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DEFLECTION AND SHEAR FORCE RESPONSES OF A DUCTILE REINFORCED CONCRETE STRUCTURE REFLECTING ON THE INTERFRAME COUPLING

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SUMMARY

Seismic responses of a ductile reinforced concrete structure coupled with two frames are examined: one is a strong column frame which develops a beam sidesway mechanism, and the other a weak column frame resulting in a column sidesway. Variation of the resultant mechanism and the responses of the deflection and shear force of the coupled structure is determined associated with that of both column strength and stiffness of the coupling frames. Results of the analysis yield the evidence that the strong column frame, even with less significance of its stiffness, dominates more significantly the responses of the coupled structure.

INTRODUCTION

A building structure is formed by a set of frames which are arranged in parallel and are connected with one another by a rigid floor slab, which situation indicates that the constituent frames of a structure are mechanically coupled with each other when lateral load is applied under such circumstances as subjected to seismic excitation. Such an interframe coupling appears significant in case the frames are dissimilar to one another in their mechanical properties.

The study presented herein examines significance of interframe coupling responses of both interstory deflection and story shear force of a moment-resisting ductile reinforced concrete structure subjected to an earthquake excitation. The structure is essentially composed of two frames coupled in parallel, one of which develops a beam sidesway mechanism and the other a column sidesway mechanism. We carry out an inelastic response analysis subjected to intense earthquake ground motions upon the coupled structure with the variation of mechanical properties such as strength and stiffness of the frame, which generally determine the mechanism of the frame. Through a numerical study, we evaluate interframe coupling responses, and then discuss significance of the interframe coupling in a ductile reinforced concrete structure.

A GENERAL DESCRIPTION OF ANALYTICAL PROCEDURE

Inelastic Analysis For each constituent component of a frame, i.e., for each column, beam and beam-column joint of a frame, we specify its own inelastic hysteresis rule. In this study, however, we presume the beam-column joints to remain elastic. Herein we employ the so-called degrading tri-linear hysteresis rule. The computer program developed in Ref. 1 is employed for a numerical study.

Response Analysis Two real earthquake motions are employed with an intention of verifying the variation of responses due to characteristics of excitation. One is the S00E component obtained at El Centro during the Imperial Valley earthquake of 1940, and the other the East-West component at Hachinohe during the Tokachi-oki earthquake of 1968. Within the response analysis, damping of the structure is assumed with a fraction to the critical damping 0.02 for the fundamental mode.

COUPLING FRAMES AND COUPLED STRUCTURE

Coupled Structure We specify a unit of coupling frames in parallel, which is four stories high as shown in Fig. 1, for the coupled structure employed in this analysis.

A unit of the structure essentially consists of two frames of which resultant mechanisms are dissimilar to each other. One, the A-Frame in Fig. 1, is a strong beam-weak column frame, which gains a column sidesway mechanism. The other, the B-Frame, is a weak beam-strong column frame developing a beam sidesway mechanism. Strength capacities of the constituent columns and beams of these frames are determined from those of the so-called fundamental frame.

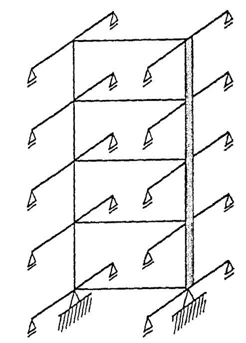

Fig. 1. The coupled structure in this analysis.

Fundamental Frame Establishing both weight of the frame and dimensions of the constituent columns and beams, we perform an elastic stress analysis upon the frame subjected to lateral load. The analysis yields the required strength of the constituent columns and beams of the frame for the lateral load with the specified distribution and prescribed base shear coefficient. With slight modification and manipulation upon the obtained strength to yield the correlation of strength among the columns and beams realistic and practical, we establish the fundamental frame (Ref. 2), of which strength of the columns is identical to that of the beams at a beam-column joint. Thus the fundamental frame is a beam-column frame of which beam and column strength capacities are identical with each other.

