EFFECTS OF HIGH STRAIN RATE ON
LOW-CYCLE FATIGUE BEHAVIOR OF
STRUCTURAL STEEL IN
LARGE PLASTIC STRAIN REGION

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This study aims to investigate the effects of very high strain rate on low-cycle fatigue behavior of structural steel under large plastic strain with strain rate order of 1.0 s⁻¹ as expected during earthquakes. Low-cycle fatigue tests were conducted using compact-tension specimens at various strain rate levels. Fatigue life based on crack size indicated that the higher strain rate caused lower fatigue life in large plastic strain region. The energy approach was employed to clarify the low-cycle fatigue mechanism in this region. Finally, a prediction method for fatigue life regarding high strain rate effect in large plastic strain region is proposed in this study.

Key Words : low-cycle fatigue, high strain rate, large plastic strain, compact tension specimens, fatigue life, crack initiation, crack propagation

1. INTRODUCTION

In the past decades, earthquakes caused various types of damage to steel structures1). Low-cycle fatigue is considered one of the most dominant damage types of steel structures during earthquakes. Low-cycle fatigue damage occurred in the form of cracks. Low-cycle fatigue is characterized by plastic strain and general failure in a small number of cycles. During earthquakes, steel structures suffer from cyclic loading with large plastic strain at the local area of steel member2)-3), which could cause low-cycle fatigue crack damage. Furthermore, low-cycle fatigue damage could induce brittle fracture. For example, during the 1995 Kobe earthquake, brittle fracture occurred in steel bridge piers. Investigations of these failures found that brittle fracture was triggered by cracks caused by plastic strain including low-cycle fatigue cracks2)-8). Consequently, there had been extensive studies focusing on low-cycle fatigue behavior of steel structures during earthquakes1)-12). However, the effects of high strain rate in large plastic strain region expected during earthquakes have not been clarified yet. According to recent investigations13)-15), strain rate could be an important factor in the low-cycle fatigue behavior of steel components, but the effects of very high strain rate in large plastic strain region expected in steel structures during earthquakes have not been investigated so far.

Recently, there had been investigations on the effects of strain rate on low-cycle fatigue behavior and the results indicated that fatigue life in low-cycle fatigue region of the steel significantly depends on strain rate13)-15). For instance, Luo et al.13) found that the effect of strain rate on fatigue life has transition trend. Structural steel under lower strain rate will have a lower fatigue life until the strain rate exceeds the transition point (around 0.01 s⁻¹) and then the higher strain rate will have a lower fatigue life instead. However, these investigations conducted ex-
periments in the strain rate range below the order of 0.10 s$^{-1}$. According to the previous studies, there is a possibility that the strain rate expected during earthquakes might exceed the order of 1.0 s$^{-1}$, which is considered higher than those in earlier studies and expected behavior above the aforementioned transition point. The fatigue life of steel members during earthquakes could be affected by higher strain rate referred to as “very high strain rate” in this study.

In this study, the effects of very high strain rate on low-cycle fatigue behavior of structural steel in large plastic region expected during earthquakes were investigated via experiment. In this study, low-cycle fatigue tests were conducted on compact-tension specimens in various cyclic loading rates to clarify the effects of very high strain rate on low-cycle fatigue behaviors including load-range drop, crack initiation, and propagation behavior. Especially, behaviors at early stage of the cracking process were found to influence the occurrence of brittle fracture. The energy approach was then used to clarify the low-cycle fatigue mechanism of structural steel subjected to high strain rate in large plastic strain. Finally, the prediction method for fatigue life regarding the strain rate effect on the large plastic strain region is proposed in this study.

2. DESIGN OF SPECIMENS

(1) Dimension of material specimens

In this study, we investigated the structural steel behaviors concerning the effect of high strain rate in large plastic region expected during earthquakes, using round notch-type compact tension specimens (CT-specimens). These CT-specimens were designed by referencing the guidelines from the standard test method for measurement of fracture toughness by ASTM for the shape of CT-specimens by using effective notch shape for round notch. The dimensions of CT-specimen are shown in Fig.1. The specimens were made from mild steel plate (JIS-SM400), which is a widely used structural steel in Japan. In this study, the strain rate level was taken into consideration. Thus, the stress-strain relationship and the fundamental material properties were obtained by tensile tests with static rate and 1.0 s$^{-1}$ nominal strain rate. The material’s stress-strain relationship is shown in Fig.2 while the material properties and chemical compositions are shown in Table 1.

