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A Representative Stress for Unified Fatigue Damage Model

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ABSTRACT

The hot spot stress approach and the notch strain approach are discussed with some results of them. And a stress model that can be applicable to several types of weld joints with single S-N curve of the base material. The stress model uses the geometric characteristics of the stress distribution vicinity of weld joints. The model was applied to five different weld joins(the base material is SM490B). By the representative stress, the experimental fatigue data are plotted very closely to the S-N curve of the base material.

Key Words : Fatigue, Weld join, S-N curve

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1. Introduction

The structure fabricated by welding has many discontinuities, a weld joint itself is like such a discontinuity. It is common that fatigue failures in welded structures are initiated from the discontinuity. Even a lot of studies have dealt with the fatigue failures of structures for long time, the fatigue failure is still a current subject. To estimate the fatigue life of a structure looks like a simple problem, for example, incorporating nominal stresses into Palmgren-Miner rule. This rule is a kind of constitutive equation as Hook's law and Huber-Mises yield criterion in elasticity and plasticity where, if the constitutive equation of a material is known, the equation can be used any structures which are made of the material. Unfortunately not is that in fatigue problems. This is because, in practice, nominal stress ranges at discontinuities are seldom definitely defined, even if the stress ranges obtained, we need experiments to determine two coefficients in S-N curves for each discontinuities. In other word, "One S-N curve for one joint"is required, that is very simple and the most accurate method. For very critical structures, this approach should not be replaced with any others. But in a design stage, a rapid estimation but less cost is essential. In this context the approach "one S-N curve for one joint"is not a wise method in early design stages. To relieve this situation, two methods have been suggested, the hot spot stress[1]and the notch strain[2]. However the hot spot stress approach has a limitation which will be discussed later, and the notch strain approach need further studies to give more precise results.

This study will give a simple stress model matching with S-N curves of plane specimen regardless the types of weld joints. For comparison, some results of previous two methods will be supplied and discussed.

2. Motive of this study

A lot of S-N curve are represented in nominal stress. But, we are frequently facing with the problem that nominal stresses are not clearly defined. On the other hand, finite element analysis becomes a normal design process, by which designers can make use of more detail stress information near discontinuities easily. The hot spot stress approach is good at this situation. However a hot spot stress may be sensitive to the points by which it is defined, see for the details Fig. 1. Thus another inspection is necessary to get proper points. As one of advantage of the hot spot stress approach, it may be possible to estimate the fatigue lives of many types of structural joints with single S-N curve. We can, to some extant, reduce the scatter band of S-N curves for several joints with hot spot stresses, for example see reference [3]. But this approach is not satisfactory enough to eliminate fatigue tests for all type of joints.

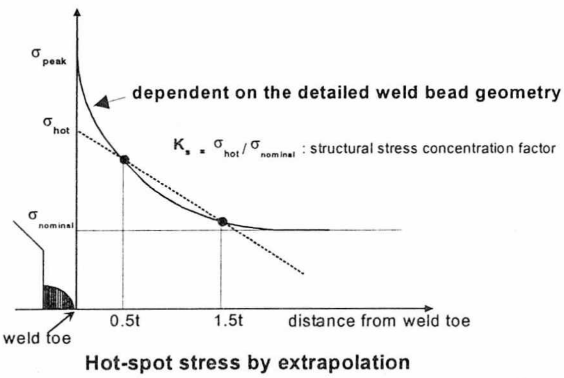


Fig.1 Determination of hot spot stress [3]

The notch stress or strain approach is using a local stress or strain. That means that it may be applicable to all type of structural joints. A hot spot stress is not local stress, so it is not suit for the hot spots where the local stress not counted in the evaluation of hot spot stress is dominant. This is easily seen from that the gradients of S-N curves with hot spot stresses are steeper than those of the base materials as the S-N curves of nominal stress approach are. In a high cycle fatigue region, the initiation lives of cracks are longer than the propagation lives, and the not-counted-local-stress is responsible for the initiation lives partly in this region. Approaching a low cycle region, the fraction of initiation lives are decreased, consequently the effect of not-counted-local-stress is decreased also. This implies the hot spot stress approach underestimates stress in high cycle fatigue region resulting steep gradients in S-N curves. In the context, the local approach has achieved an improvement. However there is a problem that will be described later.

