EARTHQUAKE HAZARD CENTRE NEWSLETTER

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Editorial: Learning from an earthquake

Last weekend I was at the Annual Conference of the New Zealand Society for Earthquake Engineering. It was held in Christchurch and was by far the best attended of any Society conferences. There is nothing like a damaging earthquake in one's own country to galvanise interest and concern! The conference theme was "Implementing Lessons Learnt", presumably from the Canterbury earthquake sequence, but it seems like it's really too early to be sure what the lessons are.

Many of the conference papers were based on the Christchurch earthquakes or at least responded to them in various ways. As we were meeting, damaged buildings in the central business district were still being demolished. It is shocking that over 50% of the high-rise buildings will suffer this fate. Some, if not many, could have been repaired but it seems that owners are not at all keen to repair their damaged (mainly) reinforced concrete buildings. (The damaged unreinforced masonry buildings have already gone.)

It was said that the fact that only three RC buildings collapsed was evidence that our buildings performed well. We need to remember that the ground accelerations were over twice those the buildings had been designed for. But there was a general feeling that we as structural engineers need to do better. However, before looking towards the future, here are some of the weaknesses of RC design and construction that have been exposed:

- Under the seismic overload the beam flexural steel yielded and the beams elongated and in many cases tore the floor diaphragms which were left with many wide cracks and precast ribs etc only just having enough seating to support their weight.

- Some shear walls also yielded and they too elongated. As they pushed up they attracted additional vertical loads from the surrounding structure for which they were not designed.

- Lightly reinforced beams and walls experienced just one major flexural crack which led to bar rupture. Rather than the well-distributed region of heavy cracking in plastic hinges that is observed in most laboratory tests, the plasticity was concentrated over such a short length that low-cycle fatigue or tension failure was inevitable.

So where will all this lead? Obviously, these and other observations of damaged RC structures need to be analysed with a view to reviewing our current methods of designing ductile RC buildings. Certainly beam elongation must be prevented and already RC beams with slots at their ends that force tension and compression yielding only in the reinforcement at the bottom of the beam are on drawing boards. Damage avoidance approaches using the PRESSS system are going to become a lot more common and more building owners will probably be attracted to base-isolation – and why wouldn't they when this technology can prevent most earthquake-related building damage at a very reasonable price. Given recent large increases in insurance premiums, base-isolation which may cost as little as 3 – 4% of the total building cost, can pay itself off in less than ten years

As you can see, there is still much to learn and so much implementation of those lessons in the future!

Virtual Site Visit No. 28: Precast panel light-industrial building

As we visit this site we can see the precast panels have been placed on and connected to the foundations. Also, at about one third of their height, the panels are joined by welded plates that tie them together along their plane, effectively creating one long precast concrete shear wall. At this stage of construction the panels are very vulnerable to out-of-plane loading and so are propped until permanent structure is attached (Fig. 1)

Figure 2 shows the eaves bond beam in the form of a steel I beam on its side. This beam is part of the lateral load-resisting system. First of all, it resists seismic inertia forces that occur on the top half of the panels (the bottom half of the inertia forces travel in bending and shear in the panel to the foundations). Secondly, this horizontal member will be one of the two longitudinal roof plane truss chords. The other chord runs parallel to it and is the circular tubular section located approximately half way between the wall and the roof apex (Fig. 3).

The roof plane truss is not yet complete. The steel rod cross-bracing has yet to be installed. When completed, together with the cross-bracing, the chords will form half of the cross-braced roof diaphragm. Its job is to resist half of the inertia forces from the top half of the building acting parallel to the steel roof rafters, and transfer them by truss action to the precast shear walls at rear and front of the building.

At the rear of the building, that section of the roof diaphragm on the left-hand side of the building will be able to transfer the horizontal forces directly into the rear shear wall, but this is not possible at the front due to the large opening. That is why the steel bond beam spans across the opening. One of its roles is to resist the forces from the near end of the cross-braced diaphragm and transfer them across the opening into the front precast concrete shear wall.

Fig. 1 Precast concrete wall panels are propped in place.

Fig. 2 Horizontal steel eaves member that functions as a roof diaphragm chord, bolted to the panels.

Fig. 3Steel rafters with chords for the cross-braced steel roof diaphragm. Rod cross-bracing is yet to be installed.

LEARNING FROM EARTHQUAKES

A summary of "the EERI Special Earthquake Report - April 2012 - The M_w 7.1 Erciş-Van, Turkey Earthquake of October 23, 2011",

by Rafael Alaluf, Ricardo Hernandez, Cemalettin Dönmez and Ayhan İrfanoğlu.