Coupling Frame A frame having strong columns and weak beams reveals a beam sidesway mechanism. Recent studies (Refs. 3 and 4) have indicated that a certain surplus of column strength over beam strength is essentially required to realize a beam sidesway mechanism. Through a numerical analysis, it has been indicated that provided the column strength is taken sufficiently great so as the ratio of column strength to beam strength greater than about 1.3, the beam sidesway mechanism is realized with a high certainty (Ref. 4).

Multiplying exclusively the column strength of the fundamental frame by a coefficient, we determine the column strength of the coupling A- and B-Frames. Since the beam strength, however, is left unchanged, the coefficient represents directly the surplus of column strength over beam strength. When a greater coefficient taken, the columns of the determined frame exceed the beams greater in strength, which situation yields the frame a beam sidesway mechanism. On the other hand, when the coefficient taken less than 1.3, for example 0.8, the strength of columns is 0.8 times as large as that of beams at a beam-column joint, which weak column condition yields the frame a column sidesway mechanism.

ANALYSIS IMPLEMENTATION

For the structure coupled with two frames, the A-Frame and the B-Frame, we examine the variation of the resultant mechanism and responses of the interstory deflection and story shear force associated with the variation of column strength and stiffness of the coupling frames subjected to an intense seismic excitation.

Variation of Column Strength of Coupling Frames The variation of column strength is established from the strength ratio of columns to beams with which the A- and B-Frames are determined from the fundamental frame. The key combination of the strength ratios is that of 0.8 and 2.0 for the weak column A-Frame and the strong column B-Frame, respectively. With the strength ratio 0.8 for the A-Frame kept constant, the ratios of 1.0, 1.3, 2.0, 3.0 and 4.5 are taken for the B-Frame, and with the ratio 2.0 for the B-Frame preserved, the ratios of 1.3, 1.1, 1.0, 0.8 and 0.6 are taken for the A-Frame, which various combination of strength ratios consequently yields nine cases of the coupling of frames specified.

Variation of Stiffness of Coupling Frames Since the A- and B-Frames are identical with each other in their dimensions of the constituent columns and beams of the frame, the fundamental stiffness of the A- and B-Frames falls in the value identical to each other, which evidence indicates that the number of units of the frame arranged in parallel immediately specifies the variation of stiffness of the coupling frames. In this study, with one unit of the strong column B-Frame, 50, 20, 10, 5, 2 and 1 units or unit of the weak column A-Frame are coupled, and with one unit of the A-Frame, 1, 2, and 5 units of the B-Frame are coupled.

RESULTS OF ANALYSIS AND DISCUSSION

Resultant Mechanism For the structure coupled with the A- and B-Frames of which strength ratios are taken 0.8 and 2.0, respectively, the resultant mechanism is determined as shown in Fig. 2.a and Fig. 2.b when subjected to the El Centro and Hachinohe earthquake components, respectively. Figures in the upper row represent the mechanism for the A-Frame, and those in the lower row that for the B-Frame. Figures from left to right reveal the variation of stiffness of the coupling frames. Circles *in the figures denote yield hinges generated at the end of con-*stituent columns and beams. Solid circles represent those of which curvature ductility factor is greater than 10. The letters "P" and "N" on each figure designate the direction of generated lateral loads during the seismic excitation.

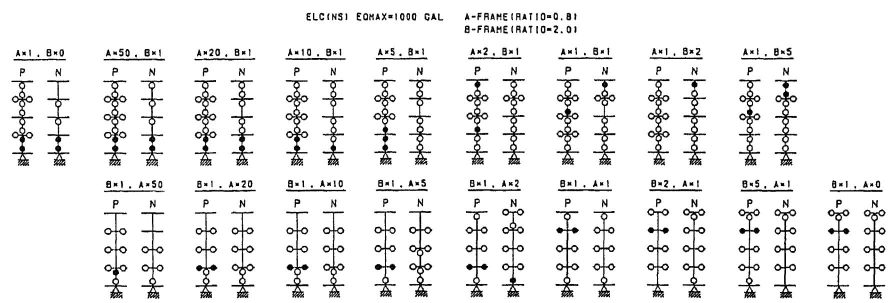

Fig. 2.a. The resulting mechanism of the coupled structure with frames of the strength ratios 0.8 and 2.0, respectively, subjected to the El Centro 1940.