(2) FEM analysis to design specimens

According to earthquakes characteristics, large plastic strain level could occur at the local area and strain rate could occur in the order of 0.1 – 1.0 s$^{-1}$. Thus, the experiment configuration is required to satisfy these earthquakes characteristics. In order to determine the experiment configurations, numerical analysis using cyclic loading were conducted on FEM models of CT-specimens using effective notch according to the recommendations for fatigue design by Hobbacher. The FEM models of CT-specimens are shown in Fig.3.

![Fig.1 Dimensions of material specimen.](image1)

![Fig.2 Stress-strain relationship of specimens.](image2)

<table>
<thead>
<tr>
<th>Table 1 Material properties.</th>
<th>Chemical composition (%wt)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mechanical properties</strong></td>
<td></td>
</tr>
<tr>
<td>Material Yield strength, $\sigma_y$ (MPa)</td>
<td>Tensile strength, $\sigma_u$ (MPa)</td>
</tr>
<tr>
<td>SM400A 310</td>
<td>483.5</td>
</tr>
<tr>
<td>376</td>
<td>514</td>
</tr>
</tbody>
</table>
a) Material models for strain rate level

In order to conduct FEM analysis on strain rate level, material properties of the strain rate level are necessary. In this study, the material properties were obtained by conducting tensile test on round bar specimens as shown in Fig.4 with various loading rates corresponding to static rate and strain rate equal to 1.0 s\(^{-1}\) (Fig.2).

In the static rate case, a diameter gauge was used during the tests. Thus, the true stress-strain curves were calculated from the diameter value. In the 1 s\(^{-1}\) strain rate case, nominal strain was obtained by attaching the strain gauge at the middle of the round bar. The true stress-strain was then calculated from nominal stress-strain via logarithm formula before necking occurred. In addition, true stress-strain was obtained from the reduction of the area at fracture point.

FEM models of round bar with 2 mm mesh size were conducted to verify material properties with load-displacement curve as shown in Fig.5. Then, material properties of the intermediate strain rate level could be calculated using the material model. According to the ABAQUS manual\(^{19}\), material properties corresponding to the intermediate strain rate level were interpolated between material properties corresponding to the static rate and strain rate equal to 1.0 s\(^{-1}\). Finally, experiment configuration could be determined by FEM models of CT-specimens (Fig.3).

b) Calculation of effective notch strain range

Since FEM models used the effective notch shape, the equivalent total strain range could be calculated by using the effective notch concept\(^{10}\). The effective notch concept was employed in the elements along the notch. The effective notch strain range, which combines the elastic and plastic components is expressed in Fig.6 and Equation (1). The elastic com-

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**Fig.3** FEM models of CT-specimens.

**Fig.4** Round bar specimen for tensile tests.

**Fig.5** Load-displacement of tensile test.

**Fig.6** Expression of effective notch concept.
ponent and plastic component are expressed in Equations (2) and (3) respectively.

\[
\Delta \varepsilon_{\text{eff}} = \Delta \varepsilon_1 + \frac{\Delta \sigma}{E} + \Delta \varepsilon_\rho \quad (1)
\]

\[
\Delta \sigma = \frac{1}{2} \left[ \left( \Delta \sigma_x - \Delta \sigma_y \right)^2 + \left( \Delta \sigma_x - \Delta \sigma_z \right)^2 + \left( \Delta \sigma_y - \Delta \sigma_z \right)^2 
+ 6 \left( \Delta \tau_{xy}^2 + \Delta \tau_{yz}^2 + \Delta \tau_{zx}^2 \right) \right]^{1/2} \quad (2)
\]

Fig. 7 Plastic strain at local area of specimens subjected to various test configurations.
where $\Delta \sigma$ : the normal stress range
$\Delta \tau$ : the shear stress range
$\Delta \varepsilon_p$ : the normal plastic strain range
$\Delta \gamma_p$ : the shear plastic strain range
$x, y, z$ : $x, y, z$ directions, respectively
$\Delta \varepsilon_{\text{eff}}$ : the effective notch strain range
$\Delta \varepsilon_t$ : the equivalent total strain range
$\Delta \bar{\sigma}$ : the equivalent stress range
$\Delta \bar{\varepsilon_p}$ : the equivalent plastic strain range

