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FULL RANGE FATIGUE LIFE ESTIMATION METHOD USING CRITICAL DISTANCE STRESS THEORY

Muhammad Amiruddin Bin Ab Wahab [1],Toshio Hattori[2(*)], and Minoru Yamashita[2]

[1]Graduate school student of Gifu University, Gifu, Japan

[2] Department of Mechanical and System Engineering, Gifu University, Gifu, Japan

(*)Email: hattori@gifu-u.ac.jp

ABSTRACT

Generally the critical distance stress theory was applied for the fatigue limit estimation of general structures using fatigue limit of smooth specimen ($\sigma_{w0)}$, and threshold stress intensity factor range ($\Delta K_{th)}$. In this paper we extended this method for the estimation of low cycle fatigue life too. In this method we define the critical distance ($r_c^{'}$) on static strength conditions, which is calculated using ultimate tensile strength (σ_B) and fracture toughness (K_{IC}), in addition to the critical distance on fatigue limit condition (r_c). Then the critical distances of any low cycle fatigue conditions can be calculated by interpolation of critical distance on fatigue limit (r_c) with critical distance on static strength ($r_c^{'}$). By unifying these low cycle fatigue life estimation method with high cycle fatigue limit estimation method we can estimate the full range fatigue life easily. And to confirm the availability of this estimation method we perform the fatigue test for any stress concentration specimens and fretting fatigue specimens.

Keywords: high cycle fatigue, low cycle fatigue, fatigue life, critical distance stress theory, threshold of stress intensity factor range, fracture toughness fretting wear, contact edge, low cycle fatigue, stress intensity factors. critical distance stress theory.

INTRODUCTION

In general the critical distance stress theory (point method and line method) were used for estimation of fatigue limit with any shape structures [1)]. In this method the fatigue limit can be obtained using typical material strength parameters such as the fatigue limit of smooth specimens σw0 and the threshold stress intensity factor range ΔK_{th} of the cracked specimens. In the case of point method, the fatigue failure supposed to occur when the stress range at specific length r_c from maximum stress point reach $\Delta\sigma_{w0}$.

In this paper we extended this method to the low cycle fatigue regions. Then I will explain this development in detail. Firstly the critical distance in low cycle fatigue region is derived by interpolating between critical distance in fatigue limit r_c as shown in above and critical distance in static strength r_c'. This static strength critical distance rc' can be derived using ultimate strength of smooth specimen σ_B and the fracture toughness K_{IC} of the cracked specimen.

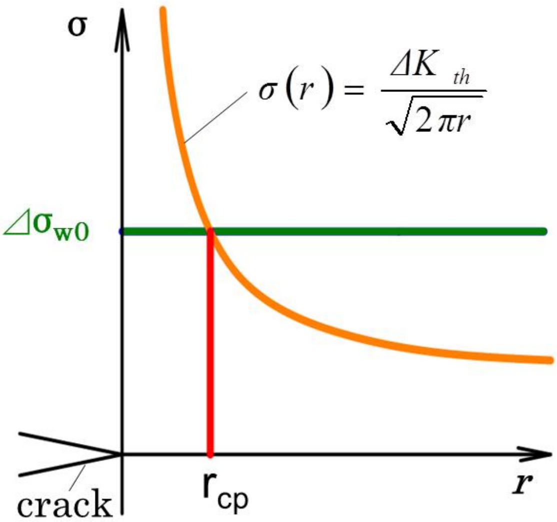
To confirm the validity of this critical distance approach we applied this method on full range cycle (including both high cycle and low cycle range) fatigue life estimation of circle hole specimens and fretting fatigue specimens. These estimated full range S-N curves coincided well with the experimental results.

CRITICAL DISTANCE STRESS THEORY

In the critical distance stress method the fatigue limit of the target structure can be obtained using typical material strength parameters such as the fatigue limit of smooth specimens σ_{w0} and the threshold stress intensity factor range ΔK_{th} of the cracked specimens as shown in Fig. 1,2. In the case of point method, the fatigue failure supposed to occur when the stress range at specific length r_{cp} from maximum stress point reach $\Delta\sigma_{w0}$, and in the case of line method the fatigue failure supposed to occur when the mean stress range between maximum stress point and specific length point r_{cl} reach $\Delta\sigma_{w0}$. Each r_{cp} and r_{cl} can be derived as follows.

For point method, $r_{cp}=(\Delta K_{th}/\Delta\sigma_{wo})^2/2\pi$ (1)

And for line method, $r_{cl}=2(\Delta Kth/\Delta\sigma wo)^2/\pi$ (2)



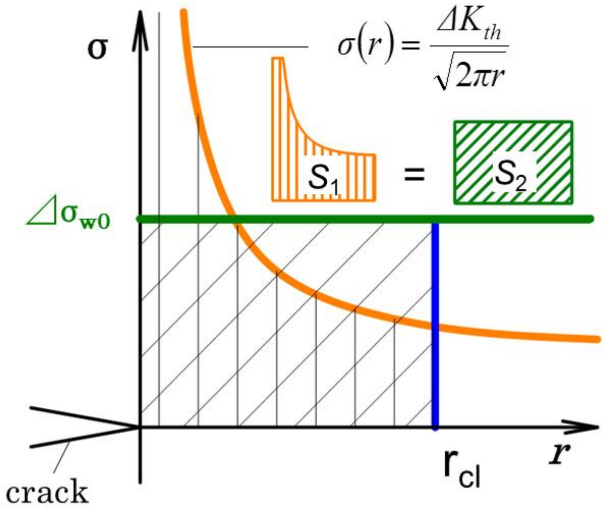


Fig. 1 Derivation of critical distance r_{cp} (point method)

Fig. 2 Derivation of critical distance r_{cl} (line method)

APPLICATION OF CRITICAL DISTANCE STRESS THEORY ON THE LOW CYCLE FATIGUE ANALYSISs

In this paper we extended this method to the low cycle fatigue regions. Then I will explain this development in detail. Firstly the critical distance in low cycle fatigue region is derived by interpolating between critical distance in fatigue limit as shown in above and critical distance in static strength. This static strength critical distance can be derived using ultimate tensile strength of smooth specimen σ_B and the fracture toughness K_{IC} of the cracked specimen as shown in Eq. (3),(4).

