

SEISMIC ASSESSMENT AND ITS VERIFICATION OF DAMAGED LOW-RISE RC BUILDINGS IN TAIWAN CHI-CHI EARTHQUAKE

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Abstract

In first part of this paper, the seismic capacities of brick wall and RC wall are proposed by a rational crack path concept. For brick wall subjects to in-plane lateral load, the anti-symmetric crack paths start from two opposite corners and go along stair steps of brick-mortar interface until these two crack paths meet the central line of the wall, and then connect with each other horizontally or vertically. For RC wall subjects to in-plane lateral load, the crack path starts from top corner and inclines 45-degree to the bottom of the wall, and then propagates horizontally through the whole wall bottom. The ultimate shear capacity of brick wall or RC wall may be calculated from the complete crack path. In the second part of this paper, a simple seismic assessment method is proposed. Assuming shear-building mode and using the sum of $Q-\Delta$ curves of RC wall, brick wall and RC column, four low-rise RC buildings which collapsed or moderately damaged in the Chi-Chi Earthquake are illustrated to verify the assessment results.

INTRODUCTION

The structural system of the traditional street buildings in Taiwan is rather unique. The width of each unit is about 4.5m. The depth of each unit is from 15m to 23m. In general, it is 3 to 4 stories in height. There is a pedestrian corridor on ground story. The ground story is used as commercial; the second story and above are used as residential. The seismic capacity of the traditional low-rise street building in Taiwan depends tremendously on the amount of shear wall in the direction of assessment. Because there are lots of shear walls in the direction perpendicular to street; but few walls in the direction parallel to street. So the seismic resistance in the direction perpendicular to street is very strong but rather weak in the direction parallel to street.

The structural system of RC school building in Taiwan is very similar to that of street building. That is classroom on one side and corridor on the other side. There are many shear walls in the direction perpendicular to corridor but few walls in the direction parallel to corridor. Almost all the shear walls of street building and school building in Taiwan were made of brick before 1980. And then transferred to RC walls gradually due to increase of labor cost after 1980. Now most of the walls of street building and school building are made of RC. The in-plane shear capacities of brick wall and RC wall are

introduced in this paper by a rational crack path concept. The calculation of $Q-\Delta$ curve for RC columns and the seismic assessment method using shear-building mode had been introduced at Sheu et al [*1]. They will not be reported again herein. Three low-rise RC buildings, which collapsed or moderately damaged in the Taiwan Chi-Chi Earthquake 1999, are illustrated to verify the assessment method in this paper. Another reinforced brick street building designed according to the Taiwan Building Code is used to demonstrate the seismic performance evaluation by the assessment method in this paper.

Q-Δ CURVE OF BRICK WALL UNDER LATERAL LOAD

In general, when subject to in-plane lateral force, brick shear wall fails by stair-step likely inclined cracks. After many experimental and field observations, the inclined shear crack path might be classified into 3 patterns as shown in Fig.1 [*2, *3]. For four-side confined wide brick wall as shown in Fig. 1(a), two anti-symmetric cracks initiate from two opposite corners and then go stair-step likely until they meet horizontal central line of the wall. Finally, a horizontal crack along closest central line of mortar interface connects these two stair-step cracks. For four-side confined narrow brick wall as shown in Fig. 1(b), these two anti-symmetric cracks will terminate at vertical central line of wall. Finally, a vertical crack has to connect them along closest vertical central line of mortar interface. However, half of the vertical crack in Fig.1 (b) goes along vertical mortar interface but the other half of the vertical crack has to split the brick obstructing on the crack path. For three-side confined brick wall as shown in Fig. 1(c), crack path can not be anti-symmetric. One half of the anti-symmetric crack will stop at the centroid of the wall and then goes along horizontal mortar interface to the free side of the wall.

The slope angle of inclined stair-step, θ , is different for different lay out of the brick blocks such as Flemish bond ($\theta \doteq 21^\circ$), English bond ($\theta \doteq 30^\circ$), and stretching bond ($\theta \doteq 29^\circ$) etc. The sum of the lateral forces to accomplish a complete inclined crack is the ultimate lateral capacity of the brick wall. The ultimate lateral capacity of brick wall is consisted of 3 components: frictional strength of horizontal mortar interface, tensile strength of vertical mortar interface, and vertical splitting strength of brick block. The ultimate strength of these 3 components may be calculated as follows from regression of experimental data [*2, *3].

