SULTANDAGI EARTHQUAKE – TURKEY

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I. General

An earthquake of magnitude Md 6.0 (Mw = 6.3) occurred on February 3, 2002 at 9:11 local time causing damage and casualties at the town of Afyon (population: 183,351) and its provinces (Sultandagi, Cay, Bolvadin, Cobanlar, Suhut, Aksehir). The macroseismic epicenter is located near the Sultandagi province and the earthquake is associated with the Sultandagi fault zone. Three major aftershocks with magnitudes between 5 and 6 followed the main event. One of those (Mw = 6.0, occurred at 11:26 local time) is also considered as another main shock. Total dead count is 42 with 325 injured. The peak horizontal accelerations recorded are around 0.1g.

II. Tectonics

The main tectonic features of Central and Western Anatolian regions are illustrated in Figure 1. Extensive investigations have showed that, numerous graben systems have been forming in the E-W and WNW-ESE directions due to the N-S substantial extension in the Western Anatolia (Ketin 1968; Dewey and Sengor 1979; Jackson and Mc Kenzie, 1984). Gokova, Buyuk Menderes, Kucuk Menderes, Gediz, Bakircay, Kutahya, Eskisehir and Simav Grabens are the ones that constitute the main tectonic structure of the region together with Fethiye-Burdur, Tuzla and Bergama-Foca fault zones that are trending NE–SW directions. A number of major normal faulting events have occurred along these faults, for example the 1899 Buyuk Menderes, 1928 Torbali, 1955 Balat, 1969 Alasehir, 1969Menderes, 1928 Torbali, 1955 Balat, 1969 Alasehir, 1969 Simav, 1970 Gediz and 1995 Dinar Earthquakes. NW to SE striking normal fault systems mostly take place in Southwestern Aegean such as Pamukkale, Dinar and Yatagan-Mugla faults. The 03 Feb, 2002 earthquake took place on the Sultandagi fault zone, which is a NW-SE trending fault separating the Sultandagi rise and the Aksehir-Afyon graben. According to Boray et al. (1985), Saroglu et al (1987) and Barka et al (1995), the fault is a thrust one. On the other hand, Kocyigit et al (2000) name the fault as the "Aksehir fault" and define it as a normal fault with oblique offset. The rapid moment tensor solutions taken from USGS maintain this opinion.

