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ABSTRACT

Effects of stiffness variation and restoring-force model choice on an inelastic dynamic response of prototypical Japanese nuclear power plant buildings were investigated from a quantitative viewpoint. Five cases for the combination of the six restoring-force models, i.e., three typical degrading tri-linear models for the flexural deformation, and three for the shear deformation; an origin-oriented, a non-symmetric origin-oriented and a degrading tri-linear models, were examined at the 1.5 times maximum credible design earthquake level. It was found that the higher flexural stiffness increases the responses but the higher shear stiffness does not always increase the responses. Significant effects of the restoring-force model choice were revealed in the flexural response of flexure dominating members. The variation of shear responses due to choice of both different models and various earthquake inputs was generally less significant than that of flexural responses.

1. Introduction

It has been recommended in Japan to utilize an inelastic response analysis for the earthquake resistant design of nuclear power plant buildings. Among various parameters which have important roles in the inelastic response computation, restoring-force models are considered to be one of the most significant factors. In order to predict reliable inelastic responses for a specified earthquake input, the consistency of restoring-force models has to be investigated by referring to a large number of experimental evidences. However, since the accurate restoring-force models with their stiffness evaluation have not been confirmatively established so far, the possible error due to an uncertainty of models should be investigated for the proof of structural safety. In other words, the consequence of a computed response when adopting different models and different stiffnesses have to be discussed quantitatively to clarify the significance of the model choice. The evaluation of variation due to the uncertainty of restoring-force models is inevitable especially for a probabilistic risk assessment.

As a typical example, the variation of inelastic responses of a BWR Mark-II type building against hypothetically intense earthquake ground motions due to the stiffness change and the various combinations of existing restoring-force models for flexure and shear deformation is numerically investigated, and the significance of their effects on the response is discussed.
2. Structure and Restoring-Force Models

A BNR Mark-II type building is employed in this study, a schematic elevation of which is shown in Fig. 1. As for the soil condition supporting the building, a rock layer is assumed with a shear wave velocity of 1000m/sec. The lumped mass model for the following response analysis is shown in Fig. 1[1] as well. Sway and rocking springs are placed to represent soil-structure interaction effects. In this paper, structural element members No.1 and No.6 are examined in detail. Member No.1 is the lowest part of the building and is subjected to high levels of stress. Member No.6 is the mid-point of the building, and is connected to the top level of the outerwall building.

Three types of hysteretic rule for flexural deformation and three for shear deformation are adopted. Rules for flexural deformation are the tri-linear rule proposed by Fukada[2] (hereinafter abbreviated M-1), that proposed by Nomura[3] (M-2), and that proposed by Muto[4] (M-3). Rules for shear deformation are the origin-oriented rule (Q-1), the non-symmetric origin-oriented rule (Q-2), and the degrading tri-linear rule proposed by Nomura (Q-3, the same as M-2). General features of each rule are summarized in Table I.

Five combination cases listed in Table II are selected in order to examine the difference of response values of models with various restoring-force characteristics. The combination of M-1 for flexural deformation and Q-1 for shear deformation corresponds to the Case-1, and the response values of the Case-1 are used to normalize the response values of the other four cases.

3. Input Motions and Responses

Three synthetic accelerograms are generated for input motions in this study by composing sinusoidal waves with random phase angles to fit the design response spectrum proposed by Ohsaki[5]. It corresponds to the response spectrum of an earthquake with a magnitude of 8.5 and an epicentral distance of 68km. A time trace of the synthetic accelerogram and its response spectrum are shown in Figs. 2(a) and (b) in comparison with the prescribed design response spectrum. Peak values of these synthetic accelerograms fall between the values 410 and 480gal. Maximum responses of the Case-1 model subjected to these synthetic motions scarcely exceed the cracking point on the primary curve at every member in Fig.1. The intensity of motions is increased to 1.5 times in this study to examine an inelastic behavior of the buildings.

