EARTHQUAKE-RESISTANT CONSTRUCTION WITH MULTI-PERFORATED CLAY BRICK WALLS

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SUMMARY

The seismic performance of multi-perforated clay brick construction is assessed. Relevant data from test programs conducted elsewhere was gathered and a database was developed. The influence of most relevant variables on wall behavior is examined. Test results clearly indicate that load-bearing wall construction with multi-perforated clay bricks is a reliable system to resist earthquakes. Brick perforations should be oriented vertically and walls should be confined with tie columns. Behavior factors are recommended for analysis when exterior or interior tie columns and horizontal reinforcement are used. It was found that wall behavior depends on lateral displacement; wall inclined cracking occurred at an average story drift angle of 0.1 percent, regardless of axial stress level and amount of horizontal reinforcement. Lateral strength of multi-perforated clay brick walls is a function of the tensile strength and penetration inside brick perforations of the mortar, size of brick interior and exterior walls, axial vertical stress and amount of horizontal reinforcement. Equations to predict the lateral load at inclined cracking and at strength are proposed. In the latter, the contribution of horizontal reinforcement is taken into account, depending upon the amount and type of steel bars. Since failure of a multi-perforated clay brick wall is inherently brittle, it was observed that deformation capacity is increased with tie columns and horizontal reinforcing bars placed along running bond joints. Recommendations are given for tie column sizing and reinforcement. Construction recommendations are given to improve wall performance.

INTRODUCTION

Housing construction throughout the world, particularly in developing countries, is primarily carried out with masonry walls. Several geometries (solid, hollow, multi-perforated) and materials (clay, concrete, lime-sand) of masonry units are available. Among them, multi-perforated clay bricks are widely used because of their attractive characteristics when compared to traditional solid units: excellent fire resistance, good thermal and acoustic insulation, and superior durability. However, doubts have been cast on the seismic performance of walls built with this type of bricks. The term “multi-perforated brick” corresponds to a masonry unit with several perforations of uniform size (Fig. 1).

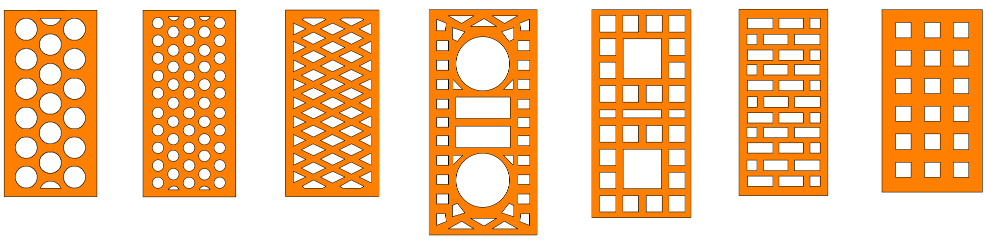

Figure 1. Typical Multi-perforated Clay Bricks

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Aimed at assessing the technical feasibility of using multi-perforated industrialized clay bricks for earthquake resistance, an experimental and analytical research program was carried out at the National Center for Disaster Prevention (CENAPRED) [Alcocer *et al.* 1995 &1997]. To extend the conclusions developed, test results from studies conducted elsewhere were also evaluated. The basic variables that affect the seismic behavior of multi-perforated brick wall construction are presented and discussed herein. Trends and conclusions are based on the reported data examined [Alcocer *et al.* 1995 & 1997; BRE 1983; Decanini y Ochat 1989; Diez *et al.* 1988; Ganz and Thürlimann 1984; Mann *et al.* 1988; Meli and Hernández 1975; San Bartolomé 1994; Tomazevic and Zarnic 1986]. Confined masonry will be discussed. It is assumed that multi-perforated bricks are part of load-bearing walls, i.e. walls designed and proportioned to resist both gravity and lateral actions. All walls were built with brick perforations oriented in the vertical direction. Walls with brick perforations in the horizontal direction are considered unsuitable for earthquake resistance due to the extremely fragile failure mode, and to the soft and weak behavior [Alcocer *et al.* 1995].

