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SEISMIC EVALUATION AND ITS VERIFICATION OF STREET BUILDINGS IN TAIWAN

Maw-Shyong SHEU [1], Tetsuo, KUBO [2], Hsin-Yi KUO [3]

SUMMARY

The first part of this paper is to propose a rational crack path method for calculation of the ultimate shear capacity for brick shear wall or RC shear wall. The load-deflection curve for brick shear wall or RC shear wall is also discussed in this part. The second part of this paper is to propose a fast seismic evaluation method for developing the performance diagram of a low-rise RC building with brick shear wall or/and RC shear wall. The performance diagram developed in this paper is a complete chart showing the relationship among peak ground acceleration, base shear and floor deflection. The floor response at different peak ground acceleration may be read directly from the performance diagram, including the 4collapse peak ground acceleration at certain return period of earthquake.

Key Words: *seismic evaluation, street building, brick wall, RC wall, seismic performance curve*

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 and above stories 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.

Almost all the shear walls of street buildings 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 shear walls of street 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-Δ curve for RC columns and the seismic assessment method using shear-building mode had been introduced by Sheu [1]. They will be introduced briefly herein. Three street buildings, which collapsed or moderately damaged in the Taiwan Chi-Chi

[1] Dept. of Architecture, National Cheng-Kung Univ., Tainan Taiwan
[2] Dept. of Architecture, University of Tokyo, Tokyo, Japan
[3] Dept. of Civil Engrg., National Cheng-Kung Univ., Tainan, Taiwan

Earthquake 1999, are illustrated to verify Sheu’s assessment method [1] in this paper. Another reinforced brick street building designed according to the Taiwan Building Code is also used to set up the seismic performance diagram 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]. In Fig.1, the inclined cracks start from the intersections of boundary elements (2 intersections in Fig.1 (a) and (b); 1 intersection in Fig.1(c)) and terminate at the mortar interface nearest to the central line of wall. The horizontal cracks in Fig.1 (a) and 1(c) go along the horizontal 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 vertical crack path. The slope angle of inclined stair-step, θ, is different for different lay out of the brick blocks such as Flemish bond (è¡_21°), English bond (è¡_30°), and stretching bond (è¡_29°) 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:

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

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:

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

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

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

$$Q_u = t \cdot (W \cdot \tau_f + \phi H \cdot f_{mbt}) \quad (4)$$

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

$$Q_u = t \cdot [\ W \cdot \tau_f + \phi W \tan\theta \cdot f_{mbt} + \phi(H - W\tan\theta)(f_{mbt} + f_{bt})/2\ ] \quad (5)$$

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

$$Q_u = t \cdot (W \cdot \tau_f + 0.5\phi H \cdot f_{mbt}) \quad (6)$$

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

the horizontal ultimate capacity of brick wall in (N).
The ultimate lateral deflection of brick wall at ultimate point may be calculated by Kuo [4] as:

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

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

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

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

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

Fig.2 shows the Q-Δ 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 = 3000mm. For W greater than 3000mm, the stronger vertical splitting crack path is getting smaller and transferring into weaker horizontal friction path. For W = 5000mm, the vertical splitting crack path disappears. So Q_u becomes minimum. Once $W >$ 5000mm, 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 0.75*H*. 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 a 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:

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

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

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

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

$$Q_{fu} = 1.33\frac{M_u}{H} \tag{14}$$

$$Q_u = Q_{sc} + Q_{ss} \tag{15}$$

M_{cr} and M_u are the crack and ultimate bending moments of RC 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 boundary columns across the diagonal crack path as shown in Fig.3 and may be calculated by shear friction concept as:

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

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 wall and column 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 the normal load acting on the wall (N).

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

$$\Delta_c = \Delta_{fc} + \Delta_{sc} \tag{17}$$

$$\Delta_u = \Delta_{fu} + \Delta_{su} \tag{18}$$

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

$$\Delta_{fu} = \frac{H^3 Q_u}{6.86\left(c E_c I_g\right)} \tag{20}$$

$$c = 0.0012\frac{H}{W_T} + 0.0693\frac{\rho_v f_y}{f_c'} + 0.0048 H W_T - 0.278\frac{A_b'}{A_g} + 0.2359\frac{I_b'}{I_g} \tag{21}$$

$$\Delta_{sc} = \frac{2.4 H Q_c}{0.33 E_c A_g} \tag{22}$$

$$\Delta_{su} = \frac{3.3 H Q_u}{c E_c A_g} \tag{23}$$

In which, ρ_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 the modulus of elasticity of concrete and taken as $4700\sqrt{f_c'}$ in (MPa).

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

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

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 proposed by Sheu [1]. The process of the seismic assessment method is introduced briefly as follows:

1. Plot lateral load-lateral deflection curve for each vertical member, including each RC column, each RC wall and each brick wall on the assessed story in the assessed direction as shown in Fig.5;
2. Sum up all the lateral load-lateral deflection curves on the assessed story to obtain the story shear-story drift curve of the assessed story as the dark curve shown in the first quadrant of Fig.6.
3. Transfer the story shear to base shear. Obtain the base shear-story drift curve;
4. In order to calculate the corresponding peak ground acceleration for a point on the base shear-story drift curve, plot bilinear curve for that point by equal energy principle as the light curve shown in the first quadrant of Fig.6;
5. Extend the inclining segment of the bilinear curve to certain point to get equivalent elastic response point, Q_e, by equal energy principle again;
6. The corresponding peak ground acceleration for that point on the base shear-story drift curve is:

$$a = Q_e / CW$$

(25)

where is the coefficent of elastic response spectrum. C may be taken as 2.5 for conservative. W is the total weight of the structure.

