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FATIGUE STRENGTH OF SCALLOP DETAILS IN STEEL BRIDGES†

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Fatigue strength of scallop details in welded structural members were investigated by experiment and FEM analysis. Fatigue strength of this detail based on nominal stress was extremely low because high stress concentration occurred in the gap of scallop. Fatigue strength based on hot spot stress are plotted on a narrow band above the JSSC's E class design curve (80 MPa for 2×10^6 cycles), which shows that fatigue assessment method based on hot spot stress is valid for estimating fatigue strength of scallop details.

KeyWords: *fatigue, scallop, stress concentration, shear deformation, hot spot stress*

1. INTRODUCTION†

For details where members intersect in welded structures , scallops or cope holes are generally provided to avoid crossing of weld lines. For example, joints of main girders and cross beams, cross beams and stringers in girder bridges, longitudinal ribs and transverse ribs or diaphragms in steel deck plates correspond to this. Furthermore, at parts other than intersections of members, scallops or similar details, e.g., scallops to avoid overlapping of flange joint and web joint in case of field welding of I section girders, exist in large number in structures.

Such scallops, because of their configurations, become causes of acute stress concentrations. Besides, the local reductions in stiffness due to the fact that gaps were left can cause the out-of-plane displacements in the gaps. By these reasons, fatigue strength of this detail is low, and fatigue damage often occur in actual structures [1)].

In this study, the fatigue properties of scallop details existing in I-section beam members bent in-plane are examined with the objective of proposing a method of fatigue assessment for this detail. This problem has not been examined very much except in studies by the authors concerning field welding details of reinforced flanges [2)]. However, local out-of-plane deformation behavior of scallop details and the importance of the influence of stress concentrations on fatigue have been pointed out from the past by Tajima and Yamashita. They have also carried out FEM analysis and loading tests on the connection details of truss structures [3)].

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2. SPECIMENS AND TESTING METHOD

The materials tested were SM490YA having the mechanical properties and chemical composition given in **Table 1**. The configurations and dimensions of the four specimens modeling scallop details are shown in **Fig.1**. Specimen 1 has four varieties of scallops with radii, R, of 25, 30, 35, and 40 mm. Specimen 2 has perpendicularly inserted plates which simulate the webs of crossing girders, and has six varieties of scallops with R of 25, 30, 40, 45, and 50 mm at both sides of the plates. Specimen 1a and Specimen 2a have boxing welds at starting points of scallops, while Specimen 1b and Specimen 2b do not have boxing welds.

Fatigue tests were performed by three point bending. The testing condition is shown in **Fig.2**.

The lower load was 1 tonf, the load range was

Table 1 Chemical Compositions and Mechanical Properties of Material

Type	Thickness (mm)	Y.S. (MPa)	T.S. (MPa)	El. (%)	C $\times 10^2$	Si $\times 10^2$	Mn $\times 10^2$	P $\times 10^3$	S $\times 10^3$
SM490YA	9	404	551	22	17	35	129	18	4
SM490YA	16	441	559	25	16	40	124	14	3

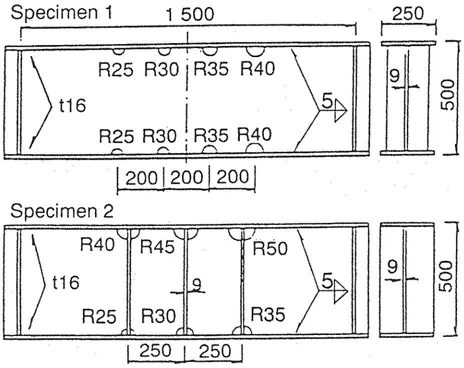

Fig. 1 Specimens

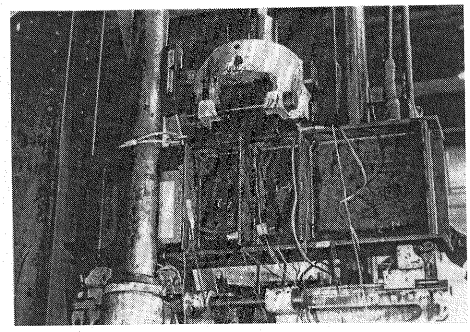

Fig. 2 Testing scene

40 to 45 tonf, and the rate of load repetition was 1 to 2 Hz. Specimen 2a was tested in the condition that the scallops of R of 25,30 and 35mm were in tension side, while Specimen 2b was tested in up-side-down, because it was found on the way of testing that larger scallop made fatigue strength lower as mentioned later.

