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Failure of Superstructures after the "February 03, 2002 Sultandagi-Cay, Earthquake"

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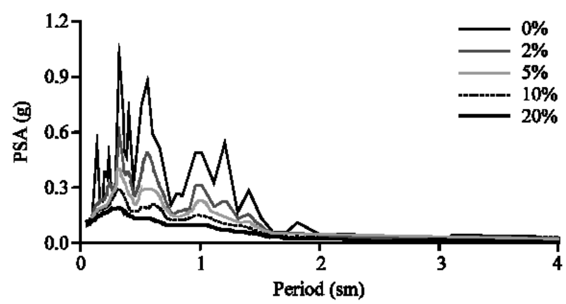
Abstract: While earthquake is an ordinary natural phenomena for most of the countries, it is a destructive nightmare for Turkey which is located in a very active seismic zone and its 98% population is under that risk. An earthquake of magnitude M_d 6.0 (M_w = 6.3) occurred on February 3, 2002 at 9:11 local time. The peak horizontal accelerations recorded are around 0.2-0.25 g. The macroseismic epicenter is located near the Sultandagi province and the earthquake is associated with the Sultandagi fault zone. The Sultandagi-Cay (Afyon) earthquake affected a zone of 50 km long and 20 km width, causing important faults and damages. The main purpose of this case study is to describe superstructure faults, damage and failure types and to give some analytical calculation about material quality and seismic behavior about the observation superstructure damages.

Key words: Superstructure damages, performance, failure type, seismic behavior

INTRODUCTION

Sultandagi-Cay (Afyon) earthquake, which occurred at 03.02.2002 and of magnitude M_d 6.0 (M_w = 6.3) according to KOERI (Kaltakci, 2002; www.koeri.boun.edu.tr), affected an area 50 km in length and 20 km in width. This earthquake caused important structural damage to buildings and failures and total dead count is 43 with 325 injured. In Fig. 1 (Erdki *et al*., 2002), NS-EW components spectrum acceleration curves are presented. The major damage was seen in Sultandagi and Cay districts of Afyon City and their villages. The intensity of damage in Sultandagi and Cay is approximately between VII-IX. The most damaged area is Cay. Damage distribution, dead and injuries are given in Table 1 (Erdki *et al*., 2002; Gulkan *et al*., 2002).

After superstructure earthquake failures in Turkey, the blame is put on contractors and reasons of failure are said to be inadequate material use (General Directorate of Minister Affairs, 1999; Aydan, 1997; Dogangun, 2004; USGS). Nevertheless, the problem is not simple like that. After earthquakes, observations show that the causes of failures are similar and can be listed as follows;



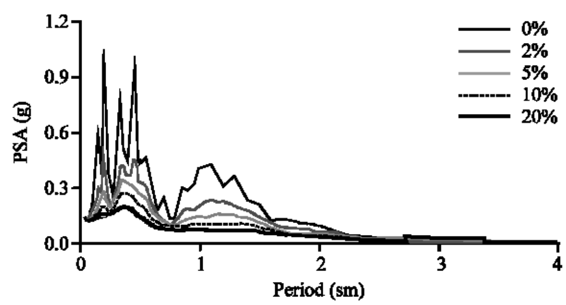


Fig. 1: NS-EW components spectrum acceleration curves are presented (pseudo-acceleration spectra)

- Mistakes made in architectural design of structures (improper geometrical configuration of structure, inadequate dimensions chosen in structural system, wrong placement of load carrying members).
- Inadequate material use.
- Mistakes made in detailing and placement.
- Wrong site selection (mistakes related to soil condition).

