FIFTY YEARS OF EARTHQUAKE ENGINEERING PRACTICE

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MY PHILOSOPHY OF EARTHQUAKE RESISTANT CONSTRUCTION

My first experience in structural design was related with the Industrial Bank of Japan, the Kabuki Theatre, and the Business of Japan Building in 1920, approximately ten years after graduation from college. Fortunately, all of these buildings survived the Kanto Earthquake of 1923 without damage.

This was the period immediately after the First World War when trade with Europe and America was flourishing and Japan made important economic progress. During this period, the Marunouchi Building, the NYK (Yusen) Building, the Japan Oil Building and others were built by the George Fuller Company and others that were designed by American engineers. Structural steel skeleton with curtain walls of brick, monolithic reinforced concrete floors, and partitions of hollow brick were generally used. The rapid construction had great appeal to Japanese engineers and builders and they competed with one another to adopt this American construction technique. Typical buildings of this character were the Naigai Building of reinforced concrete construction which suffered in the Kanto earthquakes complete collapse and the Tokyo Kaikan, Marunouchi Building, and Japan Oil Building which suffered considerable damage.

The violent earthquake in 1923 during the building boom came as a shock and it gave warning to reconsider building structures and insofar as it tended to produce sound buildings, it was fortunate.

The fact that the three buildings mentioned above, which were designed according to my theory, survived the great earthquake was very fortunate and they indicated the manner of future design for earthquake resistant buildings.

An account of how my theory of structural design originated seems to me to be important, as well as interesting. I graduated in 1910 from Tokyo University and was engaged in research on earthquake resistant buildings under the late Dr. R. Sano, who was an authority in this field. In 1916 I toured America but, in my special field, I was not successful in finding anything new. However, I profited very much from the instruction of Professor Filmore Swain at M. I. T. who impressed upon me some fundamental points in structural design. His fundamental concepts consisted of 1st, eliminating undesirable forces and 2nd, of changing bending moments as much as possible to direct compression or tension forces as building materials are weak and undergo large deformation when moments occur. These two concepts were to become directly

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related to my future research. Returning to Japan after a year's tour abroad and without much success, I was constantly thinking on this subject. One day, I recalled suddenly my experience in the United States with a trunk which I was carrying. As I had accumulated much materials to pack in this trunk, I removed the inside partitions in order to pack as much as possible when leaving San Francisco. On reaching Washington, D.C., I found the trunk almost completely destroyed. Purchasing a new trunk, I did not repeat the mistake of removing the inside partitions again but rather, after packing the trunk full with books, etc., bound the trunk tightly with rope on the outside. The trunk in this condition, even when handled roughly, was not damaged and is in good condition even today. In addition to this, I recalled that the ship I boarded in Seattle, although buffetted by heavy waves in the stormy Aleutians, was undamaged and intact from the impact of the waves. What where the reasons for this? Partitions are provided in trunks and tied with rope on the outside. This is the procedure used by packers and transportation people. In ships, horizontal decks and vertical bulk-heads are provided. In both cases, the deformation is kept to a minimum and strength increased. In other words, the key point seemed to be the elimination of unfavorable forces and keeping deformation down to the minimum as stipulated by Professor Swain. And it seemed to me that the application of this idea should result in earthquake resistant buildings.

When designing the Kabuki Theatre, the auditorium was conceived as a box with side walls of reinforced concrete and the roof securely fixed to these walls in a manner similar to the top cover of a box, giving the structure sufficient earthquake resistant qualities. In the case of the Industrial Bank of Japan, the structural frames were provided with reinforced concrete walls in the manner similar to bulk-heads in ships. These walls were made very strong which resisted the earthquake forces very satisfactorily. When floors are made monolithic with reinforced concrete slabs, the deformation of open and walled frames under lateral forces becomes essentially the same and it is possible to obtain the distribution of lateral forces to the various frames, namely, seismic distribution coefficient values. The forces on each of the frames are then determined and it is possible to design the frame members as well as to calculate the amount of deformation, which is of limited amount due to the presence of bracing walls. The Industrial Bank of Japan was designed on this basis and even the partitions made of hollow brick were entirely undamaged which may be taken as evidence of small deformation.