7. Keep moving the assessed point all the way on the base shear-story derift curve, we can get the peak ground acceleration curve, as shown in the second quadrant of Fig. 6. Fig. 6 is the performance diagram of a building structure. From this diagram, the response of base shear and story drift can be read for different peak ground acceleration.

The same assessment method is employed here to verify the damage level of 3 street buildings after the Taiwan Chi- Chi Earthquake 1999. The same assessment method is also used to set up the seismic performance diagram 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 local EPA of the Chi-Chi Earthquake from record of the Central Weather Bureau (CWB) was 0.477g.

[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 local EPA of the Chi-Chi Earthquake from record of the CWB was 0.38g.

[Example 3] moderate damaged row street building at Dow-Liou City
Fig.9 is the plan of a 3-story row street building located at Dow-Liou City. Fig.10 is the seismic performance diagram of this building. The analytical collapse ground acceleration is 0.38g. The actual local 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 confined compression force to increase the frictional strength. Fig.12 is the seismic performance diagram of this brick street building with f_c'=20.6MPa; f_b'=14.7MPa; f_m'=9.8MPa f_y=274MPa. 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 building is about 0.37g.

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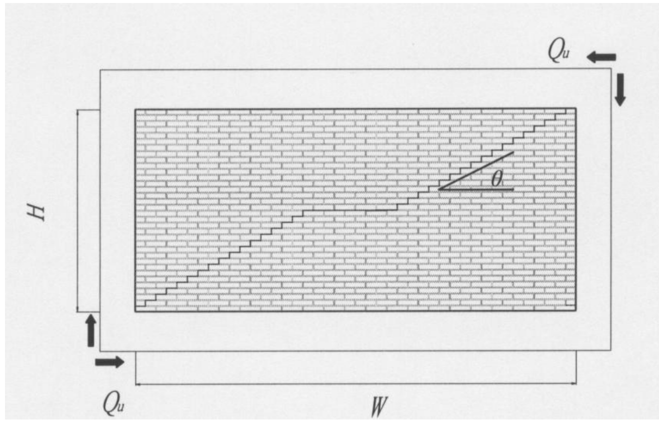
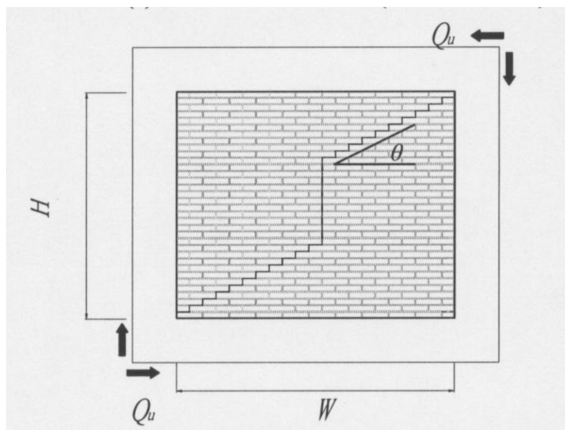
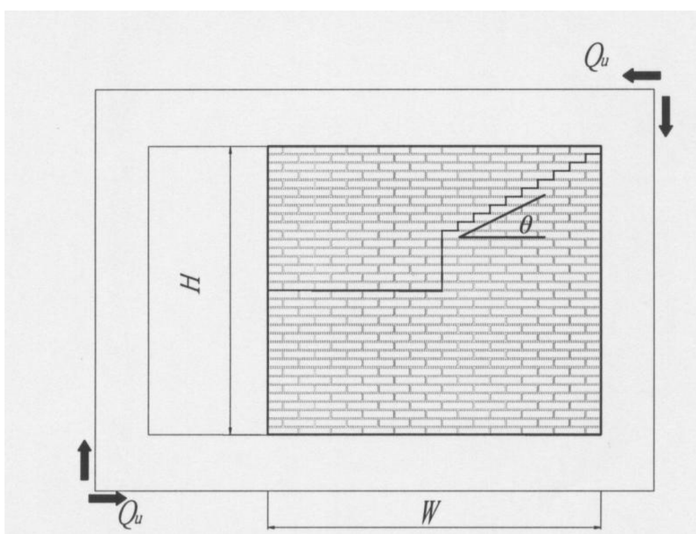


(a) tan $\theta \geq H/W$ (4-side confined)



