Performance of School Buildings in Turkey during the 1999 Düzce and the 2003 Bingöl Earthquakes

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Several school buildings were surveyed in the disaster areas of the Marmara (1999, Mw=7.4), Düzce (1999, Mw=7.2) and Bingöl (2003, Mw=6.4) earthquakes in Turkey. Among them, 21 reinforced concrete buildings were found to have an identical floor plan. Lateral load resisting structural system consisted of reinforced concrete frames (moment-resisting frame) in 16 of the buildings and structural concrete walls integrated with the moment-resisting frame (dual system) in the remaining five buildings. The number of stories above ground in these buildings ranged from 2 to 4. These school buildings provide a nearly ideal test of the effect of a single important structural characteristic on the performance of buildings with structural designs that are uniform in all other respects. Our observation is that the presence of structural walls improves the behavior of reinforced concrete systems drastically.

INTRODUCTION

Teams of researchers from various U.S. institutions and organizations led by Purdue University and in collaboration with researchers from the Middle East Technical University (Turkey) made three surveys of damage to concrete structures in the cities of Düzce, Kaynaşlı and Bolu following the 1999 Marmara (Mw=7.4) and Düzce (Mw=7.2) earthquakes and in Bingöl and its vicinity after the 2003 earthquake (Mw=6.4) in Turkey (Fig. 1). The 1999 earthquakes devastated northwestern Turkey. The 2003 event caused damage in the eastern province of Bingöl (Özcebe et al. 2003). Full reports of these surveys, including

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geological, geotechnical and structural observations in detail, are available at www.anatolianquake.org.

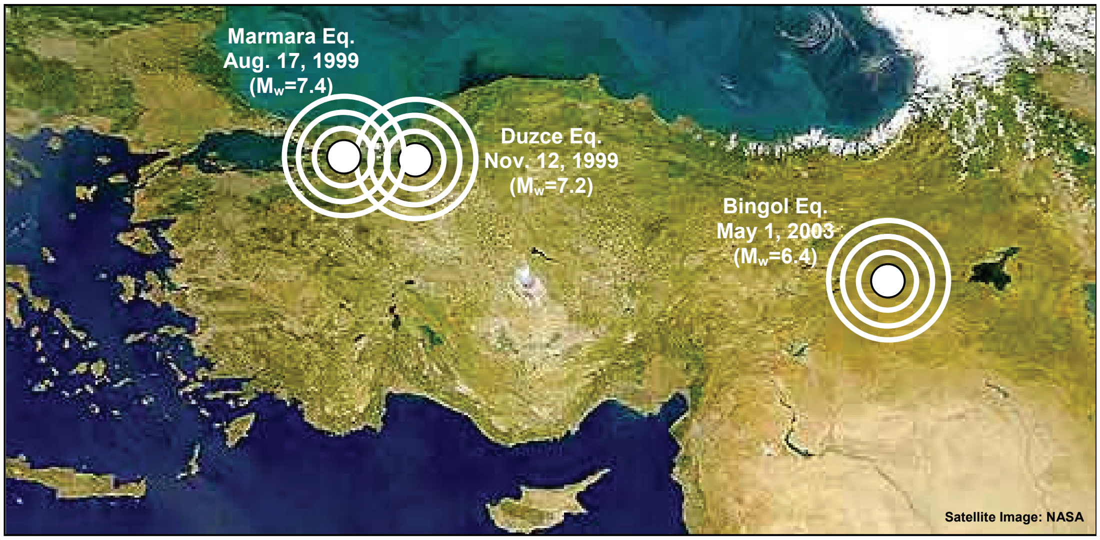

Figure 1. Locations of damaging earthquakes in Turkey in 1999 and 2003.

The combined building inventory includes 35 school and dormitory buildings. This paper focuses on the findings of the survey of 21 of these buildings with identical floor plan (Table 1) developed by the Ministry of Education of Turkey. These school buildings provide a nearly ideal test of the effect of a single important structural characteristic on the performance of buildings with structural designs that are uniform in all other respects. The structural system of the schools consisted of reinforced concrete frames (moment-resisting frame), except in five of the schools which had structural concrete walls integrated with the moment-resisting frame (dual system). The column layout in all of the schools was identical. The schools with dual systems are located in Düzce, Kaynaşlı and Bolu. All the 16 schools with moment-resisting frames were in Bingöl. School buildings with dual systems in Bingöl were excluded in the comparative study because they had different floor plans.