Fig. 4 Examples of deficient reinforcement detailing, poorly graded concrete mix, substandard concrete casting (photos: Alaluf, Dönmez, İrfanoğlu, METU group).

Introduction

At 1:41 pm local time on Sunday, October 23rd, 2011, a M_w 7.1 earthquake struck Van Province in eastern Turkey. The earthquake claimed 604 lives. The town of Erciş, with a population of 77,000, was hit hardest. Located about 40 km NNW of the estimated epicenter, it had 191 buildings collapse totally or partially, killing more than 600 people. Van, the larger provincial capital located about 15 km SSW of the estimated epicenter, was mostly spared, with only six buildings collapsed. On November 9th at 9:23 pm local time, a M_w 5.6 earthquake struck about 10 km SW of Van. This event claimed 40 lives and caused further damage in the city of 332,000, including collapse of 25 buildings, most of which had been condemned following the earlier earthquake.

Building stock and construction type

The dominant types in the region are one- to nine-story reinforced concrete (RC) buildings with infill walls and moment-frame or moment-frame and structural walls, and one- to two-story bearing-wall buildings. Buildings constructed before 2000 tend to be one to four-stories high. The majority of the buildings have full or half-basements. With the population growth in the provincial capital and the economic boom in the region over the last decade, many taller buildings of eight to 12 stories have been put up in Erciş and Van in recent years. In Erciş, where nearly 200 buildings collapsed totally or partially, most of the casualties occurred in the newer and taller buildings. We learned from local engineers that ready-mix concrete became available in the last 3-4 years, and that there has been widespread use of poorly washed sand and gravel from local creeks. Inspecting the debris of collapsed structures showed a number of deficiencies: insufficient confinement reinforcement and 90-degree hooks in transverse rebars, use of smooth rebars, improper splicing of column longitudinal reinforcing bars, poorly graded concrete mix design, and substandard concrete casting (Fig. 4). Apparently, the new RC structures were designed by engineers, but they had no quality control during the actual construction of the building. Our local contacts noted that the construction process had become so informal that land owners would hire separate local specialty workers (for formwork, rebar placement, concrete casting) and not even hire a contractor to organize the process. Few, if any, inspections or quality control checks were done.

The widespread poor material use and construction quality do not explain the variation in damage in the building stock. We observed that a majority of the damaged buildings suffered from obvious fundamental design errors such as inadequate lateral-load resisting systems, soft-story at ground level (tall and open-front ground story for commercial use), mezzanine level construction resulting in disproportionate stiffness distribution and loading of structural elements at the ground story, floor torsion, flexible block-infill joist floors, strong-beam/weak-column, pounding, and captive columns.

The majority of the commercial activity in the region takes place in mixed-use buildings. These structures are occupied by the commercial units at the first (ground) story and by residential units at upper stories (Fig. 5), particularly along the main streets. In older mixed-use buildings, lower stories are stripped of their partition walls because of commercial activity. In newer mixed-use buildings, lower stories are taller than upper stories and again lacking partition walls, particularly along the street

Fig. 5 Typical mixed-use buildings in Van (top) and Erciş (bottom) (photos: Dönmez, İrfanoğlu).

Fig. 6 Heavily damaged RC structure with tall ground story (photos: Dönmez, İrfanoğlu).

side of the buildings. Such a structure can be seen in Figure 6.

In most of these buildings, mezzanine floors are constructed to provide additional office space. Typically, the mezzanine floor slabs are wrapped around the elevator core, which typically consists of structural walls. The resulting extreme difference in the stiffnesses rendered these structural walls vulnerable.

Residential buildings not on main streets are typically free of commercial units. These residential buildings performed generally better during the earthquake. Newer mass housing buildings north of Van built mainly by TOKI, the Housing Development Administration of Turkey, sustained no damage.

Even though there are no ground motion records from Erciş or Van for the October event, it is believed that the levels of ground shaking in these towns were such that architectural infill walls, in general, assisted the actual lateral load-resisting structural systems in the buildings. However, in certain cases, these supposedly nonstructural walls interacted with the structural systems to the detriment of the latter by forming captive column conditions either from the beginning of or during the dynamic response of the building. In adjacent buildings with insufficient separation, pounding damage was observed.

The typical floor structural systems in the RC structures are two-way slab systems and infill joist floor systems, the latter being found mainly in buildings built in the last five years.

There is a tendency to have structural walls in five-story or taller buildings constructed recently. However, we observed new or under-construction buildings with improperly positioned structural walls that resulted in floor torsion.

There are few buildings with structural walls. Except in some of the school buildings, which will be discussed below, structural walls were usually not adequately proportioned. Still, walls around elevator shafts did tend to reduce damage to the rest of the structure though they sustained considerable damage themselves.

