DYNAMIC RESPONSE OF REINFORCED CONCRETE WALL SYSTEMS

by

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SUMMARY

Results of dynamic inelastic analysis of structural wall systems under seismic excitations are presented. Two significant aspects of inelastic analysis are discussed. These are axial force-flexure interaction under continuously changing axial forces and inelastic shear deformation effects. The hysteretic moment-rotation and shear force-shear distortion relationships are obtained by modifying the rules proposed by Takeda.

Results indicate that changes in axial force in a coupled wall system have significant influence on dynamic response. Shear yielding increases the shear component of distortions in the hinging region of walls, but has little effect on overall structural response.

INTRODUCTION

Advantages of structural wall systems in aseismic design derive from their ability to dissipate most of the earthquake-induced energy in secondary elements, while primary vertical-load-carrying members undergo limited inelasticity. Determination of necessary member properties requires investigation of the effect of beam-to-wall and beam-to-column stiffness ratios and strength ratios. This can be done by using dynamic analysis. However, when using dynamic inelastic analysis, it is essential to model member behavior realistically in determining deformation and force requirements in critical regions.

This paper presents procedures that allow modeling hysteretic moment-rotation and shear-distortion relationships of concrete members. Special emphasis is placed on wall system behavior.

One aspect of structural behavior inherent to systems is the coupling action between one or more members. In coupled wall systems, the coupling between the walls produces axial forces that vary both in magnitude and direction during earthquakes. These forces affect the load-deformation characteristics of walls.

While compressive force in one wall produces an increase in yield strength and stiffness, tensile force in the other wall simultaneously creates the reverse effect. This leads to shifting of forces to walls in compression. It may lead to early yielding in "tension" walls while "compression" walls are exposed to critically high shears and moments.

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Another important aspect of inelastic analysis is the effect of shear yielding. Recent experimental results (1) indicate that inelastic shear distortions can be significant in local areas where flexural yielding occurs. Tests on structural walls under slow load reversals clearly indicate a direct relationship between shear yielding and flexural yielding. Test results indicte an almost simultaneous occurrence of shear yielding and flexural yielding well below the calculated shear capacity. This has been attributed mainly to a change in the shear-resisting mechanism accompanying flexural yielding.

In this report an analytical model incorporating axial force-flexure interaction effects and inelastic shear distortion effects is described. The model is used to determine significance of these actions in the seismic response of wall systems.

ANALYSIS PROCEDURE

Dynamic analysis was carried out by using computer program DRAIN-2D (2). The program was originally developed at the University of California, Berkeley, and later modified by the Construction Technology Laboratories of the Portland Cement Association. DRAIN-2D is a general purpose program for dynamic analysis of plane inelastic structures subjected to earthquake excitation. The direct stiffness method is used to formulate a structural stiffness matrix. Step-by-step integration, assuming constant response acceleration during each time step, is used to determine dynamic response.

In the computer program each member is modeled by an elastic line element and two inelastic springs, one for flexure and the other for shear, at each end as shown in Fig. 1. Inelastic action is allowed by activating these springs beyond their respective yield levels. Properties of inelastic springs are specified such that when combined with the elastic line element the appropriate force-displacement relationships are obtained.

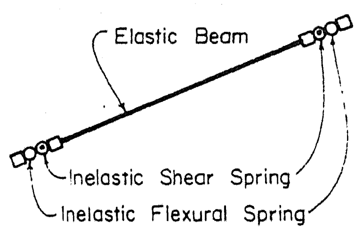

Fig. 1 Element Model

Axial Force-Moment Interaction Model

The hysteretic moment-rotation relationship in the original version of DRAIN-2D follows a set of rules based on that proposed by Takeda (3). These rules are applicable to members under constant axial force. Coupled walls, on the other hand, generally undergo substantial changes in the level of axial force during response to earthquake motions. Because of this continuous change in axial force and the interaction between axial force and bending moment, yield moment and effective stiffness of a member change continuously. This interaction between axial force and bending moment is modeled by modifying the original model of DRAIN-2D.

