INELASTIC, CYCLIC BEHAVIOR OF REINFORCED CONCRETE FRAME-WALL STRUCTURES SUBJECTED TO LATERAL FORCES

by

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SYNOPSIS

Both analytical and experimental studies on the seismic behavior of reinforced concrete frame-wall structures were described. Static, cyclic loading tests of walls and frame-wall subassemblages indicated that their behaviors could be classified into Flexural, Shear, and Flexural and Shear Types according to the failure mode and the level of strength and ductility of walls. An analytical approach which used inelastic beam models extending to walls reasonably estimated the strength, inelastic cyclic displacement as well as failure mode of such structural svstems.

INTRODUCTION

Lessons learned from the structural and/or nonstructural damage to reinforced concrete buildings due to recent destructive earthquakes have indicated the importance and effectiveness of structural walls which can provide adequate strength and stiffness of a total building. While a number of researches on walls and frame-wall structural systems have been conducted (e.g. 1-6) since our knowledge has been limited to provide appropriate guidelines for the seismic design of various types and sizes of such structural systems.

From this bakcground, a series of both experimental and analytical programs were undertaken to obtain design guidelines on the basis of experimental informations, and to develope realistic analytical procedures for the aseismic design of reinforced concrete buildings having multistory walls. Two series of static, cyclic loading tests were conducted for isolated walls and subassemblages of frame-wall structural systems. During the experimental program, the emphasis was put on; (1) to investigate the cyclic behavior of walls in terms of the failure mode, ductility as well as ultimate strength, and (2) to investigate the effect of walls on the behavior of a total structure. The experimental results of the subassemblages were analized by an analytical procedure developed by the authors in which existing test data as well as those obtained herein were reviewed to determine the cyclic behavior of structural elements.

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EXPERIMENTAL PROGRAM AND RESULTS OF ISOLATED WALLS

Test Specimens - Sixteen one-fifth scale models of isolated walls were constructed. Details of specimens are shown in Table 1 and Fig. 1. A test specimen consisted of two-story framed walls and dummy parts provided for the convenience of loading. The bottom wall represented that in a multi-story frame-wall structural system.

The variables selected for the program were (1) ratio of shear span (ho) to horizontal length (ℓw) of a wall, (2) axial stress in the gross area of a wall (σo), (3) amount of longitudinal reinforcement in a boundary column, in terms of the steel ratio to the sectional area of a column (Pg), and (4) amount of wall reinforcement, in terms of the steel ratio to the sectional area of a wall panel (Ps). Specified values of these variables which may cover those of such a structure having stories up to twenty are shown in Table 1.

Testing - Lateral forces were alternately applied by hydraulic jacks to the bottom of test wall, as shown in Fig. 1. A specimen was supported at both the top beam and the end of foundation, and also at the point above the dummy wall which may be shifted according to the value of ho/ℓw. For the case with the smallest value of ho/ℓw, 0.6, a simply supported specimen which consisted of a test wall and a foundation was loaded at its midspan. Vertical forces were also applied at the end of specimen to produce an axial stress in a wall section. All specimens were subjected to reversed, cyclic displacements of increasing magnitude. The displacement history included ten cycles of loops at each step of displacement in terms of increasing even numbers 2, 4, 6 .., to the unit value of 0.001 radian.

Test Results - In accordance with the failure mode, ultimate strength and ductility, cyclic behaviors of walls were classified into the following three types; 1) Flexural (F) Type, 2) Shear (S) Type, and 3) Flexural and Shear (FS) Type. Typical hysteresis curves are shown in Fig. 2 and envelopes of curves are schematically illustrated in Fig. 3.

In S Type behavior, a shear compression failure occurred at the bottom corner of a test wall before flexural yielding of a boundary column, and this immediately led to a shear tension failure of boundary columns. The loss of strength associated with the brittle failure was significant. The ultimate shear strength was more than 0.35Fc, where Fc is the compressive strength of concrete, in terms of the nominal shear stress of a wall, and the displacement was about 0.006 radian. In Type F, walls behaved in a ductile manner during a large number of post-yield displacement cycles. No significant loss of strength was detected until the displacement more than 0.012 radian. The failure was caused by the crush of column concrete due to bending. The observed flexural capacity was less than 0.25 Fc. The last type FS indicated rather ductile behavior compared with S Type, however, the brittle failure due to a shear compression also occurred at small amount of post-yield displacement or during displacement cycles.

