Transactions, SMiRT-22
San Francisco, California, USA - August 18-23, 2013
Division V

Discussion on Application of Inelastic Response Spectrum Approach to Seismic Fragility Evaluation

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ABSTRACT

In this paper, we discussed the application of inelastic response spectrum approach to seismic fragility evaluation. The effect of inelastic energy absorption due to plastic deformation is taken into account as inelastic energy absorption factor, F_μ, in the factor of safety approach for the evaluation. The Newmark method is one of the most popular methods to estimate the factor F_μ. We compared the results of the Newmark method with these of inelastic response spectrum approach using nonlinear time-history analysis, and investigated the applicability of the approach to seismic fragility evaluation.

INTRODUCTION

In this paper, we discussed the application of inelastic response spectrum approach to seismic fragility evaluation. The effect of inelastic energy absorption due to plastic deformation is taken into account as inelastic energy absorption factor, F_μ, in the factor of safety approach for the evaluation. The factor is defined as the ratio of inelastic spectrum to elastic one. Figure 1 shows the schematic diagram of load-deformation relationship for elastic and inelastic responses utilized to define F_μ.

Veletsos and Newmark (1965) introduced inelastic response spectrum approach to estimate inelastic responses. Newmark (1977) developed the estimation method using simple equation of ductility factor μ, and the Newmark method is one of the most popular methods to estimate inelastic responses. The method is based on the assumption of the energy-equivalence of perfectly elasto-plastic system in amplified frequency range. Riddell et al. (1979) also developed the estimation method for rigid frequency range. Kennedy et al. (1984) applied the methods to seismic fragility evaluation. The inelastic energy absorption factor F_μ obtained from the Newmark method is given by the following equation in the amplified frequency region of the floor response spectrum.

$$F_\mu = \sqrt{2\mu - 1} \tag{1}$$

For rigid equipment, F_μ is given by the following equation.

$$F_\mu = \mu^{0.13} \tag{2}$$

Inelastic response spectrum and the corresponding factor F_μ can be also obtained from nonlinear time-history analysis of one degree-freedom system (e.g. Tamura and Matsuura(2011)). The approach using nonlinear time-history analysis is more accurate compared to the Newmark method, though the former approach requires the iterative procedure to find yield strength corresponding to target ductility ratio.

We focused on the Newmark method, and conducted the parametric survey using nonlinear time-history analysis for the comparison. The comparison clarified the conservative eigen frequency range of the Newmark method and the criteria condition. Accordingly, inelastic response spectrum approach using nonlinear time-history analysis might lead to more reasonable evaluation in such frequency range.

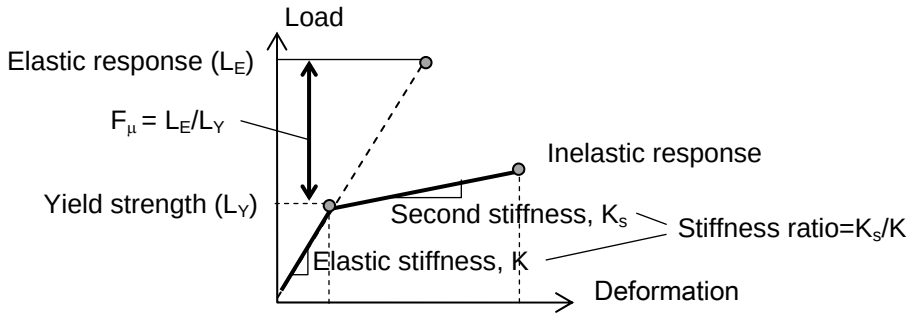


Figure 1. Schematic diagram of load-deformation relationship

SENSITIVITY ANALYSIS OF INELASTIC RESPONSE SPECTRUM

Cases of sensitivity analysis

We conducted sensitivity analysis to investigate the effect of some parameters defining model and excitation. Table 1 shows the cases of sensitivity analysis. Damping ratio and second stiffness were surveyed to investigate the effect of model parameters using wave 1 of Table 1. Duration, spectrum shape and spectrum ratio of the second to the highest peak were also surveyed to investigate the effect of excitation parameters using wave 2 through 6-3 of Table 1.

