Fatigue Strength of Fillet Welded Steel Structure Under Out-of-plane Bending Load

S. W. Kang, W. S. Kim and Y. M. Paik

Abstract

The effect of out-of-plane loads on the fatigue strength of welded steel structures is examined through fatigue tests with weldment of two fillet weld joint types. The results of the fatigue tests are compared with those under axial loads, on the basis of the hot spot stress range at the weld toe. From the result of the comparison, a method on how to incorporate the effect of the out-of-plane bending stress is proposed using design S-N curves derived from fatigue tests under the axial load. The proposed method is useful for rational assessment of the fatigue strength of fillet-welded structures, where combined stresses of the in-plane axial stress and the out-of-plane bending stress are induced simultaneously due to the complexity of applied loads and structural geometry.

Key Words : Fatigue strength, In-plane stress, Out-of-plane bending stress, Fillet weld joint, Hot spot stress

1. Introduction

The fatigue strength of the welded ship structure is assessed on the basis of design S-N curves and Miner's accumulative damage rule with the stress spectrum in consideration of variable amplitude loads. Almost all design S-N curves till now have been derived from fatigue tests with small specimens of welded joints under axial loads (in-plane loads) only. Systematic fatigue tests under plate-bending loads (out-of-plane loads) for welded structures have been carried out rarely due to the difficulty of tests and the applicability of results to actual structures. In case of most of the hot spots of welded ship structures where the fatigue strength is concerned, combined stresses of the in-plane axial stress and the out-of-plane bending stress are induced due to complexity of applied loads and structural geometry. In this case, the classification societies recommend to assess the fatigue strength of the structure with the total stress value of the in-plane axial stress and the out-of-plane bending stress in conjunction with the design S-N curve, which is derived from axial tensile fatigue tests. This recommendation is only based on the assumption that the fatigue crack initiation life would be same as far as the value of the applied stress range is same whether it is the axial stress or the bending stress.

The design S-N curves for large welded structures are derived from the fatigue test results of load cycles at which the small welded specimens have failed completely. This procedure implies that the completely failed fatigue life of small specimens would be equivalent to the fatigue life of actual welded structures when some cracks are developed but not resulted in the catastrophic failure of the structure, considering redundancy of the structural strength by the structural members in neighborhood. As far as the completely failed life of the small specimens is concerned, it is expected that there would be huge differences in results between the fatigue test under in-plane axial loads and the one under out-of-plane bending loads. This is due to the crack propagation life which is taken into account the stress gradient through the thickness of test specimens. This means the classification societies' recommendation for the assessment of the fatigue strength of the structure is inconsistent with the procedure that the design S-N curves are derived. Accordingly, to assess the fatigue strength of welded ship structures more rationally, the effect of out-of-plane loads should be incorporated separately in lieu of the one of in-plane loads.

In this research work, fatigue tests for two fillet weld joint types, which are all typical in steel ship structure are carried out under out-of-plane bending loads and the results are compared with those under axial loads. From the results of the comparison, a method on how to incorporate the effect of the out-of-plane bending stress is proposed for the assessment of the fatigue strength of fillet welded ship structures using the design S-N curve derived from fatigue tests under in-plane loads. The proposed method is verified with the fatigue strength of

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the small structural model of the hopper corner.

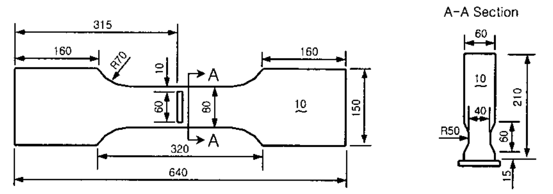
It is noteworthy that the main purpose of this r esearch work is much emphasized on the practical application to the ship structural design rather than on the academic investigation.

2. Test specimens under out-of-plane bending load

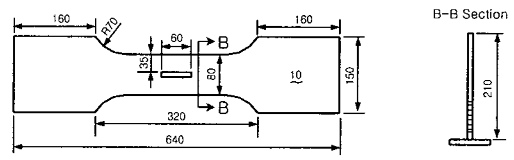
Details of specimens and the jig for the test used in this research work are illustrated in Fig. 1. (Hereinafter, specimens of the transverse fillet weldment and the box fillet weldment are called as Model 1 and Model 2 respectively.) The specimens are fabricated in accordance with actual shipbuilding workmanship and practice. The welding condition for the specimens is listed in Table 1. The material of specimens is ship structural mild steel of grade "A" with a nominal thickness of 10 mm. The major chemical composition and mechanical properties of the used steel are listed in Table 2.

