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A Proposed S-N Curve for Welded Ship Structures

A hot-spot stress-based design S-N curve for fillet weld joints takes into account the effects of static cargo loads

BY S. W. KANG AND W. S. KIM

ABSTRACT. Static loads on ship structures induced by cargo loading cause relatively higher stress histories at welded joints compared with cyclic loads induced by waves. Due to these static loads, the initial tensile residual stresses at welded joints are shaken-down to a great extent by the elastoplastic deformation behavior of the material. The redistribution of initial welding residual stresses by the preload was evaluated using finite element (FE) analysis and compared with the results obtained from an ordinary sectioning method for three types of welded specimens, which were all typical fillet weld joints in ship structures. Fatigue tests were performed to evaluate the effects of shaken-down residual stresses on the fatigue strength of the fillet weld joints. The effects of the tensile mean stress on the fatigue strength of preloaded specimens were investigated as well. From the results of fatigue tests, an empirical formula of S-N curves, taking into account the effect of the arbitrary preload and mean stress associated with static loads, was derived based on the hot-spot stress range. The standard deviation between the formula and fatigue test results was calculated. With 2.35% of probability of failure, "HD S-N Curve (Hot spot-stress based Design S-N Curve)" was proposed.

Introduction

Tensile residual stresses generally exist up to the yielding point of the material around welded joints. Much research has been carried out on the effects of residual stresses on fatigue strength. Most of this research work, however, has concentrated on the effects of initial welding residual stresses. Only a few research works were performed on the effect of redistribution of residual stresses caused by the actual service condition on fatigue strength (Refs. 1, 2).

Static loads on a ship structure, induced either by water pressure before service or by cargo pressure during the first laden voyage, cause relatively higher stress history at welded joints, compared with cyclic loads induced by waves during service. Scantlings of main ship structure are generally determined under the rule requirements of classification societies (Refs. 3–5), and the values of allowable nominal stress by design static loads are in the range of approximately 50–70% of the yield points of materials. In ship structure, local stress concentration is inevitable due to structural geometry or discontinuity. In most cases, the fatigue damage occurs at these stress-concentrated points. Due to static loads, the initial tensile residual stresses at welded joints, where fatigue strength is concerned, are expected to be shaken-down to a great extent by the elastoplastic deformation behavior of the material, although the behavior of global structure is elastic. Ship structural members are subsequently exposed to cyclic loads during service. It is therefore imperative to verify the fatigue characteristics related to the redistributed residual stresses to assess the fatigue strength of the ship structure properly.

KEY WORDS

Residual Stress
Preload Effect
Mean Stress Effect
Hot-Spot Stress
S-N Curve
Fatigue Analysis

It was also reported that the effect of cyclic stress ratio (minimum stress/maximum stress) on the fatigue strength of a structure under the initial residual stress condition by welding was minor (Ref. 6). Therefore, the mean stress effect on the fatigue strength of structures is minor, based on exposure to cyclic loads under as-welded conditions. However, the effect of a certain level of mean stress associated with static loads of cargo or ballasting would not be minor in the case of ship structures with residual stresses shaken-down by fairly large static loads, when exposed to cyclic loads induced by waves.

In this research work, the redistribution of residual stresses by the static preload was evaluated using FE analysis and compared with the results obtained from an ordinary sectioning method for three types of small specimens: a non-load-carrying box fillet weldment (Model 1); a weldment with gussets on the plate edge (Model 2); and a weldment with padding plate (Model 3). These were all typical fillet weld joints in a ship structure. Fatigue tests were performed to evaluate the effect of shaken-down residual stresses on the fatigue strength of as-welded specimens and that of statically preloaded ones. The effects of the tensile mean stress on the fatigue strength of preloaded specimens were investigated as well.

Distribution of Residual Stress

Details of the specimens are illustrated in Fig. 1. The welding condition for specimens is listed in Table 1. The specimens were fabricated in accordance with actual shipbuilding workmanship and practice. The material for the specimens was ship structural mild steel of grade A. The major chemical composition and mechanical properties of the steel are listed in Table 2. Although actual yielding stresses of the material were about 300 MPa, classifica-

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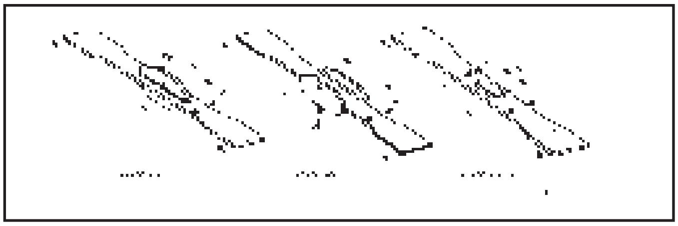


Fig. 1 — Details of specimen.

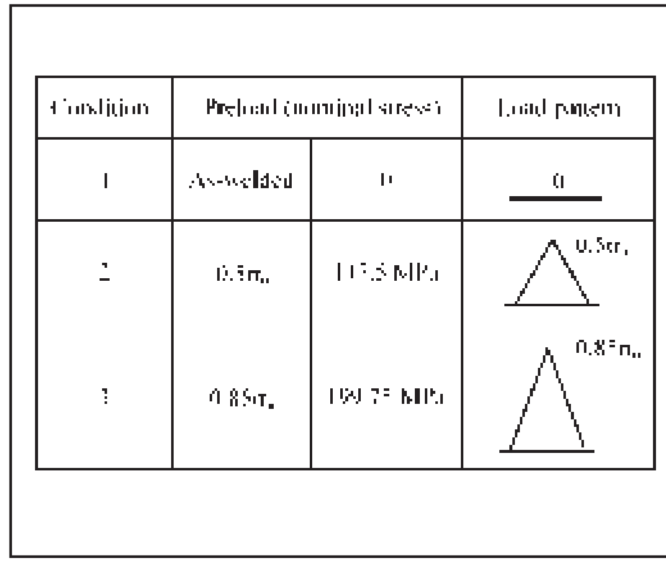


Fig. 2 — Static preload conditions.

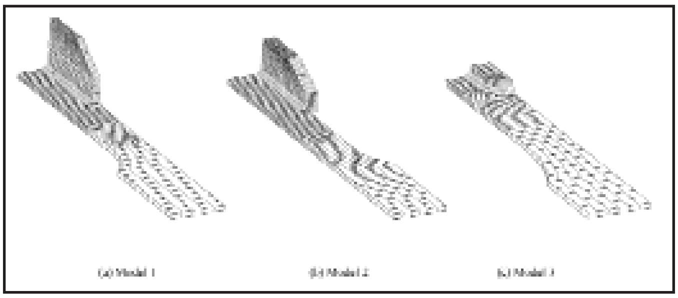


Fig. 3 — Finite element models for simulation of residual stress distribution.

Table 1 — Welding Condition

Current	250 A
Voltage	26 V
Speed	30 cm/min
Method	FCAW

Table 2 — Major Chemical Composition and Mechanical Properties of Mild Steel

Chemical Composition (%)

C	Si	Mn	P
0.13~0.17	0.15~0.18	0.46~0.65	0.012~0.019

Mechanical Properties

Yield Stress (MPa)	Tensile Strength (MPa)	Elongation (%)
290~299	427~457	34~36

tion societies define the design yield stress of σ_o as 235 MPa for ship structural mild steel. In this regard, hereinafter, the design yield stress σ_o is defined as 235 MPa according to the classification societies' specification.

