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IMPROVING THE EARTHQUAKE RESISTANCE AND SUSTAINABILITY OF CONFINED MASONRY (MIXTO) DWELLINGS IN EL SALVADOR

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ABSTRACT

The seismic vulnerability of housing stock in El Salvador was demonstrated during the recent 2001 earthquakes. Relative to other types of common residential construction, mixto dwellings (a form of confined masonry) performed well. A coordinated pilot study was conducted with the objective of improving the seismic resistance of this form of construction while reducing costs and greenhouse gas emissions. Laboratory tests examined brick strength in relation to firing temperature and duration. Analytical studies examined the potential for voided bricks to improve seismic performance and the reduction in demands associated with stiffening the roof diaphragm. This pilot study identifies the potential for reduced construction costs, reduced greenhouse gas emissions, and significant performance enhancements.

Introduction

Devastation caused by the earthquakes of January 13 and February 13, 2001 abruptly halted El Salvador's economic development. These earthquakes killed 1100 people and damaged or destroyed 20% of the homes in the country, leaving 60% of the population of El Salvador either homeless or living in substandard housing (EERI, 2004, vii). Some departments (administrative districts analogous to states) had as much as 69% of the housing stock damaged or destroyed, while some municipalities had as much as 86% of the housing stock damaged beyond repair (DIGESTYC 2001). Most of the damaged homes were built of adobe, and this type of construction was more likely to be damaged beyond repair than to suffer repairable damage (EERI 2004).

Confined masonry consists of clay brick masonry with vertical reinforced concrete tie-columns and reinforced concrete bond beams along walls at floor levels that are cast after the

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brick masonry is placed, and therefore provide more confinement to the masonry than in infilled frame construction (where the masonry is placed after the reinforced concrete members have been cast). Confined masonry construction is a common type of construction in Latin America that has generally performed well in past earthquakes (Rodriguez, 2005). More than 60% of the houses in El Salvador are built from mixto, a type of confined masonry with more closely spaced bond beams, and thus smaller panel dimensions. Mixto has is the most popular form of construction in El Salvador. Although more costly than other types of construction, its has a good record of performance in earthquakes, with only 2.4% of the mixto houses damaged beyond repair and 5.9% experiencing repairable damage in the 2001 earthquakes (EERI 2004). However, cost and perhaps the availability of bricks has limited the use of concrete/mixto in rural areas to only 34% of homes, whereas 63% of homes in urban areas are of concrete/mixto construction (DIGESTYC 1999).

The bricks required for mixto construction are typically made by relatively primitive rather than highly industrialized processes. Pollution resulting from the combustion of wood, the very limited supply of wood in a country which has been largely deforested, and the emission of greenhouse gases in the firing process are problems which must be faced. The pilot study described herein aims to reduce the environmental impacts of brick production while making safe housing available to larger numbers of people. Because forces generated in earthquakes are proportional to mass, it is possible that the use of voided bricks will reduce the amount of clay required to form the bricks, the amount of wood consumed to fire the bricks, and the forces and stresses generated within the structure during earthquake excitations. In addition, stiffening the roof diaphragm may reduce the out-of-plane response of the walls, reducing stress demands and therefore allowing lower strength bricks to be used.

Fired Clay Bricks

Mechanical Properties of Existing Bricks

Small cube specimens were cut from bricks obtained from a small producer, Ladrillera La Cuchilla, on the highway Zonzanate in Armenia, El Salvador. Each face of the cube specimen, nominally 51 mm (2-in.) on each side, was cut or trimmed using a circular saw equipped with a diamond blade; guides ensured the faces were approximately orthogonal to one another. Twenty cubes were tested in a Universal Testing Machine; the first 10 were instrumented with a clip gage to allow the stress-strain behavior and Modulus of Elasticity to be determined. A 1.6-mm (1/16-inch) thick layer of plywood was placed between the cube specimen and the loading platens, to reduce the severity of potential stress raisers. The mean compressive strength of the 51-mm (2-inch) cubes was 4.39 MPa (636 psi), with standard deviation 0.57 MPa (82 psi). The modulus of elasticity was approximately 450 MPa and the density was approximately 1300 kg/m^3. The relatively low modulus appears to be appropriate for the El Salvador bricks, but a broader effort to characterize the bricks produced by a number of manufacturers is needed.