For point method, $r_{cp}'=(K_{IC}/\sigma_B)^2/2\pi$ (3)

And for line method, $r_{cl}'=2(K_{IC}/\sigma_B)^2/\pi$ (4)

In this section we use only the point method.

The critical distance in each stress level is calculated by interpolation of critical distance on fatigue limit (r_c, estimated using σ_{w0} and ΔK_{th}) with critical distance on static strength (r_c', estimated using σ_B and K_{IC}) as shown by chain line in Fig. 3(right). The critical distance on objective conditions (structure, load) can be estimated by reflecting the stress distributions of objective structure as shown by dotted line in Fig. 3(right). The low cycle fatigue life in this objective condition can be estimated by applying this reference stress σ at critical distance r on S-N curve of smooth specimens as shown in Fig. 3(left upper).

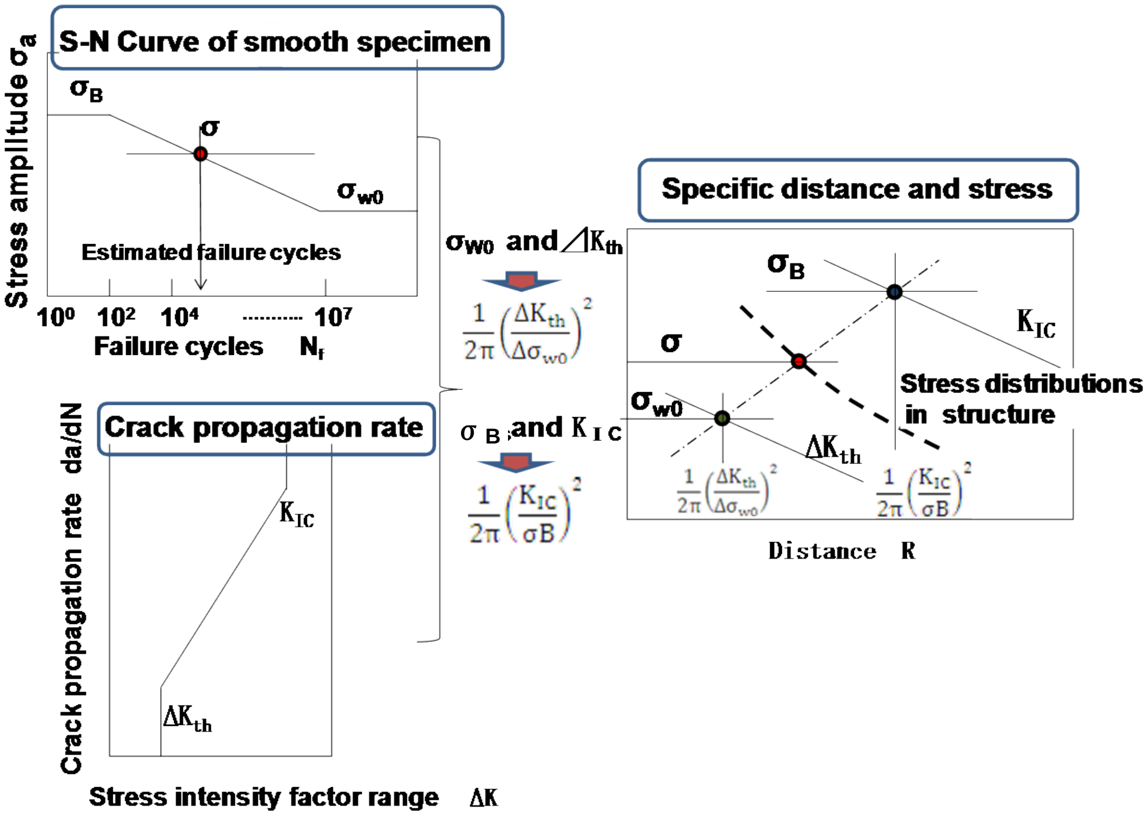


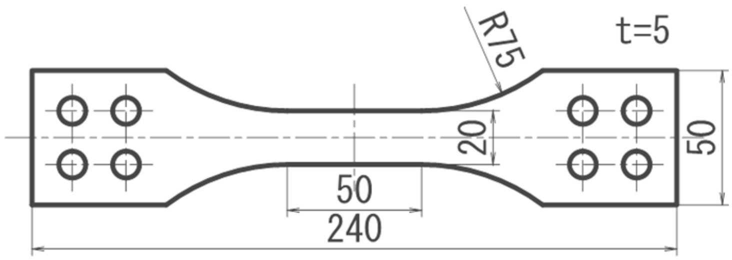
Fig.3 Derivation of specific distance in low cycle fatigue region and estimation of low cycle fatigue life

To confirm the validity of this critical distance approach we applied this method on low cycle fatigue life estimation of circle hole specimens. Smooth specimen and circle hole specimen used on this test are shown in Fig. 4, and material properties of SS400 steel are shown in Table 1.

