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Contents

EDITORIAL: THE DANGERS OF STRUCTURAL IRREGULARITIES

This issue contains two articles that remind us of the importance of avoiding structural irregularities. Even though the focus of the articles is on earthquake engineering practice and performance in two countries, Turkey and Peru, lessons learnt from these countries are relevant for every seismically-prone region.

The first article consists of a preliminary report on the Eastern Turkey earthquake of October 23, 2011. Many buildings are reported as having collapsed due to soft-storey irregularities, including a large number of apartment buildings with their ground floors higher than the storeys above. Such a structural irregularity is an invitation to building collapse where lateral loads in at least one direction are resisted by moment frames. The more flexible columns of the high storey have their strength exceeded and collapse often follows. Unfortunately it appears that few if any reinforced concrete shear walls were incorporated into these buildings since the seismic performance of shear walls is unaffected by uneven storey heights.

Soft storeys are probably the most dangerous of all structural irregularities. The reason is because a soft storey configuration sets up the columns in the soft storey to be damaged. In the event of seismic overload, which can be assumed to occur at some instant during the life of a building, either column bending failure or shear failure will occur. Shear failure, with its forty-five degree crack pattern can lead to an immediate loss of gravity and lateral load strength, but even bending failure reduces horizontal strength and stiffness and results in larger horizontal deflections that lead to building instability. It should also be noted that the two damage scenarios can also occur where the storey heights of a multi-storey building are equal, but where, as is often the case, columns are weaker than the beams. This irregularity, weak columns – strong beams is equally as dangerous.

In the article about school buildings in Turkey and Peru, another structural irregularity is described – the captive or short column. This is also a serious structural irregularity, but in a damaging earthquake it may not lead to building collapse. However it is likely that post-earthquake demolition of the building may be required. Certainly, very serious damage to short columns can be expected and this often leads to local crushing of the columns and significant and unacceptable settlement of the floors above. Frequently, the walls that are responsible for 'capturing' columns in the first place act as props and prevent total storey collapses. The usual approach of preventing captive column failure is to separate infill walls from the columns as illustrated by current Peruvian practice. The combination of limiting seismic interstorey deflections and installing vertical seismic separation gaps has proven to be a very adequate solution.

Virtual Site Visit No. 27: A New Five-storey Commercial Building with Moment and Eccentrically Braced Frames

On this virtual site visit we observe a five storey commercial building under construction. At this stage decorative glass façade panels are being attached. They suggest a three bay moment frame behind them - which is indeed the case, but unlike most buildings, the frame is set back several metres into the building (Fig.1).

It is always challenging to provide lateral load resisting structure parallel to the street frontage of a commercial/retail building. Where a primary objective is to maximize the display window area, shear walls are most unwelcome and even deep (wide) columns are unwanted. In this building, moment frames are chosen to resist transverse forces on the building. We can expect to discover two or three similar frames further back into the building. As seen in Fig. 2, the first floor columns are of RC and above them rise steel columns of steel moment frames to reach the roof level. Note that the structural depths of the columns are less than the widths of the façade panels.

Usually in this type of urban setting where buildings side-by-side face the street, longitudinal forces are resisted by shear walls parallel to the buildings' side boundaries. The walls also function as fire walls. But in this case weak fire walls have been specified, perhaps for speed of construction, or to reduce costs. This has required another longitudinal load resisting system. From Fig. 3 we can make out one bay of a steel eccentrically braced frame. Certainly other bays behind it will be found elsewhere in plan in order to provide sufficient longitudinal resistance.

Finally, note the seismic separation gap between the new and existing building (Fig.4). It is always necessary to build back from one's site boundaries so that, during an earthquake, a building doesn't deflect beyond that line and hammer an adjacent building. Most seismic codes specify the gap that must be provided between the new building and a boundary. The width of the gap depends on a number of factors, but is most sensitive to the flexibility of the building. In order to minimize gap width a stiff, rather than flexible, structural system, is designed. Sometimes designers need to size the structure, like these moment frames, to limit deflections and hence gap widths, rather than to ensure sufficient strength which is less critical.

Fig. 1 Façade panels under erection with structural frame behind.