Effect of Firing Temperature and Duration on Cube Strength

Samples of unfired clay bricks also were obtained from the same producer. The unfired material was cut into cubes nominally 51 mm (2-in.) on each side. The cube specimens were fired in an oven at temperatures between 320 and 1100°C (600 and 2000°F) for durations between 6 and 48 hours. The compressive strengths of the fired cube specimens generally ranged between 1.59 and 6.92 MPa (230 and 1004 psi), increasing with increasing firing temperature and having little dependence on the duration of firing. The data are presented in Figure 1. Two cubes, fired at 980°C (1800°F) for 48 hours had substantially higher strengths, with the highest strength reaching 16.5 MPa (2390 psi). Interpretation of this result should be made in the context of a larger sample. The color of the fired cubes was observed to vary with firing temperature. Plotted for reference on Figure 4 is the mean compressive strength of the cubes obtained from bricks fired at the brick manufacturing plant in El Salvador, which are fired for 48 hours. Based on the strength test and color data, we believe the bricks reach a temperature of approximately 820°C (1500°F) during the firing process.

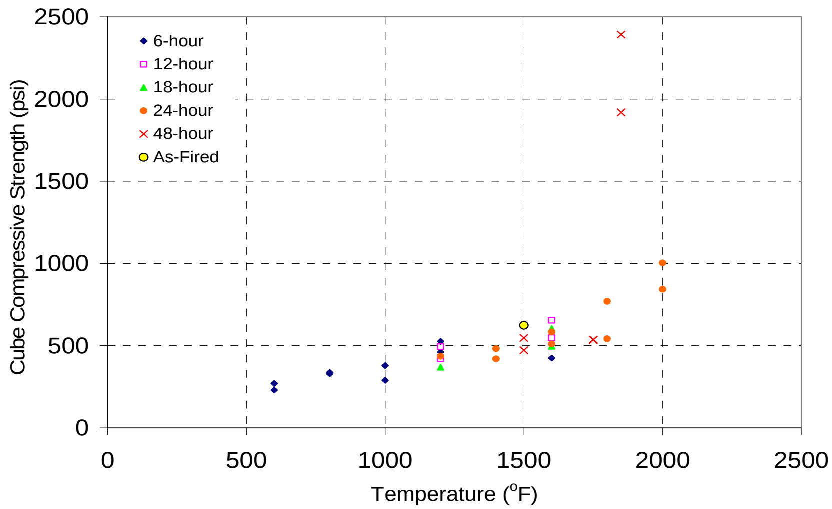

Figure 1: Effect of firing temperature and duration on compressive strengths of nominal 51-mm (2”) cubes. “As-Fired” represents the mean of the peak compressive strengths obtained for cubes cut from bricks fired in El Salvador plants.

Figure 1 indicates that comparable strengths can be obtained at shorter durations, perhaps even 6 hours or less. However, the time required for the entire firing chamber to reach 820°C (1500°F) has not been established. Some time is required for the heat to penetrate through the volume of the brick. A voided brick might be beneficial in three respects: (1) there would be less thermal mass; (2) the bricks could be placed in the kiln so that the voids provide a convective path to distribute the hot combustion gases throughout the firing chamber, and (3) the conductive pathways from the surface of the brick to the interior material are shorter and therefore less time would be required for the core of the brick to reach the firing temperature. Reducing the amount of time the kiln is fired would reduce thermal losses, the amount of wood consumed, and the pollutants and greenhouse gases emitted. Lower firing temperatures could be used if lower strength bricks were deemed adequate.

Post-earthquake Reconstruction with Mixto

Reconstruction after the 2001 earthquakes has proceeded with a multiplicity of approaches, objectives, and types of construction (EERI 2004), involving the collective efforts of various governmental and non-governmental organizations benefiting in many cases from foreign aid, A longstanding organization founded and functioning within El Salvador, the Fundación Salvadoreña de Desarrollo y Vivienda Mínima (FUNDASAL), has had a key role in the reconstruction process. FUNDASAL aims to improve the economic and social well-being of the communities that they serve. Their reconstruction efforts are developing the infrastructure and skilled labor force needed for economic growth, while addressing the immediate and profound demand for housing.

