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Notched Bar Tests of Creep-Fatigue Damage with Elastic Follow-up for High Temperature Structural Design

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R.I.Jetter proposed the Simplified Model Test Approach to account for the effects of strain redistribution and the combined effects of creep and fatigue damage in an actual structure design when subjected to comparable loading. The test article is a displacement-controlled hold-time creep-fatigue specimen with elastic follow-up. The measure of loading comparability is the maximum elastically calculated strain range in the component, including the effects of stress concentrations, compared to the elastically calculated strain range in the test specimen. The tests were performed at 550℃, using SUS304 stainless steel specimens with notches.

1 THE SIMPLIFIED MODEL TEST APPROACH

1. 1 Conceptual basis of the approach

The basic concept of the proposed Simplified Model Test (SMT) is shown in Fig.1[1]. The component design situation is represented by a hypothetical stepped cylinder with a stress concentration at the shoulder fillet radius. The component has a global elastic follow-up, q_n, which is due to the interaction of the two cylindrical sections, and a local elastic follow-up, q_L, which is due to the local stress concentration.

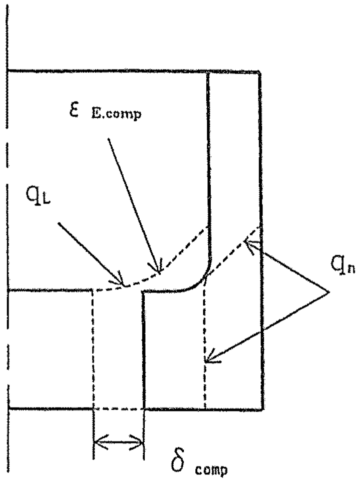

Fig. 1. Shell structure with stress concentration and elastic follow-up

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If the thick cylinder is displaced radially inward, δ_{comp} , there will be a resultant maximum strain at a stress concentration. Although the actual strain may be higher, the relevant parameter in this approach is the maximum elastically calculated strain in the component[2], $\varepsilon_{E.comp}$. The effects of plasticity, creep and strain redistribution are accounted for in the test simulation.

The damage from a strain, $\varepsilon_{E.comp}$, which is applied, held, and then cycled back to zero and reapplied is evaluated from a design curve based on data from SMT. The evaluation procedure is envisioned to be essentially the same as that used in Subsection NB of ASME Sec. Ⅲ[3] and Japanese Notice No.501[4] where the damage fraction is determined as the ratio of actual number of applied cycles, n, to the allowed number of cycles, N, with the same range, ε_E . Ideally, for a given temperature there would only be two design curves, one for short term loads, such as seismic, without a hold time effect, and another curve which envelops the effects of hold time duration and follow-up magnitude without excessive conservatism.

The design curve is to be developed from SMT data which is plotted as elastically calculated strain vs. observed cycles to failure. The specimen is sized to envelope the follow-up characteristics of interest. A design margin must be applied to the data to account for such factors as data scatter, extrapolation to longer hold times etc.

1. 2 SMT specimen characteristics

The SMT specimen must be sized to provide a stress strain histogram under cyclic loading which envelops the histogram of the components of interest. Although there is no rigorous way to demonstrate that the stepped bar model can bound the response under all circumstances, there are approaches which can be used to demonstrate that the bounding strategy is applicable to a range of practical circumstances.

A 4bar model is considered to represent a structure such as the stepped cylinder with global follow-up represented by the interaction of the cylinders and local follow-up due to the stress concentration at the houlder fillet. The model, Fig. 2, is basically that described by Kasahara et al[5].

Physically, the elastic stress in bar ① represents the maximum stress at the stress concentration, (P_L+P_B+Q+F) , in the terminology of the ASME Code[2), 3)]. The stress in bar ③ represents the stress corresponding to the primary plus secondary stress range (P_L+P_B+Q) . The follow up in the stepped bar system, q_{12} , represents the follow up due to the local stress concentration factor, K. It can be determined from an expression developed by Kasahara, as Eq.(1),

$$q_L = K^{(m-1)/(m+1)} \tag{1}$$

where m=creep exponent constant in the Norton law expression for strain rate.

The follow-up in the stepped bar system, q_{34} , represents the global follow-up due to the interaction of the two cylinders.