Fig. 2 The RC columns of the lower two storeys and the upper steel

Fig. 3 One bay of a longitudinal eccentrically braced frame.

Fig. 4 The seismic gap between two buildings. The upper section of flashing has yet to be installed.

M_w 7.1 Eastern Turkey Earthquake on October 23rd 2011

Sources: (Republic of Turkey Prime Ministry "Report on Van Earthquake", Eastern Turkey Earthquake Clearing house "M_w 7.2 October 23, 2011 10:41:21 UTC", European Mediterranean Seismological Centre "M_w 7.2 Eastern Turkey on October 23, 2011 at 10:41:21 UTC")

Earthquake Details

An earthquake of magnitude M_w 7.1 occurred on 2011/10/23 close to the city of Van in Eastern Turkey. The earthquake took place at shallow depth (10km) on the shore of lake Van. It has been largely felt in Turkey and in neighboring countries. More than 600 people died. Around 2000 buildings collapsed and 1350 people have been injured according to the latest reports. The city of Ercis is particularly affected. Rescue teams struggled to help the population and to extract victims from the rubbles. A long series of aftershocks followed the main quake.

On November 9th a 5.7 magnitude earthquake again rocked eastern Turkey, killing at least 7 people and it toppled 25 buildings in the city of Van. This earthquake was located 40 km south of the M_w 7.1 epicenter that struck this region on October 23rd. More than 1352 people were injured and at least 125, 400 people have become homeless due to the earthquake.

There has been significant damage to infrastructure. 14,156 buildings have either collapsed or were severely damaged. Regular incidents of soft storey collapse occurred in Turkish apartment buildings with bottom story height higher than the stories above. Three –to seven storey concrete frame buildings with concrete flat slabs collapsed around urban centers of Ercis and Van. Pancake collapses occurred where columns of multiple levels failed.

Buildings in Van and Ercis Center are predominately 4-8 storey reinforced concrete structures, which is a common in Turkey. In most of these buildings, asmolen slab (in filled joist slab) is used. This system has been observed in many collapsed buildings where two times the normal floor height have been determined. In the villages, buildings consist of mainly adobe, stone and brick masonry construction. These one or two storey buildings are often built by local people without considering regulation, standard and earthquake resistant design rules. In the masonry structures the horizontal and vertical supporting members are made from wood and many are inadequate and placed irregularly. Furthermore the lengths of their connections to load bearing walls are short and weak. The main reasons of damage can therefore be attributed to poor quality construction materials, structures with non-conforming earthquake code and lack of inspection(Fig. 5-8).

Fig. 5 Weak storey and asmolen slab

Fig. 6 Ground floor destroyed

Fig. 7 Example of a collapsed RC frame building

Fig. 8 Weak storey example

Summary of "Performance of Template School Buildings during Earthquakes in Turkey and Peru" by Ayhan Irfanogul. From Journal of Performance of Constructed Facilities January-February 2009.

Introduction

The design and construction process for school buildings owned by the government is well established. Design is carried out by a government agency and reviewed by government/local authority engineers. Also, because of the nature of their occupants, school buildings are designed to more stringent criteria and they are expected to perform better than privately owned buildings during earthquakes.

In this paper the author reviews and compares the earthquake performance of public school buildings in Turkey and Peru. Most of the schools within these countries are built following a small number of template architectural plans. These buildings are generally made of reinforced concrete and have moment frames or a dual system of moment frames and shear walls to resist seismic forces. These templates have similar mass distributions but the structural characteristics depend on the seismic code at the time of construction. These template buildings allow for easy comparison of performance under different earthquakes and seismic codes.

Using these templates as a ground for comparison this paper illustrates the consequences of good and bad practices. In particular, the results of captive columns are shown. Captive columns are those columns that have shortened free height and develop inclined cracks as they deflect under lateral loads. A captive condition is formed in column when adjacent elements, such as infill walls, restrain it from displacing feely. Captive columns are particularly problematic when the elements restraining the column are partial story high, limiting the column free height to 2-4 thickness in the direction of resistance. When the column restraining elements are full story high, captive conditions could develop during an earthquake when these elements deform or crush, letting the column deflect only over a short height. Observations are given from recent earthquakes in these seismically active countries.

