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Dynamic behavior of two models of adobe masonry dwelling with and without the confinement of concrete elements

Comportamiento dinámico de dos modelos de vivienda de mampostería de adobe con y sin confinamiento de elementos de hormigón armado

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ABSTRACT

The impact of seismic events on populations living in unreinforced adobe masonry buildings, mostly located in rural areas in Mexico and the rest of Latin America, has given rise to research aimed at studying construction and structural aspects in order to guarantee the stability of dwelling and the safety of the people who live there. This study presents the analysis of the dynamic behavior on the earthquake shaking table to contrast the response of adobe models at 1:3 scale without additional reinforcement in walls and roof, and with concrete reinforcement in walls and roof. The tests consider frequency, acceleration, displacement and scale factor according to the similarity laws corresponding to the physical and mechanical properties of the specimen. The results and conclusions show the stability advantages of adobe dwellings with the use of reinforcement based on concrete elements in a seismic event, compared to dwelling without reinforcement.

Keywords: Adobe; Concrete; Dwelling; Seismic; Stability; Structure.

RESUMEN

La afectación que han tenido las poblaciones que habitan construcciones con mampostería de adobe sin refuerzo, en su mayoría localizadas en zonas rurales en México y el resto de América Latina ante eventos sísmicos, ha dado pie a investigaciones dirigidas a estudiar aspectos constructivos y estructurales con el fin de garantizar la estabilidad de la vivienda y la seguridad de las personas que la habitan. En este estudio se presenta el análisis del comportamiento dinámico en una mesa vibratoria para contrastar la respuesta de modelos de adobe a escala 1:3 sin refuerzo adicional en muros y techumbre, y con refuerzo con elementos de hormigón en muros y cubierta. Los ensayos consideran la frecuencia, aceleración, desplazamiento y el factor de escala según las leyes de similitud correspondientes a las propiedades físicas y mecánicas del espécimen. Los resultados y conclusiones muestran las ventajas de estabilidad de la vivienda de adobe con uso de refuerzo a base de elementos de hormigón ante un evento sísmico, con relación a la vivienda sin refuerzo.

Palabras clave*: Adobe; hormigón; vivienda; sismo estabilidad; estructura.*

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1. INTRODUCTION

Adobe constructions are defined as a group of buildings constructed with pieces of unfired earth (1). Buildings of this type have shown a vulnerable behavior in seismic events, presenting significant damage, the lack of stiffness of the walls contributes greatly to the partial or total collapse of the structure (2), sometimes resulting in the loss of human lives (3).

Adobe is inexpensive an easy-to-use material for the construction of walls, vaults, houses, and churches, and in many regions of the world there are vestiges of entire villages that have defied time. This research addressed the stability problems of adobe dwellings, focusing especially on the junction between walls and between walls and roof.

The earthquakes occurred in the second half of 2017 in Southwest and Central Mexico, and according to the report presented by the governmental agency (4), 171 925 dwellings with partial or total damages were registered in 7 federal entities of Mexico, of these 20% were adobe-based houses. (5).

Adobe houses are seriously affected by a medium or high-intensity earthquake, due to the lack of nodal stiffness between walls and roof. Among the failure modes that are characteristic of other regions that use the same construction system are: in-plane and out-of-plane flexural failure (6), compression, flexural compression, shear, failure in wall joints, and wall-roof joints (7).

The structural vulnerability of dwellings after the September 2017 earthquakes in Central and Southeastern Mexico (8), evidenced the types of structural failure mentioned above, highlighting the lack of nodal stiffness *K*, this causes the walls to act with a larger effective length *Le* when the roof is not properly attached to the walls, causing instability, Figure 1.

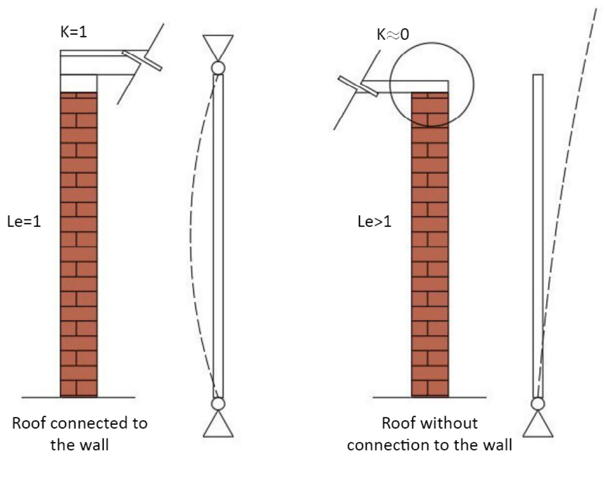


Figure 1. Effective lengths factor K

Generally, in dwellings with adobe masonry, the roof systems are composed of wooden beams or trusses, covered with a layer of brick or mud, which works as flexible diaphragms, and generally do not offer stiffness to the structure. There are also hybrid systems with reinforced concrete roofs and adobe walls, of which there is little information on their structural response (9), but they have had a positive behavior under horizontal loads, greater than when there is no reinforcement or confinement.

Research on the stability of adobe constructions has been carried out with more emphasis in the last fifty years, including experimental works on the behavior of walls with different types of reinforcements under seismic loads, such as: walls reinforced with concrete tie columns and tie beams (10); walls with plastic mesh reinforcement (3); walls with metal mesh reinforcement and plaster cement (11). However, there is little scientific literature on the dynamic behavior of buildings with adobe walls confined with concrete elements, which have been used mainly as independent walls or in walls.

For the present study, the confinement of adobe walls with concrete elements joined to a lightened concrete slab is proposed; considering the properties of concrete and adobe, which have different chemical compositions and manufacturing processes, besides having different shrinkage indexes, compressive strength, modulus of elasticity and consequently, stiffness of the structural element (12), which makes the behavior between walls and roof to be affected when the interaction between them is not considered in their construction (13).

The objective of the present work has been to contrast the results obtained from the study of the structural behavior under seismic simulation of a scale model of an unconfined adobe dwelling and a confined adobe dwelling with concrete elements and a ribbed concrete slab with polystyrene blocks.