For a given choice of area ratios, the 4bar model can be sized from the following relationships for elastic stress distribution and follow-up[6]:

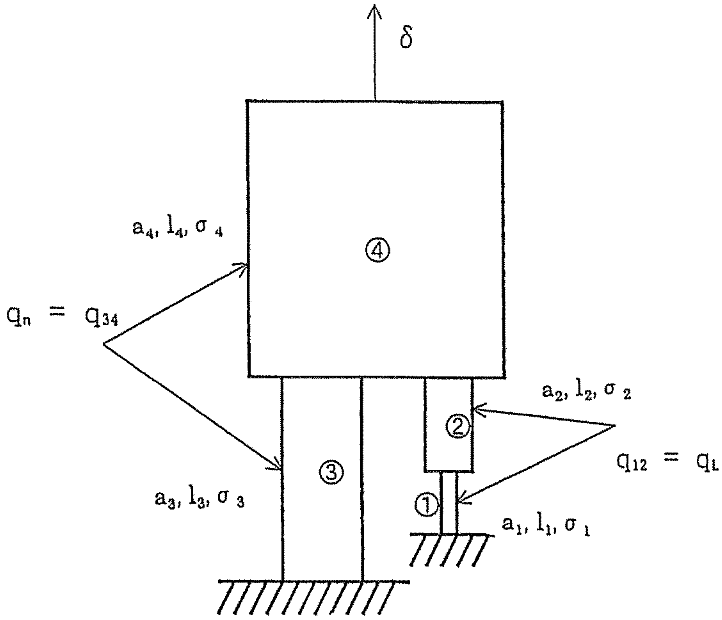

Fig. 2. 4bar model

$$\text{localq}: q_L = q_{12} = \frac{1+(l_2/l_1)(a_1/a_2)}{1+(l_2/l_1)(a_1/a_2)^m} \tag{2}$$

$$\text{globalq}: q_n = q_{34} = \frac{1+(l_4/l_3)(a_3/a_4)}{1+(l_4/l_3)(a_3/a_4)} \tag{3}$$

An approximate steady state solution for creep relaxation was developed by Kasahara et al [5), 6)],

$$\sigma_1 = -\frac{1}{q_{12}}EB\sigma_1^m + K\left[1-\frac{1}{q_{34}}\right]EB\sigma_3^m \tag{4}$$

$$\sigma_3 = -\frac{1}{q_{34}}EB\sigma_3^m \tag{5}$$

where B and m are Norton law material constants, E is the modulus of elasticity.

Assuming the stress ratio σ_1 and σ_2 is constant Kc at the steady state creep conditions,

$$\sigma_1 = Kc\sigma_3\,, \quad \sigma_1 = Kc\sigma_3 \tag{6}$$

the following relation is obtained.

$$\sigma_1 = -\frac{1}{q_{34}\cdot K_c^{m-1}}EB\sigma_1^m \tag{7}$$

From Eq (7), the local elastic follow-up factor q_L is given by $q_{34}\cdot K_c^{m-1}$, where q_{34} is equal to q_n (global elastic follow-up factor). As the Eq(8) is verified with the thermal transient test using a cylindrical shell with a notch model and a stepped cylinder model[1)],

$$K_c^{m-1} \leqq K \tag{8}$$

the resultant value of q_L is given by :

$$q_L \leqq K\cdot q_n \tag{9}$$

The strain limits of Subsection NH[2)] for the thermal stress ratchet criteria[3), 7)] are replaced by the following criteria, as the core stress will be limited by the value of S_t for the maximum sustained temperature and time,

$$(P_L+P_B/K_t)_{max}+(Q_r)_{max}/4 \leqq S_t \tag{10}$$

where the symbols follow the usual definitions of Subsection NH.

2 TESTING CONDITIONS

2. 1 Tested materials and temperature

As stainless steel of SUS304 (JIS G 4303-1991) is used most generally in the conventional elevated temperature components such as heat exchangers, pressure vessels etc, SUS304 is selected for the test specimens, of which chemical compositions are shown in Table 1. All tests are performed at the constant temperature of 550℃ by using hydraulic servo creep fatigue testing machine. The test temperature 550℃ is chosen to include a remarkable creep phenomenon and to be very close to the maximum allowable design temperature. Number of cycles to failure N_f is accounted by the separation of the specimen.