3. FATIGUE TEST RESULTS

The conditions of fatigue crack occurrence are shown in **Fig.3**.

With Specimen 1, fatigue cracks all occurred at welded toes at sides distant from the loading point (sides closer to the supporting point) of flange plates inside of scallops. Fatigue cracks were observed at both upper flange and lower flange sides. The gap zones of flange plates sandwiched by scallops will be called flange gaps herein. With Specimen 2a, a fatigue crack occurred from the welded toe with the intersecting plate of the tension side scallop (R=30mm) just below the loading point, and this crack propagated vertically along the welding line. With Specimen 2b, a crack occurred at the tension side scallop (R=50mm) 250mm distant from the loading point. This crack initiated from the welded toe on the supporting point side of the flange gap similar to the Specimen 1.

The relationship between nominal bending stress range and number of cycles when superficial length of fatigue cracks became 10mm and 20mm are shown in **Fig.4**. In the Fatigue Design Codes of the Japan Society of Steel Construction (JSSC)[4], this detail is classified as Class G (50MPa for 2×10^6 cycles). Therefore, in the figure, the design curves of Class G and Class H (40MPa for 2×10^6 cycles), the lowest class in the JSSC Codes, are shown together. The test results are plotted in a range far lower than the design curve of Class H. This detail is classified into Joint Classification 71 (71MPa for 2×10^6 cycles) in ECCS , and Class F (68MPa at 2×10^6 cycles) in BS5400 and DNV. The classification of Class G in the JSSC Codes was set at a level considerably lower than that of other design codes based on the test results of reinforced flange details [2]. However, the results here indicate that even when Class H of JSSC were to be used for the nominal bending stress, the fatigue design for this detail is still inadequate. It may also be said that this low fatigue strength deviates from the scope of ordinary fatigue assessments based on nominal stress.

4. STRESS DISTRIBUTION AROUND SCALLOP

Stress distributions around scallops were investigated by strain measurements and finite element method (FEM). Shell elements were used in FEM analyses. When examining such stresses at local parts, the stiffness of welding beads cannot be ignored. Here, based on past studies and preliminary numerical examinations [5], the plate thickness at the part where the welding bead existed

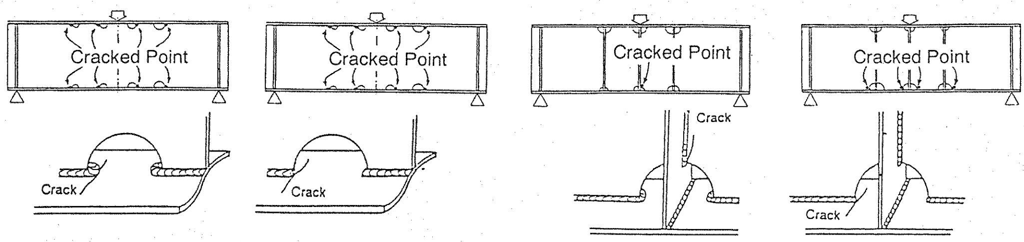

Fig. 3-a Specimen 1a **Fig. 3-b** Specimen 1b **Fig. 3-c** Specimen 2a **Fig. 3-d** Specimen 2b