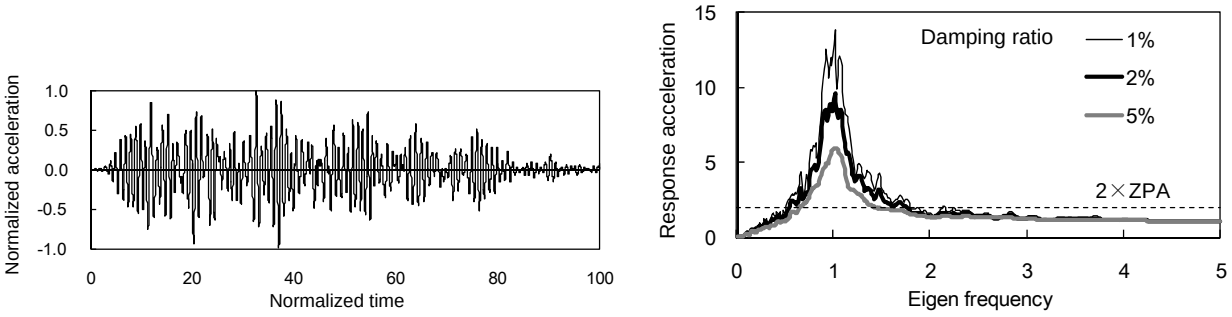
Calculated inelastic response spectrum

Figure 2 shows the time history and response spectra of wave 1 in Table 1. Figure 3 shows the calculated inelastic spectra by using nonlinear time-history analysis, and the ratio of inelastic spectrum to elastic one. As described later, we compared the results shown in Fig. 2 with those of sensitivity analysis to investigate the effect several parameters. Moreover, we also compared the calculated inelastic spectra with the results of the Newmark method defined by Eq. 1 to investigate its conservativeness of the method.

Table 1: Cases of sensitivity analysis

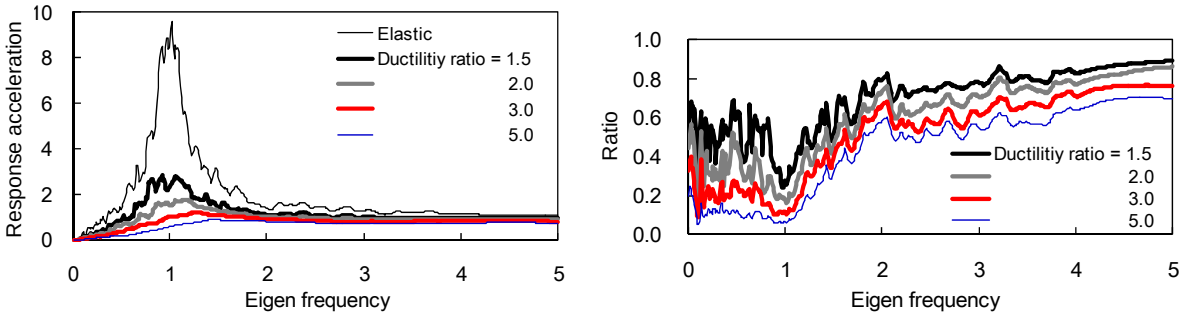
<table>
<tr><th>Wave</th><th>Dominant frequency</th><th>Duration</th><th>Spectrum shape</th><th>Peak ratio</th><th>Damping ratio</th><th>Stiffness ratio</th><th>Focused parameter</th></tr>
<tr><td rowspan="2">1</td><td rowspan="10">1.0</td><td rowspan="3">100</td><td rowspan="3">See Fig. 7(1)</td><td rowspan="7">–</td><td>2%</td><td rowspan="2">0.2</td><td>–</td></tr>
<tr><td>1, 5%</td><td>Damping</td></tr>
<tr><td rowspan="3">2%</td><td>0.001,0.1, 0.5,0.9</td><td>Stiffness ratio</td></tr>
<tr><td>2</td><td rowspan="4">0.2</td><td rowspan="2">Spectrum shape</td></tr>
<tr><td>3</td></tr>
<tr><td>4</td><td>20</td><td rowspan="2">See Fig. 7 (2)</td><td rowspan="2">Duration of excitation</td></tr>
<tr><td>5</td><td>40</td></tr>
<tr><td>6-1</td><td rowspan="3">100</td><td rowspan="3">See Fig. 7 (3)</td><td>1.0</td><td rowspan="3">Spectrum ratio of the second to the highest peak</td></tr>
<tr><td>6-2</td><td>0.5</td></tr>
<tr><td>6-3</td><td>0.3</td></tr>
</table>

Note : The maximum amplitude and dominant frequency of the waves were normalized to be unity.