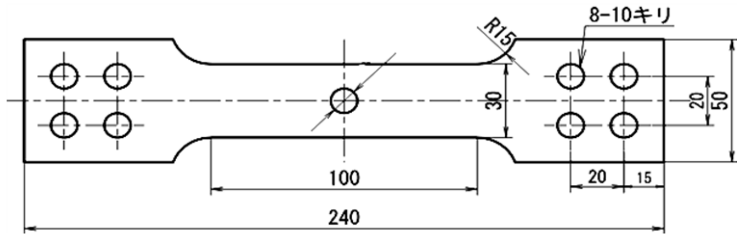
S-N curve of the smooth specimens is shown in Fig. 5. And Critical distance on fatigue limit r_c and on static strength r_c' are estimated using Eq.(1),(1)' and (3),(3)' as 0.077mm and 1.24mm respectively, and shown in Figs.6,7,8 by ●points.

$$r_c = \frac{1}{2\pi}\left(\frac{\Delta K_{th}}{\Delta\sigma_{wo}}\right)^2 = \frac{1}{2\pi}\left(\frac{6.7\times10^6}{305\times10^6}\right)^2 = 0.077 \quad \text{(mm)} \qquad (1)'$$

$$r'_c = \frac{1}{2\pi}\left(\frac{\Delta K_c}{\Delta\sigma_b}\right)^2 = \frac{1}{2\pi}\left(\frac{39.5\times10^6}{448\times10^6}\right)^2 = 1.24 \quad \text{(mm)} \qquad (3)'$$



(a) Smooth specimen



(b) Circle hole specimen

Fig.4 Dimensions of smooth and circle hole specimens

Table 1 Mechanical properties of SS400 steel

$\triangle\sigma_{w0}$ [MPa]	$\triangle K_{th}$ [MPa・m$^{1/2}$]	σ_B [MPa]	K_{IC} [MPa・m$^{1/2}$]
305	6.7	448	39.5

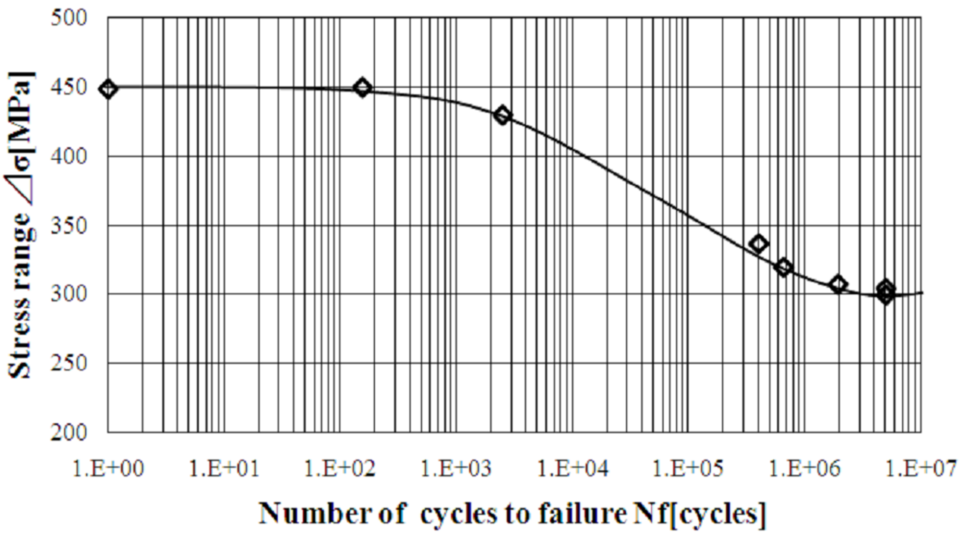


Fig.5 S-N curve of smooth specimens. (SS400 steel)

By interpolating these two points the critical distances on arbitrary conditions are estimated as solid line(predict line) in Fig. 6,7,8. The critical distance of circle hole specimens on each loading condition can be estimated as the cross point of these stress distributions lines on each loading conditions with interpolation line (predict line) as shown in Fig. 6,7,8. And by reflecting the stress σ on this cross point on S-N curve of smooth specimens we can estimate the fatigue life of each loading condition of each circle hole specimen.

