Proceedings of Ninth World Conference on Earthquake Engineering
August 2-9, 1988, Tokyo-Kyoto, JAPAN (Vol.V)

7-6-16

EARTHQUAKE RESPONSE ANALYSES OF REINFORCED CONCRETE BUILDINGS WITH BASE ROTATING SHEAR WALLS

Daisuke KATO

Department of Architecture, Faculty of Engineering, University of Niigata, Niigata, Japan

SUMMARY

This paper reports the effects of wall base rotation on the low-rise reinforced concrete frame behavior through inelastic earthquake response analyses in order to design shear walls in reinforced concrete buildings as base rotating walls. The responses of three-story reinforced concrete buildings on footing foundations are studied, paying special attention to the influence of analytical assumptions and input forces at the wall bases during earthquake response.

INTRODUCTION

Regarding to the behavior of the structural wall in a low-rise reinforced concrete building, three basic modes of failure have been identified: (1) shear failure, (2) flexural failure, and (3) base rotation. Of these three modes, the preferable inelastic deformation capacity is expected in case of the last two failure modes. In recent years the effects of base rotating shear walls have been studied gradually (Refs. 1,2,3). Authors reported on the effects of base rotating shear walls examined through static load reversal tests, paying attention to the effects of connecting beams and the wall support conditions (Refs. 4,5) and through inelastic earthquake response analyses, paying attention to the deformation capacity of buildings with base rotating shear walls (Refs. 4,6). Main findings of these studies were that the buildings with base rotating shear walls performed as good as buildings with flexurally yielding walls and showed better seismic behavior than buildings with shear failing walls.

The main objective of this paper is to examine the effects of wall base rotation on the low-rise reinforced concrete frame behavior through inelastic earthquake response analyses, paying special attention to the input shear force or the overturning moment at the wall base during earthquake response, in order to design shear walls in reinforced concrete buildings as base rotating walls.

METHOD OF ANALYSIS

In the analytical model, the inelastic behavior of frame members and the uplifting rotation of a structural wall at its base were idealized. The details of the member models were shown in Refs. 4 and 5. In this paper, the hysteresis models of the members and the rocking model of the wall are shown.

Hysteresis Models   Four different hysteresis models were used in this study; i.e., (1)Clough model for beam members and shear springs of wall members, and

(2)Degrading Tri-Linear model for column members, (3)Axial-Stiffness Hysteresis model for boundary columns of walls, and (4)Soil-Hysteresis model for foundations under the wall footings. The list of references of these hysteresis models was shown in Ref. 5.

<u>Rocking Model</u> During the rocking of a shear wall, the behavior is characterized by three basic phenomena; (1)the rotational moment of inertia force is applied to the wall, (2)the restoring force decreases with displacement amplitude caused by the gravity effect, and (3)the energy is dissipated when the wall's base touches the ground. The analytical model was developed, taking account of the rotational mass corresponding to the rotational moment of inertia of the wall, the gravity effect, and the reduction in kinetic energy over the impact.

The mass distribution is shown in Fig. 1. The mass, corresponding to the translational inertia force by the uplifting motion of the slab, was assumed to be concentrated to the beam-to-wall joint node. Furthermore, the mass, corresponding to the rotational moment of inertia force of the wall panel about the edge of the wall, was assumed to be concentrated to the wall beam center. On the other hand, the mass, corresponding to the translational inertia force by the sway motion, was assumed to be concentrated to each floor level.

During the rocking motion of the shear wall as well as the sway motion of the building, the restoring force decreases with displacement amplitude caused by the gravity effect. The analytical model was developed, taking account of this gravity effect.

The energy is dissipated when the wall's base touches the ground (Ref. 7). A reduction in kinetic energy in case of a rigid wall, shown in Fig. 1, on a rigid ground is given as follows. If the impact between the base and the ground is assumed to be perfectly plastic (no bouncing occurs after impact), the vertical momentum at the structure's base is absorbed by the ground when the wall's base touches the ground. On the other hand, the moment of momentum about the new rotation center is conserved before and after the impact. Consequently, there would be a reduction in kinetic energy by the factor r^2, where r is a reduction factor of the angular velocity over the impact written as

$$r = \frac{\Sigma\,(iIw + iMw\,(Hi^2 - B^2/4) + 2\,iMsh\,Hi^2)}{\Sigma\,(iIw + iMw\,(Hi^2 + B^2/4) + 2\,iMsh\,Hi^2 + iMsv\,B^2)} \qquad (1)$$

where, Hi is the height of the i-th floor from the base and B is the width of the wall. Another symbols of Eq. 1 are shown in Fig. 1.