This research shows the physical and mechanical properties of the elements that make up an adobe dwelling with confined walls attached to a lightened concrete slab. Reduced scale models are built taking into account the laws of scale or similarity (14-16), which are subjected to dynamic loading, which gives an approximate parameter of the structural behavior of the dwelling in a seismic event.

A structural analysis is performed highlighting the stiffness contribution of the concrete elements to the adobe wall, plus the stiffness contribution of the lightened concrete slab to the confined wall. Conclusions and recommendations are given for the testing of the adobe dwelling specimen without confinement, and contrasted with the testing of the dwelling specimens with confinement based on concrete elements.

2. MATERIALS AND TEST METHODS

2.1. Manufacture of adobe pieces

The composition of the soil, according to the analysis of granulometry and index properties of the material, is characterized by its content of inorganic clays of medium plasticity, with fine-grained dark brown sands (CL SUCS classification) (17).

The manufacturing process of adobe bricks consisted of mixing soil, sand, straw, and water in a 1:1:0.1 volume ratio until a paste-like composition was obtained, leaving it to stand for a minimum of 24 hours, and then proceeding to the manual manufacture of adobe pieces whose dimensions are, 10 cm wide, 16 cm long and 3 cm high, which were dried outdoors for 30 days.

2.2. Mechanical testing

The mechanical tests for adobe were carried out based on Peruvian Standard N.E. 080 (18) regarding design and construction

Table 1. Mechanical tests on Adobe specimens

Text	Drying time	Number of specimens	Loading speed	Allowable stress	Standard E. 0.80
	days		MPa/min	MPa	MPa
Compressive strength of the adobe cubes.	30	6		1.20	1.02
Compression test of Adobe stacks	59	6	0.97	0.86	0.61
– Design compressive stress	59	6	–	0.35	0.20
– Crushing stress	59	6	–	0.44	0.31
– Modulus of elasticity	59	6	–	258.74	–
Diagonal compression	71	6	1.29	0.077	–
– Shear stress	71	6	–	0.03	0.025
– Shear modulus	71	6	–	71.40	–
Tensile test bond strength of mortar	30	6	0.14	0.04	0.012
Adherence Testing between the adobe pieces and the concrete	30	6	0.86	0.04	–

with earth, and Standard NMX-C-464-ONNCCE-2010 (19) regarding clay and concrete pieces, the tests performed were as follows:

- Compressive strength of the adobe cube.
- Compression test of adobe stacks, from which the design compressive stress, crushing stress and modulus of elasticity were obtained.
- Diagonal compression test on adobe wallets, from which the shear stress and shear modulus values were obtained.
- Tensile test bond strength of mortar.
- Adherence testing between the adobe pieces and the concrete.

Table 1 shows the number of specimens, loading rate and allowable stress obtained in each test to know the physical-mechanical properties of the masonry to be used in the models.

Additionally, the compressive strength test of concrete specimens was performed in accordance with Mexican standard NMX-C-083-ONNCCE 2014. (20); 3 cylinders identified with the letters CC, with an average resistance of f'c= 14.91 MPa, representing the concrete used in the confining elements and roof slab in models H-2 and H-3 at 1:3 scale, were subjected to compression tests.

2.3. Model test methods

For the seismic simulation, three dwellings models of 12.96 m² each were built, on a wooden and polystyrene base at a scale of 1:3, identified with the letters H, Table 2, Figure 2., with an interior area of 9.00 m², value that represents an area to develop a rest-activity in a dwelling, the construction specifications are mentioned in the development of each one of them.

For the three models, the foundation is 12 cm wide by 15 cm deep, based on a stone of 5 to 10 cm in diameter joined with cement-sand mortar 1:3. This type of foundation was chosen because it is the most commonly used for this type of construction in Mexico and Latin America (10).

Table 2. Dwelling specimens (models), scale 1:3

Specimen	Confinement of concrete elements	Roof	Direction of the roof beams
H-1	No	Timber	Axis X
H-2	Yes	concrete	Axis X
H-3	Yes	concrete	Axis Y

Figure 2. Test specimens H-1, H-2, H-3

Table 3 shows the actual weights of the models obtained with a scale, as well as the calculated weight of the 1:1 scale prototypes according to the volumetric weight of the materials (21), which serve as the basis for the analytical calculation of their displacements.

Table 3. Weight ratio between prototypes and 1:3 scale specimens

Structural element	Specimen	Prototype	Specimen	Prototype
	H-1	real scale 1:1	H-2 and H-3	real scale 1:1
	kgf	kgf	kgf	kgf
Walls	584	17 772	484	14 076
Tie column and beam	–	–	115	3 240
Roof	14	907	120	12 462
Total weight	598	18 679	719	19 778

2.4. Construction process of specimen H-1, (scale 1:3)

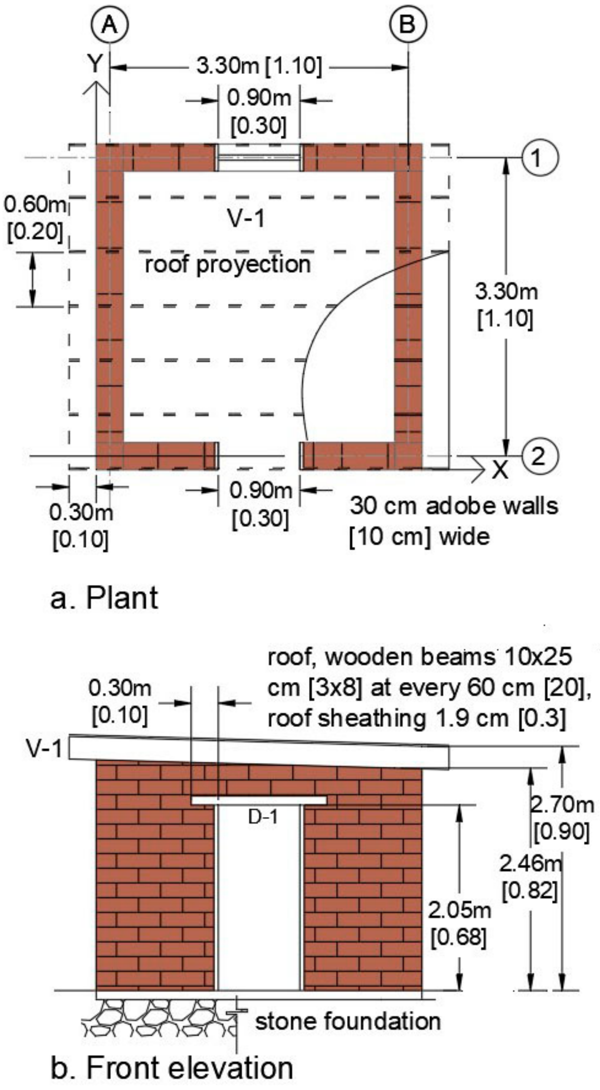


Figure 3. Specimen H-1, scale 1:3

The walls are supported on stone foundations, the adobe pieces are glued with the same material they were made of, in a running bond pattern, and in overlapping form in the joints of two or more walls, Figure 3 and 4.

