# A STUDY OF ASEISMIC STRENGTHENING FOR MULTI-STORY BRICK BUILDINGS BY ADDITIONAL R/C COLUMNS

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## SUMMARY

This paper presents experimental investigation on 1/2 scale brick walls strengthened by additional reinforced concrete columns with steel tie rods under lateral repeated loading. Three failure modes and corresponding hysteresis loops of such strengthened walls and formulae for calculating their lateral load bearing capacities and stiffnesses are developed. The calculating results are compared with testing data. Finally, recommendations for design of earthquake resistant strengthening are suggested.

## INTRODUCTION

In recent strong earthquakes in China, a lot of brick masonry buildings were seriously damaged or collapsed. Therefore, how to improve and upgrade earthquake resistence of existing brick buildings became an urgent and critical research project. In 1976 Tangshan earthquake, in downtown of Tangshan city where seismic intensity was evaluated as X or above, although some buildings strengthened by additional reinforced concrete columns with tie rods were severely damaged, yet they had no collapse. Following this fact, after Tangshan earthquake, a great number of brick buildings were strengthened by adding additional reinforced concrete columns with tie rods. As a result, it is necessary to identify seismic behavior of such strengthened brick walls.

## SPECIMENS AND PROCEDURE OF TEST

The test specimen is shown schematically in Fig.1. 1/2 scale for length and height of walls and full scale for their thickness were used. For keeping continuity of additional reinforced concrete columns, the height of test specimen is scaled by two-storey building, the test, however, only conducted on the wall in first storey. The test specimens consist of five groups. Three of them, so called "large wall" specimen, have additional reinforced concrete columns with tie rods, and the vertical normal compression stresses are of 2.0, 3.25, and 4.5 $kg/cm^2$ respectively. One of them, so called "small wall" specimen, also has additional reinforced concrete columns with tie rods and vertical normal stress is of 3.25 $kg/cm^2$, its length, however, is half of that of large wall specimen. The rest group, so called "plain wall" specimen, has no additional reinforced concrete columns, and vertical normal stress is of 3.25 $kg/cm^2$, and it is used to compare with the strengthened wall to identify strengthening effect. The sizes of specimens, properties of material and test results are listed in Table 1.

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The test begins with applying constant vertical load to the top of the wall to specified normal stress. The lateral repeated load is applied on the level of first floor (Fig.1), and transmitted to additional columns by wall and tie rods. This is the test procedure so called "push wall" test. Before cracking the test is controlled by load, one cycle for each loading increment. Atfter cracks occurred the test is controlled by deformation, three cycles for each deformation increment which consists of 0.25cm. The horizontal displacement and load-deformation hysteresis loops of walls at the level where lateral repeated load is applied, the strain of the wall surface at middle height of the wall, the strain of the reinforcements at the top and the bottom of the columns, the strain in tie rods and in reinforcements which tied the brick wall and the reinforced concrete columns together are measured in the test.

## CHARACTERESTICS AND MODES OF FAILURE

The observed behavior of strengthened wall in the test can be summarized as follows:

— When cracks in wall mainly depend on the principal stress in it, the wall and columns work together. In this case, it would be convert cross section of columns to that of wall considering a factor of wall-column joint work.

— When the ultimate load reached, the diagonal crack developed to the whole wall (photo 1). At this time, there is no crack in additional column opposite to lateral load, the reinforcements at the bottom of the column are in compression and the stress of reinforcements at the top part of the column next to lateral load is very small (Fig.2,3, and 4). It follows that the ultimate load mainly provided by shear load bearing capacity of the wall and the column opposite to the lateral load.

— In all of specimens, there are shear diagonal cracks in brick wall. For "large wall" specimens with 2.0 $kg/cm^2$ of vertical normal stress and "small wall" specimens with large ratio of height to width, however, horizontal crack was found at wall bottom next to the lateral load. It shows that for such wall the bending effect should be considered in calculating cracking and ultimate loads of the strengthened wall.

