SEISMIC BEHAVIOR AND DESIGN OF SMALL BUILDINGS IN CHILE

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Synopsis.-

Different climates and construction materials have led to a wide variety of small buildings in Chile. Surveys conducted in nine cities and towns after six destructive earthquakes including about 20000 small buildings are compared. The statistical behavior of several types of construction for degrees of intensity MM ranging from VII to IX are shown.

Characteristics of design and destruction process are briefly described and illustrated. The effect of soil conditions on damage, when significant, is mentioned.

Recommendations in order to forbid some types of construction and to strengthen others through a modified design are suggested.

Surveys of damage.-

The surveys used for this study correspond to the following cities and towns :

Site	Earthquake	Intensity
1.- Copiapó	Dec. 4, 1918	VII
2.- Chillán	Jan. 24, 1939	IX
3.- Concepción, zone a)	May 21, 1960	VIII-
4.- Concepción, zone b)	May 21, 1960	VII-VIII
5.- Talcahuano	May 21, 1960	VIII
6.- Coronel	May 21, 1960	VIII
7.- Lota	May 21, 1960	VIII +
8.- Valdivia	May 22, 1960	VIII-IX
9.- Quillota	March 28, 1965	VIII-IX
10.- Taltal	Dec. 28, 1966	VII +

After checking the individual field-sheets of six of these surveys, some 3000 were eliminated, either for refering to unusual types of construction or because the identification of the type of construction was doubtful. The field sheets of the other four surveys were not available. After the elimination, 19850 buildings were used for the study.

The degrees of intensity MM that appear in this table have been estimated by the author by ordering first the surveys according to the increasing degree of damage, and by comparing then this degree of damage with the MSK scale(1).

Most of the surveys connect the damage classification with the economical possibility of recovering the damaged buildings; survey 2 is an exception; it tries to put emphasis on the relationship between damage and energy of the earthquake at the site, regardless of economical considerations. Surveys 1

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and 8 have only three classes of damage, when compared with four in the other surveys. It was thus necessary to establish some criteria for the equivalence of damage classification.

Some irregularities in the broken lines that divide the damage classifications in graphs 1 to 5 may be explained by the decay of structures before the earthquakes. As stated(2) in connection with survey 1, most of the built-up zone of the city lays upon the sandy clays of fluvial deposits of the river Copiapó and had already suffered the 1906 floods; the economic decay of mining activities was also responsible for an inadequate maintenance of the buildings. With regard to surveys 3 to 5, Concepción and Talcahuano, old constructions, namely adobe and unreinforced brick buildings, were survivors of 1939 earthquake and had lost part of their initial strength. In Valdivia, survey 8, old wooden buildings, without diagonal bracing and founded on wooden piles weakened by moisture, suffered a high rate of damage. The lack of bracing was typical of european design imported by german settlers. In this particular case, many of the damaged houses were founded on soft reclaimed ground. Finally, in Taltal, survey 10, many of the wooden buildings were damaged by moths and moisture.

In Valdivia, survey 8, many wooden houses were damaged or destroyed by the fall of divisory brick masonry walls, built with this material for the purpose of protection against fire. These walls were independent from the wooden structure. In Taltal, survey 10, a similar situation ocurred, the divisory walls being built in this case of wooden frame with concrete fill. This explains some irregularities in the statistical behavior of wooden framed buildings, graphs 2 and 3.

Adobe buildings.-

Adobes are sun-dried clay bricks, reinforced with straw. The dimensions of adobe in Chile are usually 10x30x60 cm. They are laid in a similar way to brick masonry, using clay mud as a mortar. Old adobe buildings used to be 4 to 6 meters in height, with walls 60 cm. to 90 cm. thick; after disastrous experience on earthquakes, the height has been reduced to about 3 meters and the thickness of walls to 30 or 60 cm. Figures 1 & 2 illustrate some features of adobe construction; a detailed explanation on adobe construction practice may be found in reference (3).