Distributions of residual stresses of the specimen under three statically preloaded conditions, which are illustrated in detail in Fig. 2, were evaluated by FE analysis and measured by a sectioning method.

Condition 1 was the as-welded condition; condition 2 had a preload inducing 0.5 σ_o of tensile nominal stress; condition 3 had a preload inducing 0.85 σ_o of tensile nominal stress.

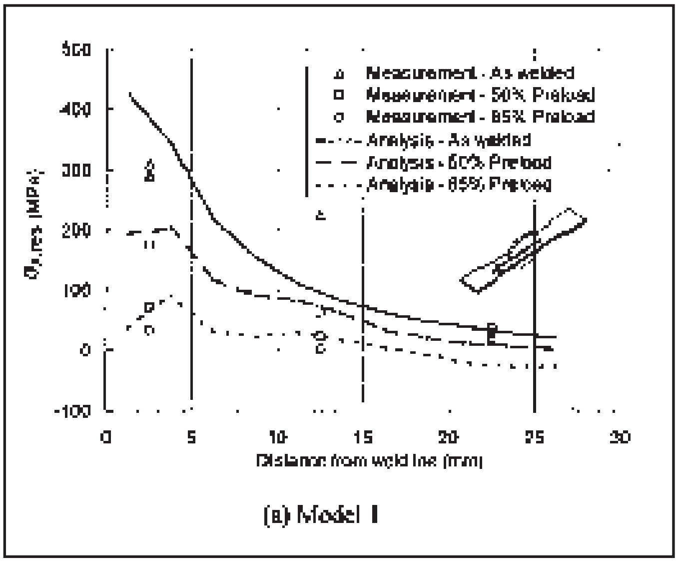
Thermo-elastoplastic FE analyses were performed using the models shown in Fig. 3 to simulate residual stress distributions by welding, and redistributions of residual stresses by preloads. One-eighth of the specimen was modeled imposing symmetric boundary conditions. Elements were 8-noded solids, and the element sizes around the weld toe were about one-fourth of the plate thickness. Mechanical properties of the stress-strain relation and material hardening due to welding were obtained from the tensile test and the hardening test. After the heat input, which was calculated from the welding condition, was fluxed to the weld bead elements, the distributions of the temperature were calculated by a transient thermal conduction analysis ignoring heat convection and radiation to the air. With the calculated distributions of the temperature with respect to time, a thermo-elastoplastic analysis was carried out to simulate initial welding residual stress distributions. From the status of the initial welding residual stresses, the static preloads depicted in Fig. 2 were applied to models to simulate redistributions of residual stresses by an elastoplastic analysis.

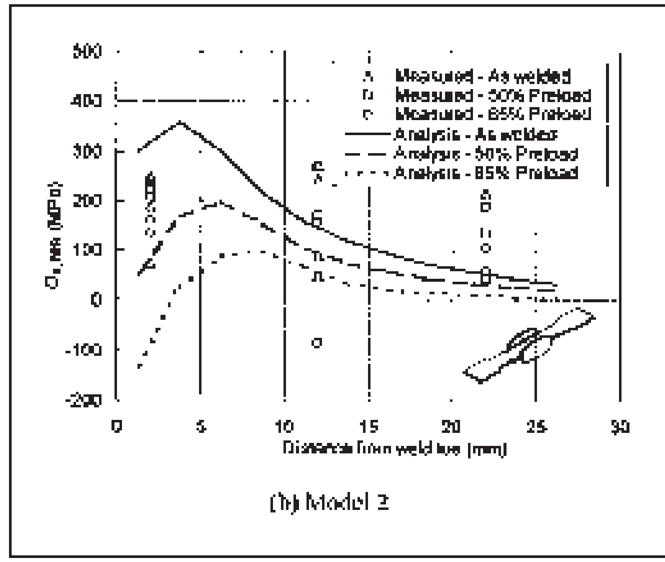
Initial residual stresses by welding and redistributed residual stresses by preloads were measured as well by using an ordinary sectioning method. Two-dimensional strain gauges with a gauge length of 1 mm were bonded on both sides of the main plates at 2-mm, 12-mm and 22-mm distances from the weld toe. Then, by sectioning the main plates around the strain gauges into small cubes, released strains were measured and converted into residual stresses using the following relationship.

$$\sigma_{x,res} = \frac{E}{1-\nu^2}\left(\Delta\varepsilon_x + \nu\Delta\varepsilon_y\right) \quad (1)$$

where, $\sigma_{x,res}$ is the residual stress in the longitudinal direction of the specimen, $\Delta\varepsilon_x$ is the released strain in the longitudinal direction of the specimen, $\Delta\varepsilon_y$ is the released strain in the transverse direction of the specimen, ν is Poisson's ratio (= 0.3), and E is Young's modulus (= 2.06×10^5 MPa).

The results of the FE analysis and the measurement for initial welding residual stress distribution and redistributed residual stresses by preloads are shown in Fig. 4. According to the results of FE analysis, the initial welding residual stresses near the weld toe of the main plate almost reach the yield stress of the material or more. The initial welding residual stress decreases from a tensile preload. The bigger the preload becomes, the more the residual stress decreases. Magnitudes of shaken-down residual stresses obtained by





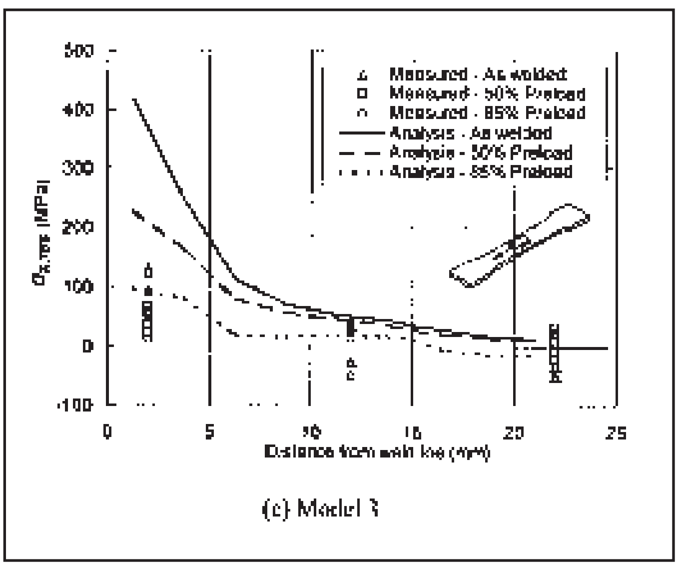


Fig. 4 — Residual stress distribution along centerline surface of main plate: Models 1, 2, 3.