Fig. 8 Stress at local area of specimens subjected to various test configurations.
In this study, the maximum and average effective notch strain ranges were calculated from eight elements along the notch as indicated in Fig. 3. The stress and strain components at the integration point of each element were used in the calculation process by Equations (1)-(3). In addition, strain rate levels $\dot{\varepsilon}_{\text{eff}}$ ($s^{-1}$) could be calculated by using loading rate $f$ (Hz) as shown in Equation (4). This equation was used in previous studies\(^{13-15}\). However, these previous studies conducted experiments on round bar specimens, which had strain only in the axial direction. Thus, it would be more realistic to calculate strain rate levels from equivalent plastic strain history $\varepsilon_p(t)$, which were obtained from FEM analysis as shown in Equation (5).

\[ \dot{\varepsilon}_{\text{eff}} = 2 \cdot f \cdot \Delta \varepsilon_{\text{eff}} \]  
\[ \dot{\varepsilon}_p = \frac{d\varepsilon_p(t)}{dt} \]

c) Local behaviors of the strain rate level

Local area behavior of the strain rate could be observed from the FEM results. Plastic strain level and stress level at maximum opening of various loading rates are shown in Fig. 7 and Fig. 8 respectively. It can be seen that high strain rate at the local area could cause slightly smaller plastic strain. However, high strain rate could cause relatively larger stress value. This means that the local area of specimens subjected with higher loading rate could have a larger plastic strain energy density. According to a previous study\(^{13}\), larger plastic strain energy density could lead to lower fatigue life. However, investigation on large plastic strain and high strain rate in the order of 1.0 $s^{-1}$ expected during earthquakes has not been done yet. Therefore, this study could clarify the effect of strain rate on fatigue life of structural steel in this region.

d) Effective notch strain range and strain rate

According to the effective notch strain range as shown in Fig. 9, loading amplitudes equal 1.20 mm, 2.40 mm, and 3.60 mm corresponded to approximately 5%, 12%, and 18% strain range, respectively. Therefore, these loading amplitudes were chosen for the purpose of this study. Moreover, the loading rate chosen in this study also corresponded to 0.1 – 1.0 $s^{-1}$ strain rate range as shown in Fig. 10. Hence, earthquakes characteristics could be satisfied by the experiment configurations in this study.