The structural factors ho/ℓw, Pg and σo, thus, strongly affected the overall behavior of walls since they directly linked to the level of the flexural capacity. While the effect of wall reinforcement appeared to be minor. The ultimate moment (Mu) and the ultimate shear strength (Qu) were reasonably estimated by the following equations reference 3. where all the symbols appeare in Tables 1, 2 and Fig. 1.

$$Mu = 0.9\ Pg \cdot B \cdot D \cdot f_y \cdot L + 0.4\ Ps \cdot t \cdot \ell s \cdot f_{sy} \cdot L + 0.5\ N \cdot L \cdot (1 - \sigma_o/Fc) \quad (1)$$

$$Qu = [0.0679\ (Pg \cdot B \cdot D/Aw)^{0.23} \cdot (Fc + 180)/\sqrt{ho/\ell w + 0.12} + 2.7\ Ps \cdot f_{sy} + 0.1\ \sigma_o] \cdot Aw \cdot \ell w/L \quad (2)$$

The ratio of estimated flexural and shear strengths A,

$$A = Mu/Qu \cdot ho \quad (3)$$

could be a index to identify the type of behavior. Boundary values of A were 0.86 and 1.10 for Types F and S, respectively. The secant stiffness at yielding or ultimate shear strength in terms of the ratio to the elastic stiffness (α) was obtained for each type of behaviors by a group of following empirical equations derived from the test results.

$$\alpha_F = -0.004 + 8.46\ Pg + 7.88\ Ps - 0.021\ ho/\ell w + 0.183\ \sigma_o/Fc \quad (4)$$

$$\alpha_{FS} = 0.032 + 16.0\ Ps + 0.040\ ho/\ell w + 0.350\ \sigma_o/Fc \quad (5)$$

$$\alpha_S = 0.417 - 30.9\ Ps + 0.032\ ho/\ell w - 0.139\ t/B \quad (6)$$

EXPERIMENTAL PROGRAM AND RESULTS OF FRAME-WALL SUBASSEMBLAGES

Test Procedure - Three one-fifth scale frame-wall subassemblages having three bays and two or three stories were provided. Each specimen represented the lowest two or three stories of a frame-wall structure. In each specimen, the bottom wall which could control the overall behavior of the structure was designed to behave in each of the three typical manners. Test specimens are illustrated in Table 2. Each subassemblage included identical walls to the previously tested isolated walls. In Specimens R2-1 and R3-1, walls located within the central span while they located within the exterior span in Specimen R3-2. The number of stories and the location of walls were determined for the convenience of test procedure to reproduce design moment diagrams of the bottom walls. The bottom walls in Specimens R2-1, R3-1 and R3-2 were designed to have identical behaviors to those of isolated walls W1-2, W1-4 and W1-6, respectively.

Lateral forces were applied by two hydraulic jacks at the midpoints of steel side beams which were bolted along with the full length of the top beam in the top wall. Axial forces were applied to individual columns as well as boundary columns of walls. The amount of axial stress in an individual column was the same as of a wall section.

Test Results - Figure 5 indicates hysteresis curves of the specimens in terms of the relationship between total lateral force and displacement of the first story. Envelopes of these curves were plotted in Fig. 4 compared with those of the isolated walls.

Specimen R2-1 failed in shear compression on the top corner of the top wall when the displacement of the first story reached 0.0067 rad. The bottom wall, however, reached almost ultimate state in which similar failure would have occurred on the bottom corner of the wall. The local disturbance due to the loading at the top story might have led to the failure on the top wall. In Specimen R3-1, flexural yielding was observed at the displacement 0.004 rad. The wall developed its flexural capacity until the displacement 0.015

rad., thereafter, failed in shear. Specimen R3-2 behaved in a ductile manner until column concrete crushed due to bending at considerably large amount of displacement, 0.033 radian.

Failure modes of the bottom walls of Specimens R3-1 and R3-2 were identical to those of walls W1-4 and W1-6, respectively. The load capacities were higher by 19% and 35% in R2-1 and R3-2 than those of corresponding isolated walls. Apparently, the increased capacity was associated with the existence of adjacent frames, however, R3-1 obtained less capacity than wall W1-4. Reasons were not clarified, however, the larger shear span ratio of the bottom wall during the test might have resulted in less capacity than designed. As shown in Fig. 6, the observed values of $ho/\ell w$ which were determined on the basis of the recorded strain distribution in columns and walls had been 1.4 or more instead of the value 1.2 of W1-4. Ductilities were much larger than those of walls. It appeared to be one of reasons for this that the bottom wall were free from the local disturbance associated with loading for lateral forces.