The ultimate frictional strength of horizontal mortar interface is:

$$t_f = 0.022(f_m')^{0.9} + 0.189(f_m')^{0.322} \cdot S_n \quad (1)$$

The ultimate tensile strength of vertical mortar interface is:

$$f_{mbt} = 0.103(f_m')^{0.329} \quad (2)$$

The ultimate vertical splitting strength of brick block is:

$$f_{bt} = 0.22f_b' \quad (3)$$

where f_m' and f_b' are compression strength of mortar block and brick block, (MPa); S_n is normal compression stress acting on brick wall (MPa). The units of t_f , f_{mbt} , and f_{bt} are in (MPa).

So the ultimate lateral capacity of brick wall in Fig.1 (a) is:

$$Q_u = t \cdot (W \cdot t_f + fH \cdot f_{mbt}) \quad (4)$$

The ultimate lateral capacity of brick wall in Fig.1 (b) is:

$$Q_u = t \cdot [W \cdot t_f + fW \tan q \cdot f_{mbt} + f(H - W \tan q)(f_{mbt} + f_{bt})/2] \quad (5)$$

The ultimate lateral capacity of brick wall in Fig.1 (c) is:

$$Q_u = t \cdot (W \cdot t_f + 0.5fH \cdot f_{mbt}) \quad (6)$$

in which t is the thickness of brick wall (mm); W and H are the net width and net height of brick wall (mm); f is reduction factor due to construction quality and tensile brittle failure and taken as 0.9; Q_u is ultimate capacity of brick wall in (N).

The ultimate lateral deflection of brick wall is [*4]:

$$\Delta_u = \frac{Q_u}{E_u t} \left\{ \frac{H}{W} \left[2.375 + 2 \left(\frac{H}{W} \right)^2 \right] + 3 \left(\frac{W}{H} \right) \right\} \quad (7)$$

and $E_u = 582c\sqrt{f_b}$ (8)

where $c = 0.161(W/H)^{0.99}$ for 3 sides confined; $c = 0.269(W/H)^{1.82}$ for 4 sides confined; E_u is the secant modulus of elasticity at ultimate point (MPa); Δ_u is in (mm) and no more than $0.01 H$.

Once the ultimate point (Δ_u, Q_u) is located, the equation of entire lateral load-deflection $Q-\Delta$ curve is regressed as polynomial:

$$Q = Q_u \left[3 \left(\frac{\Delta}{\Delta_u} \right) - 3 \left(\frac{\Delta}{\Delta_u} \right)^2 + \left(\frac{\Delta}{\Delta_u} \right)^3 \right] \quad (9)$$

Fig.2 shows the $Q-\Delta$ curves of a group of brick walls with 4 sides confined. The thickness and net height are 230mm and 3000 mm for all walls. The net width changes from 1000mm to 6000mm. It shows Q_u not necessarily proportional to W . Q_u is maximum when $W = 3000$ mm. For W greater than 3000mm, the stronger vertical splitting crack path is getting smaller and transferring into weaker horizontal friction path. For $W = 5000$ mm, the vertical splitting crack path disappears. So Q_u becomes minimum. Once $W > 5000$ mm, the horizontal frictional path is getting longer to provide some more additional capacity.

Q-Δ CURVE OF RC WALL

RC wall is considered as a big column for flexural strength with point of inflection located at $0.75H$.

But its shear capacity is calculated in different way from general column. In elastic stage, Q - Δ curve of RC wall is linear. From crack point to ultimate point, it is proposed as logarithmic curve in this paper. The crack load Q_c is the minimum of flexural crack load and shear crack load. The ultimate load Q_u is also the minimum of flexural ultimate load and shear ultimate load. That is:

$$Q_c = \min(Q_{fc}, Q_{sc}) \quad (10)$$

$$Q_u = \min(Q_{fu}, Q_{su}) \quad (11)$$

where $Q_{fc} = 1.33 \frac{M_{cr}}{H}$ (12)

$$Q_{sc} = 0.167 \sqrt{f_c'} A_g \left(1 + 0.0714 \frac{N}{A_g} \right) \cdot \left[1 - 0.1 \left(1.9 \frac{H}{W_T} - 2.6 \right) \left(1 + 2 \frac{A_g'}{A_g} \right) \right] \quad (13)$$