The paper describes the state of the buildings after the earthquakes. The experience points to a simple and obvious solution to avoid severe damage to such buildings.

DAMAGE RATING

A damage rating system was used in the surveys in order to be able to compare performances of the buildings. The aim of the rating is to group buildings with similar damage patterns rather than to define the actual damage state in absolute terms. The damage ratings (Table 1) are based on the condition of the ground story of the buildings. With the exception of building D02, the ground story sustained the major damage, if any. The damage to the reinforced concrete structures was rated using a three-level system.

Table 1. List of the surveyed schools and their damage states after the earthquakes.

	School Name	**Location**	**Building No.**	**Structural System**	**Damage to RC System**	**Damage to Masonry**	**No. of Stories**
Düzce Earthquake	Dariyeri Hasanbeyi Ilkogretim Okulu	Kaynaşlı	K01	Dual System	None	None	2
	Andolu Ticaret Lisesi	Bolu	B01	Dual System	None	None	3
	Yunus Emre Ilkogretim Okulu	Düzce	D01	Dual System	None	None	2
	Necmi Hosver Ilkogretim Okulu	Düzce	D02	Dual System	Severe *(Basement)*	Moderate *(Basement)*	4
	Azmi Milli Ilkogretim Okulu	Düzce	D03	Dual System	Light	Moderate	4
Bingol Earthquake	75. Yil Ilkogretim Okulu	Bingöl	C13-01	Moment-resisting frame	Severe	Severe	3
	Sehit Mustafa Gundogdu Ilkogretim Okulu	Bingöl	C13-05	Moment-resisting frame	Moderate	Light	2
	Kazim Karabekir Ilkogretim Okulu	Bingöl	C13-06	Moment-resisting frame	Moderate	Light	2
	Vali Kurtulus Sismanturk Ilkogretim Okulu	Bingöl	C13-07	Moment-resisting frame	Light	Moderate	2
	Kaleonu Ilkogretim Okulu	Bingöl	C13-08	Moment-resisting frame	Collapsed	Collapsed	3
	Saricicek Koyu Ilkogretim Okulu	Saricicek	C13-09	Moment-resisting frame	Collapsed	Collapsed	3
	Celtiksuyu Ilkogretim Okulu	Celtiksuyu	C13-10	Moment-resisting frame	Collapsed	Collapsed	3
	Karaelmas Ilkogretim Okulu	Bingöl	C14-01	Moment-resisting frame	Severe	Severe	3
	Mehmet Akif Ersoy Ilkogretim Okulu	Bingöl	C14-03	Moment-resisting frame	Severe	Severe	3
	Ataturk Lisesi	Bingöl	C14-04	Moment-resisting frame	Moderate	Moderate	3
	Vali Guner Orbay Ilkogretim Okulu (Main Building)	Bingöl	C14-05	Moment-resisting frame	Moderate	Moderate	3
	Vali Guner Orbay Ilkogretim Okulu (2nd Building)	Bingöl	C14-06	Moment-resisting frame	Moderate	Moderate	2
	Ataturk Ilkogretim Okulu	Bingöl	C14-07	Moment-resisting frame	Severe	Moderate	3
	Sarayici Ilkogretim Okulu	Bingöl	C15-01	Moment-resisting frame	Severe	Severe	4
	Murat Ilkogretim Okulu	Bingöl	C15-02	Moment-resisting frame	Severe	Severe	3
	Ekinyolu Koyu Ilkogretim Okulu	Ekinyolu	D16-01	Moment-resisting frame	Severe	Severe	3

Serious damage: Structures containing columns with inclined cracks (Fig. 2). We note that inclined cracking in columns represents serious damage if the amount of transverse reinforcement is light. Observations in the field as well as information obtained from typical structural plans indicated that 8-mm diameter bars with yield strength of 220 MPa were used commonly for transverse reinforcement. The center to center tie spacing in the columns was typically 20 to 25 cm. In the column end regions of some school buildings, the tie spacing was observed to be 10 to 12 cm. The transverse reinforcement ratio in the columns ranged from 0.001 to 0.002 in the schools. The transverse reinforcement ratio is defined as the ratio of the tie reinforcement area divided by the product of the center to center spacing of tie reinforcement measured along the column longitudinal axis and the column dimension perpendicular to the direction of the applied shear.

Figure 2. Examples of severe column damage.

