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INELASTIC RESPONSE SPECTRA FOR TYPICAL HYSTERETIC SYSTEMS CALCULATED FROM ELASTIC RESPONSE SPECTRA

Takafumi MIYAMA[1] Jun KANDA[2] and Ryoji IWASAKI[2]

[1]Technical Research Laboratory, FUJITA Corporation,
Kohoku-ku, Yokohama, Japan
[2]Department of Architecture, University of Tokyo,
Bunkyou-ku, Tokyo, Japan

SUMMARY

The relationship between the elastic response spectra and the inelastic response spectra has been extensively examined in order to propose an estimation technique of inelastic response spectra from the elastic response spectra. Two hysteretic rules are used, i.e., bilinear model whose energy absorption is large and whose stiffness remains constant, and the origin oriented model whose energy absorption is small and whose stiffness is degrading. The calculation for the inelastic response is carried out by applying artificial earthquake ground motions of which target spectra are defined as the simple elastic response spectra. The ratio of yield point to the maximum elastic response is expressed as a function of the ductility factor, the natural frequency of system, and the shape of the elastic response spectra.

INTRODUCTION

Nowadays, the inelastic behaviour of structures have been commonly taken into account in earthquake resistance design procedures. It seems to be rational for structure to allow the inelastic deformation against a very severe earthquake ground motion which is a rare event in the lifetime of a structure. The computation of the inelastic response is generally time consuming. The purpose of this study is to clarify the relationship between the elastic response spectra and the inelastic response, and to propose an estimation technique of the inelastic response spectra from the elastic response spectra.

There have been various studies about the inelastic response estimation methods. Newmark and Hall's study is well known for the elasto-plastic system (Ref.1). In their approach, the elastic response spectrum was divided into three zones, that is, the constant displacement zone, the constant velocity zone, and the constant acceleration zone on the tripertite paper. In the constant displacement zone and the constant velocity zone, the displacement constant law is applied, and in the constant acceleration zone, the energy constant law is applied. Elghadamsi and Mohraz studied also the inelastic response estimation method of elasto-plastic system (Ref.2). The response of elasto-plastic system is often extremely greater than that of the bilinear system with a small positive gradient for the second stiffness (as small as 1/32 of the initial stiffness) (Ref.3). At the same time, the bilinear system is more realistic for actual structure than the elasto-plastic system. In Riddle and Newmark's study, the bilinear system and other systems were used (Ref.4). They proposed a relationship between the de-amplification factor, r, and the ductility factor, μ, which are defined in Fig.1. Al-Sulaimani and Roesett proposed a similar relationship (Ref.5). In these studies mentioned above, recorded earthquake ground motions were used. Lai and Biggs proposed an estimation method for the inelastic response of the elasto-plastic system by using simulated earthquake ground motions fitted to target response spectra of a simple form (Ref.6). Using artificial earthquake motions seems to have more advantages to clarify the relationship between the elastic response spectra and the inelastic response spectra because a simple form can be used to specify the elastic response spectra, and many motions can be generated to fit the same target spectra.

Taking these previous studies into account, some artificial earthquake ground motions are generated in this study assuming simple elastic response spectra as the target spectra to compute the elastic and inelastic responses for both the bilinear model and the origin oriented model. The relationship between the elastic response spectra and the inelastic response spectra is clarified, then an estimation technique of inelastic response spectra from the elastic response spectra is proposed with a consistent formula.