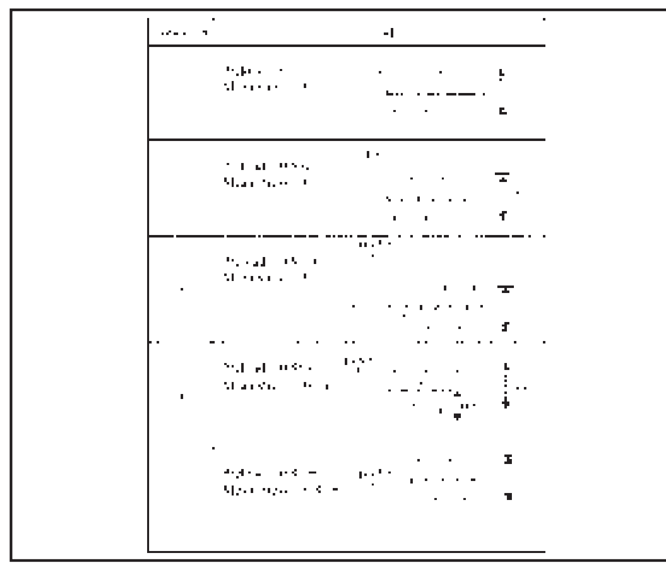


Fig. 5 — Fatigue test conditions of preload and mean stress.

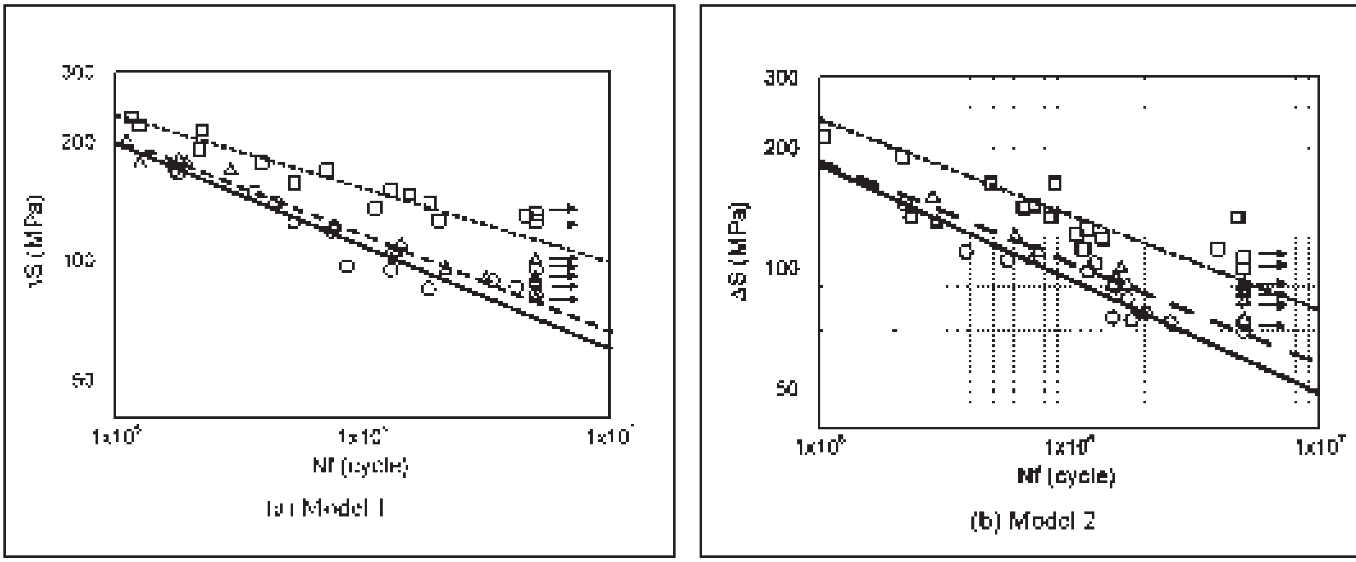
measurement were smaller than those obtained by FE analysis, but the decrement of the initial residual stress from the preload was clearly observed at the weld toe of the main plate.

Fatigue Tests

Fatigue tests were carried out under load-controlled axial loading with fully reversed constant amplitude at room temperature in air. Conditions for fatigue tests to evaluate the effects of both the redistributed residual stresses by tensile preload and the tensile mean stresses by static load are illustrated in Fig. 5. Test frequency was in the range of 6 to 20 Hz. Fifteen fatigue tests were performed per each test condition in accordance with the International Institute of Welding's (IIW) recommendation (Ref. 7). Fatigue tests

Table 3 — Hot-Spot Stress Value of Preload and Mean Stress

Model	SCF	Preload (MPa)	Mean Stress (MPa)	Case
		0	0	1
		175.0	0	3
1	1.49	297.4	0	6, 11
		297.4	175.0	12
		297.4	297.4	13
		0	0	1
		229.0	0	4
2	1.95	389.3	0	7, 14
		389.3	229.0	15
		389.3	389.3	16
		0	0	1
		155.0	0	2
3	1.32	263.5	0	5, 8
		263.5	155.0	9
		263.5	263.5	10



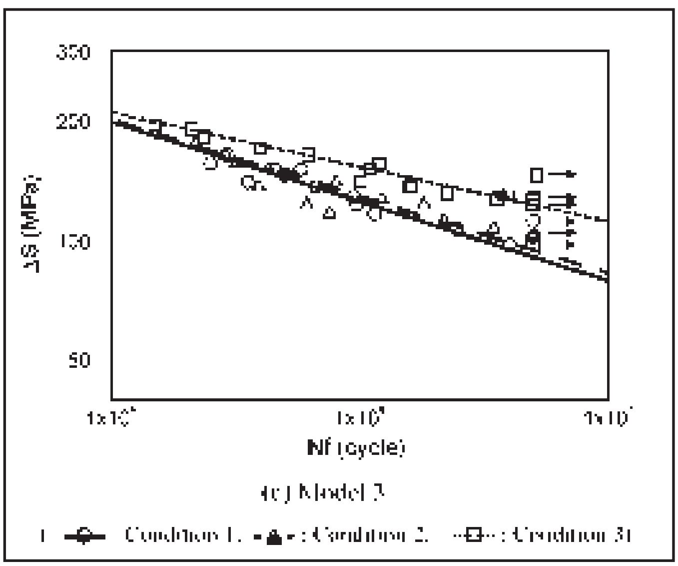


Fig. 6 — Test results and ΔS-N_f curves with redistributed residual stress by preload.

were carried out until approximately 5 × 10^6 cycles of loading and stopped, unless a fatigue crack was visually detected.