FUNDASAL is evaluating the relative merits of several alternative construction materials, including a simple rectangular plan building built of mixto. A reinforced concrete strip footing is used to support the structure; a single wythe of fired clay bricks is laid with cement mortar to create panels; and steel reinforcement and concrete are cast in place between the panels to form a system of beams and columns. A photo of a FUNDASAL mixto house is shown in Figure 2; the cement tiles used for the roofs (Figure 3) are manufactured at a FUNDASAL plant and are supported on #3 reinforcing bars, draped over a steel channel roof system. Single channels are used for the rafters, while a double channel is used for the ridge beam; the channels are nominally 50 x 100 mm (2 in. x 4 in.) with a thickness of about 1.6 mm (1/16-in.). Figures 4 and 5 show a plan view and typical details, respectively.

Figure 2. Representative mixto house used in reconstruction

Figure 3. Typical roof system, used for houses constructed of various materials.

Analytical Studies

The absence of diagonal bracing at the roof and ceiling levels is considered to produce a flexible diaphragm system. Detailed finite element models were created in order to establish in relative terms the influence of voided bricks and diaphragm bracing on the stresses developed in the bricks during seismic excitations. Peak normal stresses associated with out-of-plane motion of the walls and peak nominal shear stresses associated with the shears developed by the in-plane walls were evaluated for voids of different size with and without supplemental end-bay diagonal bracing. The end-bay diagonal bracing was located in a horizontal plane at the top of the longitudinal walls.

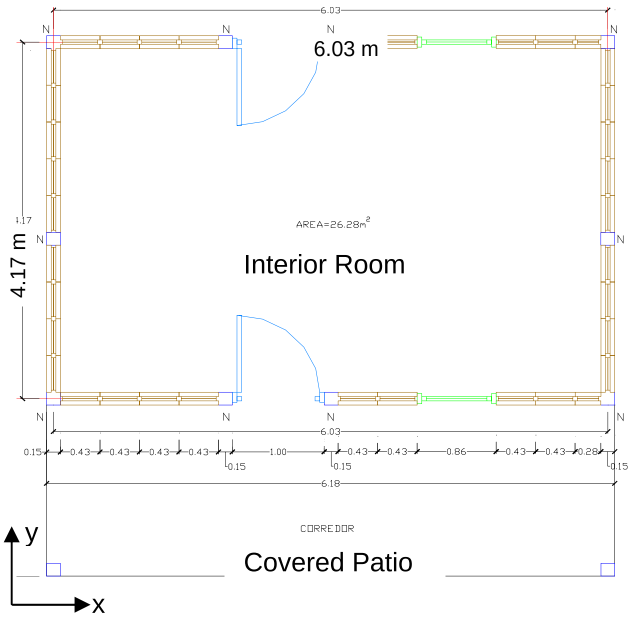

Figure 4. Plan used in analyses of mixto house.

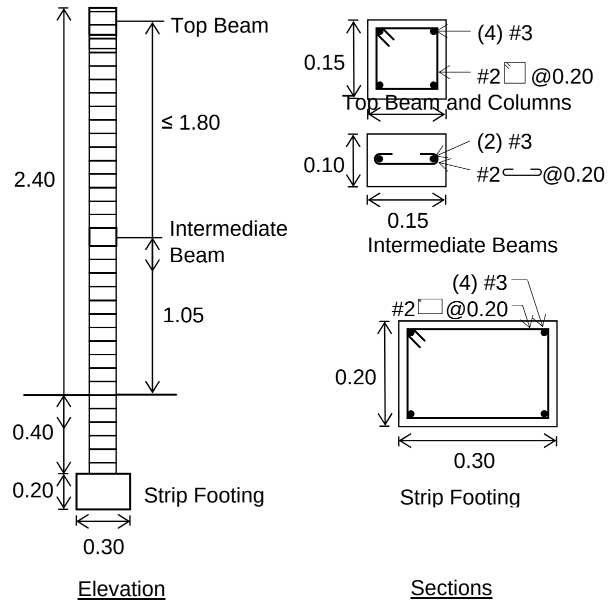

Figure 5: Typical details (reinforcing steel is in in-pound bar sizes; dimensions in meters)

Modeling

SAP2000 (CSI, 2004) was used to model the structure. Shell elements were used to represent the brick-mortar wall panels and to account for the mass of the roof, while frame elements were used to represent the reinforced concrete beams and columns as well as the rafters, ridge beam, and end-bay bracing where present. The structure was considered fixed at the base, although some movement at the soil-foundation interface might be anticipated.