Table 1. Chemical composition of SUS304 (JIS G 4303-1991) (%)

C	Si	Mn	P	S	Ni	Cr
< 0.08	< 1.00	< 2.00	< 0.045	< 0.030	8.00 ~ 10.50	18.00 ~ 20.00

2. 2 Decision of the dimensions of the tests specimens.

At the beginning of the SMT study, authors carried out the stepped bar model tests for the global elastic follow-up, where the test specimen configuration was selected as shown in Fig. 3. The value of q_n was 1.64 and K was 1.0 (no stress concentration).

The configuration of the specimens for the local elastic follow-up factor is chosen to make the circumferentially round notch at the mid center of the stepped bar model, as shown in Fig. 4. This type specimen is called hereinafter as "Notched bar specimen". 3 kinds of the specimen are fabricated with the notch radius of curvature of 0.6mm, 0.8mm, and 1.0mm, respectively.

K value of each notched radius model is obtained from Ref. (9). In due course, each q_L value for the notched radius ρ is calculated by E_q. (9) as shown in Table 2.

Table 2. K and q_L values of the notched bar specimens

ρ	K	$q_L = K \cdot q_n$
0.6	2.60	4.264
0.8	2.21	3.624
1.0	2.05	3.362

3 TEST RESULTS

3. 1 Elastic characteristic test of the specimen

Since the obtained test data are to be used for the life prediction with the elastic follow-up on the basis of elastic stress analysis, the test data must be arranged in the cycles to failure N_f vs. the elastically calculated strain ε_{ce}. The elastically calculated strain must be consistent to the strain of the elastic stress analysis.

A virgin test specimen of Fig. 3. is extended to obtain the elastically calculated strain. Both elongation of δ (mm) for the total length 120mm(stroke control length) and λ_1 (mm) for the gauge length 15mm are measured by each extension step. The elastically calculated strain ε_{ce} of the stepped bar specimen was obtained as Eq.(11)[10].

$$\varepsilon_{ce} = \lambda_1/[\text{gauge lenght}]$$
$$= \lambda_1/15(\text{mm}) = 8.67\times10^{-3}\delta \tag{11}$$

In the case of the notched bar specimen of Fig. 4 and Fig. 5, both elongation δ for the