Figure 4. Foundation and wall construction

In the 1:3 scale model, the lintels on doors and windows are 2 cm high by 10 cm wide, protruding from the span on both sides by 10 cm. The roof is made of wooden beams 2 cm wide by 6 cm high, with 18 cm spacing from axles, on which a 0.3 cm wooden cover is placed, covered with sand. Figure 5.

Figure 5. Roof beams and framing in spans

2.5. Construction process of specimen room H-2 and H-3, (scale 1:3)

The structural plan and elevation drawings of both specimens are shown with their respective dimensions, the only difference between the two specimens is the direction of the lightened concrete ceiling beams in one direction; it corresponds in the X direction for room H-2, Figure 6a, and in Y direction for specimen H-3, Figure 6b. Two types of dimensions are noted on the drawing, the dimensions in parentheses indicate the actual dimensioning of the model, the dimensions not in parentheses indicate the dimensioning of a 1:1 scale prototype.

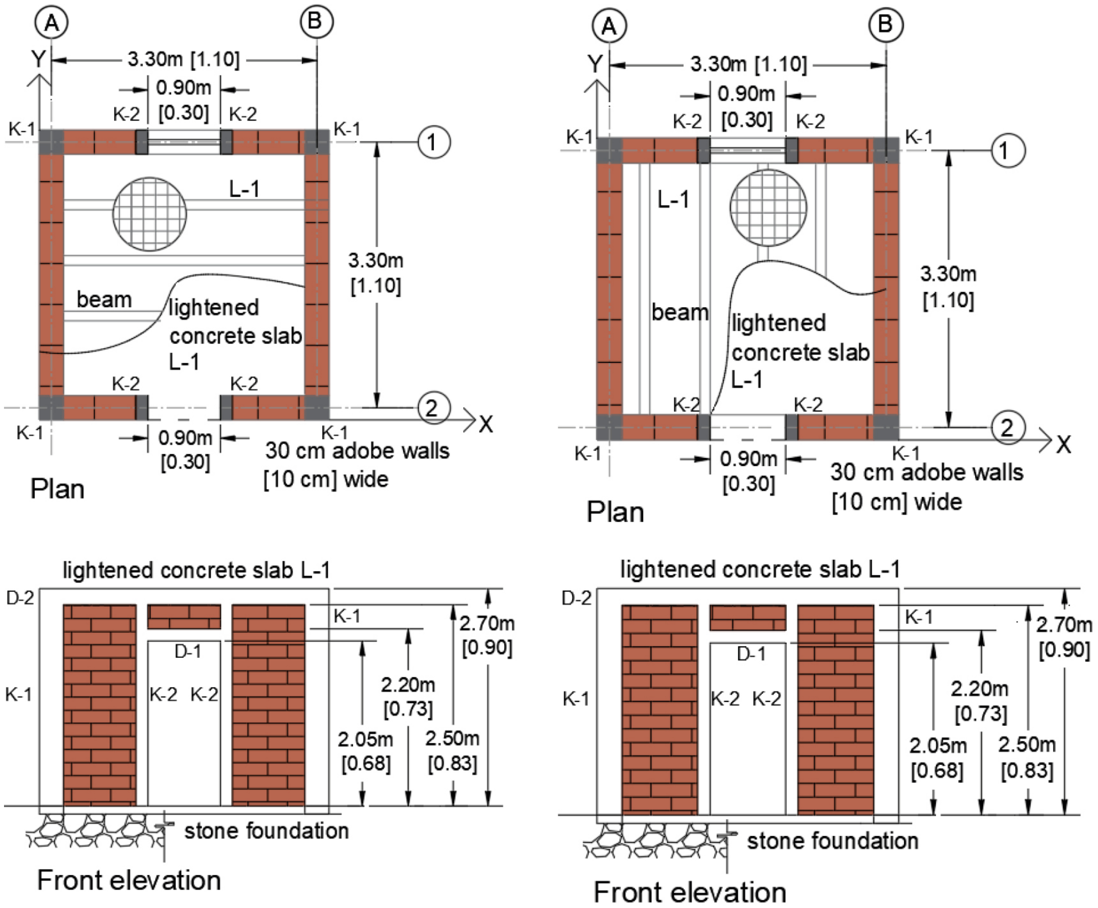
The vertical reinforcement elements that serve as confinement to the walls are anchored to the foundation.

At the intersections of the walls, 10 cm × 10 cm K-1 ties columns have been placed, reinforced with 4 # 2 bars (∅ 6 mm) 10-gauge stirrups every 6 cm, Figure 7a. In door and window openings, the K-2 tie piers, are reinforced 5 cm × 10 cm with 2 # 2 bars, 10-gauge stirrups every 6 cm (21), Figure 7b.

