DYNAMIC BEHAVIOUR OF ADOBE MASONRY HOUSES IN CENTRAL MEXICO

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ABSTRACT

The study of seismic vulnerability implies the analysis of the seismicity in a region and its effects on the constructions. In central Mexico, there are many constructions of adobe masonry (clay blocks), that depending on their characteristics could be a risk for their inhabitants in an earthquake. Most of these types of houses are located in rural communities where a great number of these houses have been reinforced without suitable work supervision (self-building). The present study analyzes real masonry structures built with adobe, located in Santa Maria Zacatepec, Puebla; Tlayacapan, Morelos; and Coyoacan, D.F. The study from the structure of adobe tries to obtain the dominant period of environmental vibration in order to know its dynamic behaviour in an earthquake. Records on the original structure and on a built scale model were taken only in Santa Maria Zacatepec. In this study the dominant period of the site was calculated by the Fast Fourier Transform (FFT) from noise records. The dominant periods were considered to determinate its vulnerability in order to find the most efficient and economic method to reinforce adobe structures, using local materials. Also a scale model of the house 1:10 was tested reproducing seismic ground motion caused by an earthquake, in order to predict the damage level that can appear in the real structure. In this study the dominant period of the site was calculated with spectral ratios H/V and FFT from vibration records. Finally, a numerical model was made to compare the reproduced damage in both models

KEYWORDS: Adobe houses, central Mexico, dynamic behaviour, seismic test, scale model, seismic vulnerability, spectral ratio, period.

SEISMICITY IN MEXICO
The Mexican territory is situated on the tectonic plates of North America, Cocos and of the Caribe. When these tectonic plates interact, they accumulate energy. The North America and Cocos plates produce the phenomenon of subduction. This phenomenon generates big quantities of energy that when they get liberated suddenly provokes earthquakes of great magnitude, which concerns great part of the country, principally to the states of the pacific coast near to the zones of the breach (Chiapas, Oaxaca, Guerrero, Michoacan, Colima and Jalisco).

In spite of the distance that exists between the zone of subduction and central Mexico (more than 300 km) the earthquakes generated in the above mentioned region could cause great number of human and economic losses as it happened on September 19, 1985 in the Mexico City, where more than 4000 people died. The earthquakes that are generated by the interaction between the tectonic plates like subduction are very important, however it is necessary to consider those who take place inside the intraplate and continental plate region of our country, like it happened on June 15, 1999, that it concerned principally the cities of the south and the capital of the capital of Puebla State where more than 800 real estate suffered damages, moreover they were the reason of important human, cultural and economic losses.

In order to regulate the designs of buildings, there was created the Civil Works Design Manual (MDOC) proposed by the Federal Commission of Electricity (CFE). This manual divides our country in regions A, B, C and D (from minor to major seismicity)

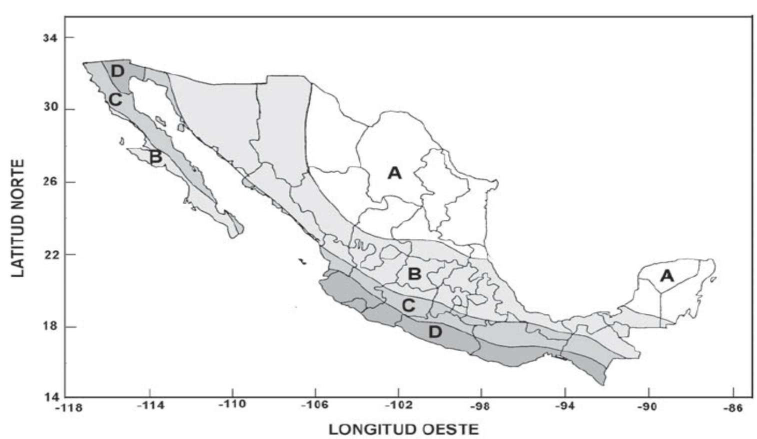

Figure 1: Seismic Regions of the Mexican Republic

ADOBE HOUSES IN TLAYACAPAN, MORELOS STATE

Adobe is currently still used in Mexico, especially people with limited economic resources. The town of Tlayacapan is located in the north-western of Morelos State (Fig. 2). This municipality has houses built with brick, cement and many with adobe and tile. The place is situated on soils composed of limestone, andesites, conglomerates, basalt, ash and volcanic soils (Tapia, 1991). In this town, there are many adobe houses and chapels and highlight their cracking due to their antiquity.