ANALYTICAL STUDY ON FRAME-WALL SUBASSEMBLAGES

Behaviors of the frame-wall subassemblages were analyzed by means of a simple approach which used the inelastic beam model extending to walls. The approach selected herein has been developed by the authors for the purpose of structural design of reinforced concrete buildings having multistory walls.

Analytical Procedure - The emphasis was directed toward; (1) to idealize walls as well as beams and columns into the inelastic beam element, as shown in Fig. 7, which consisted of an elastic beam and rigid-inelastic rotational springs, (2) to classify the behavior types of elements into three categories of F, S and FS, and to provide corresponding hysteresis rules for the end moment-rotation relationship, as shown in Fig. 8, and (3) to determine the values which control the specified hysteresis curves on the basis of experimental results of isolated walls described herein and existing test data or available empirical equations for other members (8).

The skeleton of curves in Fig. 8 was of a "Tri-Linear Model" which had two breaking points representing cracking and flexural yielding or ultimate shear strength (2). In "Degrading Stiffness Model" used for F type elements, the hysteresis rule followed reference 7. In other two models, slip effect of zero stiffness was taken into account for both reloading and unloading. Any types of failure of framing members after flexural yielding due to shear or bond were included within FS Type mode.

Analytical Results - Calculated hysteresis curves are shown in Fig. 5 compared with test results. The findings from the analytical study were summarized as follows: (1) The failure modes were adequately identified and the maximum loads were estimated with small errors, at most 11%. (2) The displacements at the flexural yielding were reasonably estimated with errors less than 15% while the calculated displacement at the shear strength was considerably smaller by 40%. (3) The stiffness at both reloading and unloading appeared to be adequately simulated, however, the calculated slip at the low level of forces was more significant than observed.

The analysis seemed to underestimate the inelastic displacement of the structure when the effect of shear in walls was significant. It was considered be important to evaluate the inelastic stiffness of walls more appropriately to improve this approach be more realistic.

CONCLUSIONS

Test results of both isolated walls and frame-wall subassemblages indicated that (1) the seismic behavior of a structural system having multistory walls may be strongly affected by those of the bottom walls, and (2) the behavior of walls, which were classified into Flexural, Shear, and Flexural and Shear Types in this paper, depend on the level of the flexural capacity or on the ratio A of flexural capacity to the shear capacity estimated by Eq. (3). It must be noticed during the structural design that a wall may behave in a ductile manner when the ratio A is less than 0.86 or the estimated flexural capacity is less than 0.25Fc while a wall may indicate shear failure when A is more than 1.10. The displacements at the yielding or the ultimate shear strength are given by using stiffness reduction factors obtained from equations (4) - (6) corresponding to the behavior types.

The analytical approach proposed herein, which used the inelastic beam model extending to walls and was based on the empirical estimation of restoring force characteristics of members, was acceptable for design purpose since it reasonably evaluated the test result of frame-wall subassemblages, though there have remained several problems to be solved to improve it be more realistic.

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Table 1 List of Test Specimens

Specimen Group No.	Spec. No.	Shear Span Ratio h_o/ℓ_w	Axial Stress *1 σ_o kg/cm^2	Reinforcement Wall *2 (P_s %)	Reinforcement Column (P_g %) *3	Concrete Strength F_c kg/cm^2
W1	1	0.6	0	Welded Wire Fabric 5mm ϕ @ 50 mm (P_s = 0.8%)	Rebar 6-D13 (#4) (P_g = 2.5%)	238
	2	0.9	0			
	3	1.2	0			
	4	1.2	20			
	5	1.8	40			
	6	1.8	20			
	7	2.4	20			
	8	2.4	40			
W2	1	1.2	20	(P_s = 0.8%)	6-D10 (#3) (1.5%) 8-D6 (0.8%)	235
	2	0.9	20			
	3	0.6	0			
	4	1.8	20			
W3	1	1.2	0	W.W.F.4mm ϕ @ 100 (0.25%) W.W.F.9mm ϕ @ 100 (1.5%)	(P_g = 2.5%)	237
	2	1.8	20			
	3	0.9	0			
	4	2.4	40			

*1 σ_o = Axial force/Gross area of a I-section *2 Steel ratio to a wall section *3 Steel ratio to a column section