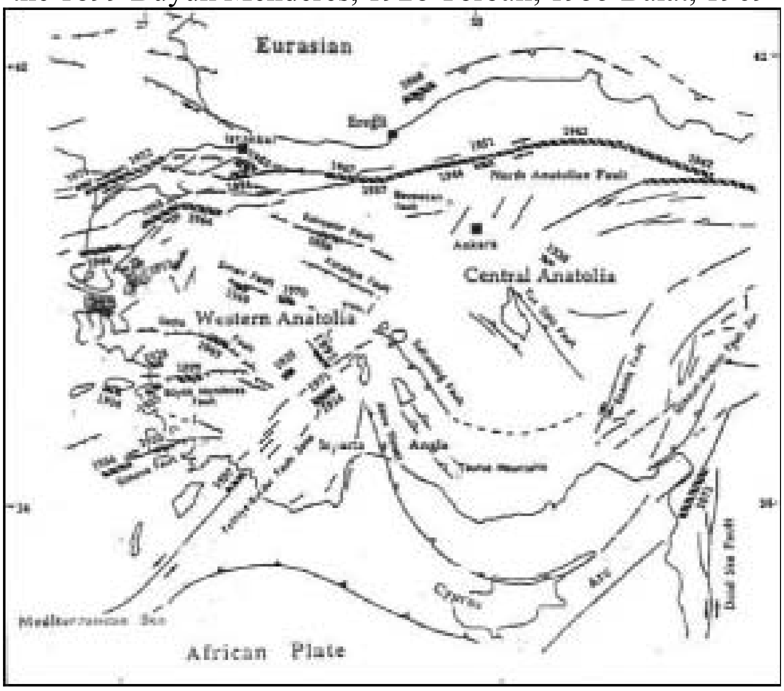

Figure 1. Tectonic features of Central Anatolian and Aegean Regions

III. Seismicity

Although the Burdur-Dinar (Apameia) region to about 100 km to the Southwest of the earthquake site has been repeatedly affected by large historical earthquakes, the site of the Sultandagi earthquake has been relatively free of the historical earthquakes. This may be the result of the very low strain rates. Records of this century indicate in October 3, 1914 (M=7, Io=IX) Burdur earthquake (37.50N, 32.50E), where about 4000 people died and about 17000 houses destroyed, about 100 houses were destroyed in the villages between Bolvadin and Cay. The earthquake is associated with a 23 km fault rupture along the southeast coast of the Burdur Lake. Another earthquake of magnitude Ms=6 (I=VIII) occurred on August 7, 1925 at Afyon-Dinar causing damage in the region lying between Hamidiye and Denizli. On May 12, 1971 an earthquake (Ms=6.2, I=IX) occurred in town of Burdur destroying 1487 houses and killing 57 persons. Another earthquake of magnitude Ms=6.1 occurred on 1st October 1995 causing extensive damage in Dinar town. The earthquake killed 90 people with 260 injured and caused extensive damage to 30% of buildings in Dinar. The fault ruptures associated with those earthquakes are illustrated in Figure 1. The Sultandagi fault was recently activated by the 15.12.2000 (Mw=6.0) Bolvadin earthquake, which occurred in the southeastern part of the fault zone. The earthquake caused 6 casualties with 82 injuries and caused damage in Bolvadin, Aksehir and Ilgin provinces. The epicenter of this earthquake is shown on Figure 2.

The Sultandagi earthquake has taken place in the first-degree earthquake hazard zone in the hazard map associated with the 1998 Turkish earthquake resistant design regulations.

IV. Soil Conditions

The affected cities Cay, Yakasinek, Sultandagi are located on alluvial fans to the north of sultandagi mountains. The soil conditions represent gradation from stiff soil site to alluvial deposits from south to north as morphology changes from mountain slopes to fan deposits. The Eber village is located essantially on holocene marshlike deposits.

V. Seismology

The main shock and the distribution of aftershocks recorded at KOERI are given Figure 2.

The epicenter and magnitude of the main shock, those of the following 3 major aftershocks and the available rapid moment tensor solutions as given by USGS are illustrated in figure below. The magnitude 6.0 event is also considered as another main shock.

The physical parameters of the earthquake are somewhat similar to the October 1, 1995 Dinar earthquake (Erdik et.al, 1998, Soil Dynamics and Earthquake Engineering 17, 99.557-578). Both earthquakes have normal fault mechanisms:

Dinar Earthquake: Mw=6.0 (USGS)
Seismic Moment: Mo=1.3*10^18 Nm

Dinar earthquake caused a fresh fault scarp with about 30cm vertical and 5cm right lateral fault offset.

The maximum PGA recorded in Dinar Earthquake 0.33g at Dinar City. A total of 90 people killed and about 1000 buildings became useless in the Dinar City of population 35,000.

The Seismic Moment of the Sultandagi Earthquake is about two times that of the Dinar Earthquake.
Sultandagi Earthquake Mw=6.3 (USGS)

Seismic Moment: Mo=2.9*10^18 Nm

Preliminary reports indicate about 30km scarp.

Peak ground accelerations caused by the Mw=6.3 and by the Mw=6.0 earthquakes are given in Figure 4.