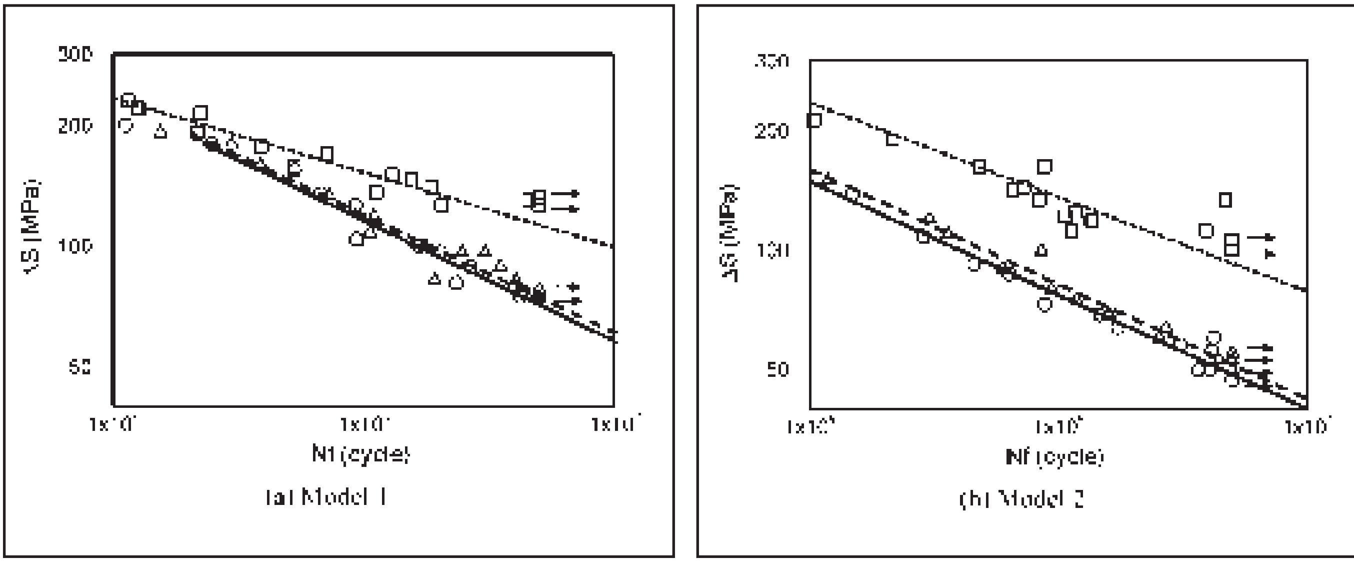
In this paper, the fatigue life of specimen N_f is defined as the number of load cycles until the specimen is totally failed because of fatigue damage in the ship structure being subject to fairly developed cracks, but not reaching catastrophic structural failure. The equation of the S-N curve for each test condition was determined with the results of N_f by least squares regression analysis. The test data stating that a crack was not detected until 5×10^6 of load cycles were not considered to derive the equation of an S-N curve.

Fatigue test results under conditions 1, 2, and 3 are plotted in Fig. 6, which represents the relation between nominal stress range (ΔS) and the failure life (N_f). The fatigue strength was clearly affected by preloads. The greater the preload, the more the fatigue strength of the weldment increased. This increment of fatigue strength was predominant at the lower cyclic stress range. Fatigue test results under conditions 3, 4, and 5 are plotted in Fig. 7. There were big differences of fatigue strength by tensile mean stresses when initial welding residual stresses had been shaken-down by the preload.

Applicability of Hot-Spot Stress

To evaluate fatigue strength properly, there should be consistency between the stress with which the S-N curve is defined and the one with which fatigue strength is calculated. Most S-N curves proposed by international institutes, such as IIW (Ref. 7) and BS5400 (Ref. 8), 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 fatigue strength is concerned, there are stress concentrations that depend not only on structural detail shapes but also on applied loading pattern. Furthermore, it is often hard to define the nominal stress due to the complexity of structure and loading. Accordingly, there is a high possibility of misevaluating the fatigue strength when it is evaluated with the nominal stress basis. Hot-spot stress is the recommended means of evaluating the fatigue strength in ship structures because it includes the stress concentration due to geometric shape. However, few S-N curves defined with hot-spot stress are proposed, except those for tubular joints. Therefore, it has been very hard to match the calculated hot-spot stress to the relevant S-N curve.

There are three different stress extrapolation techniques as commonly recommended procedures for the calculation of hot-spot stresses in welded structures, i.e. 1) linear extrapolation of stresses over reference points at 0.5 and 1.5 of plate thickness away from the hot spot; 2) linear extrapolation of stresses over reference points at 0.4 and 1.0 of plate thickness away from the hot spot; and 3) no extrapolation, but the stress value at 0.5 of plate thickness from the hot spot as the relevant hot spot stress. Finite element analyses using different types/sizes of elements and computing programs had been performed on various welded joints to calculate and to compare hot-spot stress values by these three techniques (Ref. 9). According to the results, the linear extrapolation of stresses at 0.5 and 1.5 of plate thickness had shown the least scatters of the values at the reference point in association with different types/sizes of elements and computing programs. In this regard, linear extrapolation of stresses over reference points at 0.5 and 1.5 of plate thickness away from the hot spot was adopted in this paper for the calculation of hot-spot stress values. Calculated stress concentration factors (SCFs) at the hot spot, using models constituted with 4-node plane stress elements (of which size at the concerned



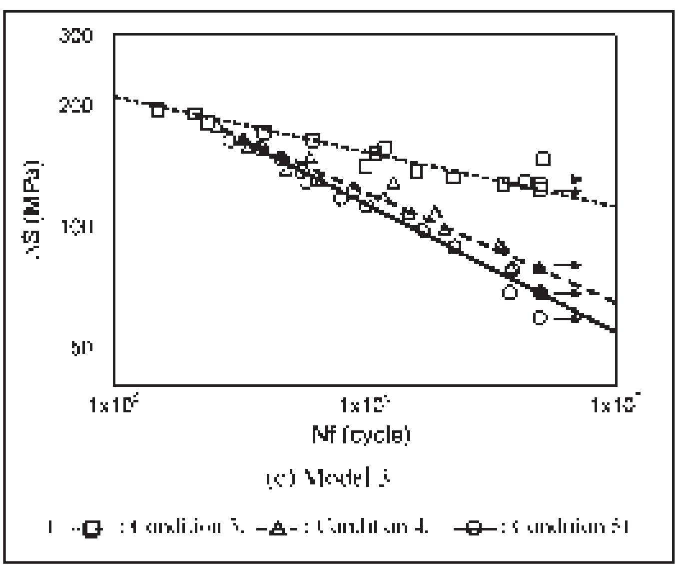


Fig. 7 — Test results and ΔS-N_f curves with mean stress: Models 1, 2, 3.

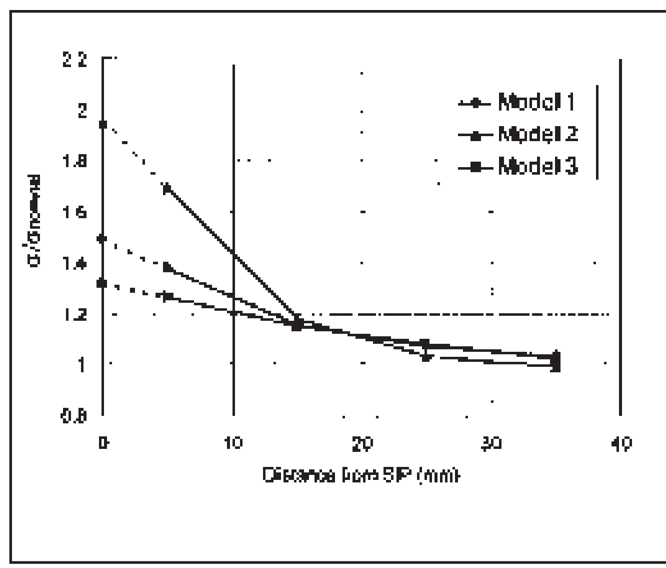


Fig. 8 — Longitudinal stress distribution from the structural intersection point (SIP) on main plate.

area was about the thickness order of the main plate), were obtained as 1.49 for Model 1, as 1.95 for Model 2, and as 1.32 for Model 3, as illustrated in Fig. 8. Table 3 lists the magnitude of preloads and mean stresses on each model, which are substituted into hot-spot stress values, and the number of cases in relation to Equations 2–8 and 12–20. To examine the applicability of a unified S-N curve based on the hot-spot stress for the evaluation of the fatigue strength of various weld joints, the fatigue test results of N_f for three models under the as-welded condition are plotted on Fig. 9 in relation to the nominal stress range of ΔS and to the hot-spot stress range of $\Delta\sigma_{spot}$. The hot-spot stress ranges were calculated by multiplying the stress concentration factors by the nominal stress ranges. The test results of Model 1, Model 2, and Model 3 coincided well with an S-N curve under the basis of hot-spot stresses, irrespective of their weld-joint type.

