

3-D inelastic earthquake response of RC frames with shear walls

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ABSTRACT: This paper presents the inelastic analytical model of shear walls in reinforced concrete structures subjected to bilateral and axial forces. In this model, the multiple inelastic axial springs are considered for expressing the material character of reinforcing steel and concrete in shear walls. The inelastic behavior of shear walls simulated by this model is examined with the experimental results of 3-story cantilever shear wall subjected to cyclic horizontal loading. The inelastic earthquake response analysis is also performed using this model. From the results obtained, it can be concluded that the proposed model for shear wall in three dimensional structures is useful and effective in predicting the inelastic behavior of wall-frame structures.

1. INTRODUCTION

It is well known that shear walls are very important in providing resistance and stiffness against the horizontal loading induced by earthquake motions. Many buildings have been able to withstand severe earthquake successfully due to the contribution of shear walls. So far, a lot of research on the behavior of single member walls as well as in-plan wall-frame systems have been carried out in terms of experiments and analyses [Ref. 1 and Ref. 2]. However, it can be said that up to now the practical way for modeling the shear wall and analyzing three dimensional wall-frame behavior considering the biaxial bending, and N-M (axial force-bending moment) interaction is difficult to perform.

Recently, with the rapid progress in computer capability, it is possible to do member by member inelastic three dimensional analysis with regard to biaxial bending and varying axial force. Therefore, it is strongly needed to offer a realistic complex model of shear wall for simulating the inelastic behavior of reinforced concrete structures subjected to multi-directional earthquake motions.

In this study, an attempt was made to offer a practical model that is capable of predicting the behavior of shear wall in three-dimensional reinforced concrete structures. Based on the concept of multi-spring model of column [Ref. 3], a method to determine the parameters of proposed model are presented. Secondly, in order to verify the availability of the proposed model, the

test results carried out at Tohoku University, Japan, are compared with the results obtained from proposed model. Finally, using the proposed wall member model, a 3-story reinforced concrete structure with single shear wall is selected to study inelastic three dimensional behavior of structure.

2. MEMBER MODEL FOR SHEAR WALLS

Inelastic analytical model of shear walls in reinforced concrete structures can be made either using a microscopic finite element approach or a macroscopic approach. The microscopic model is generally confined to analyzing the continuum elements like shear walls. However, this model is unsuitable for three dimensional analysis of wall-frame structures, because it will make complicated problems requiring very long computation time.

Since the primary objective of this paper is to analyze three dimensional wall-frame structures, the macroscopic model for shear walls in three dimensional structures is developed here.

In this model, as shown in Fig. 1, eight inelastic axial springs are connected by two rigid beams, where the plastic bending deformations of wall are concentrated. Also, three shear springs which express the shear behavior of panel and two boundary columns, are placed at the center of the model. The elastic character of shear wall is idealized as three lines connecting two

rigid beams at the top and the bottom of the wall member. The elastic line at the center represents the elastic bending behavior of in-plane shear wall, and the two elastic lines at the outer side represent the elastic bending behavior of boundary columns in the orthogonal direction to the shear wall.

In Fig. 1, \odot represent the composite springs of steel and concrete. \bullet only denote the concrete springs. The parameters of springs 1 to 8 are determined with reference to the method for multi-spring model of column [Ref. 3].

The strength of steel springs 1, 3 or 4, 6 is determined by the gross area of reinforcement in boundary column, whereas that of springs 7, 8 is determined by the reinforcement in wall panel.

The strength of concrete springs 1, 3 or 4, 6 and the distance between springs 1, 3 or 4, 6, are determined so that the yield moment of boundary column in the direction perpendicular to wall at the balancing point corresponds to that of column model composed of springs 1, 3 or 4, 6.

The strength of the concrete springs 2, 5 and 7, 8 is determined by the total compression strength of wall.

The position of springs 7, 8 is determined so that the bending yield moment of in-plane wall corresponds to that of the model.

The yield deformation of each spring is determined so that the estimated yield displacement of the member coincides with that of the model.

The proposed model of shear walls is incorporated into the program STERA-3D (three dimensional structural earthquake response analysis program).

The multi-spring model developed by Lai [Ref. 3] is adopted for representing the biaxial bending and varying axial force of individual columns. This model has plastic elements at the both ends of column, which include four inelastic vertical springs at the corners of the section representing effective stiffness of reinforcing steel and concrete, as well as fifth spring at the center of section for concrete effective stiffness (see Fig. 2).