A list of important events of the earthquake episode is provided in Table 1

Table 1. List of the major events

Date	Time (UTM)	USGS	KOERI	D USGS	Md	Mw
03.02.2002	07:11	38.521N 31.156E	38.5812N 31.2482E	10	6.0	6.3
03.02.2002	09:26	38.646N 30.819E	38.6855N 30.8350E	10	5.3	6.0
03.02.2002	11:39	38.53N 30.96E	38.6317N 30.9973E	10	5.1	
03.02.2002	11:54	38.56N 31.03E	38.6013N 31.0077E	10	5.0	

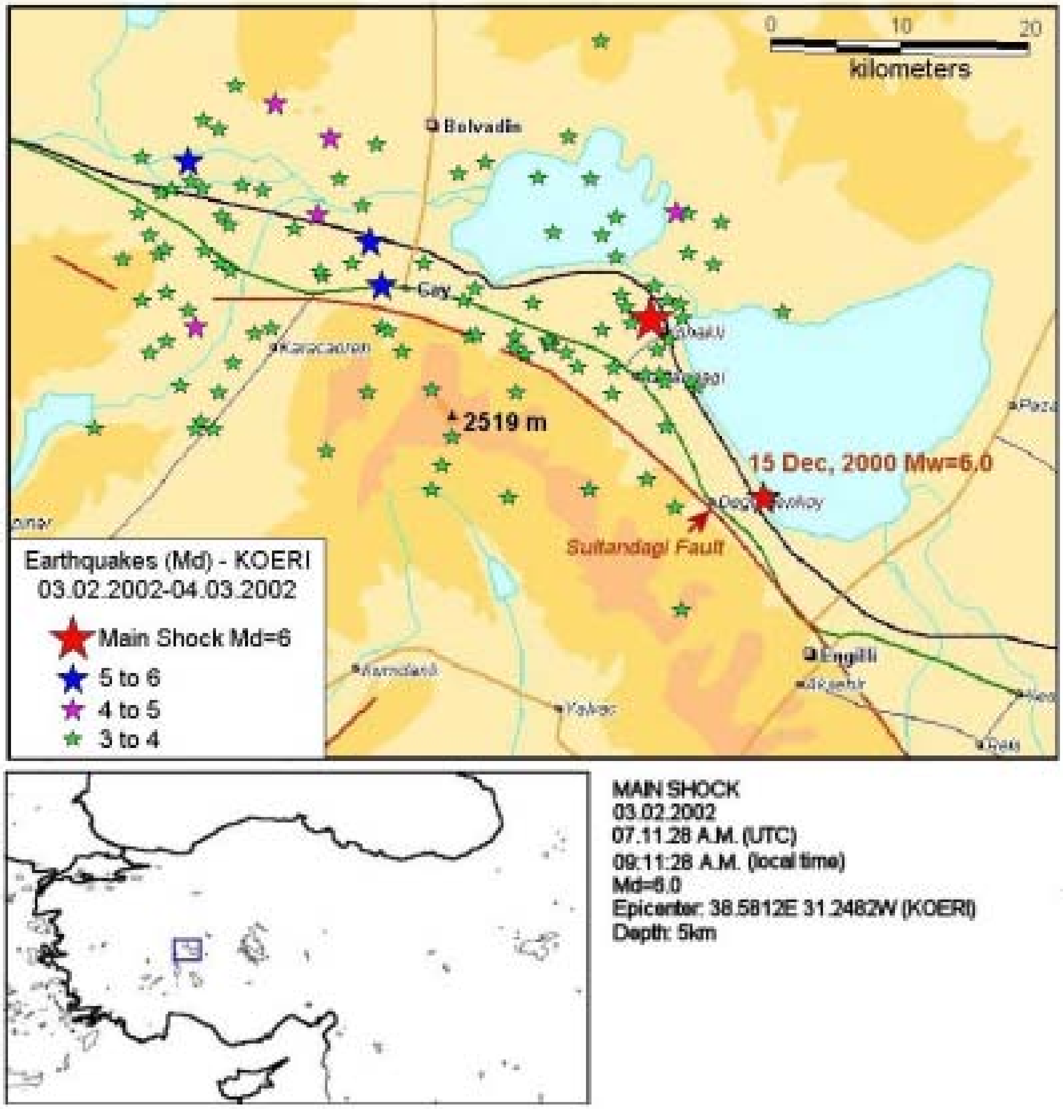

Figure 2. The main shock and the aftershock distribution

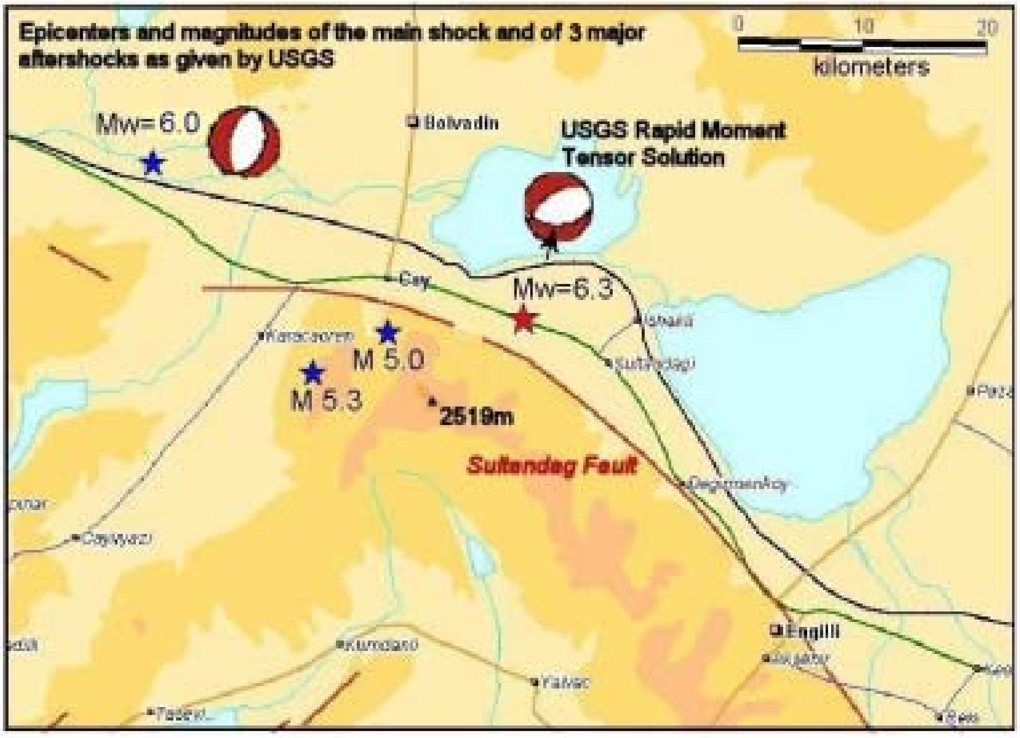

Figure 3. The main shock and the major aftershocks as given by USGS.