(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

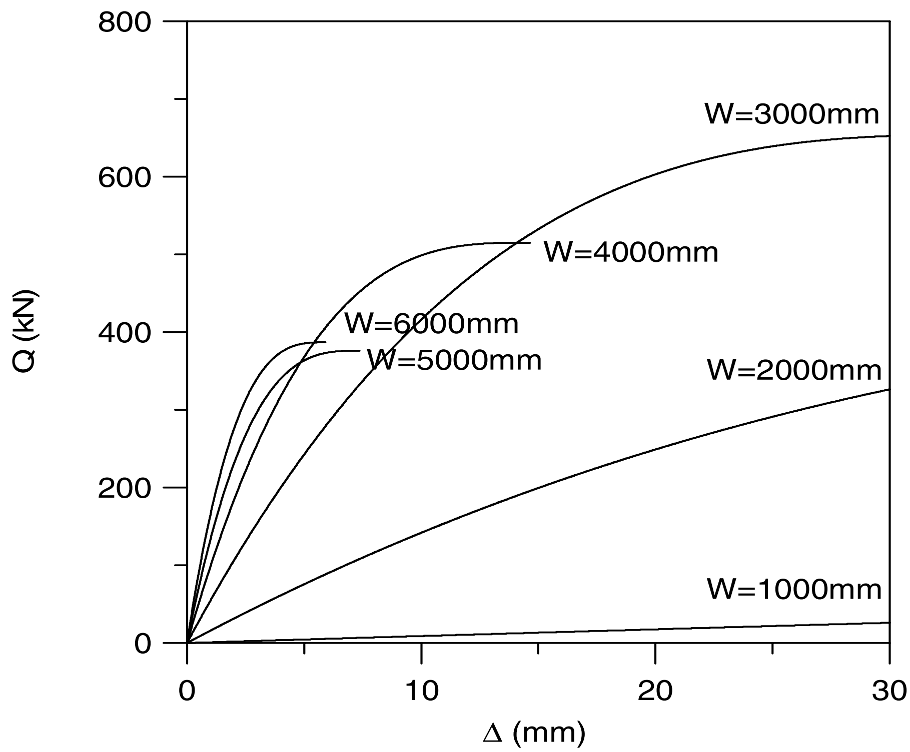
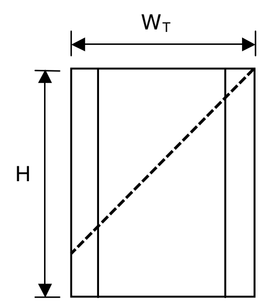
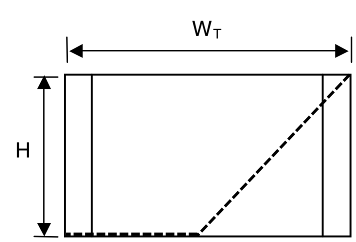