For improving fatigue damage model or making unified fatigue model(ultimately final model), here gives two recommendations.

1) The initiation of fatigue cracks is a local action governed by local states and their time histories.
2) Separate the material term and geometric term in coefficients of fatigue models.

The first implies that the fatigue damage does not know the backgrounds of local states. If the fatigue discerns, for example, how strains are induced, it is a very difficult job to make unified fatigue models. Here suppose a plane and a weld joint specimen. If the fatigue lives of two specimens are equal even at different nominal stresses, by the first recommendation the local state of the weld joint is assumed to be equivalent to the state of the plane specimen. Frequently the stress at the hot spot of the weld joint exceeds the yield stress of the material even the nominal stress is well below the yield stress, but the fatigue life of the weld joint specimen, in experiments, is longer than that of the plane specimen subjected to the same stress as the local stress of the specimen of weld joint. There is a possibility for that, no yielding in the weld joint. The degradation of the heat affected zone(HAZ) can be the possibility. But the experiment[4] shows that the discrepancyof fatigue life between the base material and the HAZ is small. Thus it seems there is an unidentified mechanism, in cyclic loads, which increases or decreases the stress ranges of the weld joint. Of course we will need further studies to uncover the mechanism. If this is true, the notch approach underestimates fatigue lives since the coefficients of notch models are tuned with a plane specimen which can be subjected to whole section plasticity, and since the local strains are evaluated by, for example, stress concentration factors, nominal stresses and $\sigma-\varepsilon$ curves. This tendency of underestimation of the local approach will be shown in Chapter 5.

Now let's discuss the second recommendation. The material coefficients of S-N curves given in follow equation are not true material coefficients.

$$\log n = c - m \log \Delta\sigma$$

This argument can be easily justified by observing that S-N curves are different from type to type of weld joint even for one material. The coefficients depend on the configurations of weld joints any way. The second recommendation is crucial for developing unified fatigue models.

Present study is not aiming at studying above discussions, but suggesting a representative stress model by which the fatigue lives of many types of weld joints can be estimated with single S-N curve of plane specimen.

3. Stress description nea hot spots

Let a stress near a weld joint be Eq.(1)

$$\left(\frac{\beta}{r} + \sigma_n - \alpha r\right) = \sigma_X \qquad (1)$$

where σ_X is a stress at distance r from a hot spot and α, β, σ_n are unknowns. This stress distribution model has two modes, inverse proportional term to distance and linear term.

The unknowns are determined by distance r_1, r_2, r_3 and the stresses at there.

$$\alpha = \frac{1}{r_1 - r_3}\left(\frac{\Delta_{12} r_1}{r_2 - r_1} - \frac{\Delta_{23} r_3}{r_3 - r_2}\right)$$

$$\beta = \frac{r_1 r_2 r_3}{r_3 - r_1}\left(\frac{\Delta_{12}}{r_2 - r_1} - \frac{\Delta_{23}}{r_3 - r_2}\right)$$

$$\sigma_n = \sigma_X^1 + \alpha r_1 - \frac{\beta}{r_1}$$

where $\Delta_{ij} = \sigma_X^i - \sigma_x^j$

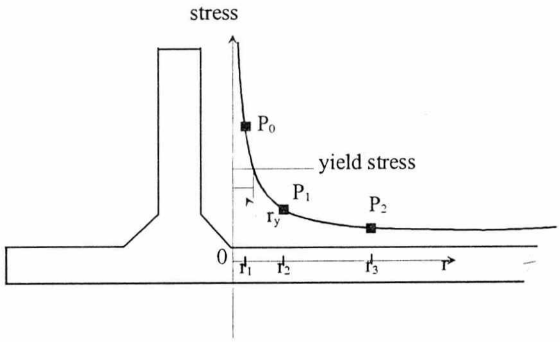


Fig. 2 Stress description in the vicinity of discontinuities

4. A new representative stress

With Eq.(1) extract following two parameters.

