ITU A|Z
VOL: 8 NO: 1, 219-228, 2011-1

Damages and failures observed in infill walls of reinforced concrete frame after 1999 Kocaeli earthquake

Serkan YATAĞAN
Istanbul Technical University, Faculty of Architecture, Istanbul, TURKEY

Received: January 2011 Final Acceptance: March 2011

Abstract:
The infilled walls are used to provide enclosure, sub-division of space and weather protection in reinforced concrete frames. In addition, the infill walls are subjected to the horizontal loads while restraining the movement of the frame systems. If the infill walls do not resist the horizontal loads, the wall is damaged and some cracks occur. Especially, faulty design and unsymmetrical arrangement of the infill walls cause the damages and failures in the infill walls. The earthquake damages of some buildings reveal the fact that the infill walls do strengthen the building. In this work, damages occurred in the infill walls during 1999 Kocaeli Earthquake are defined and some evaluations are made for the causes of the damages observed in infill walls. The paper also suggests the means of improving the load carrying capacity of infill walls.

Keywords: *Brick, damage, frame systems, horizontal loads.*

1. Introduction

On August 17, 1999, an earthquake measuring 7.4 on the Richter scale occurred along the North Anatolian Fault. The earthquake caused more than 20,000 deaths, 50,000 injury and over $30 billion of damage to properties. The duration of the earthquake was 45 seconds. The cause of the earthquake was the sudden breakage, or rupture, of the Earth's crust along a western branch of the 1,500-km-long North Anatolian fault system. The total length of the fault rupture was about 110 km. The region hit by the earthquake is the industrial heartland and the most densely populated area of Turkey. Figure 1 demonstrates the concentration of damage in regions along the fault line, particularly in Izmit, Adapazari, Sapanca, Golcuk, and Yalova. Although Avcilar, a western suburb of Istanbul, is at a considerable distance from the fault, it also experienced the damage due to the presence of soft soil conditions. A total of 140 000 structures collapsed, which represent 7.7% of the building stock in the epicenter, while 28.6% of buildings suffered light to moderate damage. 5% damped linear response spectra for fault normal components of Kocaeli region records are obtained during Kocaeli Earthquake.

Most of the deaths and injuries in the Kocaeli earthquake were due to severe ground shaking which caused the collapse of residential housing units, typically in 3-to-6-story reinforced concrete buildings with masonry infill walls.

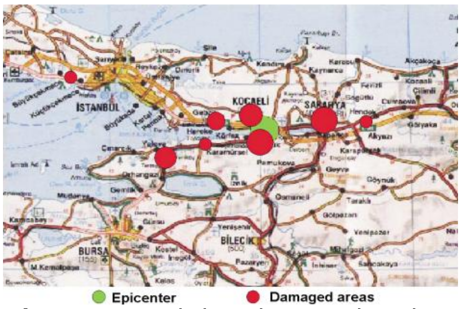

Figure 1. *Fault locations and regions of structural damage*

In this paper, damages occurred in the infill walls during 1999 Kocaeli Earthquake and their causes are defined with some examples and some evaluations are made for the causes of the damages observed in infill wall. The paper also suggests the method of improving the load carrying capacity of infill walls.

2. Damages and failures in infill walls of the reinforced concrete frame in 1999 Kocaeli earthquake

In Kocaeli earthquake the most of the building collapses occurred in towns located on the southern shorelines of the Sea of Marmara and in Adapazari. A western suburb of Istanbul, Avcilar, also suffered significant building damage despite its distance of about 100 km from source zone.

Two codes influence the design and construction of reinforced concrete buildings in Turkey: the “earthquake code” (*Specification for Structures to be Built in Disaster Areas*) and the ‘building code’ (TS-500, *Building Code Requirements for Reinforced Concrete*). The earthquake code includes procedures for calculating earthquake loads on buildings. The building code presents requirements for the design and detailing of reinforced concrete components but does not include ductile detailing requirements for use in seismic design. Such requirements are found in the earthquake code.

Many reinforced concrete buildings in Turkey that damaged during the earthquake were designed according to the 1975 edition of the *Specifications for Structures to be Built in Disaster Areas*, which had been issued by the Ministry of Reconstruction and Resettlement of the Government of Turkey (Ministry of Public Works 1975).In this code, emphasis is placed on reinforced concrete frame buildings with infill walls, since this type of structural system dominated the building inventory in the earthquake-stricken areas.