The brick-mortar panels consist of 0.272 x 0.136 x 0.066 meter fired clay bricks that are bonded to one another with mortar having a thickness of 0.013 meters. The properties of the shell elements were set to represent the composite behavior of the bricks and mortar acting together. The modulus of elasticity for the mortar was estimated to be 2000 MPa, while the modulus for the bricks was determined to be approximately 450 MPa. To approximately represent the properties of the composite brick-mortar panel, the modulus of elasticity of the shell element was set to 610 MPa, the thickness for membrane behavior was set to 0.136 m, and the thickness for flexure was set to 0.144 m.

The beams and columns were represented using elastic frame elements. The axial and shear stiffnesses of concrete beams and columns were estimated as EA and GA, respectively (no reduction for cracking), while the flexural stiffness of each element was estimated as one-half of the uncracked, gross EI value, to account for cracking.

The cement roofing tile, reinforcing steel purlins, steel channels, and added density to account for moisture resulted in a total uniform mass of 40.7 kg/m^2. For the unbraced roof diaphragm, this uniform mass was represented over the surface of the roof using shell elements that had mass but negligible stiffness. The lateral stiffness of the steel channel rafters and double steel channel ridge beam was represented using beam elements having estimated section properties ($I_{xx} = 3.87x10^{-7}$ m^4 and $I_{yy} = 1.39x10^{-7}$ m^4 for a rafter and $I_{xx}= 7.74x10^{-7}$ and $I_{yy} = 11.1x10^{-7}$ m^4 for the ridge beam).

The use of elastic elements to represent the reinforced concrete beams and columns and the brick-mortar composite panels in effect allowed these members to maintain their stiffness in the presence of unrealistic values of tension. Consequently, the numerical results cannot be interpreted in an absolute sense, but may be useful for establishing in a relative sense the influence of various modifications, such as the use of voided bricks or the effect of end-bay diagonal bracing.

Ground Motions and Scaling

Ten previously recorded ground motions were used in the dynamic analyses. Each was applied independently in the *x* or *y* directions of the model (indicated in Fig. 7). Because the structures are relatively stiff, the ground motions were scaled on the basis of their peak acceleration. Scale factors required to obtain the code design peak ground acceleration of 0.4*g* are reported along with other details about the ground motion records in Table 1.

Influence of Void Size on Peak Stresses in Walls

A model of the as-built structure (solid bricks, flexible roof diaphragm, with window and door openings represented) was subjected to each of the ten ground motion records. Envelope values of bending moments within the wall (shell) elements were reviewed for each ground motion record. A typical result are the envelope values of moment shown in Figure 6 for response to the N-S component of the 1986 El Salvador Earthquake. Figure 6a illustrates the moments generated primarily from out-of-plane response of the walls (moments about the *x*-axis of Figure 4); the highest moments are at the base of the wall and may well be sufficient to cause cracking there. Figure 6b shows the moments about the *z*-axis of Figure 4, with the highest values occurring above the door opening in response to the significant out-of-plane motion developed by the walls (in the absence of roof bracing). The reinforced concrete beams lack sufficient stiffness to restrain the walls from such out-of-plane motion.

Normal stresses induced in the walls by the bending moments were determined by a simple mechanics of materials approach, assuming the bricks and mortar to be capable of sustaining both compressive and tensile stresses. The induced normal stresses are orders of magnitude greater than those associated with the tributary dead loads, and hence the dead load contribution to normal stress can be neglected. The stress determined for the largest of the envelope values (over all shell elements) for a solid brick under each of the ten ground motion records is plotted in Figure 7a, for a void diameter of zero, together with the results for cases in which voided bricks were used. The voids affected both the mass in the walls and the moment of inertia of the shell elements, as well as the flexural stiffness used for determining the peak normal stress at the extreme fiber. One can observe that voids of 2-in. diameter and less have a negligible effect on peak normal stress, whereas a void diameter of 3 in. is found to generally cause a small increase in peak normal stress. The computed normal stresses are far less than the compressive strengths reported in Figure 1 (500 kPa corresponds to 73 psi), and the low stresses appear to correlate to the relatively good performance observed for mixto structures in past earthquakes. However, the computed demands are uncertain in an absolute sense.

