The comprehensive evaluation of verification tests for seismic analysis codes. Part 4: restoring force characteristics of reactor building -Proposal of restoring force characteristics-

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ABSTRACT: Authors proposed a evaluation method of restoring force characteristics with dynamic effect due to dynamic and static test results performed on the reinforced concrete shear wall of the reactor building. Analytical study using the proposed method was performed. It was concluded that the simulation analysis result by the proposed method shows a good correspondence to the test results and analysis results by conventional method evaluates relatively larger than the results by proposed method.

1. INTRODUCTION

NUPEC (Nuclear Power Engineering Corporation) conducted "Tests on Dynamic Restoring Force" which is a part of "Seismic Behavior Tests of Reactor Building". Those tests were performed on the reinforced concrete shear wall of the reactor building. With this test, the results obtained from the dynamic lateral loading test using dynamic jacks and shaking table were compared with the results of the static tests and pseudo-dynamic tests. As the fruits of these efforts, the test results on the restoring force characteristics with dynamic effect were obtained(1,15). This report proposes a method to apply the restoring force characteristics with dynamic effect to the seismic response analysis. The results of simulation analyses showed a good agreement with the results of the shaking table test of RC shear wall.

2. EVALUATION METHOD OF SKELETON CURVE

2.1 Relationship of Proportional Increase Rate of Strain Rate and Skeleton Curve

The formula of proportional increase rate of skeleton curve regarding the relationship of the average shear strain rate and the shear stress-shear strain (to be called 'τ-γ relationship' hereafter) is shown below. Also, the concept of the skeleton curve considering strain rate is calculated from static skeleton curve(3), which is shown in Fig.1.

\[ \alpha = \left( \frac{\dot{\gamma}}{\gamma_0} \right)^{0.02} \]  

\( \alpha \): increase proportion rate of skeleton curve
\( \dot{\gamma} \): average shear strain rate
\( \gamma_0 \): average shear strain rate on static test \( (\gamma_0 = 1.0 \times 10^4) \)

Here, the average shear strain rate is deduced from the equation (2), according to the maximum
shear strain rate in the half loop.

\[ \dot{\gamma} = \frac{2}{\pi} \times \dot{\gamma}_{\text{max}} \]

Moreover, the influence of the strain rate is not considered in relationship between the bending moment and curvature (to be called 'M-\phi relationship', hereafter. Also, this can be applicable in the range in which the average shear strain rate is less than 0.1 rad/sec.

2.2 Seismic Response Analysis Method

It was established two methods to apply the test results of the relationship of the strain rate and the skeleton curve proportional increase rate to the seismic response analysis, which are called the skeleton detailed method and the skeleton simplified method.

The seismic response analysis by the skeleton detailed method is to calculate the skeleton curve, when renewing the skeleton curve within the loop, from the maximum value of shear strain rate at each half loop of each member in seismic response analysis. The concept of this method is shown in Fig.2.

The seismic response analysis by the skeleton simplified method is, as the first step, to obtain the maximum value of the shear strain rate of the total time history of each member by seismic response analysis. From this maximum shear strain rate the skeleton curve of each member to be used for the next step is calculated. By using this skeleton curve the seismic response analysis of the next step is conducted. This calculation is repeated until the proportional increase rate of the skeleton curve is converged. The flow of the seismic response analysis method by the skeleton simplified method is shown in Fig.3.

2.3 Analytical study of skeleton curve

The seismic response analyzes were conducted by using a simplified lumped mass model of a reactor building, which was modeled as a one mass system two degrees of freedom sway-rocking model. The analytical results by using the skeleton detailed method, the skeleton simplified method and a skeleton curve applying the conventional method (to be called 'conventional method' hereafter) are compared. The analysis model is shown in Fig.4. The damping factor of the building for each case is assumed to be the constant viscous damping factor determined by initial stiffness, and considered as 5% for natural frequency. The magnitudes of input seismic motions were determined, with which the maximum responses of

Fig.1 Skeleton curve with dynamic effect

Fig.2 Idea of skeleton detailed method

Fig.3

Fig.4
the system are ranging from the first turning point of shear skeleton curve to $2.0 \times 10^4$ in shear strain. The shear strain value $2.0 \times 10^4$ is the allowable shear strain limit in designing reactor building in Japan. As the result, for the motion used for the analysis, the seismic motions of maximum acceleration of 400Gal, 800Gal, 1200Gal were determined. The acceleration time history of the original seismic motion is shown in Fig.5, and the acceleration response spectrum in Fig.6.

Fig.4 Simplified model of BWR building
Fig. 5 Acceleration time history of seismic motion

Fig. 6 Response spectrum of seismic motion
The analysis results of the maximum response acceleration and the maximum shear strain, when compared by the skeleton detailed method, the skeleton simplified method and the conventional method are shown in Fig. 7 and Fig. 8. The analysis results of skeleton simplified method and conventional method show equal value. This shows that skeleton simplified method is possible to apply analysis considering strain rate effect, as the same as the skeleton detailed method.

3. EVALUATION METHOD OF HYSTERESIS CHARACTERISTICS

3.1 *Relationship of experienced maximum deformation and equivalent viscous damping factor, and slip stiffness ratio*

The relationship of , the equivalent viscous damping factor in the stable loop of the $\tau-\gamma$ relationship and the M-$\phi$ relationship , and the experienced maximum deformation , are evaluated by the polygonal lines indicated in Fig. 9 and Fig. 10. The relationship of the slip stiffness ratio in the stable loop of the $\tau-\gamma$ relationship and the experienced maximum deformation is evaluated by the polygonal lines indicated in Fig. 11. Also, the slip stiffness ratio of M-$\phi$ relationship is not taken into consideration.