(1) Time history (2) Response spectra

Figure 2. Artificial seismic wave (wave 1 of Table 1)



(1) Elastic and inelastic spectra (2) Ratio of inelastic spectrum to elastic one

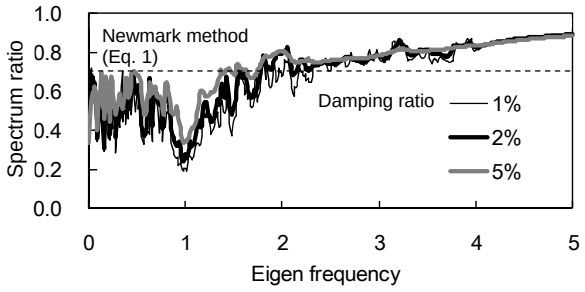
Figure 3. Calculated inelastic response spectra (damping ratio=2%, stiffness ratio=0.2)

Parametric survey of model parameters

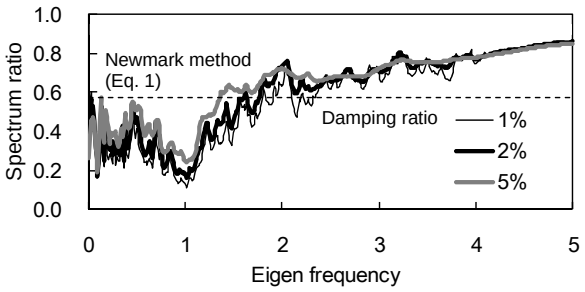
We conducted the parametric survey to investigate the effect of damping ratio and second stiffness. Figures 4 and 5 show the calculated ratios of inelastic spectrum to elastic one, which were obtained from the parametric survey of damping ratio and second stiffness respectively.

The results shown in Fig. 4 indicated that the smaller damping led to the smaller spectrum ratio in lower and amplified frequency range, though the difference due to damping was relatively small in higher frequency range. The results shown in Fig. 5 also indicated that the difference due to stiffness ratio ranging from 0.001 to 0.5 was relatively small in amplified frequency range, though the result of stiffness ratio 0.9 was differed from the others. The spectrum ratio tends to converge to $1/\mu$ as the stiffness ratio approaches unity. The results of the stiffness ratio close to unity such as 0.9, therefore, differed from the others. The results of parametric survey suggested that (1) The results of the smaller damping were more conservative, and that (2) it might be reasonable to determine an arbitrary stiffness ratio from 0.001 to 0.5 for seismic fragility evaluation, even if the stiffness ratio was unknown.

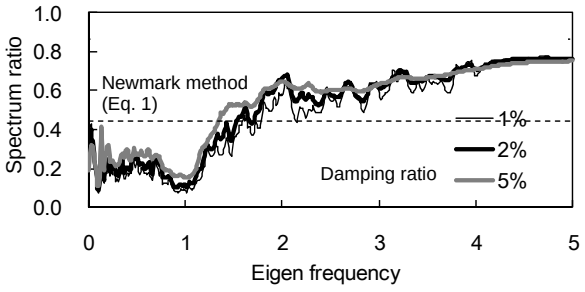
The comparison with the Newmark method showed that the method was more conservative than the calculated inelastic spectrum in lower and amplified frequency range as shown in Figs. 4 and 5. The criteria of conservative frequency range roughly corresponded to the frequency where the amplitude was a half to twice the amplitude of ZPA, though the result of the stiffness ratio close to unity was conservative on whole frequency range. Figure 6 shows the schematic diagram of the conservative range and the criteria. Accordingly, the inelastic response spectrum approach using nonlinear time-history analysis might lead to more reasonable evaluation in such frequency range for seismic fragility evaluation.