D-1 lintels, Figure. 8a, are reinforced 5 cm x 10 cm with 2 # 2 bars, 10-gauge stirrups every 6 cm (21). 10 cm × 5 cm; D-2 roof slab perimeter tie beam, Figure 8b, reinforced with 2 # 2 bars in the lower bed, 2 10-gauge bars in the upper bed, 10-gauge stirrups every 6 cm;

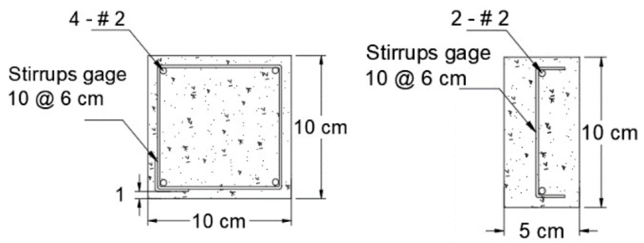
The roof slab L-1, is made of 7 cm thick concrete lightened with 2.5 cm thick polystyrene plates (22), beams in one direction every 33 cm, with 4 cm × 7 cm section, reinforced with 2 × 10-gauge bars, 12-gauge stirrups every 6 cm, Figure 9, the compression layer is 2 cm reinforced with 21-gauge mesh, the concrete ratio is 1:2:2 (one cement to two sand and two gravel).

The following illustrations show the assembly of roof slab L-1, for specimen H-2 in the X-X direction, Figure 10a; and for specimen H-3 in the Y-Y direction, perpendicular to the door and window openings, Figure 10b.



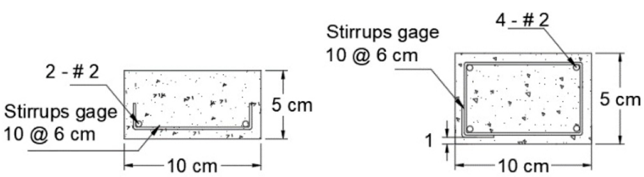
a. Specimen H-2, beams in the X direction b. Specimen H-3, beams in the Y direction
The dimensions in parentheses indicate the actual dimensioning of the model

Figure 6. Specimen H-2 and H-3, scale 1:3



a. Tie column K-1 b. Tie column K-2

Figure 7. Wall reinforcement cross-section



a. Lintel D-1 b. Perimeter tie beam D-2

Figure 8. Wall reinforcement cross-section

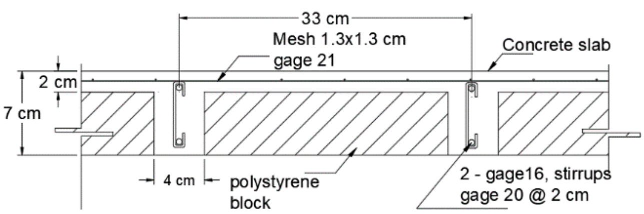


Figure 9. Roof slab L-1

a. Roof slab for H-2 specimen b. Roof slab for H-3 specime

Figure 10. Construction process of H-2 and H-3 specimen roof slab

Table 4 shows the ratio of the cross-sections of the structural elements and the areas of reinforcing steel between the 1:3 scale specimen and the full-scale 1:1 prototype.

2.6. Vibration table for seismic simulation

The seismic simulation tests were carried out on a 1.20 m × 1.20 m shaking table, which can have three independent movements: two horizontal movements (X and Y) with a load capacity of 900 kg, and a vertical movement (Z) with a load capacity of 300 kg. Its source of movement is pneumatic with a maximum working pressure of 8 kg/cm^2, frequency from 0.1 to 15 Hz, and a horizontal displacement of 7 cm, and 5 cm in the vertical axis.

Its operation is through LabVIEW software, with which you can control the frequency, duration of the test, axis movements, and obtaining data from motion sensors, Table 5, shows its functional characteristics.

Table 4. Scale ratio for H-2 and H-3 specimens

Structural element	Scale 1:1		Scale 1:3	
	Size dimensions (cm)	Reinforcing steel % area	Size dimensions (cm)	Reinforcing steel % area
Foundation	80 width	–	27 width	–
Walls	30 thickness	–	10 thickness	–
Tie column K-1	30 × 30	1.13	10 × 10	1.27
Tie column K-2	15 × 30	0.63	5 × 10	1.27
Lintel	15 × 30	0.56 (t)*	1.5 × 3	1.27 (t)*
Roof	20 heigth	–	7 heigth	-
Beams	12 × 20	0.52 (t)*	4 × 7	1.13 (t)*
Concrete slab	5	0.12	0.5	0.42

* tensión

Table 5. Functional features of vibrating table

Features	Range
Dimensions	120 cm × 120 cm
X axis load capacity	900 kgf
Y axis load capacity	300 kgf
Vertical Z-axis load capacity	150 kgf
Directional motion	3 degrees of freedom
Maximum displacement	± 70 mm
Speed range	0.1 a 10 m/s
Frequency	a 15 Hz

2.7. Scale models testing methodology

The specimen (model) is placed on the dynamic simulation table and anchored to the base in such a way that it is adequately secured, after which the linear and angular displacement of the model is instrumented, after calibration of the sensors. The instrumentation is divided into two parts: the one corresponding to the X, Y, and Z axes of the vibrating table based on ultrasonic linear distance sensors with a speed of 7 readings per second and the one corresponding to the test model, with ultrasonic linear distance sensors and angular measurement bending sensors, both with a speed of 7 readings per second.

The frequency of movement of the table and the duration of its phase are programmed, the air pressure necessary for its operation is verified and the instrumentation is sending the signal correctly; the test is started and the data of displacement, accelerations, periods and damages in the testing process in the different phases are recorded.

For the dynamic test, frequencies from 0.6 Hz to 6 Hz are proposed, comprising periods of less than 0.3 seconds, close to the period of a one-story masonry dwelling house typology, with accelerations ranging from 10 to 600 gal; Table 6 shows the phases and accelerations for the 1:3 scale models.

Table 6. Acceleration phases for 1:3 scale models

	Phase 1	Phase 2	Phase 3	Phase 4
Time	12 s	23 s	53 s	130 s
Componente	X	X	X	X
Acceleration	gal	gal	gal	gal
Specimen H 1:3 scale	10 - 300	10 - 40	10 - 60	10 - 40

2.8. Analysis methods

In this stage, the parameters for the structural analysis of unconfined and confined walls are given, and the influence of the stiffness of the lightweight concrete slab (23) on the walls forming the test specimens, for the purpose of comparing their displacements and stiffness's under seismic loading, considering the zone aspects, weight and properties of materials.