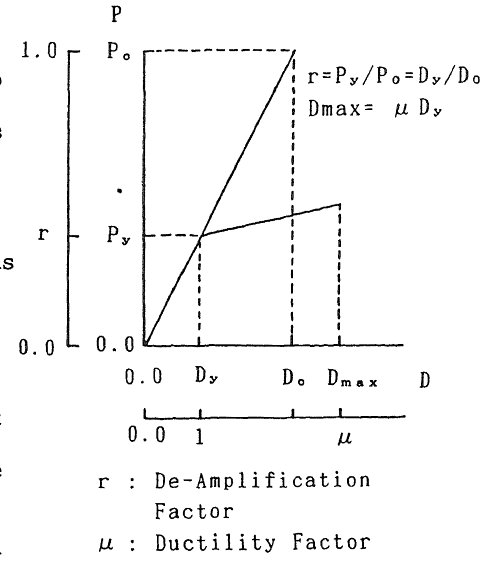


Fig.1 Definition of De-Amplification Factor

GENERATION OF ARTIFICIAL EARTHQUAKE MOTION AND RESPONSE ANALYSIS

Nine elastic response spectra, shown in Fig.2, are considered as the target spectra used in this study. They are indicated as a linear relationship on the tripertite paper, and are named A-type for constant acceleration response, V-type for constant velocity response, VA-type for constant velocity and acceleration response, DVA-type for constant displacement response combined with VA-type, and DA-type for constant displacement response combined with A-type. Artificial earthquake motions are generated by fitting to these spectra, with the Fourier series of random phases. The duration time is 20.48sec. The time history envelope has 2.0sec cosine raising phase at the beginning, and the lowest frequency is 1/10.24Hz. Ten motions with different random phases are generated to each target spectrum. An example of generated motion and its response spectrum are shown in Fig.3.

The hysteretic rules used are the bilinear model whose energy absorption is large and whose stiffness remains constant, and the origin oriented model whose

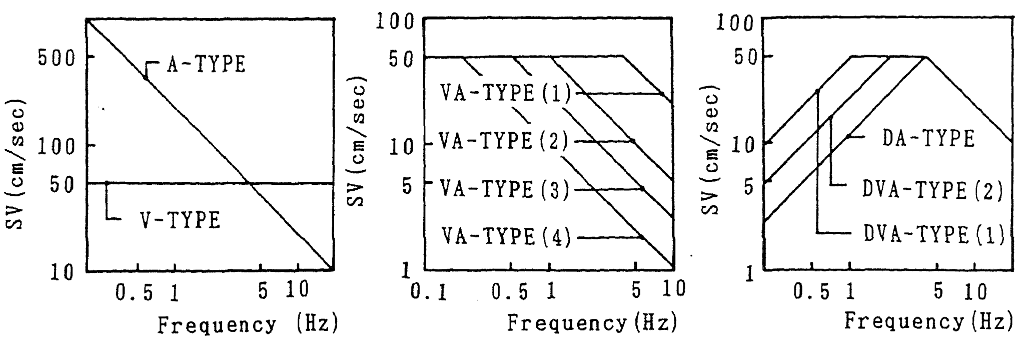


Fig.2 Target Spectra of Generated Earthquake Motion

energy absorption is small and whose stiffness is degrading. Those two models are simple and considered to be extreme cases in practical situations. The second stiffness of models is 1/8 and the damping ratio is 5% to the elastic stiffness.

The mean value of the maximum elastic responses under ten different phase motions for the same target spectra is P_0 as shown in Fig.1, then the r-value is defined as P_y/P_0. Ductility factor μ used in this paper is also the mean value of ten ductility factors computed to a specified r value with a target spectra.

RESULTS OF THE RESPONSE ANALYSIS

Figures 4 and 5 show the results of r with natural frequency, f, at the levels of ductility factors, μ=2, and μ=5, respectively for the bilinear model. Each curve represents the mean response value due to ten artificial earthquake motions fitted to each type of target spectra. The variation around each cases was found to be small. The r-value for V-type is independent with the frequency at any level of μ. The r-value for A-type increases as the frequency increases. The results of r in the constant velocity zone of VA-type and DVA-type motions coincides with those for V-type. The results of constant acceleration zone are almost the same curve as that for A-type, and the r-value decreases as the boundary