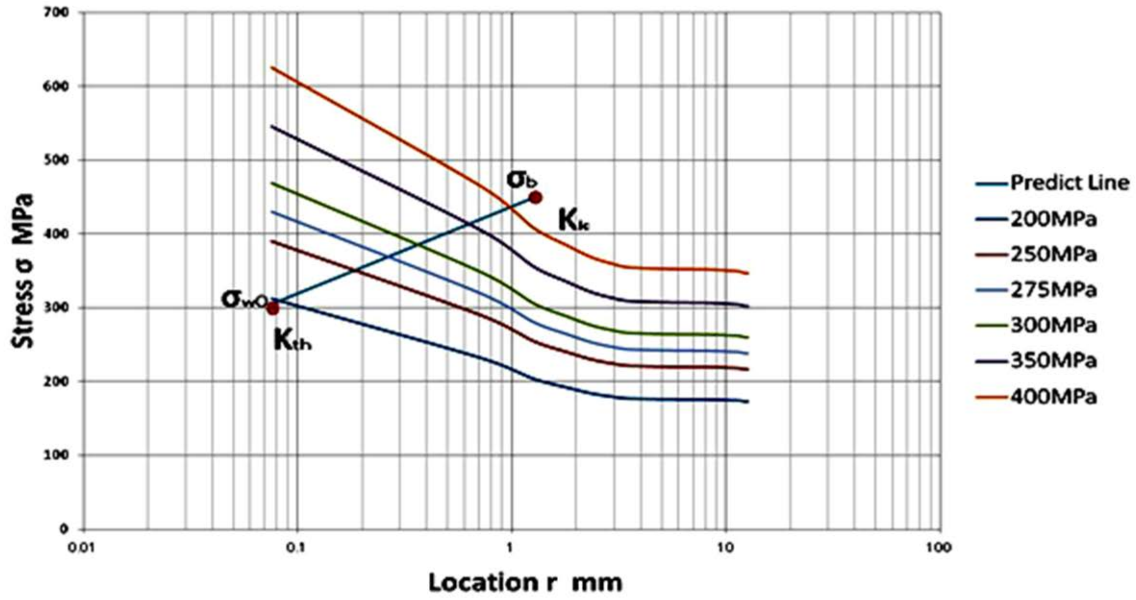


Fig.6 Stress distributions in circle hole specimen with circle diameter 4mm on each nominal stress

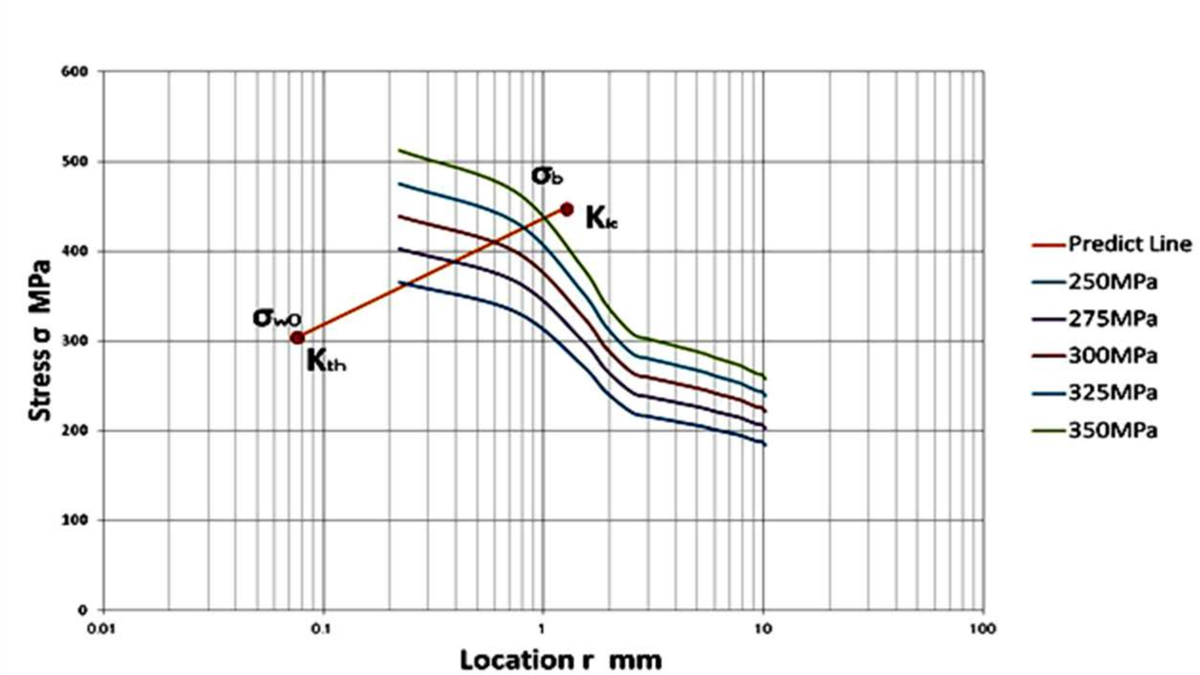


Fig.7 Stress distributions in circle hole specimen with circle diameter8mm on each nominal stress