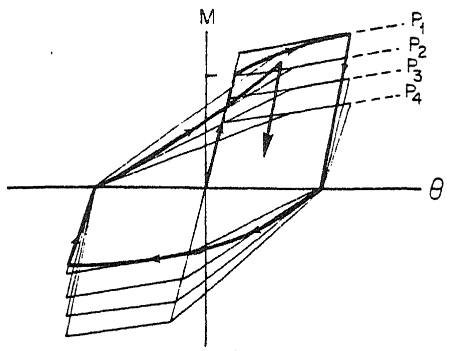

Fig. 2 Hysteretic Loops with Changing Axial Forces

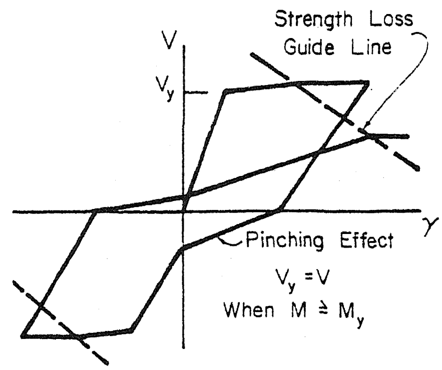

Fig. 3 Hysteretic Loop for Shear Distortion Relationship

Figure 2 shows a set of moment-rotation diagrams. Each corresponds to a different level of axial force. The primary moment-rotation relationship is idealized as a bilinear curve. Elastic stiffness is assumed to be unaffected by axial forces. Initial yielding is governed by the current level of axial force and associated bending moment. As shown in Fig. 2, slope of the post-yield branch remains constant only if axial force remains unchanged. During response, there will be smooth shifts between curves corresponding to different levels of axial force. These shifts reflect either hardening or softening of the structure due to an increase or a decrease in axial force, respectively. A more detailed description of the model is given in Ref. 4.

Inelastic Shear Model

The basic shear force-shear distortion relationship for the inelastic shear spring is assumed to follow hysteresis loops based on Takeda's rules. An important step in modeling inelastic shear behavior is to couple shear yielding with flexural yielding. Results of tests of structural walls (1), show that the onset of shear yielding is directly related to flexural yielding. A series combination of a flexural spring and a shear spring allows interaction in the sense that once either shear or flexural yielding occurs, a reduction in element stiffness occurs in terms of both flexural and shear stiffness. Of course, shear force and moment interact with each other through the equilibrium equations.

Two significant features have also been incorporated in the model to permit more realistic representation. One is a gradual loss of strength with repeated load reversals beyond a specified shear deformation. The other is slip action in the reloading branch. Strength softening is primarily due to distortion in a concrete segment and permanent strain accumulation in the reinforcement. Slip action, reflected in "pinching" of the hysteresis loops, is attributed mainly to closing of previously opened cracks under cyclic loading. The hysteresis loop for the shear force-shear distortion relationship is illustrated in Fig. 3.

A 20-story coupled wall system and a 20-story frame-wall system were selected for dynamic analyses. A brief architectural study was conducted to select structures representative of current practice. Members were proportioned on the basis of UBC-76 seismic Zone 4 provisions.

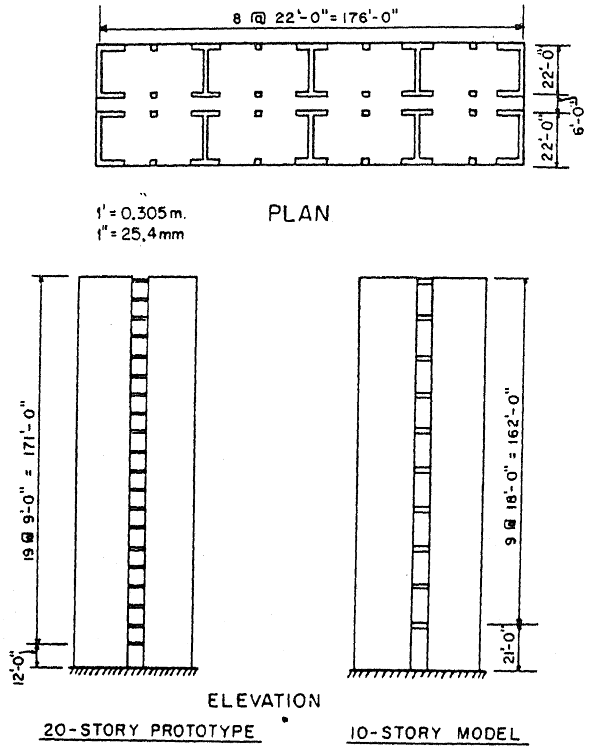

Fig. 4 Coupled Wall Structure

Coupled Wall System

Figure 4 shows the plan and elevation of the coupled-wall structure. The structure has a rectangular configuration with eight bays in the longitudinal and three bays in the transverse direction. In the long direction columns are placed at every other bay, and are assumed to carry vertical loads only. Lateral resistance is assumed to be provided entirely by the walls. Consequently, structural walls carry vertical loads acting on one bay and seismic forces acting on two bays. The initial fundamental period of the structure is 1.0 second. To reflect common practice, stiffness and strength taper is introduced at three locations along the height.

Because of the large number of cases to be covered in the project, it was essential to lump the structure to obtain a 10-story model. The lumping process has been shown to not significantly influence accuracy of the analysis (4).

Frame-Wall System

A 20-story frame-wall system was selected for this study. The structure has five bays in the longitudinal direction and three bays in the transverse direction, as shown in Fig. 5(a).