Due to flexibility of the test jig supporting the test specimen, the end boundary condition of the specimen during the fatigue tests cannot be assumed as clamped. To evaluate rotational constraint effects at the ends, measurements of the stress distribution on main plates of the specimen are carried out. As illustrated in Fig. 2, one-dimensional strain gauges with a gauge length of 5 mm are bonded on both sides of main plates at 5 mm, 15 mm, 25 mm and 35 mm distance from the weld toe. By applying static loads of 1.962 kN for Model 1 and 3.223 kN for Model 2 at the attached plates, bending stress distribution on main plates of the test specimens are observed. The obtained bending stress distribution represents the stresses of the second load cycle of the static load. This load reduces the effect of the plastic deformation near the weld toe due to the residual welding stress in the first load cycle. Subsequently two FE analyses are carried out. The first analysis is by using beam elements whereas 4-node shell elements are used in the second analysis. In case of the beam element analysis, the specimen is represented by beam elements, which have the same cross sectional moment of inertia as that of the actual test specimen as illustrated in Fig. 3. The leg length of the weld bead is assumed to be 6.5 mm with the flank angle of 45°, which is the mean value of the actual measurements. Fig. 4 shows FE models with shell elements including the boundary and loading conditions. The shape of the weld beads is not incorporated in the shell element model directly. However the property of shell elements corresponding to weld beads is modified, as suggested by Machida[1].

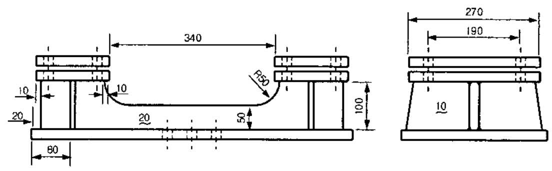
Based on the regressive FE analysis to results of the measurement of actual stress distributions on specimens, the rotationally constraint constant was determined as 90 kN-m/radian for the test jig. Fig. 5 shows comparisons of bending stress distributions between the results of measurements and those of FE analyses using the determined rotational constraint at the ends.



(a) Specimen of the transverse fillet weldment (Model 1)



(b) Specimen of the boxing fillet weldment (Model 2)



(c) Jig for the test

Fig. 1 Details of specimens and jig for the test (Unit: mm)

Table 1 Welding condition for the specimens

Current	Voltage	Speed	Method
250 A	26 V	30 cm/min	Semi-automatic CO_2

Table 2 Major chemical composition (%) and mechanical properties of mild steel

C	Si	Mn	P	S
0.13-0.2	0.1-0.19	0.51-0.79	0.008-0.025	0.003-0.007

Yield strength (MPa)	Ultimate strength (MPa)	Elongation (%)
290-333	427-457	26-34

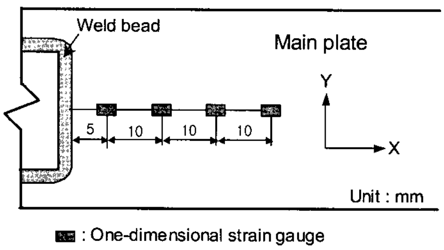
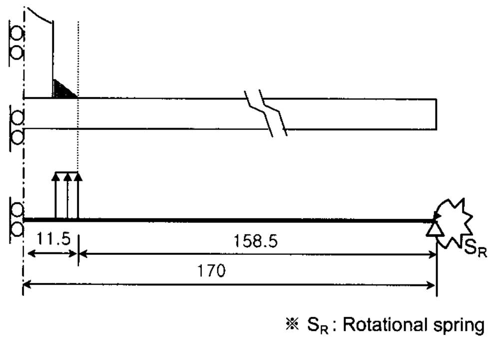
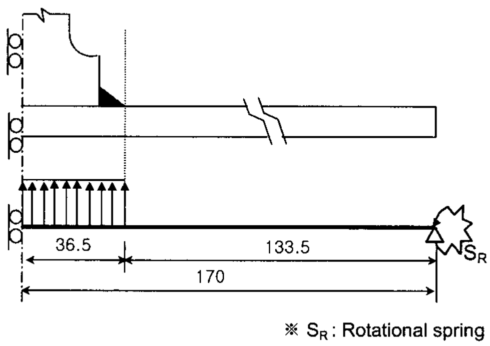