Adobe is very weak against moisture. It is usually protected with a plaster made of fine clay, but it needs a permanent maintenance of roofing a and plaster. Adobe buildings are very common in the Central Valley of Chile, the most densily inhabited part of the country. In the southern part of the country they are very scarse because of the high rainfall; in the desertic zone of northern Chile adobe is used only where clay and water are available.

The behavior of adobe buildings during earthquakes is very poor, as shown in graph 5. After the disastrous 1939 Chillán earthquake, where most of the deaths were caused by the destruction of adobe houses, the committee in charge of the building code (4) considered their prohibition. However, it was the prevailing opinion at that time that no other cheap material was available for families of low resources and adobe construction was allowed with a limit of 3 meters in height for adobe houses.

Even for weak earthquakes of intensity VI to VII, the upper parts of facade walls show horizontal cracks at the level of wooden lintels or ceilings leading in some cases to displacement over the lower part of the walls, Fig. 1. For higher degrees of intensity the upper parts of walls may tilt or fall down.

The weak connection between perpendicular walls resides only on the overlapping of adobes. With degree VI to VII, vertical cracks may appear, Fig. 2. With higher intensities these cracks are widened and each wall vibrates as a cantilever wall. In that condition, horizontal cracks appear, ordinarily near the base of the wall, causing the upper part to tilt or even fall down. In Fig. 2, the bottom of the walls is built of brick masonry and a horizontal crack appears just in the limit between bricks and adobes.

It is usual to find diagonal cracks that start from the corners of windows, upwards or downwards. This occurs mainly at the corners of houses and leds to a higher degree of damage for houses located at the corners of blocks. Fig. 2 shows this kind of damage.

A mixed type of construction of frequent occurrence consists of exterior adobe walls and interior wooden partitions. They behave somewhat better than adobe buildings, but worse than wooden framed buildings with heavy fill. The reason is that the partitions are not connected with the exterior walls, except for a weak nailed joint with a wooden piece that runs over the adobe walls and which receives the reaction of wooden trusses. The exterior walls vibrate as cantilever walls and are easily damaged or destroyed. Divisory adobe walls separating two houses have an unsupported length of 10 or more meters and are specially vulnerable.

<u>Unreinforced brick masonry buildings.-</u>

Most of buildings of this type are one-or two-story buildings. They behave slightly better than adobe, graph 4, but they are still very dangerous for degrees of intensity VIII or higher. It was prohibited by the 1940 building code after the 1939 Chillán earthquake. They have usually wooden floors and roofs, but in some cases there is a reinforced concrete slab at the floor of the second story. Figure 3 shows damage on a two-story building in Concepción, after the 1960 earthquake. Horizontal cracks appear at various levels, specially at the level of lintels. The upper parts of walls may be displaced, tilted or collapsed for degree VIII or higher. Diagonal cracks starting from the corners of windows are also common.

A mixed type is commonly seen. It combines exterior walls and interior wooden framed partitions with heavy fill. Buildings of this type may attain up to 4 stories and are older than the 1940 building code. They have wwoden floors and roofs. They show a better behavior, showing no significant damage for degree VII but beeing cracked for degree VIII of intensity. In those buildings the interior partitions are connected to the brick masonry exterior walls by bolts, providing thus a sort of lateral support. Cracked walls are in general prevented from collapse due to these connections.

<u>Wooden framed buildings with heavy fill.-</u>

These buildings are usually of one story. The frames are weak against forces acting normally to their plane when lateral supports are not disposed close enough. Other weak point of these buildings is the connection between perpendicular walls. They are made by overlapping the horizontal wooden members and by nailing them together. In figure 4, the failure of connections between walls led to a complete destruction.

Different types of fill are used : adobe or concrete fills are very common. Less commonly, brick fill is also used, with a poor behavior. It is rather frequent that fills show cracks along the vertical and diagonal wooden pieces and even fall down.

The walls may fail also by forces acting in their plane. This occurs due to the weak nailed connections between vertical, horizontal and diagonal members of the frame. When two buildings have no separation, their collision during earthquake causes damage of this kind.

The action of moisture affects mainly the bottom of vertical members and has caused considerable damage. The action of moth is also important in some localities at the sea coast such as Taltal.