— In the stage beyond ultimate load, the magnitude and discending rate of lateral load basically depend on the total elongation and tension capacity of the tie rods at yield point. The tie rods together with additional columns confined brick wall to prevent its collapse and to upgrade its integrity.

— There is no diagonal crack in the area where tie reinforcements were placed. It shows that the stability of the wall can be increased provied tie reinforcements with adequate length are installed.

The experimental investigation mentioned above indicates that there are three essential failure modes for the strengthened walls:

— Bending Shear Failure Before appearance of main diagonal crack in strengthened wall, horizontal crack took place at the bottom of the wall next to lateral load and the bending cracks were found at the bottom of the additional column. The vertical compressive split occurred in triangular brick masonry block and flange opposite to lateral load beyond ultimate load in the second to third displacement increment. The "small wall" specimens ($W_c$IV 1-3) is of this failure mode as shown in Fig.5a.

— Shear Bending Failure Before appearance of main diagonal crack in strengthened wall the horizontal crack partially took place at the bottom of the wall next to lateral load and the bending cracks begin to occur at the lower part of the column closed to lateral load beyond ultimate load in the second to third displacement increment. When the load successively increased, the additional diagonal cracks were found near by original main crack in triangular brick masonry block and flange opposite to lateral load and shear diagonal cracks occurred at the bottom of the column. The "large wall" specimen with 2.0 $kg/cm^2$ of vertical normal stress ($W_c$I 1-4) belongs to this failure mode as shown in Fig.5b.

— Principal Shear Failure The diagonal cracks were found only in the strengthened wall. Shear diagonal cracks appeared at the bottom of the column. In general, the large the vertical normal stress is, the earler the shear crack appeares at the bottom of the column. The "large wall" specimen with 3.25 and 4.5 $kg/cm^2$ of vertical normal stress ($W_c$II 1-4 and $W_c$III 1-3) is of this failure mode as shown in Fig.5c.

## IDENTIFICATION OF FAILURE MODES

In checking earthquake resistance, we have to identify failure modes of strengthened wall since its lateral load bearing capacity depends on failure mode to a great extent.Checking shear strength and eccentric compression should be conducted for both "plain wall" and strengthened wall. The failure mode may be identified by combining minor lateral load bearing capacity. It is possible to have three kinds of combination.

— If lateral load bearing capacity for both plain and strengthened wall depends on results given by checking eccentric compression, the failure mode of strengthened wall belongs to bending shear failure.

—If lateral load bearing capacity for plain and strengthened wall depends on results given by checking eccentric compression and shear strength respectively, the failure mode of strengthened wall is of shear bending failure.

— If lateral load bearing capacity for both plain and strengthened wall depends on results given by checking shear strength, the failure mode of strengthened wall belongs to principal shear failure.

Checking eccentric compression and shear strength may be conducted by following formulae:

For Plain Wall

— Checking eccentric compression (Fig.6a)

$$X = \frac{N}{R_w b} + \left(1 - \frac{b_1}{b}\right) l_1 \qquad (1)$$

$$P = \frac{1}{H}\left[R_w b_1 l_1 \left(\frac{L}{2} - \frac{l_1}{2}\right) + R_w b\,(x - l_1)\left(\frac{L}{2} - \frac{x - l_1}{2}\right)\right] \qquad (2)$$

— Checking shear strength

$$P=R_\tau A_w \quad (3)$$

For Strengthened Wall

— Checking eccentric compression (Fig.6b)

$$X=\frac{N+R_g(A_g-A_g')}{R_w b}+(1-\frac{R_h b_2}{R_w b})l_2+(1-\frac{b_1}{b})l_1 \quad (4)$$

$$P=\frac{1}{H}[-N(\frac{L}{2}+\frac{l_2}{2})+(R_h b_2 l_2+R_g A_g')(L+l_2)+ +R_w b_1 l_1(L+\frac{l_2-l_1}{2})+R_w b(x-l_1-l_2)(L+l_2-\frac{x+l_1}{2})] \quad (5)$$

