Effect of Stiffness Eccentricity on Seismic Response of Simple Irregular Structures

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1. Introduction

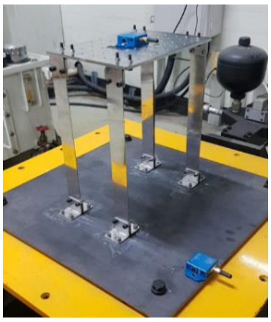
Recently, some researches have shown that the contribution of the rotational seismic response is a little higher than expected in case of strong motion beyond design basis earthquake (BDBE) for some typical structures with irregular shapes and dynamic characteristics. The design requirement considering inherent and accidental torsional moment resulting from mass or stiffness eccentricity in applicable codes like ASCE 7-10, ASCE 4-16, FEMA460, and etc. has been well defined and accepted enough conservative for the seismic design of most structures. However, there are a couple of special cases that the requirement may not be sufficient in predicting rotational effect on structural seismic response in strong earthquakes. For example, they propose the rotational component of ground motion can significantly affect the rocking response of fixed-based high rise structures, the torsional response of irregular structures or fluid tanks, the rocking and torsional response of base-isolated structures, and etc. [1,2]

In this study, one of the technical investigations has been attempted while seismic base-isolation technology is studied to improve seismic performance of nuclear power plant against BDBE. That is an analysis of a simple structure with eccentric stiffness to get some basic idea of dynamic trend of irregular structures and contribution of rotational mode to translational response. For the purpose, a simple test structure and simulated analytical model are prepared with some varied combination of support columns. And mode shapes and seismic responses of the analysis model are reviewed and compared between regular and irregular structures after adjusting the fundamental frequency of the model similar to that of the test. The results are to be referenced to check the seismic torsional and rocking response characteristics of base-isolated structures.

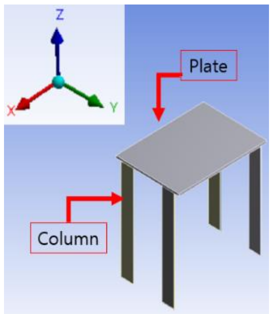
2. Schematics of structural model

2.1. Model description

The structure used for the test of regular stiffness is a single floor structure supported by 4 steel columns fixed on 1D shaking table as shown in Fig. 1. Through sign sweep test, the basic mode frequencies are searched, and simplified analytical model is set up to have similar fundamental frequency. To investigate the characteristics of mode shape and seismic response between regular and irregular structures, the number of supports is arranged to differently have 1 or 2 at each of the 4 corners to simulate concentric or eccentric stiffness of the structures.



(a) Test model



(b) Analysis model

Fig. 1. Shape of regular structures.

Table I: Material properties of test model

	Top Plate	Column
Size (mm)	180×250×5.8	34×270×1.1
Density (kg/m^3)	7467	7728
E (Pa)	2e11	2e11
Poisson's ratio	0.31	0.31

To distinguish the analysis models with different number of support columns, models are named as four-digit figures by the exact number of columns located at each corner counterclockwise. For example, the regular model using one support equally at all 4 corners is called as 1111, and the model using two supports equally at 4 corners is 2222. Otherwise, 2111 is the irregular model with double supports at 1 corner and single support at 3 corners. And 1222 is the irregular model with single support at 1 corner and double supports at 3 corners. In addition, for comparison of structural regularity and irregularity effects on the seismic responses, the regular models having equivalent shear stiffness to 2111 and 1222 are designed, by adjusting the bracket thickness equally at 4 corners, and named as 2111EQ and 1222EQ, respectively.

The basic test model consists of top plate weighing about 2 kg supported by 4 thin stainless-steel columns, and the analysis model and coordinate system is as shown in Fig.1a, and Fig.1b, respectively. As boundary conditions, 4 support columns are fixed to the shaking table and top plate using two reinforced L-shaped brackets at the bottom and top. And the contact condition between column surfaces at double support is assumed to be 'no separation' because they are located side by side and only bolted at the top and the bottom. To set up a

FEM model and to perform seismic analysis simulating the test, version 18.2 of ANSYS program is used.

2.2. Theoretical approach

Considering the actual condition of column fixed at the bottom as discussed in previous chapter, it is assumed to be a cantilever beam. From the equation of beam deflection in the case, the equivalent horizontal stiffness of the support columns can be obtained as k in equation (1). For the two support columns, the contact condition is 'no separation' because they are bolted to each other only at both ends, not welded. So, the area moment of inertia I is just twice of single column. Therefore, the stiffness of double columns equals to $2k$.

In the EQ models to make concentric stiffness, the column thickness was adjusted to have the same equivalent horizontal stiffness as 2111 or 1222. The basis of modeling for this case, for example, can be expressed in equation (1) to (3) as below.

$$k = \frac{12EI}{{l_e}^3} \tag{1}$$

$$k_{EQ} = (No\ of\ support) \times k = 5k \tag{2}$$

$$t_{eq} = \sqrt[3]{\frac{k_{EQ}{l_e}^3}{4bE}} \tag{3}$$

where k, E, I, l_e are stiffness, Young's modulus, area moment of inertia and effective length of support column. k_{eq}, t_{eq}, b are equivalent stiffness, equivalent thickness, and width of the column of EQ model.

And equation of motion for single degree of freedom system set up for theoretical approach is in equation (4).

$$m\ddot{x} + c\dot{x} + k_e x = m\ddot{x_E}(t) \tag{4}$$

where $m, c, k, \ddot{x_E}$ are mass, damping coefficient, stiffness, and seismic acceleration input of the system, respectively.