Fig.2 Q-Δ Curves of Brick Walls with 4-Side Confined

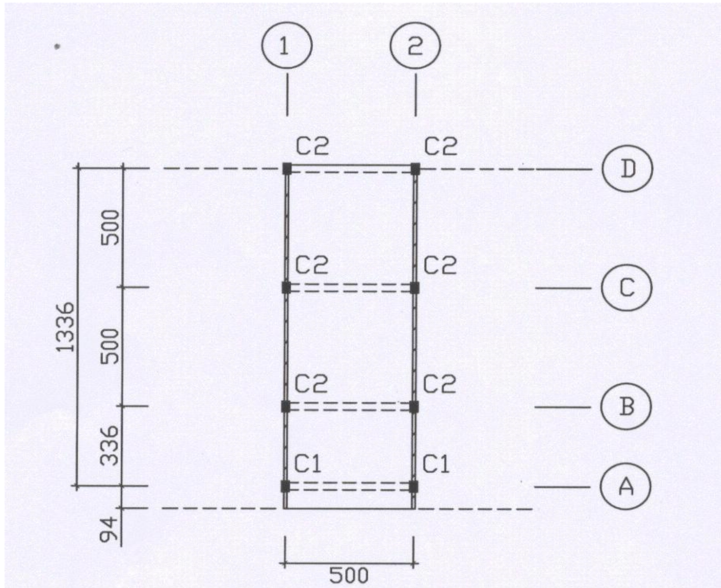


(a) High-rise Shear Wall

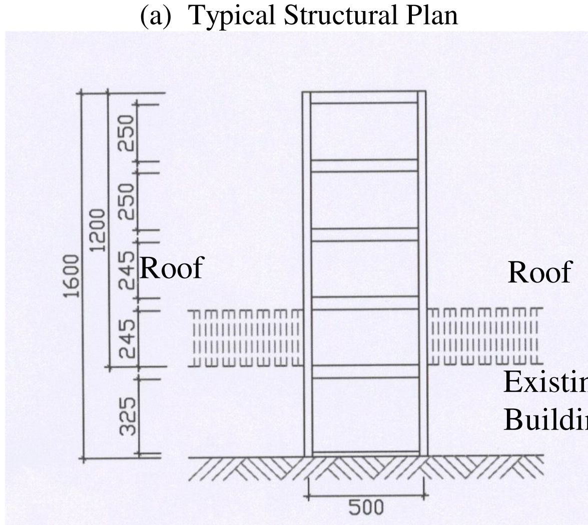


(b) Low-rise Shear Wall

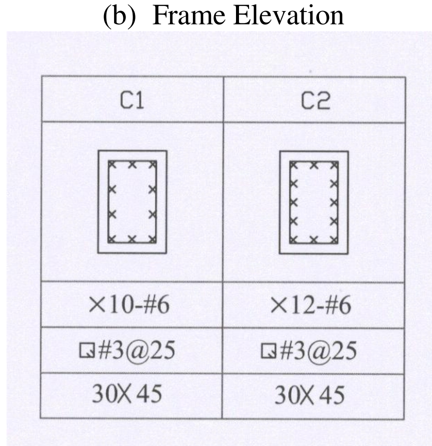
Fig.3 Shear Crack Path of RC Walls