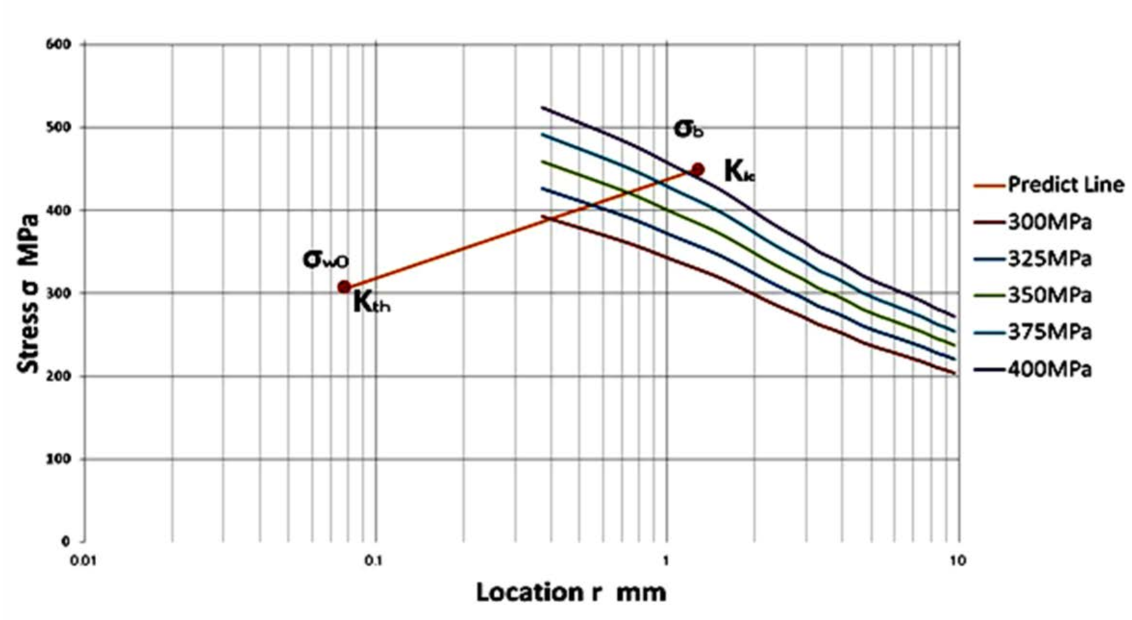


Fig.8 Stress distributions in circle hole specimen with circle diameter 10mm on each nominal stress

By repeating this estimation we can estimate the S-N curve of each circle hole specimen as shown in Fig. 9,1011by solid line. These estimated results coincided well with the experimental results shown as symbol ■ in each Figures.