2.3. Analysis model simulating the 1st mode of the test

Sine sweep test for the model on the single dimensional shaking table is done to obtain the fundamental frequencies of the regular stiffness model like 1111 under the assumption that the interaction with vertical direction is negligible. And 3D analysis model simulating fundamental mode of the test structure is set up for seismic response analysis of irregular structures. However, the frequencies of analysis models slightly differ from the test because of simplification in modeling and boundary conditions, those are, shorten length of the support column in analysis for easy theoretical calculation, and ignorance of test sensor weight, and etc. In the test, only x-directional response is checked as 1D shaking table is available. Table II compares the results from theory, analysis and test.

Table II: Comparison of fundamental frequencies (Hz)

	Theory(Hz)	Analysis	Test
1111	4.8	4.7	4.3
2222	6.7	6.5	6.3

3. Dynamic characteristics of irregular model

Table III shows modal analysis results of the models with regular and irregular stiffness. The 2nd, 3rd and 4th modes are excluded from the table because those are local modes for the support columns. The global mode of the regular model appears in the 1st, 6th, and 7th modes corresponding to translation in (x) and (y) axes, and rotation in γ_z direction. In an irregular model 1222, however, translational mode in y axis appears in 6th mode slightly mixed with rotation, and rotational mode similarly occurred in the 7th modes, respectively. In another irregular model 0222, translation in y axis and rotational modes appear to be upgraded to the 5th and 6th modes, which estimate an increase of rotational mode contribution to the dynamic behavior of the system. The ratio of rotation means the relative contribution of the rotational mode to translational response of the 1st mode.

Table III: Comparison of mode shape

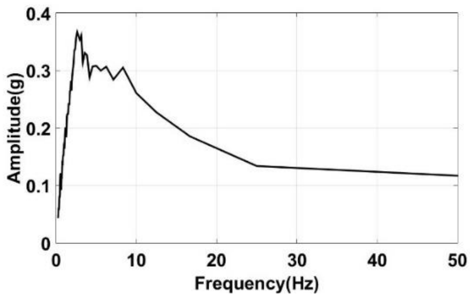
model \ mode	1st(Hz)	…	5th(Hz)	6th(Hz)	7 th(Hz)	Torsion ratio
2222 (regular)	6.5	…	81.9	135	180	1.0
1222 (irregular)	6.1	…	81.7	116	169	1.6
0222 (irregular)	5.7	…	89.3	164	178	2.3

If the contribution of rotational mode in γ_z direction in regular model is unit, it increases 1.6 times in the irregular model and 2.3 times in more irregular condition.

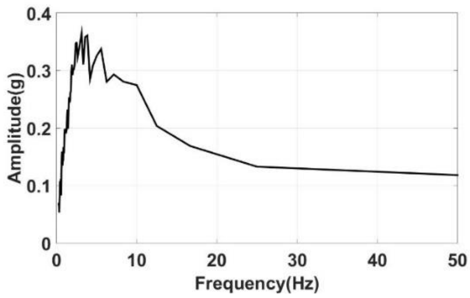
4. Response characteristics of irregular model

4.1. Seismic input

Seismic analyses are performed for the same models used for mode shape investigation in previous chapter. As inputs for the spectrum analyses, some DBEs' in horizontal direction at level of 100 ft. are applied for the Korean standard nuclear power plant, YGN 3 & 4 Units. Fig 2 depicts acceleration spectra of the seismic inputs by the name of 100EW and 100NS.[4] They are adjusted to a half scale by the operation limit of shaking table.



(a) 100EWS



(b) 100NSS

Fig 2. Spectra of horizontal seismic inputs.

4.2. Seismic response of irregular structures

Table IV shows the response spectrum analysis results of each model, and the response to the 100EWS (x-direction) and 100NSS (y-direction) input earthquakes is summed with SRSS to obtain the horizontal response. As in the shaking table test, the maximum displacement difference in the irregular model was not large, but the maximum acceleration was significantly increased in the irregular model compared to the EQ model. This is 36% for 2111 and 56% for 1222. In addition, in case of 0222, though the maximum displacement is similar to that of other irregular models, the maximum acceleration is larger than 1222 case. Result from both the shaking table test and the response spectrum analysis showed that the acceleration response increase of the irregular model is not negligible. Therefore, additional consideration may be required in case of irregular structure design with stiffness eccentricity.

Table IV: Comparison of analysis result

Models	Max. displacement [mm]	Max. acceleration [m/s^2]
2111 (irregular)	2.84E00	**7.84E00**
2111EQ (regular)	2.77E00	5.74E00
1222 (irregular)	2.08E00	**9.69E00**
1222EQ (regular)	1.98E00	6.20E00
0222 (irregular)	2.40E00	**1.06E01**

5. Conclusions

From the mode and seismic spectrum analysis of regular and irregular structural model with eccentric stiffness, the dynamic characteristics are reviewed and compared. Followings can be concluded.

1) As the irregularity increases from regular model, the torsional mode appears to become lower among the governing modes and the contribution to the translational response by rotational mode gets higher .

2) The maximum horizontal acceleration response can significantly increase by the effect of rotational behavior in irregular models. Therefore, when designing a structure with a stiffness eccentricity, the effect of rotational behavior should thoroughly be checked according to the characteristics of design earthquake for conservatism.

3) In case of local buckling of a support, the acceleration response may rapidly increase by the change of dynamic characteristics close to structural failure by the irregularity.

Therefore, next step analysis would be about the rotational response characteristics of base-isolated structures under more severe inputs like BDBE, and the quantitative review of contribution of the rotational component of seismic input to the structural response.

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