SEISMIC PERFORMANCE OF MASONRY BUILDINGS DURING RECENT EARTHQUAKES IN TURKEY

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ABSTRACT :

Many masonry structures collapsed or were severely damaged during the recent destructive earthquakes occurred in Turkey. Thus, in this study, types of masonry structures commonly used in Turkey are summarized and some information about earthquakes occurred between 1992 and 2004 are illustrated. Damaged masonry structure photos taken after the destructive earthquakes are presented. Seismic code requirements are discussed together with observed damages occurred during the earthquakes. Many structural deficiencies are highlighted by the earthquakes damages including: large opening in load bearing walls, lack of especially vertical confining elements, poor quality mortar, heavy balconies and unconfined gable walls.

KEYWORDS: Masonry buildings, earthquake damage, seismic codes, earthquakes in Turkey.

1. INTRODUCTION

Three types of structural systems; reinforced concrete, unreinforced masonry and hımış (buildings composed of timber frames and braces with some infill materials), have been commonly constructed in Turkey. Modern buildings in the cities are generally built as to be reinforced concrete. Historical masonry buildings were constructed in the old city parts and special areas such as religious areas. The other masonry buildings and hımış buildings have been generally built in relatively poor regions. According to 1998 figures, in urban areas, 30% of all buildings were reinforced concrete frame type, 48% were brick masonry or timber framed, and 22% were adobe or rubble masonry. In rural areas, 82% of the housing stock was masonry of some form, while 18% were timber-frame or reinforced concrete (Erdik & Aydınoğlu, 2003).

Even in countries where experienced in earthquake-engineering, most of the researches are focused on the study of complex structures such as high-rise buildings while little attention is given to masonry buildings. In addition, observed damages on masonry buildings were very few in comparison with the observations on reinforced concrete buildings. These structures have been severely damaged during the destructive earthquakes and have caused a great number of human death and a large amount of economic loss in some countries such as Turkey. Furthermore, historical and monumental structures have been assumed to be cultural inheritance for a community. Many of them were built as masonry structure on seismic zones in some countries like Turkey. To transfer this cultural inheritance to the next generations, it is very important that these buildings will be survived during next earthquakes with only slightly damaged or even undamaged. Therefore, further theoretical studies and damaged observations should be made to put forward the realistic behaviors of masonry structures during the earthquakes. As known, site conditions, properties of structural systems and earthquakes affect the damage level of structures during earthquakes.

2. DAMAGE TO MASONRY BUILDINGS

As known, properties of earthquake, soil and structure affect the damage level of structures during an earthquake. The influence of soil conditions on the degree of building damage is very clear, which is assumed out of this paper scope. Damage assessment results for all buildings (reinforced concrete, masonry, etc.) subjected to the earthquakes in Turkey are given in Table 2. In this table, some information about behaviors of masonry structures during these earthquakes is also given.

Table 2 Turkey earthquakes and damages of buildings

Earthquake	M_w or M_w	Buildings			Behaviour of masonry structures
		Heavily damaged	Medium damaged	Low damaged	
Doğubeyazıt, 2004	5.0	300	200	500	Since the energy release was relatively small, especially poorly constructed rubble (mud-stone) masonry structures were heavily damaged or collapsed. A great majority of the structures with non-load bearing hollow insulation bricks load-bearing walls suffered medium to heavy damage.
Erzurum, 2004	5.1	-	-	-	
Pülümür, 2003	6.0	21	-	-	
Cankırı, 2000	6.1	1500	-	-	
Dinar, 1995	6.1	4909	-	-	
Ceyhan, 1998	6.2	1388	18612	43646	Many stone masonry minarets were damaged, other masonry buildings generally performed well.
Sultandağı , 2002	6.3	4390	1730	9556	Most of the masonry buildings with less than 3 stories have survived the earthquake with minor damage (Erdik et al, 2002)
Erzincan, 1992	6.3	4157	5453	7867	The 8000 unreinforced masonry buildings, generally performed well with the exception of a complex of 40 two-storey buildings constructed with non-load bearing hollow insulation bricks (Sucuoğlu & Erberik, 1997)
Bingöl, 2003	6.4	3214	3448	6096	Throughout the city the unreinforced masonry structures were heavily damaged (KOERI, 2003)
Duzce, 1999	7.1	1364	493	825	Reinforced concrete structures presented high level of damage. Traditional structures relatively performed well (Gülhan & Güney, 2000)
Kocaeli, 1999	7.4	41266	43618	48008	

Especially during the first four earthquakes (Doğubeyazit, Erzurum, Pülümür and Çankırı Earthquakes), as given in Table 2, generally poorly constructed mud-stone masonry structures collapsed or were heavily damaged. Since the energy release was relatively small, none of or only a few of reinforced concrete structures were slightly damaged during these earthquakes. However, mud-stone masonry structures destroyed due to poor mud mortar and weak anchorage between mud and stone. For the other earthquakes, R/C structures were also damaged and they caused loss of more human lives.