On the other hand, in the Marunouchi Building, referred to before, hollow tile partitions suffered serious damage and more than twenty diagonal braces placed in partition walls of 6 m. span in the second and third stories elongated and fractured. Assuming the steel elongation to be 20%, this represents a deformation of the frames exceeding one meter. The light fixtures hung by cords of 60 cm. length from the ceiling were set in violent motion and were 100% destroyed in the Marunouchi Building whereas in the Industrial Bank of Japan building, only 58% were destroyed.

The guiding thought in earthquake resistant design should be to control the building deformation within a small range and reinforced concrete walls are a most effective means to accomplish this. This fact has been substantiated by experience in the later Fukui earthquake. I refer to these reinforced concrete walls as bracing walls and make it a point to provide them in appropriate locations in framed buildings. In the United States and elsewhere, these seem to be referred to as rigid elements and included in Building Codes.

The essential features of structural design for my first important project which was the Industrial Bank of Japan are indicated below. The building is 40 m. by 58 m. (131' x 193') in plan with one basement and seven stories above the ground. 14" Bethlehem H section steel was used for columns and 15" or 18" I beams were used for girders. These were encased in reinforced concrete to form a composite structure of steel and reinforced concrete with monolithic reinforced concrete slabs. The large banking area on the ground floor was obtained by eliminating one row of columns and was extended two stories in height. The upper stories to the 7th story were supported on trussed girders. The walls along the corridors, around the safe vault space, elevator shafts, toilets, etc. were utilized as bracing walls and light partitions were formed with hollow brick generally. Walls of one and one-half brick thickness formed the exterior. Wooden piles of 20 m. length were driven and all footings were tied together by foundation tie-beams.

Values of the seismic distribution coefficient were 3 for the exterior walls, 10 for bracing walls, and 1 for the interior open bents. A seismic coefficient value of 7% was used in combination with allowable unit stresses of 1150 kg./sq. cm. for steel and 45 kg./sq. cm. for concrete and designed statically. This building was subjected to actual earthquake accelerations estimated at 20 to 30% of gravity for the Marunouchi district and was safe and sound after the earthquake. This experience indicates the effectiveness of bracing walls in reducing the deformation. Buildings such as the Naigai Building deformed much more and the total damage was due to failure of joints between columns and girders. Factory buildings of reinforced concrete alone also suffered extensive damage. When a steel skeleton is added to the reinforced concrete, not only the strength is increased but the deformation due to bending is likewise reduced to 1/3 or 1/4, giving evidence of the stiffening effect.

Referring to the Fukui earthquake, one of the main reasons for the failure of the Daiwa Department Store building is traceable to the discontinuity of the foundation at the junction of the front sales area portion and the rear stiff stair and elevator shaft tower portion and that these two portions vibrated independently and produced large deformations, resulting in the rupture of the foundation at the junction area. Another important reason was due to assignment of a seismic distribution coefficient value of 3 to the wall girders which were actually designed for a value of 1, so that they failed at the junction with the columns, causing the whole building to fail. In contrast, although the reinforced walls in the tower portion suffered extensive cracks, this portion remained practically vertical, thus again giving evidence of the great effectiveness of bracing walls.

With such a background of earthquake damage experience, stiff or tough construction which limits deformations to small values is generally used in Japan even today. During this period, however, various schemes of construction ranging from flexible to aseismic construction based on theoretical considerations have been advanced but these are not all practical and only a few experimental buildings have been attempted to date.

Research and investigations pertaining to earthquake resistant construction received added impetus after the Kanto earthquake of 1923, including methods of analyzing building frames, computation methods for lateral forces, theoretical study of building vibrations, the strength and optimum location of bracing walls, characteristics of ground motion, dynamic or vibrational properties of soils, building response in relation to ground coupling, the question of damping and rocking of buildings. They have undoubtedly contributed greatly toward better earthquake resistant design.

Stiff buildings provided with many bracing walls undergo considerable rocking under forced vibration conditions which is advantageous in that it reduces the deformation of such buildings. The contrary condition prevails for the flexible buildings with few seismic walls.

In regard to the distribution of bracing walls in vertical frames, it was believed to be desirable to have them continuous vertically from the top to the bottom but experimental investigations have disclosed that dispersed distribution of these walls diagonally or cross-wise is more effective.