For beams, only uni-directional bending at two ends is considered, neglecting the axial deformation. The model of beams has two rotational springs which concentrate the plastic deformation at the beam ends, where the yielding capacity was expected [Ref 2] (see Fig. 2).

Shear resistance property of structural members is assumed to be independent of axial force or bending moment without considering the interaction effect.

The simplest bilinear hysteresis models

are used in program STERA-3D for steel springs, and concrete springs neglecting the tensile action. The modified TAKEDA model and origin model are adopted for bending and shear springs as shown in Fig. 3.

3. TEST SPECIMEN, EXPERIMENTAL AND ANALYTICAL RESULTS

The shear wall test had been carried out at Tohoku University, Japan, in 1979 [Ref. 6]. The specimen was a 3-story isolated wall model, equal to one-fifth of that of actual shear wall. The dimensions of the specimen are shown in Fig. 4. The properties of concrete and reinforcing steel embedded in

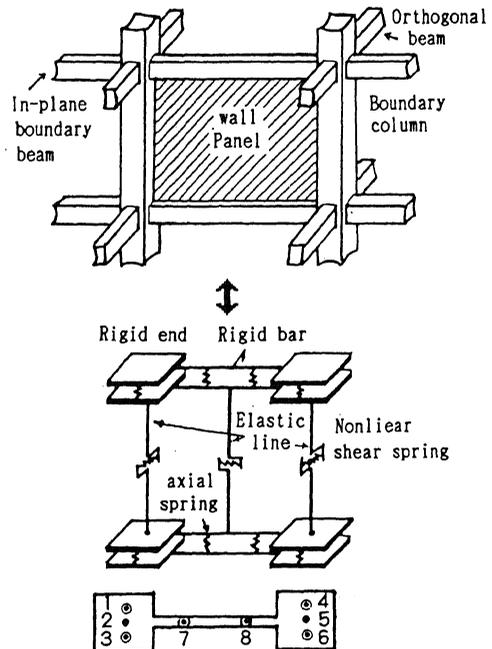


Fig. 1 The proposed model for shear wall

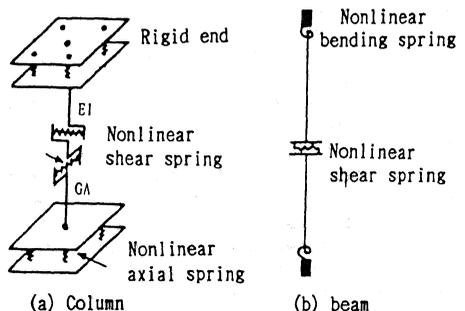


Fig. 2 The models for column and beam

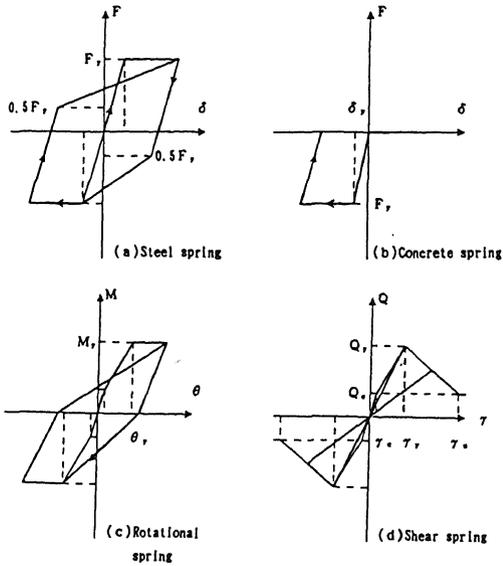


Fig. 3 Hysteresis models for structural members

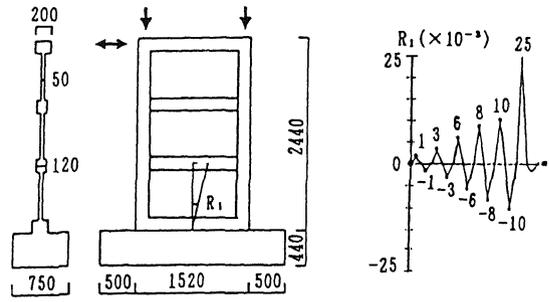


Fig. 4 The test specimen Fig. 5 The load history

Table 1 The properties of test specimen

Boundary columns	Bars	6-D10	Beams	4-D10, 4 ϕ 075
	Hoop	4 ϕ 075	Panel	4 ϕ 050, double

boundary columns and wall panel are summarized in Table 1.