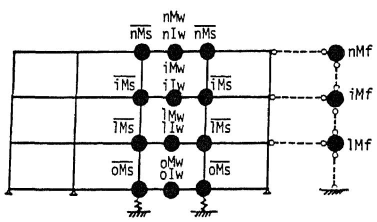
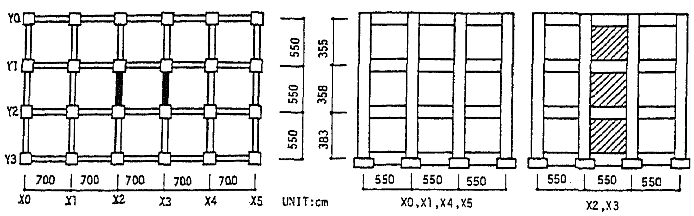


Fig. 1 Mass Distribution



(a) Plan (b) Sections
Fig. 2 Proto-Type Building Studied

In case of a deformable wall on a deformable ground, additional two assumptions were taken into account; i.e., (1)the strain velocity of the wall itself was assumed to be conserved before and after the impact, and (2)the vertical velocity of the impacted footing after the impact was assumed to be zero, which means that the ground mass was assumed to be far greater than the mass of the structure's base. Consequently, only the angular component of the velocity before the impact would be reduced by the factor of r in Eq. 1.

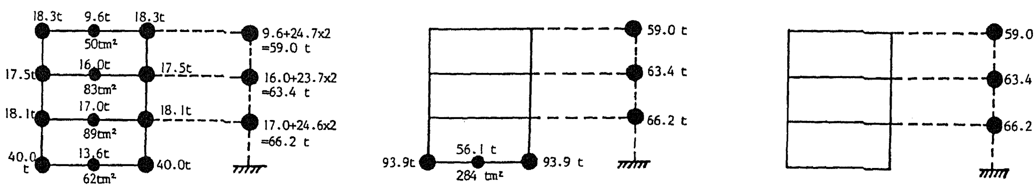
ANALYTICAL MODEL OF BUILDING STUDIED

A three-story reinforced concrete building with shear walls on footing foundations, shown in Fig. 2(a), was chosen as a prototype building. The earthquake response of the building was studied in the y-direction. Sections of the building with a shear wall (X2,X3) and the open frame (X0,X1,X4,X5) are shown in Fig. 2(b). The walls of frames X2 and X3 could rotate at the base by overturning effect. Details of the prototype building were shown in Ref. 4.

A basic model (model-2) was taken with some modifications from this prototype building. In this basic model, the four open frames were reduced to an equivalent three-story one-bay frame and the reduced frame was connected to the frames with shear walls.

Main variables of this study are (1)the amount of the wall and (2)the analytical assumption of the mass distribution. In the model-5, one frame with a shear wall was replaced by a open frame, so that the amount of the wall was half in comparison with the basic model. In addition to these two models, an open frame without a wall (model-F) and an isolated wall without connecting beams (model-W) were examined. In all models, the strength of the shear spring or the flexural spring of wall members was enhanced in order to prevent walls from failing in shear or flexure. The ratios of base shears to total weight of models-F, W, 2, 5 at roof level displacement equal to 1/150 of the total height, calculated using non-linear static analysis, were 0.32, 0.45, 0.54, 0.44, respectively. First natural periods of four standard models were 0.535, 0.196, 0.308, 0.359 sec., respectively.

The mass distribution models of the wall are shown in Fig. 3. In the model-(D), the translational inertia force by the uplifting motion of the slab and the rotational moment of inertia force of the wall panel about the edge of the wall, were considered. In the model-(C), these forces were assumed to act at the footing level. Further more, in the model-(I), these forces were neglected. Note that the energy dissipation over the impact can not be expected in the model-(I).



model-(D) model-(C) model-(I)

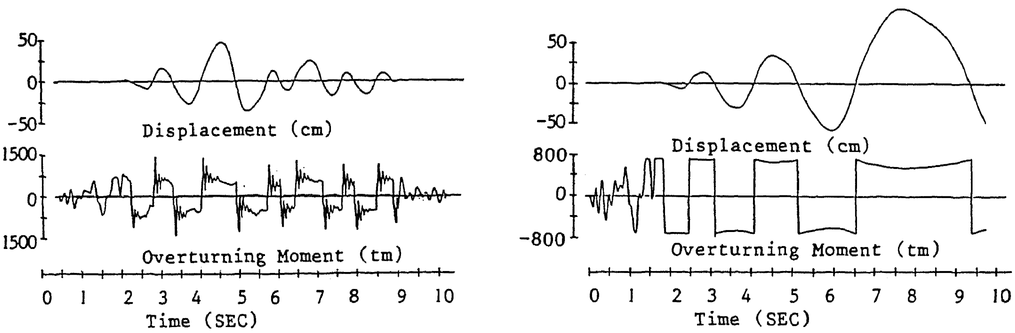
Fig. 3 Mass Distribution Models

RESPONSE OF ANALYTICAL MODELS

The analytical models were subjected to the EW component of the Tokachi-Oki earthquake (1968) motion recorded at Hachinohe, the maximum acceleration of which was 183 gal. The intensity of the base motion was varied from 75 gal to 675 gal.