In Gedikbulak, a large village with 250 buildings located about 15 km NW of the October earthquake epicenter, a three-story primary school building with structural walls collapsed during the earthquake (Figure 7). The building, constructed in 1988, had an approximately 14.4m x 21.4m footprint. It had two 7.2m x 0.3m structural walls along its plan long direction built on one end of the building and only columns, some of which were captive, at the other end. Two 4.6m x 0.3 m structural walls bordering the stairwell, which was near the centerline, acted as the main lateral load-resisting elements in the plan short direction. The seven 0.5m x 0.3m columns around the building perimeter were the sole vertical structural elements along one half of the building front, although four 0.3m x 0.3m interior columns were also present. The collapse configuration evidenced floor torsion as it appeared that the building twisted in plan as it slumped.

Buildings in low-income districts in the region are typically constructed either with concrete masonry units as bearing walls for single-story buildings, or with reinforced concrete frames with masonry infill for up to two-story buildings. These structures commonly have light timber roofs with light gage metal covers. Most of these structures survived the earthquake with no damage, an indication that their elastic limits were not exceeded. Buildings in villages are constructed typically as bearing-wall structures using concrete masonry units, bricks, or rocks. The typical failure mode in these structures was out-of-plane wall failure due to the absence of diaphragms tying the walls together (Figures 8 and 9).

Recommendations

Without doubt, Turkey has the structural engineers, seismic design code, and construction know-how to avoid earthquake disasters of this scale, but the damage clearly demonstrated that improvement is needed in pre-earthquake mitigation. Almost all of the damage and deaths were caused by the collapse of inadequately designed and constructed buildings, particularly buildings built during the last decade. Modern buildings should have had light damage, given that the shaking intensities were moderate, but they were not properly designed and/or not properly constructed. Obviously, an advanced building seismic design code does not guarantee good performance of buildings and their contents.

Design and construction. The building designs in seismic regions such as Van region should incorporate more and better distributed structural walls. Building lateral load resisting structural systems and the infill walls should be designed considering their possible interaction during earthquakes. In the current construction style the unreinforced infill walls are wedged between and flush with the structural elements. As a result, the infill walls are engaged in the structural response even though, at least on paper, they are supposed to be nonstructural elements. While these infill walls may sustain little damage at low-intensity shaking, during stronger shaking they are damaged, typically in the form of widespread cracking and even crushing. Crushing of the infill walls can cause development of captive column condition which often results in premature, brittle failure of affected columns.

Given the observed high frequency of destructive earthquakes in Turkey, it would be worthwhile to revisit the code-specified drift ratio limit considered for the design level earthquake. It is possible that lowering this drift limit would provide long-term benefits that outweigh the short-term costs.

This report was edited by Sarah Nathe, EERI Newsletter Insert Editor.

Fig. 7 The three-story primary school in Gedikbulak village after collapse (photos: Erdil, İrfanoğlu).

Fig. 8 Typical out-of-plane failure of concrete masonry unit bearing walls (photos: Alaluf and Bedirhanoğlu).

Fig. 9 Failure of mud brick bearing walls in Gedikbulak village (photo: İrfanoğlu).

A Summary of "Performance of the San Salvatore Regional Hospital in the 2009 L'Aquila Earthquake"

Earthquake Spectra, Volume 28, No.1, 2012, pages 239-256 by H. John Price, Adriano De Sortis and Marko Schotanus.

Fig. 10 Location of collapsed masonry infill and veneer from above the entrance portico (the debris had been cleared away at the time of visit).

Introduction

The 6 April 2009 L'Aquila earthquake, $M_w = 6.3$, occurred at 3:32 a.m. in the central valley area of the Abruzzo region of Italy. The epicenter of the earthquake was approximately 4 km south of the site of the San Salvatore Hospital, the centralized emergency treatment facility for the region most heavily impacted by this seismic event. Some hours following the earthquake the hospital was ordered closed as a precautionary measure and patients, including earthquake casualties, were transferred to other hospitals that were generally a significant distance away.

Description of the Hospital

The San Salvatore Hospital is a centralized regional emergency treatment facility with over 500 beds, serving a community of about 100,000 inhabitants in an area of approximately 1,800 km^2. It is located on the outskirts of the town of Coppito, a few kilometers from L'Aquila, the administrative center of the Abruzzo region.

The hospital campus comprises approximately 14 buildings with separation joints between and within some of them, resulting in several more independent structural units. The structural units are three- to five-story reinforced concrete frames, with infill hollow clay block walls and brick masonry veneer exteriors, both unreinforced and not designed as part of the structural system.