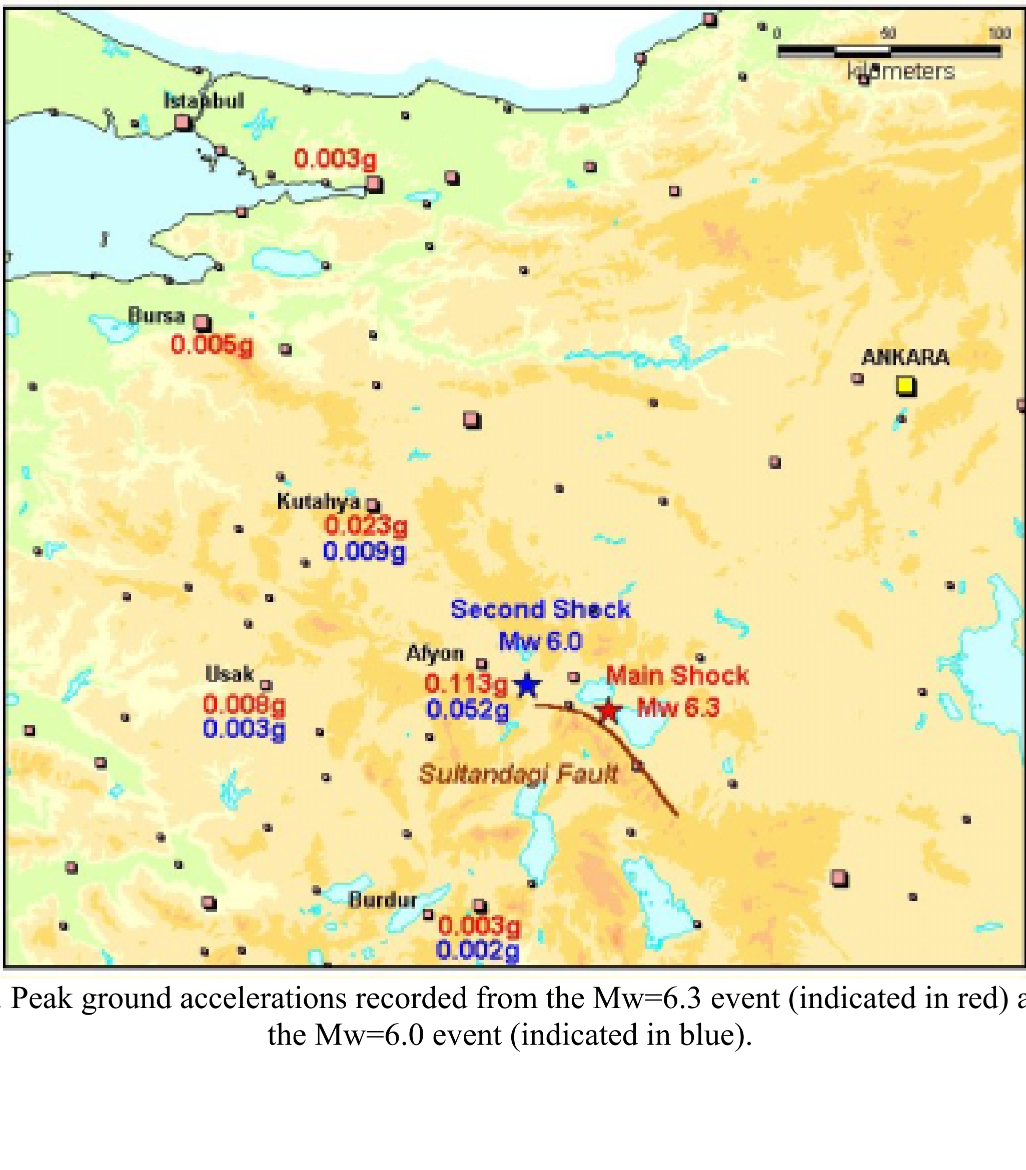

Figure 4. Peak ground accelerations recorded from the Mw=6.3 event (indicated in red) and from the Mw=6.0 event (indicated in blue).

VI. Damage

The earthquake caused damage in Aksehir, Bolvadin, Cay, Cobanlar, Iscehisar, Eber, Sincanli, Sultandagi, Suhut and Merkez districts of Afyon. The distribution of causalities and damaged buildings are given in the tables below.

Table 2. Damage Distribution

Location	Heavy damage and Collapse		Medium Damage		Low Damage	
	Residential	Commercial	Residential	Commercial	Residential	Commercial
Bolvadin	471	35	436	254	3,134	408
Cay	1,226	245	136	14	1,660	29
Cobanlar	446	5	375	35	981	37
Iscehisar	45	1	3	-	55	1
Merkez	1,116	37	143	7	1597	26
Sincanli	35	1	2	1	52	2
Suhut	-	-	-	-	99	-
Sultandagi	712	15	302	22	1,427	48
Total	4,051	339	1,397	333	9,005	551

Table 3. Casualty Distribution

Location	Dead	Injured
Aksehir	1	7
Bolvadin	2	200
Cay	23	67
Cobanlar	-	21
Merkez	2	-
Sincanli	1	-
Sultandagi	13	30
Total	42	325

The damaged towns are illustrated in Figure 5.