Brief History of Turkish and Peruvian Seismic Codes

The Turkish and Peruvian seismic codes developed differently. The Turkish code was written in 1940 following the 1939 Erzincan earthquake disaster and was initially based on the Italian code. Following developments in earthquake engineering and earthquake resistant design approaches in the United States during the 1960s, ductile detailing provisions and spectra-based design load calculations have formed the basis for the Turkish seismic codes. The Peruvian code was first established in the mid 1960's; taking the United States practice as a guide from the start. The current Turkish code was published in 2007 and the current Peruvian seismic code was published in 2003. Both these codes are similar to the respective 1997 codes that preceded them.

In this paper the 1997 Turkish and Peruvian seismic codes as well as older codes are discussed in greater detail. However because of the similarities between the 1997 codes and the current codes, observations from newer structures would apply to buildings under the current codes.

Code Requirements for School Building Design in Turkey and Peru

The 1997 Turkish and 1997 Peruvian seismic codes provide near identical formulations for the calculations of the base shear force demand. This information allows for the design base shear force coefficient for two to four-storey reinforced concrete moment-frame school buildings built on stiff soil sites in the highest seismic zone in either county to be calculated. The design base shear force coefficients determined by both codes are approximately the same at 18%. This means for the described conditions that both codes require the lateral force resisting elements be designed for at least 18% of the "seismic weight" while satisfying the allowable lateral drift limits. For reinforced concrete structures, the 1997 Turkish code permits the allowable interstory drift to be 2% while the 1997 Peruvian code limits it to 0 .7%.

In reinforced concrete shear wall school buildings, both codes reduce the seismic load reduction factor to ¾ that of the reinforced concrete frame buildings. The design base shear force coefficients are 0.23 in Turkey and 0.24 in Peru. In moment- frame and shear wall dual system reinforced concrete school buildings the design base shear coefficients are computed as the average of the values for frame-only and shear wall-only resulting in values of 0.20 (Turkey) and 0.21 (Peru). The same allowable interstorey drift ratio limits as for reinforced concrete structures apply.

Turkey: Template School Buildings

The template plans used in the construction of most of the reinforced concrete school buildings in Turkey are given in Fig. 9. The footprint of these structures is 34 x 17.5 m. The same plans are used for 2 to 4-storey buildings. Dimensions of the columns are 0.3 x 0.5 m and typical dimensions for beams are 0.3 x 0.7m. Shear walls are 0.2 m thick.

The plastered hollow clay-tile masonry infill walls are 25 cm thick for interior walls and approximately 40 cm thick for exterior walls. These walls are built flush to the structural elements. Along the perimeter of the building, and often adjacent to the columns, several window and door openings are made in the infill walls.

In structures with moment-resisting frames only, there are 43 columns in the typical floor plan, 24 of which have the strong axis oriented in the short direction of the school buildings. The total column area at ground level in the moment-resisting frame-only school buildings is approximately 1% of the floor area.

In dual system school buildings, the floor plan is the same except two bays of interior masonry infill walls in each principal direction are replaced with 20 cm thick reinforced concrete shear walls. There are 29 columns at each story in the dual system. 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.

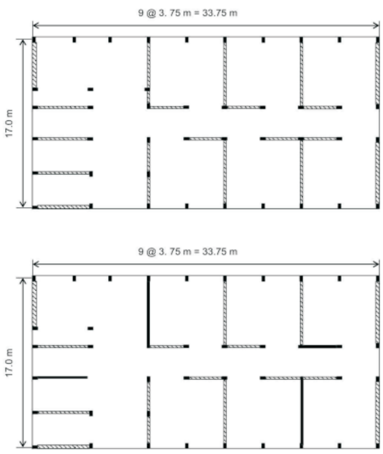

Fig. 9 Floor plans for template reinforced concrete moment-resisting frame (top) and dual system (bottom) school buildings in Turkey: (solid small rectangles) columns; (solid elongated rectangles) reinforced concrete shear walls; (hatched elongated rectangles) full-bay masonry infill walls; and (solid lines) perimeter masonry infill walls with openings

Fig. 10 Two-storey template reinforced concrete dual system school building in Kaynasli near Duzce. Building did not sustain structural or nonstructural damage during august 17,1999 and November 12, 1999 Duzce earthquakes.

