DEVELOPMENT OF EARTHQUAKE-PROOF CONSTRUCTION IN CHILE

by H. Bertling

In my contribution to the First World Conference on Earthquake Engineering, I will review, in chronological order, the most important methods of construction which have been used in Chile throughout its history and the results which have been observed after the severe earthquakes that have devastated the country.

Constructions Before the First Building Code

Adobe Construction

Since the arrival of the Spaniards in 1540, buildings that we would call typical construction were made with adobe. Great width was given to this material in the walls, up to three or four feet of thickness being used in exterior walls. The general arrangement of Spanish construction consisted of a row of rooms around a very big yard with few spaces for doors and windows. The partition walls consisted of adobe of a slightly lesser width than the other walls, and were not adequately connected to them. This resulted in severe destruction by shocks.

Roofs consisted of a system of timber beams, not square and of very irregular form, on which rested a layer of thin colihue (bamboo) poles. This arrangement gave a very uneven surface of the roof, which was corrected with a thick layer of mud or hay, and over this the tiles were placed. Lintels over windows and door openings consisted of heavy timber members. Such construction developed great weights on the roofs, and this was one of the principal causes of destruction during earthquakes. However, adobe construction in Chile, although it is not earthquake-proof, generally has given fairly good service when founded in firm soil, especially when one considers its low cost.

However, this type of construction has had a big disadvantage due to the hygroscopicity of the material used. The great majority of the Chilean population are situated in towns and farms of the Central Valley (which has a gravel subsoil). Great irrigation systems are located there which cause the elevation of underground water levels to be raised. This causes water to come up 1.5 meters through the walls above the ground level, due to capillarity. The strength of this material is in itself very low and is considerably reduced by the absorption of water as described above. This fact is aggravated by the poor quality of the foundations which generally were made of cobblestones, linked with mud and hay.

Evaluating the experience in adobe construction, we might expect it could resist earthquakes up to an intensity of 6-7 on the Mercalli, Cancani and Sieberg scale as an average. With improvements such as light roofs of galvanized iron, resistant and water-proof foundations, adequate links between walls, etc., these constructions could resist earthquakes up to an intensity of 8-9 of the same scale. In general adobe as a construction material can be

*Professor of Applied Seismology, University of Chile, Santiago

considered acceptable only when built on good gravel, soil or rock and in constructions not more than 1 story in height.

Brick-Masonry Construction

At the beginning of the second half of the nineteenth century, brick-masonry construction of buildings was started, especially in public (government) buildings, convents, churches, schools, etc.

At the beginning, due to cheap hand labor, the quality of this material was fairly good, but with social problems coming along, this good quality diminished steadily up to the present.

The thickness of the walls are 0.15, 0.20, 0.30, and 0.45 meters in accordance with the size of the bricks and the way of laying them. Bricks are 6-7 cms. thick. In general, the compressive strength is not greater than 5 to 6 kgs per sq. cm. The shear strength is not more than 1 kg/cm^2 as a whole in walls. Considering the low strength, and the low damping value*, the very bad results with earthquakes that this type of construction has given in Chile can be easily understood. Its experience is so poor that its use without reinforcement has been forbidden by the Building Codes, since the big earthquakes of Tolca in 1928 and Chillan in 1939. Failures of the walls have been found in most cases, in planes at 45° to the horizontal plane, caused principally by shear stresses.

Stone-Masonry Construction

In Chile there are very few stone-masonry buildings and it is not possible to present any seismic experience in this type of building. In any case the Building Codes forbid any construction of this kind without reinforcement.

Steel Construction

This type of construction has been very scarce in Chile due to high cost of this material, as most steel members had to be imported. Our steel mill produces structural shapes only up to 6 inches in depth, but at the present time we are manufacturing welded shapes, and the construction of a 20 story building is under consideration. These structures have behaved very well, in all the big earthquakes that have shaken this country, although in no case have these constructions been designed according to earthquake-proof construction regulations.

Timber Construction

This type of construction has proved very good for seismic areas in Chile, if buildings are made no more than four stories high.

Reinforced concrete construction

Reinforced concrete construction in Chile has been wide spread, even before the first General Building Code was dictated. The performance in this

*Log decrement at small amplitudes: for brick masonry; 0.185; concrete 0.461; adobe, 0.354.

type of construction has been heterogenous; in well-built buildings of low height or few stories, it has been excellent, even though they have not been designed to withstand earthquakes. With regard to buildings of this material over three stories in height (even though very good materials have been employed), many of these structures have been destroyed completely, due to lateral seismic forces not having been considered in design, or due to poor soil conditions. As is the case in brick-masonry building, the quality of the materials employed has been a very important factor with regards to resistance against earthquakes in buildings not designed especially for such forces.