(a) Typical Structural Plan



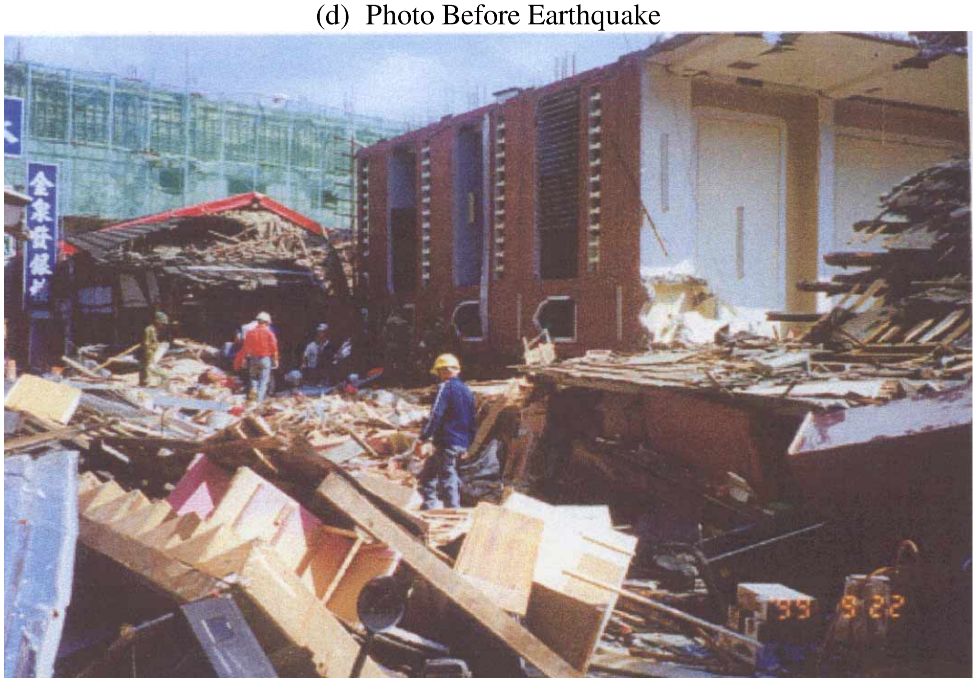
(b) Frame Elevation



(c) Reinforcement of Second Floor Columns

Fig.4 Collapse Single Street Building at Tong-Su

(d) Photo Before Earthquake



(e) Photo After Earthquake