Performance of the Hospital

The hospital continued to operate for several hours (with some, but not all, operating rooms) after the initial seismic event and to accept casualties brought in during the initial hours, even though processing of the new emergency admissions was hindered by masonry debris that had fallen from the building above the access portico of the emergency and main entrance.

Performance of the Structural System

Generally, the concrete framing of the hospital buildings performed adequately, especially if one compares the ground motion intensity to the design loads, with significant damage limited to isolated columns in three structural units on the campus (Fig. 10).

Several lower-level columns (four to eight in total) comprising the entry portico of the main entrance and emergency entrance suffered partial failure without collapse or noticeable deflection at the tops of these frame elements. The concrete cover at these locations spalled, the inner concrete core of the column appeared to have a slight offset, and the vertical reinforcement was exposed and buckled (Fig. 11). Column tie reinforcement was not observed and appears to be either very widely spaced or to have been omitted, at least at these locations. Our reviews to date indicate that, at least, a level of column tie reinforcement consistent with the 1967 design of the hospital had been intended. The portico could be considered something of a soft-story condition, as the levels above it had significant infill masonry.

A series of lower-level columns in a second building containing the pharmacy suffered damage typical of short-column behavior. Approximately six columns were thus affected, but even in the worst case a considerable vertical load capacity remained after the earthquake. The concrete cover spalled off, exposing the tie reinforcement, and in the worst cases there was some cracking to the core concrete. No collapse or noticeable deflection had occurred. The short-column condition arose because of infill masonry between the columns, capped by a rigid precast concrete wall cap.

Finally, poor structural detailing of certain seismic joints led to local damage at one column supporting the elevated corridor structure that connects the buildings on the hospital campus. Frequently, seismic separations were not achieved by bringing separate but adjacent vertical members up from a common footing, but rather, by having adjacent upper-level portions of the building supported on a common wall or a common column. In the case of one narrow column this caused local damage to the column and a loss of bearing.

At the level of seismic shaking experienced by the hospital structure, it seems reasonable to conclude that the primary lateral resistance was provided by unreinforced hollow clay tile infill masonry. The majority of this infill was generally undamaged (though some had minor cracking). The concrete frame did not perform well in the locations where it, rather than the infill, resisted the lateral load (see above). It would seem that structural damage to the concrete columns was the primary reason for the closure of the hospital, rather than nonstructural damage.

Performance of Nonstructural Components

It was generally observed that from a seismic engineering point of view, the joints between adjacent buildings and structural units were poorly detailed and constructed. Some joints were likely intended to only be expansion/contraction joints, and even as such could have been better configured. Because of this style of detailing, and because the joint width (capacity) of the exterior brick veneer and the interior hollow clay tile infill and plaster was generally less than that between the concrete structural elements, there was localized damage to the exterior veneer and interior infill and plaster, including local collapse of some exterior veneer (Fig. 12).

In one instance, a 30 to 50 mm-thick layer of plaster over a seismic separation joint at one end of a stairway created both a falling and tripping hazard. To the extent that pounding occurred, adjacent floors and the roof were constructed at the same elevation.

As noted above, the major nonstructural issues were related to the exterior masonry veneer. This unreinforced veneer was often poorly detailed at movement joints. The ties between the exterior veneer and the interior infill and concrete frame elements were widely spaced. Nevertheless, only a few panels of veneer were dislodged and fell outward. In these instances, it appeared that only a limited number of ties had been used between the exterior veneer and interior infill. Other than over the emergency entry roadway, these local collapses generally occurred in exterior zones of the facility with little traffic below them. Had the seismic event occurred during a time of the day when the facility was at maximum occupancy, injuries and fatalities may well have occurred.

Fig. 11 Damage to a separation joint that occurred over a shared column.

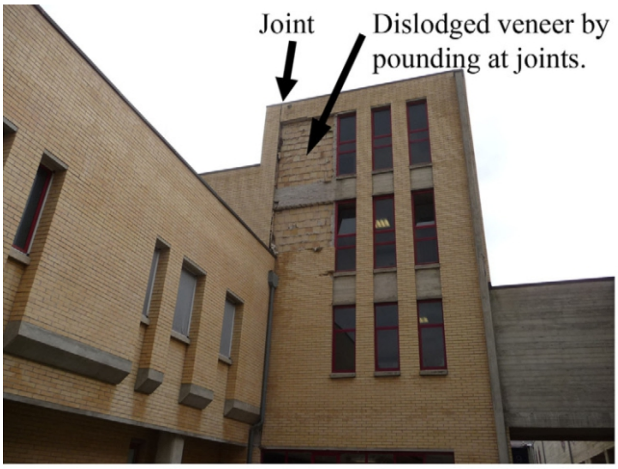

Fig. 12 Veneer dislodged by pounding at joints.

or treatment rooms. The ceiling was distorted in limited areas. This ceiling system performed very well.