$$\sigma_n \quad \sigma_X^1 + \alpha r_1 - \frac{\beta}{r_1} \qquad (2)$$

$$r_y : \quad \frac{-(\sigma^y - \sigma_n) + \sqrt{(\sigma^y - \sigma_n)^2 + 4\alpha\beta}}{2\alpha} \quad \text{for}$$

$\alpha > 0$

$$\frac{\beta}{\sigma^{y}-\sigma_{n}} \qquad \text{for } \alpha = 0 \tag{3}$$

wher σ^{y} is a yield stress and r_y is the distance giving yield stress, named plastic distance.

By combine (2) and (3), a new representative stress is modeled as

$$\sigma_r = \sigma_n(1+f(r_y)) \tag{4}$$

The function $f(r_y)$ is configured as Eq.(5).

$$f(r_y) = \kappa\frac{\beta}{r_y} - \mu\sigma^{y} \qquad r_y > 0 \tag{5}$$

$$= 0 \qquad r_y = 0$$

where χ and μ are determined by fitting experimental data.

This stress model considers the shape of stress distribution near weld joints.

5. Fitting experimental data with proposed representative stress and discussion

Experimental fatigue data are collected from five different weld joints[3]. The details of the joints are illustrated in Fig. 3 for easy reference. The stress rises near weld toes are given in Fig. 4(a)[3]. Fig.4(b), the reproduced curves of Fig.3(a) by Eq.(1), shows a good agreement with Fig.4(a) in the vicinity of weld toes.

The S-N curves of the weld joints based on nominal stress appear in Fig.5. Each curve has different curve parameters (generally known as material coefficient c, m). As discussed in Chapter 2, the coefficient c and m can not be material coefficient because they include the geometrical characteristics of weld joints as well as material properties. For unified S-N curve, the geometrical characteristics of weld joints should be separated in the coefficients. By letting the coefficients be pure material properties, much savings can be possible in engineering. This saving is because the fatigue data of base material can be used for several weld joints of different type. It will be shown later that the proposed stress model is very useful for this purpose.

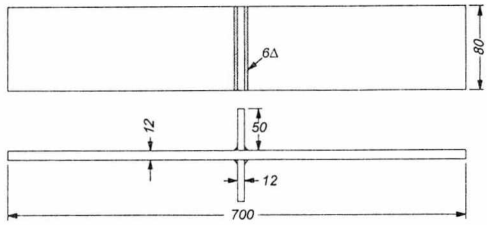
For comparison we discuss more about the hot spot stress approach. The hot spot stress is a good model, but the geometrical effects are still remained in the coefficient c and m. Fig. 6 expresses with hot spot stresses the collection of S-N curves of the same data as Fig.5. The curves have quite different gradients to that of base material[5]. It is interesting that σ_n of Eq.(2) gives very resembled S-N curves(see Fig.6) to those of hot spot stress. But σ_n has advantage over a hot spot stress because it is insensitiveness to the coordinates of points to determine the hot spot stress.

We applied the notch strain approach to the fatigue life estimations of three weld joints[not published yet]. They are briefed in Appendix. Here only refers the results. The notch strain model takes into account residual stress. The estimated S-N curves come close to experiment curves in the case of the cruciform specimen(Fig.a.1), but not so in the other cases(Fig.a.2 and Fig.a.3). As discussed in Chapter 2 the tendency of underestimation of fatigue life appears in the notch strain models adopted here. And the goodness of fit to the experimental S-N curves is swing on the types of weld joints.