Wooden framed buildings without fill.-

The wooden frames have in this case the same characteristics than the former type. They are usually one-story buildings. There is in many cases a difference in foundations, where wooden piles may replace the concrete foundations. The frames are covered by nailed boards, usually overlapped, providing in this case an additional rigidity.

The behavior of this type of construction is effective against strong earthquakes, as shown in graph 2. It presents, however, some weak points. One of these is the insufficient connection between perpendicular partitions, leading in exceptional cases to failures similar to that shown in figure 4. Other one is the weathering of the wooden piles, when used. Lack of appropriate maintenance is also an important factor of damage. Generally speaking, the frames show the kind of damage described in the former paragraph but in a minor degree.

Brick masonry, reinforced.-

Buildings of this type are considered earthquake-resistant and designed for a seismic coefficient 0.10 to 0.12. Graph 1 shows the statistical behavior.

They have been described in detail (3,4). Most of them are one-or two-story houses, but many 4-or 5-story apartment buildings have most of their walls of this type. The masonry walls have reinforced concrete columns and tie beams. In apartment buildings there is a reinforced concrete slab at each floor level and at the roof level, but in one-and two-story houses the roof slab is usually omitted, and some two-story houses may have no slab at all.

The destruction of a small percentage of buildings of this type has been explained [6] by a deficient detail of steel bars. Column and tie beams are in general 20 by 20 cm. in section with four #4 bars. When two tie beams and a column meet at a corner of such buildings, the end hooks of the twelve bars leave little space for the concrete. Insufficient bond and incapacity of concrete for supporting high stresses in this condition led sometimes to a destruction of the joint. After the failure of this connection, the wall behaves like an unreinforced brick masonry wall. This experience has contributed to a modified design where the end hooks of tie beams have been displaced from the corner.

Other causes have been mentioned(6), among them the existence of weak construction joints, a wrong disposition of bars and a deficient quality of concrete. With a better detail work and a good inspection, a reinforced brick masonry small building seems to be able to resist an earthquake of degree IX MM without danger of collapse.

Low cost one story houses have been planned and built by suppressing the reinforced concrete columns. They have shown a good behavior for degrees of intensity VI to VII, but they are damaged by stronger earthquakes, specially when their walls have large openings.

Concrete block masonry, reinforced.-

The use of hollow concrete blocks has been increased in the last few years. In several towns, specially in northern Chile, clay bricks cannot be produced by the lack of appropriate materials. Even in the Central Valley clay brick masonry has been replaced by concrete blocks masonry in large city developments; many one- and two-story houses and four-story apartment buildings have been constructed with block masonry walls.

These buildings have suffered severe damage during earthquakes. Several reasons explain this poor behavior. In some cases, the low grade of concrete aggregates is responsible of the low quality of blocks. Figure 5 shows the kind of damage that appears even at moderate intensities when the quality of block or mortar is deficient. Of course, in this figure it is also possible to detect some faulty design; the block masonry wall has no end columns and the central column does not improve its resistance against lateral forces.

Even with good materials the mortar may be damaged by insuficient humidity of the block or by an excess of humidity. Inadequate inspection has been often responsible for the weak condition of mortar and even for the absence of mortar in vertical joints between blocks. One-story houses where the reinforced concrete columns have been suppressed show a poor behavior. A large number of houses of this type were dameged in Santiago by the 1965 earthquake, with an estimated degree of intensity VI to VII. Other important number was destroyed in Tocopilla by the 1967 earthquake with degree VII to VIII.

Effect of ground conditions.-

We shall not refer to the settlement or sliding of the soil, that changes the pattern and degree of damage for each of the types of construction described. They do not have a significant influence on the statistics of damage, except in survey 8, where wooden houses built on soft reclaimed ground were badly damaged or destroyed.

A detailed study of the relationship between damage and type of soil has been made for Taltal, Concepción, Talcahuano and Valdivia(7).

Taltal is a small seaport at the foot of tall hills. Through the Taltal ravine, transported material has formed a cone where the town lies. Loose sandy layers and gravel provenient of marine deposits are intercalated with the former material at some zones of the town. Damage was much higher in buildings founded on sandy layers.