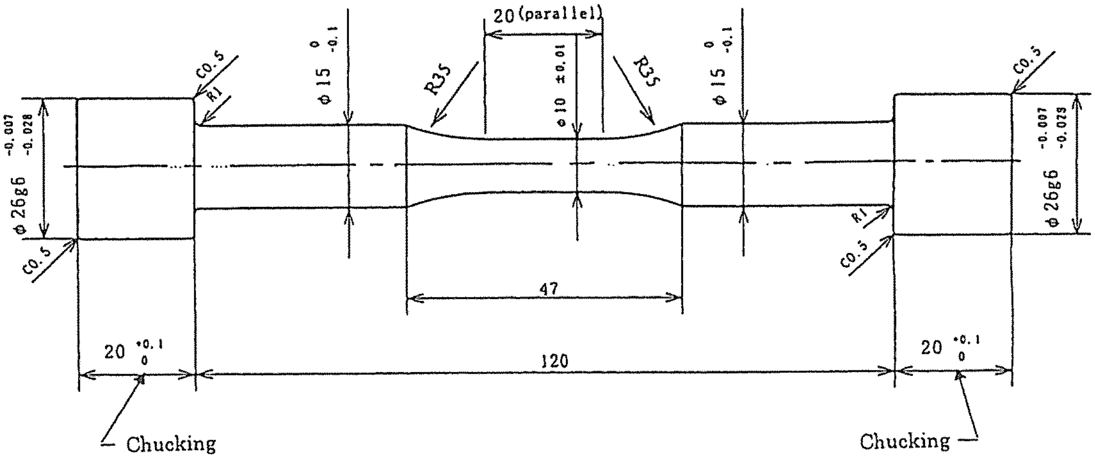

Fig. 3. Stepped bar model configuration

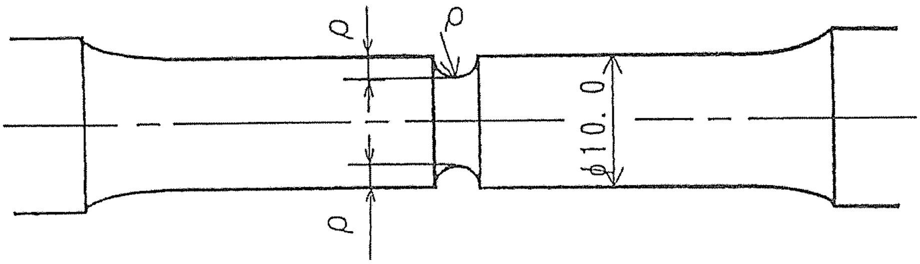

Fig. 4. Configuration of test specimen with notch

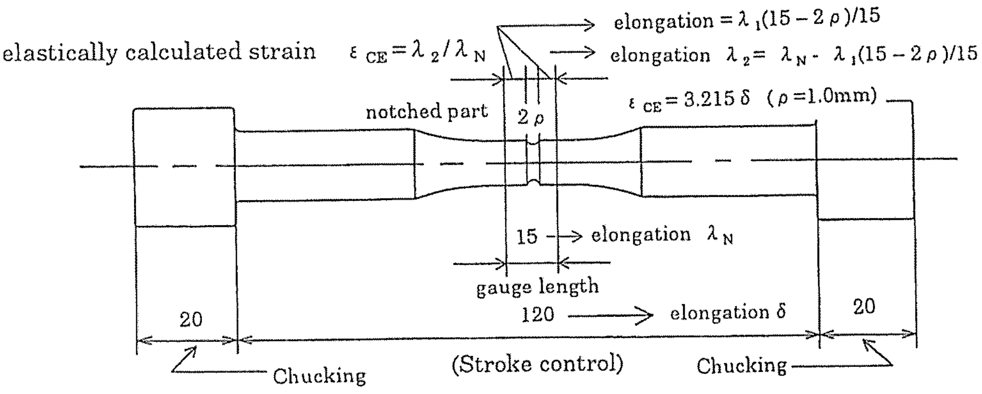

Fig. 5. Test specimen of notched bar model

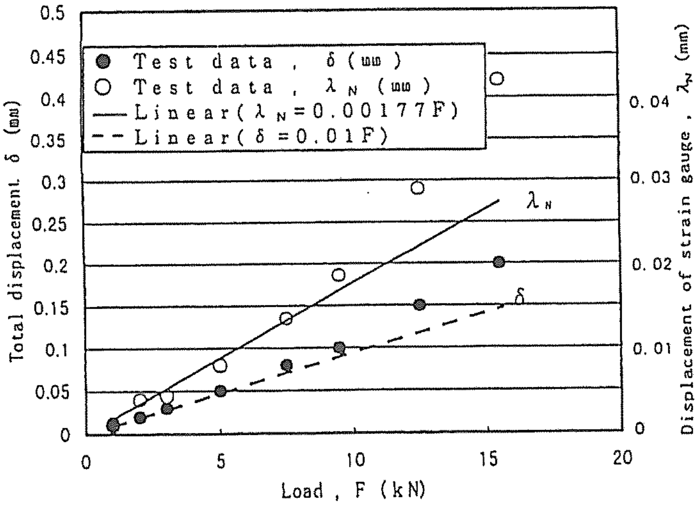

Fig. 6. Elastic characteristic of notched bar specimen (ρ = 1.0mm)

troke control stroke control length 120mm and λ_N, for the gauge length 15mm are measured by each extension step.

From the plots of δ and λ_1 vs. load F(kN), elastic characteristics are obtained in each case of ρ = 0.6mm, 0.8mm and 1.0mm. Fig. 6 shows the plots of the case of the notched bar specimen of ρ = 1.0mm. The relationship between the elongation difference (δ-λ_N) and the load F is confirmed to be quite the same in each test as shown in Fig. 7. The elongation λ_2 for the notched part (in the axial length 2ρ) can be obtained by the subtraction of the elongation $\lambda_1(15-2\rho)/15$ from λ_N. In due course, the elastically calculated strain ε_{ce} is obtained by Eq.(12).

$$\varepsilon_{ce} = \lambda_2/2\rho = \{\lambda_N-\lambda_1(15-2\rho)/15\}/2\rho \qquad (12)$$

Therefore, the following relationships are obtained for ρ = 1.0mm , 0.8mm and ρ = 0.6mm.

$$\begin{aligned}\varepsilon_{ce} &= 3.215\,\sigma \quad (\rho = 1.0\text{mm})\\ \varepsilon_{ce} &= 3.116\,\sigma \quad (\rho = 0.8\text{mm})\\ \varepsilon_{ce} &= 3.117\,\sigma \quad (\rho = 0.6\text{mm})\end{aligned} \qquad (13)$$