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

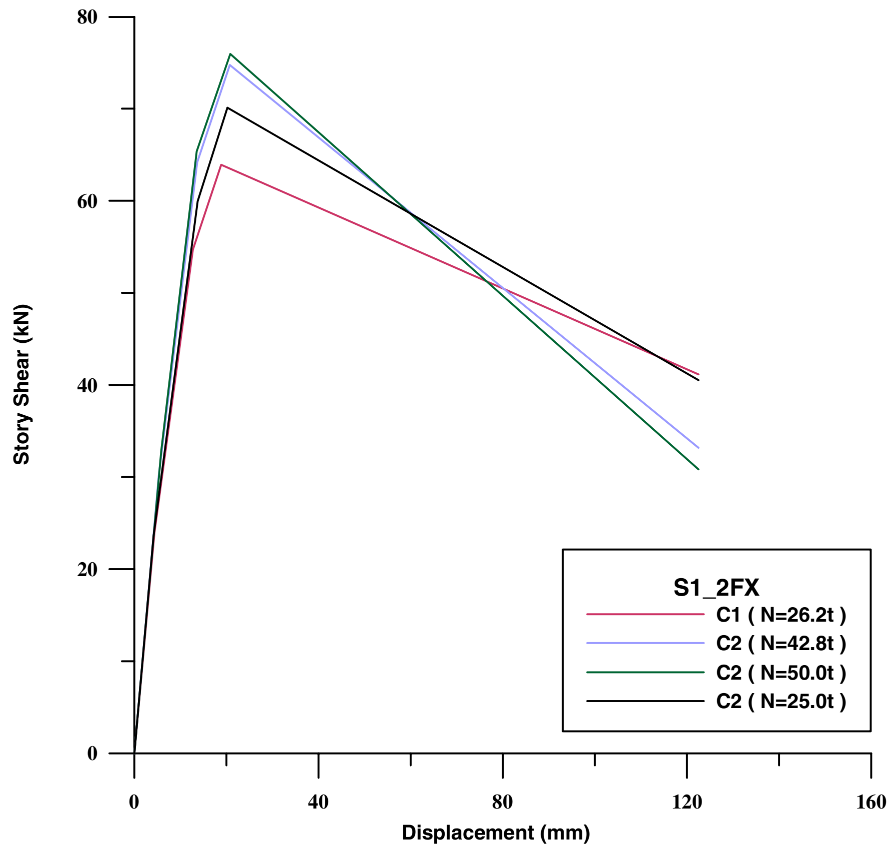


Fig.5 Q-Δ Curves of Each Column on Second Story

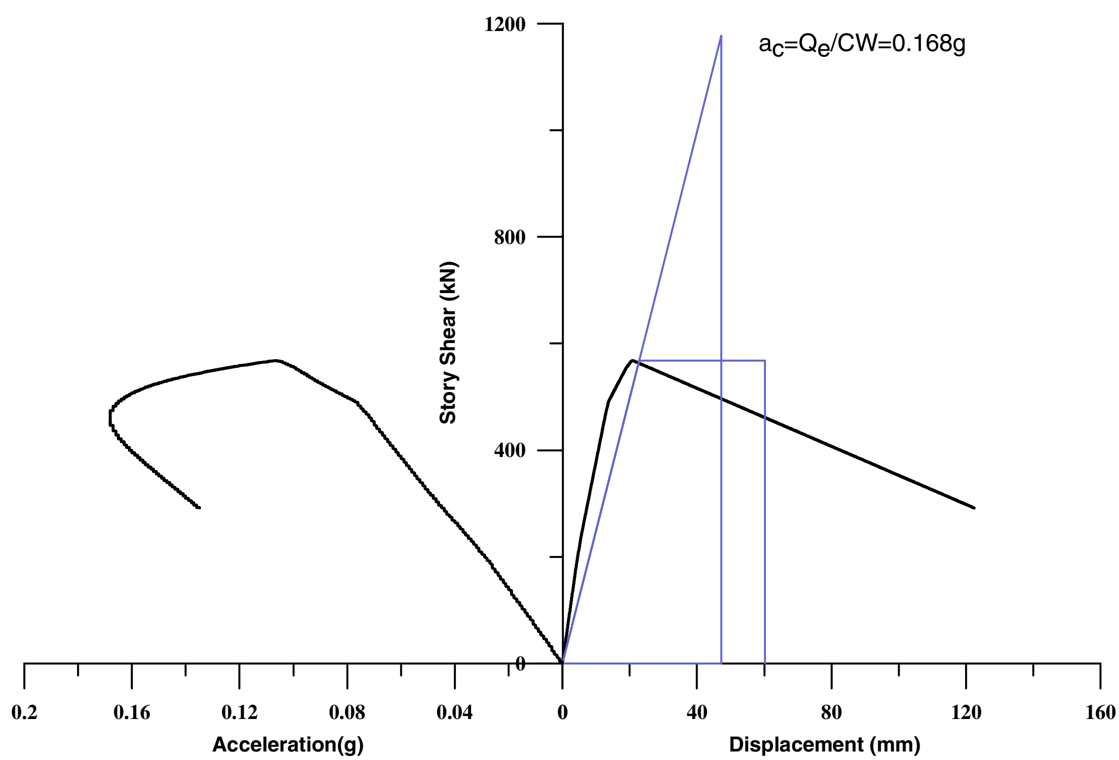
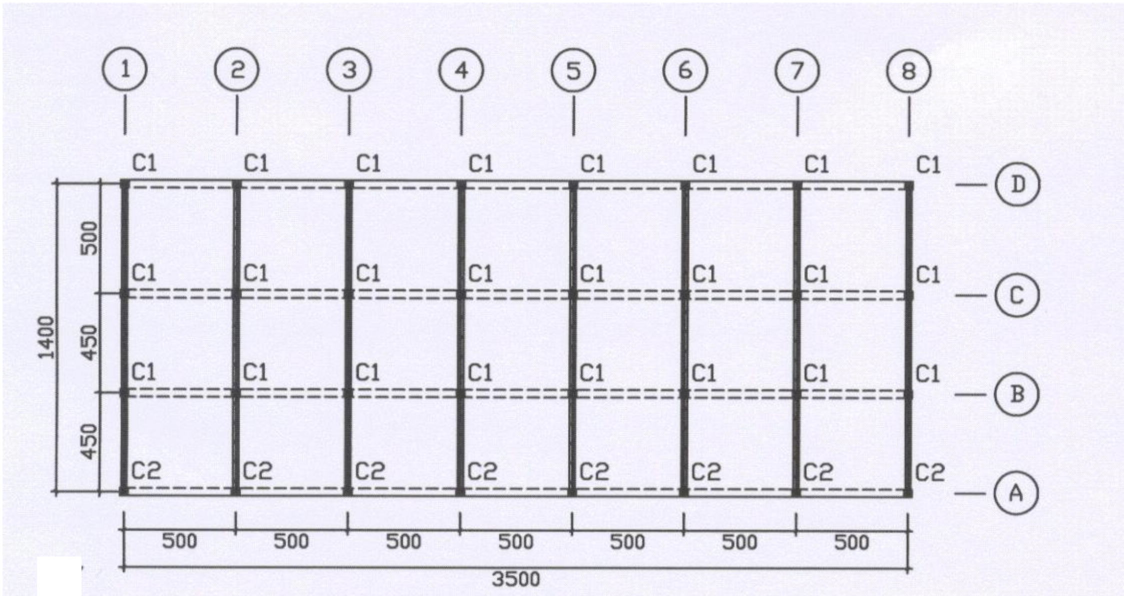
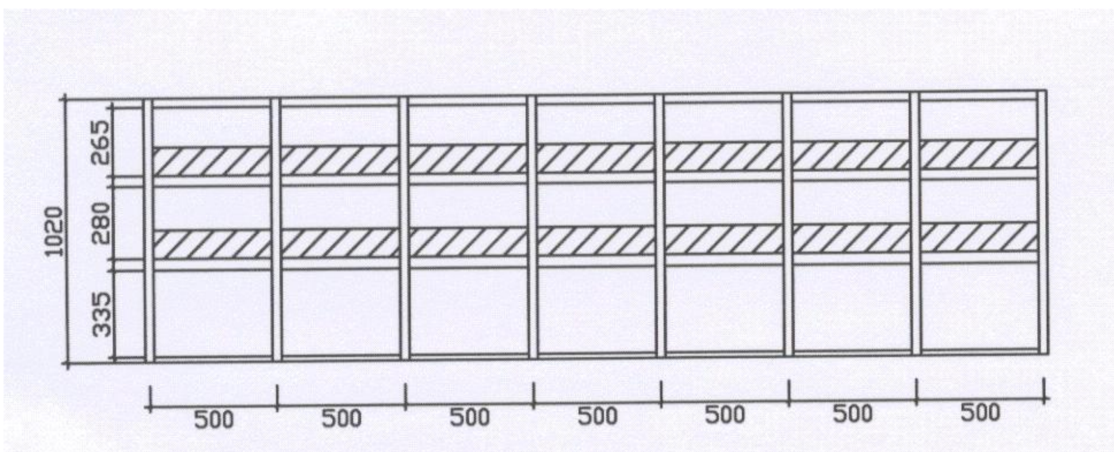