Proposed HD S-N Curve

To estimate the fatigue strength with an arbitrary preload and static load, it is necessary to derive an equation of S-N curves that reflects effects of redistributed residual stress and mean stress. From fatigue test results, the equation of S-N curves using the hot-spot stress range $\Delta\sigma$ was derived.

Pre-Load Effect

S-N curves under various preload cases, which were derived from the fatigue test results of Model 1, Model 2, and Model 3, are represented by the following equations:

Case 1 (σ_{load} = 0.0 MPa)

$$: \log N = 14.415 - 3.776 \log \Delta\sigma \quad (2)$$

Case 2 (σ_{load} = 155.0 MPa)

$$: \log N = 17.579 - 5.184 \log \Delta\sigma \quad (3)$$

Case 3 (σ_{load} = 175.0 MPa)

$$: \log N = 15.167 - 4.095 \log \Delta\sigma \quad (4)$$

Case 4 (σ_{load} = 229.0 MPa)

$$: \log N = 15.103 - 3.950 \log \Delta\sigma \quad (5)$$

Case 5 (σ_{load} = 263.5 MPa)

$$: \log N = 22.871 - 7.311 \log \Delta\sigma \quad (6)$$

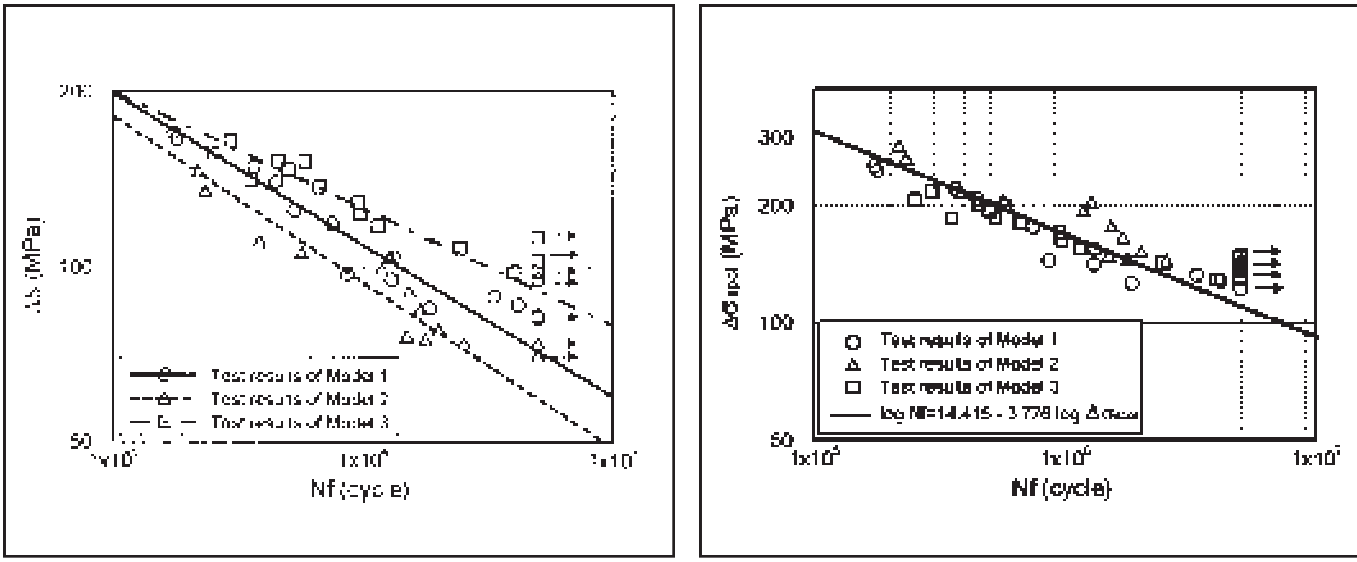


Fig. 9 — Fatigue test results under as-welded condition.

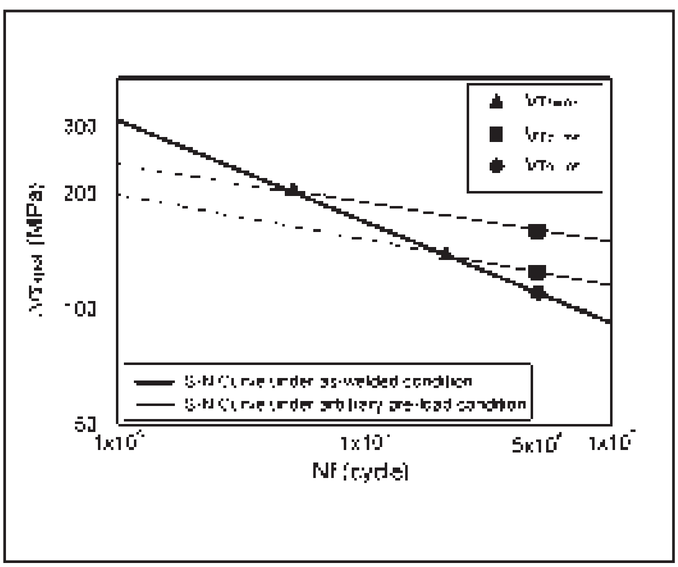


Fig. 10 — Definition of $\Delta\sigma_{same}$ and $\Delta\sigma_{p,limit}$.

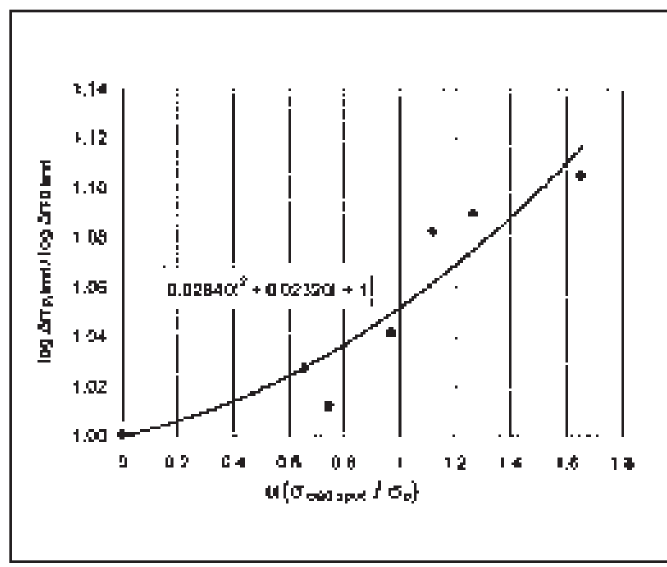


Fig. 11 — Relation between $\Delta\sigma_{p,limit}$ and magnitude of preload (α).