Moderate damage: Structures with shear and flexure cracks on beams, spalling of concrete on columns and hairline cracks in concrete structural walls (if any).

Light damage: Damage limited to hairline flexural cracks in the beams.

The damage to masonry infill walls, composed of hollow clay bricks, in the buildings was also rated using a three level system:

Severe damage: continuous cracking at boundaries, loss or crushing of masonry units (Fig.3).

Moderate damage: fine cracks in walls and at boundaries with flaking of large pieces of plaster (Fig. 4).

Light damage: hairline cracks in plaster and at boundaries.

Figure 3. Examples of severe masonry-wall damage.

Figure 4. A moderately-damaged masonry wall.

SEISMIC CONDITIONS AT THE SCHOOL SITES

GROUND MOTIONS

The stronger shaking in Düzce, Kaynaşlı, and Bolu during the two 1999 earthquakes was due to the 12 November 1999 Düzce earthquake. The November 12, 1999 Düzce earthquake was associated with a 40-km surface rupture running in the east-west direction. The ground motions in the vicinity of the school buildings surveyed were recorded in Düzce and Bolu (Fig. 1). The peak horizontal components of these records are listed in Table 2. There was no strong motion record available from Kaynaşlı, which is located at the eastern end of the 12 November 1999 Düzce earthquake surface rupture. The ground motion during the May 1, 2003 earthquake was recorded in Bingöl. The peak horizontal components of this record are also presented in Table 2. The acceleration and the displacement spectra of all three records for 2% of critical damping are given in Fig. 5 and 6. Comparison of the displacement spectra obtained from the records indicates that buildings in Bingöl were not subjected to a ground motion with higher displacement demand than those in Düzce and Bolu.

Table 2. The maxima of the ground motions recorded near the school sites during the Düzce and Bingöl earthquakes.

Station	Earthquake	Max. Ground Acc. (m/sec^2) EW	NS
Düzce	Düzce Eq.	5.04	4.00
Bolu	Düzce Eq.	7.91	7.25
Bingöl	Bingöl Eq.	2.71	5.35

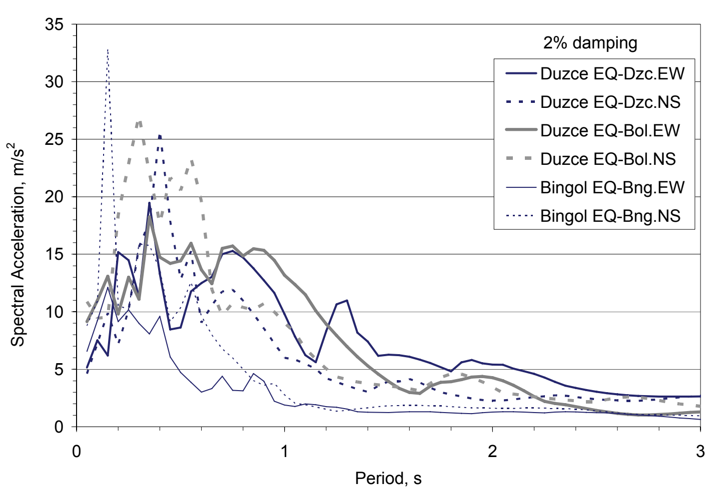

Figure 5. Acceleration spectra of ground motions recorded near the school sites during the Düzce and Bingöl earthquakes.

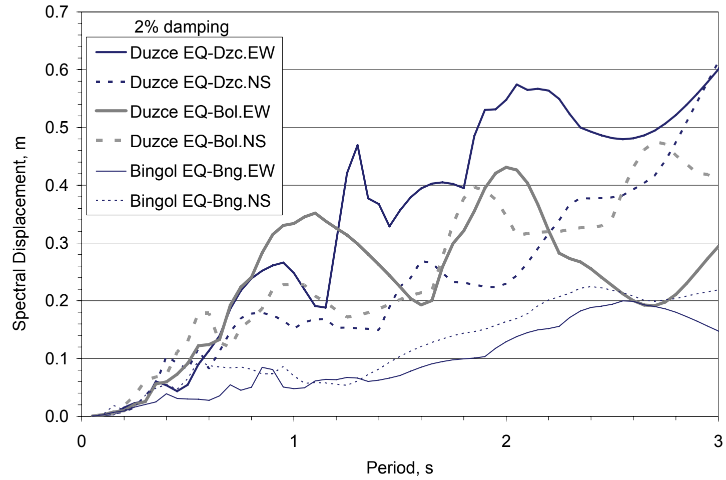

Figure 6. The displacement spectra of the ground motions recorded near the school sites during the Düzce and Bingöl earthquakes.