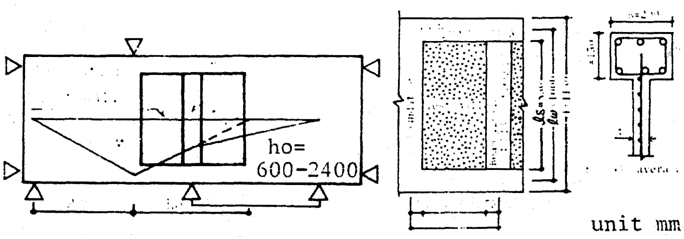


Fig. 1 Test Specimen of Isolated Walls

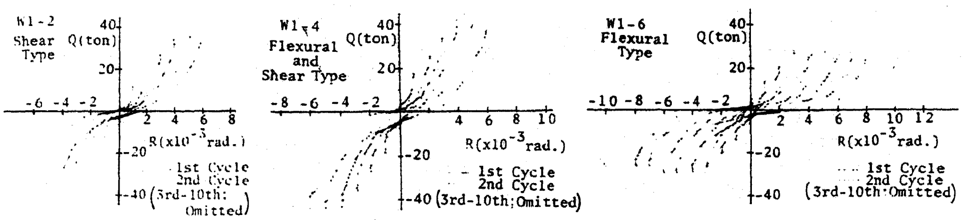


Fig. 2 Typical Hysteresis Curves of Isolated Walls

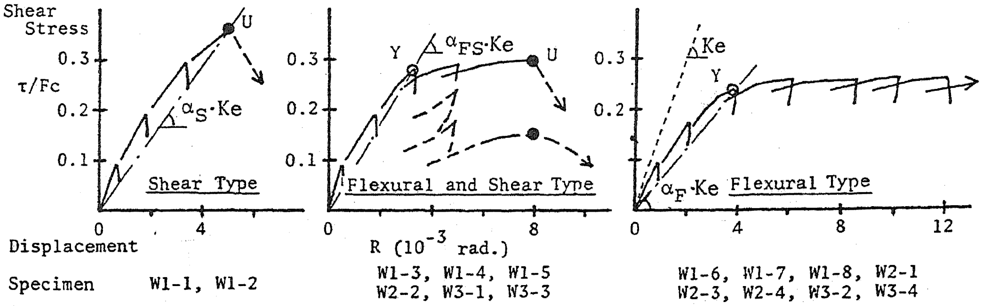
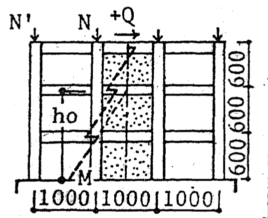
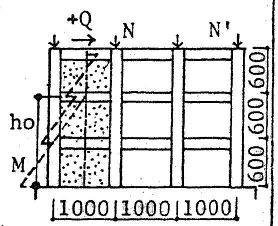
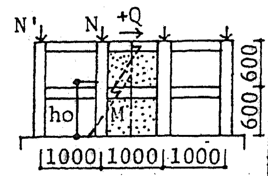


Fig. 3 Summary of Test Results of Isolated Walls

Table 2 Frame-Wall Subassemblages

	Specimen R3-1	Specimen R3-2	Specimen R2-1
Frame			unit mm 
Member	Wall t x w = 50x1000 Ps = 0.8 %	Column b x D = 200x150 Pg = 2.5 %	Beam b x D = 120x150 Pt = 2.1 %
Concrete	Comp. Strength Fc=275 kg/cm^2 (R3-1), 324 (R3-2), 326 (R2-1)		
Reinforce-ment	Main Reinforcement in Column and Beam (D13) fy=3840 kg/cm^2 Shear Reinforcement in Column and Beam (5mmφ) fwy=3970 " Welded Wire Fabric in Wall (5mmφ) fsy=4050 "		