The self-building creates great concern over the danger of any collapse in adobe dwellings in Tlayacapan. The adobe houses have cracking that remains in time. The serious damage to homes, occur without a good foundation that is partially or completely buried under the ground surface, it is designed for sustaining and anchoring the superstructure and transmits loads directly to ground through the main architectural elements of the building.

Figure 2: Location (in black circle) of Santa Maria Zacatepec (Puebla), Tlayacapan (Morelos), and Coyoacan (Distrito Federal). At the bottom center is Popocatepetl Volcano.

The adobe is formed with mud filled by hand into wooden molds; it is 20% clay and 80% sand, with water flowing form a mass that can be emptied into molds on the floor. When drying the mix takes the form of the mold which is exposed to the sun so that the water will evaporate and dry after being removed from the mold. After the block gets another 30 days under the sun, it get harder

The common measures of this brick are 38 x 38 x 38 cm or 40 x 20 x 10 cm. Some of the features of the Adobe are a litmus test, sound and no echo, also controls the temperature of the house. We must take into account that the Tlayacapan houses are made of adobe because of the economy and because its soil lets itself to be done.

Moreover analyzing the form of construction in the town of Tlayacapan, we found that 50% of the houses were made of and most of them already have constructive reinforcements so they will not be harmed in any major earthquakes or fails by overload at the important elements of construction, however there is a percentage of homes without lintels, frames in windows and doors, columns, beams supporting the roof, like light roofs that represents serious danger to the population.

In Tlayacapan, we found a house with two vertical cracks (Fig. 3) and without columns, beams or frames in windows and doors and reflecting self- building. A house with a wall of stone on its base of 0.5m to 1m thick, the adobe blocks with a large between 45 and 50 cm, which gives a good stability to adobe walls, roofs with tiles or sheets (prior coverage insulating material) and wooden beams (figure 4).

Figure 3: Adobe house in Tlayacapan, presents vertical cracking, there are no beams or columns. A short wall of stones on the base is not sufficient, on support the house on foot. Its roof is laminate.

Figure 4: Another adobe house with reinforcements. See the frames on doors and windows and on its base with stones about 50 cm high. The roof is with tiles.

ADOBE HOUSES IN COYOACAN, DISTRITO FEDERAL

We identified the techniques and materials used in various buildings (Minke Gernot, 2001; Meli, 1998), specifically rocks and mud, in the historic center of Coyoacan, south of Mexico City (Fig. 2), some of them were damaged. We sought information about buildings constructed with rocks and mud in the Historic Center of Coyoacan (INAH, 2002).

With this investigation we were able to appreciate that the construction of adobe houses and walls located in the Historic Center of Coyoacan counted as one of its most important structural elements, a wall of rocks between 50cm and 1m of height in its base.

The adobe house showed in Figure 5(a) have a good state of preservation, as well as the presence of wall on its base and frames on doors and windows made of stone, also shows coverage and flattened in good condition in the facade.

The house in the Figure 5(b) is in a state of neglect, but it does not manifest a state of conservation severely damaged from its facade. Like the previous houses presenting stone at the base of their7 walls. It is appreciated that the construction of adobe walls is reinforced by a column of brick to be located between two orthogonal adobe walls. Despite the damage to the flattened, the structure of the exterior walls of the house shows no significant damage as mud cracks.

In the Figure 5(c) a wall of stone at its base, however it shows a lack of columns at one end of the wall, just where the property ends on the street. It has in certain places on the top of the wall a cover for the rain. Some parts of the wall are leaning. At the base of the walls there is a minor than 50cm high of stones. The case of fences made of adobe, not showed the existence of a column that shared the wall of stone and adobe.

In the Figure 5(d) presents a room damaged by a diagonal crack of tension in the adobe wall viewed in its interior as in its exterior (Church “La Conchita”), because of the slight sinking of its sacristy.

(a) (b) (c) (d)

Figure 5: Adobe houses in Coyoacan D.F. (a) The first photo shows a good coverage of cement in its facade. (b) The facade neglected, without frames in its door. These houses have a wall in its base with stones near 1 m. (c) It is a fence made of adobe without columns, only a short wall of stones in its base. (d) Shows a diagonal crack in its interior as in its exterior. in the room with adobe walls (church “La Conchita”).