GROUND CONDITIONS

Düzce, Bolu and Kaynaşlı in northwestern Anatolia and Bingöl in southeastern Anatolia are all in Pleistocene basins. Most of the school sites of our study were on valley fill. The ground conditions in all school sites would be expected to be similar.

The basins in Düzce and Bolu are filled with colluvial deposits while the valley in Kaynaşlı is filled with colluvial and alluvial deposits.

In Bingöl, the soil and granular alluvial deposits are quite uniform and the subsurface materials are dense to very dense; excellent for building foundations. No sign of distress, settlement, excessive deformations, or any other indication of foundation damage was found in our inspection of several building foundations. The most damage observed was light damage to the lateral basement walls, even in buildings with severe structural damage or collapse. Given that the epicenter of the main shock was located approximately 20 km from the city, we estimate that the shaking should have been reasonably uniform throughout Bingöl. Our investigation of soil and rock foundation materials at the school sites in the Bingöl area suggest that differences in damage to school buildings from place to place in Bingöl due to the 1 May 2003 earthquake were a result of characteristics of the structures, not of foundation conditions or gross ground deformation.

STRUCTURAL PROPERTIES OF THE SCHOOL BUILDINGS AND THEIR DAMAGED STATES

SCHOOLS WITH MOMENT-RESISTING FRAMES

All the schools with moment-resisting frames were in or around Bingöl. The number of stories of the buildings ranged from 2 to 4. A typical column layout of these buildings is shown in Fig. 7. As the floor plan indicates, the lateral load resisting system in these buildings can be categorized as regular in plan. The majority of the columns were aligned in regular bays, and most of the beams framed into columns. The dimensions of the columns in the buildings were typically 0.3 m x 0.5 m. There are 43 columns in the typical floor plan, 24 of these columns had the strong axis oriented in the short direction of the school buildings. The typical dimensions of the beams are 0.3 m x 0.7 m. The locations of the masonry infill walls varied depending on the use of the space in each school. The thickness of the masonry infill, including the plaster, was estimated to be 0.25 m for interior walls and 0.38 m for exterior walls.

The total column area at ground level in these moment-resisting frame buildings was approximately 1% of the floor area, regardless of the number of floors. Consequently, the performance of these structures during the earthquake was influenced significantly by the number of floors. A similar observation was made by Dönmez and Pujol (2005). The level of damage assigned to the lateral load resisting system with respect to the number of floors was categorized as follows:

4 two-story buildings: 3 moderately damaged and 1 lightly damaged.

11 three-story buildings: 3 collapsed, 6 severely damaged and 2 moderately damaged.

1 four-story building: severely damaged.

Figure 8 shows the photos of Building C13-08 before and after the earthquake. The first story of the three-story building completely collapsed. The columns of all three collapsed buildings appeared to have failed in shear. Figure 9 shows the extent of shear damage in columns in one of the severely damaged buildings (C14-01). Figure 10 shows an internal column failed due to captive column condition evolved during the earthquake. Damage to the masonry walls was rated separately. The three- and four-story buildings typically sustained severe masonry wall damage (Table 3).

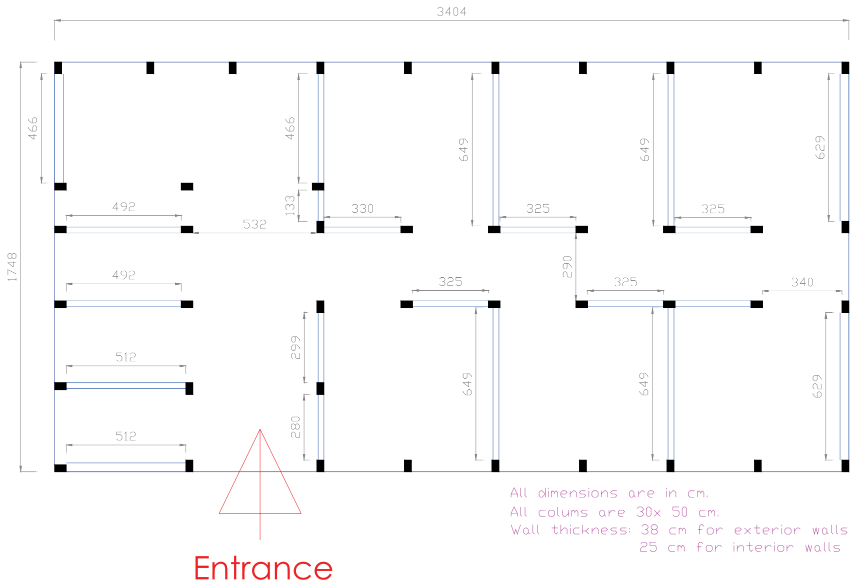

Figure 7. Typical floor plan for moment-resisting frame systems.