CHARACTERISTICS OF THE DATABASE

A database with relevant information was constructed. Data comprised results of 52 walls tested as cantilevers under simulated earthquake loads. Results of materials tests, aimed at characterizing the axial tensile/compression and shear behavior of the materials (brick, mortar and reinforcement) used in specimens, are included. The discussion herein refers to single-wythe specimens built using running bond. Specimens failed in shear. The range of the variables included in the database is shown in Table 1. Variable α refers to the ratio of net area to gross area of bricks; f'_p ,f'_b, f'_m and v_m are the axial compressive strength of bricks, mortar and masonry prisms, and the diagonal compression strength of masonry, respectively. A_c is the gross area of the concrete vertical tie column, constructed either internally or externally to confine the masonry. An internal tie column is that built inside hollow bricks. *H/L* is the wall height-to length aspect ratio; p_v is the ratio of vertical reinforcement area to the gross wall area in the horizontal direction, and p_h is the ratio of horizontal reinforcement area to the gross wall area in the vertical direction, respectively. f_{yv} and f_{yh} are the nominal yield stresses of vertical (tie columns) and horizontal reinforcement; σ is the vertical axial stress applied over the gross wall area. Although information is reported in different formats, or there is even lack of some data, the influence of some parameters on the response is apparent. Specifically, the impact on the mode of failure, lateral strength, stiffness, displacement capacity and energy dissipation capacity is evaluated. In some cases, test results of walls built with hollow clay bricks is shown for comparison. Number of evaluated data points varies from one parameter to other because of lack of reliable or enough information to include it.

Table 1. Range of Variables Included in the Database

Property	Unit	Range	Property	Unit	Range
α	%	46 – 76	*H/L*	mm/mm	0.6 – 2.0
f'_p	MPa	9.8 – 37.3	p_v	%	0 – 0.86
f'_b	MPa	7.4 – 33.7	p_h	%	0.04 – 0.38
f'_m	MPa	6.3 – 16.9	f_{yv}	MPa	412 – 460
v_m	MPa	0.44 – 1.28	f_{yh}	MPa	206 – 740
A_c	cm²	0 – 280	σ	MPa	0 – 2.38

IN-PLANE BEHAVIOR

A typical story-shear - story-drift-angle (V-R) envelope curve of a multi-perforated clay brick wall is shown in Fig. 2. Under reversed cycle lateral loads, wall behavior is elastic until cracking. After cracking, stiffness and strength decay, with greater degradation at greater lateral displacement. The degradation process depends on the failure mode, the type of brick, the vertical load, and the type of structural system (confined masonry, reinforced masonry or masonry infill).

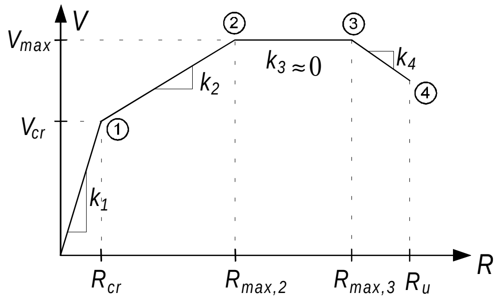

Figure 2. Typical Envelope Curve of a Multi-perforated Clay Brick Wall

Masonry is a structural material whose behavior is strongly dependent on lateral displacement. The story drift angle at inclined cracking, R_{cr}, for all data points is shown in Fig. 3. Aside from the tests by Diaz *et al.*, R_{cr} ranges from 0.05 to 0.20 percent, with an average value of 0.1 percent. R_{cr} seems not to be affected neither by the magnitude of the vertical axial stress, nor by the amount of horizontal reinforcement p_h . Diaz´s results were considered affected by the type of brick used; the measured response envelopes exhibited nonlinear behavior from the beginning of the test credited to continuous softening of the brick even before cracking. This peculiar response yields to larger cracking drifts.

A measure of the deformation capacity of a brick wall is the ratio $R_{max,2}/R_{cr}$ (Fig. 4), where $R_{max,2}$ is the story drift angle at strength (Fig. 2). In the graph, the larger the marker, the greater was the axial load; filled markers correspond to horizontally reinforced walls.

