ON THE ASEISMIC SAFETY OF SPACE STRUCTURES UNDER BI-DIRECTIONAL GROUND MOTION

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SUMMARY

Space frame structures subjected to bi-directional horizontal ground motion were experimentally and analytically studied and compared with uni-directional motion responses. Experimental results indicate that the restoring force characteristics of the steel structure under bi-directional motion is completely different from the results under uni-directional motion because of the interaction effect of bi-axial shear forces. The response analysis of space structures uses the hysteresis rule of Ramberg-Osgood, in which the relationship between the equivalent force and the corresponding deformation is defined by the yield condition and plastic work. The interaction effects depend mainly on the frequency and strength ratios of the structure to the ground motion input.

INTRODUCTION

The ultimate aseismic safety of space structures must be discussed under the multi-axial force state subjected to multi-directional ground motion. Since Dr. Nigam introduced the interaction effect of bi-axial shear force on the responce analysis [1], some investigations on the analysis of space structures were performed in different approaches [2-5]. There are, however, few papers on the dynamic test of space structures [6-7] and on the general character of space structure responses [4].

There are three objectives in this paper. Dynamic failure process of the space structures subjected to bi-directional horizontal ground motion by using a shaking table was presented and this result was compared with the behavior of the same model under uni-directional ground motion. Restoring force characteristics under bi-directional motion is complicated and quite different from the hysteresis under uni-directional motion because of interaction effect. Those experimental results were compared with the analytical responses obtained by introducing Ramberg-Osgood hysteresis on the equivalent force and corresponding deformation of an arbitrary cross section [8], which satisfactorily duplicates the dynamic behavior of space frame structures. The influence of bi-directional ground motion on the aseismic safety of the space structures was finally summerized from the results of the parametric analysis.

DYNAMIC TEST PROCEDURE

Model structures considered here are single-story, single-bay space frame structures composed of a roof plate and rigidly connected columns. Columns of the model are 8 cm with length and 10x6 mm^2 with rectangular cross section. The yield strength of the steel is 2.73 kgf/cm^2 and the weight of a roof

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plate is 540 kgf.

Dynamic tests were performed by using an electro-magnetic type shaking table of our institute, which can be independently controled to move in cross way. Figure 1 shows the overview of the test set-up, in which X-direction of a table motion is corresponding to the weak axis of the column. In Table 1, the elastic limit displacement Δy, elastic limit shear force Qy, the ratio of real axial force to the elastic limit axial force of the column N/Ny and shear force coefficient are represented with measured and calculated frequency and the fraction of the critical damping obtained from the forced vibration test. Horizontal displacements were measured by the differential transformers attatched to pin-ended light bar for elimination of the effect of the perpendicular displacement. Horizontal accelerations of the shaking table and the roof of the model structure were measured by strain gauge type accelerometers. Shear force were calculated from the elastic strains measured at the middle portions of the columns.

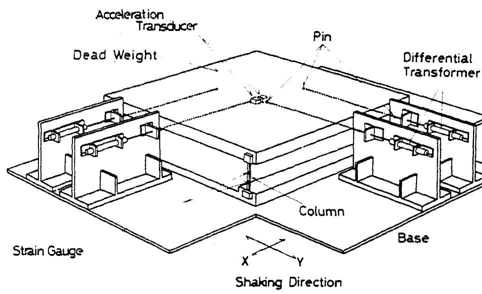


Fig. 1. View of shaking table test.

Table 1. Fundamental properties of model structure.

DIRECTION	Δy(mm)	Qy(ton)	N/Ny	BASE SHEAR	FREQUENCY(Hz) TEST	FREQUENCY(Hz) ANALYSIS	DAMPING(%)
X	0.422	0.151	0.081	0.280	10.0	12.8	0.5
Y	0.255	0.252		0.467	16.6	21.3	0.6

Two types of shaking table tests of space structures are considered here. Test A-XY is subjected to two components of El Centro earthquake wave forms, where NS component is used to X-direction and EW component to Y-direction as shown in Fig. 1. Test B-XY is subjected to oblique motion of NS component of the same wave form. Those results are compared with the results due to unidirectional ground motion. In spite of interesting results of the latter test [7], the former results are only presented here. Each maximum amplitude of input acceleration is set to be proportional to the corresponding shear strength of the model structure. The frequency characteristics of the input motion are modified by 1/2 time scale of original wave form considering the frequency of the model structures.