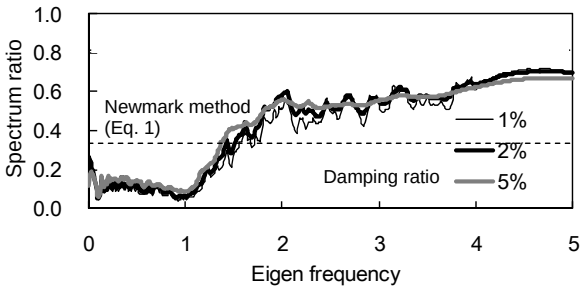
(1) Ductility ratio = 1.5



(2) Ductility ratio = 2.0

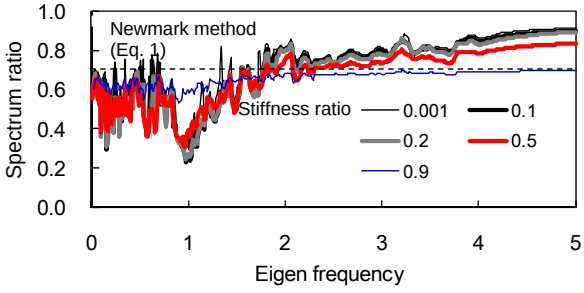


(3) Ductility ratio = 3.0

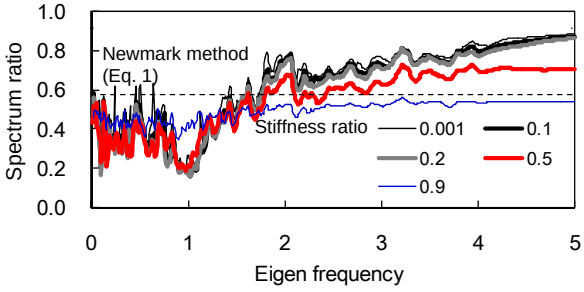


(4) Ductility ratio = 5.0

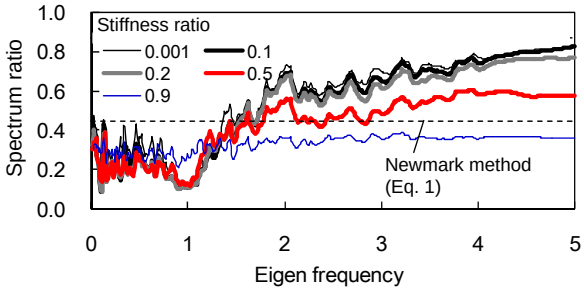
Figure 4. Parametric survey of damping ratio (Stiffness ratio = 0.2)



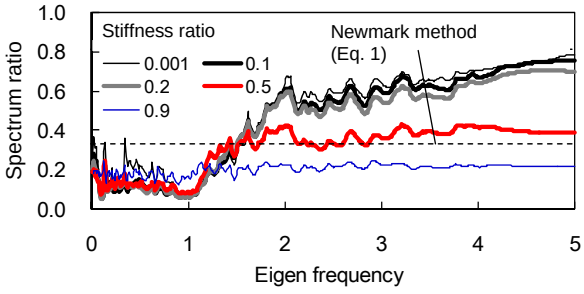
(1) Ductility ratio = 1.5



(2) Ductility ratio = 2.0



(3) Ductility ratio = 3.0



(4) Ductility ratio = 5.0

Figure 5. Parametric survey of second stiffness (Damping ratio = 2%)