In addition, a loading waveform was generated using two types of waveforms in this study, namely, the triangle waveform and the sine waveform as shown in Fig. 11. The triangle waveform is characterized by a constant velocity, which suddenly changes direction at the transition point of the waveform. The sine waveform is characterized by variable velocity, which smoothly changes direction at the transition point of the waveform. Under large plastic strain and high loading rate, the actual strain rate level could be affected by the loading waveform type, which might have an influence on the behavior of structural steel. Thus, the purpose of the two types of waveform is to observe the effects of the loading waveform characteristics.
Table 2 Configuration of specimens in the experiment.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Amplitude</th>
<th>Loading rate</th>
<th>Waveform type</th>
<th>Average strain range</th>
<th>Maximum strain range</th>
<th>Strain rate Eq.(4)</th>
<th>Strain rate Eq.(5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18-5-S</td>
<td>3.60 mm</td>
<td>5.00 Hz</td>
<td>Sine</td>
<td>0.171</td>
<td>0.287</td>
<td>1.712 s⁻¹</td>
<td>3.109 s⁻¹</td>
</tr>
<tr>
<td>18-3-S</td>
<td>3.60 mm</td>
<td>3.00 Hz</td>
<td>Sine</td>
<td>0.176</td>
<td>0.288</td>
<td>1.059 s⁻¹</td>
<td>1.862 s⁻¹</td>
</tr>
<tr>
<td>18-0_1-S</td>
<td>3.60 mm</td>
<td>0.10 Hz</td>
<td>Sine</td>
<td>0.183</td>
<td>0.296</td>
<td>0.037 s⁻¹</td>
<td>0.086 s⁻¹</td>
</tr>
<tr>
<td>12-5-S</td>
<td>2.40 mm</td>
<td>5.00 Hz</td>
<td>Sine</td>
<td>0.112</td>
<td>0.173</td>
<td>1.120 s⁻¹</td>
<td>1.694 s⁻¹</td>
</tr>
<tr>
<td>12-3-S</td>
<td>2.40 mm</td>
<td>3.00 Hz</td>
<td>Sine</td>
<td>0.113</td>
<td>0.175</td>
<td>0.681 s⁻¹</td>
<td>1.142 s⁻¹</td>
</tr>
<tr>
<td>12-0_1-S</td>
<td>2.40 mm</td>
<td>0.10 Hz</td>
<td>Sine</td>
<td>0.117</td>
<td>0.182</td>
<td>0.023 s⁻¹</td>
<td>0.044 s⁻¹</td>
</tr>
<tr>
<td>18-5-T</td>
<td>3.60 mm</td>
<td>5.00 Hz</td>
<td>Triangle</td>
<td>0.173</td>
<td>0.282</td>
<td>1.734 s⁻¹</td>
<td>2.353 s⁻¹</td>
</tr>
<tr>
<td>18-3-T</td>
<td>3.60 mm</td>
<td>3.00 Hz</td>
<td>Triangle</td>
<td>0.175</td>
<td>0.282</td>
<td>1.048 s⁻¹</td>
<td>1.353 s⁻¹</td>
</tr>
<tr>
<td>18-1-T</td>
<td>3.60 mm</td>
<td>1.00 Hz</td>
<td>Triangle</td>
<td>0.178</td>
<td>0.284</td>
<td>0.356 s⁻¹</td>
<td>0.510 s⁻¹</td>
</tr>
<tr>
<td>18-0_1-T</td>
<td>3.60 mm</td>
<td>0.10 Hz</td>
<td>Triangle</td>
<td>0.182</td>
<td>0.296</td>
<td>0.036 s⁻¹</td>
<td>0.063 s⁻¹</td>
</tr>
<tr>
<td>12-5-T</td>
<td>2.40 mm</td>
<td>5.00 Hz</td>
<td>Triangle</td>
<td>0.111</td>
<td>0.169</td>
<td>1.107 s⁻¹</td>
<td>1.582 s⁻¹</td>
</tr>
<tr>
<td>12-2_5-T</td>
<td>2.40 mm</td>
<td>2.50 Hz</td>
<td>Triangle</td>
<td>0.113</td>
<td>0.172</td>
<td>0.566 s⁻¹</td>
<td>0.811 s⁻¹</td>
</tr>
<tr>
<td>12-1-T</td>
<td>2.40 mm</td>
<td>1.00 Hz</td>
<td>Triangle</td>
<td>0.115</td>
<td>0.176</td>
<td>0.231 s⁻¹</td>
<td>0.343 s⁻¹</td>
</tr>
<tr>
<td>12-0_1-T</td>
<td>2.40 mm</td>
<td>0.10 Hz</td>
<td>Triangle</td>
<td>0.117</td>
<td>0.183</td>
<td>0.023 s⁻¹</td>
<td>0.041 s⁻¹</td>
</tr>
<tr>
<td>5-5-T</td>
<td>1.20 mm</td>
<td>5.00 Hz</td>
<td>Triangle</td>
<td>0.049</td>
<td>0.063</td>
<td>0.486 s⁻¹</td>
<td>0.731 s⁻¹</td>
</tr>
<tr>
<td>5-3-T</td>
<td>1.20 mm</td>
<td>3.00 Hz</td>
<td>Triangle</td>
<td>0.049</td>
<td>0.065</td>
<td>0.295 s⁻¹</td>
<td>0.449 s⁻¹</td>
</tr>
<tr>
<td>5-1-T</td>
<td>1.20 mm</td>
<td>1.00 Hz</td>
<td>Triangle</td>
<td>0.050</td>
<td>0.068</td>
<td>0.100 s⁻¹</td>
<td>0.153 s⁻¹</td>
</tr>
</tbody>
</table>

For reference to each experiment configuration, specimens were named according to strain range, loading rate, and loading waveform type. Details of the experiment configuration in this study including name, amplitude, loading rate, loading waveform type, equivalent total strain range, and strain rate levels are shown in Table 2.

3. EXPERIMENTAL PROCEDURE

(1) Experiment system

As shown in Fig.12, this experiment used a material testing machine to generate the cyclic displacement control loading, and the feedback to control the displacement was obtained from a displacement transducer at the opening of CT-specimens. In this study, a non-linear adjustment feedback control algorithm, i.e., PID control, was implemented on the material testing machine to control the exact displacement at the openings of CT-specimens. Finally, the experiment system for cyclic displacement feedback control that was capable of high loading rate in large plastic region was developed.

(2) Observation of crack behavior

According to the previous study, Murakami proposed that low-cycle fatigue behavior was dominated by growth behavior of small cracks. Therefore, observing all of the moments of crack initiation and propagation behavior of low-cycle during earthquakes is considered critical and significant. In this study, the high-speed microscope has a capacity of 200 frames recording speed per second with 640x480 resolution. In addition, to observe the crack length in every cycle of the experiment, a recorded video from a microscope was processed by motion analysis software with 0.01 mm precision. The microscope and one sample picture of CT-specimen captured by the motion analysis software are shown in Fig.13.