Hollow clay brick and gas-concrete masonry infill walls are widely used in the epicenter region and these walls are not reinforced and non-ductile. The walls abut the frame columns but are not tied to the frame. The high in-plane stiffness of the masonry infill that is developed by diagonal strut action can dictate the response of the more flexible moment-resisting frame. Many of the buildings were constructed with hollow clay tile infill walls in the frames perpendicular to the sidewalk. Frames parallel to the sidewalk were often filled with hollow clay tile only above the first storey to allow for commercial space on the ground level. Such an arrangement of tile infill walls created stiffness discontinuities in these buildings, which may have contributed to their collapse by concentrating the drift demands in the first storey. Damage to masonry infill walls was concentrated in the lower stories of buildings because of higher story shear demands on the strength of the moment frame-infill wall system [Sezen 2002 *et al*.]. In Figure 2, the complete and partial damage to hollow clay tile walls in four and thirteen-storey buildings, respectively are seen. The four-story building was under construction at the time of the earthquake; the thirteen-story building was constructed in the early 1970s.

Figure 2. *Varying degrees of damage to infill walls*

Residential buildings in the epicenter region typically range in height from two to seven storeys. Fig. 3a shows a photograph of a three-storey moment resisting frame building that was under construction at the time of the earthquake. A plan of the second floor is shown in Fig. 3b. The column orientations and locations are such that all of the moment-resisting frames include one or more columns with their weak axis perpendicular to the frame direction. These observations, which were typical of most buildings in the epicenter region, would suggest that the framing system is much stiffer and stronger in the direction perpendicular to the street assuming that similar rebar are used in all beams and all columns. Such framing likely possesses limited strength and stiffness, which if coupled with non-ductile reinforcement details, results in a vulnerable building in the event of earthquake shaking.

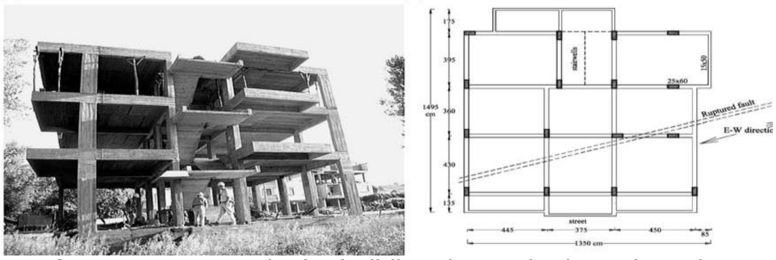

Figure 3. *Damage in the building due to the irregular axles*

Damage to infill masonry walls was concentrated in the lower stories of buildings because of higher demands on the strength of the moment-frame-infill wall system. In Figure 4, the distribution of damage to infill walls in two buildings, one near Golcuk, and one in Degirmendere are illustrated. In these buildings, the lateral stiffness of the infill walls is likely of the same order or greater than that of the moment-frames. For these buildings not to collapse following the failure of the infill walls the moment-frames must have possessed significant strength and some limited ductility.

The predominant structural system used in Turkey consists of reinforced concrete frames with masonry infill walls. Concrete, which is locally available, is generally preferred over other construction materials for economic reasons. Most of concrete is cast-in-situ construction with an increasingly percentage being ready-mix concrete. Precast concrete construction is popular for industrial buildings. Concrete shear walls have gained greater popularity only in recent years [Saatcioglu 2001 *et al*.].

Most of collapses during the earthquake were attributed to the poor performance of reinforced concrete frames and masonry infill walls. Buildings with 4–6 storey suffered the heaviest damage, inflicting most of the casualties. Structures close to the region of faulting were subjected to very high accelerations and velocities, resulting in very high seismic demands. Inspection of collapsed and damaged buildings revealed that very little or no seismic design had been carried out during the design and construction of reinforced concrete frame systems. It has been generally acknowledged that there has been very poor regulatory control over both structural design and construction. It was clear that the structural layouts were susceptible to very high drift demands due to lack of proper lateral load resisting systems and extensive presence of soft storey.

a) b)