Table 1. Ground motions used in the analyses.

Event	Station	Component Bearing	Magnitude	Record PGA (g)	Scale Factor
Spitak, Armenia Dec 7, 1988	Gukasyan	0	6.8 (M_L)	0.155	2.58
Chile Mar 3, 1985	Llolleo	10	7.8 (M_L)	0.712	0.562
Chile Mar 3, 1985	Valparaiso	70	7.8 (M_L)	0.176	2.27
Imperial Valley May 18, 1940	El Centro	180	6.3 (M_L)	0.319	1.25
El Salvador Jan 13, 2001	Unidad de Salud San Pedro Nonualco	0	7.8 (M_s)	0.554	0.722
El Salvador Jan 13, 2001	Unidad de Salud San Pedro Nonualco	90	7.8 (M_s)	0.486	0.823
El Salvador Oct 11, 1986	Natl Geografical Inst	270	5.4 (M_s)	0.541	0.739
El Salvador Oct 11, 1986	Natl Geografical Inst	180	5.4 (M_s)	0.387	1.03
Loma Prieta Oct 17, 1989	Saratoga	0	6.9 (M_w)	0.504	0.794
Northridge Jan 17, 1994	Sylmar Hospital	90	6.7 (M_w)	0.604	0.662

Peak base shear forces developed during the dynamic analyses were noted. Nominal shear stresses, determined as the ratio of the base shear tributary to a wall and the net cross sectional area of the wall (accounting for voids, where present) were determined for each dynamic analysis. The calculated peak nominal shear stresses are plotted in Figure 7b. Voids of 2-inch or smaller diameter are seen to have a negligible influence on the nominal shear stresses developed

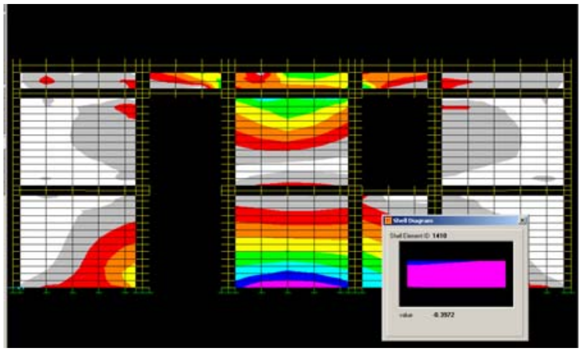

Figure 6a. Envelope values of M22 bending moment.

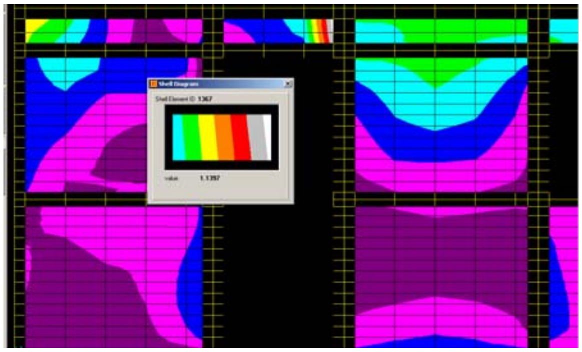

Figure 6b. Envelope values of M11 bending moment.

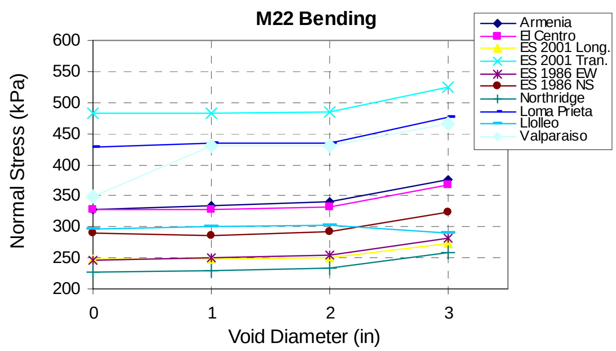

Figure 7a. Influence of void diameter on peak normal stress of out-of-plane walls (unbraced roof diaphragm)