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Table 1: Sultandagi-Cay (Afyon) earthquake damage and dead-injury distribution

	Damage condition			Life loss	
Place	House	Commercial	Goverments	Dead	Injury
Bolvadin	65	22	10	1	200
Cay	85	200	3	24	67
Cobanlar	75	5	2	2	21
Merkez	38	15	8	-	7
Sandikli	6	-	3	-	-
Suhut	31	1	2	-	-
Sultandagi	40	3	8	15	30
Total	340	246	36	43	325

Observations made after earthquakes are important since they gives vital key points about earthquake resistant structural design and construction. For that reason, the authors searched the earthquake-affected area after Sultandagi-Cay (Afyon) earthquake and summarized their findings especially about superstructures in this study. In this study, topographic and soil conditions are defined shortly and then the behavior of superstructure and lifeline systems in this region is studied and damaged are outlined. In addition, some analytical calculations about materials and structural behavior is given.

SOIL AND TOPOGRAPHIC CONDITIONS OF THE EARTHQUAKE AFFECTED AREA

Sultandagi district of Afyon is situated near the mountain of Sultandagi (north east side). The soil of the district is alluvium. Also soil conditions vary considerably and this creates a terrible condition from earthquake point of view. Cay district is situated north-east side of Sultandagi Mountain and situated on a inclined (20%) and alluvium ground which is bad for earthquake phenomena. The other districts are situated near Eber lake. The soil condition is loose, sandy, partly clayey and contain high organic material. Due to the fact that, the district is situated near lake side, the groundwater level is near the surface and swamp zones also exist. These conditions resulted in magnification in earthquake effects. This is also dangerous from future earthquakes point of view. For that reason all buildings should be rebuilt at another more suitable place. During field surveys surface fault was seen only in Cay. The fault fracture was seen in the north-east direction (60-75°) and in a zone of 10 m in width. The width of fracture was measured as 25-30 cm while it was 2-3 cm near the bridge under river. In Fig. 2 (www.koeri.boun.edu.tr; Erdik *et al*., 2002) the main shock and the aftershock distribution are presented on a map of region.

FAILURE TYPES OF SUPERSTRUCTURES: OBSERVATIONS AND EVALUATIONS

Superstructure types: Even though Turkey has a modern seismic code that is periodically revised and upgraded to reflect new findings and changes that come into existence in the field of earthquake resistant design, the implementation of this code is limited primarily. This situation can be linked to several factors including lack of technical control and supervision, improper regional construction practice and irregular practices.

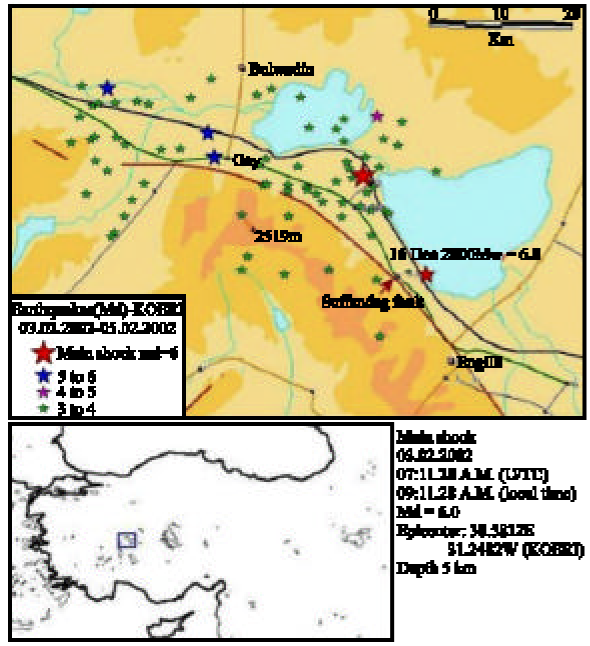

Fig. 2: The main shock and the aftershock distribution

The superstructures in earthquake region can be divided into three categories,

- Reinforced Concrete (RC) frame buildings
- Traditional buildings
  - Stone-masonry type
  - Hybrid masonry type
- Engineered masonry buildings

Observing damages and their causes: Except for RC buildings there are many heavy damaged and totally collapsed unreinforced masonry buildings and himis (Turkish traditional rural dwelling type, timber framed and infill walls are produced from mud bricks) buildings in region. The majority of heavy damage and collapse of RC buildings have been limited to a narrow region in Cay.