$$Q_{fu} = 1.33 \frac{M_u}{H} \quad (14)$$

$$Q_{su} = Q_{sc} + Q_{ss} \quad (15)$$

M_{cr} and M_u are crack and ultimate bending moments of wall when considered as a big column (N-mm); A_g is the gross cross-sectional area of wall including boundary columns (mm^2); A_g' is the gross cross-sectional area of boundary columns (mm^2); W_T is the total width including boundary columns (mm). In Equ. (15), Q_{ss} is the shear capacity contributed by all the reinforcement of wall and columns across diagonal crack path as shown in Fig.3 and calculated by Equ. (16):

$$Q_{ss} = 0.324(A_{ch} f_{fh} + A_{wh} f_y + A_{v1} f_y) + 0.48(A_{v2} f_y + N) \quad (16)$$

In which A_{ch} and A_{wh} are hoop of column and horizontal reinforcement of wall cut by 45 degree inclined path (mm^2); A_{v1} is the total vertical reinforcement of column and wall cut by 45 degree inclined path (mm^2); A_{v2} is the vertical reinforcement of wall and columns cut by horizontal path (mm^2); f_{yh} and f_y are yield strength of column hoop and other rebars (MPa); N is normal load acting on the wall (N).

The lateral deflection at crack point or ultimate point is the sum of corresponding flexural deflection plus shear deflection. For flexural deflection, the point of inflection is assumed at $0.75H$ from bottom of RC wall. For conservative concern, Δ_u of RC wall is no more than $0.015H$.

$$\Delta_c = \Delta_{fc} + \Delta_{sc} \quad (17)$$

$$\Delta_u = \Delta_{fu} + \Delta_{su} \quad (18)$$

where
$$\Delta_{fc} = \frac{H^3 Q_c}{6.86(0.3E_c I_g)} \quad (19)$$

$$\Delta_{fu} = \frac{H^3 Q_u}{6.86(cE_c I_g)} \quad (20)$$

$$c = 0.0012 \frac{H}{W_T} + 0.0693 \frac{r_v f_y}{f_c'} + 0.0048 HW_T - 0.278 \frac{A_b'}{A_g} + 0.2359 \frac{I_b'}{I_g} \quad (21)$$

$$\Delta_{sc} = \frac{2.4HQ_c}{0.33E_c A_g} \quad (22)$$

$$\Delta_{su} = \frac{3.3HQ_u}{cE_c A_g} \quad (23)$$

In which, r_v is the reinforcement ratio of vertical rebars of wall; A_b' is the cross-sectional area of boundary columns in the portion protruding from wall (mm^2); I_b' is the moment of inertia for A_b' with respect to neutral axis (mm^4); the unit of HW_T is in (m^2); E_c is modulus of elasticity of concrete and taken as $4700\sqrt{f_c'}$ in (MPa).

The Q - Δ curve between crack point of wall and ultimate point of wall may be regressed as a logarithmic equation [*4]:

$$Q = \frac{Q_u - Q_c}{\ln(\Delta_u) - \ln(\Delta_c)} (\ln \Delta) + \frac{Q_c \cdot \ln(\Delta_u) - Q_u \cdot \ln(\Delta_c)}{\ln(\Delta_u) - \ln(\Delta_c)} \quad (24)$$

ILLUSTRATED EXAMPLES OF STREET BUILDING

From field observations of the damaged low-rise RC buildings [*5] and from shaking table tests of small scale RC building structures [*6], it is believed that shear-building model is reasonable for seismic assessment of low-rise RC building. The details of the assessment method had been presented by Sheu et al [*1]. The same assessment method is employed here to verify the damage conditions of 3 low-rise RC buildings after the Taiwan Chi-Chi Earthquake 1999. The same assessment method is also used to demonstrate the seismic performance evaluation of a reinforced brick street building designed according to the tentative Taiwan Building Code.

[Example 1] collapse of a 5-story single street building at Tong-Su Town

Fig.4 shows the plan, elevation, column reinforcement, and collapse photo of the single bay street building at Tong-Su Town. Fig.5 is the Q - Δ curves in x-direction for each vertical RC column. Fig.6 is the seismic performance diagram of this street building. From this diagram, the analytical collapse ground acceleration is 0.168g. But the actual EPA of the Chi-Chi Earthquake from record of the Central Weather Bureau (CWB) was 0.477g. This was the reason why it collapsed.