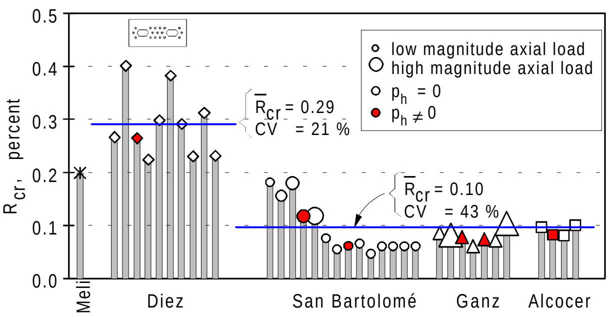

Figure 3. Story Drift Angle at Cracking

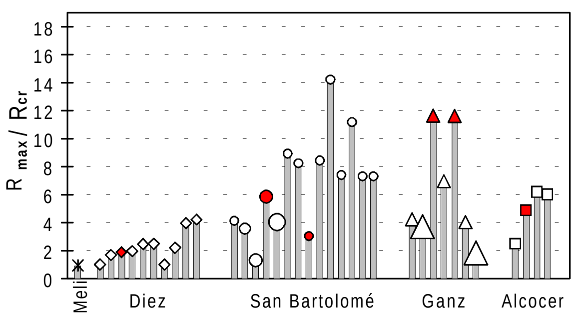

Figure 4. Wall Deformation Capacity

PARAMETERS THAT AFFECT MATERIAL AND WALL BEHAVIOR

Brick Type

It is a quite well-accepted idea among structural engineers and contractors that the compressive strength of multi-perforated bricks, f'_p, increases when α diminishes. This assumption implies that for solid bricks, i.e. α=1, strength is maximum. In Fig. 5, brick compressive strength is presented; strength was calculated over both the gross and net brick areas. Although strength over gross area is independent of α, the strength over net area decreases with α. The latter, though contrary to what had been excepted, could be explained by looking at the fabrication process of extruded bricks. In the stiff-mud extrusion process followed in all brick units evaluated, the clay-water mixture is compressed against the extrusion nozzle while a vacuum pressure, aimed at removing air particles, is applied. Such pressure is adjusted in the factory according to clay plasticity and water content. The direct effect of air removal due to vacuum is to increase the extrusion pressure and, then, to improve clay mixture homogenization. Clay mixture homogenization is directly related to the brick compressive strength. Air removal is easier for smaller values of α. Scarce data suggest that brick strength increases with brick gross unit weight (weight/gross volume); that is, the heavier the brick the more resistant. More information is needed to support any conclusion in this regard.

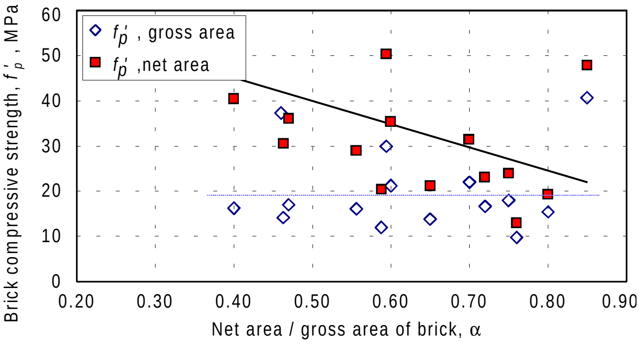

Figure 5. Brick Compressive Strength

A visual examination of the failure modes of multi-perforated clay bricks in walls subjected to earthquake-type loading indicates a clear dependence on α; more exactly, on the thickness of interior and exterior brick walls. When shear stresses act along the brick length, most forces are resisted, as expected, by the stiffest elements, i.e. the longitudinal exterior brick walls [Mann *et al.* 1988]. When the cracking tensile strain at the joint between exterior and interior walls is reached, joints crack and exterior walls spall off the brick. Immediately, a sudden stress redistribution takes place, overstressing the interior walls. Commonly, this increase in shear demand onto the interior brick walls leads to further cracking and crushing; this stage is the onset of the brittle brick failure. In accordance with this reasoning, brick strength under shear stresses could be augmented should thicker brick walls were provided.

It is common that the design strength of masonry under lateral loads (diagonal tension) is expressed as a fraction of the strength measured in small wall specimens. In these tests, square specimens are failed under monotonic diagonal compression loading. Strength measured in this rather arbitrary material test is commonly affected by corrective factors that are intended to take into account the size effect, the load routine and strain rate, as well as, in some instances, different conditions of the structural elements. It if often assumed that the diagonal compression strength, v_m, increases with f''_p. However, for the data analyzed of multi-perforated bricks, no relation was found.