Building type-1 (industrial type of buildings): Estimated Peak Ground Acceleration (PGA) in Cay, which is approximately 10 km away from the epicenter, is around 0.20-0.25g. The industrial zone of Cay was deeply affected. Some factories or workshops were heavily damaged. Figure 3 (Erdik *et al*., 2002) shows heavily damaged industrial facility of Cay Town (Kaltakci *et al*., 2002; Erdik *et al*., 2002; Gulkan *et al*., 2002). Most of the

Fig. 3: Industrial facility of Cay town

Fig. 4a: Insufficient material and detail in a beam

Fig. 4b: Insufficient material and detail in a column

buildings of the Cay commercial blocks were destroyed by the earthquake with very heavy damage. Fortunately, collapse of these structures did no cause any fatalities since it was an off-day for the Cay Commercial blocks' workers. The mentioned industrial facilities were placed near Cay river and the soil conditions are sandy and gravelly. Also ground water level was very close the ground and the ground is uncompacted or unconsolidated. All these conditions related with the site of industrial facilities magnify the effects of the earthquake. It must be said that, this factory was built at very unsuitable site.

Fig. 5: Insufficient material and detail in a joint

The mentioned facility was constructed during 1991-1996 and consisting of 4 spans in one direction and 5 spans in perpendicular direction. The typical RC system is repeated for the whole structure. Upper and intermediate floors were made of RC and infill walls were existing between end axes. The lateral rigidity and longitudinal and transverse steels were found to be inadequate. There was also lack of longitudinal reinforcement anchorage and transverse reinforcement spacing was too wide Fig. 4a and b. The concrete quality varies strongly and is poor. Figure 5 shows used big aggregate in concrete mixture. The average strength was calculated as 10-12 MPa. Because of observed concrete degradation, it is concluded that sand and aggregate are dirty and river aggregates were generally used. Although TEC-98 and TEC-75 code's had brought significant restrictions about material quality (for instance, according to TEC-98, in all buildings to be built in seismic zones, concrete with strength less than that of C16 (compression strength of concrete is 16 MPa) shall not be used. However it is mandatory to use C20 (compression strength of concrete is 20 MPa) quality or higher strength concrete in below defined buildings to be built in the first and second seismic zones.), the reconnaissance team of Selcuk University documented that poor quality of concrete is major default of buildings. Concrete quality is a about 10 MPa which was also observed after the 1998 Adana, 1999 Marmara and 2003 Bingol (Sezen *et al*., 1999; Adalier and Aydingun, 2001; Celep and Ozer, 1998). Aggregate granulometre is not suitable, water/cement ratio is very high causing a lower compressive strength of concrete (Fig. 5).

In damaged columns and beams, the transverse ties are smooth rebars of 6-8 mm diameter with 90-degree hooks. The spacing of transverse ties is between 300 mm

Fig. 6: Insufficient material and detail in a column

and 400 mm and there is no confined region. Further, anchorage length, l_b, is less than code's requirement's. In addition, the poor concrete affected anchorage length negatively. The majority of moment-frame component failures was in columns and was due to the use of nonductile details and unconfined lap splices (Fig. 4a and b). Also in columns clear cover was inadequate, plain reinforcing bars were used and hoop angels were 90° instead of 135°. Figure 6 (Erdik *et al.*, 2002) shows insufficient material and detail in a column. According to TEC-98, the longitudinal rebar ratio (ρ_l) ranges between 1% and %4. The authors have observed that in seismic regions column's ρ_l is ranges less than 1%. 12-16 mm diameter smooth rebar are generally used but with respect to TEC-98 minimum bar diameter must be 14 mm. For instance, Fig. 7 shows that the damaged column's ρ_l is less than 1% and the spacing of transverse ties is between 300 mm.

Fig. 7: Buckling column damage in industrial facility of Cay

Figure 4b was taken from damaged beams that had no adequate transverse ties in any section of it. Figure 5 shows damages that were occurred from insufficient material and detail on a beam-column connection.