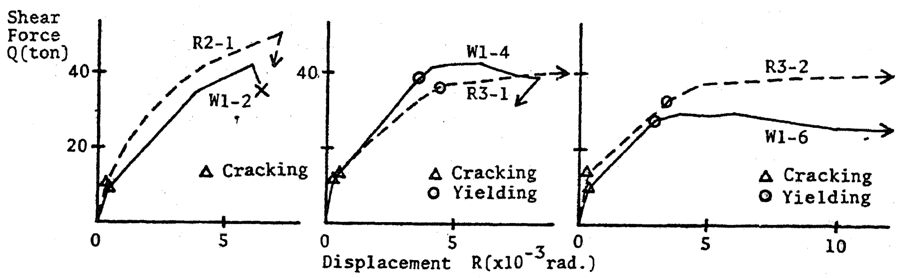


Fig. 4 Envelopes of Hysteresis Curves

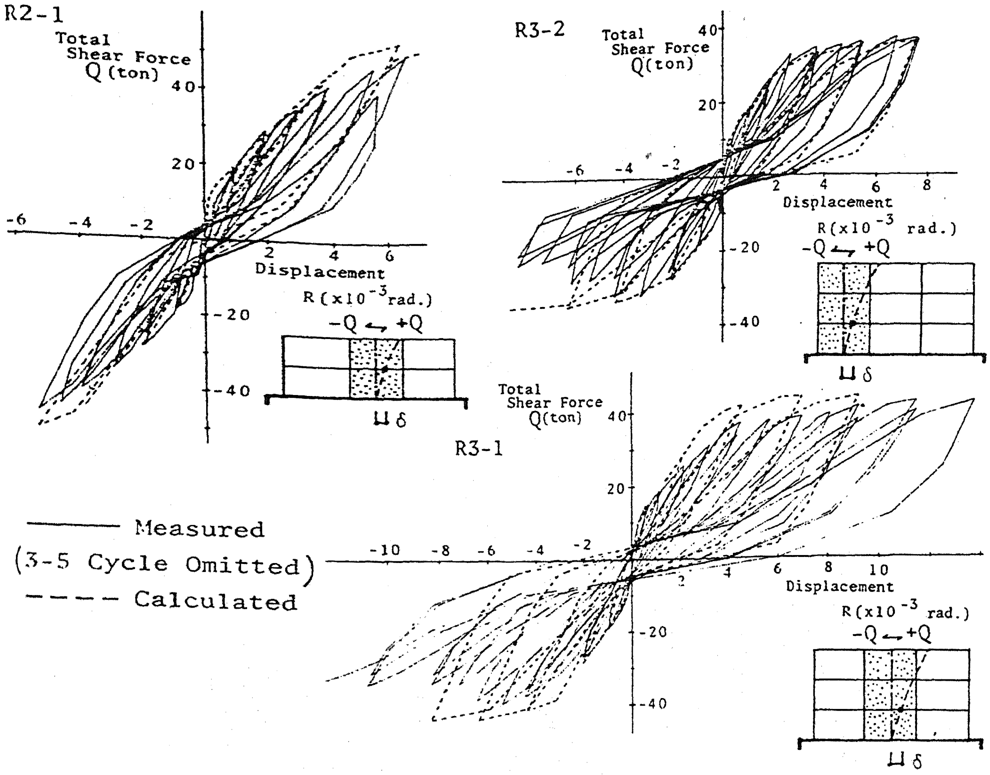


Fig. 5 Total Shear Force vs Displacement (1st Story)

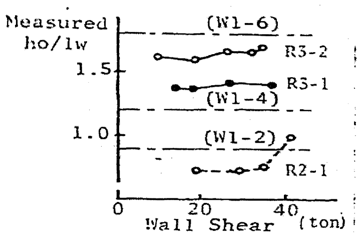


Fig. 6 Observed Shear Span Ratio

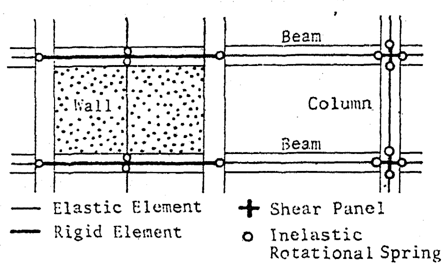


Fig. 7 Analytical Models

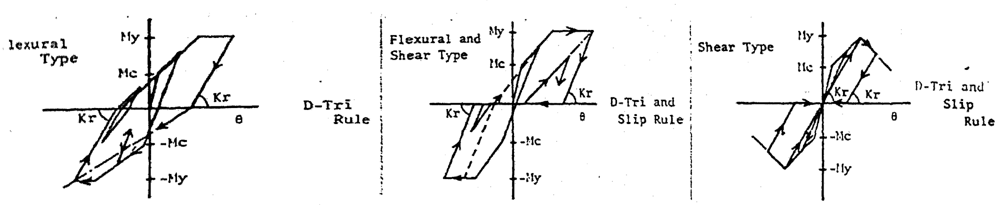


Fig. 8 Idealized Hysteresis Rules for Beam Models