Mortar

Mortar characteristics (compressive and tensile strengths, Poisson ratio and others) are known to impact masonry behavior under monotonic and cyclic loading. Multi-perforated brick construction is not an exception. Typically, during construction of load-bearing walls with this type of bricks, fresh mortar is placed over the horizontal face of the bricks. The mortar that penetrates into the brick vertical perforations works as shear key once it has hardened. If it is accepted that the shear strength of a mortar key depends on the mortar tensile strength, it can be expected that masonry diagonal compression strength would increase with f''^{γ}_b, where γ is a coefficient less than 1, commonly adopted as ½ (Fig. 6). In the graph, mortar proportions are described as *x:y:z*, where *x*, *y* and *z* are the volume proportions of portland cement, lime and sand, respectively. A similar trend, not presented here, was observed in the shear rigidity G_m; in fact, it increases with f''^{γ}_b, and, through f''^{γ}_b, with strength v_m. Most data points collected are associated to diagonal tensile failures, regardless of mortar strength.

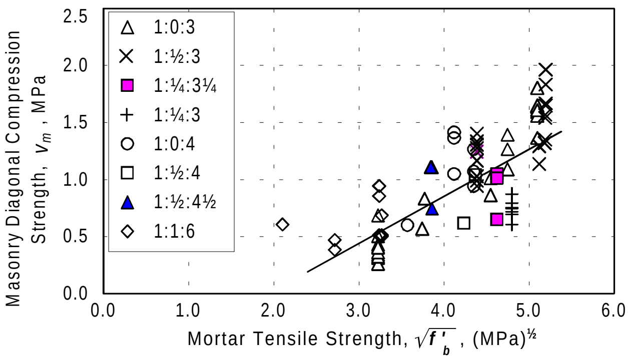

Figure 6. Relation of Masonry Diagonal Compression Strength and Mortar Tensile Strength

Some authors have suggested that mortar retentivity and fluidity affect the shear stiffness and strength of multi-perforated brick masonry [Diez *et al.* 1988]. Although a least-squares fit through retentivity points might suggest an increase of v_m with retentivity, data points are largely scattered. Moreover, for same mortar retentivity, v_m varies from 0.5 to 2 MPa. An analogous observation is made when fluidity data are plotted. The latter is inconsistent with the role assigned to the mortar that penetrated in brick perforations. It would be expected that mortar penetration be larger if mortar were more fluid, thus enhancing the shear transfer mechanism. Nevertheless, this reasoning has proved to be valid for those cases where care was taken to assure that fluid mortar had penetrated into the perforations.

Axial Load

The effects of axial load on wall behavior have been assessed in different test programs. In almost all cases, vertical load increased the cracking load and the lateral strength in comparison with identical walls tested under zero axial stress. The increase in strength capacity was almost linear with axial load. The measured strength at inclined cracking, V_{cr}, was normalized by the calculated strength, V_{calc}, for all cases evaluated (Fig. 7). Calculated strength was estimated by $V_{calc} = 0.4\ v_m A_T + 0.3\ P < 1.5\ v_m A_T$, where A_T is the wall gross transverse area and P is the applied vertical load. In this calculation, the average diagonal compression strength reported was used. Note that in Tomazevic, Mann and Ganz the average diagonal compression strength was not provided; therefore, v_m = 0.45 MPa was assumed. This value is considered to be a low estimate in multi-perforated brick construction (see Fig. 6). The average ratio V_{cr} / V_{calc} is 1.11. It is clear that the proposed equation agrees reasonably well with test data. For design purposes v_m should be replaced by a characteristic strength v^*_m that includes the scatter among data, as well as the material acceptance criterion prescribed in the local codes. No clear trend was found on the influence of *H/L* on wall strength.

Axial load diminishes wall deformation capacity (Fig. 4). For same test series, walls with larger σ-values showed less deformation capacity. This conclusion is valid regardless the magnitude of *H/L*, f'_p, f'_b, α, as well as size, A_c, and reinforcement of tie columns.