The deformation analysis is performed according to the linear homogeneous and isotropic elastic behavior (24), using the wide column model. The horizontal seismic force *Pi* applied at the center of mass of level *i* acting on the 1:1 scale prototype is obtained Equation [1]:

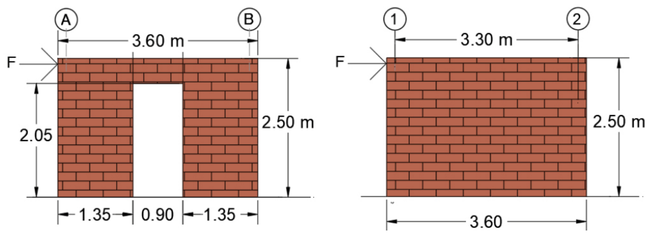
$$[1]\ P_i = (Wi\ Hi / \Sigma\ Wi\ Hi)\ C\ \Sigma\ Wi$$

Where *Wi* is the weight of the level or story, *Hi* is the height of the force application mass *Pi*, and *C* is the seismic coefficient. The structure is classified according to its destination, soil type, and seismic behavior factor *Q*, (25). For the calculation of the displacement δ and lateral stiffness *K* at the centroidal point in solid unconfined cantilevered walls Figure 11, the following expressions, Equation [2 and 3], are used:

$$[2]\ \delta = (Ph^3/3EI) + (Ph/GA)$$

$$[3]\ K = P/\delta$$

Where *P* is the lateral force at its centroid point, *h* is the height of the wall, *E* is the modulus of elasticity, *A* is the cross-sectional area of the wall and *G* is the shear modulus.



a. Axis 2, A-B b. Axis A, 1-2

Figure 11. Structural analysis of walls, H-1 prototype

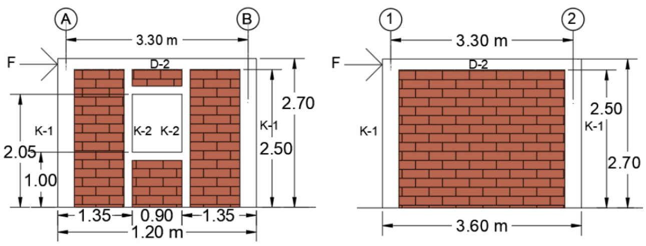
For the analysis of the adobe masonry walls confined with concrete elements, Figure 12, the wide column analogy model is used where the wall is replaced by a column in the geometric center (24).

The system of equations is solved by means of the direct stiffness method (26), the displacements *d* and the lateral stiffness of the wall K_Δ are obtained with equations Equation [4 and 5]:

$$[4]\ d = S^{-1}P$$

$$[5]\ K_{\Delta} = P/d$$

Where P is the force acting on the node, and S^{-1} is the inverse of the general matrix.



a. Axis 2, A-B b. Axis A, 1-

Figure 12. Structural analysis of walls, prototype H-2 and H-3

Table 7 shows the walls of the 1:1 scale prototypes to be analyzed by the wide column model, according to the axes shown in Figures 11 and 12.

Table 7. Structural analysis of walls

Prototype	Axis	Condition
H-1	2. A-B	Without confinement
H-2 , H-3	2. A-B	Confined with roof
H-2 , H-3	2. A-B	Confined without roof
H-1	A, 1-2	Without confinement
H-2 , H-3	A, 1-2	Confined with roof
H-2 , H-3	A, 1-2	Confined without roof

3. RESULTS / DISCUSSION

3.1. Seismic simulation results of 1:3 scale models with no confinement and flexible roof, and with concrete confinement and rigid lightweight concrete roof

Results are presented under horizontal dynamic loading applied to the three 1:3 scale models with 68 days of drying, which describes the response of the specimens in relation to the applied frequency and acceleration, the displacements of its base and the walls perpendicular to the movement are shown, according to the reading of the sensors placed specifically for this purpose.

A comparison is made of the dynamic behavior of the specimens with emphasis on the wall-to-wall junction and the wall-to-roof junction.

Due to the characteristics of the type of construction, its natural period and the capacity of the vibrating table, periods between 1.67 and 0.17 seconds were used. The results shown include the scale factor according to the similarity laws corresponding to the physical and mechanical properties of the specimen.

3.2. Result of unconfined H-1 specimen

Three dynamic tests were applied to the model in the direction horizontal to the X-axis, parallel to the plane of door and window spans with factored time duration (t/3), Table 8.

Table 8. Dynamic simulation phases, H-1 specimen

Phase	Time (s)	Acceleration (gal)	Frequency (Hz)
1	12	7.53 a 244.40	0.6 a 6.0
2	23	8.27 a 36.55	0.6 a 1.8
3	53	8.10 a 53.18	0.6 a 1.6

Figure 13 shows the physical condition of the specimen before testing, which shows no damage.

a. Front elevation b. Back side elevation

Figure 13. Physical condition of specimen H-1 before dynamic testing

3.3. Horizontal dynamic test, phase 1, duration 12 seconds

Description: Figure 14 shows the relationship of Acceleration with respect to Displacement and Period. First visible damage appears for an acceleration between 90 gals and 174 gals, with a displacement of 10 cm, which corresponds to a period between 0.30 s to 0.22 s, and moderate damage for an acceleration between 174 gals and 244 gals corresponding to a period between 0.22 s and 0.17 s.

Figure 14. Cracks around the door opening, front view

Figure 15 shows the damages where there is stress concentration, mainly in the door and window openings, where cracks and fissures can be seen at an angle of approximately 45°, which starts at the vertices of the span outwards from them, there is no damage to the rest of the structure. The structure remains stable but with moderate damage that may be repairable.

Figure 15. Cracks around the window opening, back side view

3.4. Horizontal dynamic test, phase 2, duration 23 seconds

Description: Moderate to heavy damage is observed in an acceleration range between 10 gals and 40 gals, which corresponds to a period between 1.5 s to 0.56 s, fractures in the foundation for accelerations between 22 s and 36 gals, which corresponds to a period of less than 1.0 s.

Figure 16 shows how the cracks are more accentuated around the door and window openings, with an approximate angle of 45° through the wall, door and window frames are separated from the wall, foundation failures are observed with different cracks in its perimeter, no damage is visible at the corner junction between walls, nor on walls perpendicular to the openings. Regarding the roof, the separation of the longitudinal wooden beams from the adobe walls can be observed. The structure due to the damage severity, is considered unstable and uninhabitable.

