STRUCTURAL BEHAVIOR DURING THREE MODERATE MEXICAN EARTHQUAKES.

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SUMMARY

This paper summarizes the experiences obtained by the Grupo Interuniversitario de Ingeniería Sísmica (GIIS), of three epicentral Mexican areas during three important earthquakes in 1995: September 14th, in Ometepec, Guerrero; October 9th, in Manzanillo, Colima; October 21st, in Villaflores, Chiapas. Different types of failures are analyzed and discussed in adobe, masonry, concrete and steel structures.

INTRODUCTION

The Mexican engineering has proposed new criteria and specifications, since the 1985 Michoacán, Mexico earthquake, to provide safer margins of security in design and construction codes. It is important to study the damages occurred during moderate earthquakes, in order to understand the structural behavior of structures. This paper analyzes the structural behavior in the epicentral areas; the purpose of this analysis is to understand the structural behavior of buildings during moderate and large earthquakes, and therefore improve the Mexican codes in those regions where seismic events tend to be destructive.

INFLUENCE OF THE STRUCTURAL CONFIGURATION IN THE ASEISMIC BEHAVIOR

In seismic regions the structural configuration of buildings must include aseismic characteristics; there are few basic principles before choosing it. According to some authors these basic principles have been pointed out for a long time in earthquake engineering, such as symmetry and simplicity in plan and elevation configurations, and continuos and uniform distribution of resistance and stiffness. The election of the structural materials, which ideal properties have been discussed widely before, is another significant factor to determine the structural configuration, [*Arnold and Reitherman, 1987*].

The main purpose in earthquake engineering is that structures resist earthquakes of large proportions in well conditions of service, but aseismic design procedures not always accomplish this objective, this paper shows a significant number of examples in which design procedures prove that. The actual procedures of saseismic design considered only two parameters: resistance and stiffness demands; ignoring other parameters, such as acceleration demand, [*Terán, 1997*]. During this decade other conceptual procedures on earthquake engineering, such as performance-based design, were born; this procedure states that the process of structural design should emphasize

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that all the activities involved in planning, conception, numerical design, construction and maintenance of structures must have the same relevance.

STRUCTURAL RESPONSE

Construction practice in the epicentral areas range from owner constructed unreinforced adobe houses to modern steel frame and reinforced concrete multi-story buildings. Some modern structures have adequate design engineering and quality control during construction, and these structures usually exhibited good seismic performance. In others, poor structural configurations, bad quality construction, damage from past earthquakes and lack of proper maintenance led to poor behavior during those three earthquakes. The main characteristics of the three events are shown in table 1.

Location	Date (GMT)	Epicentral coordinates	Magnitude
Ometepec, Guerrero	Sep/14th/1995	16.8º N; 98.6º O	7.2 (Ms)
Manzanillo, Colima	Oct/9th/1995	19.25º N; 104.19º O	7.3 (Ms); 7.3 (Mw)
Villaflores, Chiapas	Oct/20th/1995	16.89º N; 93.45º O	6.50 (Mc); 7.3 (Mw)

Table 1. Characteristics of the studied earthquakes, (USGS).

A discussion of the principal types of constructions in those regions and their associated damage patterns are presented here. Details of the earthquakes are presented in specific papers written by: [*Sordo, et al, 1995; Juárez et al, 1997; Tena and Del Valle, 1996*], among others.

THE SEPTEMBER 14TH, 1995, OMETEPEC, GUERRERO, EARTHQUAKE.

Unreinforced adobe structures.

In the southeastern region of the state of Guerrero, there are small communities and towns, most of them with bad roads and comunications. The people living in those rural communities build their own houses with load bearing adobe walls. The approximate dimensions, in plan, of the houses are 4 x 8 Mts., with no other structural elements to resist lateral forces, (figure 1). The adobe houses which suffered light damage, were constructed with a high quality adobe bricks, that is why the adobe quality is very important in terms of its aseismic behavior, [*Sordo et al, 1996*]. In those houses which damages were considered as heavy, four types of failures were detected:

1) The first was the lack of adequate connection in the corners that led to the outward failure of the walls, (figure 1).
2) The second was the failure due to excessive stess concentration at the corners of doors and windows, (figure 2).

Figure 1. Outward failure of walls due to inadequate connection of corner walls.