PUEBLA STATE

The adobe is an economical construction material of easy accessibility that is elaborated in many Mexican rural communities. The structures of adobe generally are self-built, and the constructive technique depends on the own inhabitants of each region. Specifically in Puebla State there are around a hundred thousand houses of this type of material (INEGI, 2000).Most of these houses are very old (around a century) and have been damaged due to the degradation of their materials and by seismic events. Evidently, it represents a risk for their inhabitants. From the damage in constructions caused by the earthquakes, building codes have been elaborated in many cities. Nevertheless, many rural municipalities do not have this type of regulations and resort to the self-building. For these reasons a study of seismic vulnerability was planned to determine the seismic resistance of an adobe structure localized in Puebla State.

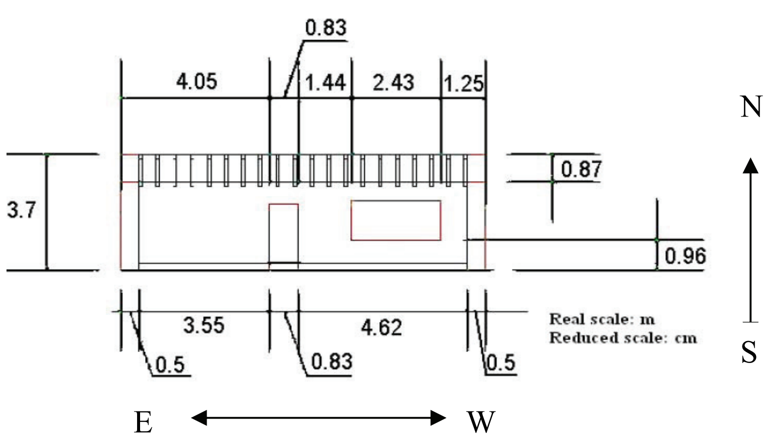

Figure 6: Sketch of adobe house

Figure 7: Facade of adobe house

In the environment exists vibrations (environmental vibration) generated by diverse sources that are in the structures or their surroundings. These sources cause that the structures vibrate to a natural frequency (*fn*). The determination of the *fn* is indispensable for a seismic safe construction. The purpose of applying the method of environmental vibration is to obtain the natural periods of vibration, which will allow us to know the conditions of the buildings. In addition, after happened a seismic event would be possible to determine the variation in the vibration periods of the structures provoked by the degradation of the structural elements submitted to seismic solicitations since there can exist imperceptible damages that evidently are difficult to detect and evaluate. Another aspect of the application of this system is to assure that the reinforcement of a building should be the awaited one, observing the decrease of the vibration period during this process. Finally, if the *fn* of the structure is equal to the one of the ground, it generates the phenomenon known as resonance, which invariably produces the collapse of the structures.

In order to analyze a representative construction of the existing buildings of adobe a search was made in the municipalities of Puebla, Cholula and Huejotzingo. The selected house is located in the locality of "Santa Maria Zacatepec" 15 km from Puebla City. Its measures and configuration are showed in figures 2 and 3.

Also with the aim to determine the *fn* of the selected adobe house selected, we registered, with special equipment, the precise environmental vibration on its base and roof (figures 6 and 7). They were recorded 3 minutes of vibration in every point.

The determination of its natural period was by the obtaining of the Fast Fourier Transform (*FFT*). The registry of each component (the North-South, East-West, vertical) divided in 5 windows, each of 30 seconds (*e.g.* Fig. 10). For each window of time was calculated the FFT and averaged with the rest of the windows of the same registry and component. From this average *fn* of the structure was determined.

The *fn* is 4.42 Hertz (fig. 11) in both directions (the North-South and the East-West), reason why its natural period is 0.22 s.