METHOD OF RESPONSE ANALYSIS

Test results indicate the characteristic features on the hysteresis of the structure, that is, the restoring force characteristics under unidirectional ground motion can be represented by curvilinear hysteresis, while the interaction effect among generalized forces must be considered when subjected to bi-directional ground motion.

A method of response analysis of space structures presented here was already formulated in the previous paper [8], where Ramberg-Osgood type hysteresis was introduced into the equivalent force and corresponding deformation by considering the yield condition of multi-axial force field and orthogonality criteria of deformation in an arbitrary cross section. Brief explanation of this method is as follows.

The equivalent force $\bar{f}$ and the rate of corresponding plastic deformation $\dot{\varepsilon}^p$ are defined through the rate of the plastic work $\dot{w}^p$ by coincidence with the sum of plastic work rate of individual force.

$$\bar{f}(w^p) = \{\Sigma(f_i^{\,2})\}^{1/2} \qquad i = X,Y,N,T \tag{1}$$

$$\dot{w}^p = \bar{f}\,\dot{\varepsilon}^p = \Sigma f_i\,\dot{v}_i^p \tag{2}$$

where f_i and v_i show the nondimensional generalized force and the corresponding deformation of the i-th direction such as nondimensional bending moment and curvature of X- or Y- axis. Ramberg-Osgood type hysteresis is introduced in the relation between $\bar{f}$ and ε^p as in the case of the skeleton curve,

$$\varepsilon^p = \frac{c}{1+c}\bar{f}^{2r+1} \tag{3}$$

and in the case of branch curve,

$$\frac{\varepsilon^p-\varepsilon^p_0}{2} = \frac{c}{1+c}\left(\frac{\bar{f}-\bar{f}_0}{2}\right)^{2r+1} \tag{4}$$

where parameters c and r can be determined from a result of a uni-axial repeated loading test. When the both ends of columns are fixed, increments of slopes or axial elongation of the column member can be obtained by integrating curvature or axial strain of an arbitrary cross section through the column length.

$$\dot{\psi}_x = \frac{1}{1+c}\int_0^1\{\dot{m}_{x\xi}+c(2r+1)\bar{f}_\xi^{\,2r-2}(\tilde{m}_{x\xi}^{\,2}\dot{m}_{x\xi}+\tilde{m}_{x\xi}\tilde{m}_{y\xi}\dot{m}_{y\xi}+\tilde{m}_{x\xi}\tilde{n}_\xi\dot{n}_\xi)\}\xi d\xi \tag{5}$$

$$\dot{\psi}_y = \frac{1}{1+c}\int_0^1\{\dot{m}_{y\xi}+c(2r+1)\bar{f}_\xi^{\,2r-2}(\tilde{m}_{y\xi}^{\,2}\dot{m}_{y\xi}+\tilde{m}_{y\xi}\tilde{m}_{x\xi}\dot{m}_{x\xi}+\tilde{m}_{y\xi}\tilde{n}_\xi\dot{n}_\xi)\}\xi d\xi \tag{6}$$

$$\dot{\delta} = \frac{1}{1+c}\int_0^1\{\dot{n}_\xi+c(2r+1)\bar{f}_\xi^{\,2r-2}(\tilde{n}_\xi^{\,2}\dot{n}_\xi+\tilde{n}_\xi\tilde{m}_{x\xi}\dot{m}_{x\xi}+\tilde{n}_\xi\tilde{m}_{y\xi}\dot{m}_{y\xi})\}\xi d\xi \tag{7}$$

where, $\tilde{m}_j$ and $\tilde{n}_j$ mean m_j and n on the skeleton curve and $(m_j-m_{j0})/2$ and $(n-n_0)/2$ on the branch curve of the hysteresis of j-th direction. The values attatched suffix 0 indicate the coordinates of the starting point of the branch curve.