Case 6 (σ_{load} = 297.4 MPa)

$$: \log N = 18.683 - 5.383 \log \Delta\sigma \qquad (7)$$

Case 7 (σ_{load} = 389.3 MPa)

$$: \log N = 16.204 - 4.209 \log \Delta\sigma \qquad (8)$$

where σ_{load} is the magnitude of hot-spot stress by preload.

In this paper, the fatigue strength of hot-spot stress range at 5 × 10⁶ cycles under an arbitrary preload with zero mean stress is defined as fatigue limit $\Delta\sigma_{p,limit}$, as illustrated in Fig. 10. Then the fatigue limit under the as-welded condition $\Delta\sigma_{0,limit}$ is 110.44 MPa. Figure 11 shows the relation between the fatigue limit $\Delta\sigma_{p,limit}$ and the magnitude of preload, α. Provided the relation between log $\Delta\sigma_{p,limit}$ and α is approximated to the second order equation, the relation can be represented as follows by the least squares regression analysis.

$$\log \Delta\sigma_{p,limit} = (0.0284\alpha^2 + 0.0232\alpha + 1) \log \Delta\sigma_{0,limit} \qquad (9)$$

where α is magnitude of tensile preload (σ_{load}/σ_o; σ_o = 235 MPa) and $\Delta\sigma_{0,limit}$ is the fatigue limit under the as-welded condition (= 110.44 MPa).

Intersected points between the S-N curve under the as-welded condition and the ones under various preload cases are defined as $\Delta\sigma_{same}$, as illustrated in Fig. 10. The value of $\Delta\sigma_{same}$ means the stress range at which the effect of redistributed residual stress on fatigue strength is diminished under each preloaded case. At the stress range beyond $\Delta\sigma_{same}$, it is expected there would be no change of fatigue strength between the as-welded condition and the preloaded case. Figure 12 shows the relation between $\Delta\sigma_{same}$ and α. The data of $\Delta\sigma_{same}$ for Cases 4 and 7 were discarded because they were far from a reasonable range. Provided the relation between $\Delta\sigma_{same}$ and α is approximated to be linear, the relation can be represented as follows by the least squares regression analysis.

$$\log \Delta\sigma_{same} = (0.196\alpha + 1)\log \Delta\sigma_{0,limit} \qquad (10)$$

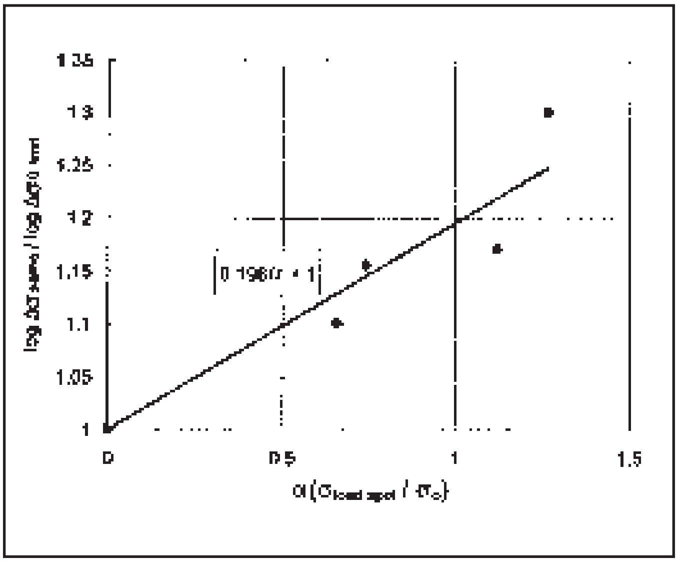


Fig. 12 — Relation between $\Delta\sigma_{same}$ and magnitude of preload (α).

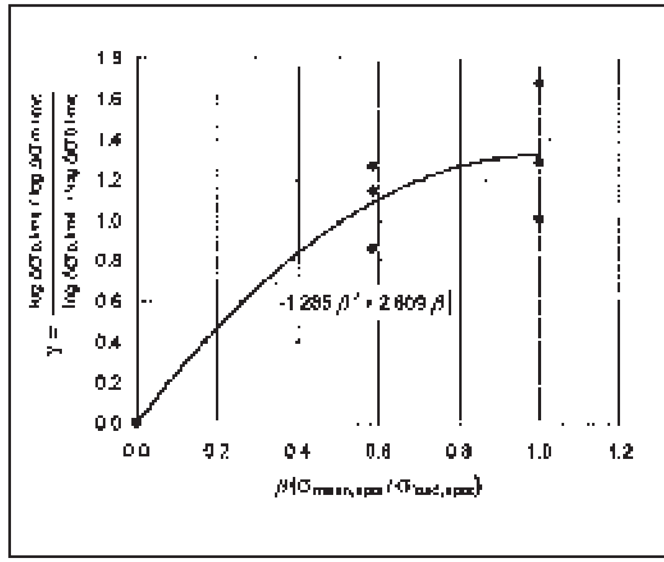


Fig. 13 — Relation between $\Delta\sigma_{p,limit}$ and magnitude of mean stress (β).

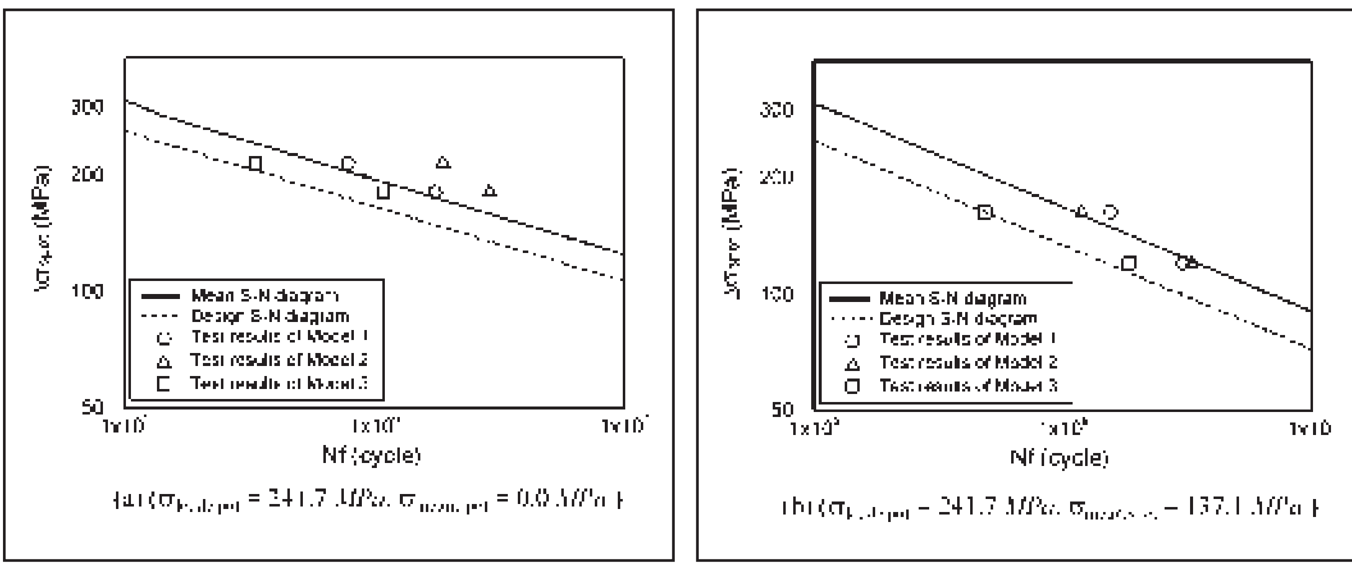


Fig. 14 — Comparison of HD S-N diagram and additional fatigue test results.