3. 2 Notched bar test results

The obtained data of the displacement controlled creep-fatigue tests are shown in Table 3 and Fig. 8. The strain controlled tests of ρ = 0.8mm notched bars are performed at the gauge length 15mm for reference. N_f of the stroke stroke controlled tests with ρ = 0.8mm notch and 600 sec. hold time reduces comparably from that of the ρ = 0.8mm notch and with no-hold time. However, N_f curves of the stroke controlled tests with each notched bar seem to be very close in each other.

Table 3. Notched bar tests results

ρ = 1.0mm Stroke control

Total stroke δ (mm)	Calculated elastic strainε_{ce} = 3.215δ (%)	Number of cycles to failure N_f
1.2	3.858	15
0.6	1.929	80
0.24	0.772	1400

ρ = 0.8mm Stroke control

Total stroke δ (mm)	Calculated elastic strainε_{ce} = 3.166δ (%)	Number of cycles to failure N_f
1.02	3.229	35
0.6	1.9	82
0.36	1.14	422
0.24	0.76	2800

ρ = 0.8mm Stroke control (Hold time 600sec)

Total stroke δ (mm)	Calculated elastic strainε_{ce} = 3.166δ (%)	Number of cycles to failure N_f
1.02	3.229	28
0.6	1.9	110
0.36	1.14	245
0.24	0.76	1522

ρ = 0.6mm Stroke control

Total stroke δ (mm)	Calculated elastic strainε_{ce} = 3.117δ (%)	Number of cycles to failure N_f
1.02	3.179	35
0.6	1.87	175
0.36	1.122	700
0.24	0.748	2000

ρ = 0.8mm Strain control

Total Strai ε_t (mm)	Calculated elastic strainε_{ce} = 3.166δ (%)	Number of cycles to failure N_f
1	3.779	
0.85	3.229	225
0.7	2.659	
0.5	1.9	1545

ρ = 0.8mm Strai control(Hold time 600sec)

Total Strai ε_tz (mm)	Calculated elastic strainε_{ce} = 3.166δ (%)	Number of cycles to failure N_f
1	3.779	
0.85	3.229	
0.7	2.659	90
0.5	1.9	49

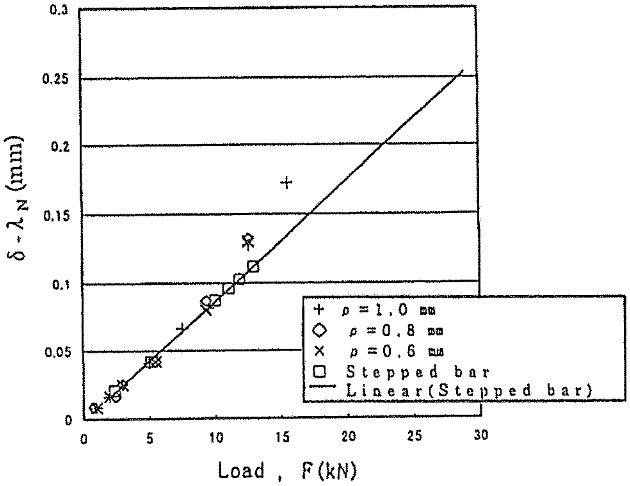

Fig. 7. Relationship between (δ-λ_N) and F

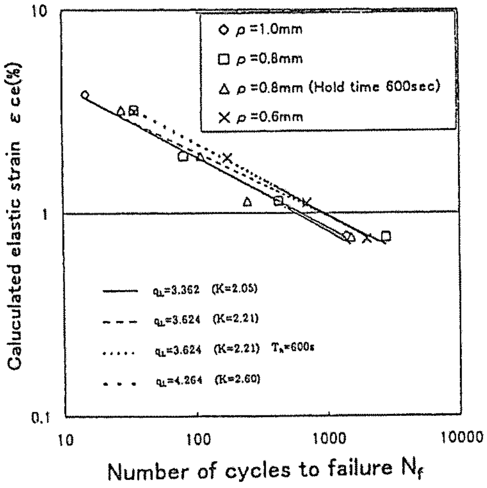

Fig. 8. Results of experiment of notched bar

4 DISCUSSIONS

4. 1 Elastic follow-up of notched bar tests

Referring Fig. 8, the dependency of stress concentration factor K seems to be relatively small between K=2.60 through 2.05. As the values of the stress concentration factor K=2.60 to 2.05 of the test specimens belong to a relatively high value level in the practical component design, the lowest fit curve of $q_n = 3.624$ (K=2.21, $\rho = 0.8$mm) seems to be applicable for the short term loads evaluation of the creep fatigue of local elastic follow-up, if the elastically calculated strain rate is applied to the curve.