3.5. Horizontal dynamic test, phase 3, duration 53 seconds

Description: Heavy to extreme damage is observed in an acceleration range of 10 to 26 gal, which corresponds to a period between 1.6 to 0.63 s, for the period between 0.83 s and 0.71 s, fractures are accentuated in the entire structure until total collapse is reached.

Figure 17 shows the damage sequence, the total detachment between the span frames and the wall can be seen, cracks increase in size to the point of partial or complete separation of parts of walls, for the period between 0.83 and 0.71, fractures are accentuated throughout the foundation, shifting away from the wall axis., no damage is seen at the corner junction between walls, but total separation leading to collapse (out-of-plane failure) in the central axis of the specimen passing through the spans, the roof is completely separated from the walls when collapse occurs.

In the specimen tests, 3 readings were taken with previously calibrated ultrasonic sensors to know the linear displacement on the outer walls perpendicular to the movement of the base (X-axis), and four readings with 5 cm high variable resistance bending sensors attached to the same exterior walls at a height of 2.00 m with previous calibration, to know the angular deformation caused by the different frequencies.

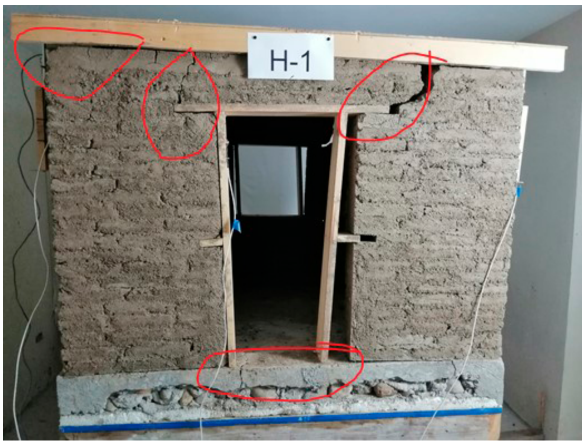
The maximum displacement with the similarity factor applied was 0.61 cm at the stage of structural damage, phase 3 was not implemented to avoid damage to the sensors in the event of model collapse.

3.6. Result of specimen with confinement H-2 and H-3

Three dynamic tests were performed in the horizontal direction along the X axis equal to specimen H-1, the stability of the structures of H-2 and H-3, a fourth phase was added, all of them parallel to the plane of door and window openings with factored time duration (t/3), Table 9.

Table 9. Dynamic simulation phases, specimen H-2 and H-3

Phase	Time (s)	Acceleration (gal)	Frecuency (Hz)
1	12	7.53 a 244.40	0.6 a 6.0
2	23	8.27 a 36.55	0.6 a 1.8
3	53	8.10 a 53.18	0.6 a 1.6
4	130	8.31 a 33.69	0.6 a 2.0



a. Large cracks around the door opening, front view

b. Large racks around the window opening, interior view

Figure 16. Damage in dynamic test for H-1 specimen, phase 2

a. Extreme door damage and foundation fracture, front view

b. Total collapse, side backside view.

Figure 17. Damage in the dynamic test for H-1 specimen, phase 3

a. Front elevation b. Interior view

Figure 18. Physical condition of H-2 after dynamic test

a. Front elevation b. Back side and lateral elevation

Figure 19. Physical condition of H-3 after dynamic test

3.7. Phase 1, 2, 3 and 4 horizontal dynamic test

Description: No visible damage was observed during the four dynamic test phases, the reinforcements in door and window openings, wall junction, walls, foundation and roof, preserved their structural integrity.

Figure 18 and 19, show the structural integrity of specimen H-2 and H-3, there is no visible damage to the entire structure.

The model with structural confinement based on concrete elements in walls and roof slab, elements showed an efficient performance under the same dynamic loads as the model without confinement., there was no damage around the door and window openings, foundation and concrete roof.

The direction of the concrete roof beams parallel to the spans (specimen H-2), and perpendicular to them (specimen H-3), provided the necessary stiffness for the stability of the structure.

3.8. Structural analysis results

Structural analysis of unconfined and confined walls is carried out, and the stiffness contribution of the bond between the lightweight concrete slab and the adobe walls confined with concrete elements; the results of the displacements and lateral stiffness's of the adobe walls analyzed are given below. The data on the mechanical properties of the materials are taken from section 2.1. Equation 1 was used to obtain the horizontal seismic force, and Table 10 shows the data and coefficient used.

Table 10. Proposed seismic strength for prototype analysis

Story	Weight	Height	Seismic coefficient	Seismic force (Pi)
No.	kgf	cm		kgf
1	19778	270	0.44	8702

As they are unconfined walls and due to the type of wood sheathing roof proposed, their restriction at the junction with the wall is disregarded, and were therefore analyzed as cantilever walls. For the evaluation of confined walls, the wide column method was used through the direct stiffness matrix method.

Table 11 shows the results of the displacement and lateral stiffness analyses of the walls under different constraint conditions.

Table 11. Results of displacement and lateral stiffness of walls

Prototype	Axis	Condition	Displacement (δ)	Lateral stiffness (K)
			mm	kgf/cm
H-1	2. A-B	Without confinement	3.53	35.31
H-2, H-3	2. A-B	Confined with roof	0.034	0.34
H-2, H-3	2. A-B	Confined without roof	0.041	0.41
H-1	A, 1-2	Without confinement	0.42	4.24
H-2, H-3	A, 1-2	Confined with roof	0.001	0.001
H-2, H-3	A, 1-2	Confined without roof	0.007	0.07

4. CONCLUSIONS

Specimen testing based on scale models, gives an approximate parameter of the structural behavior of adobe dwellings in a seismic event. Conclusions from unconfined adobe specimen testing are given, and are compared with tests of specimens with confined concrete elements.

4.1. Mechanical material properties

1) Allowable compressive stress of adobe, obtained from the average allowable stacks stress was satisfactory, with an average of 43% higher resistance than the minimum required by E.080 Standard.

2) Elastic modulus evaluated according to NMX-C-464-ONNCCE-2010 Standard, may vary due to the difficulty of identifying the elastic zone of the stress-strain curve, adobe is considered a non-elastic material with less rigidity than the annealed clay bricks and concrete blocks considered in this standard.