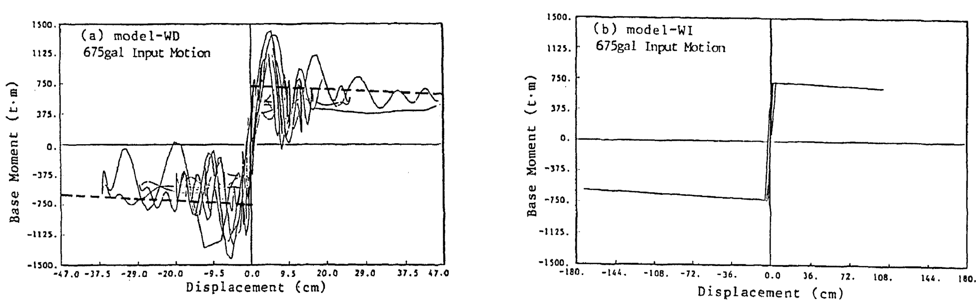
<u>RESPONSE OF ISOLATED WALL</u> Typical response waveforms of displacement at the top and overturning moment at the base under 675 gal input motion of base rotating shear walls without connecting beams and open frames (model-W series) are shown

in Fig. 4. Figure 4(a) shows waveforms of model-WD in which rotational mass moment was considered, and (b) shows those of model-WI in which rotational mass moment was neglected. The relations between the overturning moment and the displacement at the top floor of model-WD and model-WI are shown in Fig. 5(a)(b). The maximum displacement of model-WD was approximately ten times the displacement at uplifting of the wall. However, the waveforms did not show a significant elongation in oscillation period and the residual displacement was small. The overturning waveforms of model-WD showed remarkable ripples of higher modes caused by the vertical inertia force of the wall. On the other hand, model-WI showed waveforms different from those of model-WD; i.e., (1)the overturning waveform showed no ripples, and, (2)the maximum displacement was about twice as large as that of model-WD.



(a) model-WD (b) model-WI

Fig. 4 Typical Waveforms of Isolated Walls

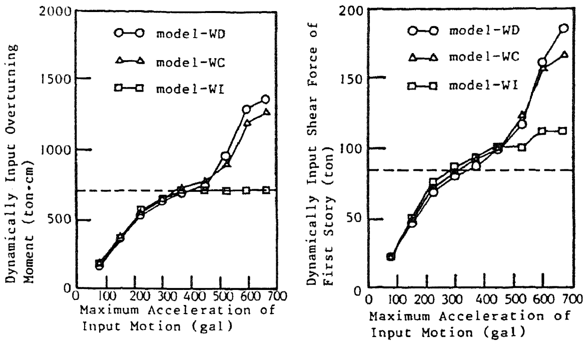


(a) model-WD (b) model-WI

Fig. 5 Overturning Moment - Displacement Relations of Isolated Walls

Maximum overturning moment responses and maximum shear force responses at the base of models-WD, WC, WI with respect to the intensity of input motion are compared in Fig. 6(a)(b). The statically input moment and the shear force calculated in the nonlinear static analysis are shown with dashed lines in Fig. 6. Model-WD and model-WC showed larger overturning moment responses than the statically input force under more than approximately 400 gal input motion, caused by the translational inertia force by the uplifting motion of the slab and the rotational moment of inertia force of the wall panel. All models showed larger shear force responses than the statically input force under more than approximately 300 gal input motion, caused by higher modes of translational inertia force by the sway motion besides the reasons in case of the overturning moment.

RESPONSE OF BUILDINGS WITH BASE-ROTATING WALLS Maximum displacement responses of all models at the top floor with respect to the intensity of input motion are compared in Fig. 7. The ordinate is maximum displacement in logarithmic scale. The maximum displacements of model-2D and model-5D were lower than those of model-2I and model-5I, respectively. This is because the translational inertia force by the uplifting motion of the slab and the rotational moment of inertia force of the wall panel were taken into account in model-2D and model-5D.