Fig. 3 Fatigue cracks

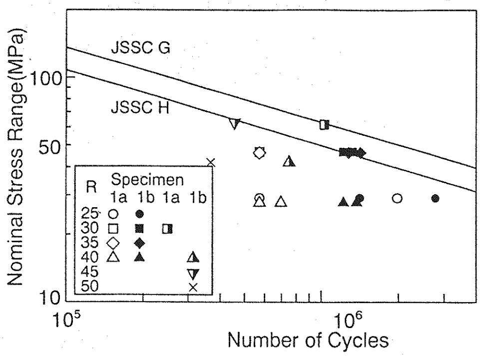

Fig. 4-a Crack length of 10mm

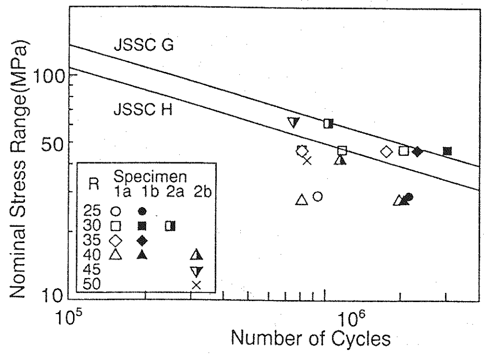

Fig. 4-b Crack length of 20mm

Fig. 4 S-N diagram arranged on nominal stress range

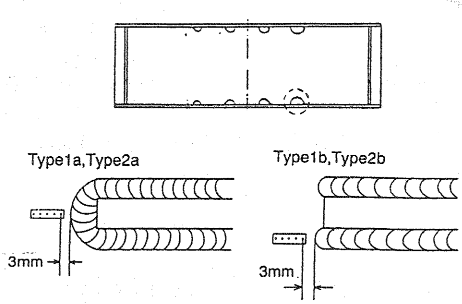

Fig. 5 Arrangement of strain gauges

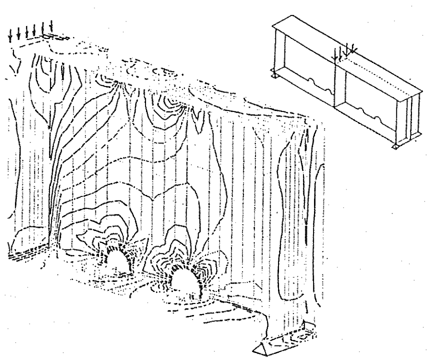

Fig. 6 Contour of principal stress of specimen 1

was increased to be 1/2 of the leg length added to the thickness of the base plate. Strains were measured using triaxial gauges of 1mm length and stress concentration gauges of 1mm length. The strain gauges were attached at the position shown in **Fig.5**.

(1) Web Scallop Detail (Specimen 1)

The finite element mesh and contours of principal stress obtained by FEM analysis are shown in **Fig.6**. It can be seen that very high stress concentration have occurred at welded toes of scallops.

Regarding stresses at flange gaps, the results of FEM analyses are shown in **Fig.7** with measured stresses and nominal stress calculated by the beam theory.

Comparing measured stresses with analyzed stresses obtained by FEM, it may be said there is a good agreement in spite of such very local stresses being considered. However, as a whole, the peak value of measured stress distribution was slightly higher than that of analyzed stress distribution. This difference is considered to be caused by the fact that the stiffness of welding beads in the vicinities of scallop starting points was not sufficiently taken into consideration in FEM analysis.