[Example 2] collapse of a 3-story row street building at Chu-San Town

Fig.7 shows the plan, elevation, column reinforcement and collapse photo. Fig.8 shows the seismic performance diagram of this building. The analytical collapse ground acceleration is 0.07g. But the actual EPA of the Chi-Chi Earthquake from record of the CWB was 0.38g.

[Example 3] moderate damaged row street building at In-Lin County

Fig.9 is the plan of a 3-story row street building located at In-Lin County. Fig.10 is the seismic performance diagram of this building. The analytical collapse ground acceleration is 0.38g. The actual EPA of the Chi-Chi Earthquake from record of the CWB was 0.27g.

[Example 4] demonstration for seismic performance of a 3-story reinforced brick street building

The so-called reinforced brick building in Taiwan is different from that in America or Europe. Fig.11 is the typical plan of a 3-story reinforced brick row street building designed according to the tentative Taiwan Building Code. For this type of building, brick wall is laid out first. Two weeks later, the concrete of RC column, RC beam, and RC slab is poured. Once concrete shrinks, the brick wall inside the RC frame will get confinement compression force to increase the frictional strength. Fig.12 is the seismic performance diagram of this brick street building with $f_c'=20.6\text{MPa}$; $f_b'=14.7\text{MPa}$; $f_m'=9.8\text{MPa}$; $f_y=274\text{MPa}$. It shows that if street building is designed according to the descriptive rules of the tentative Taiwan Building Code without any structural analysis, the collapse EPA of the brick street building is about 0.37g.

CONCLUSIONS

1. The ultimate shear capacity of brick wall and RC wall may be calculated by the crack path concept proposed in this paper.
2. The proposed seismic assessment method, by assuming shear-building mode, is feasible for low-rise RC buildings. It has been verified with some actual street buildings and school buildings damaged in the disaster area of the Chi-Chi Earthquake, Taiwan, 1999.
3. The proposed assessment method may be used for seismic performance evaluation for low-rise RC buildings w/o shear wall.
4. Once verification with some more damaged low-rise RC buildings is finished, a simple chart for quick check of collapse EPA will be provided.

ACKNOWLEDGMENT

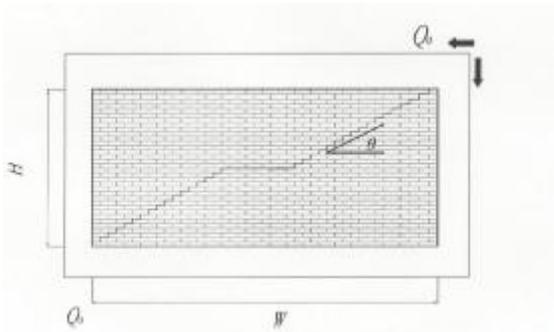
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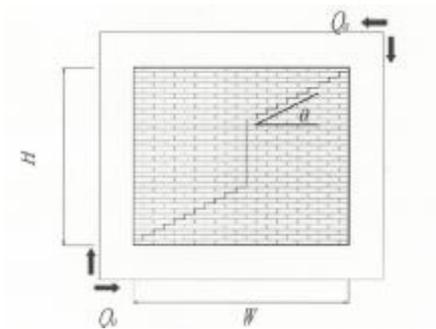
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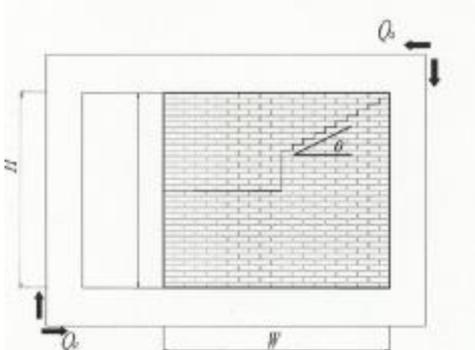
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(a) $\tan \theta \geq H/W$ (4-side confined)



(b) $\tan \theta \leq H/W$ (4-side confined)