In Valdivia, 33% of all wooden houses were damaged or destroyed (survey 8). When they are classified according to the soil characteristics, their percentages of destruction are as follows :

Reclaimed soil (soft fill)	70%
Sandstone	40%
Sandstone and silty layers	15%
Silty sand	34%

In Talcahuano, damages were studied by dividing the town in different zones according to the soil conditions. When the degree of intensity is computed for each zone by following the criteria of reference (1), variations of about one degree are obtained. The higher degrees of intensity correspond to transported material at the foot of the hills and to artificial soils in the harbour zone. The lower degrees correspond to tertiary rocks and to sands from fluvial deposits. However, sands with a water table very near the surface show a higher degree of intensity.

In Concepción, the city was divided first on a geological base in eight zones, and the degree of intensity was computed in a similar way, with differences of about one degree. The four zones of lesser intensity were grouped in zone a) and the four others in zone b). Recent sand deposits show higher intensity than old ones, transported material at the foot of the hills and artificial soils have the higher damage ratio.

Recommendations.-

Adobe buildings should be prohibited, because their poor seismic behavior is a menace to life and property. The present economical conditions are different from those prevailing in 1940. Adobe construction is no longer cheap, because the cost of labor in agricultural zones is now close to the cost of labor in industries. Other construction types, such as wooden frames, have an advantage from economical considerations and their behavior during earthquakes is uncomparably superior.

Adobe and unreinforced brick masonry buildings should be replaced and a priority for this process should be established, by considering the actual use of those buildings, their present condition and the soil characteristics.

Wooden frames should be improved by strengthening some connections. Nailed connections of diagonal members, joints of perpendicular partitions and anchor of frames to foundations are weak points of these structures. Bolted joints with steel plates could prevent most of actual damage.
Brick or concrete block masonry, with reinforced concrete columns and tie beams, could be strengthened by a good detail of bars and by a good inspection at the site.

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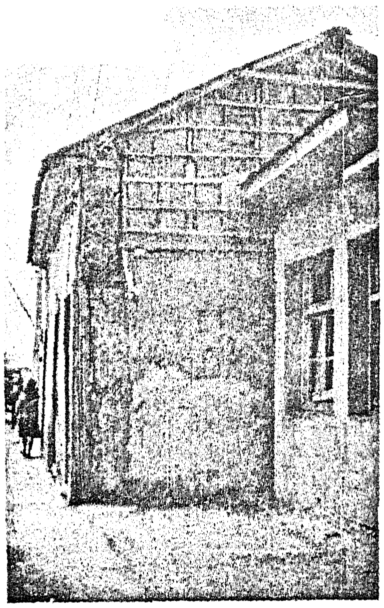


Fig. 1.- Serena, Sept. 26, 1967 Earthquake, MM VI-VIII. Adobe house.

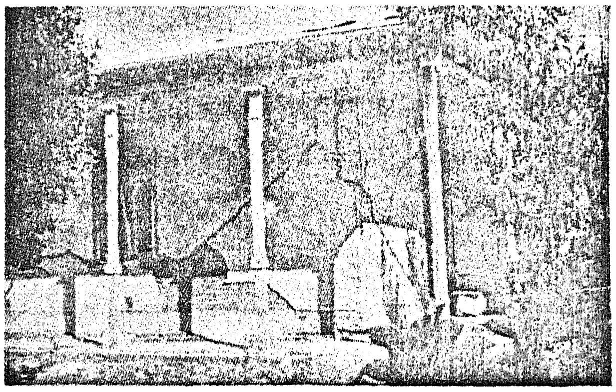


Fig. 2.- La Ligua, March 28, 1965 Earthquake, MM VIII-IX. Old adobe hospital.