3) The admissible shear stress of adobe, obtained from the average allowable diagonal compressive stress of the walls was satisfactory, an average of 20% higher than the minimum required by E.080 Standard.

4) The ratio between the modulus of elasticity Em and shear modulus Gm was 27.6%, which does not correspond to that suggested by NMX-C-464-ONNCCE-2010 Standard of 0.4 of the modulus of elasticity, due to the low stiffness of the material.

4.2. Specimen without confinement H-1

5) First visible damage occurred at 0.25 to 0.17 s after 4 Hz frequency and 244 gal acceleration, taking as a reference that the earthquakes in 2017 in the southwest of Mexico that affected dwellings had a period of fewer than 0.3 seconds.

6) Nodal stiffness at the wall-to-wall junction showed high fragility to in-plane and out-of-plane forces, by not having a connecting element between the walls.

7) Poor structural behavior under dynamic actions due to low stiffness and inelastic response of adobe.

8) Wood lintels, due to their discontinuity, do not contribute to the stiffness of the structure because they do not have continuity and anchorage with a structural element.

9) The roof with no connection to the walls, causes them to vibrate independently and act as cantilever walls, affecting the stability of the dwelling and causing partial or total collapse of the dwelling.

4.3. Specimen with confinement and lightened concrete slab H-2 y H-3

10) No structural damage was recorded in slabs or walls; the specimens maintained their structural integrity during the whole test process.

11) Wall confinement with vertical and horizontal concrete elements, provided stability to door and window spans, dissipating the kinetic energy thanks to the stiffness provided by these elements.

12) The ribbed concrete slab with polystyrene blocks transmits the inertia loads through the tie beams to the tie columns and wall, while at the same time linking these elements, acting like a rigid diaphragm.

13) The difference in damage and stability between the confined and unconfined model at the same frequencies and accelerations could be appreciated, being the confined specimen showing high structural stability compared to the unconfined specimen.

14) The use of horizontal and vertical elements of reinforced concrete, in addition to the concrete ribbed concrete slab, provides the necessary stiffness to the adobe construction to mitigate the damages that may be generated in a seismic event.

4.4. Structural analysis

15) The analysis performed by the wide column model confirms the results obtained in the specimens in relation to the displacement of a wall under a horizontal load.

16) The confinement of walls with concrete elements greatly increases the stiffness of the wall.

17) The confined wall with concrete elements attached to a lightened concrete slab as roof, increased the stiffness of the wall by 20%.

18) Mathematical simulation tested by experimentation allows transpolations to other dwelling models.

5. RECOMMENDATIONS

Based on the studies related to the subject of this paper, the experimentation carried out and the conclusions drawn from it, the following recommendations are suggested that can be used to carry out similar research studies or in the construction process of this type of dwelling.

a) This research refers only to the samples tested, independent tests should be carried out for each type of mix for adobe manufacture (as future research work), in order to obtain accurate data for each site where confined concrete construction is manufactured or carried out, due to the different degrees of plasticity of the clays.

b) Studies should be carried out to obtain the modulus of elasticity of adobe more accurately, (these tests will be carried out in the course of future research). Although the standard procedures for annealed clay bricks and concrete blocks can be followed, identification of the elastic zone in the stress-strain curve is uncertain, because the adobe has mechanical properties of compressive strength and stiffness in different proportions compared to annealed clay bricks.

c) In the ratio between the modulus of elasticity and shear modulus of adobe less than 30%, the shear modulus should be adjusted so that there is congruence in the deformations.

d) In the construction of confined dwelling units with reinforced concrete elements, steel bars must be continuous, or have the necessary overlapping at the junction of the tie column with the tie beam and the lightened concrete slab, to ensure adequate stress transmission.

e) The dynamic tests considered maximum spans between walls of 3.30 m, and window and door spans of 0.90 m; for larger clearances, the corresponding analysis must be performed.

f) A minimum wall thickness of 0.30 m is recommended for structural integrity; the tie columns must have a minimum width equal to the thickness of the wall.

g) In the instrumentation of the test models, in addition to using linear displacement sensors, it is advisable to use angular displacement or bending sensors, this type of sensor gives a measurement of wall flexure when the wall is in motion.

h) For the wide column model analysis considerations must be made for shape factors, where the transformed section of the wall is involved, which will depend on the ratio of modulus of elasticity of the materials

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REFERENCES

(1) Silveira D., Varum H., Costa A., Martins T., Pereira H., & Almeida J. (2012). *Mechanical properties of adobe bricks in ancient constructions*. Construction and Building Materials, 28(1), 36-44. https://doi.org/10.1016/j.conbuildmat.2011.08.046

(2) Avila, D. F. J., Aviles, T. E. R., & Freire, V. M. C. (2015). *Las innovaciones tecnológicas como respuesta a las debilidades y aprovechamiento de potenciales en el sistema constructivo tradicional del adobe*. In Tierra, sociedad, comunidad: 15° Seminario Iberoamericano de Arquitectura y Construcción con Tierra (pp. 500-512). Universidad de Cuenca. https://www.scribd.com/document/496274644/Dialnet-

(3) Blondet, M., Vargas, J., Tarque, N., Paz, J. S., Sosa, C., & Sarmiento, J., (2015). *Refuerzo sísmico de mallas de sogas sintéticas para construcciones de adobe*. In Tierra, sociedad, comunidad: 15° Seminario Iberoamericano de Arquitectura y Construcción con Tierra. (pp. 67-80). Universidad de Cuenca. ISBN 978-9978-14-313-1.

(4) Secretaría de Desarrollo Agrario, Territorial y Urbano. *Censo de Viviendas Dañadas por los sismos del mes de septiembre de 2017*. https://www.gob.mx/sedatu/, (accessed October 2018).