Sudden changes in stress are observed more re-

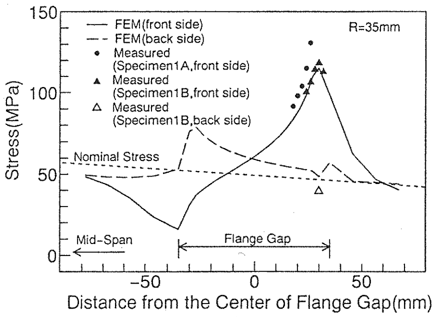

Fig. 7-a Tension side

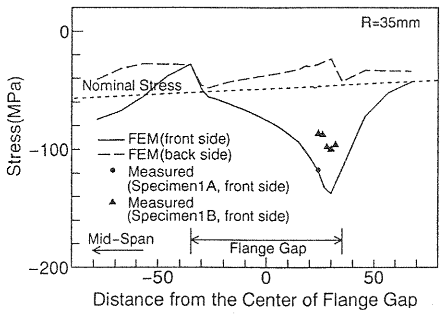

Fig. 7-b Compression side

Fig. 7 Stress distribution in flange gap of specimen 1

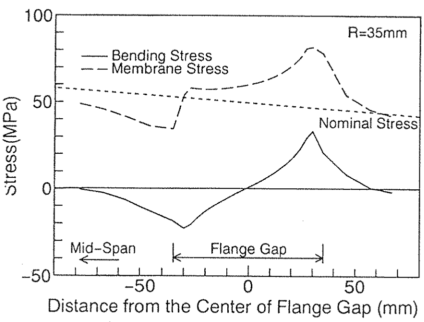

Fig. 8 Membrane and out-of-plane stress components

markably at the front side of the flange (web-flange weld side) than at the back side. At a scallop on the tension flange side, stress increases suddenly in the vicinity of the weld toe on the side of the supporting point, and reaches close to three times the nominal stress. On the other hand, stress decreases suddenly in the vicinity of the starting point at the side of the center of span. This property is opposite at compression flange-side of scallops. According to measured stresses, it may be said that the peak stresses in a specimen with boxing weld are higher than that without boxing weld.

Fig.8 shows the results of separating the stress

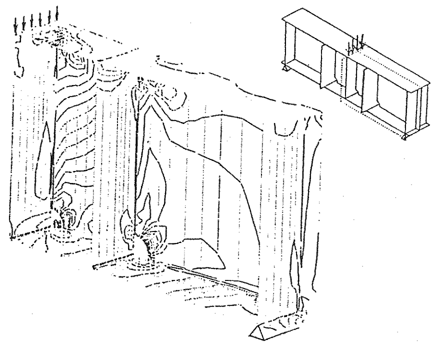

Fig. 9 Contour of principal stress of specimen 2

distribution obtained by FEM analysis of Specimen 1 into membrane stress component and out-of-plane bending stress component. It can be seen that local bending is induced at the flange gap, and stresses change suddenly in the vicinity of the scallop starting point with both the membrane stress and out-of-plane bending stress components.

(2) Girder Intersecting Detail (Specimen 2)

The contours of principal stress obtained by FEM analyses are shown in **Fig.9**. Very high stress concentrations have occurred at the flange gap and the welded toes of the intersecting plate on the side of scallop.

Measured stresses, nominal stresses calculated by beam theory, and FEM analysis results are shown in **Fig.10**. **Fig.10-a** shows the stress distribution at a scallop located 250mm away from the loading point and Fig.10b shows the stress distribution at a scallop located just under the loading point on the tension side. Comparing **Fig.10-a** with **Fig.7-a**, the peak stress in the vicinity of the scallop starting point in a specimen with an intersecting plate is slightly lower than that without an intersecting plate. This is considered to be due to the local deformation occurring at the scallop portion being restricted by the existence of an intersecting plate. Further, with Specimen 2 , sudden changes in stresses are observed at the middle part of the scallop (location where the intersecting plate is jointed) in addition to the scallop in the vicinity of the scallop starting point.

At a scallop directly below the loading point (**Fig.10-b**), stress at the top surface of the lower flange suddenly changes from tension to compres-