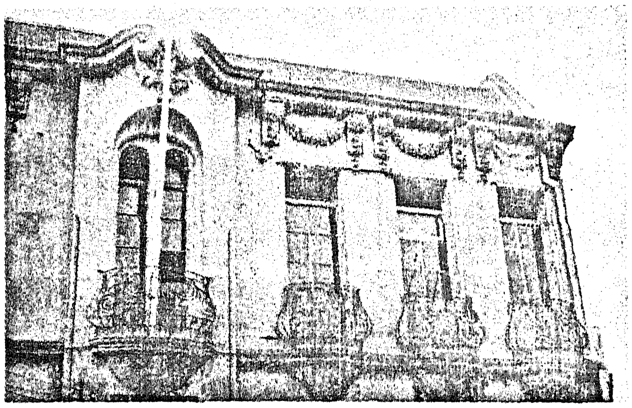


Fig. 3.- Concepción, May 21, 1960 Earthquake, MM VIII. Two-story unreinforced masonry building.

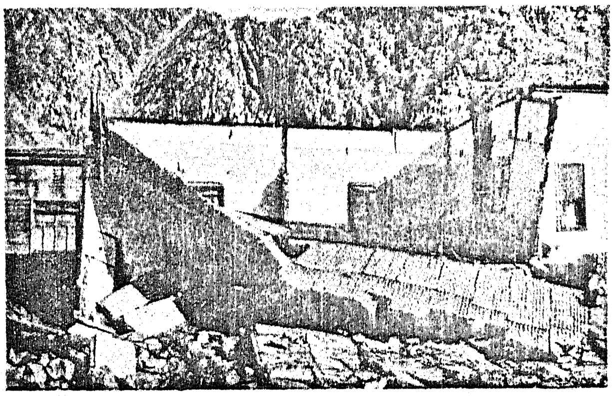


Fig. 4.- Tocopilla, Dec. 20, 1967 Earthquake, MM VII-VIII. Wooden framed house with heavy fill.

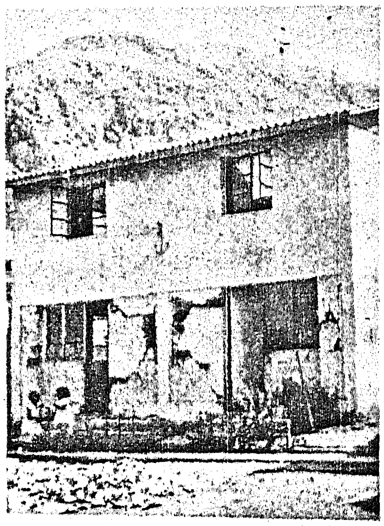
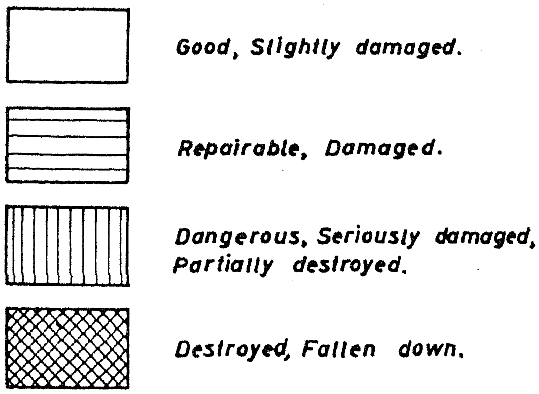
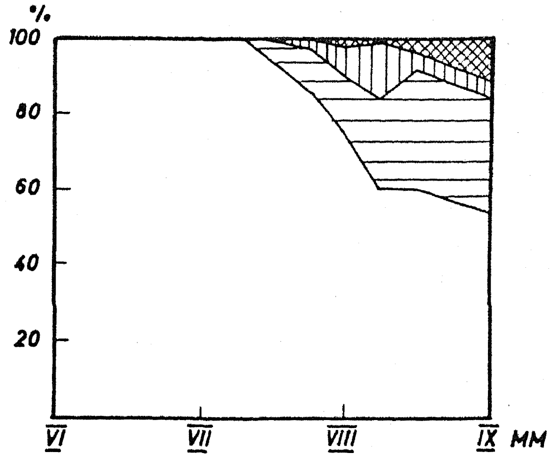