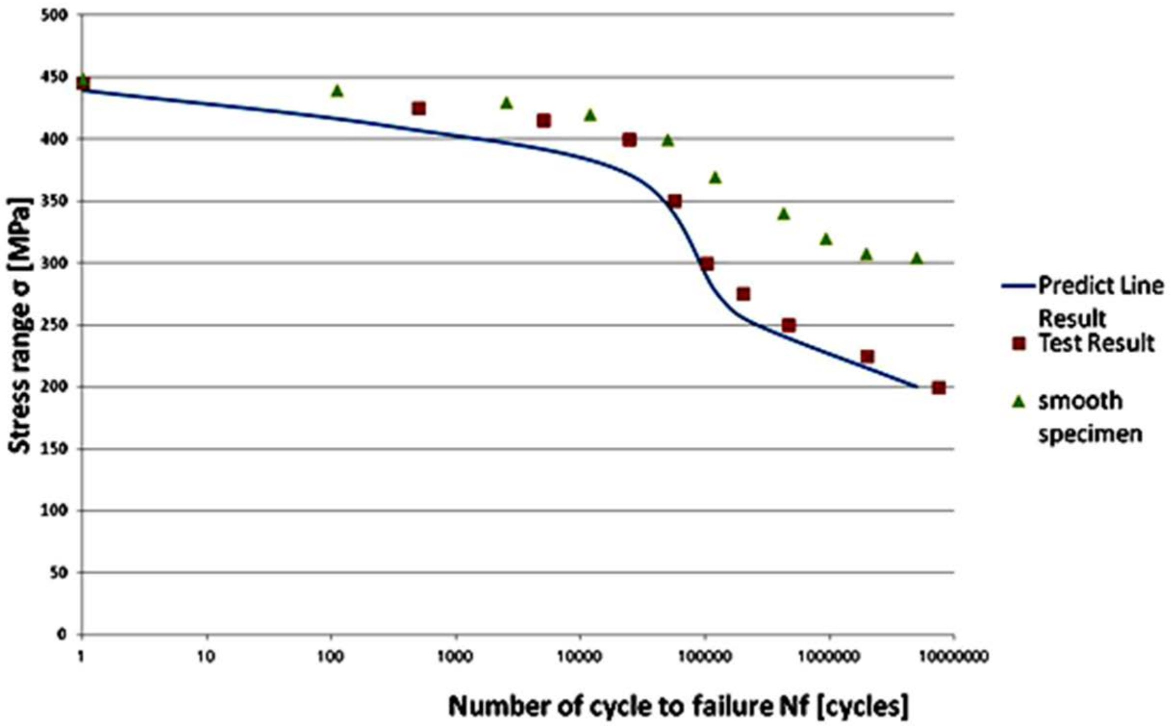


Fig.9 Estimated and experimental S-N curves of circle 4mm specimens

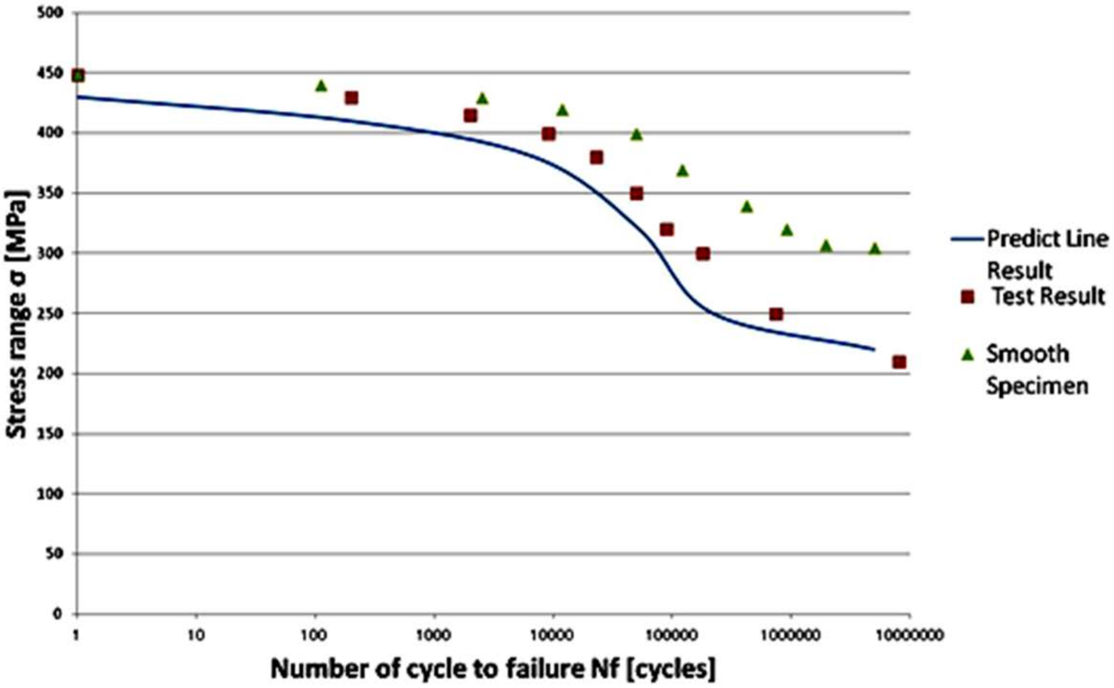


Fig.10 Estimated and experimental S-N curves of circle 8mm specimens

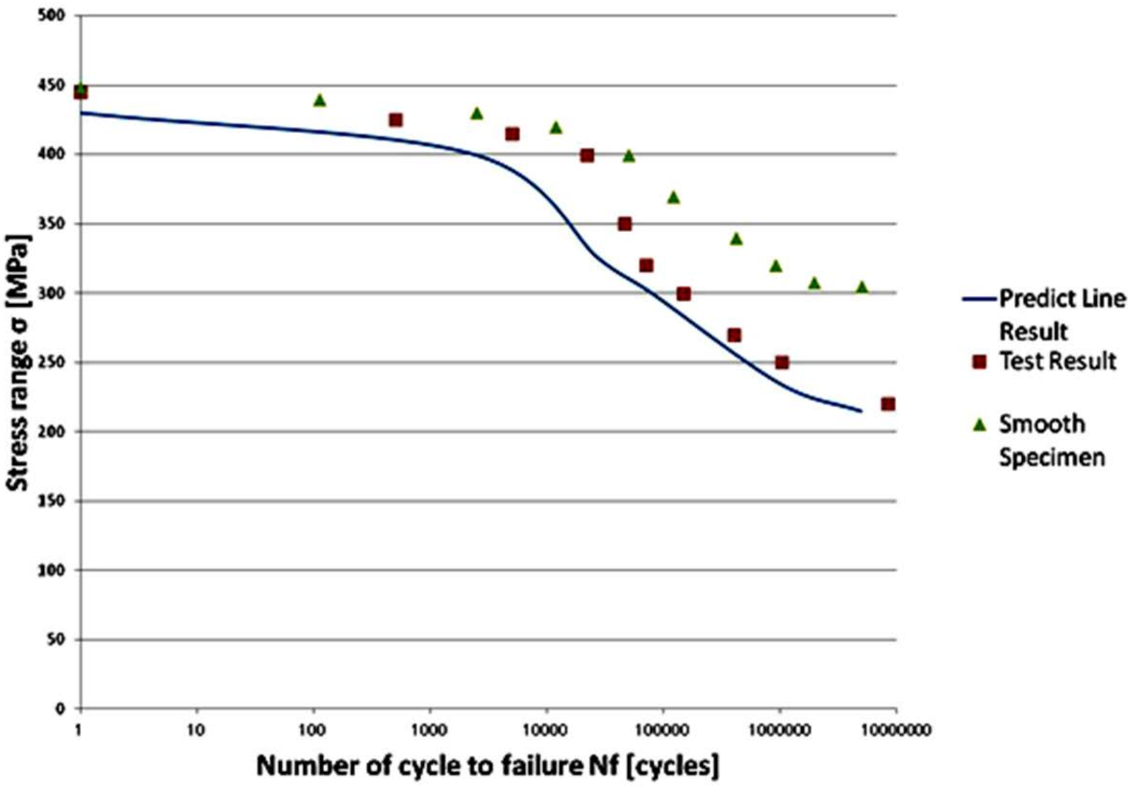


Fig.11 Estimated and experimental S-N curves of circle 10mm specimens

APPLICATION ON LOW CYCLE FRETTING FATIGUE ANALYSIS

As mentioned in previous papers, in general the fretting fatigue accidents were dominated by high cycle fatigue failure, and so many fretting fatigue strength and life analysis were carried out especially on high cycle region[2-18]. But, recently in accordance with the increase of daily start stop operations in such as the turbine machinery the increase of low cycle fretting fatigue failure can be observed in power plant industrial fields.

Then we will apply this extended critical distance theory on the fretting fatigue life prediction. In Fig.12 (left upper) the S-N curve of Ni-Mo-V steel smooth specimen in complete reversed loading conditions (R=-1), and in Fig.12 (left under) the crack propagation characteristic of cracked specimen

is shown. From these material characteristics we can obtain the critical distance r_c as 0.011mm and r_c' as 2.13mm as shown in Fig. 12 (right). The stress distributions in fretting conditions were calculated using FEM model as shown in Fig. 13. The calculated example of stress distribution near the contact edge is shown in Fig. 14. The mean contact pressure σ_p and mean axial stress σ_a in this case are 200MPa and 100MPa respectively.