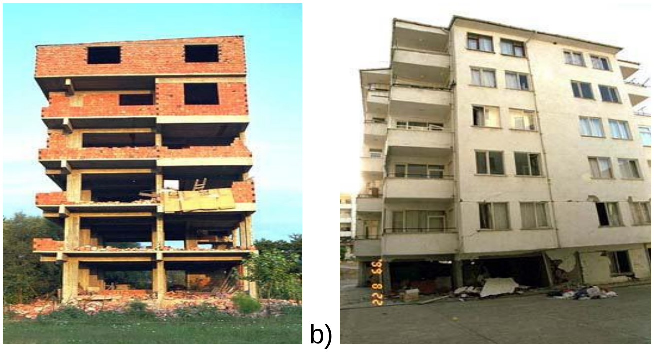

Figure 4. *Damage to infill masonry walls in Golcuk (a) and in Degirmendere (b)*

The high seismic demands became increasingly critical due to the amplification of ground motion by soft soil. The only mechanism of defense for such structures with inadequate lateral load resisting systems is the ability of the structural members to undergo inelastic deformations without experiencing brittle failures. Unfortunately, all the frame buildings inspected lacked appropriate seismic design and detailing practices, which could have provided the required ductility and energy absorption. Proper design practices were missing in spite of the seismic design requirements of the 1975 Turkish code (Saatcioglu, 2001 *et al*.).

Reinforced concrete moment-resisting frame buildings behaved poorly during the Kocaeli earthquake. According to official estimates, more than 20,000 moment frame buildings collapsed, and many more suffered moderate to severe damage. Many of the collapses are attributed to the formation of soft first storeys that formed as a result of differences in framing and infill wall geometry between the first and upper stories, the use of non-ductile details, and poor quality construction in some cases.

Figure 5 shows two six-storey non-ductile moment-frame buildings in Golcuk. One of the buildings collapsed completely, whereas the adjacent building exhibited shear cracks in the first storey. Both buildings were likely subjected to similar levels of earthquake shaking, yet one building performed well, while the other collapsed. This raises many questions regarding the limit state for non-ductile moment frames. Small differences in the strength of these non-ductile buildings possibly caused by the variation in material strength, construction practice, and workmanship could account for the drastic difference in performance.

Figure 5. *Damages in two six-storey non-ductile moment-frame buildings in Golcuk*

Lateral bracing for reinforced concrete frame structures was provided by brick and (or) concrete masonry walls. The brick masonry was often in the form of the hollow architectural blocks. During the earthquake, these walls were able to participate in lateral load resistance to varying degrees and were often damaged prematurely, developing diagonal tension and compression failures or out-of-plane failures. The degree of lateral load resistance depended on the amount of masonry used and the framing system provided. In contrast to modern moment resisting frames of North American practice, the use of light partitions, such as dry walls, was not common in the earthquake-stricken areas. Instead, masonry was used extensively for interior partitioning, as well as exterior enclosure of buildings, increasing wall-to-floor area ratios. Therefore, in spite of lower strength and expected brittleness of this type of masonry walls, the frames did benefit somewhat from such extensive use of masonry until the threshold of elastic behavior was exceeded. Beyond the failure of brittle masonry, there was no lateral load resisting system with sufficient stiffness to control lateral drift, thereby resulting in high drift demands on the frame members. Figures 6 and 7 reveals different degrees of masonry failure, resulting in partial damage, severe damage, and collapse of the frame structure [Saatcioglu, 2001 *et al*.].

a)  b) 

Figure 6. *Showing (a) extensive damage in masonry infilled walls with no apparent distress in concrete frames (b) complete collapse of masonry infilled walls with some distress in first storey columns*

During the seismic response, the failure of brittle masonry walls placed a heavy demand on the first-storey columns of multi-storey buildings. The columns sustained heavy damage mostly because of lack of sufficient transverse reinforcement. The transverse reinforcement consisted of 8 mm diameter smooth reinforcement, generally placed at 300 mm or wider spacing. The infill walls suffered brittle failures and increased the base shear level, demonstrating that non-ductile frames with brittle infill walls are poor lateral load resisting systems for earthquakes [Saatcioglu, 2001 *et al*.].

a)  b) 

Figure 7. *Showing (a) very limited damage to infill, (b) complete structural collapse including the infill.*

In Figure 8, the views of a collapsed apartment building in Golcuk are seen. The first two storey of this building failed completely, but damage in the upper four storey with unbroken glass windows was limited. The long infill walls in the upper four storey have significant elastic strength and stiffness probably much greater stiffness and strength than the moment-resisting frame. The brittle fracture of the first and second storey infill walls prior to flexural yielding of the columns would have overloaded the brittle first and second storey columns in shear, likely resulting in the observed gravity load failure [Sezen 2002 *et al*.].

a)  b) 

Figure 8. *Views from a collapsed apartment building in Golcuk: (a) view of front facade of building; (b) view of infill wall perpendicular to sidewalk*

The first two storey of the building in Figure 9 collapsed. The masonry infill walls and moment-frame construction in the third and fourth storey (first and second storey in the photograph of the collapsed building) suffered major damage. Damage in this building reduced with increased height above the ground. Failure of the masonry infill in the first and second storey of the building likely precipitated the collapse of the building.

