Fatigue damage evaluation of thin-walled short elbow under seismic loadings

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ABSTRACT
A fatigue damage evaluation method was developed for thin-walled short elbow under seismic loadings, which uses detailed numerical analysis along with the classic LCF evaluation. The applicability of the method was validated by comparisons with dynamic failure tests of short elbows. The usage factors of fatigue damage obtained by the method could predict the occurrence of through-wall-crack failure in the tests with errors less than 25%. It was shown that the fully numerical approach is feasible for the LCF evaluation of piping systems under seismic loadings.

1. INTRODUCTION

The primary vessels of the Japanese DFBR (Fig. 1) are connected by reverse U-shaped piping systems which use short elbows for the purpose of reducing plant dimensions. It is necessary to accumulate experimental data of short elbows regarding the failure modes and the elastic-plastic dynamic response during earthquakes.

In the previous study[1], the authors conducted experiments on the dynamic strength and the failure mode for the in-plane-bending of short elbows, which showed low cycle fatigue (LCF) is the dominant failure mode under seismic loadings.

Some studies have been performed on LCF during seismic events which is characterized by extremely small number of cycles (typically, less than 100 times) and extremely large strain (typically, larger than 5%). Matsuura and Hirata[2] performed elastic-plastic dynamic analyses of piping systems with elbow elements which uses Fourier series expansion for circumferential direction. But in such models, it is difficult to simulate local strain on thin-walled elbows, because the local buckling deformation could not be simulated by elbow elements. Ogiso[3,4,5] developed a fatigue damage evaluation method for cylindrical shells which uses quasi-static elastic-plastic large deformation FEM in combination with non-linear SDOF dynamic analysis, however, strain histories were not directly evaluated from the dynamic analysis.

On LCF life of materials which are used for FBRs, Wada et al.[6] statically generated a best fit curve of the fatigue strength for austenitic stainless steel (304ss, 316ss, 321ss) based on comprehensive test data. These LCF data were obtained by the tests in which the strain range was less than 5% and the cycles of fatigue life was more than a hundred times. Ogiso[3,4,5] conducted additional LCF tests in order to complement data, however, material data for the extremely low cycle fatigue are still insufficient.

Consequently, any generalized procedures have not been prepared for this particular LCF problem, which occurs under extremely low cycles, large deformation and large strain range.
In this study, a fatigue damage evaluation method of elbows was developed, which uses strain time histories calculated by detailed numerical analyses along with the classical LCF evaluation method. The applicability of the method was validated by comparisons with dynamic failure tests on in-plane-bending of short elbows.

2. EVALUATION METHOD OF FATIGUE DAMAGE

Low cycle fatigue life of general steel structures under dynamic loadings is evaluated by the following procedure.

Step1: Count peak ranges of strain history calculated by theoretical analysis and/or FEM analysis at the point of concern
Step2: Obtain LCF curve of the material
Step3: Calculate usage factor of fatigue damage by Minner's law

This procedure has been established for general LCF evaluation in which the cycles to failure are more than one hundred times and strain range is less than 5%. There exists little knowledge about the applicability of above-stated classical approach for extremely-low-cycle fatigue, which should be prepared for DFBR's piping system under severe seismic loadings.

In this study, a fatigue damage evaluation method based on detailed numerical analyses were performed by the following three steps. The applicability of the method was validated by comparisons with dynamic failure tests on the in-plane-bending of short elbows.

(1) Numerical Analysis
Seismic response analyses were conducted by dynamic elastic-plastic large-deformation FEM with 3-D shell element models in order to obtain strain time histories at the points of concern on elbows.

(2) LCF Curve
Uniaxial fatigue tests were carried out to complement existing LCF curves regarding the total strain range between 3% to 6% and the cycles of fatigue life between 50 to 300.

(3) Calculation of Usage Factor
The usage factors of fatigue damage were calculated by Minner's law.

3. DYNAMIC FAILURE TESTS OF THIN-WALLED SHORT ELBOW

(1) Test Conditions
Dynamic failure tests of thin-walled short elbows were conducted using a dynamic failure test apparatus (Fig. 2). The test apparatus was anchored on a shaker table maintained by CRIEPI and excited with a simulated seismic time history.