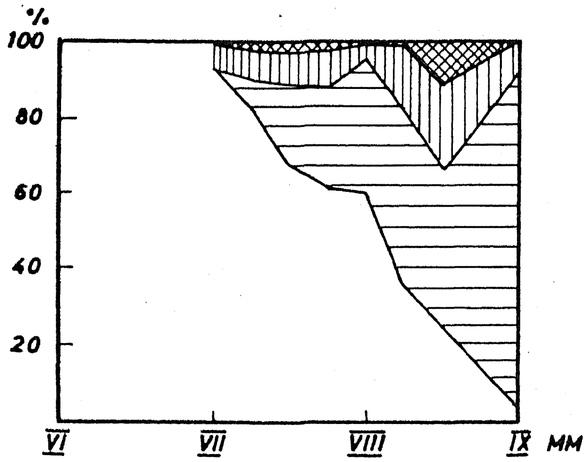
Fig. 5.- Tocopilla, Dec. 20, 1967 Earthquake, MM VII-VIII. Two -story reinforced block masonry house.

SURVEYS OF DAMAGE (Tables 1 to 10)

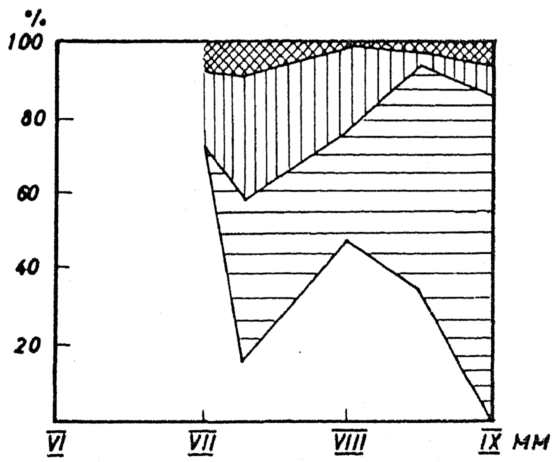




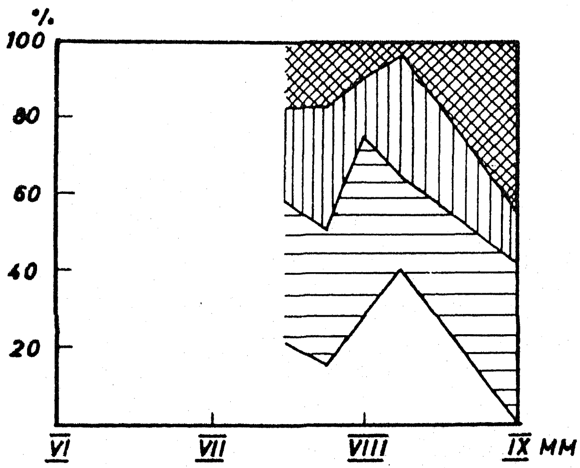
Graph 1.- BRICK MASONRY, REINFORCED



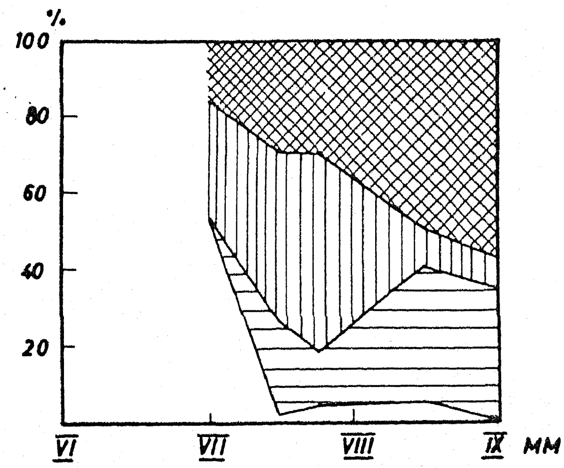
Graph 2.- WOODEN FRAME WITHOUT FILL



Graph 3.- WOODEN FRAME WITH HEAVY FILL



Graph 4.- BRICK MASONRY, UNREINFORCED



Graph 5.- ADOBE