— Checking shear strength

$$P=R_\tau A_w+R_f l_2 b_2+\frac{1}{\sqrt{3}}R_g A_g \quad \text{or}$$
$$P=[(1-\frac{H}{2L})R_j+f\sigma_0]A_w+R_f l_2 b_2+\frac{1}{\sqrt{3}}R_g A_g \quad (6)$$

Where X denotes the height of compression zone, P the ultimate load, $R_w$ the compression strength of brick masonry, $A_w$ the net cross section of brick wall, $R_j$ the shear strength of brick masonry, $R_\tau=R_1\sqrt{1+\sigma_0/R_1}$, $R_1$ the tension strength of brick masonry and usually $R_1=R_j$ (Since actual compression strength $R_w$ is larger than $\overline{R_w}$ given by "Design Code for Brick Masonry Structures", $R_1=0.84(R_w/\overline{R_w})R_j$ is used based on finite element analysis), $\sigma_0$ the vertical normal stress in brick wall, $R_g$ the tension yield strength in longitudinal reinforcements of the column. $A_g$ the cross section of longitudinal reinforcements in a column, $A_g'$ the cross section of longitudinal reinforcements in compression zone of the column, $R_h$ the bending compression strength of column concrete, $R_f$ the cracking strength of column concrete, and f the friction factor of brick masonry. In general case, f=0.7, and according to skeleton curve of plain wall f=0.8 was used in this paper. When lateral load is applied directly to the column(so called "push Column" test), it is necessary to replace $R_f b_2 l_2+1/\sqrt{3}\,R_g A_g$ in Eq.6 with $2/\sqrt{3}\,R_g A_g$. The failure modes of plain and strengthened wall are determined by the failure mode corresponding to minor ultimate load calculated by Eq.2,3 and 5,6 respectively.

## FORMULAE FOR CALCULATING LATERAL LOAD BEARING CAPACITY

The lateral cracking load $P_k$ and ultimate load $P_u$ of strengthened wall can be calculated by following formulae, except bending shear failure in which case $P_u$ should be determined by checking eccentric compression.

$$P_k=\frac{R_\tau}{\xi}A_w'(1+s) \quad \text{or}$$
$$P_k=(R_j+f\sigma_0)A_w'(1+s) \quad (7)$$
$$P_u=[(1-\frac{H}{2L})R_j+f\sigma_0]A_w'+R_f l_2 b_2+\frac{1}{\sqrt{3}}R_g A_g \quad \text{or}$$
$$P_u=R_\tau A_w'+R_f l_2 b_2+\frac{1}{\sqrt{3}}R_g A_g \quad (8)$$

For $P_k$ and $P_u$ the minor values are used. In Eq.7 and 8, $s=\eta\frac{G_c}{G_w}\frac{2A_c}{A_w'}$, $A_w'$ denotes effective shear resistant cross section of brick wall given by Table 2, $A_c$ the cross section of a column, $G_w$ the shear modulus of brick masonry, $G_c$ the shear modulus of column concrete, the ununiform distribution factor for shear stress, for rectangular cross section $\xi$=1.2, and $\eta$ the wall-column joint work factor, $\eta$=0.05H/L+0.2.

The testing and calculating results for lateral cracking and ultimate load of 16 specimens conducted in present experiment are listed in Table 1, where calculating values are worked out by formulae suggested in this paper. It shows that calculating results are well consistent with testing data for ultimate load. As regard to cracking load, however, calculating and testing results are different significantly, since cracking load is observed at a stage beyond initial cracking. Comparison between testing and calculating results for 35 similar specimens tested in this country are shown in Fig.8. It shows that for lateral ultimate load calculating results are also well consistent with testing data

