DESIGN, CONSTRUCTION AND PERFORMANCE OF REINFORCED MASONRY BUILDINGS SUBJECTED TO SEISMIC FORCES

James E. Amrhein[I]

Summary

Masonry structures, since earliest time, have been subjected to earthquakes and the unreinforced buildings have performed with various degrees of survival. This paper presents the seismic design requirements and methods for masonry design of buildings. The performance of unreinforced and reinforced buildings in numerous earthquakes in the United States since 1906 is discussed.

Introduction

Masonry has been one of the first materials used for wall enclosures to protect mankind from the elements. In the book of Genesis, the first book of the Holy Bible, Chapter XI, Verses 3 and 4, "....They said to one another, 'Come, let us make bricks and bake them.' They used bricks for stone and bitumen for mortar. Then they said, 'Let us build ourselves a city and a tower with its top in the heavens.'" This is one of the first recorded statements on the use of masonry for structures.

Also recorded in the Bible is the record of earthquakes. In Acts of the Apostles, Chapter 16, Verses 25 and 26, "About midnight, while Paul and Silas were praying and singing hymns to God as their fellow prisoners listened, a severe earthquake suddenly shook the place, rocking the prison to its foundations. Immediately all the doors flew open and everyone's chains were pulled loose."

The Temple of Solomon was built of stone masonry; the pyramids of the Yucatan are stone masonry; and the ancient structures of Egypt are fired clay brick masonry, as are many of the structures in Rome. The castles, churches and public buildings throughout Europe are built of stone masonry. Masonry has been an elemental particle, a fundamental system to the construction of nations. Old cities of Rome, Athens, Istanbul and London, and newer cities in the United States such as Boston, New York and Chicago have all been basically constructed of masonry. Masonry is a material that has weathered the test of time for both strength and durability.

However, the imposition of lateral forces on masonry structures raises a new problem. Masonry is an excellent material in compression but lacks any significant strength in shear or tension to resist lateral forces.

The first masonry structures were built substantially with very thick walls, small windows, and relatively few stories. The technique of design was a gravity design; build the walls thick enough and they will support the walls and floors above them. It is not uncommon to find today old buildings with masonry walls 30" (0.76 m) thick carrying three to five stories on them.

[I]Structural Engineer, Director of Engineering - Masonry Institute of America
Los Angeles, California, U.S.A.

How did these massive unreinforced masonry buildings perform in an earthquake? A review of the records and pictures of the 1906 San Francisco, California, earthquake indicated that although many of them were damaged, many withstood this tremendous earthquake. In the Santa Barbara, California, earthquake of 1925, unreinforced masonry walls fell away from the buildings if they were not properly tied into the floor system. In the Long Beach, California, earthquake of 1933, unreinforced masonry schools collapsed and major structures in the downtown area were significantly damaged.

Due to the 1933 Long Beach earthquake, the State of California required that all school buildings be properly reinforced against earthquake forces and that they be designed by a titled structural engineer. This event, more than any other, instigated the development of reinforced masonry systems to resist the lateral forces of an earthquake.

Current Seismic Design Requirements (1980)

The current seismic design requirement is that base shear be obtained in accordance with the equation V = ZIKCSW. This approach is the equivalent lateral static force approach on a building. It takes into account each of the factors that are significant and must be considered either in design or the function of the building.

Z is the earthquake zone in which the coefficient reflects the potential frequency of occurrance and the severity of the earthquake that could occur.

I, the importance factor, shows consideration for the use of the building either function or occupancy.

K, the framing coefficient, assigns a value placed upon the rigidity of the building.

C, the structural response coefficient, $C = \div (15\sqrt{T})$, is determined by the period of the building.

a. A rough rule-of-thumb for a frame building for period T would be 0.1 times number of stories.
b. For any building, and conforming to the code requirements, the period of the building would be $T = 0.05\ h_n \div \sqrt{D}$ in which D is the maximum dimension of the building and h_n is the height of the building.
c. The period of the building may be determined by a more rigorous analysis based upon weight distribution and rigidity of the building itself. This period may be determined in accordance with the following equation: $T = 2\pi\sqrt{\left(\sum_{i=1}^{n} w_i\delta_i^2\right) \div \left(g \sum_{i=1}^{n} f_i\delta_i\right)}$

S, a site coefficient to reflect the site structure interaction. The combination of the building response coefficient C and the site structure interaction coefficient S together, CS, need not exceed 0.14.

W is the dead load of the building, which may include some live load if it is the case of a warehouse.

This equation, V = ZIKCSW, is the seismic base shear force which is considered acting on the building. It is a static force rather than a variable, reversible, dynamic force which actually occurs in an earthquake.