Incremental slope deflection is finally obtained as follows, by supposing asymmetric distribution of bending moment and constant axial force.

$$\dot{\psi}_x = a_{11}\dot{m}_x+a_{12}\dot{m}_y+a_{13}\dot{n} \tag{8}$$

$$\dot{\psi}_y = a_{21}\dot{m}_x+a_{22}\dot{m}_y+a_{23}\dot{n} \tag{9}$$

$$\dot{\delta} = a_{31}\dot{m}_x+a_{32}\dot{m}_y+a_{33}\dot{n} \tag{10}$$

Equations of motion of the space structure are represented by the equilibrium equations of two directional horizontal force and torsional moment, the restoring force characteristics of which can be formulated by using inverse relation of equations (8)-(10).

COMPARISON OF EXPERIMENTAL AND ANALYTICAL RESULTS

In the following three figures and Table 2, the results of the shaking table tests are compared with the results of the dynamic response analysis. Natural frequency of the experimental model is rather lower than the calculated frequency because of the unexpected flexible connection of the columns. Hence, Young modulus used in the analysis is adjusted to the same value as the test results in the following analysis. Parameters presenting the hysteresis rule are selected as c=0.12 and r=3 to fit the hysteresis obtained by the uni-directional test as shown in Fig. 2. In the following figures, experimental shear forces are approximately replaced by inertial forces. Left half of this figure shows experimental hysteresis of each direction and right half is analytical result under uni-directional motion. Restoring force characteristics are stable and look like masing type hysteresis, as usually pointed out on the hysteresis of steel structures. The wave form of the input motion used in the dynamic analysis was obtained from A-D transformation of the measured table acceleration.

Typical time history responses of model A-XY are shown in Fig. 3. The plastic deformations of X and Y components simultaniously occur due to the interaction effect of bi-axial shear force. The analytical responses can satisfactorily trace the experimental results throughout the duration time of the input motion. Figure 4 represents the restoring force of model A-XY, which are quite different from the hysteresis of plane frame as shown in Fig. 2.

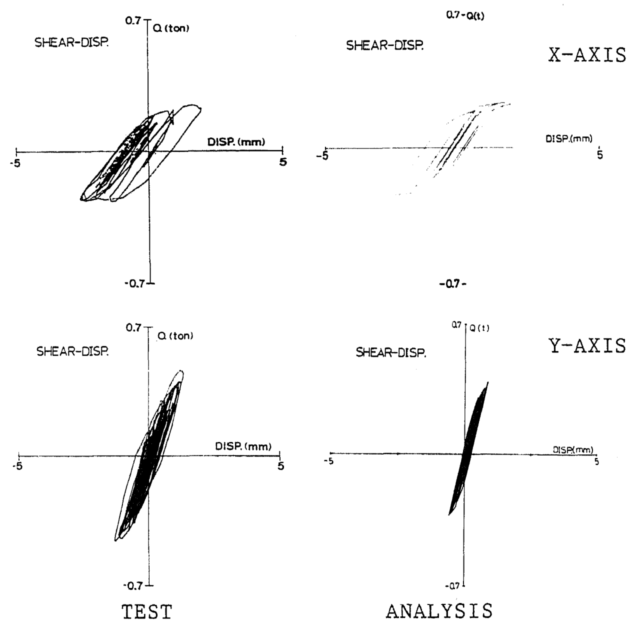


Fig. 2. Restoring force characteristics of the plane frames, A-X and A-Y.

Table 2. Maximum responses of model structures.

	MODEL	DIR.	INPUT ACC. (g)	ROOF ACC. (g)	INERTIA (ton)	DISP. (mm)	DUCTILITY
TEST	A-X	X	0.43	0.47	0.26	2.74	6.51
	A-Y	Y	0.71	0.86	0.48	1.47	5.79
	A-XY	X	0.41	0.51	0.29	11.98	28.38
		Y	0.99	1.00	0.56	10.03	39.33
ANALYSIS	A-X	X	0.43	0.51	0.28	2.57	6.09
	A-Y	Y	0.71	0.82	0.44	1.57	6.18
	A-XY	X	0.41	0.56	0.31	7.67	18.18
		Y	0.99	1.08	0.58	11.93	46.78