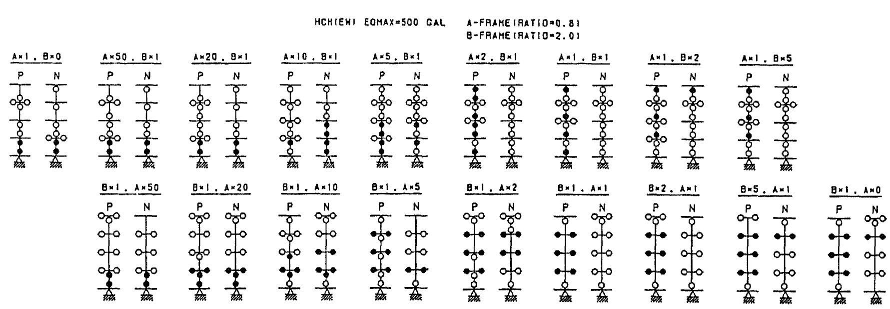

Fig. 2.b. The resulting mechanism of the coupled structure with frames of the strength ratios 0.8 and 2.0, respectively, subjected to the Hachinohe 1968.

A weak column A-Frame reveals an illustrative column sidesway mechanism at the first story, while a strong column B-Frame develops a beam sidesway mechanism. When the stiffness of the A-Frame is significant, i.e., when the number of the coupling A-Frame is large, the resultant mechanism appears a column sidesway mechanism at the first story generating yielding hinges at both top and bottom of the first story column of the B-Frame. With the stiffness of the A-Frame less significant, the curvature ductility factor responses of the sidesway column of the A-Frame decrease in value resulting in increase of ductility factor responses of other constituent columns and beams, which observation indicates that the excited oscillating energy is dissipated within the entire frame of the structure.

<u>Shear Force Response</u> Story shear force response of the coupled structure above examined is shown in Fig. 3 subjected to the El Centro component. For cases when the stiffness of the A-Frame is significant, i.e., when one unit of the B-Frame is coupled with 50 through 10 units of the A-Frame, responses of the B-Frame at the first story gain large shear forces. Fractions of the shear force within a large number of the A-Frame units are yielded to the shear force response of the B-Frame resulting in the column sidesway mechanism at the first story of the coupled structure, which examination well correlates with the coupled mechanism.

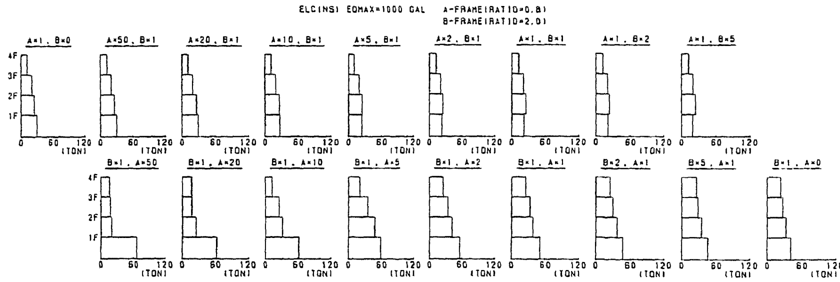

Fig. 3. Story shear force responses of the coupled structure with frames of the strength ratios 0.8 and 2.0, respectively, subjected to the El Centro 1940.

<u>Interstory Deflection Response</u> Interstory deflection responses of the coupled structure are shown in Figs. 4.a through 4.d, in which the x and y axes denote the interstory deflection angle and the story number, respectively. For the coupled cases when the stiffness of the A-Frame is significant, a remarkable lateral deflection at the first story is realized, which recognition indicates the resultant mechanism of the structure to be a column sidesway at the first story. For the cases when the stiffness of the B-Frame becomes significant, the coupled deflection appears similarly identical to that of the uncoupled B-Frame, which condition yields the evidence that while yielding hinges are generated at the both ends of the column of the A-Frame, the coupled structure reveals deflection distributed uniform along the height of the structure indicating not a column sidesway mechanism at a particular story but a beam sidesway mechanism.