For irregular buildings, buildings with special configurations, framing for unusual features, a dynamic analysis may be needed to accurately determine forces that may occur on a building in an earthquake.

Another facet to consider in a seismic design is drift control of the structure. Allowable tolerances on drift are 3/4" (20 mm) per story height. A shear wall building is normally a very stiff building and drift limitations would not generally become a critical matter.

Seismic Forces on a Building

The static seismic base shear is determined by the equation V = ZIKCSW. This force is distributed throughout the height of the building based upon the dimensions of the building and the weight of each floor level.

The forces are distributed on the building in accordance with the following equation: $F_x = (V - F_t)\, w_x h_x \div \sum_{i=1}^{n} w_i h_i$ This is proportioning the static lateral force on the building minus the force at the top to each floor in proportion to the weight of the floor compared to the total weight of the building. This force on each floor is the contribution of the floor. The total force on the floor is the summation of all the forces above that acting on the floor to produce forces within the shear walls of the structure.

Distribution of Lateral Force to Each Resisting Element

The lateral force on a floor level must then be resisted by the diaphragm which distributes it to each of the lateral force resisting elements which are masonry shear walls. The direct shear force to each wall is directly proportional to the rigidity of the wall divided by the sum of the rigidities. $V_{wall} = V_{total} \times R_{wall} \div (\Sigma R_{walls})$. The height of each wall, in order to determine its rigidity, should be considered as a cantilever element from the foundation.

Torsional Forces

At each floor level, the center of mass and the center of rigidity for each floor level must be determined. The lateral earthquake force acts through the center of mass, which creates a torsional moment about the center of rigidity.

It is required to include accidental or actual eccentricity in every structure. This is for rigid diaphragms as they will transmit torsional forces. Flexible diaphragms are assumed not to transmit torsional forces, and load is distributed to the resisting elements in proportion to the tributary area.

The accidental torsional eccentricity is specified as 5% of the maximum dimension of the building. If the calculated eccentricity, the distance from the center of mass to the center of rigidity is less than 5%, an eccentricity of 5% of the maximum dimension must be used. If the calculated eccentricity is more than 5%, the calculated eccentricity must be used.

The force to the floor level times the eccentricity between the center of mass and rigidity, or the minimum eccentricity multiplied together, give the torsional moment that must be imposed on the resisting wall system. The torsional moment is distributed to the walls in accordance to both their rigidity and the distance from the center of rigidity.

Forces due to torsional moment = Tor. Mom. x Rd $\div$ (ΣRd^2), where R is the rigidity of the wall and d is the perpendicular distance from the center of rigidity to the wall. Forces due to torsion can be both parallel to the applied shear force or in opposition to the applied shear force. However, when the torsional force is in opposition to the applied shear force, it is usually ignored and the applied shear force is not decreased.

Wall Design

After the direct lateral force to each wall has been calculated and the contribution of the torsional moment force to each wall determined, the wall must then be designed for these forces. These forces impose two conditions: overturning moment and shear. Overturning moment is the force at the top of the floor level times the height of the floor, or one-half the height of the floor in case that it is considered fixed between floor levels. Shear is the direct force on top of the wall that will impose diagonal tension on the wall element. In each case, reinforcing steel may be used to resist overturning forces or shear forces.

Details of Design

In the design of reinforced masonry load bearing masonry buildings, many details are governed by code minimum standards. The use of reinforcing steel is required for resisting tensile forces due to overturning moments and to resist shear forces when the shear forces exceed the allowable capacity of the masonry. It is also required that a minimum amount of steel be used in a wall to qualify as a reinforced masonry system.

The required minimum steel is 0.0007bt for steel in any direction with a total minimum amount in both directions of 0.002bt. An example of this, for an 8" concrete masonry wall, a #5 bar, 5/8" (16 mm) in diameter, spaced 48" (1.22 m) apart would provide A_s = 0.0013bt.

Although these requirements are minimum, many times it is necessary to exceed minimum values. Regardless of the amount of steel in one direction, the other direction must always have a minimum of 0.0007bt area of steel to accommodate shrinkage and temperature stresses. In addition, the maximum steel spacing for a shear wall system is 48" (1.22 m).

Another arbitrary but sound requirement is for the connections between floors or roof diaphragms; the walls which must be connected with a minimum capability of 200 plf (300 kg/m). This is to insure that minimum connection is made between the wall system and the floor or roof diaphragm system to resist this force. This force may be parallel to or perpendicular to the wall system.