(c) Brick Wall with 3-Side Confined

Fig.1 Crack Paths of Confined Brick Walls under In-Plane Force

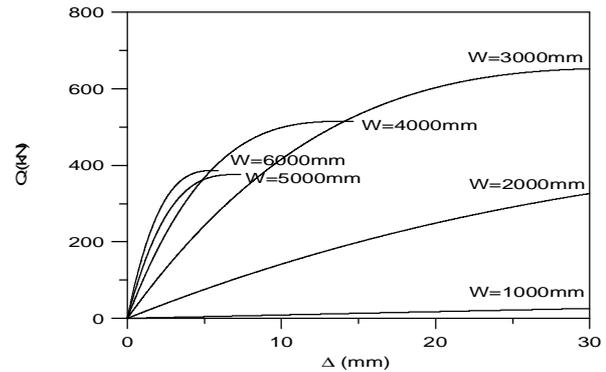
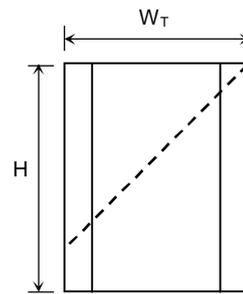
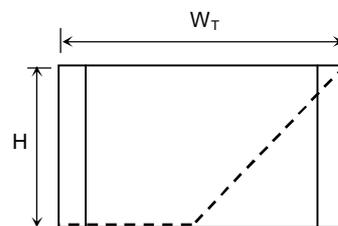


Fig.2 $Q-\Delta$ Curves of Brick Walls with 4-Side Confined

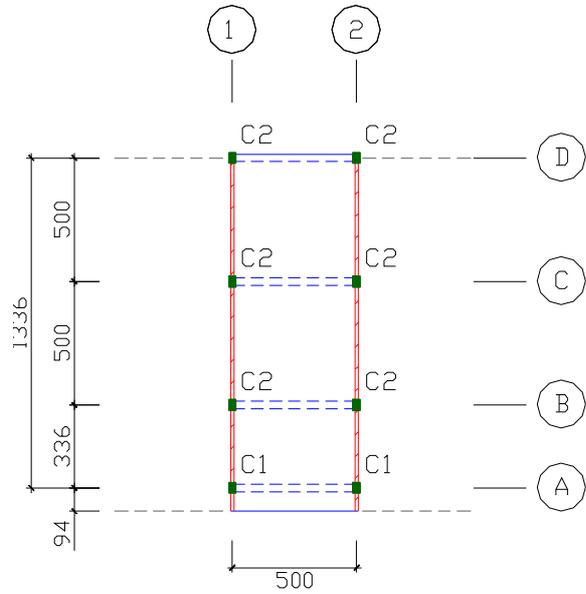


(a) High-rise Shear Wall

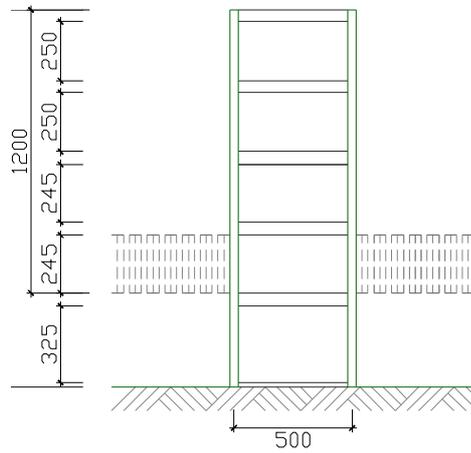


(b) Low-rise Shear Wall

Fig.3 Crack Paths of RC Walls under In-Plane Force



(a) Typical Structural Plan



(b) Frame Elevation

C1	C2
×10-#6	×12-#6
□#3@25	□#3@25
30×45	30×45

(c) Reinforcement of Second Floor Columns

Fig.4 Collapse Single Street Building at Tong-Su



(g) Photo Before Earthquake



(h) Photo After Earthquake

Fig.4 Collapse Single Street Building at Tong-Su (continued)