Some columns have met the buckling damages in this area. During the earthquake, this kind of failure type has been seen rarely. But in this sample, critical load acting on weak column is exceed the limit value of buckling. The limit (critical) buckling load level (Euler's Formula) is given in Eq. 1. In this formula, it is obvious that the critical buckling load decreases with the square of the column length. Figure 7 shows buckling RC column damage in industrial facility of Cay.

$$F_{cr} = \frac{E \times I \times \pi^2}{L^2} \quad (1)$$

The second degree effect and moment is equal to,

$$\begin{aligned} F\omega - M_{second} &= 0 \\ M_{second} &= F\omega \end{aligned} \quad (2)$$

From the Eq. 2, it can be easily seen that, the increase of w causes increasing of second degree moment. In the structural calculation, columns are assumed having small mid-deflection (w), but the column that is represented in Fig. 7 have 35-40 cm deformation and this deformation caused the columns collapse.

Building type-2 (tall buildings): In the west of Cay-Bolvadin highway there were 3 RC structures which were ground floor+7 floors and not occupied at the time of earthquake (S.S. Yesil Cay Dwelling Construction Cooperative). One of them failed and another one is heavily damaged by failing ground and first floor. The third structure was damaged due to differential settlement and rotation of the foundation (Fig. 8).

Fig. 8: Damaged multistory structure

Fig. 9: Highly damaged non-engineered structure

The structural system of the buildings was designed as containing columns and shear walls that were placed in the walls. The average strength of the concrete was found as 8-14 MPa (with Schmith Hammer) and inappropriate detailing of steel and reinforcement caused sliding of bars in the beam-column joints. Excessive lateral and vertical displacements of the mentioned blocks showed that the maximum load carrying capacity of soil was exceeded and structures higher than 3 or 4 stories must not be constructed. This site and neighborhood can be used as green zone. Also in this site it was observed that sand were extracted from river bed was used without washing.

Building type-3 (traditional buildings): Damages in Sultandagi district is observed especially in non-engineered structures which were made from traditional materials and techniques. These are earthen adobe brick (sun dried), semi wooden (bagdadi which is a traditional Turkish rural housing type) and masonry structures. The failed structures were very old and not in good condition. The minarets of some mosques failed due to low quality of mortar (Fig. 9). In this region, the number of stories is generally 2 and the building stock consists of traditional building type that are made with rural and traditional materials. The neighboring structures are adjacent at one side. The materials used are sun dried earthen bricks and wood. The damage was concentrated on non-engineered structures which were one story and earthen adobe or two story wooden structured and infilled with mud. The roof system was, 7 cm clay laid on a 6-8 cm bamboo and wooden beams. After the decay of wooden roof beams, they could not withstand the load of the heavy roof. The walls of damaged buildings were also decayed due to ground water and atmospheric conditions. Also minarets of mosques failed. In this town, there was almost non-engineered structure.

Fig. 10: X Cracks in a masonry structure

Generally the dwellings in this region are also produced with sun dried mud bricks. Structures with 2 or 3 storey can be seen in the region. An important mistake in these structures is that, there is no hatil construction (ring tie beams) It is well known that, the earthquake behavior of sun dried mud (earthen) structures are very poor. The structures throughout this region are heavily damaged or collapsed.

Building type-4 (engineered masonry buildings (burned brick)): The structure which was composed of ground floor and first floor, was constructed with horizontal and vertical wooden frame filled with brick and random stones. Due to lack of water insulation, the wooden frame decayed due to ground water and joints of vertical members failed under reversed cycling loading causing out of plane failure of infill material. Masonry structures, made from factory produced bricks (burned brick), were also damaged. These structures were generally ground+1 or ground + 2 stories and vertical cracks were observed between openings (Fig. 10a). There was no life loss in these structures but they are now unserviceable. Failure of chimneys and overthrow of non framed walls were observed very frequently.