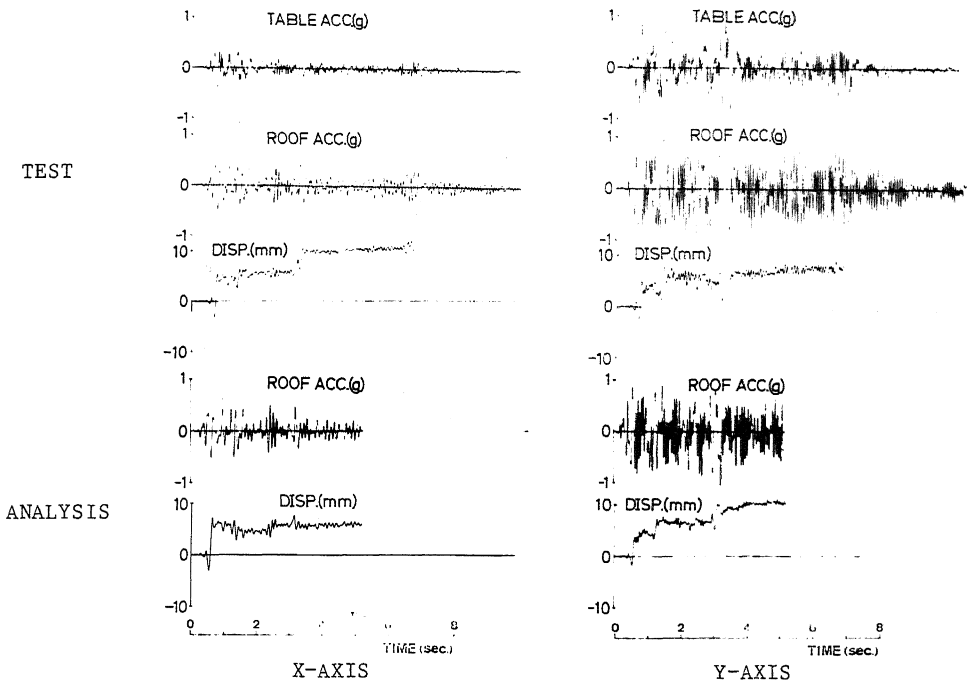


Fig. 3. Time history of model A-XY under bi-directional motion.

Hysteresis of X-axis (weak axis of column) is very complicated and looks like digrading type, while that of Y-axis (strong axis of column) is similar to masing type hysteresis. In Fig. 5, orbits of the roof displacements and shear forces of the model are shown. Shear force orbit shows the yield surface of the model. As shown in these figures, the analytical results considering the curvilinear hysteresis on the equivalent force and corresponding deformation are quite similar to the experimental results. Calculated relation between equivalent force and plastic deformation is shown in Fig. 6.

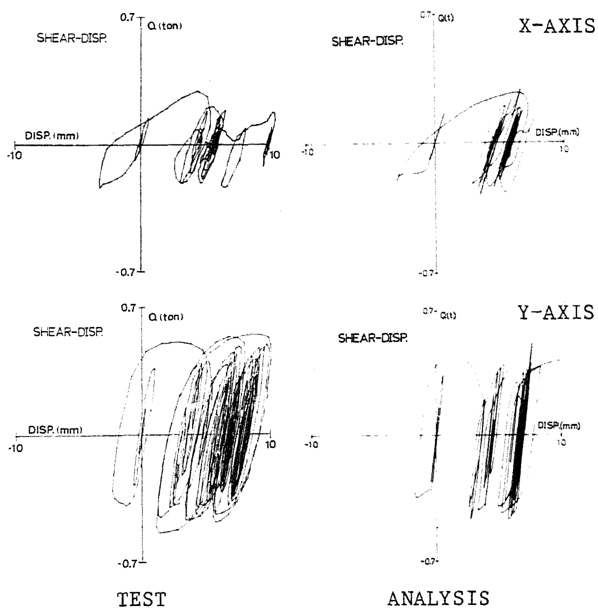
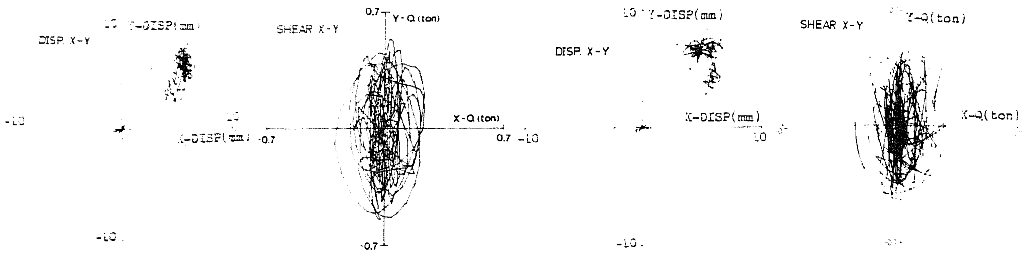


Fig. 4. Restoring force characteristics of space structure, A-XY.