The boundary columns in the shear wall were subjected to equal axial forces ($F_c/6 \times$ column area) which simulated the gravity loading. Cyclic lateral force was applied on top of the specimen. The loading history controlled by the first story deformation angle R_1 of the specimen is illustrated in Fig. 5.

The test results of the specimen mentioned above are used to calibrate the performance of the proposed shear wall model. Fig. 6, and Fig. 7 depict the comparisons of the analytical (a) and experimental (b) results. Referring to Fig. 6, it can be seen that the analytical response curve for first story shear force vs horizontal displacement is best matched with the experimental response curve. A similar remark can be drawn for the relationship between the third shear force and the

horizontal displacement in Fig. 7. Even though the simplest bilinear hysteresis model was used for reinforcing steel and concrete springs, the proposed model is able to estimate the behavior of the reinforced concrete shear walls.

4. STRUCTURAL MODELS FOR EARTHQUAKE RESPONSE ANALYSES

Inelastic earthquake response analyses are performed in comparing the two different structure models of a three dimensional wall-frame building.

Considering three dimensional mechanism of structures and the restraint effect of beams orthogonally connected to shear walls, model 1 is assumed to be a 3-story reinforced concrete structure with a shear wall in the center of frame plan. The

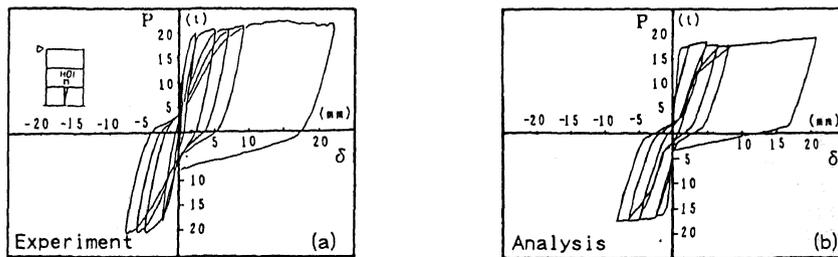


Fig. 6 The relation between the shear force and displacement of the first story

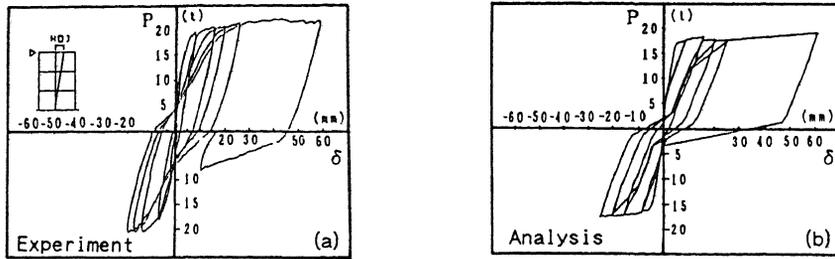


Fig.7 The relation between the shear force and displacement of the third story

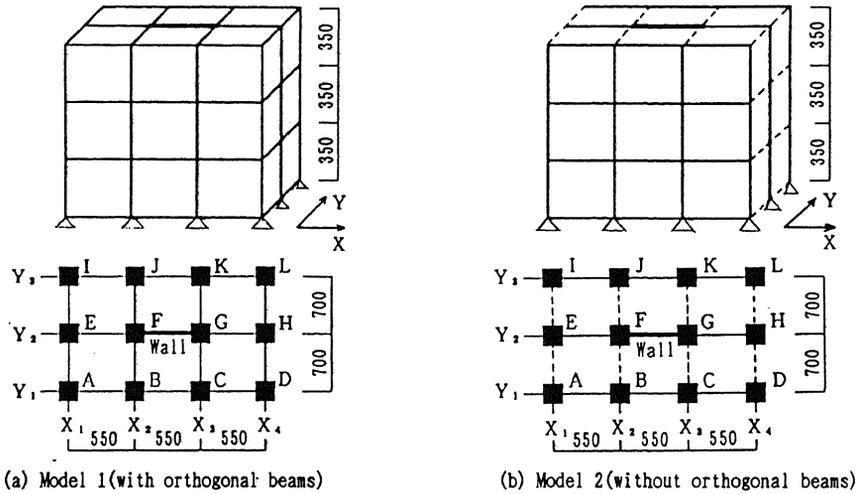


Fig.8 The structural models

Table 2-The properties of structural models

	Story	Foundation	1	2	3		Area	60×60cm ²			
	Beam	X	Top	5-D22	4-D22		3-D22	5-D19	Column	Steel	12-D19
Bottom			5-D22	4-D22	3-D22	5-D19	Hoop	Ø13 φ 100			
Area			40×120cm ²	35×75	30×70	30×70	Shear Wall	Boundary	Area	60×60	
Y		Top	4-D25	5-D22	4-D22	3-D22		Columns	steel	12-D19	
		Bottom	4-D25	5-D22	2-D22	2-D22		Wall Panel	area	490×20	
		Area	40×120cm ²	40×70	35×75	35×75		steel	2-9 φ Ø200		

general plan view and elevation of the structure are shown in Fig.8 (a). In order to conduct plane analysis for comparison with three dimensional analysis, a structure that is similar to model 1 but ignores all orthogonal beams is assumed to be model 2 as shown in Fig.8 (b) [Ref.5]. The rigid floor assumption was adopted for the both structural models. Material properties of both structural models is tabulated in