Many masonry buildings subjected to destructive earthquakes collapsed and were severely damaged due to some unsuitable designs or some mistakes on projects or applications. Therefore sometimes the idea of unsuitable type of buildings was adduced for masonry buildings. However, sometimes many masonry buildings especially historical ones survived the earthquake with only slightly damaged or even undamaged. In spite of the fact that many new reinforced concrete structures built at the same location have been severely damaged or collapsed. Thus, if masonry buildings are designed to be resistant against earthquake and constructed with good quality materials, they would survive during the earthquakes. Although the structural type of masonry buildings varies in different earthquake zones, their damage resulting from earthquakes can be commonly classified. It is observed that the following main reasons cause damage of masonry buildings during the destructive earthquakes in Turkey.

4.1. Inadequate brick unit

Masonry materials to be used in the construction of load-bearing walls shall be natural stone, solid brick, solid concrete blocks and bricks with vertical holes satisfying the maximum void ratios defined in codes. The minimum compressive strength of masonry structural materials shall not be less than 5 N/mm^2 on the basis gross compression area, and compressive strength of natural stones to be used in basements shall be at least 10 N/mm2 according to TEC (2007). In spite of these requirements, two types of non-bearing masonry that are not allowed for these structures are commonly encountered, hollow clay tiles (multi-cell clay blocks with large rectangular holes or smaller circular holes). The buildings with hollow clay tiles are sometimes called masonry structures whereas they are not classified as masonry structures technically due to exceeded void ratio for brick. Although the usage of them is improper in a bearing wall application, even such a slight variation in shape had repercussions on seismic behavior (Bruneau & Saatçioğlu, 1994). Observed heavy damages and collapses of the buildings in the earthquake regions are generally associated with hollow clay tiles used instead of solid brick units. Fig. 6 shows a collapsed two-storey unreinforced masonry building in which load-bearing walls with hollow clay tiles were cut laterally.

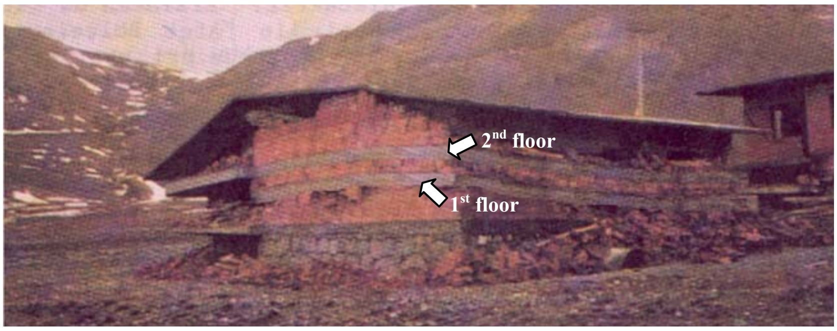

Figure 6 Two-storey building collapsed during Erzincan Earthquake (Bayülke & Doğan, 1993)

4.2. Poor mortar

Mortars to be used in load-bearing walls shall be lime mortar enhanced with cement (cement/lime/sand volumetric ratio=1/2/9) or cement mortar (cement/sand volumetric ratio=1/4) according to TEC (2007). But it is not generally observed that mortar quality was the same one defined in the codes. Poor quality mud or cement mortar caused in the disintegration of masonry units and loss of support to floors as shown in Fig. 7. Especially, mud-stone masonry structures collapsed or were heavily damaged even in small earthquakes due to poor mud mortar and insufficient anchorage between mud and stone. Many people and animals have lost their lives under debris of these structures. So, this structural system should not be constructed in the earthquake zones or some wood structural elements should be inserted in this system adequately to prevent total collapse.

(a) Poor cement mortar in the elementary school building (Emre et al, 2003)

(b) Poor mud mortar

Figure 7 Collapsed and damaged masonry units due to poor mortar during Bingöl Earthquake

4.3. Irregularities in plane and vertical direction

Load-bearing walls of masonry buildings must be arranged in plan, as much as possible, regularly and symmetrically in respect of the two main axes. Fig. 8a shows a collapsed three-storey masonry building subjected to torsion opposite of clockwise.