Figure 8: Registering vibration in the ground

Figure 9: Measurement of vibration in the roof

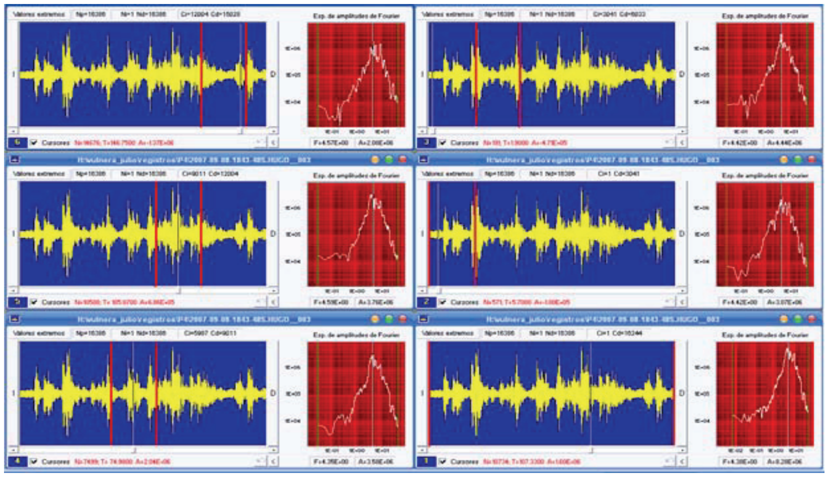

Figure 10: Obtaining of the FFT in component N-S

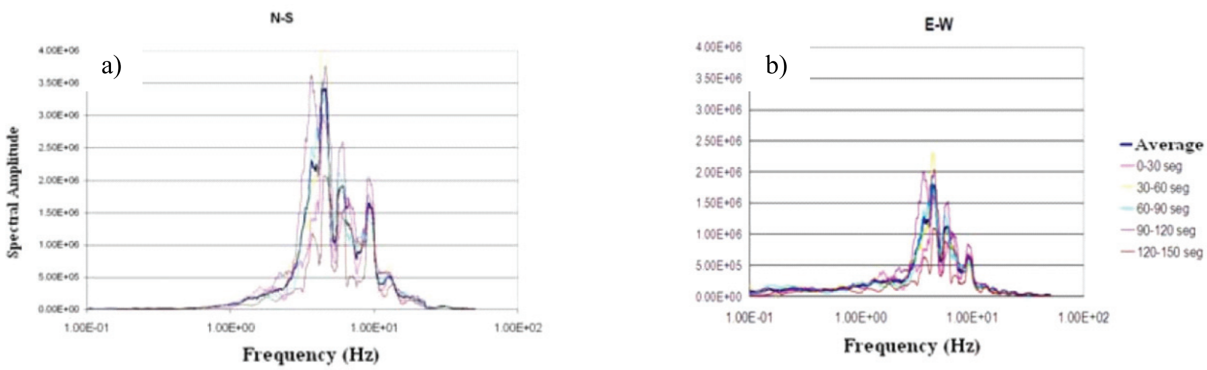

Figure 11: Average of FFT in directions: a) North-South b) East-West

In order to know in a better way the behaviour of a masonry structure of adobe, it was taken the decision to construct a model on 1:10 scale from the house. The dimensions of scale model were chosen in base on the capacity of the civil engineering laboratory. The study of vulnerability was made to the scale model (fig. 8 and 9). The model was damaged with a seismic simulation so that later a restoration method for the same this model is proposed, also to predict the possible damage in the real structure.

Figure 12: a) Positioning the noise tester b) Registering vibration on scale model

The seismic event was simulated on rollers trying to reproduce a seismic event; it was shaking the base from one side to another in the E-W direction, in order to observe the damages that would be generated on the structure. Also environmental vibration registries were taken on the scale model (fig. 12) before and after the simulation to be able to observe in both cases the dominant periods with the same method previously seen. The *fn* before the test was 10.9 Hertz (fig. 13 and 14) both directions (the East-West North-South and) reason why its natural period is of 0.0917s, and after the test *fn* was of 10.07 Hertz in both directions reason why its period after the test is of 0.0993 s.

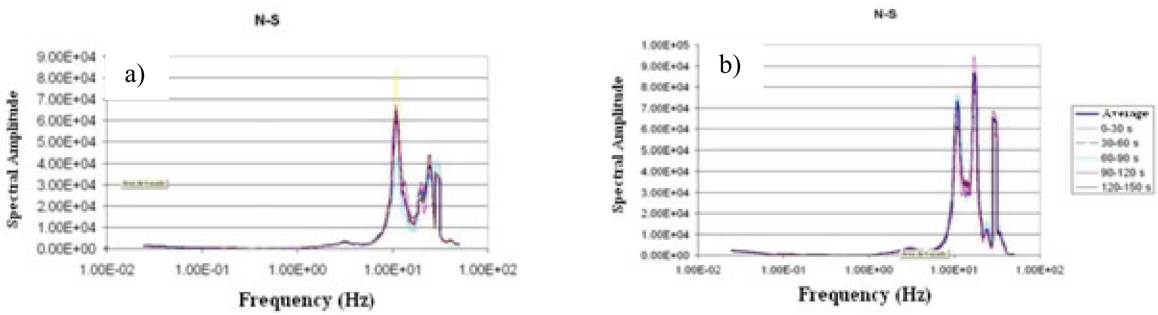

Figure 13: a) Average of the FFT N-S before the test b) Average of the FFT N-S after the test