The dynamic failure test apparatus is a nonlinear single degree of freedom (SDOF) system which is composed of a test model and a large mass. The test model is composed of a stainless steel elbow (SUS304 10B Sch5S 90° short elbow) and straight pipes (SUS304 10B Sch5S). The length of the straight pipes is long enough (2.5 times the pipe diameter) to eliminate the effect of the radial restraint of the flanges. The dimensions of the test model and of the corresponding reactor piping system are shown in Table 1. The material properties of the test model are shown in Table 2. The tests were conducted under room temperature, and no pressure was applied to the piping models.
A simulated acceleration time history "ENVELOPE" was applied for the seismic excitation. Its response spectrum envelops the seismic response of half-embedded reactor buildings at the reactor support level. The time history and the acceleration response spectra of the ENVELOPE are shown in Fig. 3. The time scale of the seismic motion was expanded 2.78 times as long as the original time scale based on the difference of the fundamental frequencies between the reactor piping system (6.67Hz)[7] and the test model (2.4Hz). The input seismic acceleration amplitude is strong enough to cause failure on the elbows, disregarding the design conditions for the actual piping systems. Two test models were used and two test cases were conducted; C500 and C600 whose maximum input acceleration levels were 542 cm/s² and 659 cm/s².

(2) Test Results
The load-displacement relation obtained in the tests are shown in Fig. 4. Though moderate load reduction appeared after the maximum load occurrence, the overall response remained stable and no total collapse of whole structure occurred. Through-wall cracks appeared test case C500-3 (third large excitation for model C500) at 31 seconds and C600-2 (second large excitation for model C600) at 69 seconds (Fig. 5). Figure 6 shows typical hoop strain hysteresis obtained by a strain gauge located at 30 degrees downward from the crack in the central cross section of the elbow. The accumulation of ratchet strain was observed.

4. NUMERICAL ANALYSIS

Dynamic elastic-plastic large deformation FEM analyses were performed in order to simulate strain history during the seismic response in the dynamic failure tests.

(1) Method of Analysis
The general purpose FEM code ABAQUS was used for the analysis. The analytical model is 1/2 of the test model. Figure 7 shows the analytical model of the elbow using S8R5 isoparametric/quadratic shell elements. The linear bearing of the test apparatus was considered in the model as a friction element with coefficient 0.0016 and a dash pot element with viscous damping factor 0.01. The Rayleigh damping factor 0.0002 at the fundamental frequency 2.4Hz was applied in order to make the model equivalent to the initial linear-elastic state of the test model. Figure 8 shows the stress-strain curves for the analyses which were obtained from the test pieces sampled from stainless steel plate subjected to the same heat treatment as the elbow. Isotropic hardening was used for the constitutive rules.

(2) Results
Table 3 shows the comparison between the analyses and the tests on the maximum load and displacement. Figure 9 shows the load-displacement relations of analytical results. The analytical maximum loads agreed with test results with errors less than 20%, however the analytical maximum displacement were 40%-60% smaller than test results. Figure 10 shows typical hoop strain hysteresis at the same point as test result shown in Fig. 6. In this figure, the progressive ratchet strain is observed which is similar to the test results, and the accuracy of the analysis on the strain is acceptable.

The large difference between the test and the analysis on the displacement may be caused by the use of the mean thickness in the analytical model, or the isotropic constitutive equation of the material (SUS304 is considered to be isotoropic/kinematic-mixed hardening material), or the estimation error of the friction force and the viscous damping.

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5. FATIGUE STRENGTH OF SUS304

In order to obtain the material properties on extremely-low-cycle fatigue, uniaxial fatigue tests were carried out. The test pieces were sampled from a stainless steel plate subjected to the same heat treatment as the elbows.

Figure 11 shows Wada's LCF curve and additional plots of the uniaxial fatigue test data in this study. The test results are distributed within factor of 2 for Wada's LCF curve. In this study, Wada's LCF curve is applied for the extremely-low-cycle fatigue which is beyond the original applicable range. This strategy may be revised in the future, considering the interaction between ductile fracture and low-cycle fatigue.

6. VERIFICATION OF FATIGUE DAMAGE EVALUATION

Damage evaluation was conducted with the rainflow method and Minner's law.

The peak range of strain history were counted by the rainflow method. The histogram of strain range are shown in Fig. 12.

Accumulated usage factor $D_s$ was directly calculated by Minner's law. Table 4 shows the results on fatigue damage evaluation. The accumulated usage factors for through-wall cracks evaluated by our numerical approach were 0.768 and 0.979 for the case C500-3 and C600-2, respectively, which showed acceptable accuracy for seismic margin evaluation.

Though the constitutive equations may have an essential role in the application of nonlinear analysis for low-cycle fatigue, our numerical approach using simple isotropic hardening rule could predict the occurrence of through-wall-crack failure in the tests with acceptable accuracy.

These results may be obtained by the condition of the tests, such as the thin wall of the elbows which cause local strain concentration. It is necessary to improve the constitutive equations of material in order to make the numerical approach applicable to general steel structures' extremely-low-cycle fatigue during earthquakes.

7. CONCLUSION

The fatigue damage evaluation method was developed, incorporating detailed numerical analysis with the classical LCF evaluation methodology. The applicability of the method was verified by comparisons with dynamic failure tests of short elbows. The usage factors of fatigue damage obtained by the numerical approach could predict the occurrence of through-wall-crack failure in the tests with errors less than 25%.