Fig. 11: Bridge damage

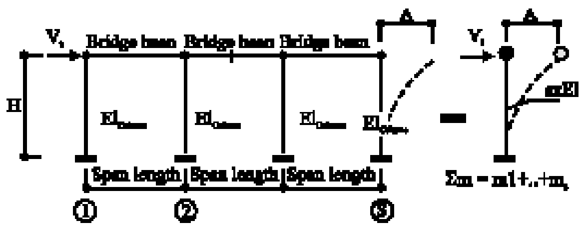

Fig. 12: Displacement of bridge columns under lateral loading

Building type-5 (lifelines, bridges): The behavior of major lifelines of the earthquake stricken region consists on roads. The damage to the roads of the region was very low and most of them remained operational. At the bridge, which is on the road of Afyon-Konya, the following damages were observed, shear cracks at the lateral beams, crushing of concrete in longitudinal beams, 2-5 cm lateral displacement and settlement of infills in longitudinal directions were observed (Fig. 11). The earthquake load acted on bridge caused some lateral displacement. But in this case the most important problem arisen is exceed earthquake codes displacement limits. For a bridge type superstrucrures this limit is (Eq. 3).

$$\Delta \leq 0.02H \tag{3}$$

Figure 12 represents the finite element (bar) model of bridge under lateral loading. The long span pretensioned beams are assumed having hinged column connection. The bridge columns have fixed support and this column behavior is similar to cantilever beam. In the Eq. 4, the method of lateral displacement calculation is given.

$$\Delta = \frac{H^3}{3EI} \times \frac{V_t}{s} \tag{4}$$

The column height is the most dominant factor that effects displacement values directly. In the earthquake-affected region, the bridge column height is 5-7 m averagely. Almost all bridge beams have separated from each other after the earthquake. But there was no falling down beam.

CONCLUSION

Precautions that have to be taken to prevent superstructure failures:

- Site selection must be done considering geotechnical test and number of stories and type of foundation must be determined in the light of scientific parameters. If it is necessary site change can be considered.
- Special care in construction quality control must be given and precautions must be taken to construct earthquake resistant structures.
- Structures in Turkey which are in the first and second earthquake zone of Turkey must be evaluated from earthquake resistance point of view. Non-resistant structures must be retrofitted by specialized civil engineers. Other non-resistant structures, which are not economical to strengthen, such as rural residences, must be rebuilt. Necessary laws and economical conditions must be supplied for that purpose.
- The authors investigation in the affected region shows that, even though 3-4 story buildings are preferred, three 8 story RC buildings were built in the region. Unfortunately two of the 8 story buildings totally collapsed and only one remaining block suffered very heavy damage. It is obvious that the building stock in Turkey faces serious risks about earthquake safety. Observed damage and collapse of reinforced buildings in the region are caused by poor of quality of concrete (about 10 MPa), architectural and structural defect, defects of detailing and defects during construction period.

In this case study, the authors observed damages on superstructures (residential, governmental and industrial buildings etc.) due to lack of control mechanism in construction process and material quality. Due to that fact quality control of construction of materials must be done carefully. The first reason of damage and failure is a non resistant building construction due to not obeying earthquake codes. Also it is important not to repeat the same mistakes made in the past. Also, as stated before, civil engineers, architects, geology engineers and city planners must work together. Also graduated personals must be educated through seminars. Hence the most important factor in earthquake resistance of structures is the dynamic behavior of the building. It is not important to do calculations precisely, if the construction period is not controlled. Under these conditions nobody can buildings, which can withstand earthquake is an adequate manner. For that reason, an active and effective control mechanism must be established in Turkey that does not exist in present.

Since the same mistakes that cause damage and failure, are repeated, the observations after each earthquake in Turkey remain the same. If we don't want to see the same scenes correct precautions must be taken.

NOTATION

L	:	Length of the column.
E	:	Young's modulus of the column material.
I	:	The area moment of inertia of the cross section.
F_{cr}	:	Critical buckling load.
V_t	:	The base shear of earthquake.
s	:	Number of axe.
Δ	:	Lateral displacement.
H	:	Bridge column height.
w	:	The transverse displacement of the buckled column.
M_{second}	:	Second degree moment.

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