For the analysis, the structure is simplified into a basic model that consists of a single structural wall connected to a single-bay frame by hinged rigid links. This essentially involves horizontal lumping of a multi-bay frame into a single-bay frame. Moments transferred by beams framing into the wall are neglected to allow a closer examination of

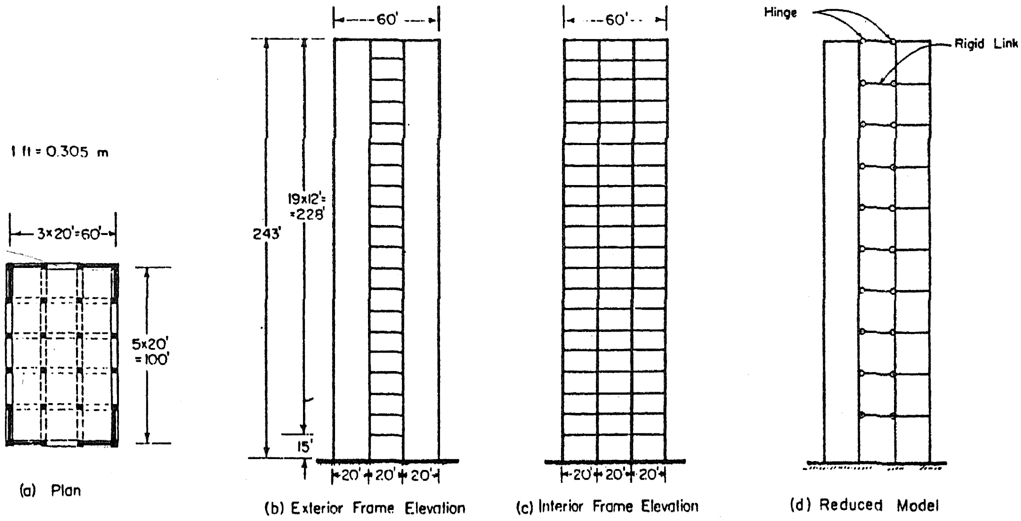

Fig. 5 Frame Wall Structure

frame-wall interaction effects. The structure is further reduced to 10 stories by vertical lumping. The final basic model is shown in Fig. 5(d). Member stiffnesses in the lumped model are calculated using an equivalent stiffness concept in which both prototype and lumped model give the same horizontal displacement.

DYNAMIC INELASTIC RESPONSE

Dynamic inelastic analyses of coupled wall and frame-wall systems were carried out using computer program DRAIN-2D. Both structures were fully fixed at foundation level and assumed to have 5% of critical damping. Input motions used were selected so as to excite each structure critically. The 1971 Pacoima Dam S16E component was used as input motion for the structure with fundamental period of 1.0 sec. For the structure with fundamental period of 2.2 sec. the 1940 El Centro E-W component was used. The amplitudes of the acceleration pulses were adjusted to yield a spectrum intensity equal to 1.5 times that of the 1940 El Centro N-S record.

Effect of Axial Forces

To assess the effect of axial force-flexure interaction, two analyses were carried out on coupled wall systems using two different moment-rotation hysteretic loops. In one case, the effect of axial forces was neglected and the hysteresis loop followed the rules proposed by Takeda. In the other case, axial force-flexure interaction was considered and the model developed for this investigation was used for the hysteresis loop.

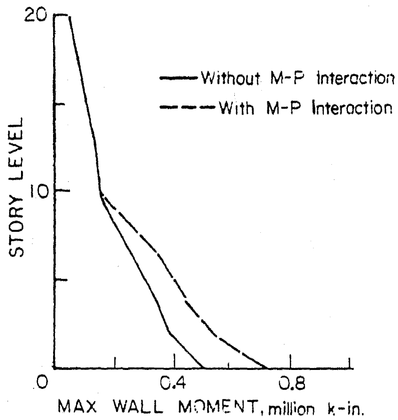

Fig. 6 Bending Moment Envelope for Walls

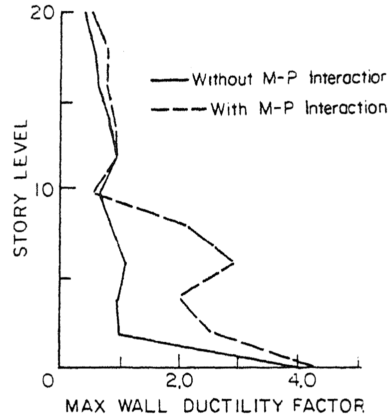

Fig. 7 Rotational Ductility Envelope for Walls

Response envelopes for bending moment and rotational ductility are shown in Figs. 6 and 7. Comparison between the two analyses clearly indicates that the effect of axial force on dynamic inelastic response of coupled-wall structures can be very significant. Elastic shear stiffness is used in both analyses.