From Equations 9 and 10, the equation of S-N curves that reflects the effects of redistributed residual stress with an arbitrary tensile preload but without tensile mean stress can be derived as follows.

$$\log N = C_1 + m_1 \log \Delta\sigma \qquad (11)$$

where

$$C_1 = [(14.415 - 3.776 \log \Delta\sigma_{same}) \cdot \log \Delta\sigma_{p,limit} - 6.699 \cdot \log \Delta\sigma_{same}] / \log \Delta\sigma_{p,limit} - \log \Delta\sigma_{same}$$

$$m = \frac{6.699 - (14.415 - 3.776 \log \Delta\sigma_{same})}{\log \Delta\sigma_{m,limit} - \log \Delta\sigma_{same}} \qquad (\alpha > 0)$$

In the case of $\Delta\sigma \geq \Delta\sigma_{same}$ or $\alpha = 0$, Equation 2 is to be applied.

In the case of compressive preload, the S-N curve under the as-welded condition is recommended for the design purpose because there would be no large redistribution of residual stress from an engineering judgment.

Mean Stress Effect

It was determined that the effect of cyclic stress ratio (minimum stress/maximum stress) was minor on the fatigue strength of a structure under the initial residual stress condition by welding that almost reached yield stress of the material at the weld toe (Ref. 6). Therefore, the mean stress effect on the fatigue strength of structures is minor as far as they are exposed to cyclic loading under the as-welded condition. At the stress range beyond $\Delta\sigma_{same}$, where the effect of preload is diminished, the effect of the mean stress is also ignored, and Equation 2 of the as-welded condition may be applicable to arbitrary preloaded cases with mean stresses.

From Equations 2 and 10, fatigue test results under tensile mean stresses are represented as follows:

Case 8

$$(\sigma_{load} = 263.5 \text{ MPa}, \sigma_{mean} = 0.0 \text{ MPa}) \qquad (12)$$

$$: \log N = 14.415 - 3.776 \log\Delta\sigma \qquad (\Delta\sigma \geq \Delta\sigma_{same})$$

$$: \log N = 18.083 - 5.248 \log\Delta\sigma \qquad (\Delta\sigma < \Delta\sigma_{same})$$

Case 9

$$(\sigma_{load} = 263.5 \text{ MPa}, \sigma_{mean} = 155.0 \text{ MPa}) \qquad (13)$$

$$: \log N = 14.415 - 3.776 \log\Delta\sigma \qquad (\Delta\sigma \geq \Delta\sigma_{same})$$

$$: \log N = 13.756 - 3.512 \log\Delta\sigma \qquad (\Delta\sigma < \Delta\sigma_{same})$$

Case 10

$(\sigma_{load} = 263.5 \text{ MPa}, \sigma_{mean} = 263.5 \text{ MPa})$ (14)

$: \log N = 14.415 - 3.776 \log\Delta\sigma \quad (\Delta\sigma \geq \Delta\sigma_{same})$

$: \log N = 12.910 - 3.172 \log\Delta\sigma \quad (\Delta\sigma < \Delta\sigma_{same})$

Case 11

$(\sigma_{load} = 297.4 \text{ MPa}, \sigma_{mean} = 0.0 \text{ MPa})$ (15)

$: \log N = 14.415 - 3.776 \log\Delta\sigma \quad (\Delta\sigma \geq \Delta\sigma_{same})$

$: \log N = 18.570 - 5.405 \log\Delta\sigma \quad (\Delta\sigma < \Delta\sigma_{same})$

Case 12

$(\sigma_{load} = 297.4 \text{ MPa}, \sigma_{mean} = 175.0 \text{ MPa})$ (16)

$: \log N = 14.415 - 3.776 \log\Delta\sigma \quad (\Delta\sigma \geq \Delta\sigma_{same})$

$: \log N = 14.838 - 3.942 \log\Delta\sigma \quad (\Delta\sigma < \Delta\sigma_{same})$

Case 13

$(\sigma_{load} = 297.4 \text{ MPa}, \sigma_{mean} = 297.4 \text{ MPa})$ (17)

$: \log N = 14.415 - 3.776 \log\Delta\sigma \quad (\Delta\sigma \geq \Delta\sigma_{same})$

$: \log N = 14.385 - 3.765 \log\Delta\sigma \quad (\Delta\sigma < \Delta\sigma_{same})$

Case 14

$(\sigma_{load} = 389.3 \text{ MPa}, \sigma_{mean} = 0.0 \text{ MPa})$ (18)

$: \log N = 14.415 - 3.776 \log\Delta\sigma \quad (\Delta\sigma \geq \Delta\sigma_{same})$

$: \log N = 20.120 - 5.884 \log\Delta\sigma \quad (\Delta\sigma < \Delta\sigma_{same})$

Case 15

$(\sigma_{load} = 389.3 \text{ MPa}, \sigma_{mean} = 229.0 \text{ MPa})$ (19)

$: \log N = 14.415 - 3.776 \log\Delta\sigma \quad (\Delta\sigma \geq \Delta\sigma_{same})$

$: \log N = 13.917 - 3.593 \log\Delta\sigma \quad (\Delta\sigma < \Delta\sigma_{same})$

Case 16

$(\sigma_{load} = 389.3 \text{ MPa}, \sigma_{mean} = 389.3 \text{ MPa})$ (20)

$: \log N = 14.415 - 3.776 \log\Delta\sigma \quad (\Delta\sigma \geq \Delta\sigma_{same})$

$: \log N = 13.466 - 3.426 \log\Delta\sigma \quad (\Delta\sigma < \Delta\sigma_{same})$

where σ_{mean} is the magnitude of hot-spot mean stress.

Figure 13 shows the relation between the fatigue limit with an arbitrary mean stress $\Delta\sigma_{m,limit}$ and the magnitude of the mean stress, β. Provided the relation between $\Delta\sigma_{m,limit}$ and β is approximated to a second order equation, the relation can be represented as follows:

$$\log \Delta\sigma_{m,limit} = \log \Delta\sigma_{p,limit} - \gamma(\Delta\sigma_{p,limit} - \log \Delta\sigma_{0,limit}) \quad (21)$$

where β is magnitude of tensile mean stress $(\sigma_{mean}/\sigma_{load})$ and

$$\gamma = \frac{\log\Delta\sigma_{p,limit} - \log\Delta\sigma_{m,limit}}{\log\Delta\sigma_{p,limit} - \log\Delta\sigma_{0,limit}}$$

$$= -1.285\beta^2 + 2.609\beta$$

From Equations 9 and 21, the fatigue limit with an arbitrary tensile mean stress under an arbitrary tensile preload can be derived as follows.

$$\log \Delta\sigma_{m,limit} = [(0.0284\alpha^2+0.0232\alpha+1) + (1.285\beta^2 - 2.609\beta)(0.0284\alpha^2+0.0232\alpha)] \cdot \log\Delta\sigma_{0,limit} \quad (22)$$

In the case of compressive mean stresses, the S-N curve under zero mean stress is recommended for the design purpose.