4. EXPERIMENTAL RESULTS

(1) Relationships between load and displacement (P-δ curves)

The relationships between load (P) and displacement (δ) are shown in Fig.14. The results show that load range decreases every cycle due to plastic...
deformation and crack propagation in the CT-specimens.

As shown in Fig.15, CT-specimens subjected to higher loading rate (higher strain rate) will have steeper slope of load-displacement curve due to the rate-dependent effect. Consequently, specimens subjected to higher strain rate will have a larger area of the load-displacement curve, which can represent
the cyclic energy per cycle. Similarly, cumulative cyclic energy can be calculated from the cumulative area of the \( P-\delta \) curve. To clarify the amount of cyclic energy, Fig. 16 shows the relationship between cumulative cyclic energy and number of cycles. The results confirmed that specimens suffered larger amount of energy with higher strain rate.

(2) Load-drop range due to the strain rate effect

Figure 17 and Fig. 18 show the load range in every cycle for each specimen. The load ranges have been normalized by the maximum value of each specimen so that the effect of strain rate can be compared. The results show that specimens subjected to a higher strain rate tend to have an earlier load drop, leading to a lower load range than those subjected to a lower strain rate. This load drop could be an evidence that indicates lower fatigue life with high strain rate. However, specimens subjected to higher strain rate tend to have significant larger load range at first cycle due to the higher loading rate. This considered biased criteria for indicated fatigue life of structural steel for the present study. Therefore, there should be further investigation on fatigue life based on crack length.

Fig. 17 Load drop of specimens subjected to sine loading waveform with various loading rates.

Fig. 18 Load drop of specimens subjected to triangle loading waveform with various loading rates.

Fig. 19 Load drop curves of specimens subjected to loading amplitude = 1.20 mm with various loading speeds.
(3) Significance of strain rate effect due to the plastic strain level

The experiment using 1.20 mm displacement amplitude (corresponding to 5% strain range) represents the intermediate region between low-cycle fatigue and high-cycle fatigue due to the smaller amount of plastic strain level. Figure 19 shows that specimens subjected to a higher strain rate have a lower fatigue life, but the effect of strain rate is not as significant as for those subjected to 2.40 mm and 3.60 mm (corresponding to 12% and 18% strain range, respectively). This result is similar to those of the previous studies\(^2\)\(^3\), as loading frequency has no effect on high cycle fatigue regions, shown by the fact that much smaller scale of plastic strain occurred in high cycle fatigue compared to low-cycle fatigue. During earthquakes, plastic strain could exceed 15%\(^2\)!\(^3\). Therefore, the effect of strain rate could become more significant during earthquakes due to the large plastic strain.

(4) Load-drop due to the loading waveform-type effect

In this study, two series of loading waveform shown in Fig.11 were used. Figure 20 shows the difference in fatigue life of specimen due to the effect of the loading waveform type. Specimens subjected to the sine waveform tend to have an earlier load drop than the triangle waveform with the same loading rate. One of the reasons could be explained in terms of maximum strain range as shown in Table 2, where it indicates that the sine waveform could cause larger strain range and strain rate level at the local area of specimens.

(5) Crack initiation behaviors

The surface crack initiation was investigated using high-speed microscope camera. The number of cycles at the first observed crack in each specimen is defined as crack initiation life \((N_c)\) and the results are shown in Table 3. It is found that specimens sub-
jected to lower strain rate tend to have earlier surface crack initiation with smaller crack size. Figure 21 shows that the size of the first observed crack that could be observed in lower strain rate is considered smaller compared with high strain rate case. This behavior is in agreement with the previous studies\textsuperscript{13)-15), which indicated that in the low strain rate crack initiation will occur earlier in the form of secondary crack (i.e., crack that propagates from micro-cracks) and crack initiation in the high strain rate will have originated from nucleation of void instead. Moreover, the previous studies\textsuperscript{13)-15) also indicated that longer loading time due to low strain rate case allows more time to develop creep damage. This might be one of the explanations for crack initiation earlier in low strain rate. However, there are possibilities that high strain rate could cause the earlier crack initiation point found in this study (specimen: 18-5-T, 12-5-T).