(a) Damaged during Ceyhan Earthquake (Tezcan & Boduroğlu, 1998)

(b) Damaged during Bingöl Earthquake

Figure 8 Collapsed three-storey masonry building and RC storey resting on stone masonry storey

It may be seen in Turkey that some masonry buildings in which different types of masonry units (stone, solid brick and hollow clay tiles) used for every different storeys exist. In these cases, lateral rigidities of every storey were very different from each other. The worse, it is still possible to see a reinforced concrete storey is resting on a stone masonry ground storey (columns are located only in sides of the building) as shown in Fig. 8b or a masonry storey constructed on the reinforced concrete storey. The different stiffness and weight of these upper storeys increase the risk of failure.

4.4. Weak load-bearing walls

According to TEC, the ratio of the total length of masonry load-bearing walls in each of the orthogonal directions in plan (excluding window and door openings), to gross floor area (excluding cantilever floors) shall not be less than $\boldsymbol{0.25\ I}$ (m/m^2) where $\boldsymbol{I}$ represents Building Importance Factor changing between 1.0 and 1.5. Total length of the load-bearing walls is the main important factor for masonry building damages occurring during the earthquakes. Excessive bending and shear may produce in-plane failures, depending on the aspect ratios of the unreinforced masonry elements. Many masonry buildings had sustained very significant damage to walls, in the form of X (double-diagonal shear) cracking, typical of weak unreinforced masonry walls in shear as shown in Fig. 9. However, this cracking seldom reaches total collapse. But the triangular sections of the X crack can become unstable leading to collapse when a full X crack occurs during an earthquake (Decanini et al, 2004). This cracking was not only apparent to masonry buildings but also the most commonly observed damage in reinforced concrete structures was in the form of cracking and collapsing of infill walls.

Figure 9 Typical X cracks occurred in the load-bearing inner walls during Bingöl Earthquake

4.5. Lack of vertical confining elements

Vertical confining elements (see Fig.2) should be located at the end of the load-bearing walls, at the both sides of the doors and windows opening. Fig. 10 shows two damaged masonry buildings due to the lack of vertical confining elements. Side of load-bearing wall next to joint space failed as shown in Fig. 10a and the door opening was extremely narrowed around the middle of the door height as shown in Fig. 10b due to the lack of vertical confining elements.

(a) Damage during Kocaeli Earthquake

(b) Damage during Bingöl Earthquake

Figure 10 Damaged masonry buildings due to lack of vertical confining elements.

4.6. Weak out-of-plane response

Unreinforced masonry buildings are the most vulnerable to flexural out-of-plane failure. If the connection between the walls and floors is not adequately restrained, the whole wall panel or of a significant portion of it will overturn due to seismic excitation in the perpendicular direction to the wall plane. Fig. 11 shows a view of out-of-plane collapse of load bearing walls. Added vertical R/C confining elements contribute to earthquake resistance of the wall; in this manner, out-of-plane failure does not easily occur.

Figure 11 A view of load bearing walls collapsed in the out-of-plane direction during Bingöl Earthquake

Parapet and gable wall failures fall into this category. If unrestrained these non-structural unreinforced masonry elements behaves as a cantilever wall extending beyond the roof line (Bruneau, 1994). Gable walls located at the top of the buildings are subjected to the greatest amplification of the ground motions, and are consequently prone to flexural failures under the roofs. The falling of gable walls of lodgings for security personals as shown in Fig. 12a caused broking about 20 cars and the falling of gable wall as shown in Fig. 12b caused death of a child during Bingöl Earthquake. Authors also observed many building damages and vulnerability of people and cars due to falling of gable walls during Erzincan, Kocaeli and Düzce Earthquakes. It is stated in the masonry buildings section of TEC that in the case where the height of the end wall resting on the horizontal bond beam at the top storey exceeds 2m, vertical and inclined bond beams shall be constructed. But almost all the buildings which have large gable walls in the earthquake region did not satisfy this requirement.