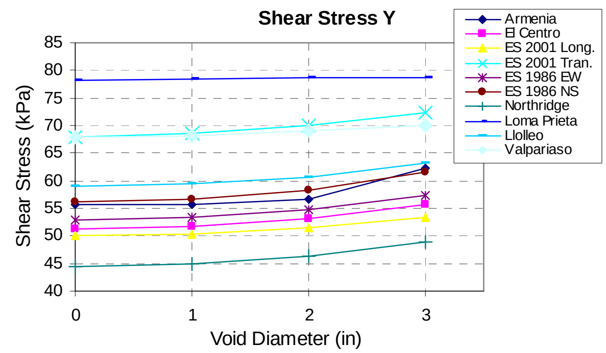

Figure 7b. Influence of void diameter on peak nominal shear stress of in-plane walls (unbraced roof diaphragm).

be slightly higher than those for the smaller voids. Given that the presence of voids may create a more complex shear stress distribution than occurs in a solid section wall, the shear demands should be interpreted relative to the shear strengths determined experimentally for wall panels with voids of varied diameter.

Influence of Diaphragm Bracing

This section examines the potential reductions in normal and shear stresses if bracing is added to the roof diaphragm. The reinforced concrete beam that runs along the top of the longitudinal walls (Figures 2 and 5) apparently is too flexible to appreciably restrain the out-of-plane movement of the walls. An end-bay bracing scheme is investigated herein, in which the steel channels currently used for the roof framing are used to provide diagonal bracing as shown conceptually in Figure 8. The bracing would be configured to connect into existing reinforced concrete beams and/or columns. Connection details and capacities have not been established, but will be the subject of a later investigation.

The bracing of Figure 8 is intended to provide a relatively stiff horizontal diaphragm. Out-of-plane motion of the short transverse walls is limited directly at the brace attachment point. Out-of-plane motion of the longitudinal walls is limited by the reinforced concrete beam at the top of the wall, which is restrained by the diagonal bracing acting in concert with the reinforced concrete beams at the end bay. The attachment of the diagonal bracing along the transverse walls requires that the uppermost horizontal ring beam of the longitudinal walls extend into the transverse walls, to become a full perimeter ring beam.

Dynamic analyses were run to determine peak normal stresses and nominal shear stresses for each of the scaled ground motions. Mean values of the peak stresses, for the ten excitations, are reported in Figure 9 for three cases: solid bricks and no bracing, solid bricks with bracing, and bricks with 2-inch diameter voids with bracing. Simple end-bay bracing is seen to substantially reduce the peak normal stresses, and that the peak stresses are effectively unchanged when 2-inch diameter voids are introduced into the bricks. The introduction of end-bay bracing generally had a minor effect on the peak base shear developed in the response to each motion.