Shear Design of Masonry Walls

Masonry has a capability to resist shear forces and has a limitation of $0.9\sqrt{f'_m}$ psi or a maximum of 34 psi (234 Pa) for values of $M/Vd \geq 1$. For values $M/Vd = 0$, allowable masonry shear is $2.0\sqrt{f'_m}$ psi with a maximum of 50 psi (345 Pa).

When the shear stresses exceed the allowable for masonry, all the shear force must be resisted by horizontal reinforcing steel. The maximum shear stress is $1.5\sqrt{f_m'}$ psi, 75 psi (715 Pa) maximum, for $M/Vd \leq 1$. When $M/Vd = 0$, the maximum shear stress is $2.0\sqrt{f_m'}$ psi, 120 psi (827 Pa) maximum. All allowable shear values may be increased 1/3 when the shear stresses are due to seismic forces.

Overturning Moment Design of Masonry Walls

Seismic forces on top of a masonry shear wall create not only shear forces but also an overturning moment. The overturning moment and vertical load on the wall cause an interaction of stresses which must be considered in design. The interaction relationship is governed by the unity ratio equation of $(f_a/F_a + f_b/F_b) \leq 1.33$, in which $f_a = P/\text{area}$, actual axial compressive stress; $F_a = 0.2\, f_m' (1-(h/40t)^3)$, maximum allowable axial compressive stress; $f_b = M/bd^2 \times 2/jk$, actual flexural compressive stress and $F_b = 0.33\, f_m'$, maximum allowable flexural compressive stress.

Materials of Construction

One of the basic principles of the construction of reinforced masonry systems to resist earthquake forces is that the material shall be of the proper strength. A determination of the strength requirements is made in the evaluation of the stresses in the building. The force level and the stress level will determine what must be the strength requirements for the masonry systems. Many times, the strength of masonry systems need not be any greater than the standard strength of the masonry components. However, many times, particularly for high rise buildings or isolated shear walls which are being subjected to very high stresses, high strength materials must be used.

When high strength materials are required, it is necessary (a) to specify that strength of materials be delivered that will conform and result in walls of adequate strength. It is recommended that the strength of the masonry units and grout be at least 25 to 40% more than the required f_m' value. (b) Tests must be made on wallets or prisms to assure that these materials when combined together, masonry unit, mortar and grout, will produce a wall system of adequate strength in complying with the specifications and needs of the project.

Prisms are constructed and tested with materials to be used in the project and constructed in the manner that will be used in the project. This is an initial determination that the delivered materials are of adequate strength. Field control is required when high strength materials are used so that it can be assured that the materials in the structure are as required and the structure will be strong enough to resist the calculated forces of the earthquake. Prism testing, both for initial establishment of strength and field control, is a vital part of the construction of high rise buildings subjected to seismic motions.

Another requirement is that the minimum compressive strength of mortar be 1800 psi (12.4 MPa) on a two-inch cube. It is specified in the Uniform Building Code as Type M or Type S mortar. This is required so that proper strength and bond are achieved between the masonry units.

Reinforced masonry walls must be grouted with concrete in order to tie the reinforcing steel to the masonry units and have it act as a total structural unit as reinforced masonry. Grouting also increases the cross-sectional area of the wall by filling the cells or between the wythes.

It is necessary that the concrete grout be fluid with a slump of eight to 10 inches so that it will flow through the narrow spaces in the masonry walls, through the cells and through the bond beams that join cells. The masonry units act as an abosrbent form, soaking up the extra water in the grout, which is water of transportation to make it flow. This reduced water/cement ratio increases the strength of the grout to the required level, which must be a minimum of 2000 psi (13.8 MPa).

The combination of the masonry, mortar, reinforcing steel and the grout that ties it together, results in a homogeneous structural system of reinforced masonry. This structural system of reinforced masonry is capable of resisting vertical load, lateral load, overturning forces and shear forces. The allowable stress levels are for working stress design and may be increased 1/3 for the temporary dynamic loads of an earthquake.

For low rise buildings up to three stories high, the f'_m for design is normally up to 1800 psi (12.4 MPa), while for high rise buildings such as 10, 12 or 15 stories high, f'_m may be 3000 to 4000 psi (20.7 to 27.6 MPa).

Performance of Masonry Buildings in Earthquakes

Masonry buildings being one of the oldest wall-enclosure materials that mankind has used, has been subjected to lateral forces due to earthquakes since the earliest of times. The Bible records this in the book of Judges, Chapter 5, Verses 4 and 5; in 2nd Samuel, Chapter 22, Verse 8; in Isaiah, Chapter 13, Verse 13; and many other places.

Unreinforced masonry, which has been built throughout the world up until the last 50 years, has a limited capability to withstand lateral forces. This capability has been demonstrated in the following reported earthquakes.