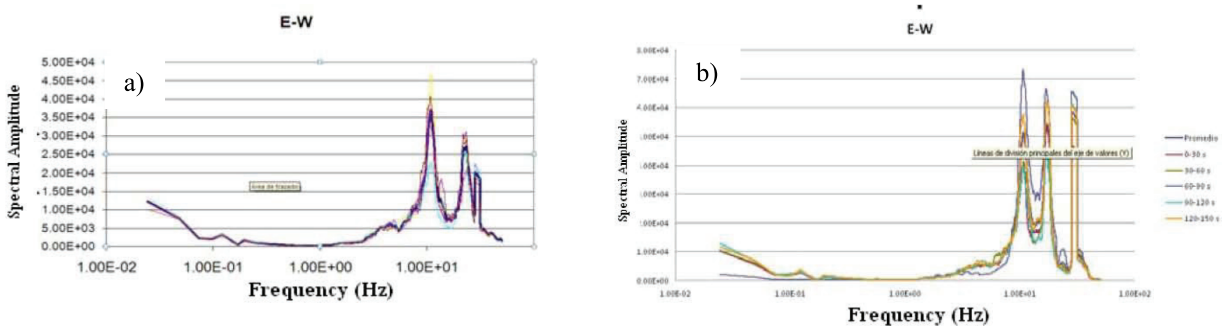

Figure 14: a) Average of the FFT E-W before the test b) Average of the FFT E-W after the test

DETERMINATION OF THE NATURAL PERIODS IN A COMPUTER MODEL

With the intention of corroborating the dynamic behaviour of the real adobe masonry structure (Fig 6), it was considered to shape this structure on software, designed for the static and dynamic (modal) analysis (SAP 2000). This program is based on the calculation of finite elements and it is of great utility to determine the vibration modes of structures, the efforts caused to the materials in the above mentioned manners, as well as the deformations caused due to loads. This numerical model is very useful to understand possible failures caused by deformations occurred in a seismic event. Furthermore, this modal analysis could show us possible places where cracks could begin in an earthquake, because if the material strength limit is lower than the stresses showed in the modal analysis, these stresses on materials will cause fracture on the adobe block. Finally, a comparison between both models was made in order to define possible sites of failure in a seismic event and with this, a proposing of suitable reinforcement method.

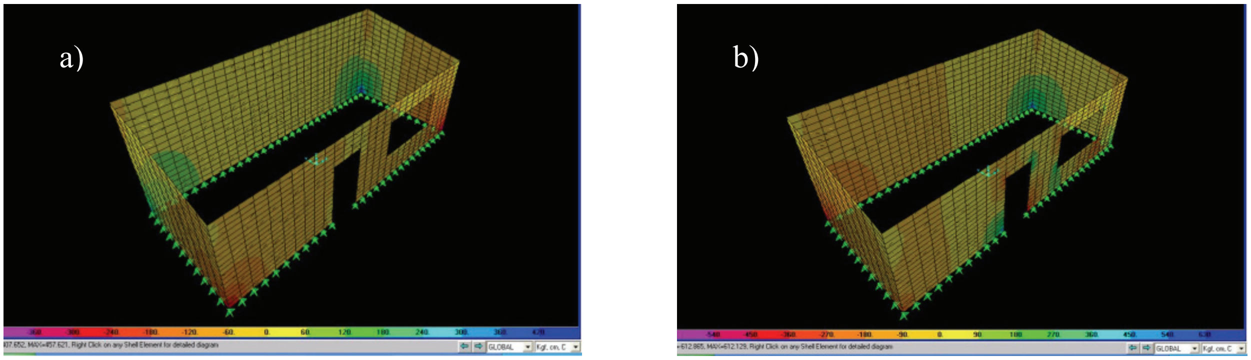

Figure 15: a) 1° Vibration mode vertical loads direction E-W (T=0.3284 s.) b) 2° Vibration Mode Vertical loads direction N-S (T= 0.3154 s.)