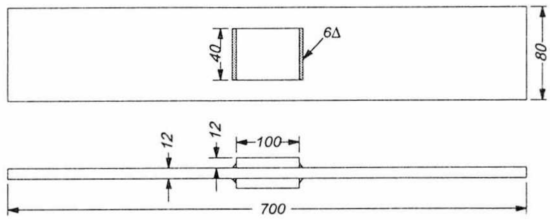
Finally, the experimental data of the five different weld joints are re-plotted by the proposed representative stress model with coefficient $\chi=0.85, \mu=0.35$. As seen in Fig.8, the S-N curves of the five joints and the base material appear nearly on a curve.

5. Conclusion

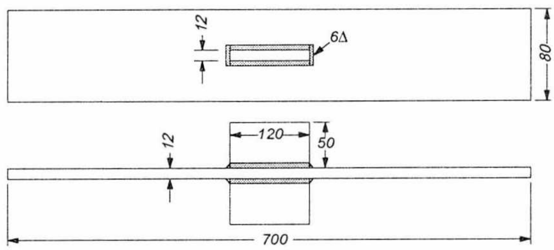
Toward unified fatigue damage modeling, the hot spot stress approach and the local strain approach have done much contribution. But they should be elaboratedfurther for more precise estimation. Based on the discussion of Chapter 2, a new representative stress model is proposed. The plastic distance which measures the nonlinear rising of stress vicinity of weld toes is introduced as a parameter in the model. The parameter makes crucial roles for unified S-N curves. Beside the plastic distance, the stress model has a parameter σ_n representing linear component of stress rising. The parameter σ_n gives very close results to the hot spot stress. The stress model proposed in this study appears to give a promise results for the unified fatigue damage modeling. Yet the model has to be studied further, especially on the form of $f(r_y)$ in Eq.(4).



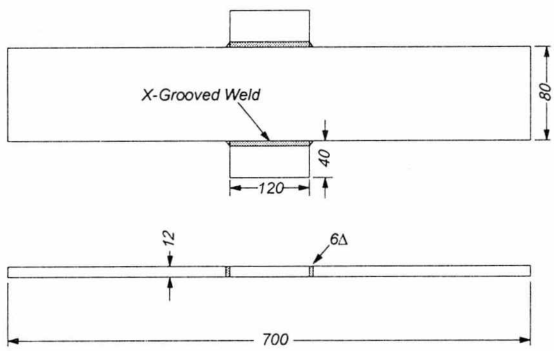
(a) Cruciform



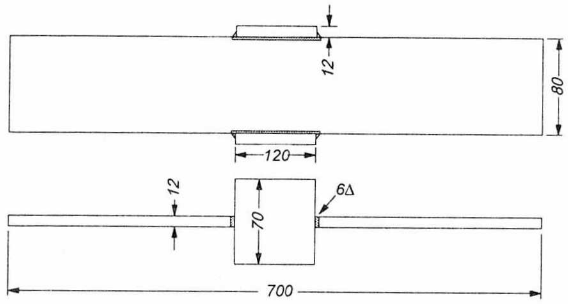
(b) Cover plate



(c) Longitudinal stiffener



(d) Gusset



(e) Side attachment

Fig. 3 Configurations of 5 weld joints[1]

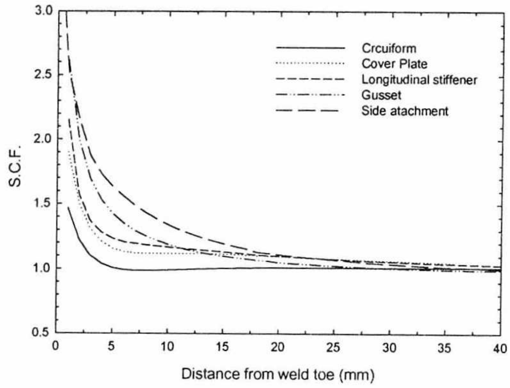


Fig. 4(a) Stress concentration curves by FEM [5]