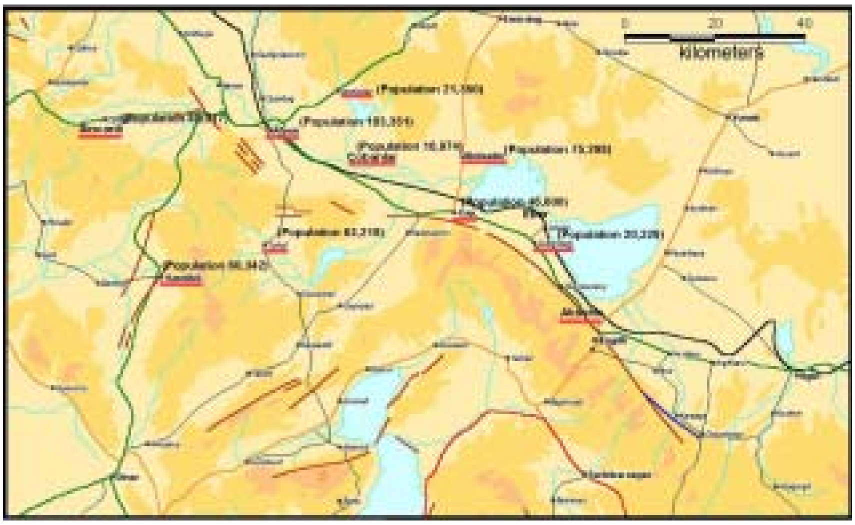

Figure 5. Damage distribution

The intensity map compiled with the help of the above mentioned damages and field observations is given in Figure 6.

VII. Performance Of Building Structures

Heavy damage and total collapse were particularly concentrated in a narrow region in Cay. Older single story buildings in the region are commonly himis structures (buildings composed of timber frames and braces with adobe infills), whereas newer ones are unreinforced masonry and reinforced concrete structures typically with two or three stories.

Performance of Himis Buildings

Most of the injuries and casualties in the region are associated with the total collapse of himis buildings. Himis buildings had been widely preferred in rural areas three or four decades ago and