The results of this study show that the fully-numerical approach can be feasible for the extremely-LCF evaluation of piping systems under seismic loadings. Further study should be continued to get realistic constitutive rules of materials and the fundamental fatigue test results in the extremely-low-cycle/large-strain range.
REFERENCE


### Table 1: Dimensions of short elbows

<table>
<thead>
<tr>
<th></th>
<th>Reactor H/L*</th>
<th>Reactor M/L*</th>
<th>Test model C/L*</th>
<th>10B Sch 5S</th>
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<tbody>
<tr>
<td>Diameter : $D_b$ mm</td>
<td>965.2</td>
<td>762.0</td>
<td>267.4</td>
<td></td>
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<tr>
<td>Thickness : $t$ mm</td>
<td>15.9</td>
<td>15.9</td>
<td>4.18**</td>
<td></td>
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<tr>
<td>Curvature radius : $R$ mm</td>
<td>965.2</td>
<td>762.0</td>
<td>254.0</td>
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<td>Section radius : $r$ mm</td>
<td>474.65</td>
<td>373.05</td>
<td>131.625</td>
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<tr>
<td>$R/D_b$</td>
<td>1.0</td>
<td>1.0</td>
<td>0.950</td>
<td></td>
</tr>
<tr>
<td>$D_b/t$</td>
<td>60.70</td>
<td>47.92</td>
<td>64.43</td>
<td></td>
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<tr>
<td>$r/t$</td>
<td>29.85</td>
<td>23.40</td>
<td>31.72</td>
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<tr>
<td>$\lambda = R/t^2$</td>
<td>0.0681</td>
<td>0.0871</td>
<td>0.0605</td>
<td></td>
</tr>
</tbody>
</table>

*H/L: hot leg, M/L: middle leg, C/L: cold leg

**measured data

### Table 2: Material properties

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<tr>
<th></th>
<th>0.2% Proof stress $\sigma_{0.2}$ (MPa)</th>
<th>Young's modulus $E$ (GPa)</th>
<th>Poisson's ratio</th>
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<tr>
<td>Straight pipe</td>
<td>249</td>
<td>188</td>
<td>0.276</td>
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<tr>
<td>Elbow</td>
<td>232</td>
<td>194</td>
<td>0.261</td>
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### Table 3: Summary of results

<table>
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<tr>
<th>case</th>
<th>Input acc cm/sec$^2$</th>
<th>Load (test) kN</th>
<th>Load (analysis) kN</th>
<th>Disp. (test) mm</th>
<th>Disp. (analysis) mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>C500-1</td>
<td>529.0</td>
<td>18.5</td>
<td>20.0</td>
<td>104.0</td>
<td>64.3</td>
</tr>
<tr>
<td>C500-2</td>
<td>520.2</td>
<td>17.4</td>
<td>20.1</td>
<td>122.2</td>
<td>70.2</td>
</tr>
<tr>
<td>C500-3</td>
<td>541.6</td>
<td>16.9</td>
<td>20.2</td>
<td>192.7</td>
<td>77.5</td>
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<tr>
<td>C600-1</td>
<td>601.9</td>
<td>19.9</td>
<td>21.0</td>
<td>146.5</td>
<td>86.2</td>
</tr>
<tr>
<td>C600-2</td>
<td>659.3</td>
<td>18.3</td>
<td>21.3</td>
<td>201.5</td>
<td>86.6</td>
</tr>
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</table>

### Table 4: Fatigue damage estimation

<table>
<thead>
<tr>
<th>case</th>
<th>$D_f$</th>
<th>Accumulated usage factor</th>
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<tbody>
<tr>
<td>C-500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C500-1</td>
<td>0.318</td>
<td>0.318</td>
</tr>
<tr>
<td>C500-2</td>
<td>0.357</td>
<td>0.675</td>
</tr>
<tr>
<td>C500-3**</td>
<td>0.093</td>
<td>0.768</td>
</tr>
<tr>
<td>C-600</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C600-1</td>
<td>0.536</td>
<td>0.536</td>
</tr>
<tr>
<td>C600-2**</td>
<td>0.443</td>
<td>0.979</td>
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</tbody>
</table>

* Crack occurrence case
Fig. 1: System concept of the FBR

Fig. 2: Test apparatus of the dynamic test

Fig. 3: Seismic Motion

Fig. 4: Load-displacement relations (test result)

Fig. 5: Cracks of the specimen

Fig. 6: Hoop strain hysteresis (test result)
Fig. 7: FEM model

Fig. 8: Stress-strain curve

Fig. 9: Load-displacement relations (analytical results)

Fig. 10: Hoop strain hysteresis (analytical result)

Fig. 11: LCF curve

Fig. 12: Histogram of strain range