Fig. 2 Position of strain gauge

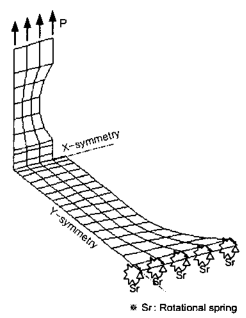


(a) Model 1

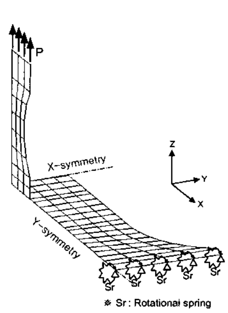


(b) Model 2

Fig. 3 Boundary and loading condition of beam element analysis

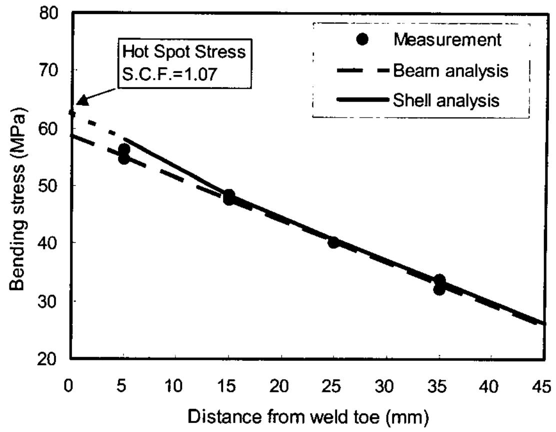


(a) Model 1

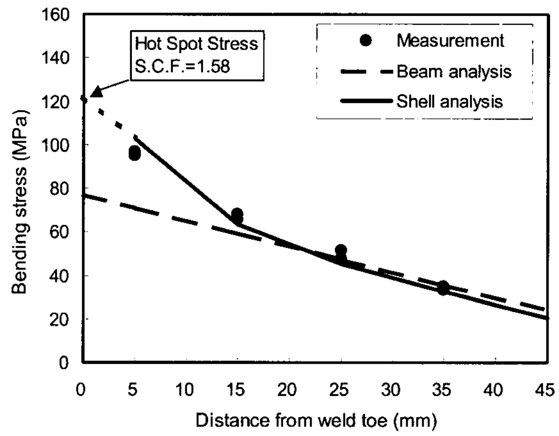


(b) Model 2

Fig. 4 Boundary and loading condition of shell element analysis



(a) Model 1 (Applied load = 1.962 kN)



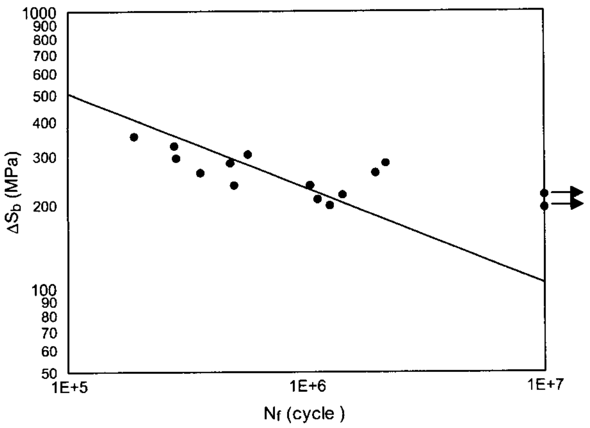
(b) Model 2 (Applied load = 3.223 kN)

Fig. 5 Comparison of plate-bending stress distributions between the measurements and FE analyses