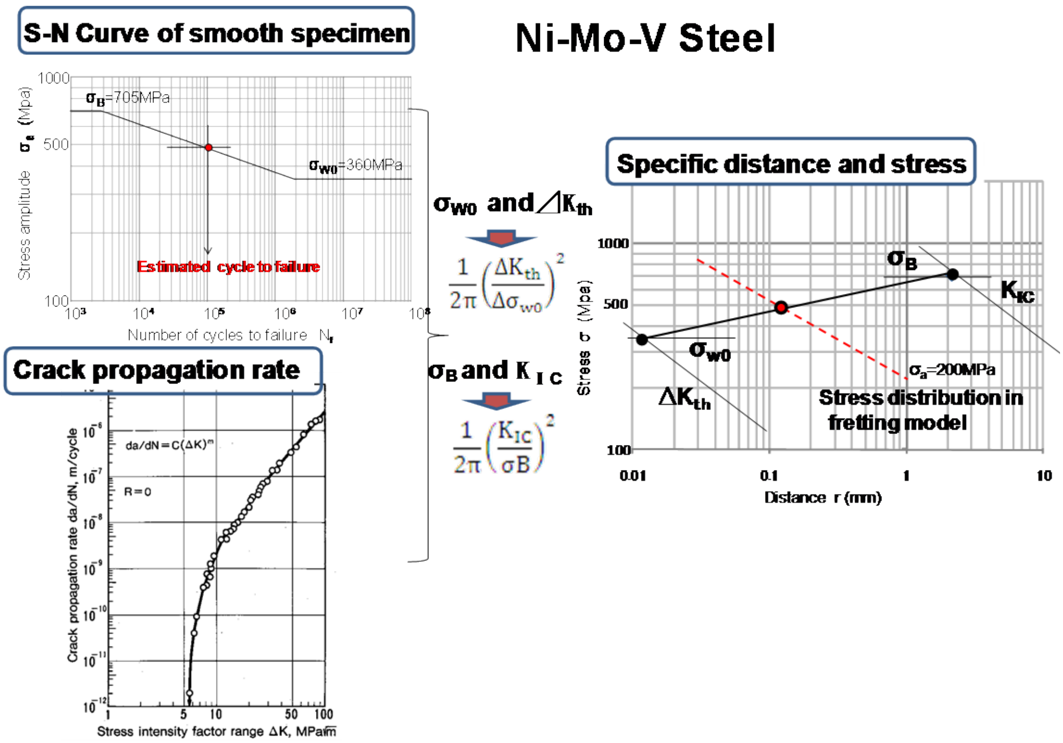


Fig.12 Derivation of specific distance in low cycle fatigue region and estimation of low cycle fretting fatigue life

The critical distance on each loading conditions can be estimated by reflecting these stress distributions on Fig.12 (right) as shown by dotted line. The low cycle fretting fatigue life in this loading condition ($\Delta\sigma/2=\sigma_a$ is 200MPa) can be estimated by applying this stress level at critical distance (cross point σ =490MPa) on S-N curve of smooth specimens as shown in Fig. 12 (left upper). By connecting these fretting fatigue life on each stress level we can estimate the fretting fatigue S-N curve as shown in solid line in Fig.15.