4. 2 Hold time considerations

From the aspect of simplifying the design procedure, it would be desirable to have only two curves at each temperature for cyclic damage evaluation, one curve for short time loading and the other for all non short time events.

Hold time tests at 600sec. are carried out for the notched bar specimen of $\rho = 0.8$mm. The results are compared with the no-hold time tests at the same elastically calculated

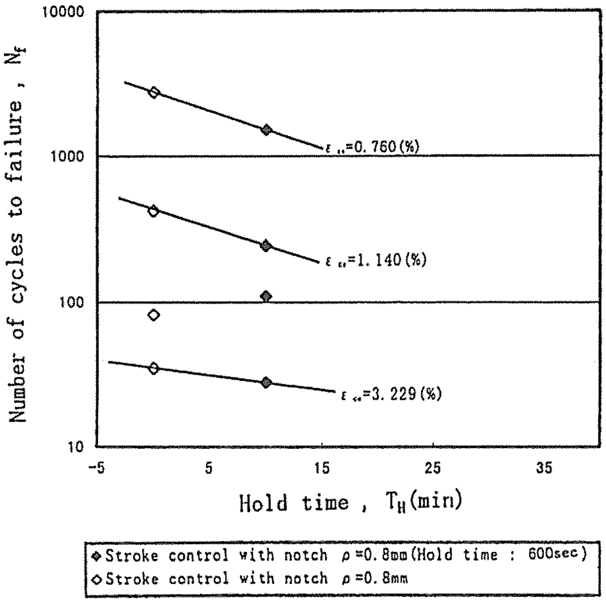

Fig. 9. Hold time effect of notched bar

strain ε_{ce} as shown in Fig. 9. Each N_f number shows to decrease due to the creep damage at the hold time 600sec. Considering a representative number of significant events over the life time of a plant, a reference hold time of 1000hr does not seem unreasonable. However, such a hold time is clearly not attainable directly from testing. One approach to the problem is to extrapolate shorter hold time data to longer hold times assuming that cyclic life continues to decrease at the same exponential rate with hold time. A review of hold time creep-fatigue data (without elastic follow-up) is suggested that the cycle life reduces a factor of 2/3 to1/3 for each factor of 10 increase in hold time[11]. The cycle life would normally be reduced about factor of 10 in extrapolating to a hold time of 1000hr. Therefore, the obtained best fit curves is expected to be extrapolated by the suggestion.

4. 3 Comparison of stroke control and strain control

In Fig. 10, numbers of cycles to failure N_f of the stroke controls of $\rho = 0.8$mm notched bars are compared with those of strain controls, where the elastic follow-up q_L is consistently 3.624 and K=2.21. Fig. 10 shows the elastic follow-up phenomenon reduces N_f clearly at the both conditions with and without hold time.

4. 4 Combination of q_L and q_n

For the practical evaluation by SMT, two design curves are required, one for short time effect, such as seismic, without a hold time effect, and another curve, which