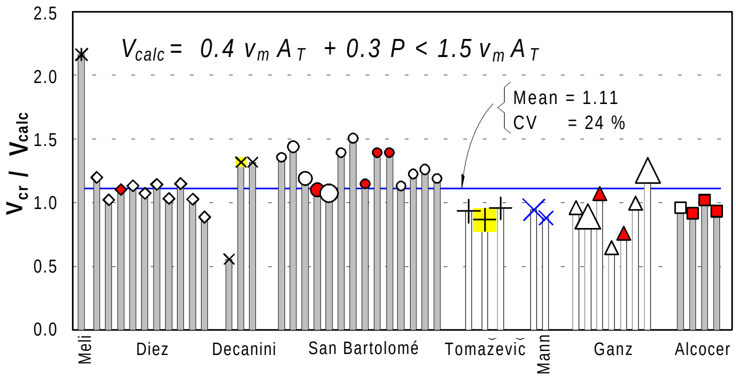

Figure 7. Inclined Cracking Strength of Walls

Horizontal Reinforcement

Aimed at improving the lateral load strength and deformation capacity of multi-perforated brick masonry walls, horizontal steel reinforcement has been used along mortar joints. In sufficient quantities, this reinforcement has also been shown to reduce the strength deterioration rate (Stages 2-3 and 3-4 in Fig. 2), and to improve the distribution of wall cracking. Horizontal reinforcement is usually made of small-diameter steel wires or bars. In this paper the term "bar" will be adopted regardless. Reinforcement could be either smooth or deformed bars. Prefabricated reinforcement made of small-diameter smooth wires welded together (ladder-shaped, for example) is not considered. This type of reinforcement exhibits brittle failures at very low drift angles and, therefore, is not considered appropriate for seismic applications. Mild-steel and cold-drawn bars were used in the studies assessed. Mild-steel bars typically exhibit a nearly elasto-plastic tensile stress-strain behavior, whereas cold-drawn reinforcement does not show a definite yield plateau, but strain hardens immediately after the elastic range. Although mild-steel bars strain harden, it occurs at larger strains than those usable. In most reports evaluated, the full stress-strain curve of the reinforcement was not provided. However, the type of reinforcement was assumed in accordance with the magnitude of the nominal yield stress, f_{yh}, and the shape of the envelope curve of the wall. Values of f_{yh} less than 30 MPa commonly correspond to mild-steel bars.

It has been hypothesized that when inclined cracking crosses horizontal bars, the reinforcement is strained longitudinally while it tries to keep the cracked surfaces close together. Stresses developed in the reinforcement are then considered to contribute to the total wall load carrying capacity. This phenomenon, extrapolated from the behavior assigned to stirrups in reinforced concrete (RC) beam theory, assumes that the larger the strains in the bars, the larger the contribution to strength.

In order to assess the contribution to strength of horizontal reinforcement, the difference between V_{max} and V_{cr} was calculated. V_{max} corresponds to wall lateral strength (Fig. 2). The difference calculated represents the reserve carrying capacity after inclined cracking. Such difference was normalized by the product $p_h\, f_{yh}\, A_T$. This product is the contribution to strength of *all* horizontal reinforcement at yield (or measured yield in the case of laboratory tests). It is recognized that this factor fails to properly consider the type of stress-strain behavior and, more exactly, the ability of steel bars to strain harden. Two distinctly different families of data points are noted in Fig 8. Solid markers correspond to walls reinforced with cold-drawn bars, whereas empty markers represent those with mild-steel bars. For low $p_h\, f_{yh}$ values, the contribution of cold-drawn bars is largest and decreases for larger values of $p_h\, f_{yh}$. In contrast, the contribution of mild-steel bars to strength seems to be unaffected by $p_h\, f_{yh}$. The first finding is consistent with the trend observed in other specimens built with hand-made clay bricks [Aguilar *et al.* 1996]. In walls with low $p_h\, f_{yh}$ values, horizontal bars are strained well beyond yield, thus increasing their contribution to lateral strength; on the contrary, due to the large elastic axial stiffness and yield strength of horizontal reinforcement in walls with high $p_h\, f_{yh}$ values, strains remain elastic.