To clarify the crack initiation mechanism, compliance method was implemented with the unloading line of load-displacement curve at each cycle (see Fig.22) defined as compliance slope. The compliance slope could be an indicator of stiffness related to crack size and geometry of specimens. Thus, the change in compliance slope could be used to detect the crack initiation point. In addition, the compliance slope was normalized with a maximum slope value of each specimen in order to observe the effect of strain rate. The results of the compliance method are shown in Fig.23. The figure shows that the knee point of the compliance slope has correlation with the first observed crack, and the compliance slope of

<table>
<thead>
<tr>
<th>Specimen</th>
<th>1st observed surface crack ($N_c$)</th>
<th>Number of cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>18-5-T</td>
<td>1.8x10(^4)</td>
<td></td>
</tr>
<tr>
<td>18-3-T</td>
<td>2.6 x10(^3)</td>
<td></td>
</tr>
<tr>
<td>18-1-T</td>
<td>2.4 x10(^3)</td>
<td></td>
</tr>
<tr>
<td>18-0_1-T</td>
<td>2.4 x10(^3)</td>
<td></td>
</tr>
<tr>
<td>12-5-T</td>
<td>6.0 x10(^3)</td>
<td></td>
</tr>
<tr>
<td>12-2_5-T</td>
<td>6.2 x10(^3)</td>
<td></td>
</tr>
<tr>
<td>12-1-T</td>
<td>6.2 x10(^3)</td>
<td></td>
</tr>
<tr>
<td>12-0_1-T</td>
<td>5.8 x10(^3)</td>
<td></td>
</tr>
</tbody>
</table>

![Fig.22 Operative definition for compliance method.](image)

![Fig.23 Compliance slope of specimens on number of cycles.](image)

![Fig.24 Compliance slope of specimens on cumulative energy.](image)
specimens with high strain rate (18-5-T, 12-5-T) tends to decrease earlier. In addition, this tendency could be clearly observed with specimens subjected to large plastic strain as shown in Fig.23(b). Then, the compliance slope was plotted against aforementioned cumulative energy (see Fig.16) as shown in Fig.24. The result indicated that the change in compliance slope is related to the amount of energy absorbed by specimens without significant differences between strain rate levels. Thus, crack initiation behaviors will be mainly dominated by the amount of energy, which results in earlier crack initiation on the higher strain rate due to larger amount of energy.

To observe the significance of strain rate, crack initiation life ($N_c$) was plotted against strain range as shown in Fig.25. High strain rate (18-5-T) was found to have influence on crack initiation life. However, the effect of strain rate on crack initiation life was found to be less significant than the strain range. In addition, the Manson four-point correlation method\(^{24-27}\) as expressed in Equation (6) was implemented for comparison with previous studies.

$$\Delta \varepsilon = \varepsilon_f (N_c)^{\alpha_1} + \frac{S_f}{E}(N_c)^{\alpha_2}$$  \hspace{1cm} (6)

where $\Delta \varepsilon$: total strain range
$\varepsilon_f$: fatigue ductility
$S_f$: fatigue strength coefficients
$\alpha_1$: fatigue ductility exponents
$\alpha_2$: fatigue strength exponents
$E$: modulus of elasticity
$N_c$: crack initiation life.

Table 4 Fatigue constants obtained from Manson four-point correlation method.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>STATIC</td>
<td>1.0 s(^{-1})</td>
</tr>
<tr>
<td>Fatigue ductility coefficient, $\varepsilon_f$</td>
<td>0.880</td>
<td>0.694</td>
</tr>
<tr>
<td>Fatigue ductility exponent, $\alpha_1$</td>
<td>-0.506</td>
<td>-0.478</td>
</tr>
<tr>
<td>Fatigue strength coefficient, $S_f$</td>
<td>1650</td>
<td>1672</td>
</tr>
<tr>
<td>Fatigue strength exponent, $\alpha_2$</td>
<td>-0.116</td>
<td>-0.112</td>
</tr>
</tbody>
</table>
In order to obtain fatigue constants, two straight lines corresponding to the elastic line and plastic line were generated. According to previous study\cite{24}, elastic line could be generated from two points based on tensile test as shown in Fig. 26. The first point is located at \(\frac{1}{4}\) cycle with an ordinate \((2.5\sigma_f)/E\), where \(\sigma_f\) is the true fracture stress. The second point is located at 10\(^5\) cycles with an ordinate \((0.9\sigma_u)/E\), where \(\sigma_u\) is the ultimate tensile strength. Then, power-fitted equation was used to determine \(\beta_f\) and \(\alpha_f\). To generate the plastic line, the plastic part of effective notch strain as expressed in Eq. (3) was plotted against crack initiation life as shown in Fig. 27. Then, the curve was fitted by power law equation to determine \(\beta_f\) and \(\alpha_f\). Since tensile tests were conducted in different strain rates in this study, therefore, fatigue constants could be determined in two sets with various strain rates and average value as shown in Table 4. Furthermore, as the large plastic strain region is the main focus in this study, from the comparison between Fig. 25 and Fig. 27, it could be seen that the plastic line is the dominant component in the relationship between the effective notch strain range and the crack initiation life.