Vibration tests on actual buildings to determine their periods of vibration and deformation curves have also enabled us to judge the structural soundness of these buildings and to apply the findings to actual design. It is generally believed that the smaller the period of vibration, the safer the building is against earthquakes.

BUILDING MATERIALS AND EARTHQUAKE RESISTANT CONSTRUCTION

We should indeed be grateful that there are such materials as steel and concrete. Without these two, it would be impossible to develop theories or to construct earthquake resistant structures. Materials such as stone, brick, wood, and mud have been used in past periods but buildings of masonry construction alone have failed abruptly to claim thousands and many more victims as earthquake experience in Taiwan, Italy, Iran, Turkey, and Morocco indicate. The same was true in the San Francisco and Santa Barbara earthquakes in the United States and also in Mexico. In these cases, usually thin masonry bearing walls were erected on which floor and roof constructions were just placed so that under the action of lateral forces the buildings collapsed easily. If each story is tied tightly with steel or reinforced concrete and, in addition, monolithic reinforced concrete slabs are used, the buildings would be greatly strengthened. These precautions were recommended years ago by Dr. Sano but were steel and concrete not available this would be impossible to do. At any rate, the aim should be to keep the building deformation small.

On the other hand, although we have steel and concrete to work with, there are many buildings standing today that are non-earthquake-resistant. This is a situation to be deplored. At the time of the 1923 Kanto earthquake, it was generally thought that reinforced concrete buildings were the most resistant but it so happened that some of them were the most dangerous. Those that were designed along the principles of strong boxes were safe but those of skeleton framing along with weak curtain walls invariably suffered great damage. In the latter case, large deformation produced by earthquake forces caused joints to fail.

This type of skeleton construction is often seen in non-seismic regions of the United States and is also generally true in Europe. However, in seismic regions, I wish strongly to recommended that adequate amounts of bracing walls be used always. When steel framing is encased in reinforced concrete and joints made adequately strong, there is little to fear from earthquakes. The increase in the cost occasioned by these precautions would be rather insignificant and would perhaps increase the structural cost by roughly 5%.

TOKYO (RADIO AND TELEVISION) TOWER

In closing, I should like to refer to the subject of steel towers. The first radio tower in Japan of 55 m. height was built at Tokyo in 1925. Subsequently, a tower of 100 m. was erected in Osaka and also some sixty others. The steel tower in Osaka withstood the fury of the Muroto typhoon which registered a wind velocity of 60 m./sec. and also the 60 m. tower in Fukui rode through the 1948 earthquake without damage. Based on experience gained from these earlier towers, the 180 m. tower in Nagoya and the recent 333 m. Tokyo Tower were designed. Fortunately, the Nagoya Tower survived the Ise Bay typhoon without any damage and also the Tokyo Tower was unharmed although it was subjected to a wind velocity of approximately 50m./sec. The lateral forces from wind and earthquake were considered and the larger of the two forces was adopted in the design. The computation for the wind load followed the provisions of the Architectural Institute of Japan's structural standards and the earthquake forces were determined in accordance with the Standard Building Laws effective in Japan, which specify a minimum basic seismic coefficient of 0.2 increasing gradually upward to 1.0 at the top. In the case of this tower, the bending moments from wind and earthquake were of the same magnitude. The allowable stress for steel was taken as 2400 kg./sq. cm. Three seismographs are installed; one each at the top, at the observation platform level, and in the basement. Five wind velocity meters are also installed in this tower. These instruments will obtain records of wind and earthquakes.

At the time of the Ise Bay typhoon of September 27, 1959, with a registered wind velocity of 37.9 m./sec. (50 m./sec. at the top), the period of vibration of the Tokyo tower was 2.9 seconds, the double amplitude was 86 cm. and the acceleration registered was 410 gals. The computed deformation during the design stage was 100 cm. under a wind velocity of 50 m./sec. which is considered to be fairly good agreement.

The amount of steel for Tokyo tower was 3,600 tons (metric) as compared to 7,300 tons for the Eiffel Tower. The foundation under each of the legs of the tower consists of a cluster of eight concrete piers which bear on a hard gravel stratum approximately 20 meters below the ground level.