Earthquake Resistant Construction, First Code

Up to the beginning of the twentieth century, we cannot say there was any example of the so-called earthquake-proof construction. The construction methods used copied vaguely the European design methods in the cases of public buildings, churches, commercial and industrial buildings, but did not achieve European quality in material and workmanship.

During the present century, Chile was affected by very severe earthquakes; for example, the Valparaiso earthquake in 1906, Vallena in 1922, and the Talca earthquake of 1928, and the most severe of all, the Chillan earthquake of 1939. The destruction caused by these shocks was extraordinarily great in property and lives, and produced in the professional field and in the government the desision of changing this situation. Studies were begun in technical public offices, universities and engineering societies to prepare legal dispositions about building and municipal regulations.

These studies were highly influenced by all the theoretical literature of the epoch (1927-1932) in which concepts of resonance prevailed, and the recommendations which were adopted were intended to avoid it. From these studies was finally brought out a General Code of Constructions, Law #4563. This code is a General Law applicable to all cities of the Republic and not only gives rules for construction, but also for the design of structures. In this code, in its first form, the text indicated a series of specifications, with the object of getting continuity (monolithic action) in the structures, if possible; limiting the use of certain materials, and forbidding some kinds of constructions, which up to that date had been widely used.

With reference to seismic forces, it required that all structures should be checked for lateral forces varying from 1/10 to 1/20 of the weight of the structure in accordance with the quality of the ground (correction factors increasing for soils of poor quality). As it can be seen, the Code was a kind of book of recipes to build structures which should have a sufficient degree of seismic resistance; however, it did not create a system of earthquake-proof construction as a whole.

This Code began to be applied in a provisional way in 1930 and ruled the construction in Chile up to the tremendous destruction caused by the big earthquake in Chillan in 1939, which made necessary a revision of this ordinance and a proposal of a new Code (2nd text). In 1939 this new Law or General Code of Construction was passed and its application was made compulsory. Its text classifies the different types of construction in accordance with the materials used, as follows:

Class A - Buildings of reinforced concrete

The height of these buildings should not be more than 40 meters or 12 stories. All structural elements should be entirely of reinforced concrete with the exception of partition walls, which should be securely anchored to the frame or walls. Floor slabs should also be of reinforced concrete. In this country, all specifications related to the materials of construction are ruled by the Chilean Code (which is a translation of the German Code).

With regard to constructions built under this system, as is usually the case, the quality of the materials has a very important effect on the structural capacity to resist severe earthquakes. It can be said that, in Chile, this type of structure is safe, if the reinforced concrete effectively has the prescribed strength given by the Code. Otherwise, its security is doubtful, especially on soils of a poorer quality than usual.

Observing the behaviour of these structures in severe quakes, we can see that the American building codes are right with respect to distribution of lateral forces. As usual, the upper stories show cracks after earthquakes of fairly severe intensity, because the buildings have been designed with uniform lateral forces. Because the Code mentioned indicates a rectangular diagram for the lateral stresses, the upper stories are not sufficiently safe against shear stresses and bending moments.

Class B - Buildings with steel frameworks

These buildings should not be more than 40 meters or 13 stories high. The calculations for steel framework buildings must be done according to the code of steel construction which was recently approved.

The number of examples of this kind of construction in Chile is practically nil, therefore no information can be given as to its earthquake performance.

Class C, D, and E - Buildings constructed with reinforced brick-masonry, and reinforced with columns and chains* of reinforced concrete.

These three types are similar in general regulation and methods of construction, but there are differences in detail. The reinforced brick-masonry, consists in adding to the common brick-masonry, two round steel bars in the horizontal joints tied together with wire every 40 cm. and placed 2 cm. from the outer edges of the walls with their ends anchored to the columns. In walls 40 cm. thick these bars are placed every 6 rows and in thicker walls, every 4 rows. The mortar used to place the bricks must be very rich. These types of buildings were objected to strongly by the constructors and practically none of these buildings have been built.

Class F - Buildings made with outer walls and partition walls of non-reinforced masonry, having columns and chains of reinforced concrete.

The height is limited to 8 meters in this class and the stories to two. The outer walls and partition walls of the ground floor must be brick-masonry

*Horizontal tie-beams of reinforced concrete at the top of masonry walls are referred to as "chains" in Chilean practice.

and reinforced concrete columns are required in the intersections of the walls. The outer walls of the second floor must be of brick masonry and the inner partitions can be of wood if their intersections with the outer walls are at columns of reinforced concrete. The ratio between the height and the smaller side of the rectangle circumscribed about the base shall not be less than 2. It must be remembered that all structural elements of reinforced concrete should be cast after erecting the masonry walls.