(6) Crack propagation behaviors

Figure 28 shows the values of crack length in each cycle. The results show that specimens subjected to a higher strain rate tend to have a higher crack propagation rate than those subjected to a lower strain rate. The significance of strain rate due to large plastic strain also can be observed in crack propagation behaviors. However, there is a possibility that lower strain rate could have larger crack length due to earlier crack initiation as found in comparison between specimens 12-0_1-T and 12-1-T. Moreover, larger energy caused by higher strain rate could overcome the earlier crack initiation by low strain rate after a certain number of cycles as found in specimen 18-0_1-T in which the crack length got overtaken by specimen 18-1-T after crack length around 2.7 mm.

In this study, appropriate fatigue life criteria based on crack length had to be defined for creating non-biased situation to evaluate the strain rate effect. One of the reasons is that CT-specimens have long span of crack propagation state and the order of crack length could be overtaken by high strain rate after a certain number of cycles. Thus, choosing large crack length to define fatigue life might not be appropriate for low strain rate. As seen from the results, the crack length was overtaken when the crack length reached around 2.7 mm. Thus, the appropriate fatigue life based on crack length should be smaller than 2.7 mm.

To be precise, the crack length reaching 2 mm could be the proper fatigue life criteria in this study. As shown in Fig. 24, specimens’ compliance slope already reaches over knee point and tends to drop drastically. Therefore, for this study, fatigue life (\(N_f\)) was defined as the number of cycles that the crack length reached 2 mm.

(7) Fatigue life due to the strain rate effect

Fatigue life based on crack length is shown in Table 5. Results indicated that high strain rate caused lower fatigue life in the order of 1.0 s\(^{-1}\). To explain the effect of strain rate on fatigue life, higher strain rate caused larger cyclic energy and fatigue life of structural steel in high strain rate and large plastic strain region expected during earthquakes was dominated by the amount of cyclic energy. Therefore, higher strain rate will cause lower fatigue life due to larger amount of energy.

In addition, Table 5 also shows the ratio between crack initiation life and fatigue life (\(N_c/N_f\)) to be larger than 0.75, which implies that fatigue life was dominated by the crack initiation process in this study. One of the reasons could be notch shape. Previous studies\cite{24-26} indicated that stress concentra-

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**Table 5** Fatigue life of specimens.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Fatigue life (Number of cycles)</th>
<th>(N_c/N_f)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18-5-T</td>
<td>2.1 x10(^2)</td>
<td>0.86</td>
</tr>
<tr>
<td>18-3-T</td>
<td>3.0 x10(^2)</td>
<td>0.87</td>
</tr>
<tr>
<td>18-1-T</td>
<td>3.2 x10(^1)</td>
<td>0.75</td>
</tr>
<tr>
<td>18-0_1-T</td>
<td>2.9 x10(^1)</td>
<td>0.83</td>
</tr>
<tr>
<td>12-5-T</td>
<td>6.9 x10(^1)</td>
<td>0.87</td>
</tr>
<tr>
<td>12-2_5-T</td>
<td>7.7 x10(^1)</td>
<td>0.80</td>
</tr>
<tr>
<td>12-1-T</td>
<td>7.9 x10(^1)</td>
<td>0.78</td>
</tr>
<tr>
<td>12-0_1-T</td>
<td>7.7 x10(^1)</td>
<td>0.75</td>
</tr>
</tbody>
</table>
tration factor could be affected by notch shape, which resulted in different fractions of crack initiation life. These studies indicated that the smooth notch shape will result in higher fraction of crack initiation life due to the blunt notch at the start of crack initiation process.

To clarify the significance of strain rate, the fatigue life based on crack length was plotted against the strain range as shown in Fig. 29. Fatigue life was found to be dominated by total strain range rather than strain rate effect. In addition, a previous study\(^\text{10}\) proposed fatigue life based on strain as shown in Equation (7). However, the previous study conducted experiments on load-carrying cruciform joint, which was considered a sharp notch shape. Thus, the fatigue life in the previous study was mainly dominant on crack propagation life. Hence, the proposed fatigue life based on strain level from the previous study should be modified in order to compare results with those of the present study.

\[
\Delta \varepsilon = 0.1847 (N_p)^{-0.313} \tag{7}
\]