3.2 Seismic response analysis method

As the conventional restoring force characteristics model that can apply the equivalent viscous damping factor and the slip stiffness ratio in the stable loop, the Inada model is useful. In this method the aforementioned equivalent viscous damping factor and the slip stiffness ratio shall be applied to the Inada model. This hysteresis model has a rule that the hysteresis changes as
shown in Fig. 12, with the structural damping factor and the slip stiffness ratio as the parameter. It is proposed two methods with this hysteresis characteristics, one is a method using damping factor set as an variable value due to variable stiffness (to be called 'hysteresis detailed method'), the other is a method using damping factor set as an constant value due to initial stiffness (to be called 'hysteresis simplified method'). Moreover, regarding the influence that strain rate has on hysteresis characteristics, it was determined not to take into consideration because a definite trend was not observed in the test results.

3.3 Analytical study of hysteresis characteristics

By using a 1 mass system 2 degrees of freedom sway rocking model of a simplified upper reactor building the seismic response analysis is conducted, and the analysis results were compared by using the hysteresis detailed method, the hysteresis simplified method and the hysteresis characteristics using the conventional method (to be called 'conventional method' hereafter). The analysis conditions were same as in the previous section. With the conventional method, damping factor was set as constant value due to initial stiffness. The damping factor of the upper structure was determined as 2% for the natural vibration frequency. The analysis is conducted to clearly evaluate the influence of the hysteresis characteristics, thus the damping factor was set at slightly smaller value. Also, in order to make equal the level of the analysis results indicated in previous section on the maximum response strain, the magnitude of input seismic motions were determined as maximum accelerations of 400Gal, 600Gal and 800Gal.
The analysis results of the maximum response acceleration and the maximum shear strain are compared by the hysteresis detailed method, the hysteresis simplified method and the conventional method, which are shown in Fig.13 and Fig.14. The analysis results of the hysteresis detailed method and the conventional method show equal value. This indicates that the analysis results by the conventional method show the same value as the analysis result that considered the hysteresis in detail by the hysteresis detailed method.

4. PROPOSAL OF EVALUATION METHOD OF RESTORING FORCE CHARACTERISTICS

With the basis on the test results regarding dynamic effect of the restoring force characteristics, the analysis studies were conducted up to the preceding sections. From these results, as the restoring force characteristics that consider the dynamic effect of the reacor building the authors proposed herein the evaluation method (to be called 'proposed method' here after) as follows.

\[ \tau - \gamma \text{ relationship} \]
- skeleton curve  skeleton simplified method
- hysteresis loop  conventional method

\[ M - \phi \text{ relationship} \]
- skeleton curve  conventional method
- hysteresis loop  conventional method

5. SIMULATION ANALYSIS

A simulation analysis of an excitation test of a reinforced concrete shear wall\(^4\) was conducted by the Proposal method. The object test specimen of the simulation analysis is shown in Fig.15. For the analysis, in order to simulate well the curvature distribution, the modeling was done to 10 mass model. The base slab of the test specimen was considered as fixed. The analysis model is shown in Fig.16. The damping is internal viscous damping type, and the damping factor was determined 2% for the primary natural frequency of the specimen. The tests were conducted in total of 6 steps of RUN 1, 2, 2’, 3, 4 and 5, and the input level was increased in consecutive order. For this reason, even with the analysis it is necessary to consider the
The analysis results of the maximum response acceleration and the maximum response displacement are compared with the test results for each RUN, and shown in Fig.19 and Fig.20. When the maximum response accelerations are observed, the results of RUN 1- RUN 3 show a good correspondence to the test results. However, with RUN 4, which development of non-linear is significant, the analysis result by the conventional method show somewhat larger response value when compared with the analysis result by the proposal method. Also, the decrease of stiffness of the specimen from past excitations. Therefore, under the analysis it was conducted as a single seismic motion by connecting the 6 input motions, and after dividing the obtained response motion form into 6, the evaluation of the results were done. Of the input motions used for analysis, the acceleration time history of RUN 1 is shown in Fig.17., and the acceleration response spectrum is shown in Fig.18. Also, the input seismic motions used for the analysis were measured at the top of the base slab of the specimen during the test.
when the results of the maximum response displacement is viewed, it can be seen that, quit the same as the response acceleration, about RUN 4 where the non-linear development is significant, the conventional method indicates somewhat larger response value. Although the Proposal Method evaluates the maximum response displacement somewhat small at RUN 5, overall, it is found that the test results can be simulated very well when compared with the conventional method.

6. CONCLUSION

The conclusion of this report is as follows:

(1) As the restoring force characteristics of reactor building that takes the dynamic effect into consideration, a proposal was made wherein the skeleton curve is postulated as the skeleton simplified method that considered the influence of the strain rate, and the hysteresis characteristics as the conventional method.

(2) Regarding the analysis results by conventional method, it was found that, analysis results well agree with test results when the strain level is small, while there are some cases when excessively large deformation is indicated if the strain level is large.

(3) The simulation analysis results by Proposal method correspond approximately with the test results.

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