This type of construction is the one that has gradually become the most common system of the Chilean seismic construction. The dimensions of the structural elements are clearly defined in detail in the articles of the code. The behavior of this type of construction has been very satisfactory when two conditions are complied with:

1. The materials of structural elements shall be of high quality.
2. The ground shall not be of much inferior quality to the clayey gravel of the Central Valley of Chile.

Class G - Buildings constructed with outer walls of unreinforced brick-masonry and with inner partitions of wood.

This type was eliminated from the original text of this Code due to the tremendous destruction caused to this type of building in the earthquake of Talca (1928) and Chillan (1939).

Class H - Timber Buildings

These buildings cannot be more than 12 meters high and may not have more than three stories.

All the resisting elements of the construction, including the floors and roofs, are made of timber. The inner partitions can be built with filled in materials of various types if the resisting framework is of wood and if the filling materials have a specific weight not higher than wood (and are firmly anchored to the framework). The results with this type of construction have been highly satisfactory in the cases where they have been well built.

Class I - Adobe Buildings

These constructions for housings cannot have more than one story and not more than 3.50 meters of height. In all cases the walls must rest upon foundations of cement or masonry with footing walls 0.30 meters in height as a minimum to avoid moisture in the walls. The thickness of the walls should not be less than 0.50 meters. The distance between the walls should not be more than 4.50 meters. The height of the openings for doors should be no more than 2.30 meters. The lintels are formed by wooden beams of the same width of the wall and the spans should not be more than 1.30 meters. The roofs must be of light-weight materials.

The behavior of this type of construction has been very satisfactory in soils of good quality, like rocks and gravel. In sandy and clayey soils their results are very questionable, even if the quality of the materials used is good. In any case, adobe buildings with the best of materials cannot stand earthquakes with an intensity greater than grade 9 of the Sieberg scale.

DEVELOPMENT OF ASEISMIC CONSTRUCTION

In calculating the stability of buildings, special importance is given by this code to the action of earthquakes. The magnitude of the seismic coefficient will be taken as follows:

1. Vertical component, 0.15.
2. Horizontal component in any direction and with a value between 0.1 and 0.2, depending on the quality of the soil and the degree of security given to the work. These values will be applied to buildings of types C, D, E, F, H, and I.

For the buildings of types A, and B as well as those meant for theatres, banks, stadiums, factories and, in general, for all constructions of large spans, the value of the period of vibration of the structures will be considered. If this value is lower than 0.4 sec., the seismic coefficient must be considered as shown above. If the value of the period is higher than 0.4 sec., the seismic action will be considered equivalent to horizontal forced vibration of the following characteristics:

Acceleration-0.1g to 0.2g
Amplitude - 4-6 cms.
Period - 1-2 sec.

The lower values of the acceleration will be taken for buildings built on rock, adding 20% for sandstone or similar material, 50% for gravel or loose sand, and 100% for filled ground.

All structures with a natural period between 1 and 2 seconds are forbidden. Allowable stresses are 10% greater than for static loads.

Earthquake Resistant Construction, Present Code

Immediately after the promulgation of this building Code, architects, engineers and builders made important and heavy criticism against it, accusing it of being responsible for the increase of building costs. The pressure of people connected with the building business compelled the Chilean Government (1945) to appoint a commission for the purpose of writing a less expensive and more up-to-date Building Code. The appointed commission prepared this in 1949. In this code, the regulations specify more simple methods in the computation of stresses and design, and less severe requirements of the safety of buildings.

Because of the fact that this Building Code is in force at present and all the constructions we build now are in accord with its regulations, I shall describe in some detail all qualifications relating to earthquake-proof design.

Classification of Buildings

In regard to the methods of construction and the building materials, the structures are classified in the following types:

Type A - Steel framework structures. All the resistant members must be covered with fireproof materials. Floors must be built with structural steel shapes or reinforced concrete slabs. Walls must be connected rigidly to the framework.

Type B - Reinforced concrete buildings. Floors consist of reinforced concrete slabs and the walls must be connected rigidly to the framework. This classification includes buildings in which the reinforcing is in the form of structural shapes.

Type C - Brick Masonry Structures. Structures of this type have bearing walls of brick masonry between columns and chains of reinforced concrete. Buildings may not have more than four stories. The value of the ratio between the height of the building and the length of the least side of the rectangle circumscribing the base must not be over 2.5. The maximum height of any story is 5 meters.

Vertical loads must be transmitted to the foundation soil by means of the masonry walls built between chains and columns of reinforced concrete or by means of columns of the same material. Isolated columns must be connected with the walls at every floor level by means of reinforced concrete members.