The displacement of the weak axis of the column tend to increase by the interaction effect and the frequency



TEST ANALYSIS

Fig. 5. Orbits of displacements and shear forces of model A-XY.

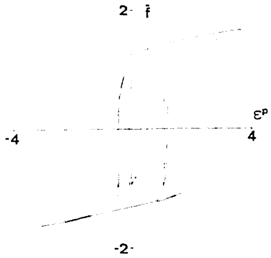


Fig. 6. Equivalent force vs. plastic deformation of model A-XY.

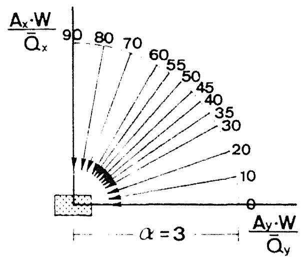


Fig. 7. presentation of input direction.

characteristics of input motion. Next step is, therefore, to clarify the frequency effect of the input motion on the coupling response of space structure.

FREQUENCY EFFECTS ON THE SPACE STRUCTURE RESPONSES

The effects of the direction of input ground motion on the responses of space structures are presented in the first half of this chapter. Fundamental periods for X and Y axis of the model are (0.122, 0.122 sec)in the case of Model O with square column, (0.156, 0.094 sec) in Model A with same column as so far mentioned dynamic test and (0.188, 0.078 sec) in Model B with rectangular column. Figure 7 is schematic presentation of input direction, in which both coordinates indicate the ratio of maximum input acceleration to the limit strength along X and Y axis of the model structure. Thirteen kinds of input angle and three types of input wave form are considered here. As shown in fig. 8, maximum displacement under oblique ground motion, D_2, is about 1 to 5 times larger than the response under one way motion, D_1, when one way responses are in smaller range. Difference between the responses under El Centro NS and the responses under Hachinohe NS can be explained by the non-linear response spectrum of the input motions. Fig. 9 shows the ratio of the maximum displacement vector under oblique motion to the same vector under one way motion, where the responses are seen to amplify under 30° to 60° input angle, reflecting the shape of yield surface due to two axis shear forces.

General tendency on the effects of bi-directional ground motion is represented in the latter half of this chapter. In the left side of Fig. 10, maximum displacement with (solid line) and without (broken line) interaction subjected to NS and EW components of El Centro earthquake are shown, where 6 x 6 pairs of periods of structures are considered. Maximum input acceleration of each direction was set to be proportional to the corresponding

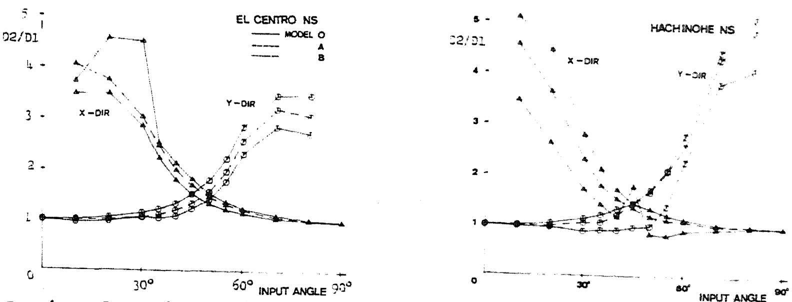


Fig. 8. Ratio of maximum displacements under oblique motion to one way motion.

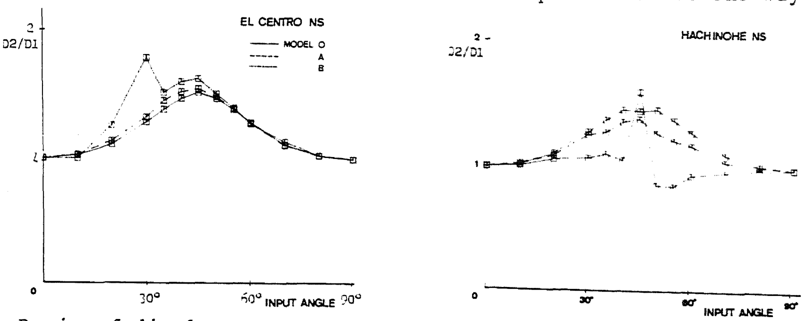


Fig. 9. Ratio of displacement vector under oblique motion to one way motion.