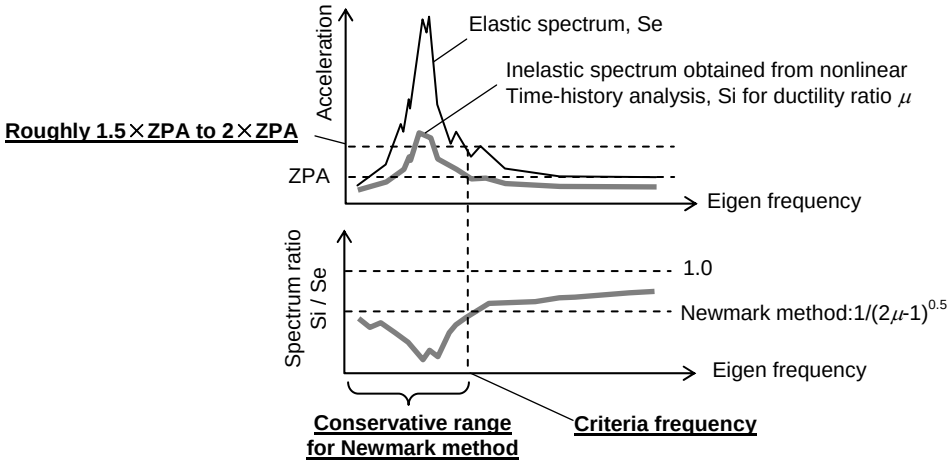


Figure 6. Schematic diagram of conservative range for Newmark method

Parametric survey of excitation parameter

We conducted the parametric survey to investigate the effect of duration, spectrum property and spectrum ratio of the second to the highest peak. Figure 7 shows the elastic response spectra utilized for the survey.

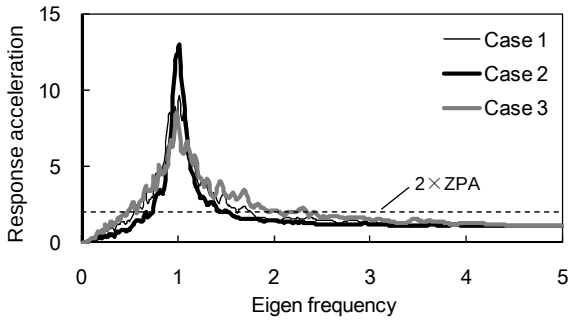
Figures 8 and 9 show the calculated ratio of inelastic spectrum to elastic one, which was obtained from the parametric survey of excitation parameters. The comparison with the Newmark method showed that the criteria of conservative frequency range for the Newmark method roughly corresponded to the frequency where the amplitude was a half to twice the amplitude of ZPA as shown in Fig. 8, though the results differed from spectrum shape. The difference due to the duration was relatively small on inelastic response spectrum as shown in Fig. 9, and the criteria of conservative frequency range for the Newmark method were almost the same.

Figure 10 shows the calculated spectrum ratio obtained from the parametric survey to investigate the second-peak ratio. The comparison with the Newmark method showed that the criteria of the conservative frequency range were almost the same with those for a single peak case as described previously. We confirmed that the criteria were applicable to the expectation of the conservativeness in Newmark method, even if the excitations had several spectrum peaks as observed in actual waves.

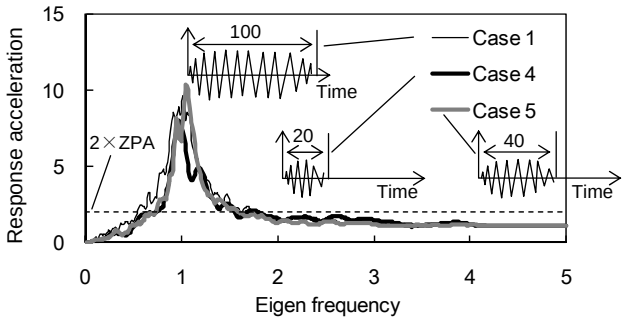
Accordingly, it was suggested that the above-mentioned criteria of conservative frequency range for the Newmark method were applicable to arbitrary types of excitations, and that inelastic response spectrum approach using nonlinear time-history analysis might lead to more reasonable evaluation of the inelastic energy absorption factor F_μ in the frequency range for seismic fragility evaluation.

CALCULATED EXAMPLES OF OBSERVED WAVES

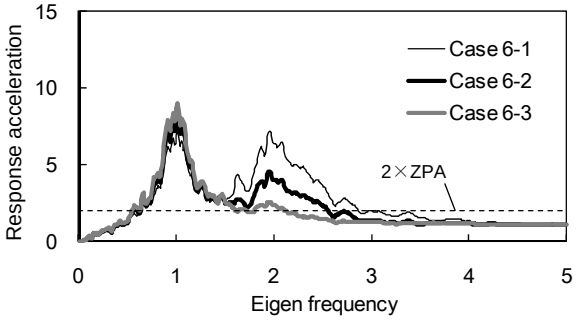
Figure 11 shows the calculated inelastic response spectra of observed two waves. The first wave is the floor response observed at the reactor building of Kashiwazaki-Kariwa NPPs, Unit 7 in Niigata-Chuetsu-Oki earthquake, and was provided by the Tokyo Electric Power Company. The second wave is the floor response observed by the Chugoku Electric Power Company at the reactor building of Shimane NPPs, Unit 2 in Western-Tottori Earthquake. The results indicated that the criteria of conservative frequency range for Newmark method were almost the same with those for the artificial waves as described previously. Accordingly, we confirmed that the criteria were applicable to the evaluation of the actual observed waves.