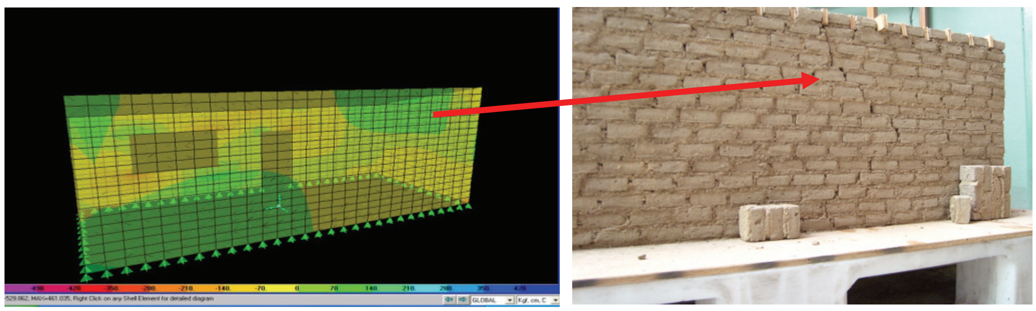

Figure 16: Visible failures showed in the computer and the scale model

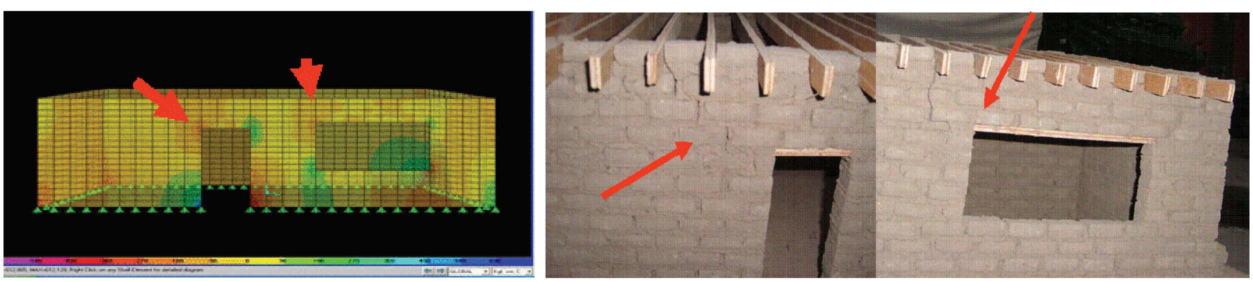

Figure 17: Visible failures showed in both models on the door and window

Table 1: Material Properties used on the numerical model

Property/ Material	**Adobe**	**Wood**
Mass per unit volume: (kg/m^3)	187	91.74
Wight per unit volume: (kgf/m^3)	1836	900
Modulus of elasticity: (kg/m^2)	1040110	122366
Poison's Ratio:	0.3	0.3

Table 2: Modal responses in numerical model

StepType	StepNum	Period	Frequency
Text	Unitless	Sec	Cyc/sec
Mode	1	0.328489	3.0442
Mode	2	0.315459	3.17
Mode	3	0.285297	3.5051
Mode	4	0.273612	3.6548
Mode	5	0.26159	3.8228
Mode	6	0.248202	4.029
Mode	7	0.225703	4.4306
Mode	8	0.206734	4.8371
Mode	9	0.204292	4.895
Mode	10	0.193056	5.1799
Mode	11	0.18625	5.3691
Mode	12	0.180816	5.5305

The *fn* of the numerical model is T=0.3284s. in the E-W direction. The real structure has a period of 0.22s. The difference between both structures could be because of two principal reasons. The first one, the real structure has another two structures next to it that can make the structure more rigid and also it can be the reason why period in N-S and E-W directions is equal (Fig. 19). The second one, in the numerical model was not taken in account the rigid provoked by lintels that supports the roof.