Figure 8. Building C13-08 before (small photo) and after (big photo) the 2003 Bingöl earthquake. The first story is completely collapsed during the earthquake. The captive columns in the ground floor were shown at the right end of the school (small photo).

Figure 9. The remains of the corner column of the ground floor of the building shown in Fig. 7 (Building C13-09). The corner column failed in shear.

Figure 10. A captive column in Building C14-01 created by the crushing of the corner regions of infill walls.

Table 3. Basic structural parameters of the buildings.

	Bldg No.	Damage to RC System	Damage to Masonry	N_{floor}	A_{floor} (m^2)	A_{sw} EW (m^2)	A_{mw} EW (m^2)	A_{sw} NS (m^2)	A_{mw} NS (m^2)	A_c (m^2)	CI (%)	WI (%)
Düzce Earthquake	K01	None	None	2	595	2.9	12.5	2.4	6.8	5.1	0.21	0.26
	B01	None	None	3	595	2.9	12.5	2.4	6.8	5.1	0.14	0.17
	D01	None	None	2	595	2.9	12.5	2.4	6.8	5.1	0.21	0.26
	D02	Severe	Moderate	4	595	2.9	12.5	2.4	6.8	5.1	0.11	0.13
	D03	Light	Moderate	4	595	2.9	12.5	2.4	6.8	5.1	0.11	0.13
Bingöl Earthquake	C13-01	Severe	Severe	3	595	0	16.0	0	10.6	6.5	0.18	0.06
	C13-05	Moderate	Light	2	585	0	18.7	0	11.7	6.5	0.28	0.10
	C13-06	Moderate	Light	2	589	0	15.7	0	11.0	6.5	0.27	0.09
	C13-07	Light	Moderate	2	589	0	16.8	0	11.9	6.5	0.27	0.10
	C13-08	Collapsed	Collapsed	3	595	0	18.3	0	7.4	6.5	0.18	0.04
	C13-09	Collapsed	Collapsed	3	595	0	16.0	0	9.3	6.5	0.18	0.05
	C13-10	Collapsed	Collapsed	3	595	0	16.0	0	9.3	6.5	0.18	0.05
	C14-01	Severe	Severe	3	595	0	15.7	0	9.4	6.5	0.18	0.05
	C14-03	Severe	Severe	3	595	0	5.4	0	12.7	6.5	0.18	0.03
	C14-04	Moderate	Moderate	3	595	0	12.5	0	11.4	6.5	0.18	0.06
	C14-05	Moderate	Moderate	3	595	0	7.4	0	17.1	6.5	0.18	0.04
	C14-06	Moderate	Moderate	2	595	0	16.0	0	10.7	6.5	0.27	0.09
	C14-07	Severe	Moderate	3	595	0	16.0	0	8.9	6.5	0.18	0.05
	C15-01	Severe	Severe	4	595	0	14.9	0	7.3	6.5	0.14	0.03
	C15-02	Severe	Severe	3	595	0	14.4	0	10.6	6.5	0.18	0.06
	D16-01	Severe	Severe	3	595	0	14.8	0	7.7	6.5	0.18	0.04

N_{floor} :Number of floors; A_c: Total column area; CI: Column index — WI: Wall index

A_{sw}EW: Total shear wall area in the east-west direction — A_{sw}NS: Total shear wall area in the north-south direction

A_{mw}EW: Total masonry infill wall area in east-west direction — A_{mw}NS: Total masonry infill wall area in north-south direction

SCHOOLS WITH DUAL SYSTEMS

Of the five school buildings with dual systems, three are in Düzce, one in Bolu and one in Kaynaşlı. These buildings have the same floor plan as those in Bingöl with moment-resisting frames except that two bays in each orthogonal direction are occupied by reinforced concrete walls (Fig. 11). The thickness of these walls is 0.2 m. The total concrete wall area is estimated to be 0.4% of the floor area in the long direction and 0.5% in the short direction of the building. These buildings range from two-story to four-story. In addition, buildings with three and four stories had an additional stairwell separated from the main structure by an expansion joint.