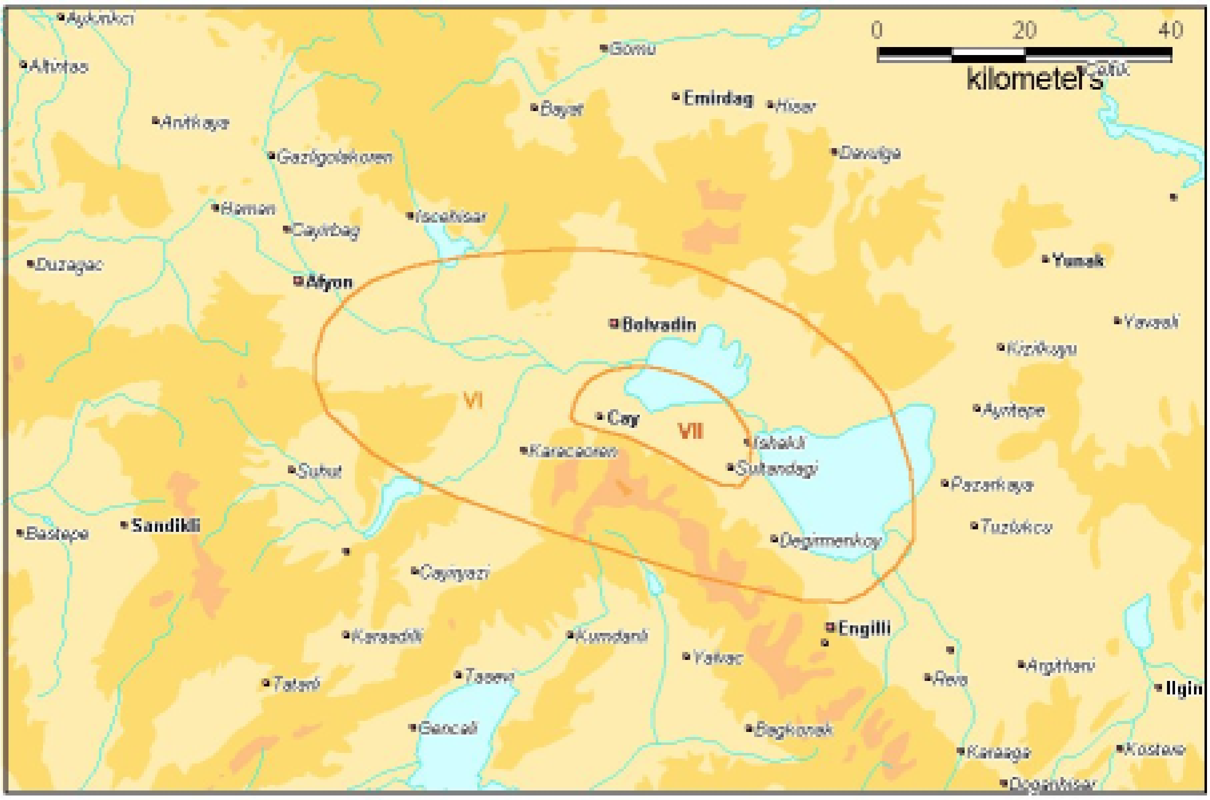

Figure 6. Intensity Distribution

were traditionally built by their residents without engineering considerations. Thick perimeter walls and heavy roofs are common features of himis buildings providing heat isolation of the structure. The observed performance level of himis buildings indicated heavy damage and total collapse due to the poor strength and brittle behavior of the walls and considerable mass of the buildings. Observations suggest that due the lack of rigid diaphragm action, most of the walls responded individually during the seismic attack. Moreover observation on collapsed buildings indicated that as a consequence of weak connections between the perimeter and orthogonal partitioning walls, separation occurred and most of the thick perimeter walls collapsed in the out of plane direction. Figure 7 shows a collapsed himis buildings in Eber.

Performance of Unreinforced Masonry Buildings

Unreinforced masonry has always been preferred to reinforced masonry in Turkey despite its handicaps in seismic behavior. However Turkish seismic codes have eliminated the disadvantages by limiting the number of stories (e.g. maximum 2 stories for Seismic Zone 1, and 3 stories for Seismic Zone 2) with conservative detailing and force reduction factors. Eventually most of the buildings in the region satisfy the story limitation rules for seismic Zone 1, however newer masonry buildings with 3 or 4 stories have also been inspected.

Observed heavy damage and collapse of unreinforced masonry buildings in the region are associated with hollow clay tiles used instead of solid brick units. Hollow clay tiles are widely used as infill panels in reinforced concrete buildings and are not allowed for masonry structures as load bearing members. First story collapse (Figure 8) is the common type of mechanism for the structures built with hollow clay tiles as a consequence of their very limited ductility capacities and poor strengths. Wide shear cracks between voids in the walls and evidence of crushing (Figure 9) has commonly been observed in heavily damaged hollow clay tiled buildings. However most of the buildings with less than 3 stories have survived the earthquake with minor damage even though they were built with hollow clay tiles.

Performance of Reinforced Concrete Buildings

The majority of heavy damage and collapse of reinforced concrete buildings have been limited to a narrow region in Cay. Estimated peak ground acceleration (PGA) in Cay, which is approximately 10km away from the epicenter, is around 0.20-0.25g. Most of the buildings of the Cay Commercial Blocks collapsed while the remaining ones survived the earthquake with very heavy damage (Figure 10). One of the triple 8 story apartment buildings in Cay that is very close to the Cay Commercial Blocks, totally collapsed (Figure 11) and the mosque of the Cay Commercial Blocks suffered considerable damage (Figure 10-Upper left). Fortunately collapse of these structures did no cause any fatalities since it was an off-day for the Cay Commercial Blocks' workers and the 8-story buildings were unoccupied at the time of the earthquake.

Buildings in Cay out of this region, Eber and Sultandagi performed well due to either the adequate design considerations taken into account or the level of ground motion that is not strong enough to test these structures.