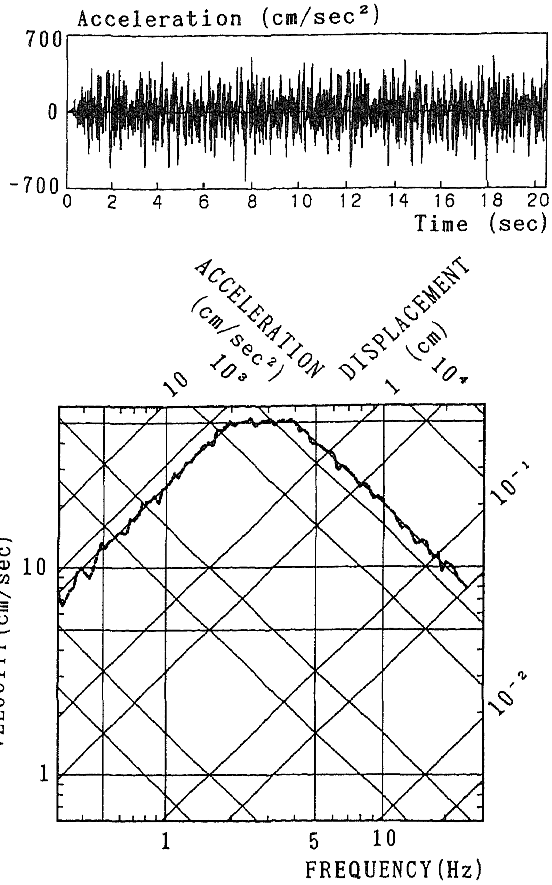


Fig.3 An Example of Generated Earthquake Motion DVA-Type(2)

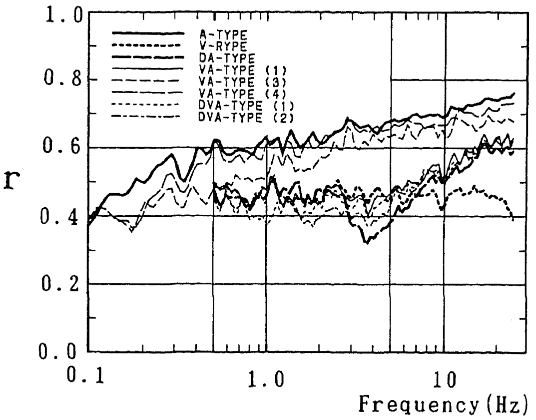


Fig.4 De-Amplification Factor (r) (BILINEAR MODEL, μ=2)

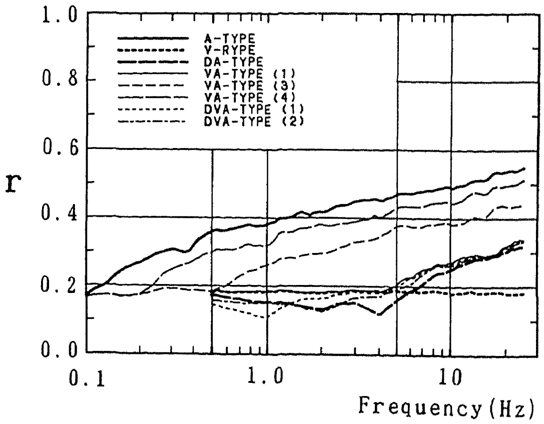


Fig.5 De-Amplification Factor (r) (BILINEAR MODEL, μ=5)

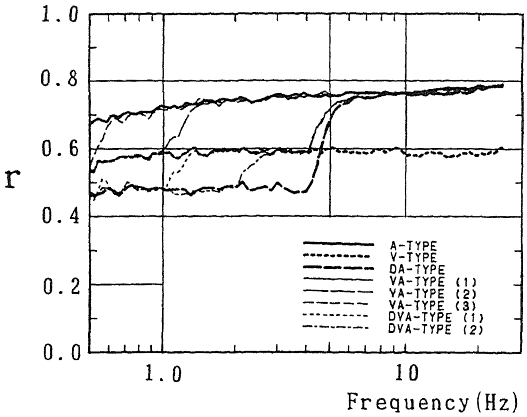


Fig.6 De-Amplification Factor (r)
(ORIGIN ORIENTED MODEL, μ =2)