Lateral forces must be transmitted to the soil by means of walls without openings having a thickness not less than 0.20 m. In the cases of walls with openings, the required thickness must be determined by computation. The partition walls must be connected to the main structure by satisfactory methods in order to avoid destruction with earthquakes, with the sole exception of the removable partition walls. The floors must consist of reinforced concrete slabs. However, it is possible to build timber floors on the upper floors in buildings of 2 or 3 stories.

The ceilings of the upper stories shall consist of reinforced concrete slabs or timber framework. In the first case, it will be permitted to eliminate the upper chain if the slab is able to take its place. In the one story buildings it is permitted to eliminate the chain if the roof is a continuous slab of reinforced concrete.

Type D - Rock masonry buildings. All the regulations applied to Type C construction must also be applied to this type for buildings up to two stories in height. The height of any story may not be more than 3.50 meters.

Type E - Timber framework buildings. The total height of these buildings may not be over 7 meters and no story may be over 3.50 meters. Attic space may be used under the roof.

Type F - Adobe buildings. The height of this kind of building used for dwellings may not be over 3 meters and may be of only one story.

For purposes other than dwellings, the height may be greater.

Mixed Types

1. It is permissible to use in the different stories of a building Type B construction in the first or lower stories of Type C in the upper stories. It is also permissible to use both types in the same story.

2. It is permissible in two story buildings to use Type C or D in the first story and Type E in the second story.
3. In all cases, where mixed types are used, the joints of the different types must be satisfactorily connected in order to insure the stability of the structure for vertical loads and lateral forces.

Earthquake design and seismic computations

1. In the computation of stability of all buildings, it is necessary to take account of the lateral forces produced by earthquakes and all the stresses produced by these forces in all the different members of the structure. The stresses must be added to those caused by the dead load, and to those produced by the half of the live load, plus the half of the stresses produced by differences of temperature. The values obtained must be less then those permitted by the regulations for each material. The stability computations of the building and its foundation must be considered as a whole.
2. The stresses produced by dead load, live load, temperature, wind, and foundation settlement without seismic stresses must be less than the allotted stresses determined by the regulations for the various materials.

   The building of Types A and B must be designed according to ordinances of Steel Construction and Reinforced Concrete Construction. The same applies for Types E and F. For the design of buildings of Type C, there are two possibilities:
   a) Design according to the principles of Strength of Materials and of the above regulation,
   b) Design according to regulations in full detail given in the Building Code.

Seismic Coefficient

The seismic coefficient varies according to the types of soil and to the stiffness of the structure (period of the natural vibration of the structure), as indicated by the following table:

Qualities of Soil		Seismic Coefficient
Rigid construction ($T < 0.4$ sec.)		
Sand and filled ground	Mat foundation or similar	0.10
	Without mat	0.12
Conglomerated or very compact soil		0.12
Rock		0.08

Qualities of soil		Seismic coefficient
Semi-rigid construction (0.4 < T < 0.75 sec.)		
Sand and filled ground	Mat foundation	0.12
	Without mat	0.15
Conglomerated or very compact soil		0.10
Rock		0.05

The building code contains other different regulations related to the computations of the natural period of vibration of the building. These regulations are obsolete and structural engineers ignore them.

Regulations regarding construction of members not submitted to the requirement of stability computation (Referred to Type C)

The regulations of this chapter are not applied to those buildings generally subjected to the action of forces of extraordinary magnitude, or to repeated loads due to mechanical vibrations. The dimensions of the members of such buildings must be determined by special computations.

The specifications presented in this chapter cover the details of design of all major structural elements: walls, columns, chains, etc. Because of limitations of space, it is not possible to describe all of these details here.

The behavior of buildings of this type has been very satisfactory when the prescribed quality of materials have been used.

A major problem existing at present time for building business in Chile is to improve the quality of construction materials especially with respect to concrete aggregates.

New Special Building Codes

Although the last General Building Code has lower requirements with regard to stability, especially for constructions of type C, the political and economic pressure has been so great toward more inexpensive building, especially with regard to construction of popular and economic types of dwellings, that the Government has approved two new Building Codes that have even lower requirements. These are: "The Economical Dwelling Construction Code" (a City Planning Code) and the "Pereira Law."

These two new codes have limitations with regard to the number of stories and the floor area, and apply especially to small and economical groups of houses.

The new requirements refer to Type C construction, in particular, and accept thinnner walls and less steel reinforcing bars in columns and chains.

With regard to the behavior of these new systems of building having reduced requirements of stability, although they are very numerous in Chile there is no real experience with their capacity to stand any kind of severe earthquake, because no severe shocks have occurred since the approval of these laws.

Naturally, this multiplicity of Codes and specifications is highly dangerous, and, at present, the professional people in the construction field are trying to gain the acceptance of a single code in Chile.