It is well known that fatigue life \(N_f\) could be separated into crack initiation life \(N_c\) and crack propagation life \(N_p\) as shown in Equation (8). Since crack initiation life in this study was determined by Equation (6) and coefficient from the average line in Table 4 was found to be in good correlation with the results (Fig. 25), therefore, reference for fatigue life based on strain level for comparison with this study could be determined by combining Equation (6) with coefficient from average line and Equation (7) as shown in equation (9).

\[
\Delta \varepsilon_{\text{eff}} = \begin{bmatrix}
0.823 (N_c)^{-0.499} \\
+ 1672 \\
+ 0.1847 (N_p)^{-0.313}
\end{bmatrix} \tag{9}
\]

This relationship can also be shown by the following equation using only fatigue life \(N_f\) by power-fitted equation as shown in Fig. 29.

\[
\Delta \varepsilon_{\text{eff}} = 1.01 (N_f)^{0.442} \tag{10}
\]

It is clear that fatigue life was dominated by total strain range rather than strain rate effect. However, fatigue life in large plastic strain region (10%-18%) as represented by loading amplitude 2.40 mm (12% strain range) and 3.60 mm (18% strain range) could be considered an extremely low-cycle fatigue region where the number of cycles to failure was less than 100 cycles. Thus, strain rate could cause significantly lower fatigue life in the large plastic region. To illustrate, fatigue life in each plastic strain level has been normalized by fatigue life of low strain rate in order to compare the effects of strain rate. Figure 30 shows that high strain rate in the order of 1.0 s\(^{-1}\) could result in approximately 10%-30% decrease in fatigue life in the large plastic strain region. This situation is expected on structural steel during earthquakes. Therefore, the effects of strain rate on a large plastic region should be considered to improve safety and accuracy of fatigue strength assessment in this region. Thus, this present study proposed predicted fatigue life of strain rate effects using strain rate level and fatigue life conducted on low strain rate level, which can be expressed in Equation (10).
Note that this correction factor has applicable range in strain range of 10% to 18% and strain rate order of 0.01 – 1.0 s\(^{-1}\).

\[
N_f^\varepsilon = (1 - 0.0336 \varepsilon^{-2.46}) N_{f,\text{low}} \quad (11)
\]  

where \(N_f^\varepsilon\) : predicted fatigue life  
\(\varepsilon\) : strain rate  
\(N_{f,\text{low}}\) : fatigue life based on static rate

**Figure 31** shows the plot of predicted fatigue life and experimental fatigue life in the present study.

Time-dependent mechanism\(^{13)-15)}\) was also found in this study. The results can be expressed in the relationship between time to failure \(t_f\) (s) and strain rate \(\dot{\varepsilon}\) (s\(^{-1}\)) in the order of 1.0 s\(^{-1}\) as shown in **Fig.32** and results could be expressed by the following power law equation:

\[
t_f = 17.041 \dot{\varepsilon}^{-1.153} \quad (12)
\]

**Table 6** shows the time-dependent relationship proposed by the previous studies\(^{13)-15)}\). The results of the present study extended the investigated range of strain rate order of 0.1 s\(^{-1}\) – 1.0 s\(^{-1}\). In addition, the tendency of power law expression fitted by the present study is in agreement with the previous studies\(^{13)-15)}\). However, time to failure was found to significantly decrease at high strain rate (1.0 s\(^{-1}\)) in this study. Moreover, the power law equation also gives a time-dependent mechanism that becomes less significant on a higher strain rate. Therefore, fatigue life on a high strain rate region expected during earthquakes will mainly be dominated by energy while time-dependent mechanism influence will decrease.

### 5. CONCLUSIONS

In this study, the effects of high strain rate on low-cycle fatigue behaviors of structural steel in large plastic strain region, which are expected during earthquakes were investigated via experiment. CT-specimens with effective round notch type were used to clarify fatigue life based on crack initiation and propagation behaviors.

The results showed that low-cycle fatigue behaviors in the strain rate order of 1.0 s\(^{-1}\) in large plastic strain region including load drop, crack initiation, crack propagation were dominated by the amount of cyclic energy. Higher strain rate and larger plastic strain expected during earthquakes could cause the release of larger amount of energy, which could result in lower fatigue life. However, total strain range was found to be more significant on fatigue life than on strain rate.

Despite the fact that fatigue life dominated on total strain range, strain rate could not be neglected in the
extremely low-cycle fatigue region where large plastic strain (more than 10%) occurred. In this region, strain rate order of 1.0 s\(^{-1}\) could cause 10%-30% decrease in fatigue life. The prediction method for fatigue life regarding strain rate effect in this region is proposed in this study.

REFERENCES


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