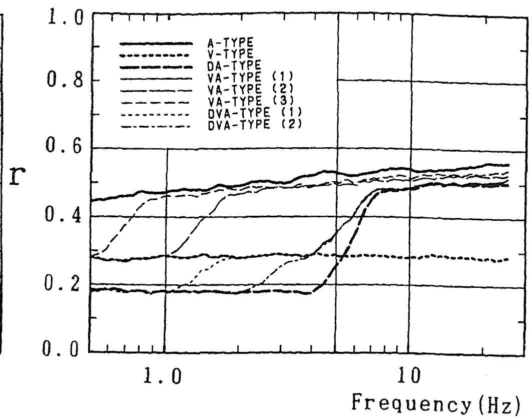


Fig.7 De-Amplification Factor (r)
(ORIGIN ORIENTED MODEL, μ =5)

frequency between the constant velocity zone and constant acceleration zone, f_3, increses. The r-value in the constant displacement zone for DVA- and DA-types is smaller than that for V-type at the boundary frequency between constant displacement zone and constant velocity zone, f_2. And as the frequency increases or decreases from f_2, the r-value approches to that for V-type.

Figures 6 and 7 show the results of r with f at two levels of ductility factor, μ=2, and μ=5, respectively for the origin oriented model. The r-value for each result has some different tendencies in comparison with that of the bilinear model. The r-value for V-type is constant with frequency in the same manner as the bilinear model, and that of the constant velocity zones for other types coincides with that for V-type. But the r-value of the constant displacement zone is also constant with frequency, but smaller than that of V-type. The r-value of A-type increases linearly as the frequency increases, and that of the constant acceleration zone of other type coincides with this line.

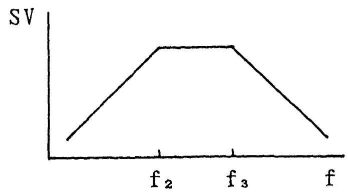
PROPOSAL OF INELASTIC RESPONSE SPECTRA ESTIMATION

When the elastic response spectra are specified in a form composed of the constant displacement zone, the constant velocity zone, and the constant acceleration zone on the tripertite paper, the estimated inelastic response spectra can be presented in Eq.1 and shown in Fig.8 illustratively.

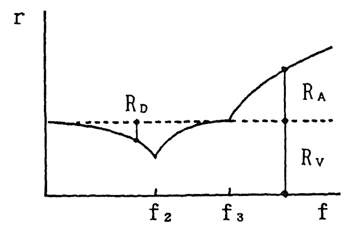
$$ {}_i r(\mu, f, f_2, f_3) = {}_iR_V(\mu) - {}_iR_D(\mu, f, f_2) + {}_iR_A(\mu, f, f_3) \qquad (1)$$

where
i = B : Bilinear model
i = O : Origin oriented model

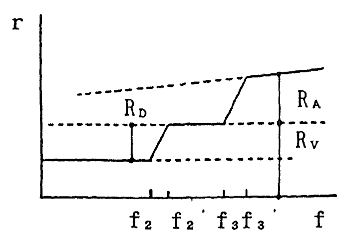
${}_iR_V$ is the function of μ. ${}_iR_D$ is the function of μ,



Target Response Spectra
of Input Motion



De-Amplification Factor (r)
(BILINEAR MODEL)



De-Amplification Factor (r)
(ORIGIN ORIENTED MODEL)

Fig.8 Proposed Estimation Method of Inelastic Response Spectra natural frequency of the system, f, and the boundary frequency between the constant displacement zone and the constnat velocity zone, f_2. And ${}_iR_A$ is the function of μ, f, and the boundary frequency between the constant velocity zone and the constant acceleration zone f_3. Eq.1 is applicable in the range of frequency f=0.3 to 25 Hz, and the ductility factor μ=1 to 5.

Estimated values for the bilinear model are shown as follows,

$$ {}_BR_V = \mu^{-1.081} \tag{2} $$

$$ {}_BR_D = (\mu^{-1.081} - \mu^{-1.361})\, e^{-5\log\frac{f}{f_2}} \qquad (f \leqq f_2) \tag{3A} $$

$$ {}_BR_D = (\mu^{-1.081} - \mu^{-1.361})\, e^{-10\log\frac{f}{f_2}} \qquad (f_2 \leqq f) \tag{3B} $$

$$ {}_BR_A = C_1 \left(\log\frac{f}{f_3}\right)^{C_2} \qquad (f_3 \leqq f) \tag{4A} $$

$$ C_1 = 0.15(\mu - 1)^{0.2} \tag{4B} $$

$$ C_2 = 0.7 \tag{4C} $$

$$ {}_BR_A = 0 \qquad (f \leqq f_3) \tag{4D} $$

Because the r-value for V-type motion is constant with μ and equal to the velocity constant zone of other type motions, ${}_BR_V$ is determined from μ and the mean r value for V-type between 0.3Hz and 25Hz by the least squares method. According to the Newmark and Hall's study, the displacement constant law is applied to the elasto-plastic system with 5% damping in the constant velocity zone and the constnat displacement zone. This means that the power index in Eq.2 is -1.0, while it is -1.081 in this study. The r-value at f_2 is expressed in Eq.5 where power index -1.361, is determined by least squares method.