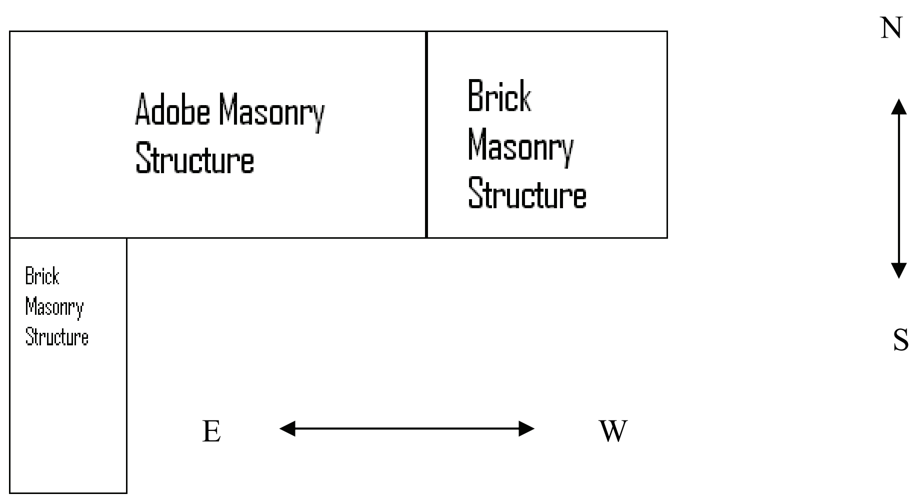

Figure 18: Sketch of the distribution of buildings in Zacatepec, Puebla

TYPICAL DAMAGES IN ADOBE MASONRY HOUSES

Adobe houses are made of mud that has been dried but not burned, this is the reason why this material has been degraded by the environment with the time. The adobe houses that do not have covering in the walls present a lot of degradation that makes the material weaker and in consequence weaker walls. This degradation principally occurs at the base where the direct contact with soil transmits dampness to walls. This is visible in figure 14c where it is showed a leaned wall due to the degradation at its base. In

Tlayacapan is possible to observe the solution to this problem, which is a 0.5m base of stone that isolates the adobe wall from the soil.

Another typical failure in adobe houses is the cracking of the walls due to the absence of columns or beams or adequate frames at door or windows, which gives to the structure the stability and flexibility necessary. This type of failure can be appreciated in figure 3 where is showed a vertical crack. Moreover, due to most of adobe houses have very large walls without reinforcement this provokes flexion at middle of the wall (figure 9) that generate failures in some elements.

Finally, due to the instability of walls in a seismic, and to the fact that roofs are usually heavy, the fall of the roof could occur as it can be appreciated in figure 3 where the original roof has fallen and has been replaced by a laminate roof that is less heavy.

Figure 19: Back side of adobe house in Zacatepec, Puebla

RECOMMENDATIONS

It is recommended the training in construction techniques and reinforcement, to safeguard the life of any inhabitant before the earthquake. It is vitally important, to create awareness on people who build on sites with seismic risks, as well as offer training in handling techniques of reinforcement structural, to reduce the damage that buildings may suffer thereby achieving the greatest possible safety for users of the building. Buildings of adobe since the earliest constructions and today are made of a way to make more resilient and efficient its home. To have a well document in hand capable of giving sufficient information to prevent further damage or even a single disaster in the future.

CONCLUSIONS

The study of Seismic Vulnerability determines the resistance of the structures and it is of great help for the detection of vulnerable sections to earthquakes which having a suitable reinforcement can avoid both, the cracking and the collapse of the walls. The repair and the reinforcement on a structure can be vital in a seismic event for which is necessary to do a study of vulnerability to the houses, especially to adobe houses due to the fact that they are ancient structures that have been, in the major of the cases, repaired without having the suitable supervision.

The methodology to determinate the dynamic response of adobe structure is simple if all the factors that affect in the vibrating period of the structure are taken in mind. Based on the effects in the scale model, it is possible to determinate a scale factor in a real structure and therefore quantify the damages on a given event.

We found dynamic response of a simple adobe structure in Santa Maria Zacatepec in Central Mexico, experimentally in situ. From a model of adobe house made in laboratory in a reduced scale 1:10, was established its dynamic behaviour due to earthquake of important magnitude. This scaled model was tested in a vibration table, reproducing seismic ground motion caused by an earthquake. We calculated the period vibration of the typical adobe house and from scale model.

Inside of Coyoacan, the adobe houses presenting stone at the base of its walls, it is appreciated that the construction of adobe walls is reinforced by a column of brick to be located between two orthogonal adobe walls. Despite the damage of the facade, the structure of exterior walls of the house shows no significant damage as mud cracks. In Tlayacapan, adobe house presents vertical crack, there are no beams or columns, short wall of stones in base is not sufficient, on supporting the house on foot. The roof normally is laminate or with tiles. Damage can be repaired with established reinforcement techniques in a fast and economic way with materials from the same region and applying appropriate construction techniques.

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