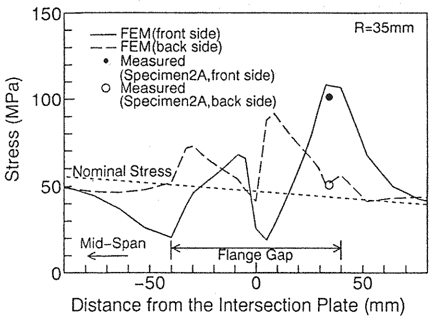

Fig. 10-a For scallop located 250mm away from the loading point

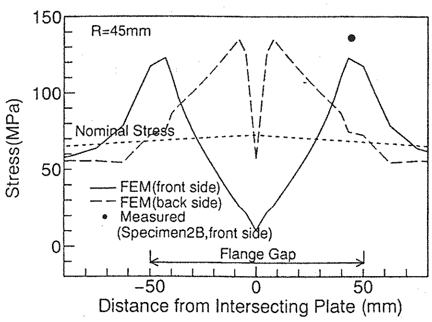

Fig. 10-b For scallop located directly below the loading point

Fig. 10 Stress distribution in flange gap of specimen 2

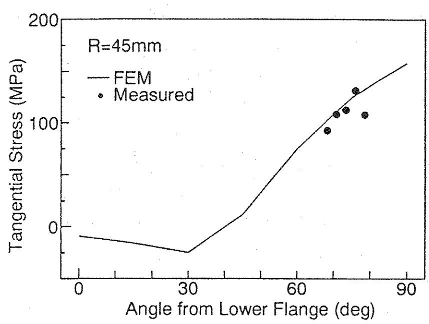

Fig. 11 Tangential stress along circumference of scallop in Specimen 2 (located directly below the loading point)

sion according to the location along the line from the starting point of the scallop to the intersecting plate, and this stress distribution is different from others. It is considered to be because load is transmitted directly to the lower flange through the intersecting plate and the lower flange is pushed by the plate.

The distribution of tangential stress along the periphery of the scallop is shown in **Fig.11**. The analyzed stress and measured stress show good agreement. A very high stress has occurred in

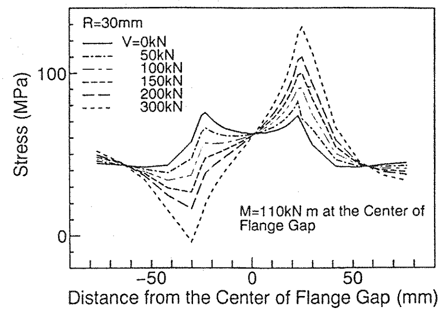

Fig. 12-a Specimen 1, Flange Gap

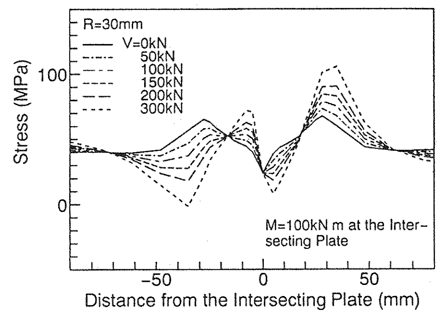

Fig. 12-b Specimen 2, Flange Gap

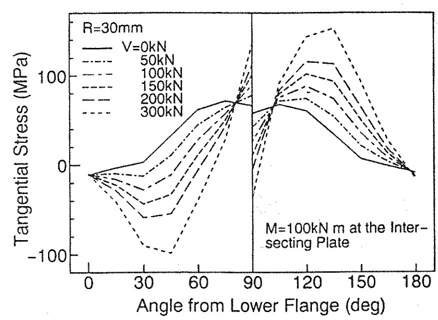

Fig. 12-c Specimen 2, tangential stress (just below the loading point)

Fig. 12 Influence of Shear Force on Stress in Flange Gap

the vicinity of the welded toe on the side of the intersecting plate, and this is slightly higher than the stress in the vicinity of the scallop starting point shown in **Fig.10-b**.

(3) Influence of Shear Force

The characteristic stress distributions at the fillet welded toes on the two sides of a flange gap are considered to be due to the influence of shear force. **Fig.12** shows the results of FEM analyses carried out on a model in which bending moment was kept constant and shear force was varied. With both Specimen 1 and Specimen 2, stress distribution in pure bending condition (shear force