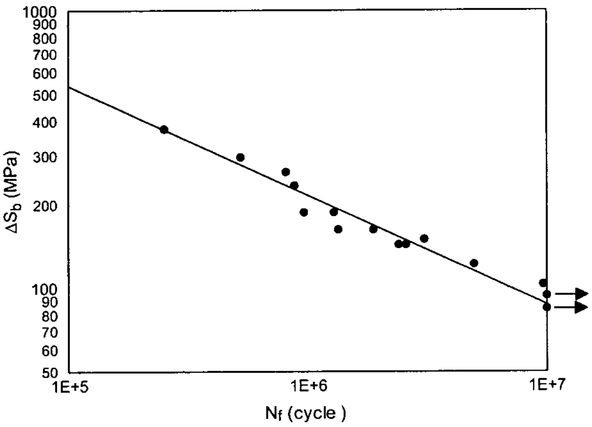
3. Fatigue tests under out-of-plane bending load

Fatigue tests are carried out under load-controlled bending loads with fully reversed constant amplitude at room temperature and in air. The test frequency is in the range of 3 to 10 Hz. Fatigue tests are carried out until around 1×10^7 load cycles and stopped unless a fatigue crack is detected visually.

The fatigue life of a specimen, N_f, is defined as the number of load cycles when the specimen is totally failed and the nominal plate-bending stress range, ΔS_b, is defined as the stress value obtained from the beam analysis at the weld toe. Fatigue test results with as-welded specimens are plotted in Fig.6, which represents the relation between ΔS_b and N_f.



(a) Model 1



(b) Model 2

Fig. 6 Fatigue test results under out-of-plane bending load

4. Comparison of fatigue strength

To evaluate fatigue strength properly, there should be consistency between the stress with which S-N curve is defined and the one with which fatigue strength is calculated. Most of the proposed S-N curves by international institutes, such as IIW[2)] and BS5400[3)] are defined with the nominal stress range and the related weld joint type. The nominal stress excludes the stress concentration due to geometric shape such as structural discontinuities and presence of attachments. At most of the critical points in ship structure where the fatigue strength is concerned, there are stress concentrations which depend not only on structural detail shapes but also on applied loading patterns. Furthermore, it is often very difficult to define the nominal stress due to the complexity of the structure and the loading. Therefore, it has been investigated that the hot spot stress is more recommendable to evaluate the fatigue strength of general welded structures, such as the ship structure, because it includes the stress concentration due to geometry of the structures[4)].

To determine the hot spot stress of Model 1 and Model 2, the stress concentration factors are calculated using the FE models shown in Fig. 4. In the FE model with 4-node shell elements, the size of the element at concerned area is about the thickness of the main plate, 10x10 mm. The commonly recommended procedure for the calculation of the hot spot stress in ship structures, i.e. linear extrapolation of stresses over reference points at 0.5 and 1.5 of plate thickness away from the hot spot, is adopted in the present work. The calculated stress concentration factors are 1.07 for Model 1 and 1.58 for Model 2, as illustrated in Fig. 5. The hot spot plate-bending stress range, $\Delta\sigma_{b,spot}$, is calculated by multiplying the stress concentration factors with the nominal plate-bending stress ranges, ΔS_b.

As a part of the Joint Industry Project 'FPSO – Fatigue Capacity'[5)], fatigue tests with small scale specimens of three fillet weld joint types, which were all typical in steel ship structure, were carried out under load-controlled axial loads with fully reversed constant amplitude at room temperature and in air. Fig.7 shows the three types of the specimens, (a) non-load carrying box fillet weldment, (b) weldment with gussets on plate edge and (c) weldment with padding plate on both sides, used for the fatigue tests under axial loads. The material and the welding conditions of the specimens were just same as those of Model 1 and Model 2. The fatigue test results of three types of the as-welded specimen are illustrated in Fig. 8. The test results coincided well with an S-N curve, which can be represented by the following equation on the basis of the hot spot axial stress range, $\Delta\sigma_{a,spot}$, irrespective of their weld joint type.