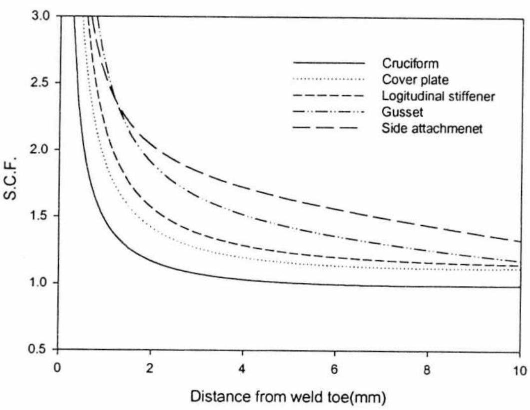


Fig. 4(b) Stress concentration curves by present representative stress

$(r = 0.1, 0.5, 0.9)$

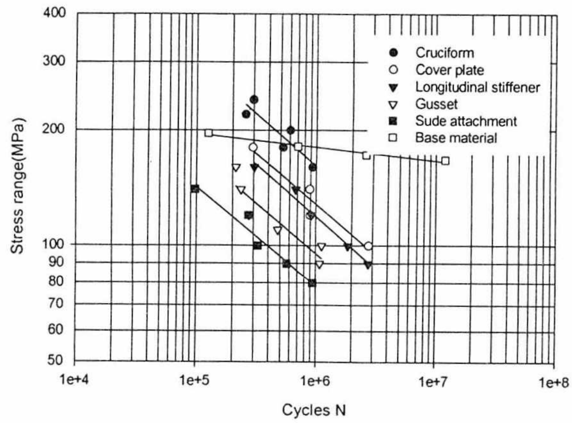


Fig. 5 S-N curves of weld joints with nominal stress(SM490B)

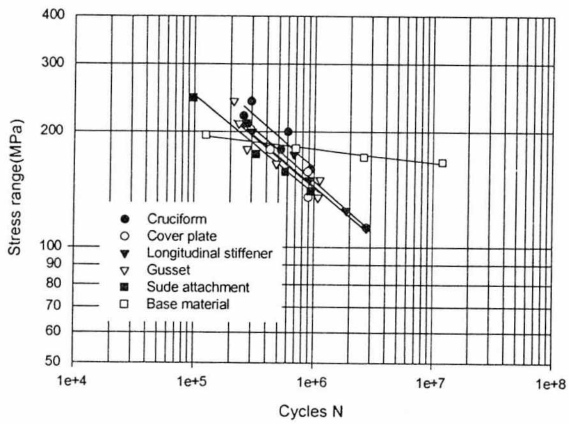


Fig. 6 S-N curves with hot spot stress(r1=0.5t, r2=1.0t)

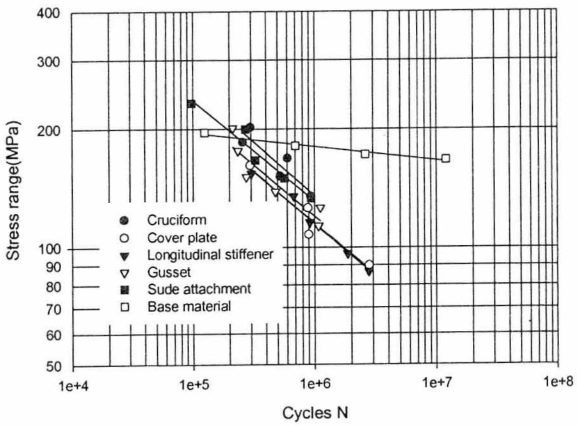


Fig. 7 S-N curves with Eq.(2)