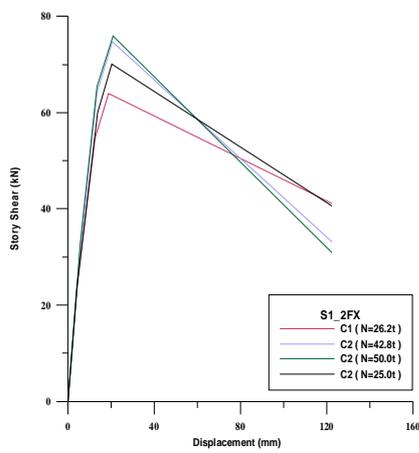


Fig.5 $Q-\Delta$ Curves of Each Column on Second Story

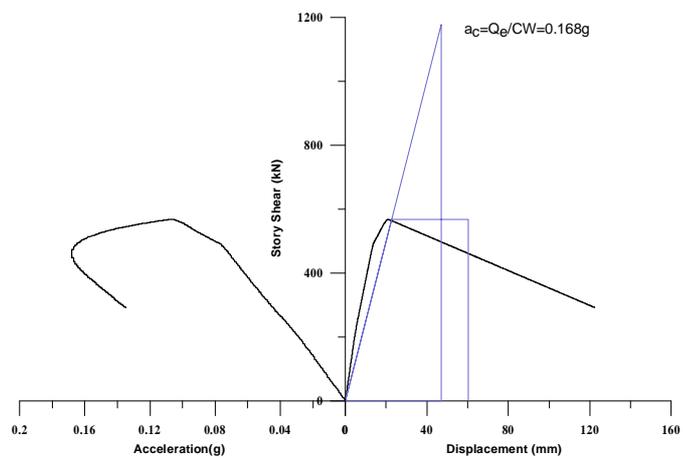
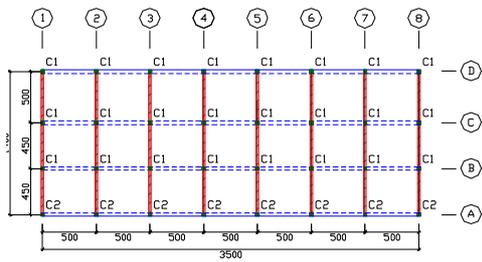
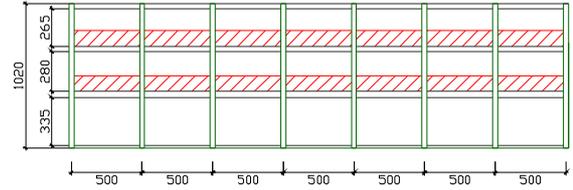