Each maximum response of the Case-1 model subjected to these three input motions is concentrated around the average taken across these three responses. The fluctuation around the average is about 0.1 times the average[6]. The maximum tip response accelerations are about 3500gal and the maximum tip response displacements about 8cm, respectively. With regard to flexural responses, the maximum response of member No.1 exceeds the yielding point. Maximum responses members Nos.2-7, however, exceed the cracking point, while not exceed the yielding point on the primary curve. Members Nos.8 and 9 remain in the elastic range. The maximum shear responses of members Nos.1, 2 and 8 are situated between cracking and yielding points, and those of members Nos.5 and 6 are beyond the yielding point. The shear responses of other members remain in the elastic range. The maximum flexural and shear responses of members Nos.1 and 6 of the Case-1 model are shown in Fig.3.

Obtained are the responses of the Case-1 model subjected to the synthetic earthquake ground motion with the set of phase angles of the real East-West component accelerogram at

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the Hachinoche harbor recorded during the Tokachi-Oki earthquake of May 16, 1968. The maximum responses are nearly equal to the smallest values of the maximum responses subjected to the three sets of synthetic accelerograms except for a few members.

4. Effects of Stiffness Variation on Inelastic Responses

Effects of the stiffness variation on the inelastic responses are evaluated by carrying out dynamic analyses for the Case-1 model, in which flexural stiffnesses and shear stiffnesses are parametrically varied. The results are shown in Figs.4(a)-(f). Natural period, maximum response acceleration and displacement at the top of the model, and responses of the members Nos.1 and 6 are investigated in this analysis.

The fundamental natural period of the Case-1 model is 0.298 seconds. Changing flexural and shear stiffnesses, the fundamental natural period is 0.91-1.11 times that of the Case-1 model. Taking flexural and shear stiffnesses 1.5 times those of the Case-1 model, the fundamental natural period becomes 3.91 times shorter compared with the Case-1 model. And taking the stiffnesses 0.7/(1/1.5) times, the fundamental natural period becomes 1.11 times longer compared with the Case-1 model.

Figures 4(a)-(f) represent maximum responses of each case having the specified flexural and shear stiffnesses. The results are normalized by the corresponding quantity obtained for the Case-1 model. Diameters in the figures indicate the normalized response quantities of the maximum acceleration and the maximum displacement at the top of the model(Figs.4(a) and (b), respectively), and responses of the members Nos. 1 and 6(Figs.4(c) and (f), respectively).

Shear stiffness variation has no significant influence in the maximum response acceleration. The normalized response quantities are in the range of 0.99 and 1.01. When considering flexural stiffness variation, the normalized response quantities are 0.96 and 1.12. The normalized response quantities of the maximum displacement are varied from 0.89 to 1.23 with variation of flexural and shear stiffnesses.

When taking both flexural and shear stiffnesses 1.5 times those of the Case-1, the maximum response of the member No.1 is 1.52 times larger for the flexural response and 1.24 times larger for the shear response, respectively. It can be found that the variation of shear stiffness significantly dominates flexural and shear responses. The normalized quantities of flexural and shear responses of the member No.6 are increased when the flexural stiffness increased and the shear stiffness decreased. The normalized quantities are varied from 0.90 to 1.10 with flexural stiffness variation, and from 0.82 to 1.19 with shear stiffness variation, respectively. When comparing the responses of the member No.6 with those of the member No.1, the effect of stiffness variation is found to be less significant in the member No.6 than in the member No.1.