Turkey: Performance of Template School Buildings during 1999 Kocaeli (M_w 7.6), 1999 Duzce (M_w 7.2), and 2003 Bigol (M_w 6.4) Earthquakes

The seismic performance of template reinforced concrete school buildings in Turkey can be judged by their response to three recent earthquakes. A total of 21 template school buildings affected by these earthquakes were surveyed: five reinforced concrete dual system school buildings in the Duzce region and 16 reinforced concrete moment frame school buildings in Bingol after the May 1, 2003 earthquake.

Figure 10 shows a two story reinforced concrete dual system template school building built according to the 1975 Turkish seismic code. Despite close proximity to the fault, the dual system building sustained no damage during the two earthquakes in 1999.

Fig 11. View of dual system reinforced concrete template school building in Duzce after November 12, 1999 Duze Earthquake. Captive exterior columns in basement failed.

Fig. 12 Three story reinforced concrete moment-frame template school building with captive columns in Bigol before and after the may 1, 2003 Bingol earthquake.

Fig. 13 Another view of collapsed school building. Note Column failure near beam joint.

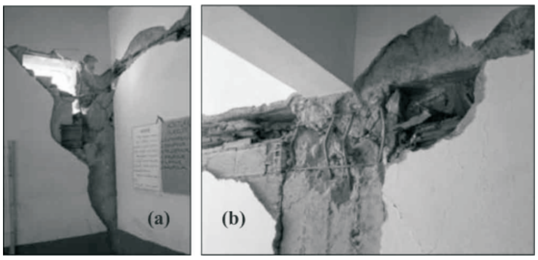

Fig. 14 Typical captive column failures observed in: (a) exterior; (b) interior columns restrained by full-bay masonry infill walls.

Fig. 15 Captive Column condition due to adjacent infill walls providing sufficient restraint in their out of plane direction.

Figure 11 shows another dual system reinforced concrete template school building. This one is four stories and sustained no damage in its shear walls. However the structure suffered heavy damage at its perimeter columns at the basement level. The infill masonry walls restrained the perimeter columns forcing them to deform over a very short length resulting in the formation of a captive column condition. As such, the captive columns failed in shear before they could develop their flexural capacity fully.

The performance of template school buildings in which reinforced concrete moment-resisting frames form the lateral load resisting system were documented after the May 1, 2003 Bingol earthquake. Figures 12-13 show a three-story school building in Bingol after it was built in 1999 and after the 2003 Bingol earthquake. During the earthquake, the first-story columns failed, lowering the second floor to the ground level.

The most common failure patterns in interior and exterior columns that were initially restrained by full-bay masonry infill walls are shown in Fig. 14. These failure patterns indicate that captive column conditions can develop dynamically in columns restrained by full-bay masonry infill walls. Infill walls in contact with a column could cause formation of captive column conditions in directions orthogonal to their longitudinal axes. Figure 15 shows the state of a captive column in a three-story reinforced concrete moment-resisting frame template school building in Bingol after the 2003 earthquake. The crack patterns indicate that the infill walls constrained the columns in the direction perpendicular to the walls causing shear failure in the columns.

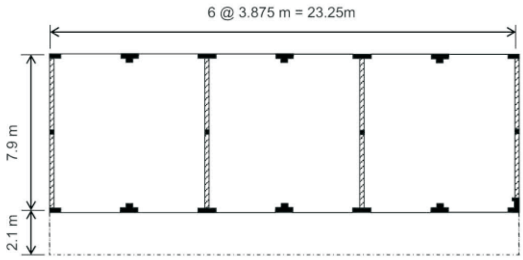

Fig. 16 Floor plan for template school buildings in Peru built according to 1997 code: (solid rectangles/squares/t-shapes) columns; (hatched rectangles) confined masonry walls; and (solid lines) perimeter masonry infill walls; 2.1 m balcony overhange is also shown.