To evaluate the interstory deflection responses of the coupled structure, we introduce the indices "A" and "B" defined as follows (Refs. 2 and 5):

$$A = \rho_B / \rho_o \qquad B = \rho_A / \rho_o \tag{1}$$

in which $\rho_A{}^2=\Sigma(R - R_A)^2$, $\rho_B{}^2=\Sigma(R - R_B)^2$ and $\rho_o{}^2=\Sigma(R_A - R_B)^2$ where R, R_A and R_B designate the interstory deflection of the coupled structure, the uncoupled A- and B-Frames, respectively. When the deflection of the coupled structure is identically similar to that of the uncoupled B-Frame, the index "B" equals unity while the index "A" equals zero. Figures 5.a through 5.c illustrate the deflection indices with a variety of strength ratios, and Figs. 5.a and 5.d reveal those with variation of the seismic excitation. The x and y axes denote the variation of stiffness of the coupling frames and the indices defined by Eq. (1), respectively.

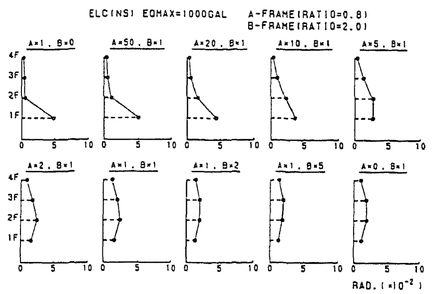

Fig. 4.a. Interstory deflection responses of the coupled structure with frames of the strength ratios 0.8 and 2.0, respectively, subjected to the El Centro 1940.

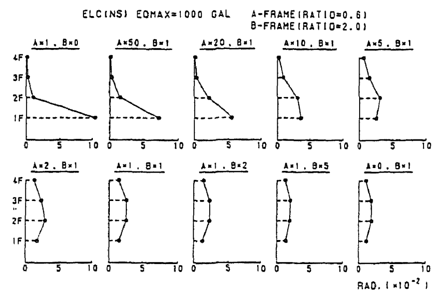

Fig. 4.b. Interstory deflection responses of the coupled structure with frames of the strength ratios 0.6 and 2.0, respectively, subjected to the El Centro 1940.

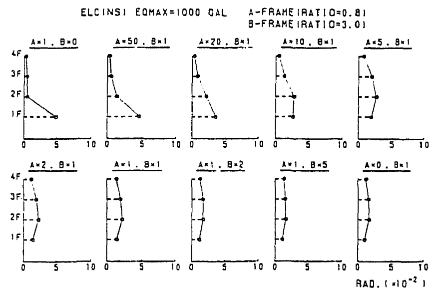

Fig. 4.c. Interstory deflection responses of the coupled structure with frames of the strength ratios 0.8 and 3.0, respectively, subjected to the El Centro 1940.

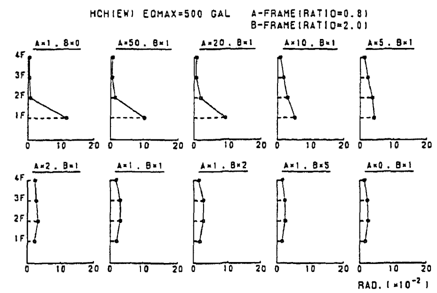

Fig. 4.d. Interstory deflection responses of the coupled structure with frames of the strength ratios 0.8 and 2.0, respectively, subjected to the Hachinohe 1968.

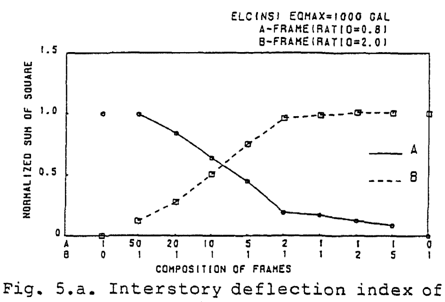

Fig. 5.a. Interstory deflection index of the coupled structure with frames of the strength ratios 0.8 and 2.0, respectively, subjected to the El Centro 1940.