The central plant and building utility provision of the hospital typically performed to the desired standard. Emergency systems kicked in with flawless operation. Since being inspected by ATC in 2003, several components of this plant had been adequately retrofitted and restrained. This effort appeared to have been performed by the on-site facility manager on an ad-hoc basis, rather than a systemic requirement from administration. Most of the heavier components at risk of overturning had been restrained.

Conclusions and Questions that could apply to hospitals generally, not just this facility

Decisions to close part or all of an essential facility such as a hospital can be easily made in the heat of the moment after an earthquake. Sometimes such decisions may be based on local political factors (not least of all, the appearance of doing something quickly to protect safety) and may be made without appropriate technical and professional input regarding realistic safety concerns. Decisions to re-open portions of such a facility are far more complex and raise a large number of operational issues that are not likely routine within the hospital's operation.

The U.S.-Italy collaborative program reports contain a comprehensive set of recommended practices to help hospital operators improve the seismic safety of their facilities and prepare for a seismic event. The on-site, case-specific experience at the San Salvatore Hospital confirmed the validity of these recommendations, which include, among other items:

1. Seismic vulnerability assessments of structural and nonstructural components;

2. Mitigation of hazards and reorganization of health functions;

3. Development of post-earthquake inspection procedure and preparation, and;

4. Training.

While the general topic of seismic vulnerability assessments (the first recommendation above) has been advanced in both the United States and in Italy, no site specific building specific assessments of this hospital campus were reported to have been performed before the earthquake besides the inspections that occurred within the scope of the U.S.-Italy collaborative project. As insights into potential vulnerabilities continuously change with the advancement of research and through lessons learned from earthquake occurrences, hospital operators should reassess the need for the reevaluation of their buildings on a regular basis. Regarding the second recommendation, specific on-site mitigation of hazards appeared to be limited to nonstructural items, as described earlier in this paper, rather than to the structures themselves. The post-event reorganization of health functions was well planned and well executed, although in a rapidly deployed tent hospital format.

Community expectations need to be appropriately managed both before and after an earthquake event, especially regarding the serviceability and continued operation of an essential facility. There needs to be an understanding that some damage at the facility is to be expected and is normal. It is noted that even though the current Italian seismic code contains requirements for the operational continuity of hospitals, the design-level ground shaking for that particular limit state has a return period of less than 100 years (a level of shaking lower than that experienced in this event). Thus operational continuity after a rare event is not a strict design requirement for new hospitals. While many people may expect continued post-event operation, that goal may not actually be fully achieved and some disruption is to be expected. Plans need to exist to manage housekeeping disruptions (local dust, debris, fallen contents, etc). The existence and implementation of the post-event safety inspections is an integral part of this management of expectations. Management of realistic expectations is also vital to the continued operation of an essential facility.

Conclusions that may be specific to this hospital, but also affect others

Aside from limited and localized structural damage to portions of three buildings, the most noticeable systemic problem at this facility relates to its seismic separation joints, which did not perform adequately, most noticeably affecting the exterior and interior finishes and the inadequately anchored exterior veneer. Local exterior veneer collapses were the result of inadequate anchorage of the veneer and pounding of the veneer across seismic movement joints (as a result of the poor detailing of those joints).

Based on the level of contents displacement within the facility, which would be described as slight-to-moderate, it may be that an appropriate description of the seismic shaking experienced by the facility is significant, but nevertheless moderate. More intense shaking seems possible and should be considered when reviewing our observations reported in this paper. The fundamental question remains: What would the performance be at more intense levels of seismic shaking?

Earthquake Hazard Centre
Promoting Earthquake-Resistant Construction in Developing Countries

The Centre is a non-profit organisation based at the School of Architecture, Victoria University of Wellington, New Zealand.

Director (honorary) and Editor: Andrew Charleson, ME.(Civil)(Dist), MIPENZ
Research Assistant: Kate Bevin (BAS)

Mail: Earthquake Hazard Centre, School of Architecture, PO Box 600, Wellington, New Zealand.
Location: 139 Vivian Street, Wellington.
Phone +64-4-463 6200 Fax +64-4-463 6204
E-mail: andrew.charleson@vuw.ac.nz

The Earthquake Hazard Centre Webpage is at :
http://www.vuw.ac.nz/architecture/research/ehc/