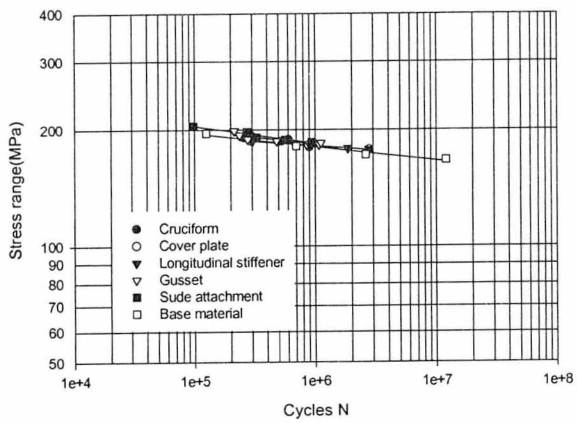


Fig. 8 S-N curves with proposed representative stress

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Appendix

A.1 Notch strain model

The notch strain model suggested by Smith-Wasten-Topper[2] was tried.

$$\sigma_{\max}\frac{\Delta\varepsilon}{2}=\frac{(\sigma'_f)^2}{E}(2N_I)^{2b}+\sigma'_f\varepsilon'_f(2N_I)^{b+c}$$

where $\sigma'_f, \varepsilon'_f, b, c$ are coefficients determined by experiments, and N_I is failure lives.

Residual stresses were incorporated into $\sigma_{\max}$ by three methods.

1) Lawrence model[6] :

$$\sigma_{\max}\varepsilon_{\max}=\frac{(K_f S_{\max}+\sigma_r)^2}{E}$$

2) Reemsnyder model[7] :

$$\sigma_{\max}\varepsilon_{\max}=\frac{1}{E}\left(\frac{K_f S_{\max}}{1-\sigma_r/\sigma_{\max}}\right)^2$$

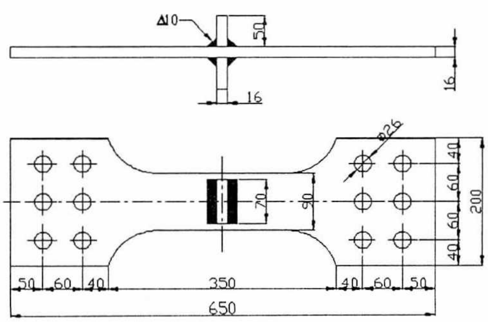
3) Seeger model[8] :

$$\sigma_{\max}\varepsilon_{\max}=\frac{(K_f S_{\max})^2+\sigma_{\max}\sigma_r}{E}$$

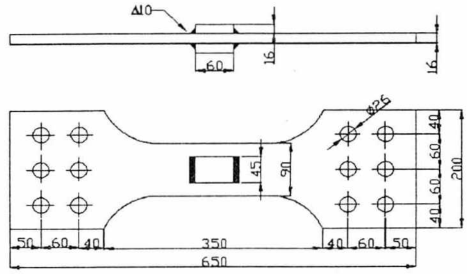
where K_f is a fatigue notch factor, σ_r a residual stress, and $S_{\max}$ a maximum nominal stress.

A.2 Experiment 1

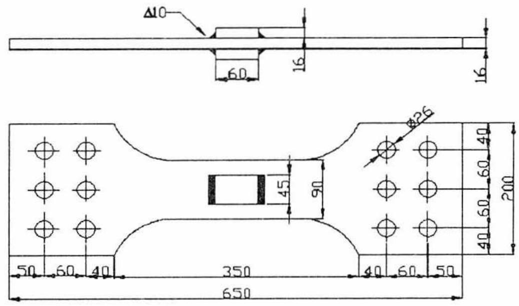
This experiment is a conventional fatigue test with the load control. Three types of weld joints were considered.



(a) Cruciform



(b) Cover plate



(c) Longitudinal stiffener

Fig. a.1 Configurations of weld joint specimens (base material is SM490B)

A.3 Experiment 2

This experiment is to determine the coefficients of notch strain model. The specimen was heated by flowing electric current through it to imitate HAZ of weld joints. The fatigue test was conducted under the strain control.