(a) Overturning Moment (b) Shear Force

Fig. 6 Maximum Force Response of Isolated walls

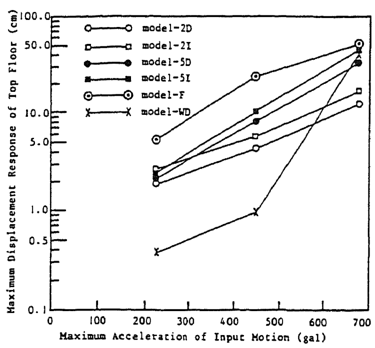
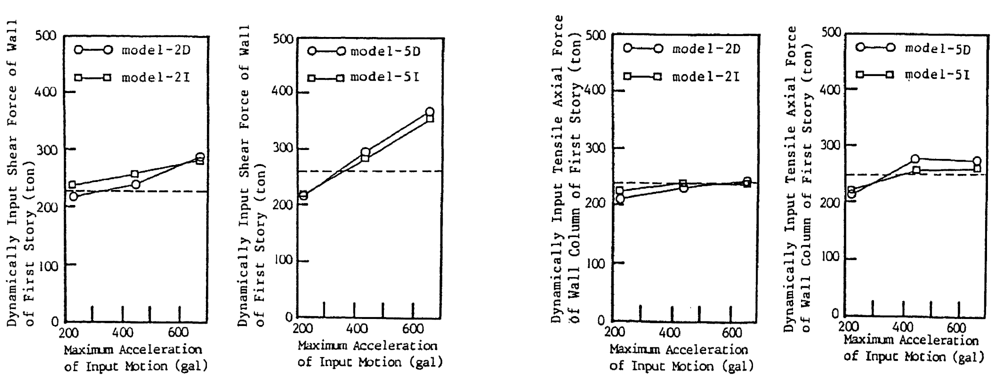


Fig. 7 Maximum Displacement Response of Buildings

Figure 8(a)(b) shows maximum shear force responses at the wall base and maximum axial force responses of the wall boundary column of the first story of models-2D, 2I, 5D, 5I with respect to the intensity of input motion. The statically input shear force and the axial force calculated in the nonlinear static analysis are shown with dashed lines in Fig. 8. All models showed larger shear force responses than the statically input force under more than approximately 300 gal input motion. This reason is as same as that of isolated walls.

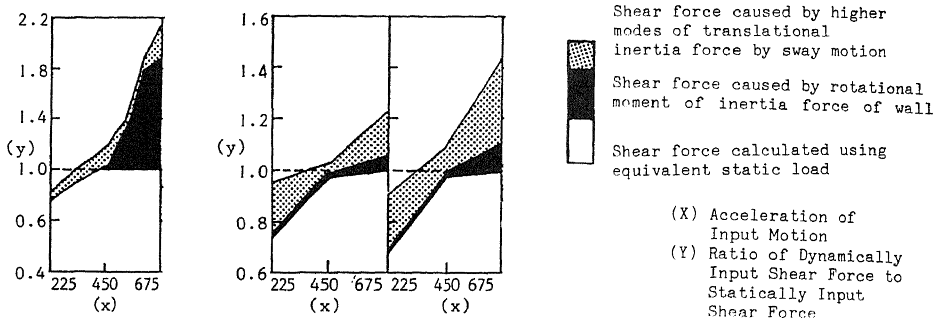


(a) Shear Force of Wall Base (b) Axial Force of Wall Boundary Column

Fig. 8 Maximum Force Response of Buildings

Figure 9 shows the ratios of dynamically input shear forces to statically input shear forces at wall bases of models-WD, 2D, 5D. Horizontal axes are intensity of input motion. Dynamically input shear forces were divided into three portions; i.e., (1)the shear force calculated using the equivalent static load which represented the first mode of vibration, (2)the shear force caused by the translational inertia force by the uplifting motion of the slab and the rotational moment of inertia force of the wall panel, and (3)the shear force caused by higher modes of the translational inertia force by the sway motion.

Most of the excessive shear force from the statically input shear force of model-WD was caused by the second item, whereas those of other models were caused by the third item.



(a)model-WD (b)model-2D (c)model-5D

Fig. 9 Ratios of Dynamically Input Shear Force

CONCLUSION

Main findings are as follows: (1)The translational inertia force by the uplifting motion of the slab and the rotational moment of inertia force of the wall panel had a significant influence on the behavior of wall-frame buildings. (2)During the rocking of a shear wall, the shear force of the wall panel was generated dynamically mainly by the translational inertia force by the uplifting motion of the slab and the rotational moment of inertia force of the wall panel. (3)Consequently, this increment force must be taken into account in order to design shear walls as base rotating walls.

ACKNOWLEDGMENTS

A part of this study was undertaken in the Department of Architecture, the University of Tokyo. Author express deepest appreciation for the advice by Professor H. Aoyama and Professor S. Otani of the University of Tokyo.

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