## HYSTERESIS LOOP MODELS AND CALCULATING FORMULAE FOR STIFFNESS

For the wall with bending shear failure mode, such as "samll wall" specimen, its skeleton curve can be reasonably well approximeted as three straight lines as shown in Fig.9b, and its hysteresis loop belongs to stiffness-degrading type, as shown in Fig.9a. For walls with other failure modes, such as "large wall" specimen, its skeleton curve can be reasonably well approximated as four straight lines with negative stiffness, and its hysteresis loop also is stiffness-degrading type, as shown in Fig.10a and 10b. The initial stiffness of strengthened wall can be calculated by following formula :

$$k_o = \frac{\lambda G_W A_W'(1 + s)}{H} \left[1 + 0.35 \left(\frac{\sigma_0}{\sigma'} - 1\right)\right] \qquad (9)$$

Where $\lambda = 1/\left[1 + \frac{4 G_W A_W'(1 + s) H^2}{12 E_W J_c \zeta}\right]$, $J_c = 2\eta \frac{E_c}{E_W}\left(\frac{L + l_2}{2}\right)^2 A_c + \frac{1}{12} b_2 (L + l_2)^3$,

$\zeta = 1.2$, $\sigma' = 3.5$ kg/cm$^2$. The stiffnesses of second and third straight lines in the skeleton curve are of $k_1 = 0.058\ k_o$ and $k_2 = -0.0176\ k_o$ for strengthened wall with bending shear failure mode, and $k_1 = 0.11\ k_o$ and $k_2 = (P_p - P_u)/\Delta_{gl}$ for other failure modes. Where $P_p = f\sigma_o A_W + R_{gl} A_{gl}$, $R_{gl}$ denotes the tension yield strength of tie rod, $A_{gl}$ the total cross section of tie rods, and $\Delta_{gl}$ the total elongation of tie rods at the yield point.

The calculating and testing results of stiffness for tested wall also listed in Table 1. We can see from this table that they are consistent well except a few wall specimens.

## CONCLUSION AND RECOMMENDATION

— The experimental invertigation discribed in this paper shows that there are three failure modes for the wall strengthened by reinforced concrete columns with tie rods, they are bending shear failure, shear bending failure and principal shear failure. The lateral load bearing capacity and hysteresis loop of strengthened walls are closely related to failure modes. Therefore in checking seismic resistance, the failure mode should be identified.

— The formulae for calculating lateral load bearing capacity, stiffness and hysteresis loop of strengthened wall are recommended. The comparison indicates that a reasonably good correlation exists between calculating results and testing data.

— The effect of longitudinal wall should be considered in seismic analysis for transversal wall. The width of the flange $b_1$ is detedmined by the least value among the width of pier wall, $6\ l_1 + b$, and $L/2$. The tie reinforcements with 1.5 m of length should be placed in two courses each storey. The foundation of column may be designed by lifting tension force $T = R_g A_g$.