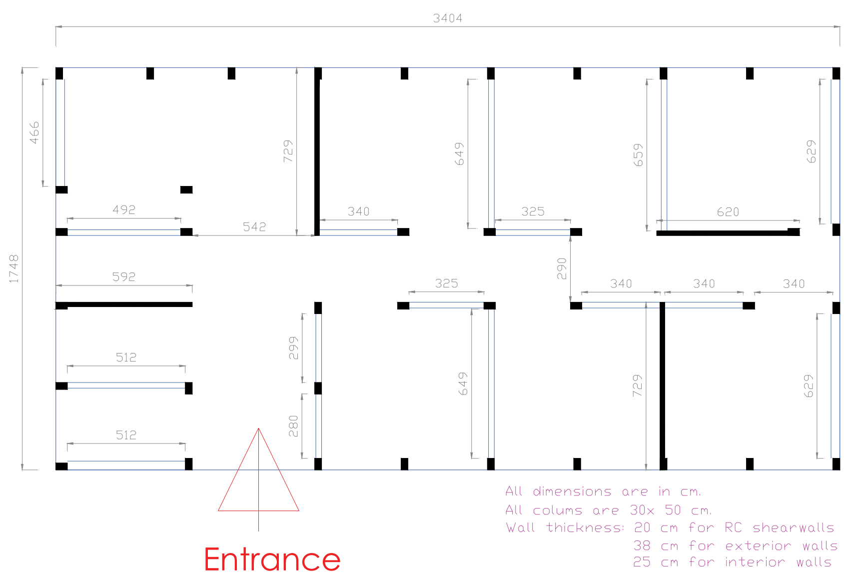

Figure 11. Typical floor plan for the dual systems.

The most severely damaged dual system was one of the four-story buildings (D02) in Düzce (Fig. 12). The damage was concentrated in the half-buried basement surrounded by partial height earth-retaining concrete walls (Fig. 13). There are windows between the earth-retaining walls and the beams of the basement. The exterior basement columns, that were captive along their weak axis, failed in shear (Fig. 14). Columns and structural walls in other stories did not suffer damage. There were moderately damaged masonry infill walls in the basement. Unlike other buildings, the damage rating of building D02 was based on the damage state of the basement rather than that of the ground floor.

The columns of the rest of the dual-system buildings (without a basement) had no visible damage. The structural system of the other four-story building (D03) in Düzce was rated to be lightly damaged because of the observed beam damage. Masonry infill walls in building

D03 were moderately damaged. There was no damage observed to the structural and nonstructural elements of the two-story school buildings (D01 and K01) in Düzce and Kaynaşlı and the three-story school building (B01) in Bolu. Building K01 was only 50 m away from (south of) the main surface rupture of the Düzce earthquake.

Figure 12. A four-story dual-system building in Düzce (Building D02).

Figure13. View of the captive exterior columns in the basement of Building D02 from outside and inside. The columns are captive in their weak axis.

Figure 14. A failed captive column in the basement of Building D02.

DAMAGE COMPARISON

One of the most significant structural deficiencies commonly observed in the school buildings was the presence of captive columns formed by openings for the small windows in the masonry infill walls. There were at least two captive columns adjacent to the windows in the bathrooms and around the stairwells in each school building. In addition, in seven of the schools in Bingöl, there was a furnace room on the ground floor level where the presence of small window openings adjacent to columns increased the number of captive ones from two to eight.

The observed difference in the performance of the dual systems and that of the moment-resisting frame systems cannot be attributed to defects arising from construction quality. The construction quality was similar and quite uniform across all of the surveyed school buildings. Visual inspection of the concrete revealed honeycombs and inclusion of disproportionately large pieces of aggregate. Unwashed river aggregate had been used in most of the buildings inspected. There were detailing problems. The ends of the transverse reinforcement were typically not anchored in the concrete core. Sufficient confinement was not observed in the column end regions. In general, ductile detailing was lacking in the structural members (Figure 15).

Figure 15. Typical column end reinforcement detailing exposed in Building C14-01.