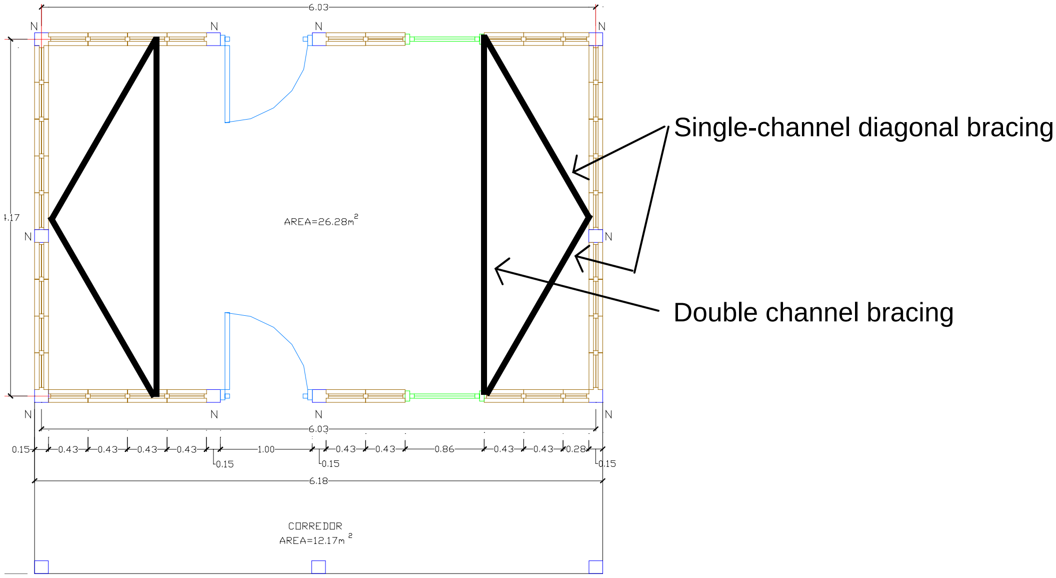

Figure 8. End-bay channel bracing

Peak axial forces in the bracing members are plotted in Figure 10 for each of ten dynamic analyses, taken as the larger of the peak forces developed for each record in independent analyses in the *x* and *y* directions. It can be readily observed that the peak forces in the transverse and diagonal members are nearly the same, and an upper bound of 10 kN (2.25 kips) was determined for the particular model and assumptions used.

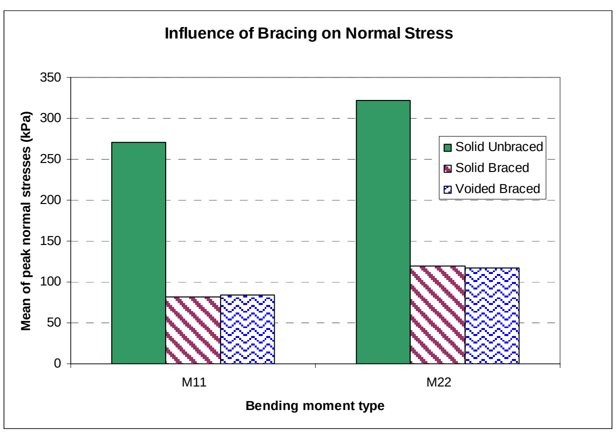

Figure 9. Influence of end-bay bracing on the average peak normal stresses.

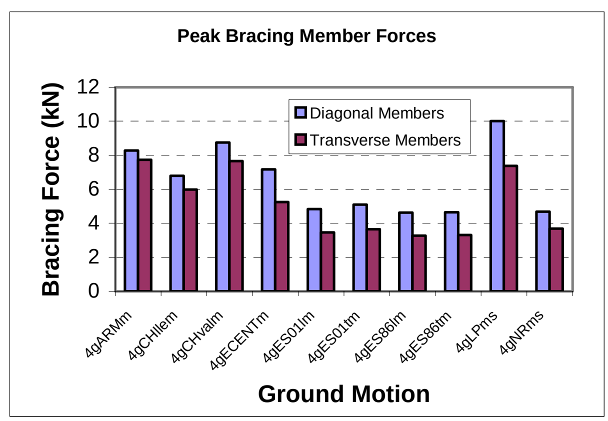

Figure 10. Bracing member forces for the solid brick model

Conclusions

While confined masonry dwellings have been observed to perform well in earthquakes in many parts of the world, modifications may potentially enhance seismic safety while allowing the production process to be fine-tuned to reduce environmental costs. Although this paper focuses on typical materials and construction procedures used for flexible diaphragm mixto construction in El Salvador, most of its findings are applicable for improving seismic safety and construction procedures for confined masonry dwellings in a number of countries in Latin America.

Analytical studies indicate peak compressive stresses on the order of 550 kPa (80 psi) for excitations scaled to the design peak ground acceleration of 0.4g. While such values are a function of many parameters (e.g. building configuration, material properties, modeling assumptions, and intensity of shaking), they are relatively insensitive to void size and can be reduced appreciably by the introduction of horizontal end-bay diaphragm bracing. The data of Figure 1 indicate that if a strength of three times the peak value cited above were acceptable, the bricks could be fired at only 600^{o}C for 6 hours, rather than the being fired at approximately 1500^{o}C for durations approaching 48 hours, as apparently is currently done.

The lack of sensitivity of peak compressive stress to void size is attributed to the reduction of mass associated with the use of voided bricks and the central location of the void, near the neutral axis. It is suggested that end-bay bracing be considered as a means to improve the seismic safety of mixto construction while allowing lower strength solid or voided bricks to be used. The lower strength bricks can be produced more efficiently and cost effectively, with less wood consumed in the firing of the bricks and lower emissions of pollutants and greenhouse gases. Cost savings achievable by using less material and firing this material at lower temperatures and shorter durations would make mixto construction affordable to even more sectors of the population, allowing it to displace less costly types of construction that have a poorer record of performance in earthquakes.

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