Figure 2. Stress concentration at the corners of doors and windows.

3) The third one was associated to the roof system (figure 3), which is made of wooden girders that support the roof tiles. Two slopes are presented in the roof system, there is a large wooden girder in the center of the slopes. The ground motion provoked inertial forces that struck the main central girder, provoking the outward failure of walls due to flexure, (figure 4). During the earthquake the roof tiles were thrown form

their places because of the inadequate anchorage. Even though this fact reduces the total weight of the roof and the seismic forces, it is important to provide adequate anchorage in the roof tiles.

4) Finally, the most common failure was the cross-diagonal cracking of bearing walls generated by earthquake shear forces.

The churches, that sometimes are the largest structures in these communities, were also affected in the Ometepec earthquake, most of them presented heavy damage, but no collapses were reported. Cracks and damages from past earthquakes were retrofitted with new materials, sometimes both vertical and horizontal reinforced concrete elements called castillos and dalas, were embedded in the damaged walls as a retrofitting and reinforcing technique.

Figure 3. Typical roof system in the epicentral region of Ometepec.

Figure 4. Flexural failure provoked by the roof system.

The adobe quality in the town of Ometepec is very good, in comparison with those qualities reported in other communities, the adobe walls were covered in order to resist the weather, and the adobe bricks presented natural fibers inside of them, which led to good behavior.

Reinforced adobe structures.

In this epicentral region of Guerrero there are few structures having vertical and horizontal elements that improve the seismic behavior of these adobe structures. These reinforcing elements are made of wood or concrete, (called dalas and castillos). This region of Guerrero has an important seismic activity, and therefore the adobe structures have been retrofitted and reinforced with those elements, some of the adobe structures were reinforced before the Ometepec earthquake, (figure 5).

Figure 5. Reinforced adobe wall structure.

Figure 6. Reinforced masonry structure.

Reinforced masonry structures.

The masonry structures have dalas and castillos as horizontal and vertical elements to resist lateral forces, these dalas and castillos are placed in distances ranging from 1.5 to 3 Mts., this provides confinement and resistance to the masonry walls, improving the seismic behavior, (figure 6). These structures have no technical advice in the epicentral region, but their simplicity, symmetry and regularity provide good seismic behavior.

Steel Structures.

Few steel structures were found in the epicentral region, and some schools were made of thin walled steel elements, exhibiting good seismic behavior. The only failure reported, occurred in the tile bricks used as walls, due to the inadequate connection between the tile bricks and the steel structure, and this provoked the outward collapse of the walls, (figure 7).

Concrete structures.
The reinforced concrete structures of the epicentral region were found in the town of Ometepec, and only three of them were reported with slight damage. The damages were provoked because of the poor structural configuration, such as short columns, or inadequate position of structural elements, (figure 8).

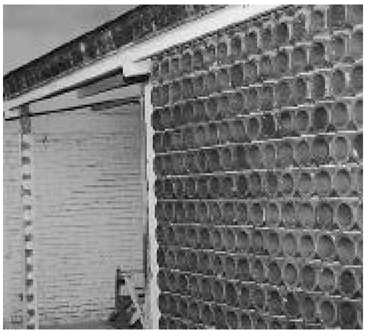

Figure 7. Outward failure of walls due to inadequate connection.

Figure 8. Inadequate position of structural elements.

Bajareque structures.
Most of the houses found in the epicentral region have an additional room, which is used, as a barn. But in the poorest communities this room is used as a home. The additional room is a bajareque structure, made by two grids of wooden poles. Between these two grids there is a 15 centimeters space, approximately, which is filled with mud, debris, stones, broken tiles, wooden poles, branches or another natural materials, and entangled with natural fibers, these structures behave adequately during this earthquake.

THE OCTOBER 9TH, 1995, MANZANILLO, COLIMA, EARTHQUAKE.

Unreinforced masonry structures.
The most common type of residential construction in this epicentral region is a non-engineered self-constructed unreinforced brick masonry house. Most of the unreinforced masonry structures have load-bearing walls made of baked clay bricks. The oldest houses have 40 cm thick brick walls with mud commonly used as mortar, in contrast with newer houses with standard size bricks and cement mortar. Four typical types of failure were observed in both old and new structures, these failures are just alike as those described in the Ometepec earthquake.