$$\log N = 14.415 - 3.776 \log \Delta\sigma_{a,spot} \quad (1)$$

The test results of Model 1 and Model 2 are illustrated in Fig. 8 on the basis of the hot spot plate-bending stress range, $\Delta\sigma_{b,spot}$. The fatigue strength under the plate-bending load is much higher than the one under the axial load even though the hot spot stress range is same. Through the comparison of the fatigue test results, it is clearly observed that the recommendation of classification societies, i.e. to assess of the fatigue strength with the total stress value of the in-plane axial stress and the out-of-plane bending stress on the basis of the design S-N curve derived from axial tensile fatigue tests, may lead to the mis-evaluation of the fatigue strength of ship structures. To assess the fatigue strength of ship structures rationally, the effect of out-of-plane bending stresses should be considered in a different manner. Assuming the inverse slope of the S-N curve as 3.776, which is the same value of the one under axial loads, the fatigue strength under plate-bending loads can be represented by following equation irrespective of weld joint types.

$$\log N = 15.276 - 3.776 \log \Delta\sigma_{b,spot} \quad (2)$$

From equations (1) and (2), the equivalent hot spot axial stress range, $\Delta\sigma_{a,spot}$, to the plate-bending stress range, $\Delta\sigma_{b,spot}$, can be expressed as given below with regard to the same fatigue life.

$$\Delta\sigma_{a,\,spot} = 0.592\ \Delta\sigma_{b,spot} \quad (3)$$

Accordingly, for the assessment of the fatigue strength of welded structures where combined stresses of the in-plane axial stress and the out-of-plane bending stress are induced simultaneously, it is recommended to apply the equivalent hot spot stress range, $\Delta\sigma_{e,spot}$, expressed as given below, on the basis of design S-N curve derived from fatigue tests under axial loads.

$$\Delta\sigma_{e,spot} = \Delta\sigma_{a,spot} + 0.592\ \Delta\sigma_{b,spot} \quad (4)$$

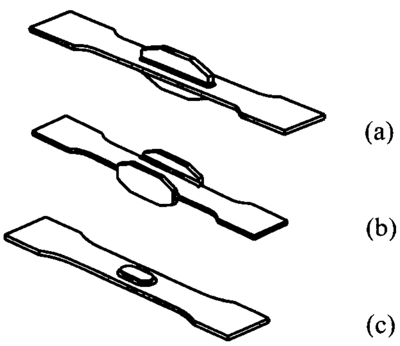


Fig. 7 Shapes of specimen of (a) non-load carrying box fillet weldment, (b) weldment with gussets on plate edge and (c) weldment with padding plate on both sides

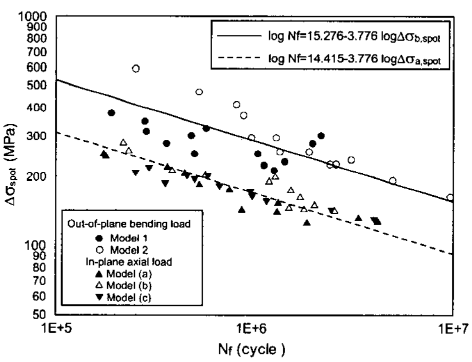


Fig. 8 Comparison of fatigue test results under in-plane axial load and out-of- plane bending load

5. Fatigue strength of small structural model of hopper corner

To verify the applicability of equation (4), the fatigue test results of the small structural model of the hopper corner, where the in-plane axial stress and the out-of-plane bending stress are induced simultaneously due to the structural geometry, are examined. The shape and size of the structural model of the hopper corner is illustrated in Fig. 9. The material for the hopper corner model is the high tensile steel of grade "AH32" with a nominal thickness of 10 mm. The major chemical composition and mechanical properties of the used steel are listed in Table 3.

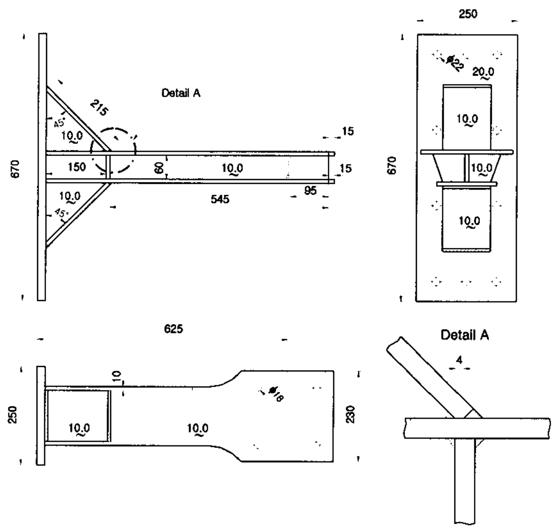


Fig. 9 Shape and size of specimen of weldment of hopper corner structure(Unit: mm)