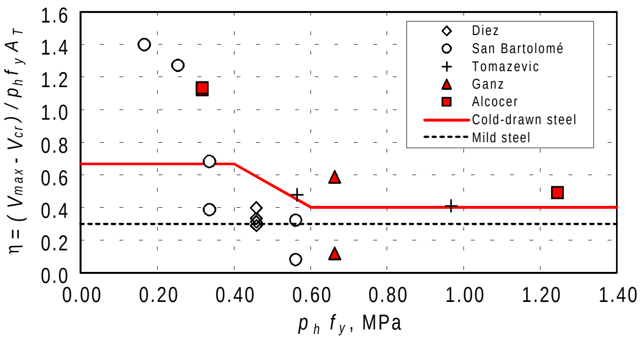

Figure 8. Contribution of Horizontal Reinforcement to Wall Strength

Based on this evaluation, a design equation is proposed to calculate the strength of horizontally reinforced multi-perforated clay brick walls. The same approach followed in reinforced concrete design was adopted; the strength is calculated by adding up the masonry inclined cracking strength presented before and the contribution of horizontal bars to strength, $\eta\, p_h\, f_{yh}\, A_T$. The value of η is readily obtained from Fig. 8 as a function of $p_h\, f_{yh}$ and the type of steel. The adequacy of this procedure can be judged in Fig. 9.

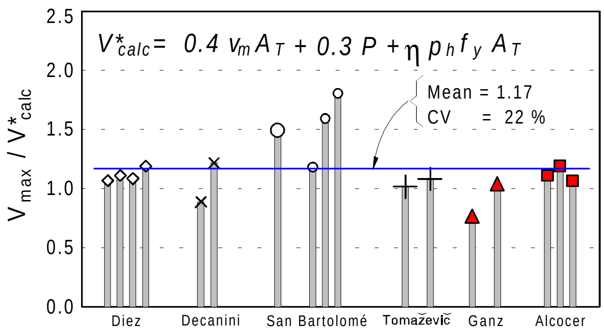

Figure 9. Calculated Wall Lateral Strength Considering the Contribution of Horizontal Bars

The influence of horizontal reinforcement on wall deformation capacity can be studied in Figs. 4 and 10. For same test series, those reinforced horizontally exhibited the largest deformation capacities. Moreover, in some instances, the sole placement of small percentages of horizontal reinforcement (p_h = 0.05 percent) was sufficient to increase R_{max}/R_{cr}. All walls tested under high axial loads were not reinforced horizontally. It can be safely stated that the deformation capacity of walls with high axial loads could be improved if horizontal reinforcement is provided in sufficient amounts.

Effectiveness of horizontal reinforcement in improving wall behavior is obtained if bars are anchored inside the tie columns through 90-deg hooks [Alcocer *et al.* 1997; Alcocer & Zepeda 1999]. Alcocer [1997, 1999] have recommended that the maximum percentage of horizontal reinforcement $p_{h,max}$. be obtained by $0.15\, f'_m/f_{yh}$. This equation is aimed at reducing the likelihood of shear-compression failures of the masonry panel by limiting p_h.

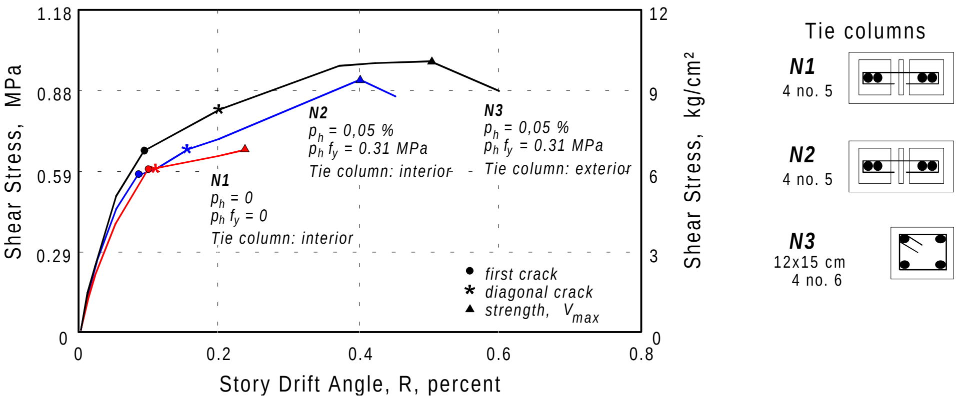

Figure 10. Story Shear – Story Drift Angle of Horizontally Reinforced Walls and with Interior and Exterior Tie Columns (Alcocer et al. 1997 & 1999)