Comparison of the performance of the dual and moment-resisting systems during the earthquakes has been organized on the basis of number of stories in the buildings:

- *Two-story buildings:* The two structures with dual systems showed no signs of visible damage. The moment-resisting frame structures survived without any damage to their columns. The displacement demand on these structures by the earthquakes was not high enough to damage the captive columns and the masonry walls severely. The masonry walls remained intact and contributed to the stiffness of the structures. In buildings C13-07 and C14-06 there was moderate damage to the masonry infill walls.

- *Three- and four-story buildings:* The three dual-system structures suffered almost no damage to their concrete structural walls. Of the three buildings, only building D02 was rated as severely damaged. Unlike other buildings in the inventory, building D02 suffered damage to its basement. The exterior columns in the basement were captive columns due to the partial-height concrete earth-retaining walls restraining the columns (Fig. 12, 13, and 14). The structural walls appear to have contributed to collapse prevention. Further, columns above the basement level in D02 were not damaged. Of the twelve schools with moment-resisting frames as the lateral load resisting system, ten of them were either severely damaged or collapsed (Fig. 8 and 9). Only two survived without any damage to the columns. The displacement demand was high enough to result in severe damage to the masonry infill walls. Damage to the masonry walls appears to have affected the structural response in two ways: (1) The stiffness of the system was reduced, and (2) crumbling of the masonry at the wall corners resulted in formation of additional captive columns (Fig. 10) and the structure failed due to a loss of gravity-load capacity.

Performance of both groups of school buildings in the damage assessment was further studied using the procedure proposed by Hassan (1997). Two indices, called the column index and the wall index, were suggested in the Hassan procedure to order the structures according to their relative resistance to lateral loads. The wall and column indices are defined as follows:

Column index (CI) = Half the total column area at the base level divided by the product of the floor area and number of floors above the ground level.

Wall index (WI) = Sum of the area of reinforced concrete shear walls and a tenth of area of masonry walls in a given horizontal direction divided by the product of the floor area and the number of floors above the ground level.

The wall index is calculated for both principal horizontal axes of the buildings, and the smaller of the two is taken as the wall index for the given building. The wall and column indices calculated for the school and dormitory buildings are given in Table 3.

The effect of reinforced concrete walls on the structural performance is presented graphically in Fig. 16. The buildings were grouped in the graph according to their damage levels. The horizontal axis shows the wall index for each building. It is clear from Fig. 16 that the buildings with higher wall index performed better as indicated by the level of damage observed during the earthquakes.