Table 3 Major chemical composition (%) and mechanical properties of high tensile steel of grade "AH32"

C	Si	Mn	P
0.16	0.18	0.96	0.012
	Yield Stress (MPa)	Ultimate Strength (MPa)	Elongation (%)
From Mill Sheet	358	490	26
From Tensile Test	319~333	514~531	28~36

Fatigue tests of the as-welded hopper corner model are carried out under load-controlled axial loading with fully reversed constant amplitude at room temperature and in air. The position where fatigue cracks initiate is at the weld toe of the intersection of the inner bottom plate and the hopper plate as shown in Fig. 10. In this section, the fatigue crack initiation life of the test model, N_i, is defined as the number of load cycle when a crack is first detected visually, and the fatigue failure life, N_t, is defined as the number of load cycle when the crack penetrates fully through the thickness of the inner bottom plate.

Fig. 11 shows the FE model, which is used to calculate the hot spot stress of the hopper corner model. The model constitutes of 4-node plane stress elements of which the size at concerned area is equal to the thickness of the inner bottom plate, 10x10 mm. The weld is ignored in the model. Fig. 12 shows resulted distributions of the membrane stress and the plate-bending stress at the inner bottom plate in the longitudinal direction. The values of the stress are at the centerline of the model from the intersection point of the inner bottom plate and the hopper plate ignoring the weld. To get the stress distributions at the centerline of the model, linear extrapolations of two values of the stress at distance of t/2 and 3t/2 from centerline are performed. Subsequently by additional linear extrapolation of the two values of stress at distance of t/2 and 3t/2 of the centerline to the intersection point, the stress concentration factors for the hot spot stress are obtained as 1.563 in case of the membrane stress and as 7.853 for the plate-bending stress. Due to the geometry of the structure, the stress concentration factor for the plate-bending stress is very high.