Figure 9. Flexural failure provoked by the roof system.

Figure 10. Stress concentrations at the corners of windows.

A poor response also resulted from inappropriate connection between stories, (figures 11 and 12), generally in old houses where a second story was added to an older pre-existing single story house, damages were found in the second story. In these cases, the first story was often made of unreinforced masonry walls, usually exhibited inadequate anchorage and overlapping of the longitudinal bars of castillos and dalas of the second story.

Reinforced masonry structures.

Although this construction type has proved to have good seismic behavior when it is properly designed, the lack of good engineering and quality control resulted in some cases in poor seismic response, as reflected by the diagonal cracking of the walls in some of these structures.

Figure 11. Inadequate connection between stories.

Figure 12. Inadequate anchorage of castillos.

In addition, there were also inappropriate structural configurations, such as excessive door an window openings on the first floor; corner buildings with high plan eccentricity; irregularities in elevation and plan; and, in some cases, the lack of adequate separation between neighboring structures resulting in pounding between them.

Castillos and dalas add confinement and resistance to the masonry walls, (figure 13). It should be noted that Jaluco and Barra de Navidad were two of the towns affected by the Manzanillo earthquake and the liquefaction, a geological effect of the earthquake. Even though, the reinforced masonry structures of these two towns were properly design and constructed some of them were heavily damage by liquefaction and subsidence. A maximum subsidence of about 50 cm was observed, resulting in large differential settlements and severe structural damage to the houses in the area.

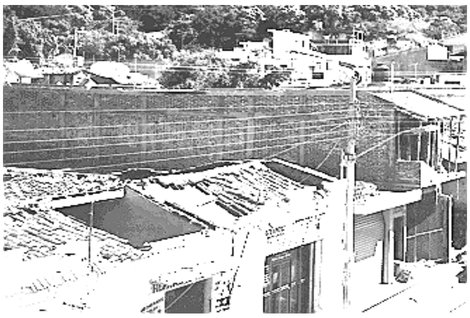

Figure 13. Dalas and castillos improve the seismic behavior

Figure 14. Weak first story failure.

Figure 15. Weak first story failure.

Figure 16. Adequate design procedures led to good seismic behavior.

Inadequate structural configurations led to poor behavior of structures, in figure 14 and 15 the irregularities in plan and elevation, the poor amount of longitudinal and transversal bars in the dalas and castillos provoked the collapse and heavy damage of the first story.
Reinforced masonry structures have good seismic behavior when they are properly designed, as shown in figure 16, regularity, simplicity and symmetry led to a good behavior in the Manzanillo earthquake, even tough this structure was placed in the most affected area by the earthquake.

Concrete structures

There are many concrete structures in the large cities and resorts with large hotels located in the epicentral area, which general performed well during the earthquake. And only an eight-story hotel collapsed, which was reported as poorly retrofitted after the 1985 Michoacán earthquake, and some other buildings were reported with light damages, [*Juárez, et al, 1997 and Tena and del Valle, 1996*].

Steel structures.

Steel structures, in general, performed well during the earthquake, but a shopping mall in Manzanillo did not have an adequate performance. Four separate steel buildings comprised this shopping mall complex. A light steel-framed structure was the backbone of each of the separate square-shaped structures. Corridors of reinforced masonry walls surrounded each structure on two or three sides. Many plan and elevation irregularities, with structural elements having great differences in stiffness, resulted in heavy damage. The poor anchorage and overlapping in reinforcing bars in the corridors of the shopping mall allowed partial collapse, and ten people were reportedly killed, (figure 17).

Figure 17. Failure of corridors in the shopping mall complex.

Figure 18. Roof system in Villaflores, Chiapas.

THE OCTOBER 21ST, 1995, VILLAFLORES, CHIAPAS, EARTHQUAKE.

Unreinforced adobe structures.

Those adobe structures observed in Villaflores are very similar to those in Ometepec and Manzanillo, except on the roof system, (figure 18). The roof system is made of wooden poles supported along the peripheral walls; some wooden poles are placed as dalas around the walls, providing confinement to the typical adobe houses. This configuration of the roof system improves the seismic behavior of the entire structure. The failures observed in this epicentral area are similar to those discussed before. The roof system did not induce failures of walls, but it was very common that the roof collapses inside of structures. The quality of the adobe bricks was very good, having natural fibers inside of it, improving its seismic behavior, (figure 20).