Where axial force-flexure interaction was neglected, flexural yield level remained constant throughout the response. Since there was no change in stiffness and strength of walls due to varying axial forces, both walls of the coupled wall system behaved identically. Total shear and bending moment was distributed equally between the two walls. Due to this symmetrical behavior, the yielding pattern in the walls was identical, i.e. both walls yielded at the same time. The identical response of the two walls was reflected in the absence of axial forces in the coupling beams.

When axial force-flexure interaction was considered, the response of individual walls was affected by magnitude and direction of axial forces. As the level of axial force increased, the corresponding flexural capacity also increased. Therefore, in the wall with compressive load yielding took place at a level of bending moment higher than the initial value. Decrease in axial force, on the other hand, produced early yielding in the tension wall.

Although the structure was initially symmetrical, increase of axial force in one wall increased its strength and stiffness, while the decrease in axial force in the other wall simultaneously led to corresponding reduction in strength and stiffness. This caused forces to shift from the less stiff to the stiffer wall. Under reversal, this process results in increased maximum forces for both walls. Early yielding of tension walls, either due to net tension or due to reduced dead weight of the structure, produced higher ductility demands. The difference in response between the walls induced axial forces in the coupling beams. Magnitudes of axial forces in coupling beams became substantial in lower floors where inelastic action in the walls was most pronounced. However, overall lateral displacement responses for both cases were about the same.

The effect of axial force varies with degree of coupling. If coupling is strong, most of the overturning resistance of the system is provided by the axial force couple. To investigate the effect of the degree of coupling on dynamic response, coupled wall structures were analyzed with different beam-to-wall strength and stiffness ratios (5). The results of these analyses indicate that there is a range beyond which variation of member properties, for structures having same fundamental period, produces undesirable results. While stiff and strong beams tend to produce excessive tension and yielding in walls, flexible and weak beams result in high beam ductility demands. Through dynamic inelastic analysis, practical lower and upper bounds can be established for variation of relative stiffness and strength ratios of members. This aspect is discussed in more detail in Ref. 5.

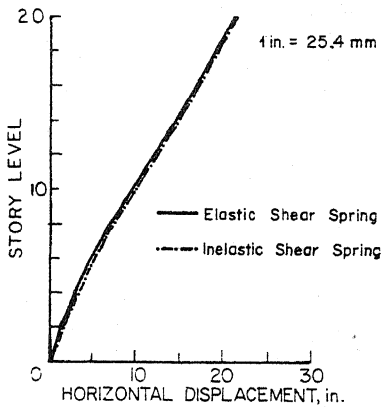

Fig. 8 Displacement Envelopes

Effect of Inelastic Shear

The frame-wall structure was analyzed to investigate the effect of shear yielding. A comparative study was made between two cases. In one case, the inelastic shear springs were placed at both ends of the wall members, while in the other case a linear shear-shear distortion relationship was used. In the former case the shear yielding was dependent on the flexural yielding in a sense that shear yielding was to initiate with the onset of flexural yielding. Also included was a nominal pinching effect in the inelastic shear force-shear distortion relationship (6).

Envelopes of story shear force over the height of the frame-wall system are compared for the two cases in Fig. 8. When inelastic shear behavior in the wall is considered, base shear in the wall is reduced by 8%, whereas base shear in the frame is increased by the same percentage. This comparison and the horizontal displacement envelopes shown in Fig. 9, indicate that inelastic shear distortions have little effect on response envelopes.

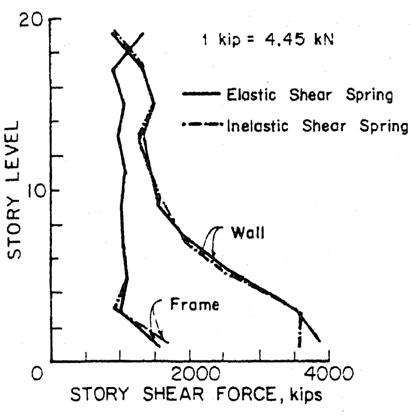

Fig. 9 Shear Force Envelope

Evaluation of "hinging region" deflection, which is the deflection of the first two stories at the base, shows an increase in deflection due to shear yielding. In the elastic shear case, the shear component constitutes 7% of the total hinging region displacement. This percentage increases to 13% when shear yielding is considered.

CONCLUSIONS

The effect of axial force on strength and stiffness of coupled walls can be very significant. For the structure considered in this investigation, this effect causes an increase of about 40% in force response envelopes. The sequence of yielding in a structure can also be affected significantly. Higher ductility demands are obtained when axial force-flexure interaction is considered.

Shear yielding, on the other hand, increases the shearing component of distortions in the hinging region, but the effect of inelastic shear on overall behavior of wall systems is very small.

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