Reinforced Concrete Tie columns

Reinforced concrete tie columns have a very important effect on the reserve strength, ductility and stability of walls after inclined cracking. They also provide the connection among orthogonal walls. Tie columns can be constructed exterior or interior to the masonry panel. Exterior tie columns often have larger cross-sectional dimensions than interior tie columns. Interior tie columns have been built inside hollow clay bricks and have been reinforced with common longitudinal bars and, in some instances, with ties or cross ties. The effect of the type of tie column on wall behavior is presented in Fig. 10. It is clear that the specimen with exterior tie columns was stiffer, more ductile, and more stable than its replicate with interior tie columns. It is, therefore, preferable to confine the masonry panel with exterior, thus visible, tie columns. For proper confinement with interior tie columns, cross-sectional dimensions should be made as large as possible to increase the concrete area and to facilitate concrete placement. Special hollow bricks without transverse walls may serve this purpose. Regardless of the type of tie column, transverse steel should be provided at closer spacing at the ends. A spacing of the lesser of one-half the tie column depth or the brick height is recommended over one-sixth of the tie column height at either end. Analysis of test data collected did not reveal any significant effect of the column size and reinforcement on the ratio V_{max}/V_{cr}, nor on the stiffness deterioration of walls (Fig. 11). The secant stiffness was calculated using a straight line between the maximum load and the corresponding drift angle points for the positive and negative directions in a loading cycle. All specimens exhibited a similar rate of stiffness deterioration.

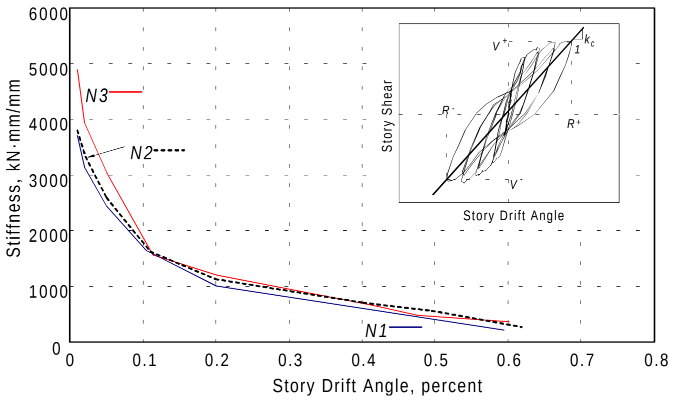

Figure 11. Secant Stiffness Deterioration (Alcocer et al. 1997 & 1999)

CONCLUSIONS

1. Test results clearly indicate that load-bearing wall construction with multi-perforated clay bricks is a reliable system to resist earthquakes. Brick perforations should be oriented vertically and walls should be confined with tie columns.
2. Walls can be analyzed and designed as confined masonry. When exterior tie columns and horizontal reinforcement are provided, a similar behavior factor to that used for confined masonry walls built with solid

clay bricks is advisable. For the case of interior tie columns, a smaller factor (typically three-fourths) should be used.

3. Wall behavior depends on lateral displacement; wall inclined cracking occurs at an average story drift angle of 0.1 percent, regardless of axial stress level and amount of horizontal reinforcement.
4. Lateral strength of multi-perforated clay brick walls is a function of mortar tensile strength and penetration inside brick perforations, size of brick interior and exterior walls, axial vertical stress and amount of horizontal reinforcement.
5. Equations to predict the lateral load at inclined cracking and at strength are proposed. In the latter, the contribution of horizontal reinforcement is taken into account, depending upon the amount and type of steel bars. Prefabricated reinforcement made of welded wires should be avoided.
6. Failure of a multi-perforated clay brick wall is inherently brittle. Deformation capacity is increased with tie columns and with horizontal reinforcing bars placed along running bond joints. High axial loads adversely affect wall deformation capacity. Tie columns should be made as large as possible and should be reinforced with transverse ties or crossties.
7. Horizontal reinforcement should be continuous along the walls and should be properly anchored inside tie columns. Standard 90-deg hooks are sufficient, regardless bond conditions along the mortar joints. A minimum percentage of 0.05 percent is recommended. Maximum reinforcement ratio should be determined to avoid a shear-compression failure of the masonry.
8. Wall lateral stiffness increased with exterior tie columns. Regardless of the type of the tie columns, stiffness decays following a parabolic curve.
9. Since wall behavior is strongly affected by the amount of mortar penetration inside brick perforations, the volume of mortar needed for proper penetration should be carefully checked during construction. This volume is additional to that required for the joints.
10. Due to the large scatter recorded in masonry diagonal compression strength, a conservative estimation is recommended for design.

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