Figure 9. *Failure of two stories of a reinforced concrete frame building with infill walls.*

Buildings constructed using shear walls as the primary lateral load-resisting system performed quite well in the 1999 Kocaeli earthquake. Some buildings with a dual wall-frame lateral load-resisting system were damaged because the shear walls were not sufficiently stiff to keep the displacements of the non-ductile framing system in the elastic range. The most significant damage observed by the team in a dual wall-frame building is shown in Figure 10. The wall and first-storey exterior columns shown failed and shortened. No cracks were observed in the shear wall, but the right end settled approximately 500 mm due to bearing failure of the supporting soils. Although the shear wall was likely sufficiently stiff to protect the non-ductile frame, the rotation at the base of the shear wall and the settlement of the footings beneath the moment-frame columns contributed to the failure of the first-story columns.

Figure 10*. Damage observed in a dual wall-frame building*

Blade columns or narrow shear walls were often constructed near stairwells (Fig. 11). These walls or blade columns were detailed similarly to regular moment frame columns with light transverse reinforcement with 90-degree hooks and no cross ties.

Figure 11. *Damages in blade columns or narrow shear walls near stairwells*

Irregular placement of masonry infill walls can produce discontinuities of stiffness in moment- frame buildings. Consider the building in Figure 12 in which the moment frame is both flexible and weak in the first storey by comparison with the upper storey. In the first storey of this building, masonry infill walls are present in the back face of the building and in the two faces perpendicular to the sidewalk. The front of the building was open in the first storey. The lateral stiffness of the building was considerably larger in the direction perpendicular to the sidewalk compared with parallel to the sidewalk. Deformations are concentrated in the first storey of this building parallel to the sidewalk, due to the weakness and flexibility of the moment frame because of lack of masonry infill walls in the front of the building. The first-storey columns in this building were severely damaged and likely close to failure due to gravity load instability [Sezen, 2002 *et al*.].

3. Evaluation

- The reinforced concrete frames with infilled walls is the structural system that still attracts many research efforts. The experience gained from the 1999 Kocaeli earthquake in Turkey shows that the structures suffered either due to the irregular distribution of infill walls or ignoring the structural interaction between the frame and infilled walls.

Figure 12. Soft first stories caused many residential and commercial buildings to collapse

- The weakness of structural components may cause the collapse of the entire buildings. In addition to providing architectural functions, infill walls do resist lateral forces with substantial structural action, and should, therefore, be assumed to be part of the primary lateral-force-resisting system and may have significant influence on the overall earthquake response of the building.

- The earthquake damages of some building reveal the (support) contribution of the infill walls to the strength of the building. Test results have shown that the reinforced concrete frame with the infilled walls has higher strength than the reinforced concrete frame without the infilled walls [Vintzeleou,1989]. Although, the infilled walls have an important effect in resisting the earthquake loads, infilled walls are not given due importance in construction. Due to the poor quality control in construction of the infilled walls, buildings collapse during the earthquake although they are built according to the seismic design requirements. The use of poor quality materials, poor workmanship and faulty designs decrease the resisting capacity of the infilled walls to the lateral loads.

- Therefore, it is recommended that the infilled walls in concrete frames must be built with good quality bricks and mortar because these walls increase the horizontal load bearing capacity of the buildings. Moreover, the infilled walls must be designed and constructed according to the building codes with adequate site supervision. It is also recommended that the interface between the infilled wall and the reinforced concrete frame should be investigated further and the behavior of the infilled walls during the earthquake should be monitored.

- When the load-bearing capacity of the infilled walls is increased, supporting the compression of the rectangular cross section of the infilled walls depends on the effective width and the thickness of the wall. The effective width is 5,4 times as the thickness of the wall (Makino,1980 *et al.*).

- The settlement of the infilled walls into the frame and the joint between walls and frame affects the construction and the elasticity of the building. The infilled walls are defined as the wind wall at the joint between the walls and the column and the beam and also, the strength and the elasticity of the infilled walls should be developed. The main aim of all the reinforcement methods is the supplying the required strength, creep and the rigidity of the building. The relative strains of the mezzanine which has the lowest rigidity forms the big deflections. For these types of the buildings, the suitable places of the frame are filled with the concrete infilled walls (Cicek, 2006).

- Until the reliable standard for the design of the infilled walls of the frame system is formed, the building should be analysed with the effect of the infilled walls on the strength of the frame and without the effect of the infilled walls. The most inconvenient cross sections of the two analysis are defined and the suitable dimensions of the building elements and the steel reinforcement should be selected. (Tekin, 2007 *et al*).