## ACKNOWLEDGMENT

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TABLE 1 SPECIMEN DESCRIPTION AND TESTING AND CALCULATING RESULTS

| number of specimen | dimension & property of brick wall | | | | | mark of concrete | steel tie rods | normal stress in wall | cracking load (t) | | | ultimate load (t) | | | initial stiffness $k_c$ x$10^5$ (kg/cm) | | | testing method | notes |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | L (m) | mark of mortar | $R_w$ (kg/cm$^2$) | $R_j$ (kg/cm$^2$) | $E_w$ x$10^4$ (kg/cm$^2$) | | | $\sigma_o$ (kg/cm$^2$) | test | cal. | cal./test | test | cal. | cal./test | test | cal. | cal./test | | |
| $W_c$ I-1 | 480 | 26.0 | 49.34 | 2.10 | 3.1 | 232 | 2¢12 | 2.00 | 37.40 | 37.65 | 1.01 | 44.64 | 44.84 | 1.00 | — | — | — | push column | for all specimens: |
| $W_c$ I-2 | 480 | 27.3 | 49.34 | 2.10 | 3.1 | 232 | 2¢12 | 2.00 | 41.58 | 37.65 | 0.91 | 42.31 | 44.84 | 1.06 | — | — | — | | |
| $W_c$ I-3 | 480 | 19.6 | 61.12 | 1.73 | 4.0 | 180 | 2¢14 | 2.00 | 40.10 | 32.83 | 0.82 | 46.28 | 46.65 | 1.01 | 14.92 | 14.30 | 0.96 | push wall | b= 24cm |
| $W_c$ I-4 | 480 | 25.8 | 61.12 | 2.03 | 4.0 | 180 | 2¢14 | 2.00 | 43.88 | 36.01 | 0.82 | 50.49 | 49.80 | 0.99 | 14.92 | 14.30 | 0.96 | | $l_1$= 24cm<br>$b_1$= 49cm |
| $W_c$II-1 | 480 | 12.4 | 55.73 | 1.35 | 3.9 | 213 | 2¢12 | 3.25 | 58.17 | 48.16 | 0.83 | 62.30 | 59.93 | 0.96 | 16.77 | 15.98 | 0.96 | | $l_2$= 15cm |
| $W_c$II-2 | 480 | 16.8 | 55.73 | 1.56 | 3.9 | 213 | 2¢14 | 3.25 | 59.42 | 51.57 | 0.87 | 67.62 | 62.22 | 0.92 | 16.67 | 15.98 | 0.94 | | $b_2$= 24cm |
| $W_c$II-3 | 480 | 10.6 | 55.73 | 1.35 | 3.9 | 213 | 2¢14 | 3.25 | 61.42 | 49.07 | 0.80 | 65.63 | 59.93 | 0.91 | 16.89 | 15.98 | 0.95 | | H= 134cm<br>$E_c$= 1.8x$10^6$ (kg/cm$^2$) |
| $W_c$II-4 | 480 | 20.7 | 61.12 | 1.77 | 4.0 | 180 | 2¢14 | 3.25 | 65.25 | 58.05 | 0.89 | 67.82 | 66.47 | 0.98 | 10.65 | 16.82 | 0.63 | | |
| $W_c$III-1 | 480 | 17.1 | 55.73 | 1.58 | 3.9 | 171 | 2¢14 | 4.50 | 70.95 | 56.01 | 0.79 | 77.67 | 73.92 | 0.95 | 20.07 | 18.03 | 0.92 | | $R_g$= 2517 (kg/cm$^2$) |
| $W_c$III-2 | 480 | 14.8 | 55.73 | 1.46 | 3.9 | 171 | 2¢14 | 4.50 | 65.06 | 54.00 | 0.83 | 74.58 | 72.62 | 0.97 | 19.52 | 18.03 | 0.92 | | $E_g$= 2.1x$10^6$ (kg/cm$^2$) |
| $W_c$III-3 | 480 | 15.6 | 55.73 | 1.50 | 3.9 | 171 | 2¢14 | 4.50 | 64.16 | 54.67 | 0.85 | 70.57 | 73.05 | 1.04 | 9.33 | 18.03 | 0.52 | | $R_{gl}$= 235[illegible] (kg/cm$^2$) |
| $W_c$IV-1 | 240 | 20.7 | 60.49 | 1.77 | 3.1 | 186 | 2¢14 | 3.25 | 25.91 | 23.86 | 0.92 | 31.03 | 33.53 | 1.08 | 5.11 | 4.97 | 0.97 | | |
| $W_c$IV-2 | 240 | 17.7 | 60.49 | 1.61 | 3.1 | 186 | 2¢14 | 3.25 | 21.86 | 22.33 | 1.02 | 30.20 | 33.53 | 1.11 | 4.61 | 4.97 | 1.08 | | $E_{gl}$= 2.1x$10^6$ (kg/cm$^2$) |
| $W_c$IV-3 | 240 | 14.4 | 60.49 | 1.43 | 3.1 | 186 | 2¢14 | 3.25 | 25.30 | 21.49 | 0.85 | 27.26 | 33.53 | 1.23 | 4.60 | 4.97 | 1.08 | | mark of brick 10[illegible] |
| W V-1 | 480 | 26.8 | 61.12 | 2.07 | 4.0 | — | — | 3.25 | 63.17 | 59.04 | 0.93 | 63.80 | 59.04 | 0.93 | 16.80 | 15.51 | 0.92 | | longi[illegible]nal reinforcement: |
| W V-2 | 480 | 19.4 | 61.12 | 1.70 | 4.0 | — | — | 3.25 | 60.05 | 53.85 | 0.90 | 61.20 | 53.85 | 0.88 | 13.77 | 15.51 | 1.13 | | 4[illegible] |