HD S-N Curve

From fatigue test results, Equation 10, the equation of the intersected point between the S-N curve under the as-welded condition and the ones under the preloaded case, and Equation 22, the equation of fatigue limit, have been established taking account of effects of the preload and the mean stress. The equations are based on the hot-spot stress and expected to be applicable for the fatigue assessment of various fillet welded structural joints. To propose "Hot spot stress-based Design S-N Curve (so called HD S-N Curve)," the standard deviation between equations and test results was calculated as 0.181 using the following equation.

$$s^2 = \frac{1}{n-1}\sum_{i=1}^{n}\left(x_i - \bar{x}_i\right)^2 \quad (23)$$

where, s is standard deviation of logN, x_i is the logarithm of the number of cycles obtained from fatigue test results, and $\bar{x}_i$ is the logarithm of number of cycles calculated from the equation.

With 2.35% of probability of failure, the HD S-N Curve with mean minus two standard deviations, Equation 24, may be proposed in general for the assessment of the fatigue strength of fillet weld joints at the design stage.

$$\log N = C + m \log\Delta\sigma - 2s \quad (24)$$

where

$$C = [(14.415 - 3.776 \log\Delta\sigma_{same}) \cdot \log\Delta\sigma_{m,limit} - 6.699 \cdot \log\Delta\sigma_{same}] / (\log\Delta\sigma_{m,limit} - \log\Delta\sigma_{same})$$

when $(\Delta\sigma_{spot} < \Delta\sigma_{same})$, or $C = 14.415$ when $(\alpha = 0$ or $\Delta\sigma_{spot} \geq \Delta\sigma_{same})$;

$$m = \frac{6.699 - (14.415 - 3.776 \log\Delta\sigma_{same})}{\log\Delta\sigma_{m,limit} - \log\Delta\sigma_{same}}$$

when $(\Delta\sigma_{spot} < \Delta\sigma_{same})$, or $m = -3.776$ when $(\alpha = 0$ or $\Delta\sigma_{spot} \geq \Delta\sigma_{same})$;

s = the standard deviation of log N (= 0.181);

$\log \Delta\sigma_{same} = (0.196\alpha + 1)\log\Delta\sigma_{0,limit;}$

$\log \Delta\sigma_{m,limit} = [(0.0284\alpha^2+0.0232\alpha+1) + (1.285\beta^2-2.609\beta)(0.0284\alpha^2+0.0232\alpha)] \cdot \log \Delta\sigma_{0,limit;}$

α = the magnitude of tensile preload when $(\sigma_{load}/\sigma_o \geq 0)$, or, in the case of compressive preload only, $\alpha = 0$;

β = magnitude of tensile mean stress when $(1.0 \geq \sigma_{mean}/\sigma_{load} \geq 0)$, or, in the case of compressive mean stress, $\beta = 0$;

$\Delta\sigma_{0,limit}$ = fatigue limit under as-welded condition (=110.44 MPa);

σ_o = design yield stress (= 235 MPa);

σ_{load} = magnitude of hot-spot stress by preload (design load in general);

σ_{mean} = magnitude of hot-spot stress by actual static load related to concerned load condition.

Verification of HD S-D Curve

Additional fatigue tests were carried out under an arbitrary preload and two mean stress conditions to verify the HD S-N Curve. Fatigue test results and the HD S-N Curve under related test conditions are shown in Fig. 14. The additional fatigue test results show reasonable agreement with the HD S-N Curve.

Conclusion

Contemporary assessment proposals for the fatigue strength of ship structures have been derived from the research results for other industries such as steel bridges and offshore structures. It should be noted that, in ship structures, not only structural details in geometry and material but also loading patterns of the dynamic and the static types are different from those of other structures.

To examine the effect of static load history on ship structure, simulation by FE analysis and measurement by a sectioning method for the distribution of the residual stress were both carried out. Initial welding residual stresses at the weld toe, which almost reached tensile yield point of the material, were shaken down by the tensile preload. The bigger the preload became, the more the residual stress decreased, according to results of both the simulation and the measurement. Due to the effect of the tensile preload, the fatigue strength was changed. The bigger the tensile preload was, the more the fatigue strength increased, and this fatigue strength increment was predominant at the lower cyclic stress range.

Fatigue tests were also carried out applying the tensile mean stresses under preloaded conditions to examine the effect of the mean stress on fatigue strength. There were big differences of fatigue strength from tensile mean stresses when the preload had shaken-down initial welding residual stresses. The fatigue strength decreased drastically from the tensile mean stress, and this decrement was predominant at the lower cyclic stress range.

It is noteworthy that the main purpose of this research work emphasizes its practical application to ship structural design. From the results of fatigue tests, an empirical formula of S-N curves, taking account of the effect of the arbitrary preload and mean stress in consideration of loading conditions in ship structures, which was based on the hot-spot stress range, was derived in the closed form. The standard deviation between the formula and the fatigue test results was calculated. With 2.35% of probability of failure, “HD S-N Curve (Hot spot stress-based Design S-N Curve)” was proposed. However, to generalize and to utilize the HD S-N Curve in the shipbuilding industry, further research work on the following areas is recommended.

Fatigue tests on lower cyclic stress range. The fatigue tests were carried out until around 5×10^6 cycles of loading and stopped in this research work. In ship structure, the fatigue strength 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. Most fatigue damage is contributed by dynamic stress at the level of $2 \times 10^6 \sim 1 \times 10^8$ load cycles. In this regard, when a new Design S-N Curve is established, fatigue test results at the high cycle load region (around 1×10^7 cycles) are important to enhance the reliability of the S-N curve, even though it is very time-consuming to carry out tests at low stress ranges.

Definition of hot-spot stress. The resulting value of hot-spot stress may differ depending on the FE program or on the element type, although the procedure for the calculation is just the same (Ref. 9). It is necessary to establish a more appropriate procedure for the calculation of the hot-spot stress that may represent the state of stress in relation to the fatigue behavior of welded joints.

Different workmanship of welding. Fatigue strength of the welded structure is highly dependent on the quality of the fabrication. All specimens in this research work were fabricated by only one shipyard, with its normal workmanship. Comparison of test results with specimens fabricated by a variety of shipyards will be required.

Verification of shaken-down residual stresses in actual ship structures. The redistributions of initial welding residual stresses by preloads in small-scale specimens may not necessarily represent those in actual ship structures due to complexity of the structural geometry. In addition to welding residual stresses, other mechanical residual stresses, induced by forced restraints during block assembly and so on, are imposed simultaneously. It is necessary to measure shaken-down residual stresses at the hot spot of the ship structure by the cargo loading history and to calibrate the effect of preloads on the fatigue strength.

Accumulation of further experimental data. In this research work, fatigue tests were performed with only three fillet-welded joint types of specimens, which were fabricated with ship structural mild steel of grade A. Accumulation of experimental results with other joint types, such as lap joints, and other materials, such as higher tensile steel, is necessary. In addition, further fatigue tests under lower mean stress levels are recommended.

Fatigue tests under other types of loading. Fatigue tests were performed under uniaxial loads only. Fatigue strength under other types of loading such as out-of-plane bending loads and bi-axial loads should be verified.

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