Cay Commercial Blocks

At least 30% of the blocks were totally collapsed and the remaining blocks suffered very heavy damage. The blocks were designed and completed in 90's where each block was composed of 4 spans in the transverse direction and 5 spans in the longitudinal direction. Observations suggest that plain round bars (f_y=220 MPa, 40 ksi) and deformed bars (f_y=420 MPa, 60 ksi) have been used as reinforcement. Bond failure of the column bars has been observed to be the major cause of the collapse where the column bars were not bent as 90^0 hooks in the beam-column joints and splices at column bases inadequately lapped. This resulted in the slip of the column bars from the joints and foundations before a sound plastic mechanism commences in the potential plastic hinge zones. Most of the collapsed blocks support this idea, that is, some of the columns either collapsed in the opposite direction of the collapsed slab or survived the earthquake even though the slab it has been supporting collapsed (Figure 12, Figure 13). Blocks that could survive the seismic attack also show the evidence of wide flexural cracks concentrated at the beam-column joint faces and splitting cracks in the beam-column joints, indicating some level of bar slip.

There are instances of column core concrete crushing as a consequence of inadequate transverse reinforcement failure. Transverse reinforcement spacing of 200 mm is common in most of the columns and most of the transverse reinforcement with 90^0 hooks opened (Figure 14) during the earthquake due to their poor anchorage features particularly after cover concrete spalling. Exterior beam-column joint failures have also been observed in some blocks. Details of the joints suggest that outer column bars buckled and joint cores crushed to some extent due to the lack of joint transverse reinforcement (Figure 15).

The Mosque of Cay Commercial Blocks

This soft story building survived the seismic attack with considerable damage. The structure is reinforced with plain round bars (f_y=220 MPa, 40 ksi). Full depth single flexural cracks of 3-4mm wide at beams that are concentrated at column faces suggest some level of beam bar slip (Figure 16). Observed damage indicate that the building responded dominantly in the oblique direction causing biaxial bending at columns. Most of the bars buckled and cover concrete spalled at column corners. None of the columns exhibited shear-flexure cracks distributed over a constant length however one of the columns adjacent to infill walls in the first story failed in shear (Figure 17). It was observed that corner beam-column joints exhibited beam bar slip, longitudinal column bar buckling and some level of diagonal tension cracking (Figure 18).

It was not very easy to observe the behavior of member at the upper stories from outside screening however outer face of the building does not indicate any evidence of significant outer column damage.

Triple 8-Story Apartments

One of the buildings of three identical apartments totally collapsed and the other lost its first two stories. Observations suggest that loss of column bar anchorage at the foundation level and probably at the story levels (Figure 19) caused the collapse of the former building. Columns of the collapsed building showed no evidence of distributed flexural or shear cracks suggesting the possibility that column bars slipped before the attainment of flexural capacity. First two stories of the latter building collapsed due to inadequate transverse reinforcement details. There are many instance of crushed concrete due to excessive transverse expansion of the core concrete and shear cracks in the weak direction of the columns.

Figure 7. Collapsed himis building in Eber

Figure 8. Collapsed masonry building built with hollow clay tiles

Figure 9. Heavily damaged 4 story masonry building in Cay.

Figure 10. Cay commercial blocks and its mosque

Figure 11. Collapsed and damaged 8-story apartment buildings

Figure 12. Collapsed column and slab in opposite directions

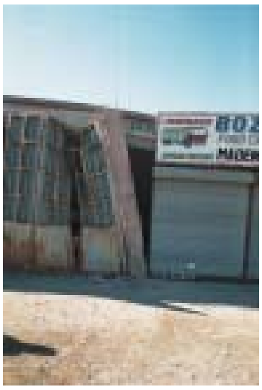

Figure 13. Collapsed slab due to bond failure of the column bars

Figure 14. Spacing of transverse reinforcement visible in a column

Figure 15. Exterior beam-column joint damage

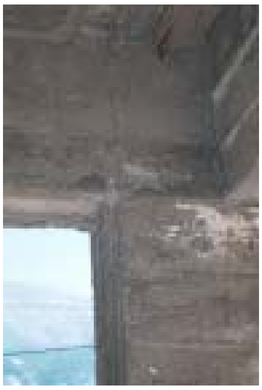

Figure 16. Full depth beam flexural crack

Figure 17. Observed column shear failure

Figure 18. Damage at a beam-column joint

Figure 19. Bond failure at column base

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