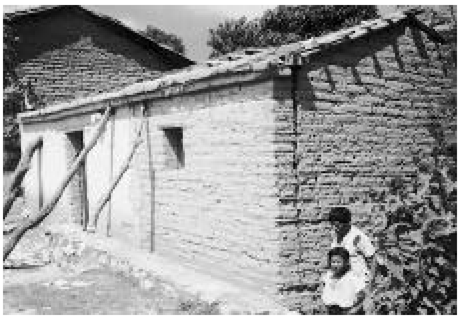

Figure 19. Inadequate connection in the corner walls.

Figure 20. High quality adobe brick houses.

Unreinforced masonry structures.
The type of failures observed in this epicentral area is similar to those discussed before:

1) Stress concentrations at the corners of doors and windows, (figure 21).
2) Cross-diagonal cracking generated by earthquake shear forces.

Reinforced masonry structures.
These types of structures performed well during the Villaflores earthquake, even though wooden poles were used as dalas and castillos, (figure 22). In figure 23, a reinforced masonry structure presented no damage, while this adobe structure was completely collapsed. Those structures that performed poorly during the earthquake were because of the poor structural configurations, irregularities in plan and elevation, weak first stories, (figure 24), and inadequate lateral reinforcement.

Figure 21. Stress concentrations.

Figure 22. Wooden poles used as dalas and castillos.

Concrete and steel structures.
In general these structures performed well during the earthquake, but some of them were reported as damage. The poor seismic behavior was because the lack of engineering advice, and these two problems were detected: short columns with inadequate stirrup spacing, (figure 25); and inadequate disposal of longitudinal bars, package of bars with inadequate stirrup spacing, (figure 26). No damages were reported on steel structures.

Figure 23. Reinforced masonry structures with no damage.

Figure 24. Weak first story failure.

Figure 25. Short column configurations led to poor behavior.

Figure 26. Inadequate stirrup spacing.

CONCLUSIONS

If seismic design procedures would have been taken into account, no damages were occurred in the Ometepec, Manzanillo and Villaflores earthquakes, some redundant conclusions and recommendations are listed below:

1) The quality of the adobe brick materials and the protection from weather conditions improve the seismic behavior of these structures.
2) The unreinforced masonry structures improve their seismic capacity when dalas or girders are placed around the top of the walls.
3) Adding dalas and castillos, even if they are made of wood, improve the seismic behavior of masonry structures.
4) The structural configuration of reinforced masonry structures must have a symmetric, regular and simple shape; short column configuration, irregularities in plan and elevation, and weak first stories should be avoided, and technical advice is needed to properly design these reinforced masonry structures.
5) Few aspects should be taken into account in steel and concrete structures:
   - The selected materials for structural and non-structural purposes, must have an adequate dynamic behavior according to that exhibited by the whole structure.
   - Foundation and structure behavior should be studied, in order to avoid unproper seismic behavior.
   - Structural configurations must consider regular, symmetric and simple shapes.
   - Involving expertise in engineering is the solution to enhance structural behavior in future earthquakes.

Those conclusions stated before are well known and redundant, but in many seismic regions of Mexico the adobe, masonry, concrete and steel structures have inadequate seismic behaviors, leading to heavy damage and collapse in moderate earthquakes. These earthquakes were generated in the subduction pacific zone of Mexico, which is the seismic region that generates the most destructive earthquakes in Mexico. The states of Mexico that are affected by this seismic activity are: Chiapas, Colima, Guerrero, Jalisco, Michoacán and Oaxaca.

The primary reason that damaged structures performed poorly during those earthquakes was their lack of structural design. In spite of the big earthquakes occurred in 1932 and 1985 in this subduction zone of Mexico, little public memory remained in terms of the necessity of an adequate seismic design for residential structures.

These moderate earthquakes that cause damages, ought to be considered as seismic warnings, because we are far from an adequate seismic performance of our structures and buildings. These earthquakes also show that is necessary to proceed with the adequate seismic retrofitting of damaged and weak structures and to build new ones which will properly perform in future events.

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