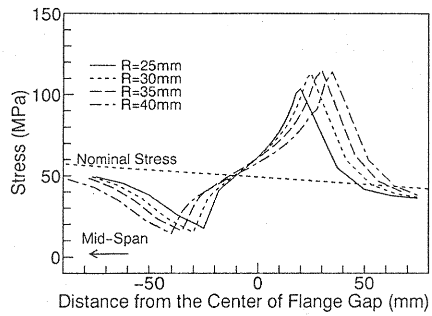

Fig. 13-a Specimen 1, Flange Gap

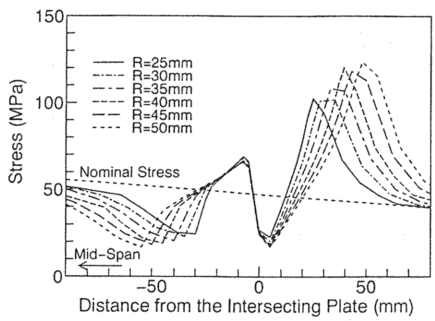

Fig. 13-b Specimen 2, Flange Gap

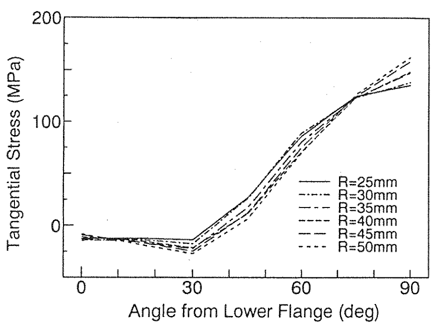

Fig. 13-c Specimen 2, tangential stress (just below the loading point)

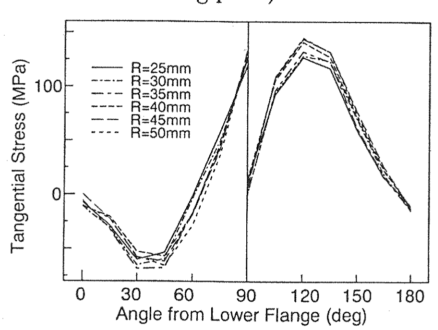

Fig. 13-d Specimen 2, tangential stress (250mm away from the loading point)

Fig. 13 Influence of scallop radius on stress

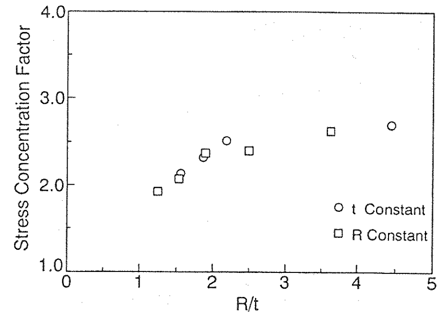

Fig. 14 Relationship between stress concentration factor and R/t

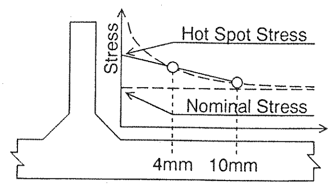

Fig. 15 Definition of hot spot stress

V=0) has a symmetric form, and stress concentrations are of the same degree. As shear force is increased, stress declines sharply in the vicinity of the starting point on the center side of span, while conversely, sudden increase of stress is observed at the starting point on the supporting point side. Also, stress in the vicinity of the welded toes on the side of the intersecting plate is increased as shear force becomes larger. That is, the stress distribution in the vicinity of the scallop starting point is subjected to the influence of shear force as well as bending moment.

Therefore, if a fatigue assessment for a structural detail including an in-plane scallop is performed by nominal bending stress only, it may be possible that stress concentration unimaginable from nominal stress will occur at a scallop starting point (especially, the starting point on the supporting point side) or at the weld of an intersecting plate and cause fatigue damage. When designing a member having an in-plane scallop structural detail, it is important that much attention must be given to the influence of shear force.

(4) Influence of Scallop Radius and Flange Thickness

Analyses were carried out on a model in which the locations of scallops was fixed so that magnitude of shear forces would be equal. In an analy-