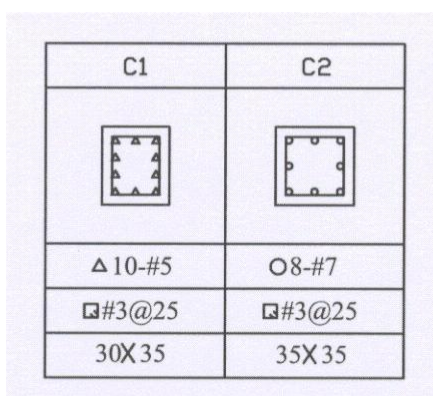
Fig.6 Seismic Performance Diagram of Tong-Su Street Building



(a) Typical Structural Plan



(b) Frame Elevation



(c) Reinforcement of Second Story Columns

Fig.7 Collapse Row Street Building at Chu-San

(d) Photo After Earthquake

Fig.7 Collapse Row Street Building at Chu-San (continued)

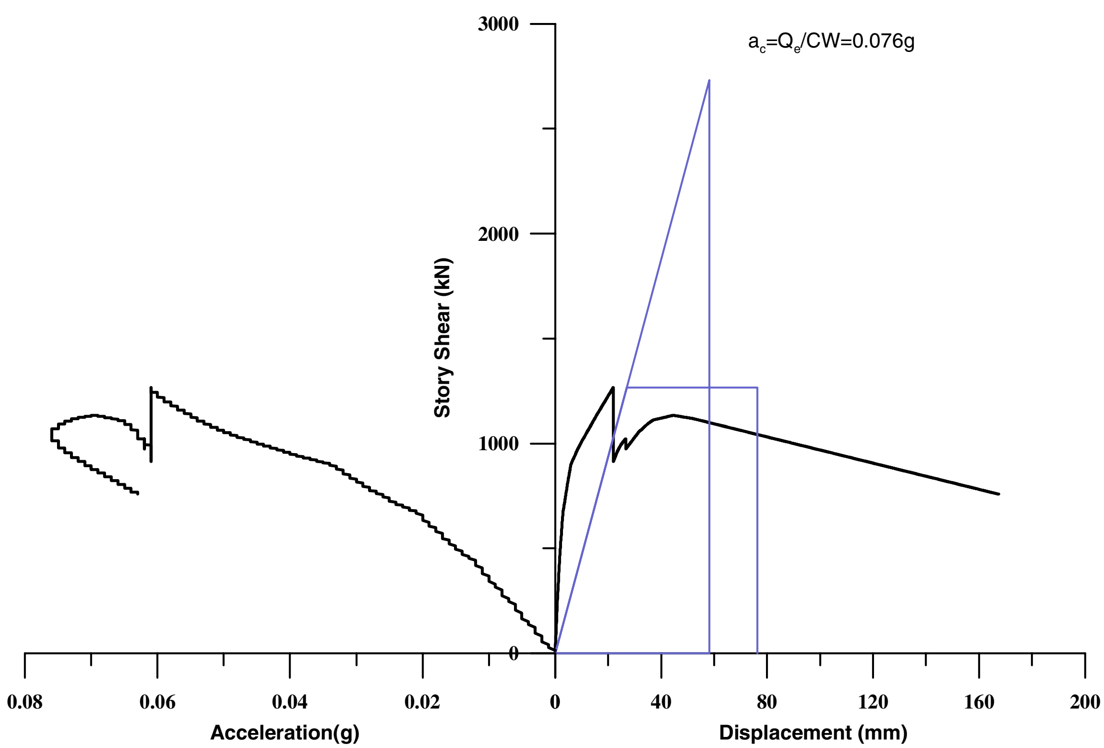


Fig.8 Seismic Performance Diagram of Chu-San Street Building