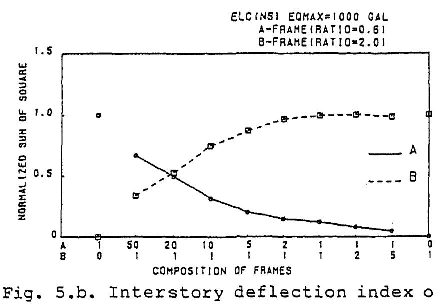

Fig. 5.b. Interstory deflection index of the coupled structure with frames of the strength ratios 0.6 and 2.0, respectively, subjected to the El Centro 1940.

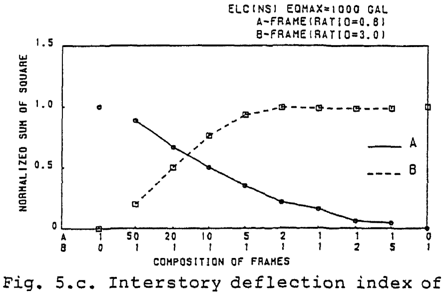

Fig. 5.c. Interstory deflection index of the coupled structure with frames of the strength ratios 0.8 and 3.0, respectively, subjected to the El Centro 1940.

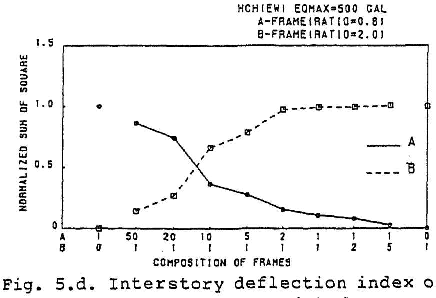

Fig. 5.d. Interstory deflection index of the coupled structure with frames of the strength ratios 0.8 and 2.0, respectively, subjected to the Hachinohe 1968.

When the stiffness of the strong column frame taken moderate, i.e., when a moderate number of strong column frames coupled, the deflection of the coupled structure appears almost similar to that of the uncoupled B-Frame yielding the index "B" equal to unity. With a greater stiffness of the strong column frame beyond a specific combination, the variation of the obtained deflection reveals small fluctuation. Comparing the results in Fig. 5.a with those in Fig. 5.d, we realize the variation of responses due to seismic excitation, variation which is recognized slight. Comparing Fig. 5.a with Fig. 5.b or Fig. 5.c, we examine the evidence that the smaller is the strength ratio of columns to beams for the weak column frame or the greater for the strong column frame, the more significant is the strong column frame for the coupled responses with less significant stiffness.

CONCLUSIONS

We determine the interframe coupled responses of a ductile moment-resisting reinforced concrete structure which is essentially composed of two frames with their own mechanical properties in both strength and stiffness dissimilar to each other, and examine the variation of the resultant mechanism and responses of the interstory deflection and story shear force of the coupled structure associated with the variation of the strength and stiffness of the coupling frames. Summarized are the results obtained in this analysis as follows:

1. With a strong column frame coupled, an excessive interstory deflection response at a particular story of a weak column frame, which results from a column sidesway mechanism, will not be realized. Although the yield hinge generation remains intact resulting in generation of hinges at the ends of the columns of a weak column frame, the excessive interstory deflection is uniformly distributed over the coupled structure resulting in the beam sidesway mechanism, which is desirable for a ductile reinforced concrete structure indicating identical interstory deflection responses with one another among stories.
2. A coupling strong column frame with a greater strength ratio of columns to beams is dominant over the entire deflection response of the coupled structure, though its stiffness within the coupled structure is of less importance.
3. The above mentioned evidence appears more notable when the strength ratio of columns to beams for the strong column frame is taken greater or when the strength ratio for the weak column frame is taken smaller: i.e., when there exists a larger column strength difference between the strong column and weak column frames.

With an application of the results obtained in this analysis, we can evaluate how strong and how stiff the strong column frames shall be which are required to be placed within a structure to realize a preferable beam sidesway mechanism.

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