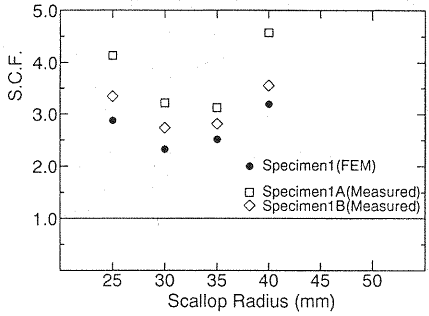

Fig. 16-a Specimen 1

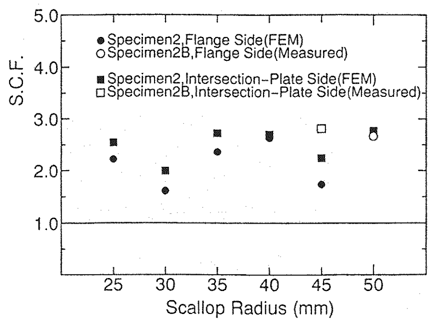

Fig. 16-b Specimen 2

Fig. 16 Stress concentration factors

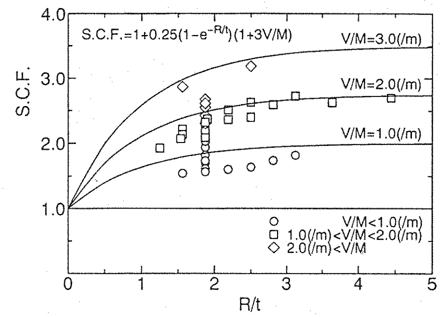

Fig. 17 Relationship between stress concentration factor and R/t,V/M

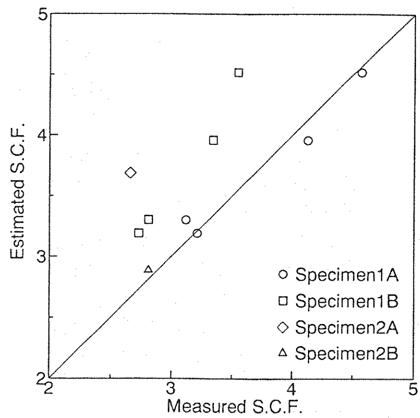

Fig. 18 Comparison between measured and estimated stress concentration factors

sis model, scallop radius R was varied with constant flange plate thickness t or t was varied with constant R. The results of analyses when plate thickness t was kept constant and scallop radius R was varied are shown in **Fig.13**. The peak stress at the flange gap is slightly increased as scallop radius is increased. For the welded toe on the side of the intersecting plate, stress is increased with the increase in scallop radius with regard to the scallop directly under the loading point, but regarding a scallop at a location away from the loading point, there is not so much influence from the scallop radius.

The relationship between R/t and the stress concentration factor defined later is shown in **Fig.14**. The stress concentration factor becomes larger as scallop radius is increased, but when R/t is equal to or greater than 2, the increase in stress concentration factor becomes smaller. Therefore, it may be said to be desirable for the scallop radius to be as small as possible. As all data are roughly on the same curve, the degree of stress concentration can be arranged with R/t when shear force is constant. That is, it may be said that the parameters influential on the local stress of the scallop are shear force and R/t.

5. FATIGUE ASSESSMENT BY HOT SPOT STRESS

(1) Method for Estimating Hot Spot Stress

In this study, hot spot stress was taken as the value extrapolated to the welded toe using the straight line connecting the measured stresses at points 4mm and 10mm away from the welded toe as shown in **Fig.15** [6)-8)]. The ratio between the hot spot stress defined in this manner and the nominal bending stress will be called stress concentration factor herein.

The analyzed and measured values of stress concentration factor are shown in **Fig.16**.

Comparing the measured values of identical scallop details of Specimen 1a with those of Specimen 1b, stress concentration factors of Specimen 1a are larger in all cases. This may be the influence of the rigidity of the welded toe being increased by boxing weld. With both Specimen 1a and Specimen 1b, the analyzed value is lower than the measured values, but it may be said that the qualitative property has been expressed well by the analyses. With Specimen 2, stress concentra-