TABLE 2 EFFECTIVE SHEAR RESISTANT CROSS SECTION OF BRICK WALL ( $A_W'$ )

| failure mode | cracking load | ultimate load | initial stiffness |
|---|---|---|---|
| I | 0.8 L b | —— | 0.8 L b |
| II | | L b | L b + 2($b_1$-b)$l_1$ |
| III | L b + 2($b_1$ − b) $l_1$ | | |

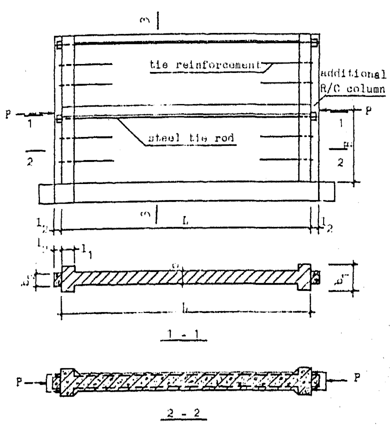


Fig.1 Test specimen

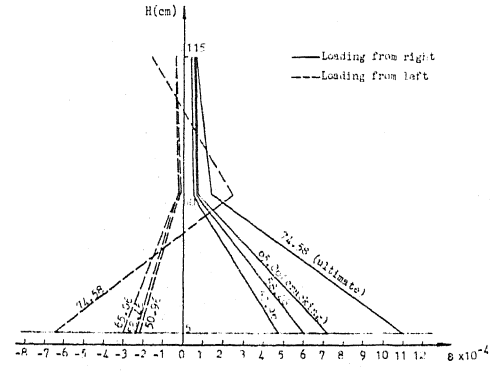


Fig.2 Stress distribution of longitudinal reinforcement

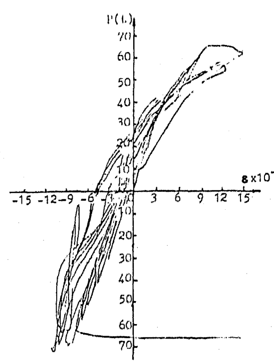


Fig.3 Hysteresis loop of strain in longitudinal reinforcement at the bottom of the column

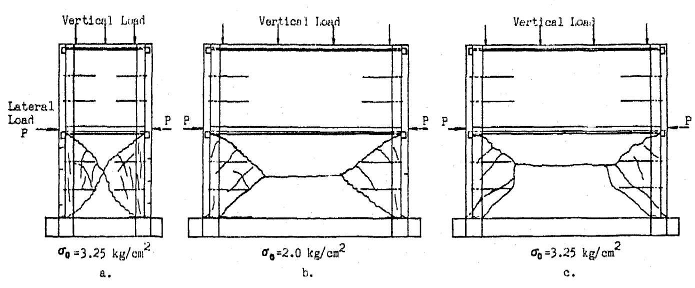


Fig.5 Failure modes of strengthened wall

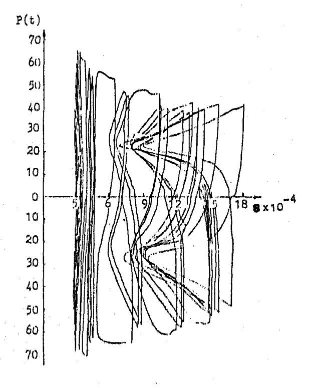


Fig.4 Hysteresis loop of strain in steel tie rod

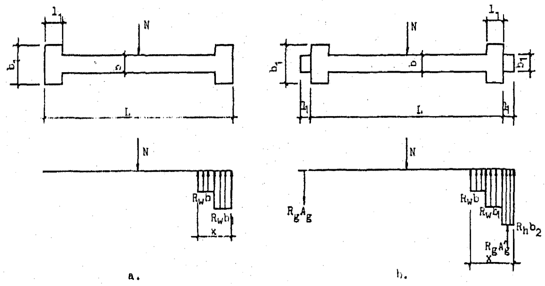


Fig.6 Normal stress distribution of the cross section of brick wall when checking eccentric compression