(5) Pérez-Gavilán, J. J., Aguirre, J., & Ramírez, (2018). *Sismicidad y seguridad estructural en las construcciones: lecciones aprendidas en México*. salud pública de México, 60 (Supl. 1). https://doi.org/10.21149/9300

(6) Wu, F., Wang, H. T., Li, G., Jia, J. Q., & Li, H. N., (2017). *Seismic performance of traditional adobe masonry walls subjected to in-plane cyclic loading*. Materials and Structures, 50(1), 69. https://*doi*: 10.1617/s11527-016-0927-0

(7) Nivelo, R., Andrés, B., Sarmiento, Z., & Esteban, P., (2017). *Evaluación sísmica de casas de mampostería de tierra vulnerables a modos de falla fuera del plano*. http://dspace.ucuenca.edu.ec/handle/123456789/27365

(8) Atienza, V. M. C., Singh, S. K., & Schroeder, (2017). ¿Qué ocurrió el 19 de septiembre de 2017 en México? https://www.revista.unam.mx/ Revista Digital Universitaria, 18(7).

(9) Yamín Lacouture, L. E., Phillips Bernal, C., Ortiz, R., Carlos, J., & Ruiz Valencia, D., (2007). *Estudios de vulnerabilidad sísmica, rehabilitación y refuerzo de casas en adobe y tapia pisada*. Apuntes: Revista de Estudios sobre Patrimonio Cultural-Journal of Cultural Heritage Studies, 20(2), 286-303. ISSN 1657-9763

(10) San Bartolomé, A., & Quiun, D., (2012, December). *Experimental Research and Seismic Design Proposal for Confined Adobe Masonry*. In 12th Canadian Masonry Symposium. https://www.researchgate.net/profile/Daniel-Quiun-2/publication/287975485

(11) Yamin, L. E., Phillips, C. A., Reyes, J. C., & Ruiz, D. M., (2004, August). *Seismic behavior and rehabilitation alternatives for adobe and rammed earth buildings*. In 13th World Conference on Earthquake Engineering. BC Canada: Vancouver. https://www.iitk.ac.in/nicee/wcee/article/13_2942.pdf

(12) Jesús A. Velarde Gil L., María T. Sánchez M., Rubén S. Roux G., José A. Espuna M., (2021). *Experimental Study of Adobe Masonry and its Adherence with Reinforced Concrete Confinement Elements*. https://doi.org/10.13189/cea.2021.090213

(13) Vargas-Neumann, J., Oliveira, C., Silveira, D., & Varum, H., (2018). *Seismic Retrofit of Adobe Constructions*. In Strengthening and Retrofitting of Existing Structures (pp. 85-111). Springer, Singapore. https://doi.org/10.1007/978-981-10-5858-5_4

(14) Catalán Quiroz, Policarpo & Arroyo Matus, Roberto. (2020). *Comportamiento sísmico de la vivienda de adobe*. https://doi.org/10.13140/RG.2.2.26633.80486

(15) Arias, A. J. (2005). *Ensayos en mesa vibradora de un modelo a escala 1: 2 de edificio de mampostería confinada de tres niveles*. M. Engrg. Thesis, Graduate School of Engineering, National University of Mexico, Mexico. https://repositorio.unam.mx/contenidos/ensayos-en-mesa-vibradora-de-un-modelo-a-escala-12-de-edificio-de-mamposteria-confinada-de- tres-niveles-144417?c=4XQgyJ&d=false&q=*:*&i=1&v=1&t=searc

(16) R. Meli, O. Hernández. (1978). *"Refuerzos de viviendas de adobe en zonas sísmicas"*. Revista de Ingeniería Sísmica, No. 20, pp. 24-35. https://doi.org/10.18867/RIS.20.385

(17) Roca, J. G., De La Torre, M. E. G., & Signes, C. H. (2017). *Clasificación de un suelo según SUCS*. http://hdl.handle.net/10251/84314

(18) NTE, E. 080. Adobe. ININVI (2017). *"Adobe construction. Technical Standard for adobe building"*. Special disposition for seismic-resistant adobe building. Lima, Peru. https://www.getty.edu/conservation/publications_resources/pdf_publications/pdf/testing_materials_spanish.pdf

(19) NMX-C-464-ONNCCE-2010 (RATIFICADA EN 2021) Industria de la Construcción - Mampostería - Determinación de la Resistencia a Compresión Diagonal y Módulo de Cortante de Muretes, así como Determinación de la Resistencia a Compresión y Módulo de Elasticidad de Pilas de Mampostería de Arcilla o de Concreto - Métodos de Ensayo.

(20) NMX-C-083-ONNCCE 2014. Concreto – Industria de la construcción. Determinación de la Resistencia a la Compresión de Especímenes Método de Ensayo. https://www.dof.gob.mx/nota_detalle.php?codigo=5630811&fecha=24/09/2021

(21) Normas Técnicas Complementarias de Diseño y Construcción de Mampostería 2017, Ley de Edificaciones del Estado de Baja California en Materia de Seguridad Estructural. http://sidurt.gob.mx/doctos/2017/normas/I-04%20DISE%C3%91O%20Y%20CONSTRUCCION%20DE%20MAMPOSTERIA%202017.pdf

(22) Organismo Nacional de Normalización y Certificación de la Construcción y Edificación, S.C. NMX-C-406-ONNCCE 2014. Componentes para Sistemas de Losas Prefabricadas de Concreto - Especificaciones y Métodos de Ensayo. https://platiica.economia.gob.mx/normalizacion/nmx-c-406-onncce-2019/

(23) Jiménez Orrego, D. (2017). *Identificación de la condición de diafragma rígido o flexible a partir de instrumentación sísmica y modelación de losas tipo Shell o membrana en sistemas de resistencia lateral*. (Doctoral dissertation, Universidad EAFIT). http://hdl.handle.net/10784/12269

(24) Tena, A., & Pineda, P. (2018). *Revisión del límite de esbeltez global del método simplificado de análisis sísmico para estructuras de mampostería.* Revista Internacional de Ingeniería de Estructuras, 22(2). https://journal.espe.edu.ec/ojs/index.php/riie/article/view/643

(25) Normas Técnicas Complementarias de Diseño Sísmico 2017, Ley de Edificaciones del Estado de Baja California en Materia de SeguridadEstructural. https://www.isc.cdmx.gob.mx/storage/app/uploads/public/62d/849/d81/62d849d812008797163429.pdf

(26) Kassimali, A. (2020). *Matrix Analysis of Structures*, Third edition. Cengage Learning. https://www.academia.edu/36080840/Matrix_Analysis_of_Structures_2nd_ed