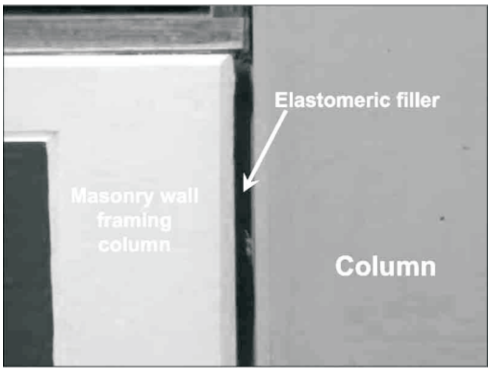

Fig. 17 Separation between structural column and nonstructural perimeter wall assembly

Peru: Template School Buildings

The template plan for school buildings built following the 1997 code in Peru is given in Fig. 16. The footprint of these structures was approximately 23.4x7.4 m with 2.35 m balcony overhangs. Typically these school buildings have 1-4 stories. Lateral loads are resisted by reinforced concrete moment resisting frames along the longer axis of the structure and confined solid masonry walls along the shorter axis of the structure. The reinforced concrete columns are either rectangular shaped with 0.9 x 0.25 m cross section or have a T-shaped cross section with a 0.9-1.2x.25 m flange and a 0 .2 x 0.3m stem.

The thickness of the confined masonry walls is 30 cm. These walls are typically 7m in length spanning between rectangular columns and act in the longitudinal direction of the building. The solid confined masonry walls have a 30 x 30 cm column at mid-length. The face perimeter beams typically measure 25 x 55 cm in cross section. The non-structural perimeter walls below the window openings are 13 cm in thickness and made out of masonry. A reinforced concrete perimeter frame, made out of a

Fig. 18 Template school building designed according to 1977 code after 2001 Atico earthquake: (lower left) ground story column; (lower right) second story column

Fig. 19 Front and back views of reinforced concrete template school building built in accordance with 1997 Peruvian seismic code seen after June 23, 2001 Atico, Peru earthquake. School is located in Arequipa region. Structural and nonstructural elements sustained no damage.

13 x 10 cm beam and two 13 x 25 cm columns, confine the non-structural masonry walls. There is a 2.5 cm gap between infill walls and the structural columns of the building. This gap is filled with elastomeric material to protect the building from the outside climate effects (Fig. 17).

Peru: Performance of Template School Buildings during 2001 Atico Earthquake.

Figure 18 depicts a two-story reinforced concrete template school building in the coastal area of the Arequipa region. This building was designed according to the 1977 Peruvian seismic code where the infill wall assemblies were not separated from the columns sufficiently. The architectural infill wall assemblies restrained the columns inappropriately and caused them to fail due to the resulting captive column condition.

In contrast school buildings built following the 1997 code that were shaken in the region during the 2001 Atico earthquakes sustained no damage in their structural or non-structural elements. Fig. (19) shows the front and back from the school buildings in the Arequipa region, designed and constructed by the 1997 code. A view of the elastomeric material filled 2.5 cm gap region from this school building can be seen in Fig. 17. None of the template school building designed and constructed per the 1997 code sustained any structural or non-structural damage during the 2001 Atico earthquake.

Conclusions

Modern Turkish and Peruvian approaches to seismic design of reinforced concrete structures are similar with regard to procedure and minimum requirements for strength of lateral load resisting structural elements. However, recent Peruvian seismic design codes require these structures to be designed much stiffer than the earlier codes. The Turkish seismic design codes allow the structures to be more flexible. Based on the performance of the template reinforced concrete school buildings during recent earthquakes in Peru and Turkey, it could be concluded that captive columns are the leading cause of heavy damage and at times, cause collapse in these school buildings.

In the case of school buildings in Turkey, it was observed that the presence of shear walls improve performance of the structures significantly compared to those seen in moment frame only structures, but that they are no guarantee of damage-free performance. In the case of school buildings in Peru, it was observed that starting with the 1997 Peruvian seismic design code, the new Peruvian approach eliminated captive column conditions altogether by requiring the structural systems designed to be significantly stiffer and constructed with adequate separation between structural and non-structural elements. This new Peruvian approach has been producing school buildings that perform excellently even during strong earthquake ground shaking.

Earthquake Hazard Centre
Promoting Earthquake-Resistant Construction in Developing Countries

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