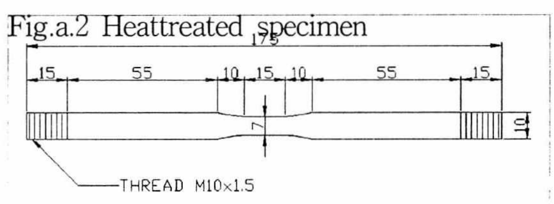


Fig. a.2 Heat treated specimen

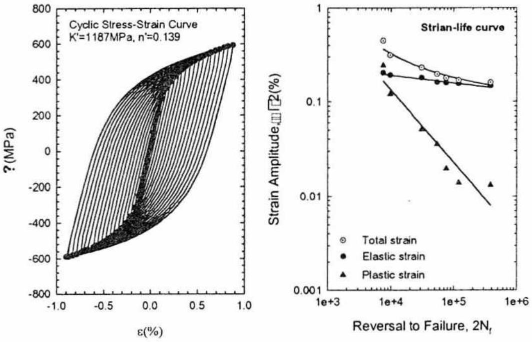


Fig. a.3 Cycle stress-strain curve and life curves

Table a.1 Determined coefficients for the notch strain model

Cyclic strain hardening coefficient, K'(MPa)	1187
Cyclic strain hardening exponent, n'	0.139
Fatigue strength coefficient, 'f	878
Fatigue strength exponent, b	-0.083
Fatigue ductility coefficient, 'f	1.632
Fatigue ductility exponent, c	-0.772

A. 4 Results

The fatigue lives were divided into the initiation and propagation lives, and estimated with deferent method respectively. The initiation lives were estimated by the notch strain approach, and the propagation lives by Paris's law with FEM calculations. The estimated fatigue lives are summarized in Fig. a.4-6.

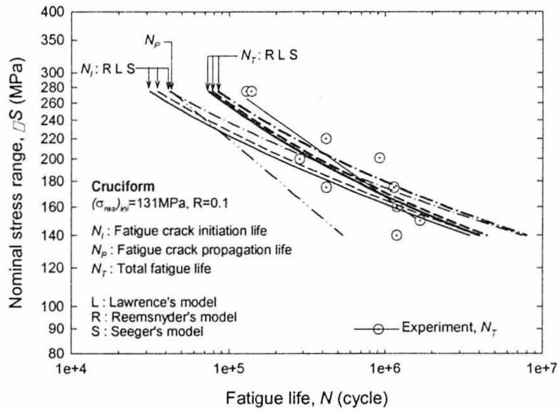


Fig. a.4 S-N curves of cruciform

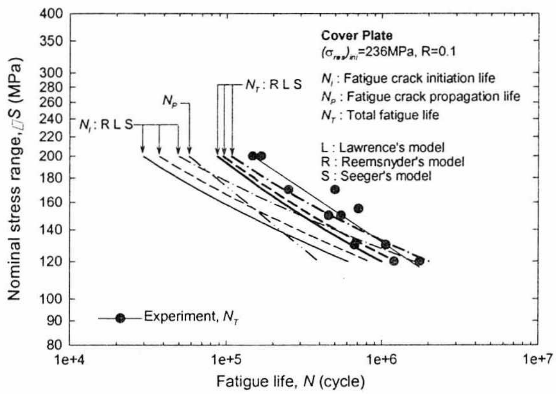


Fig. a.5 S-N curves of cover plate

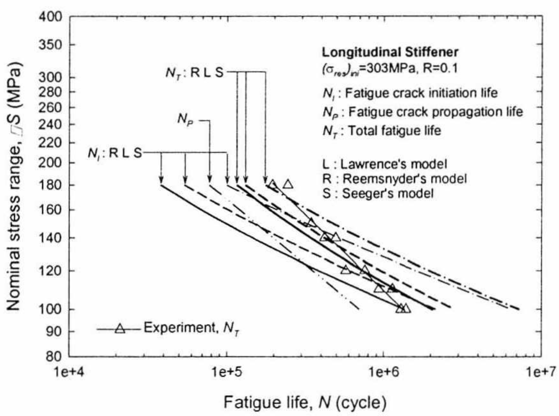


Fig. a.6 S-N curves of longitudinal stiffener