(1) parametric survey of spectrum shape

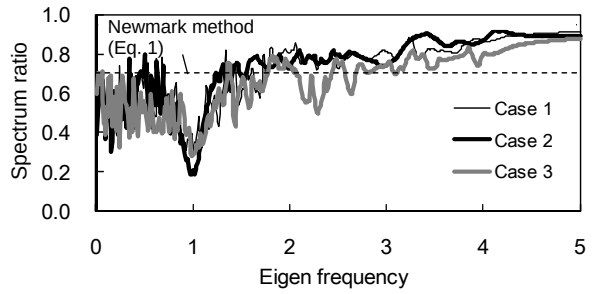


(2) parametric survey of excitation duration

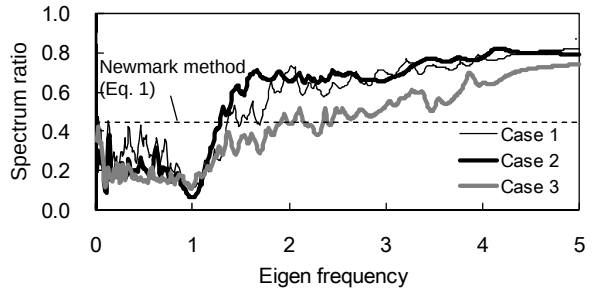


(3) parametric survey of the second-peak ratio

Figure 7. Elastic response spectra of artificial waves for parametric survey

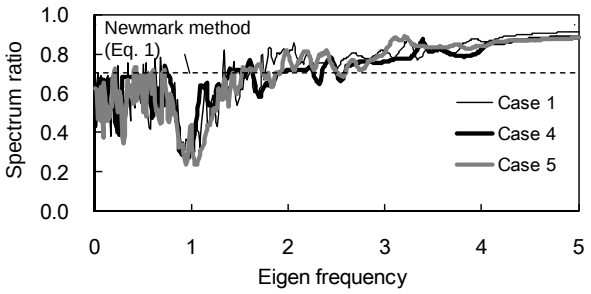


(1) Ductility ratio = 1.5

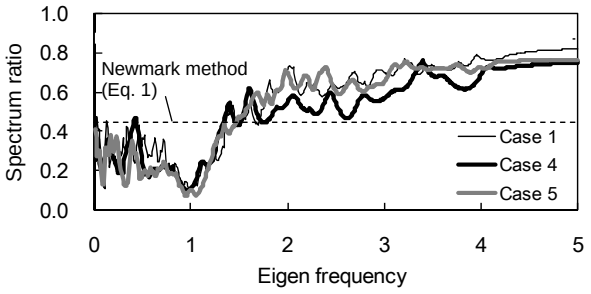


(2) Ductility ratio = 3.0

Figure 8. Parametric survey of spectrum shape (Damping ratio=2%, stiffness ratio=0.2)

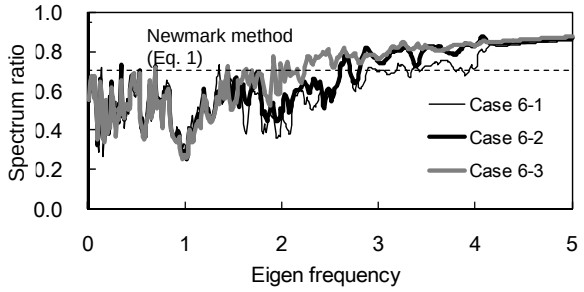


(1) Ductility ratio = 1.5

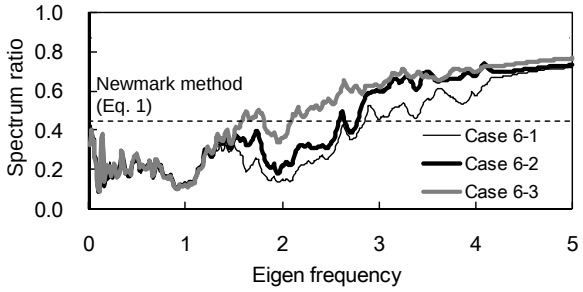


(2) Ductility ratio = 3.0

Figure 9. Parametric survey of excitation duration (Damping ratio=2%, stiffness ratio=0.2)