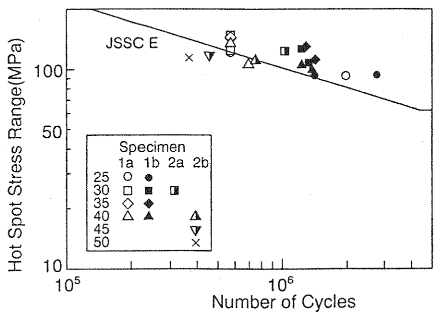

Fig. 19-a Crack length of 10mm

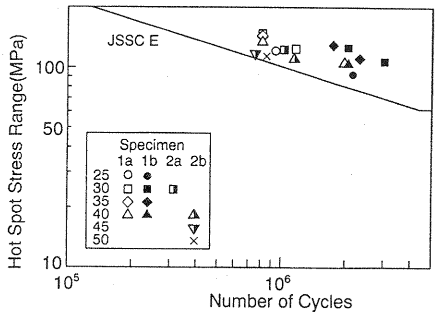

Fig. 19-b Crack length of 20mm

Fig. 19 S-N diagram arranged on hot spot stress range

tion factors at the welded toes at both the flange side and the intersecting plate side are shown. The nominal stress for calculating stress concentration factor was the value at the top surface of the lower flange in all cases. The stress concentration factors for scallop radii 30 and 45 mm just below the loading point are lower when compared with another scallops 250mm distant from the loading point. The stress concentration factors at the intersecting plate side are slightly larger than the values at the flange side for all scallops, but the differences are not so large when compared with the differences by shear force.

The stress concentration factors obtained in all of the analysis cases are summarized in **Fig.17**. The symbols in the figure are distinguished according to the ratio of shear force to bending moment, V/M. Since the stress distributions for the scallop just below the loading point in Specimen 2 are much different from others, they are excluded. In case of V/M of the same level, stress concentration factor is slightly increased as R/t becomes large. Besides, stress concentration factor becomes higher as V/M becomes large, and the influence of V/M is greater than that of R/t.

Based on **Fig.17**, it was considered that the stress concentration factor of a scallop detail can be estimated by the following equation:

$$S.C.F. = 1 + \alpha(1 - \exp(-\frac{R}{t}))(1 + 3.0\frac{V}{M}) \quad (1)$$

where V is shear force (tonf), M is bending moment ($tonf \times m$), R is scallop radius, t is flange thickness and α is an unknown parameter.

The curve for the case of $\alpha = 0.25$ is shown in the figure. In this case, the estimated value by this equation expresses well the trend of the analyzed value. However, since analyzed values were smaller than measured values, it is necessary for α to be taken larger by referring to **Fig.16** in order to estimate stress concentration in an actual member. After some trial calculations, it was found that the estimation by Eq.(1) gave a conservative result when taking $\alpha = 0.4$. The relationship between measured and estimated stress concentration factors when $\alpha = 0.4$ is shown in **Fig.18**.

(2) Fatigue Assessment

The relationships between hot spot stress range and the fatigue life when the crack length became 10mm and 20mm are shown in **Fig.19**. In contrasted to the large scatter when fatigue strength are arranged on nominal stresses (**Fig.4**), scatter becomes small when arranged on hot spot stress, and most of data are distributed at the regions of which the lower boundary is roughly Class E of JSSC. Consequently, as to the fatigue assessment method for scallop details, it is considered that fatigue strength can be evaluated more accurately by employing hot spot stress than nominal stress.

6. CONCLUSIONS

1. A very high stress concentration occurs locally due to shear deformation at the gap inside a scallop.
2. The degree of stress concentration in a scallop is greatly affected by shear force, and the stress concentration becomes higher as shear force becomes larger. Therefore, when designing a structural member with in-plane scallop details, the influence of shear force must be considered.
3. The stress concentration inside a scallop becomes lower as the ratio of scallop radius to flange thickness decreases. Hence, it is de-

sirable for scallop radius to be as small as possible.

4. A detail with boxing weld provided at the starting point of a scallop results in higher local stress than a detail without boxing welds.
5. When the fatigue strength of an in-plane scallop detail is assessed by nominal stress range, it is not sufficient even if Class H, the lowest of the joint classes of JSSC, were to be applied, and fatigue assessment by nominal stress is not possible.
6. An equation for estimating stress concentration factor, which is defined as the ratio of hot spot stress to nominal stress, was proposed. This equation needs two parameters, that is, the ratio R/t of scallop radius to flange plate thickness and the ratio V/M of shear force to bending moment.
7. When arranging the fatigue strength by hot spot stress range, test results were located within a narrow range of which the lower boundary is almost Class E of JSSC. Therefore, fatigue assessment by hot spot stress is effective for an in-plane scallop detail.

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