The literature and the photos of the April 18, 1906, San Francisco, California, earthquake (Richter magnitude 8.3) indicate that more damage was caused by fire and the preventative action to stop fire-spread than by the earthquake itself. The unreinforced masonry did suffer damage in this great earthquake, as did all types of construction.

In the June 29, 1925, Santa Barbara, California, earthquake (Richter magnitude 7.3), unreinforced masonry buildings suffered very badly, as in the case of the Santa Barbara Mission Church. The walls of the church were adobe brick with great weight and low strength and were very badly damaged.

In the Long Beach, California, earthquake of March 10, 1933, (Richter magnitude 7.4) masonry walls that were not tied to the floors did fail and fall out from the buildings.

In the El Centro earthquake of Imperial Valley, California, May 18, 1940, (Richter magnitude 7.2) unreinforced masonry buildings were significantly damaged. This was the earthquake in which a seismograph record was obtained and became the basis for much of the initial dynamic design for seismic-resistant buildings.

In the Tehachapi, California, Kern County earthquake of July 21, 1952, (Richter magnitude 7.2) there was an excellent comparison between reinforced and unreinforced masonry at the Methodist Church, Bakersfield, California. The old unreinforced masonry building collapsed but the new Sanctuary, which was reinforced masonry, performed very well.

In the Prince William Sound, Alaska, earthquake of March 27, 1964, (Richter magnitude 8.6) the reinforced masonry buildings performed very well, as was evident in the Mush Inn, a reinforced concrete block structure.

In the Seattle, Washington, Puget Sound earthquake of April 29, 1965, (Richter magnitude 6.2) there was considerable damage to unreinforced chimneys, parapets and masonry veneer.

The San Fernando Valley, California, earthquake of February 9, 1971, (Richter magnitude 6.5) gave further dramatic demonstration of reinforced vs unreinforced masonry structures. The San Fernando Mission Church suffered damage for its unreinforced adobe brick walls failed similar to the Mission Church in Santa Barbara in the 1925 earthquake. Reinforced masonry buildings performed very well in this earthquake and failures in these structures occurred only when connections or details were ignored.

The 1971 San Fernando earthquake imposed significant seismic forces on the 14-story Pasadena Hilton Hotel but there was no damage to the hotel, which is a reinforced masonry shear wall structure, while serious damage occurred in the 10-story concrete frame building next to it.

In the Camarillo, California, earthquake of February 21, 1973; the Orville, California earthquake of August 2, 1975, (Richter magnitude 5.7); the Santa Barbara, California, earthquake of August 13, 1978, (Richter magnitude 7.0); and the El Centro, California, earthquake of October 15, 1979, (Richter magnitude 7.1), all demonstrated that (1) unreinforced masonry walls would perform reasonably well for forces perpendicular to the wall if they were tied in and supported at the top as well as the bottom; (b) unreinforced masonry parapets for forces perpendicular to the parapet would fail and fall from the building or crack seriously and have to be removed; (c) forces parallel to the unreinforced masonry wall, if they exceeded the capability of the wall, would fail by displacement, usually in a step-pattern along mortar lines. Mortar was usually a lime cement mortar with low bond strength, thus allowing the wall to fail in this fashion. Although the wall failed and displaced laterally, the wall or structure would not collapse; and (d) veneer not tied to the backup wall would peel away from the building.

The reinforced masonry walls performed very well when the seismic forces were perpendicular to the wall. The walls would flex between lateral supprts or flex back and forth if cantilevered such as a parapet. This demonstrated the function of reinforcing in the masonry, holding the walls together and resisting all forces imposed upon the wall.

When the seismic forces were parallel to the wall, the masonry and the reinforcing steel would function together, preventing failure. In many of these structures no cracks would be visible, indicating that the steel and masonry were functioning together to resist lateral forces of the earthquake. If cracks were visible, it would indicate that the shear resistance of the masonry was exceeded and the steel was resisting the shear.

Conclusion

From a review of past earthquakes and the performance of unreinforced and reinforced masonry buildings to these dynamic forces, it is evident that the development of the design methods being used is improving the performance of our buildings. The design of the reinforced masonry building with an adequate amount of reinforcing steel, the details for integrity for tieing the structure together, the concepts of ductility and flexibility are providing safe structures that will perform in an earthquake.

Modern, reinforced masonry buildings have been designed and built in high seismic areas and their performance has proven that principles of reinforced masonry design are sound in resisting the forces of earthquakes.

The future of masonry as a seismic-resistant material is excellent and the development of new parameters in research are providing new opportunities for the engineer to use and exploit an old material.

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