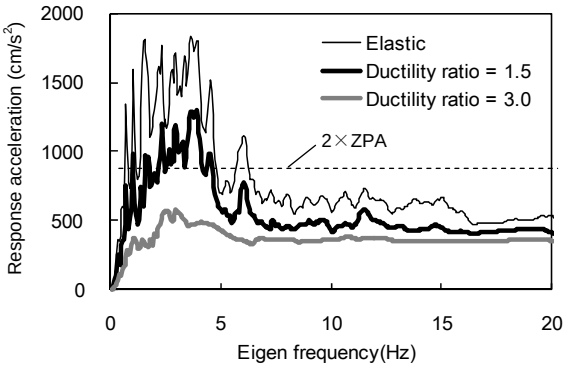


(1) Ductility ratio = 1.5

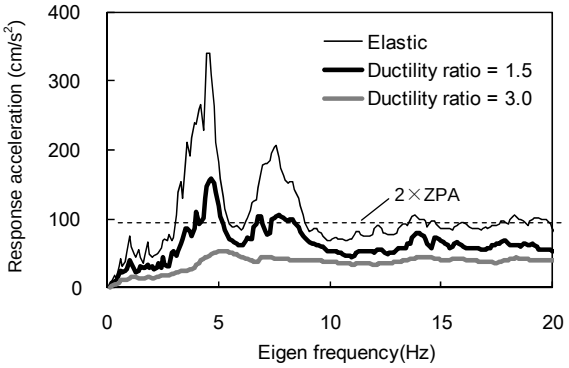


(2) Ductility ratio = 3.0

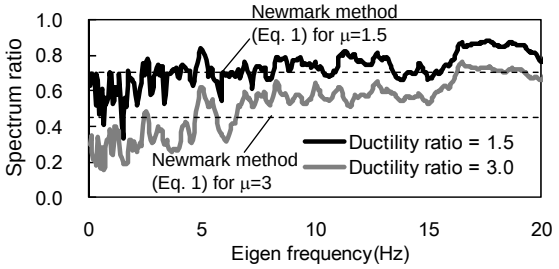
Figure 10. Parametric survey of the second-peak ratio
(Damping ratio = 2%, stiffness ratio = 0.2)



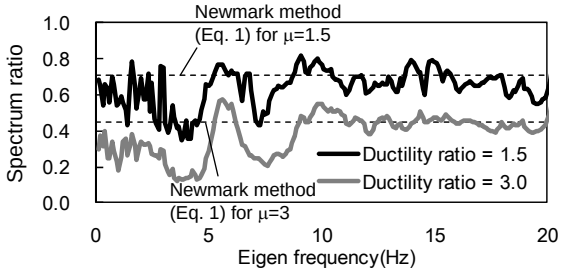
(a) Elastic and inelastic spectra



(a) Elastic and inelastic spectra



(b) Ratio of inelastic spectrum to elastic one



(b) Ratio of inelastic spectrum to elastic one

(1) Kashiwazaki-kariwa NPPs

(2) Shimane NPPs

Figure 11. Calculated inelastic response spectra of observed waves
(Damping ratio = 2%, stiffness ratio = 0.2)

CONCLUSIONS

We discussed the application of inelastic response spectrum approach to seismic fragility evaluation. We conducted the sensitivity analysis of model and excitation parameters by using nonlinear time-history analysis, and compared the results with those of the Newmark method. The comparison clarifies that the Newmark method is more conservative than the inelastic response spectrum using nonlinear time-history analysis in lower and amplified frequency range. The criteria of conservative frequency range roughly correspond to the frequency where the amplitude was a half to twice the amplitude of ZPA. We confirm that the criteria are applicable to the expectation of the conservativeness for the Newmark method, and that the inelastic spectrum approach using nonlinear time-history analysis might lead to more reasonable evaluation of the inelastic energy absorption factor F_μ for seismic fragility evaluation.

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