$$ r = \mu^{-1.361} \tag{5} $$

The ${}_BR_D$ value shown Eq.3 is determined from Eq.2 and Eq.5 taking into account that ${}_BR_D$-value approches 0 as the natural frequency increases or decreases from f_2. The results of the constant acceleration zone are described as the same curve beginning at the point of Eq.2 at f_3. In the case for A-type motion, f_3 should be considered as 1/10.24Hz. Then ${}_BR_A$ is assumed to be expressed in Eq.4A in which c_2 is determined from the value averaged with μ for A-type result. By using the c_2 value, c_1 is determined in the form of Eq.4B from the results of acceleration constant zone.

Estimated values for the origin oriented model are shown as follows,

$$ {}_OR_V = \mu^{-0.816} \tag{6} $$

$$ {}_OR_D = \mu^{-0.816} - \mu^{-1.068} \qquad (f \leqq f_2) \tag{7A} $$

$$ {}_OR_D = (\mu^{-0.816} - \mu^{-1.068}) \frac{\log f'_2 - \log f}{\log f'_2 - \log f_2} \qquad (f_2 < f \leqq f'_2) \tag{7B} $$

$$ {}_OR_D = 0 \qquad (f \leqq f'_2) \tag{7C} $$

$$ {}_OR_A = 0 \qquad (f \leqq f_3) \tag{8A} $$

$$ {}_OR_A = (C_3 + C_4 \log f) \frac{\log f - \log f_3}{\log f'_3 - \log f_3} \qquad (f_3 < f \leqq f'_3) \tag{8B} $$

$$ {}_OR_A = C_3 + C_4 \log f \qquad (f_3 \leqq f) \tag{8C} $$

$$C_3=\mu^{-0.476} \quad (8D)$$

$$C_4=0.65 \quad (8E)$$

$$\frac{f'_i}{f_i}=0.2\mu+0.8 \qquad (i=2, 3) \quad (9)$$

The r-values in the constant velocity zone including V-type motions are constant with μ and f in the same manner as the bilinear model. Then ${}_0R_V$ is determined from μ and the r-value averaged with f between 0.3Hz and 25Hz by the least squares method. In the constant displacement zone, the r-value is constant with the frequency for any types of motions. Eq.7A is obtained from the value averaged between 0.3Hz and f_2. The r-value in the constant acceleration zone increases as the frequency increases, and it mostly coincides with the r-value for A-type motions. Then c_4 is obtained from the results of the constant acceleration zone, and c_3 is determined by the least squares method in the constant acceleration zone of every type of motions. The r-value of displacement constant zone increases as the frequency increases from the boundary frequency, f_2, to the r-value for constant velocity zone. The r-value of velocity constant zone increases from f_3 in the same manner. The width of this transient zone shown in Fig.8 is obtained from the results for all types of motions as the value of f_i'/f_i, where $f_i'$is the highest frequency of transient zone, which is a function of μ obtained by the least square method. The transient zone in Eq.7B and Eq.8B is obtained based on the assumption that the r-value linearly changes in the transient zone.

CONCLUSIONS

The relationship between the elastic response and the inelastic response have been investigated in the bilinear model and the origin oriented model. Inelastic response computations are carried out by using artificial earthquake ground motions, whose elastic response spectra are in a simple form. The relationship between the elastic response spectra and the inelastic response spectra is clarified, and the inelastic response estimation method is proposed in Eq.1 as the function of μ,f,f_2,and f_3. In this method, the effects of the boundary frequencies in the elastic response spectra are taken into account by introducing a transient zone of the inelastic response spectra.

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