- During the project process, the negative effects of the infilled walls should be determined and these negative effects must be prevented during the design of the load bearing system. In order to see the effect of the infilled walls on the building, the infilled walls of the building should be analyzed. Therefore, the eccentricity of the building and the change in the rigidity of the floors should be controlled. Also, the change in the frequency of the building is determined. Therefore, it is possible to guess the changes in the earthquake loads.

- In order not to form the short column behavior, the infilled walls are masonned away from the joint between the column and the beam.

- The most important factor affecting the infilled walls is the material of the walls. In this view, when the infilled walls are constructed, instead of using materials demolishing under loads, high durable and strong, light and homogeneous materials must be used. Moreover, the increasing of the weight of the building should be decreased and the demolishing of the infilled walls are prevented.

- There are some rules and limitations in the regulations for the dimensions of the building elements according to the earthquake loads. These rules and limitations should be practiced for the infilled walls, too.

- The negative effects of the infilled walls on the building were seen while observing the damages of the 1999 Kocaeli earthquake. It is necessary to determine these negative effects of the infilled walls. When the negative effects of the infilled walls are removed, the positive effects of the infilled walls are emerged because the infilled walls increase the strength, rigidity and the capacity of the energy absorption (Budak, 2011).

References

Budak, A., **Dolgu Duvarların Yönetmeliklerimizde Yeri**, TMMOB Chamber of Civil Engineers - Electronic Library, Ankara, pp.337-350, http://www.e-kutuphane.imo.org.tr/pdf/12928.pdf (ET: 25/04/2011)

Cicek, R.O.,(2006). **Betonarme Çerçevelerin Betonarme Dolgu Duvarları ile Güçlendirilmesi**, Master's thesis, Harran University, Institute of Science and Technology, Şanlıurfa.

Makino, M., Kawano, A., Kurobane, Y., Saisho, M. and Yoshinaga,K.,(1980). "*An investigation for the design of framed structures with infill walls"*, The Proceedings of World Conference on Earthquake Engineering, Indian Institute of Technology Kanpur, No.7, vol: 4, pp.369-372.

Saatcioglu, M., Mitchell, D.,Tinawi, R.,Gardner, N.J.,Gillies, A.G.,Ghobarah, A.,Anderson, D.L. & Lau D.,(2001). The August 17, 1999, Kocaeli (Turkey) earthquake-damage to structures, **Canada Journal of Civil Engineering***,* vol.28, pp.715-737.
Sezen, H.,Whittaker, A.S.,Elwood, K.J. & Mosalam, K.M., (2003). Performance of reinforced concrete buildings during the August 17, 1999 Kocaeli, Turkey earthquake, and seismic design and construction practise in Turkey, **Engineering Structures**, vol.25/1, pp.103-114.
Tekin, M., Alsancak, E. and Ay, M., (2007). Betonarme Çerçevelerde Dolgu Duvar Etkisinin İncelenmesi, **Celal Bayar Üniversitesi, Fen Bilimleri Dergisi**, No:3.1, pp.95-104, Manisa.
Vintzeleou, E., (1989). Infilling of Reinforced Concrete Frames as a Strengthening Intervention, *Seminar on the Assesment and Redesign of Reinforced Concrete Structures*, 12-13 April, 1989, İzmir, Türkiye.

1999 Kocaeli depreminden sonra betonarme çerçevelerde dolgu duvarlarda gözlenen hasarlar ve bozulmalar

Dolgu duvarlar, çerçeve oluşturmak, bölücü mekanlar yaratmak ve iklimsel koşullardan korumak amacıyla yapılmaktadır. Buna ek olarak, dolgu duvarlar çerçeve sistemlerinin hareketlerini kısıtlarken yatay yüklere karşı koyarlar. Eğer, dolgu duvarlar yatay yüklere karşı koyamazlarsa, duvar zarar görür ve çatlaklar oluşur. Özellikle, dolgu duvarların hatalı tasarımı ve simetrik olmayan yerleştirilmeleri, duvarlarda hasarlara yol açmaktadırlar. Bazı binalardaki deprem hasarları, dolgu duvarların yapıyı güçlendirdiğini göstermiştir. Bu çalışmada, 1999 Kocaeli depreminde dolgu duvarlarda oluşan hasarlar belirlenmiş ve dolgu duvarlarda gözlenen bu hasarların nedenleri hakkında bir değerlendirme yapılmıştır. Ayrıca, dolgu duvarların yük taşıma kapasitesini geliştirme durumu hakkında da tavsiyeler verilmiştir.