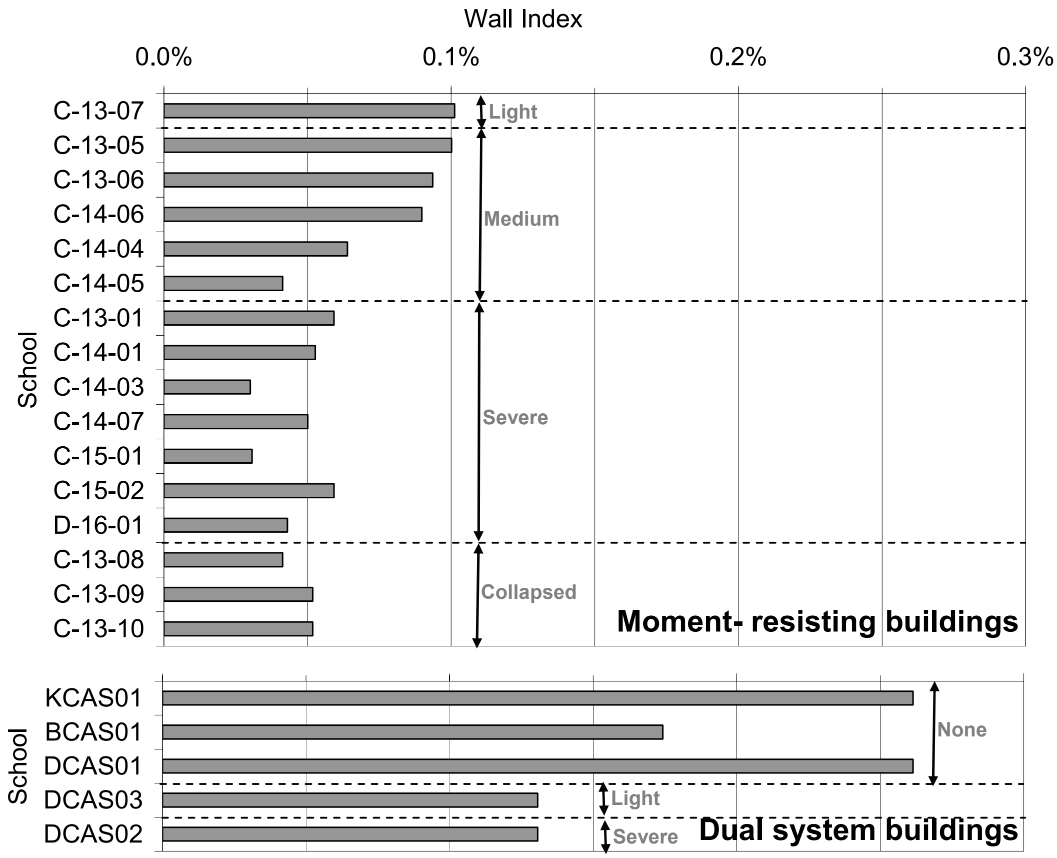

Figure 16. Correlation between the structural performance and the wall index defined by Hassan (1997).

DISCUSSION

An indication of the essential structural difference of the two types of buildings is reflected in the structural wall areas. The dual system structures had structural walls in 0.4% and 0.5% of the floor area in the long and short directions of the buildings, respectively.

The dual system buildings were located in Bolu, Düzce and Kaynaşlı and strongly shaken by the 1999 Düzce earthquake whereas the moment-resisting frames were in Bingöl and affected by the 2003 Bingöl earthquake. However, comparison of the acceleration and displacement spectrum calculated from the records of the two earthquakes near the school sites indicate that the moment-resisting frame buildings in Bingöl were not subjected to a ground motion with higher acceleration or displacement demand than those in Düzce and Bolu (Fig. 5 and 6).

In the moment-resisting frame systems, lateral loads were resisted by the combined action of the columns and the masonry walls. For the two-story structures, the contribution of the masonry walls to the strength and the stiffness of the structures were sufficient to control the first-story drift in the buildings because the force and displacement demand on these structures during the Bingöl earthquake was low. In structures three stories or higher, the lateral strength of the building was exceeded. The captive columns and the masonry walls were damaged severely. The masonry wall damage caused reduction of the lateral stiffness of the structures and increase in the story drifts. The masonry wall damage in the form of crushing in the corner regions created new captive columns. The buildings with excessive number of captive columns failing in shear had their gravity load carrying capacity compromised and collapsed, or collapse was imminent.

In the dual systems, the masonry infill wall damage was not as critical as in the case of reinforced concrete structural frames without walls. As observed in the case of four-story dual structure (Building D02), the story drift demand during the earthquake might exceed the deformation capacity of the captive columns and severely damage masonry walls. However, it need not lead to the collapse of the building because of the presence of structural walls which control the interstory drift and enhance the gravity load capacity of the structure.

CONCLUSIONS

The damage survey of the school buildings in two earthquake areas in Turkey has re-emphasized a well-known principle of earthquake-resistant design. The collapse of multistory, reinforced concrete buildings with hollow-brick infill walls, which are typical of construction throughout Turkey, can be prevented by including a few properly-located structural walls. This is in agreement with what has been recommended by Gülkan and Utkutuğ (2003) for use of structural walls in school building construction in Turkey.

Performance of the surveyed buildings with moment-resisting frames appears to be correlated with the number of floors in the buildings because the column size is uniform in all the schools. The two-story buildings could survive the earthquake without any damage to their columns. The three- and the four-story buildings, however, did not perform satisfactorily. Of the 12 buildings with three stories or higher, ten buildings suffered shear damage to their columns. Three of them collapsed because of the columns failed in shear.

The efficacy of the structural walls to prevent building collapse is demonstrated by the fact that all school buildings in the inventory with dual-system frame structures, with the exception of one, were lightly damaged or not damaged at all. The sole severely damaged structure was damaged not by failure in the ground story, as all the other school buildings, but by failure of captive columns at basement level as a result of discontinuity of the foundation walls in height. The structural walls of the building, which were not damaged at all, prevented the collapse of the building by providing sufficient lateral strength and enhancing the gravity load capacity.

The observations in the school buildings showed that structural walls improve the behavior of reinforced concrete systems drastically. Accordingly, in school buildings, especially in those over two stories high, use of structural walls along with reinforced concrete frames is recommended. In all cases, captive columns should be avoided. These columns tend to fail in a brittle mode and may even lead to loss of gravity load carrying capacity.

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