since the effect of γ/γ^* has to be discussed in relation to aspect ratio, web slenderness ratio, secondary bending stress at flange-to-web connection and horizontal stiffener-to-web connection, a further study will be needed.

5. The author is carrying out an analytical and experimental studies to establish the relations among the maximum initial deflection, δ_0, the out-of-plane web movement, δ_p, the applied in-plane bending stress, σ and the relative rigidity ratio of horizontal stiffeners, γ/γ^* , with the equation

$$\delta_p/h = f(\sigma, \delta_0, \gamma/\gamma^*).$$

Summary Conclusion

Fatigue cracks of Type-1 and Type-2 proper to deep thin-walled stiffened plate girders were discussed through a number of tests of girders and model specimens.

When a plate girder either homogeneous or hybrid with a web in ordinary mild steel is subjected to repeated bending, the initiation and growth of Type-1 cracks will be prevented by controlling secondary bending stresses at the toe of fillet welds in a compression flange below about 167 to 176 MPa (24 to 26 kipf/in.^{2}). In addition to the stress control, mechanical-finishing at the toe or the control of initial web deflections will be very useful.

On the other hand, Type-2 cracks will be prevented by reducing web tensile stresses during repeated bending below about 93 MPa (13.5 kipf/in.^{2}) or by finishing at the toe of fillet welds in vertical stiffeners.

As far as Type-1 cracks are concerned, in-plane bending stresses of a web are related to secondary bending stresses of the web only by initial web deflections or out-of-plane movements. A survey of actual initial deflections of webs in plate girder bridges will be required.

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