table 2. The nominal design strength of concrete is 210kg/cm². The grade of steel is SD35, yield strength being 3500kg/cm² for the longitudinal reinforcement, and SR24, yield strength being 2400kg/cm² for the transverse reinforcement.

The building gravity load, 0.91t/m² for each story, is supported by individual footings. The bases of columns and shear wall are assumed to be pin and vertical

inelastic spring support respectively. Also, the base of shear wall could uplift from the footing spring under tensile action. The vertical stiffness of footing spring under compression is elastic (see Fig.9). The loads applied on footing springs of shear wall are considered to include soil and footing gravity load with the average density of $2t/m^2$, confining to the footing area of $(3.3*3.3)m^2$ and depth of 1.5m.

5. RESULTS OF INELASTIC EARTHQUAKE RESPONSE

The both structural models are analyzed by computer program STERA-3D, of which member models are explained above. Response analyses are made only for the x direction. The NS component of EL CENTRO record (1940) is used by increasing the intensity 1.5 times, simulating a very strong earthquake motion. For numerical integration, Newmark's beta method with beta value of 0.25 is adopted. Also, the damping is assumed to be proportional to initial stiffness with its damping factor of 0.05 for the first mode.

The first natural periods of model 1 and model 2 in the x direction are 0.226(sec.) and 0.228(sec.) respectively.

Two similar response waveforms shown in Fig.10 (a), (b) present the displacements - time history of floor for the both structural models. By comparing the maximum and minimum values of displacement, we can see that the model 2 has larger displacement of story-floor in x direction than that of model 1.

Because of the concentration of the earthquake load on walls, the footing of shear wall easily undergoes up-lift from the soil. As the resistance of orthogonal beams is neglected in model 2, the footing up-lift phenomenon was more significant at the footing F, in model 2 than in model 1, under a strong earthquake motion (see Fig.11 (a) (b)).

Fig.12 shows the ratios of wall shear force to shear force of Y2-frame and total story shear force including three parallel frames in the x direction.

The ductility factors of structural members in wall-frame (Y2-frame) are shown in Fig.13. Because orthogonal beams are neglected, the ductility factors of beams in model 2 are seen to have larger values than these of model 1.

6. CONCLUSIONS

We can draw the following conclusions through the above static simulation and the inelastic earthquake response analyses:

1. Based on the multi-spring model of

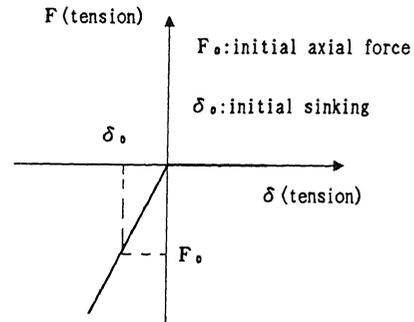


Fig.9 Hysteresis model for wall footing spring

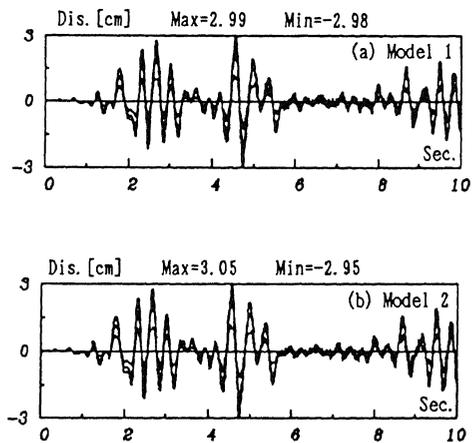


Fig.10 Floor displacement waveforms

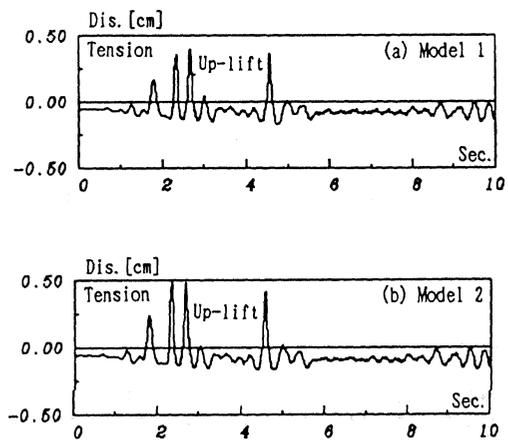


Fig.11 Displacements of wall footing

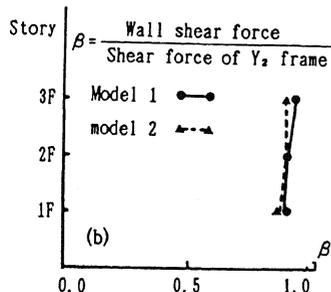
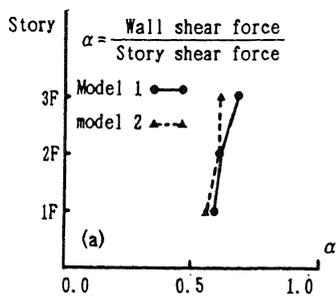
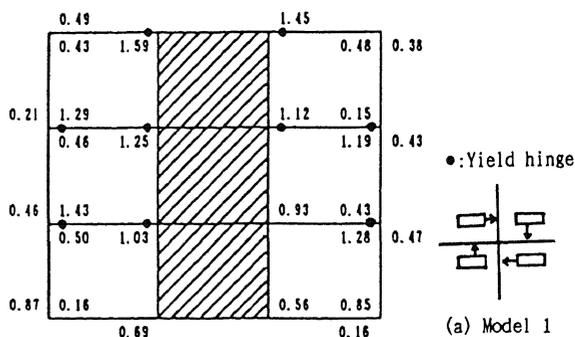
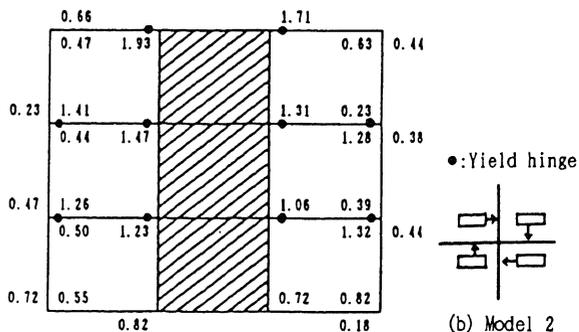


Fig.12 The ratio of shear wall forces



(a) Model 1



(b) Model 2

Fig.13 The distribution of ductility factors

columns, a useful and reliable model for shear walls in three dimensional reinforced concrete structures was developed.

2. By comparing the results from experiment and analysis using the proposed model of shear wall, it is observed that the proposed model is able to predict the behavior of shear walls subjected to lateral load.

3. Inelastic earthquake response analyses of reinforced concrete structural models were performed, one considering the orthogonal beams and the other neglecting them. Through the results obtained, it is found that when a structure is subjected strong earthquake motion and structural members go into plastic range, orthogonal beams restrict the footing up-lift of shear wall, causing increase of wall shear force and decrease of the damage in in-plane boundary beams. This trend will become more conspicuous as structures are very tall.

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