5. Effects of Restoring-Force Models on Inelastic Responses

The maximum flexural and shear responses of the members Nos.1 and 6 are shown in Figs.5(a)-(d). Responses in the figures are normalized by those of the Case-1 model. The Y-axis represents this normalized response; i.e. ratio of the corresponding case to the Case-1. These figures include both the average and the range of ratio for each case. The ratio for the Case-1 is essentially unity, and the results for the Case-1 are not included in the figures.
Figures 5(a) and (b) represent variation of responses of the member No.1 with combinations of various restoring-force models. It is one of the characteristic features of the member No.1 that the flexural yielding capacity is smaller than the shear yielding capacity. Figure 5(a) indicates that variations of the flexural responses of the Cases-2 through 5 are fairly large. The maximum value of the ratios of the Case-3 is 1.8, while the average value is about 1.4. In the Case-5 model, the average of the response ratios is nearly unity; i.e. equal to 1.04. The variation caused by variety of the input earthquake motions, however, is quite large. Values of shear responses, illustrated in Fig.5(b), are close to one another. The range of ratios is from 0.94 to 1.0 on an average. Similarly, the variation of the responses is small. Ratios fall in the value from 0.89 to 1.11. From results of the Cases-4 and 5 in Fig.5(a), it is revealed that the flexural responses are varied when not only different flexural restoring-force models but also different shear restoring-force models are adopted. Shear responses are located close together. A possible reason for this fact is that the ratio of stiffness beyond the yielding point to the initial stiffness is taken to be 0.12 for shear restoring-force models, but the ratio is taken to the value of 0.001 to 0.057 for flexural restoring-force models. The possible cause why the flexural response of the Case-3 is extremely larger than that of other cases is that the hysteretic loop area of the M-3 model (the Muto model) is smallest among the three degrading tri-linear restoring-force models for flexural response. The equivalent viscous damping property of the M-3 model, therefore, is least among the three.

The shear yielding capacity of the member No.6, in contrast to the member No.1, is smaller than the flexural yielding capacity. It is shown in Fig.5(c) that the flexural responses of the Cases-2 and 3 are about 1.3 times that of the Case-1, while those of the Cases-4 and 5 are about 0.9 times that of the Case-1. Figure 5(d) indicates the shear responses for the Cases-2 through 5. Except for the Case-2, the ratios of responses are in the value of nearly unity with slight variation. The responses of the Case-2 are smaller than those of the Case-1. The ratio is nearly 0.8. In this case; i.e. in the Case-2, the shear responses remain within the yielding deformation.

Maximum accelerations and displacements at the top of the model are very close with one another. The ranges of variation of maximum accelerations and displacements are from 0.96 to 1.06 and from 0.89 to 1.01, respectively.

6. Concluding Remarks

Effects of stiffness variation and restoring-force models upon an inelastic response analysis of a BWR Mark-II type nuclear power plant building have been examined from numerical and quantitative standpoints. Summarized are the following conclusive statements obtained in this study.

(1) Fundamental periods due to stiffness variations fluctuate with a variation of 0.1 to that of the Case-1 model when stiffnesses are taken to 1.5 times or 0.7 times those of the Case-1 model. When stiffnesses are varied, the maximum response of the member No.1 which is subjected to high levels of both flexural and shear stresses and deformations is increased nearly 1.52 times larger than that of the Case-1 model for the flexural response. The responses at the top of the model fall in the value within the range of 0.9 to 1.1 for the maximum acceleration, and of 0.9 to 1.2 for the maximum displacement, respectively.
(2) The restoring-force models for flexural response and those for shear response have significant variations on responses of certain members in the nuclear power plant building model. The influence is considered remarkable for flexural responses. The flexural response of the member No.1 subjected to high levels of stresses have been largely affected not only by the type of restoring-force model for flexural response but by the type for shear response. The responses of other members in both flexural and shear deformations, however, have been less significantly influenced by the types of restoring-force models.

7. Acknowledgements
This paper is intended to be a companion paper with the Reference No.7 in this set of transactions, and includes a first half part of the results conducted by the research group in "The Committee of a Response Evaluation of a BWR Type Reactor Building" organized by the Kenchiku-Kenkyu-Shinko-Kyokai, Tokyo, Japan. Authors are indebted to members of the Committee for their valuable suggestions and active discussions. Gratefully acknowledged are financial supports provided by the following private construction firms; Fujita Corporation, Hazama Gumi, Kumagai Gumi, Maeda Kensetsu Kogyo, Nishimatsu Construction, Sato Kogyo and Toda Construction Companies Ltd.