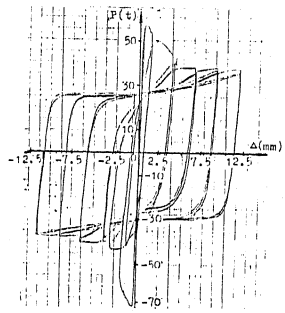



Fig.7 Hysteresis loop of displacement of the plain wall

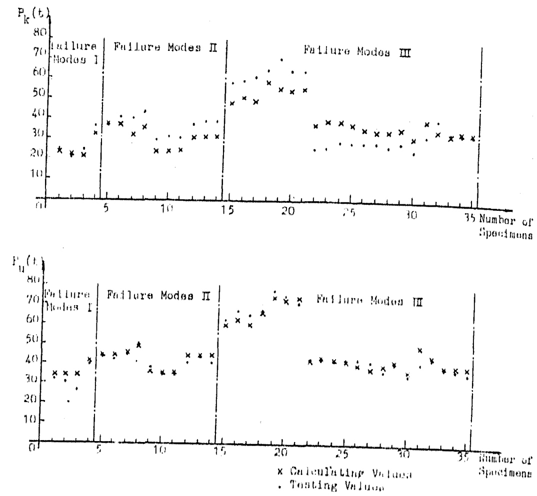



Fig.8 Comparison between testing and calculating values for cracking and ultimate lateral load

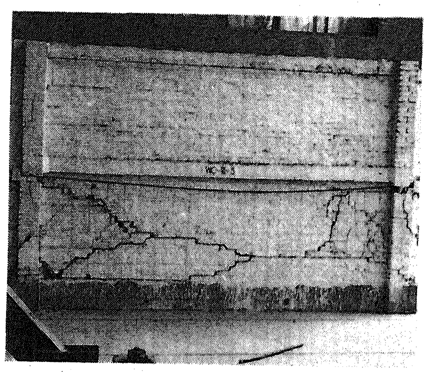
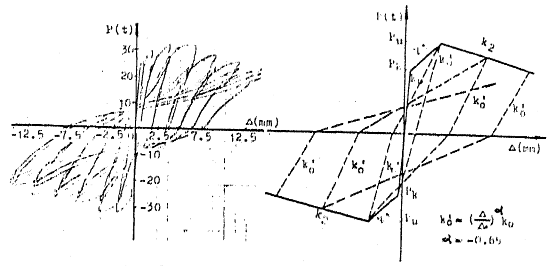


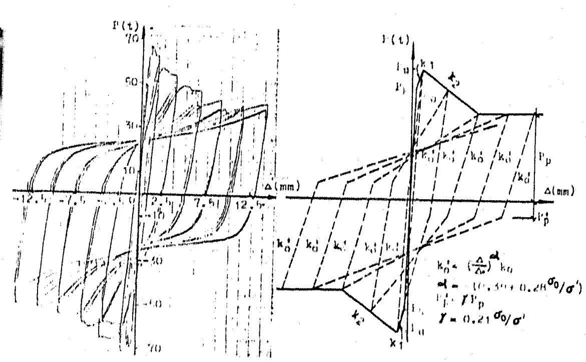
Photo 1 Failure of specimen




a. tested b. Calculated

Fig.9 Hysteresis loop of displacement in "small wall" specimen

Photo 2 Failure at the bottom of the column




a. tested b. calculated

Fig.10 Hysteresis loop of displacement in "Large wall" specimen with $\sigma_0 = 4.5$ kg/cm$^2$