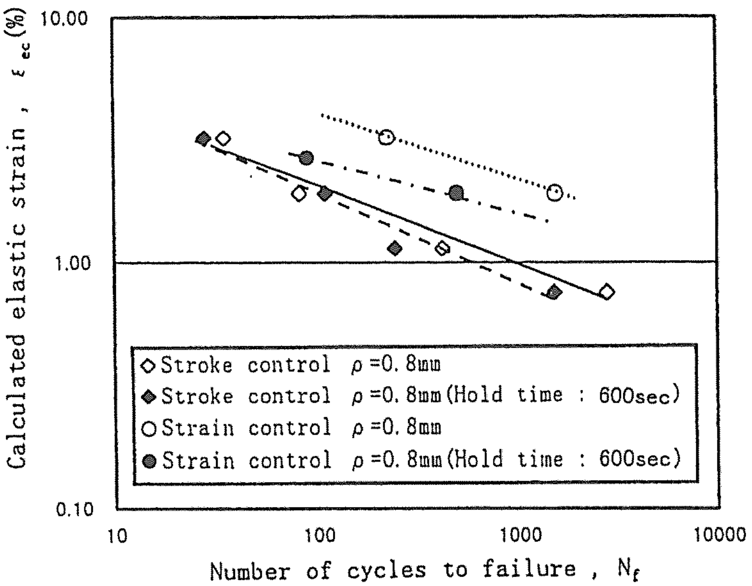

Fig. 10. Comparison of stroke control and strain control at the notched bar ($\rho = 0.8$mm)

envelops the effects of hold time duration.

As authors had performed the global elastic follow-up (q_n) tests in Ref. (8), both N_f data of q_L and q_n are combined for short term loads and hold time loads in Fig. 11, (a) and Fig. 11, (b) respectively. Further test data are needed for practical use.

5 SUMMARY

The simplified model tests of SUS304 are performed for an alternate approach to the creep fatigue evaluation of an elevated temperature structural design. The obtained best fit curves shows the effect of the elastic follow-up and the feasibility of the application to the practical design evaluation on the basis of the elastic analyses.

From the notched bar tests, the dependency of stress concentration factor is confirmed to be relatively small between K=2.60 through 2.05. N_f reduces with 600sec. hold time. The lower boundary of these tests seems to be applicable to the evaluation of a local stress concentrated structure.

In future, test date should be supplemented and a design margin must be applied to the statistically treated data.

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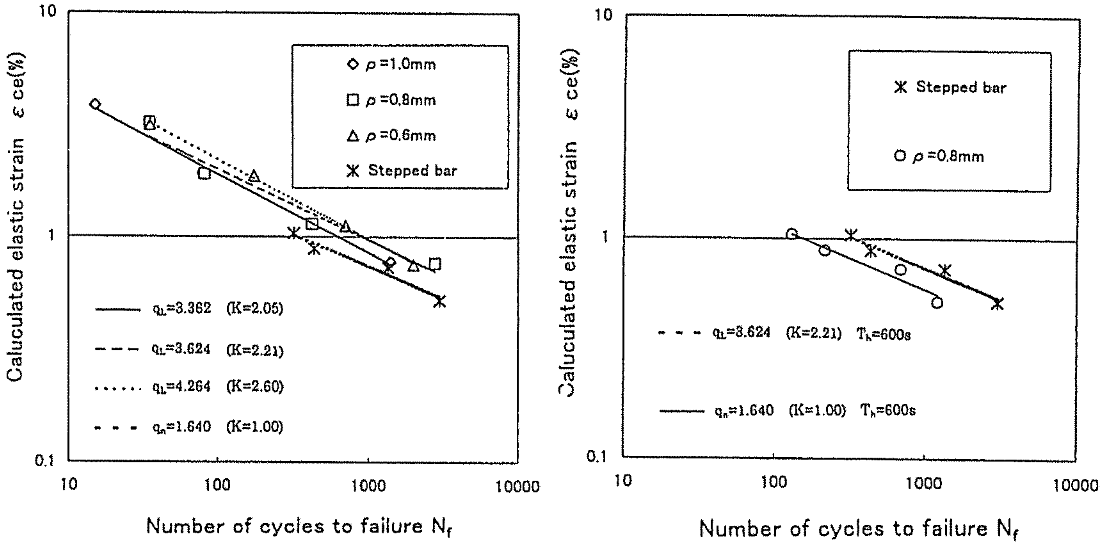

(a) q vs N_f at short term loads (b) q vs N_f at hold time loads

Fig. 11. Combination of the local elastic follow-up (q_L) data and the global elastic follow-up (q_n) data

performing the experiments.

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高温構造設計のための切欠付き試験片による弾性追従を伴うクリープ・疲労損傷試験

小畑清和・太田博光・石山英樹・貝原 亨・上野 修

応力集中を伴う高温構造物は，高温繰返し負荷により弾性追従発生下のクリープ・疲労損傷で著しい寿命低下をきたす。本研究では，R.I.Jetterが提案した簡易評価法に準じて，汎用ステンレス鋼SUS304の切欠付き試験片を550℃で試験し，既報の平滑試験データと組み合わせて，簡易評価法の寿命評価曲線を求めた。