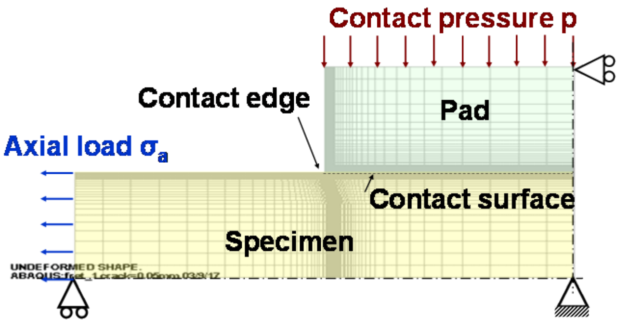


Fig.13 FEM Fretting model

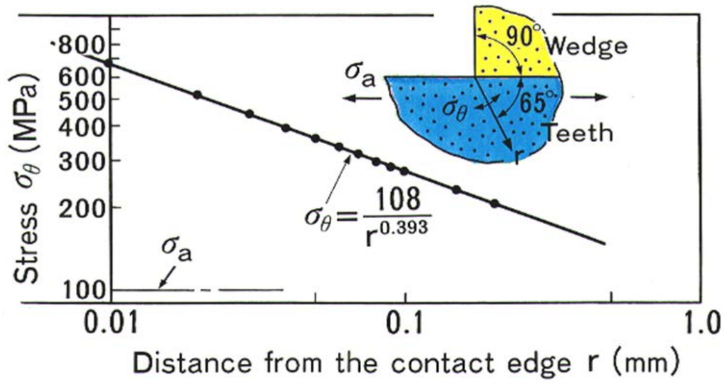


Fig. 14 Calculated result of stress distributions

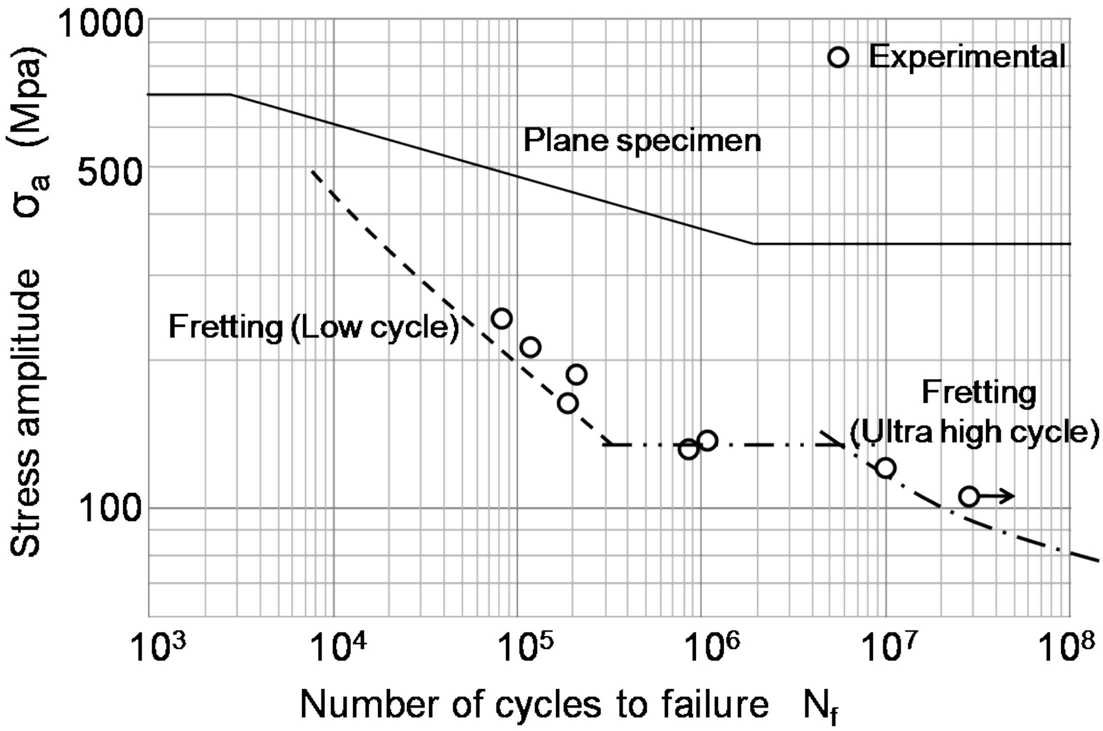


Fig.15 Estimated and experimental fretting fatigue S-N curves

COMPARISON WITH THE EXPERIMENTAL RESULTS

To confirm the validity of this fretting fatigue life estimation method we compare these estimated results with the experimental results. The fretting fatigue test apparatus is shown in Fig. 16. The specimen material is Ni-Mo-V steel. The contact pressure between specimen and pads is set as 200MPa by screw. The contact pressure and crack initiation at the contact edges are monitored by the strain gage A and strain gage B Respectively. The experimental results of fretting fatigue tests are shown in Fig. 15 by symbol ○. The estimated results of low cycle fretting fatigue life using critical distance theory is shown by dotted line in Fig. 15. The estimated results of high cycle fretting fatigue life considering fretting wear process which was presented in previous paper[17,18)] is shown by dash line in Fig. 15. And the estimated fretting fatigue limit (142MPa) without considering fretting wear which was presented in previous paper[13)] is shown by two points of dot-dash line in Fig. 15. We can see that these three kinds of fretting fatigue strength and life prediction results coincided well with the experimental results in each stress and life level. And we can confirm the validity of these fretting fatigue strength and life estimation methods.

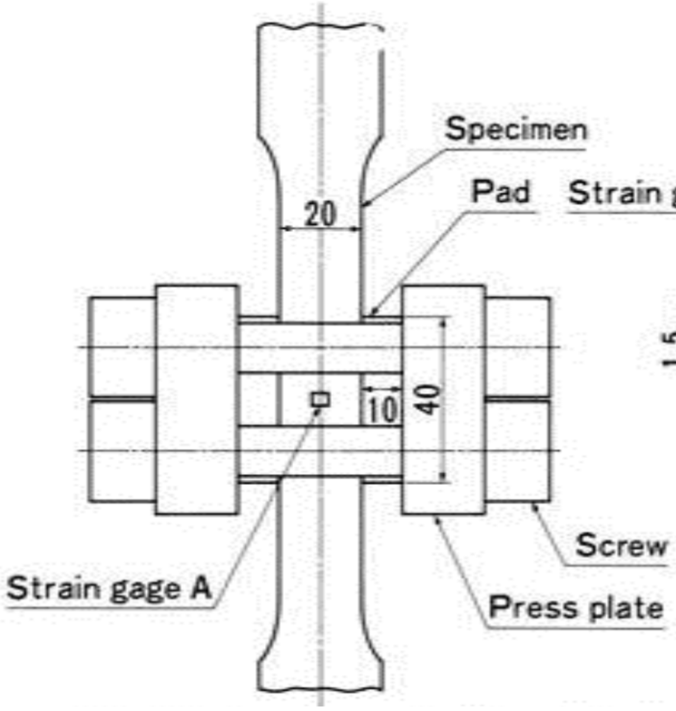


Fig.16 Fretting fatigue test apparatus

CONCLUSIONS

1. We developed the total region fatigue strength and life estimation method by modifying the critical distance stress theory, which mainly applied on high cycle fatigue analysis, in order to make applicable for low cycle fatigue analysis too.
2. This modified critical distance stress theory was applied on fatigue strength and life estimation of hole specimens, and the estimated S-N curve coincided well with the experimental results.
3. Low cycle fretting fatigue strength was estimated using the developed critical distance theory, .and this estimated results coincided well with the fretting fatigue test results And we can confirm the availability of these fretting fatigue strength and life estimation methods as the standardized fretting fatigue S-N curve estimation method.

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