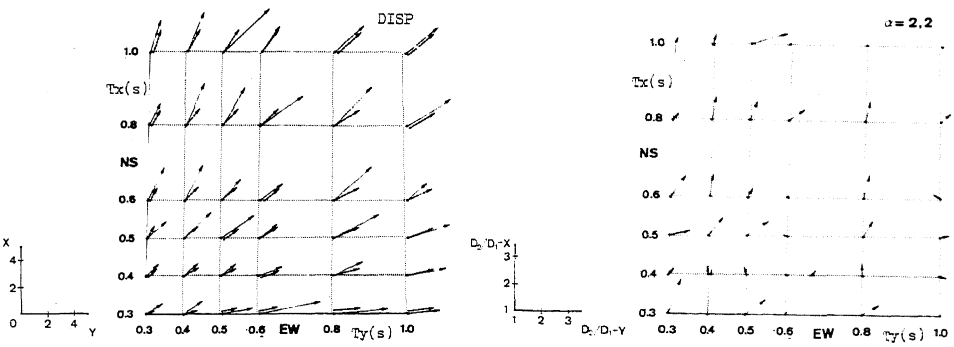


Fig. 10. Maximum displacement vector with and without interaction and ductility amplification factor due to interaction.

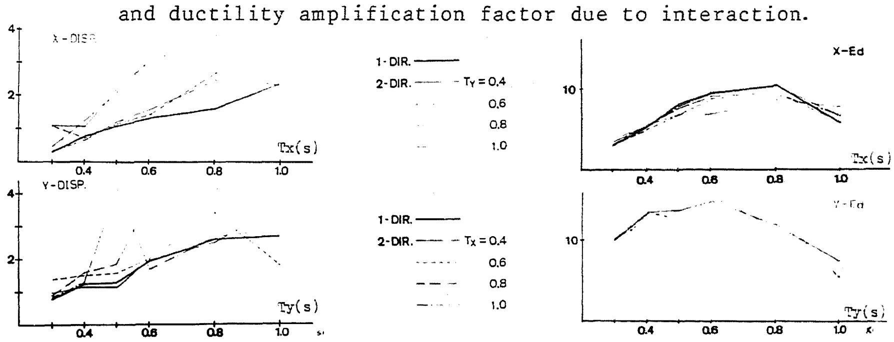


Fig. 11. Max. displacement and energy dissipation with and without interaction.

strength of the structure. Vectors composed from each directional ratio of the maximum displacement with interaction to the value without interaction are presented in the right side of Fig. 10. Interaction effect appears mainly on the response of the weak axis of the structure. In this analysis, strength of the structure is inversely proportional to each directional period. As shown in the last figure, the maximum displacement response with interaction becomes larger than the response without interaction, while final energy dissipation is mutually resemble. It means that total energy dissipation does not always represent the aseismic safety of space structures.

CONCLUSIONS

Dynamic behaviors of the single-story, single-bay space structures subjected to bi-directional ground motion were experimentally and analytically discussed in order to make clear the interaction effect of the generalized forces. The following conclusions were obtained.

1) Restoring force characteristics of a steel frame structure under uni-directional motion are stable and look like masing type hysteresis. Ramberg-Osgood function can suitably represent such a hysteresis.
2) The hysteresis under bi-directional motion is much complicated, especially in weak axis of the column. A hysteresis rule of Ramberg-Osgood type between equivalent force and corresponding deformation was introduced here. The results of the response analysis satisfactorily duplicate the dynamic behavior of space structure obtained from the shaking table tests.
3) Responses of each direction increase about 2 or 5 times when subjected to oblique ground motion. This tendency is remarkable in the case of 30° to 60° input angle. It seems to depend on the shape of yield function.
4) Displacement responses of weak axis of the structure tend to become larger when considering interaction effect, while the total energy due to bi-directional motion is almost similar to the total energy due to independent ground motion. It means that the interaction effect has the tendency to balance the two components of ductility responses as shown in Ref. [3]

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