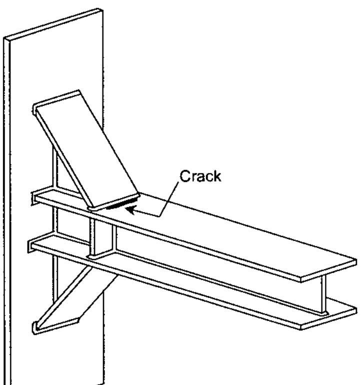


Fig. 10 Crack initiated points during fatigue tests

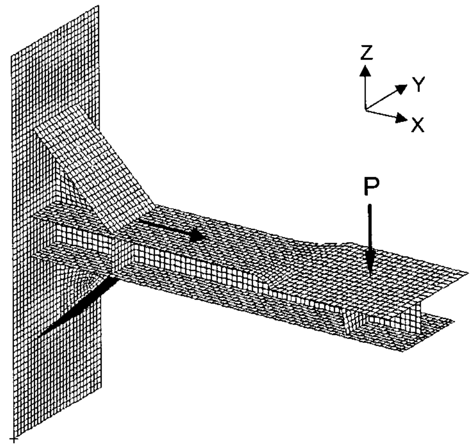


Fig. 11 FE model to calculate hot spot stress of hopper corner model

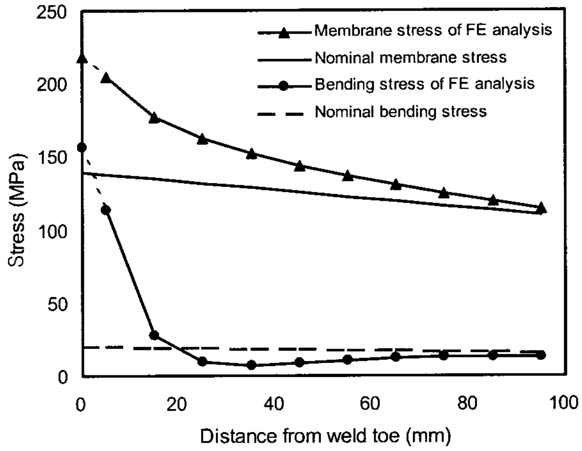
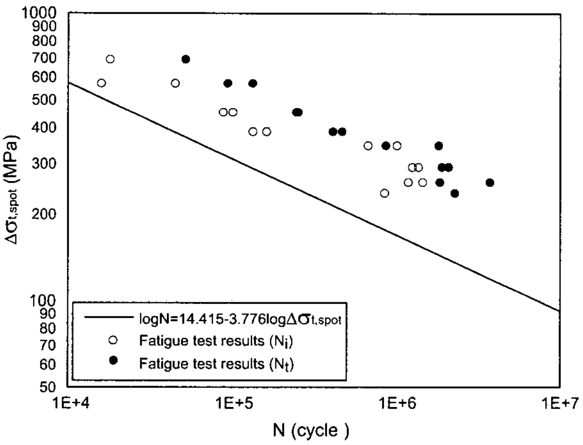
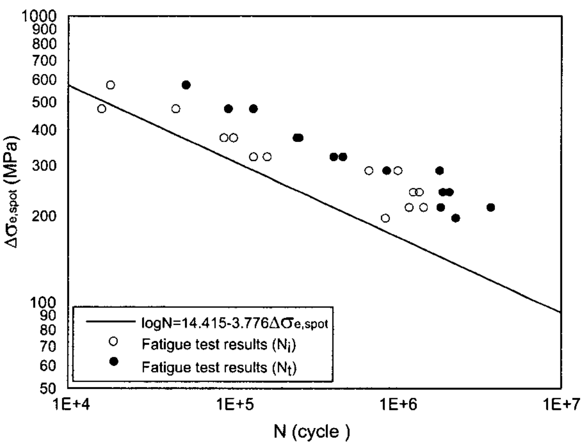


Fig. 12 Distribution of stress at inner bottom plate in longitudinal direction

Fig. 13 shows the comparison of the fatigue test results of the hopper corner model and the S-N curve of equation (1), which is derived from the fatigue tests of small-scale specimens. Fig. 13(a) is the case that the test results are defined on the basis of the hot spot total stress range, $\Delta\sigma_{t,spot}$, which is merely the value of the sum of $\Delta\sigma_{a,spot}$ and $\Delta\sigma_{b,spot}$ as recommended by classification societies. According to the recommendation of the classification societies, the fatigue strength of the hopper corner model is much underestimated. Fig. 13(b) is the case that the test results are defined on the basis of the equivalent hot spot stress range, $\Delta\sigma_{e,spot}$, in equation (4), which is the value considering the effect of the out-of-plane bending stress on the fatigue strength of fillet weld joints. The fatigue strength of the hopper corner model may be estimated better based on the equivalent hot spot stress range. It means the effect of the out-of-plane bending stress should be incorporated separately for rational assessment of the fatigue strength of welded ship structures where the in-plane axial stress and the out-of-plane bending stress are induced simultaneously due to the complex structural geometry.



(a) Based on $\Delta\sigma_{t,spot}$



(b) Based on $\Delta\sigma_{e,spot}$

Fig. 13 S-N curve of small scale specimen and fatigue test results of hopper corner model

6. Concluding Remarks

To investigate the effect of out-of-plane loads on the fatigue strength of welded ship structures, fatigue tests for two fillet weld joint types, which are all typical in steel ship structure, have been carried out. The results are compared with those under axial loads. The fatigue strength under the out-of-plane load is much higher than the one under the in-plane load in case the value of the hot spot stress range is same. Based on these results of the comparison, a method is proposed to incorporate the effect of the out-of-plane bending stress for the rational assessment of the fatigue strength of fillet welded ship structures in conjunction with the design S-N curve which is derived from fatigue tests under in-plane loads. The proposed method is verified by the experimental investigation on the fatigue strength of small structural models of a hopper corner. The fatigue strengths of the hopper corner model are agreed well with the proposed method in which the effects of the out-of-plane bending stress are incorporated. The procedure recommended by the classification societies, in which effects of plate-bending stresses are not considered, underestimates them too much. Therefore, to assess the fatigue strength of welded ship structures more rationally, it is recommended to incorporate the effect of plate-bending stresses.

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