(a) Falling of gable walls caused broking about 20 cars

(b) Falling of gable wall caused death of a child

Figure 12 Typical out-of-plane failure of unanchored gable walls during the Bingöl earthquake

4.7. Unconfined wall corners

Another failure can be the formation of vertical cracks at the corners of an unconfined masonry building in which the wall begins to form a hinge from the swaying. Failures and cracks at the corners occurred because of the insufficient connections between the walls and floors (Fig. 13). As seen in Fig. 13a, the failure occurred in the bearing wall between the window and the corner. If there were vertical confining elements at the corners, these elements would have contributed to the earthquake resistance of the wall. Fig. 13b shows separation of adjacent walls due to connection of stresses at the building corners and poor connection between walls. Likewise, for all types of masonry buildings, this has been playing a vital role in the damage. According to TEC, plan length of the load-bearing wall segment between the corner of a building and the nearest window or door opening to the corner shall not be less than 1.5 m in the first and second seismic zones (maximum ground accelerations are assumed in these zones as 0.4g and 0.3g, respectively). Again, vertical confining elements are recommended for confined masonry buildings to prevent this type of failure occurred around the corner.

(a) Damaged during Bingöl Earthquake

(b) Damaged during Sultandağı Earthquake (Ulusay et al, 2002)

Figure 13 Collapse of a corner and vertical cracks near the corner for masonry buildings

4.8. Weak first storey

The first storey collapse is the common type of mechanism for the reinforced concrete structures known as *soft storey* and *weak storey* behaviours (Durmuş et al, 1999; Doğangün, 2004). The first storey collapse is also occurred in the masonry structures as a consequence of limited ductility capacity and poor strength of masonry unit materials. Fig. 14 shows a first storey collapse of a building with hollow clay tiles.

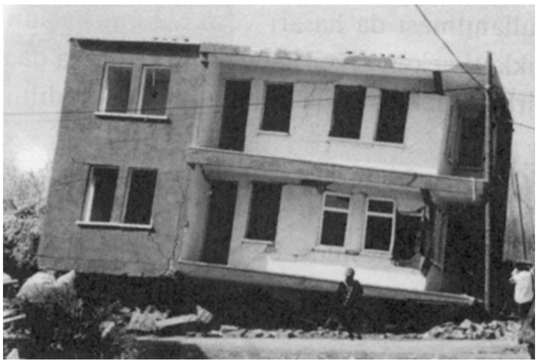

Figure 14 A collapsed building with hollow clay tiles during Sultandağı Earthquake (Ulusay et al, 2002)

4.9. Inadequate cantilever elements

According to the TEC, the free cantilever length should not be more than 1.5 meters. This requirement is not enough to describe inadequate cantilever elements for masonry buildings. If vertical component of the ground acceleration is large and cantilever is a heavy one, the mass of cantilever can be a very important parameter for seismic behaviour. As seen from Fig.15, the balcony is weakly supported due to window openings in the bearing wall and lack of R/C vertical and horizontal elements. In addition, corner walls constructed inadequately at the upper storey collapsed and applied to a force to the end point of the balcony span. As a result, heavily damage was occurred on this part of the masonry building. The upper storey balcony did not collapse due to smaller dead loads, continuous horizontal bond beams and absence of walls fallen on it during the earthquake. If this unreinforced masonry structures were confined, this damage would almost prevented.

Figure 15 A failure occurred around the balcony of a masonry building during Bingöl Earthquake

5. CONCLUSIONS

Hollow clay tiles used as brick units have been observed to be the major cause of partial or total collapse of building. Therefore, the use of the hollow clay tiles in the masonry walls is restricted with depending on the void ratio. Thousands of these buildings exist in the earthquake regions. As removing of these buildings is not an economic solution, effective seismic strengthening method must be developed and performed for these buildings. Mud-stone masonry structures collapsed or were heavily damaged due to poor mud mortar and insufficient anchorage between mud and stone even during small earthquakes. At least, some wood structural elements should be inserted adequately in this system to prevent total collapse. The performance of the unreinforced masonry buildings was not generally so good in such earthquakes. Many of collapses and damages are attributed to following items in order of importance: Inadequate masonry units, poor mortar, lack of vertical confining elements, irregularities in plane and in vertical direction, inadequate connection of load-bearing walls, insufficient length of load-bearing walls, unconfined gable walls and heavy cantilever elements. Only limited confined masonry buildings were observed. Despite these confined masonry buildings did not satisfy requirements given in Turkish Earthquake Code, they behaved better than the unreinforced masonry buildings. Especially the Kocaeli earthquake points out the fact that reinforced concrete frame system should not be seen as the only alternative for contemporary construction systems. If the masonry buildings can be designed to be earthquake resistant and constructed in order to survive.

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