Fig.6 Seismic Performance Diagram of Tong-Su Street Building for Second Story



(a) Typical Structural Plan



(b) Frame Elevation

C1	C2
△ 10-#5	○ 8-#7
□ #3@25	□ #3@25
30X 35	35X 35

(c) Reinforcement of Ground Story Columns



(d) Photo After Earthquake

Fig.7 Collapse Row Street Building at Chu-San

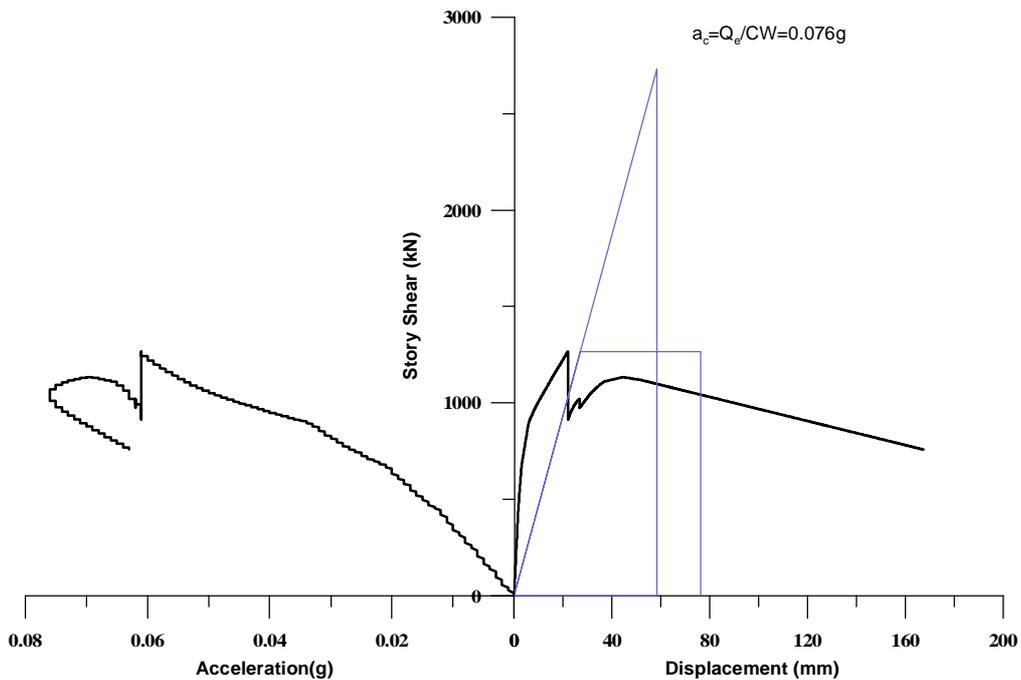


Fig.8 Seismic Performance Diagram of Chu-San Street Building for Ground Story

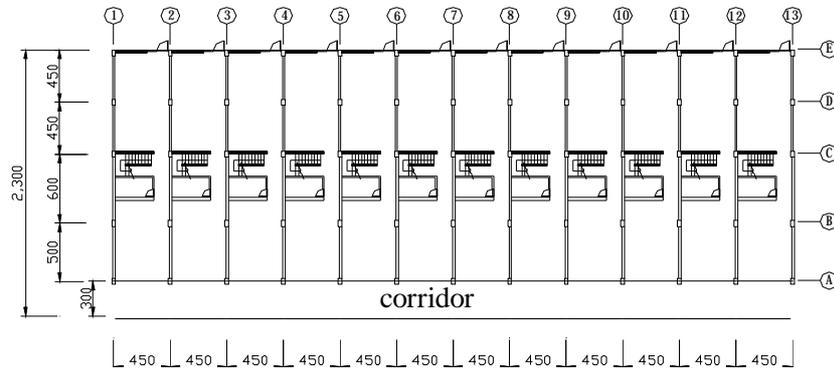


Fig.9 Plan of Ground Story of Row Street Building at In-Lin County

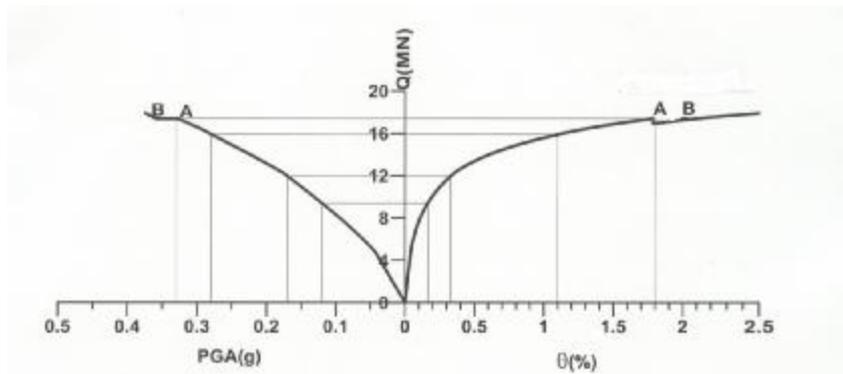


Fig.10 Seismic Performance Diagram of In-Lin Street Building for Ground Story

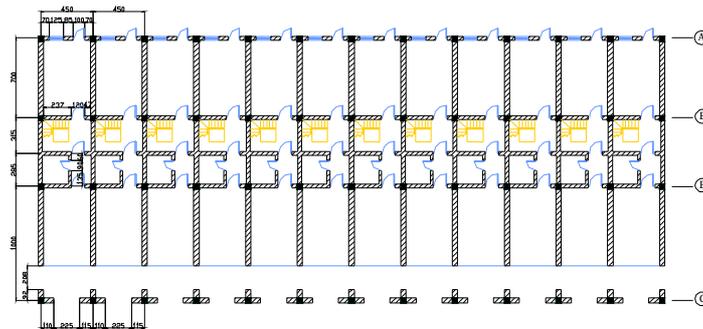


Fig.11 Typical Plan of Reinforced Brick Street Building

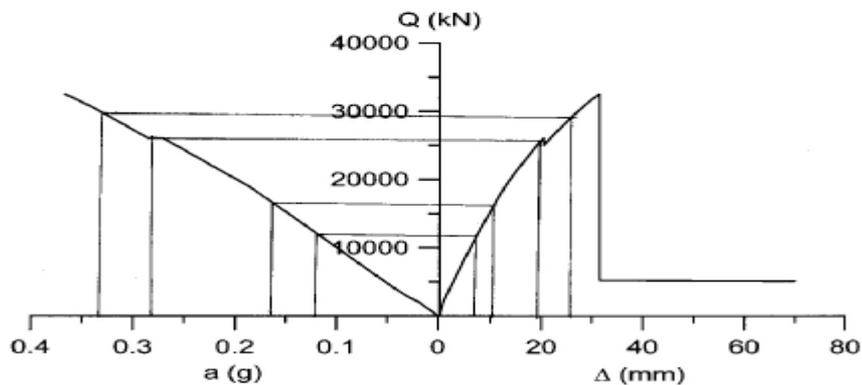


Fig.12 Seismic Performance Diagram of Reinforced Brick Street Building