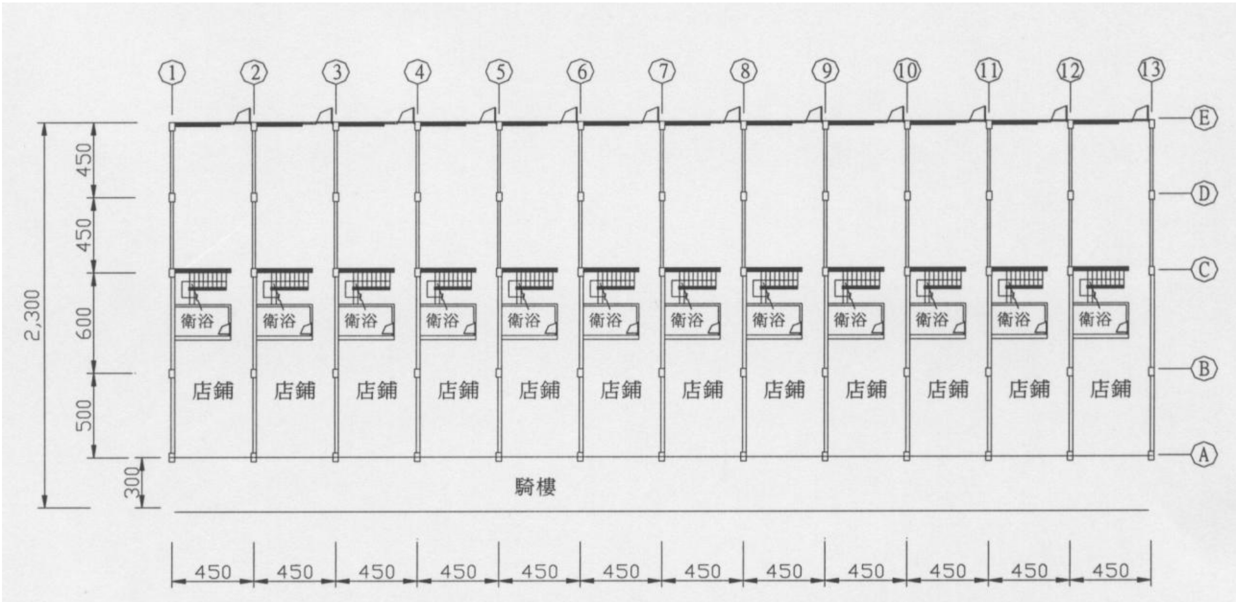


Fig.9 Row Street Building at Dow-Lio

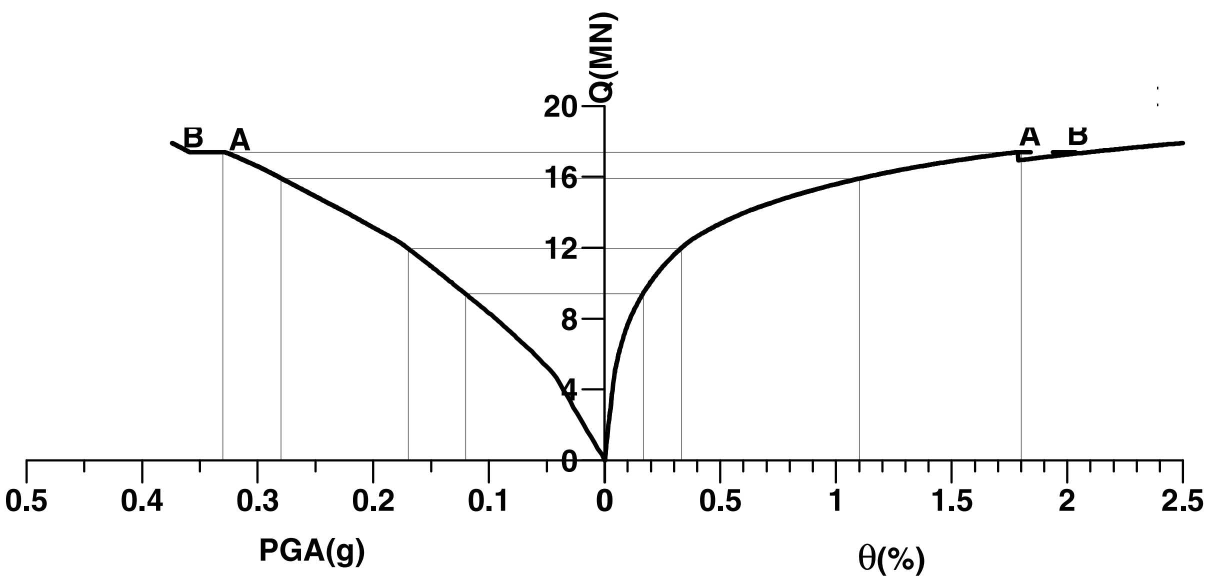


Fig.10 Seismic Performance Diagram of Dow-Lio Street Building

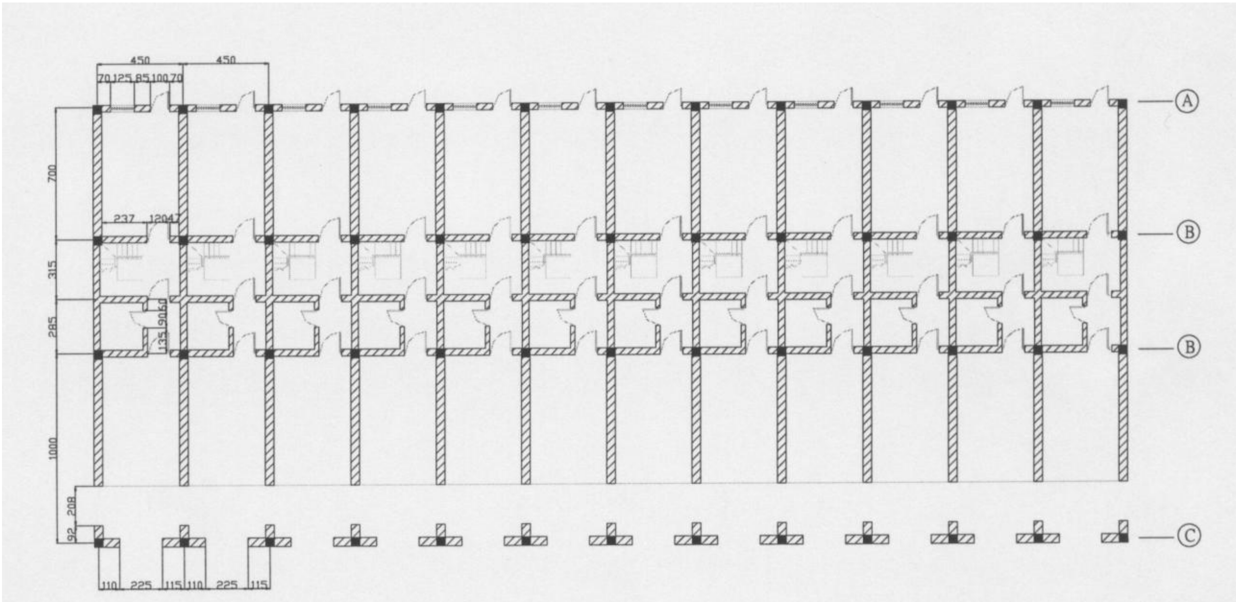


Fig.11 Typical Plan of Reinforced Brick Street Building

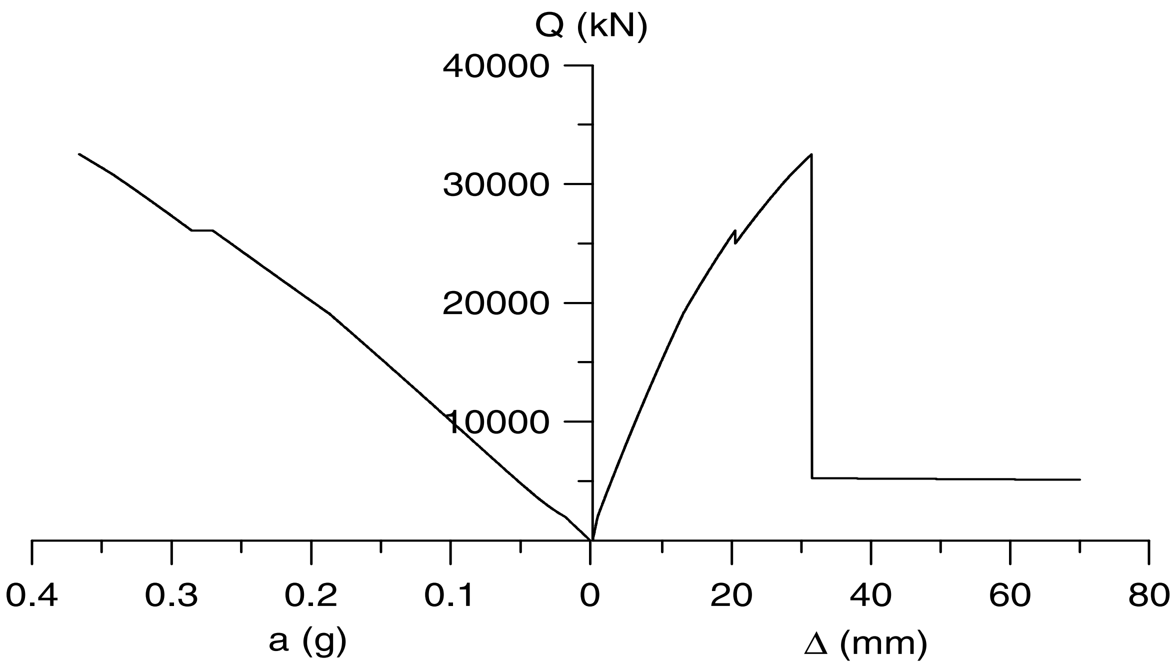


Fig.12 Seismic Performance Diagram of the Brick Street Building