8. References
### TABLE 1 RESTORING-FORCE HYSTERETIC MODELS

<table>
<thead>
<tr>
<th>Model</th>
<th>$P_c \sim P_y$</th>
<th>$P_y \sim$</th>
</tr>
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<tbody>
<tr>
<td>M-1 (Fukada)</td>
<td>$*1$</td>
<td>$*2$</td>
</tr>
<tr>
<td>M-2 (Nomura)</td>
<td>$*3$</td>
<td>$*3$</td>
</tr>
<tr>
<td>M-3 (Muto)</td>
<td>$*4$</td>
<td>$*3$</td>
</tr>
<tr>
<td>Q-1 (O-O)</td>
<td>$*4$</td>
<td>$*3$</td>
</tr>
<tr>
<td>Q-2 (Non-sym.)</td>
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<td>$*5$</td>
</tr>
<tr>
<td>Q-3</td>
<td>Same as M-2</td>
<td></td>
</tr>
</tbody>
</table>

#### Notes

- $P$: Load
- $\delta$: Deformation
- $(P_c, D_c)$: This point corresponds to the first break on the primary curve representing stiffness reduction. In the case of a flexural restoring-force model, this break is caused by flexural cracking in the concrete element. In the case of a shear restoring-force model, it is similarly caused by shear cracking in the concrete.
- $(P_y, D_y)$: This point corresponds to the second break on the primary curve. In the case of a flexural model, this break is caused by yielding of the tensile reinforcing bars. In the case of a shear model, $P_y$ is taken to be 1.5 times of $P_c$. In this study, this break is regarded as a ‘yielding point’ in the shear restoring-force model.

- $*1$: The rule is identical to the so-called bi-linear rule.
- $*2$: The equivalent viscous damping ratio caused by the hysteretic loop is constant without regard to the maximum deformation.
- $*3$: The unloading rule has a break when the applied load changes its notation, i.e., when crossing the x-axis. The segment after applied load changing its notation is directed towards the maximum deformation in the opposite direction ever obtained.
- $*4$: The unloading stiffness beyond the cracking deformation is determined by the rule that the unloading segment is directed towards the origin point, and its extended production in the opposite direction, i.e., after crossing the x-axis.
- $*5$: The first unloading stiffness is determined directing the unloading segment from the maximum deformation point to the origin. The second stiffness, however, is determined by the segment connecting the origin and the maximum deformation in the opposite direction. The rule has a break at the origin point, and therefore makes an non-symmetric configuration.
**TABLE II** COMBINATION OF RESTORING-FORCE MODELS

<table>
<thead>
<tr>
<th></th>
<th>FLEXURE</th>
<th>SHEAR</th>
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</thead>
<tbody>
<tr>
<td>CASE 1</td>
<td>M-1</td>
<td>Q-1</td>
</tr>
<tr>
<td>CASE 2</td>
<td>M-2</td>
<td>Q-1</td>
</tr>
<tr>
<td>CASE 3</td>
<td>M-3</td>
<td>Q-1</td>
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<tr>
<td>CASE 4</td>
<td>M-1</td>
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</tr>
<tr>
<td>CASE 5</td>
<td>M-1</td>
<td>Q-3</td>
</tr>
</tbody>
</table>

![Figure 1: Lumped mass model with sway and rocking springs for a BWR Mark-II type building.](image)

(a) synthetic accelerogram  
(b) response spectrum and design spectrum

![Figure 2: Time trace and its response spectrum of a synthetic earthquake.](image)

(a) flexural response  
(b) shear response

![Figure 3: Maximum responses for the members Nos.1 and 6.](image)
Fig. 4 The normalized responses with variation of flexural and shear stiffness.

Fig. 5 Maximum flexural and shear responses normalized by those of the Case-1.