EARTHQUAKE HAZARD CENTRE
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Contents

EDITORIAL: MASONRY INFILL – A BLESSING OR A CURSE?

Findings from the 6 April 2009 M_w 6.3 L'Aquila, Italy, earthquake throw some light on this difficult and reoccurring question. Later in this newsletter we summarize a research paper that reports on building damage during this quake.

Over 60,000 buildings were damaged. While most were built from unreinforced masonry and stone there were many RC frame buildings included in this group. These were typically 2 – 4 storeys, or even higher, with infill walls. On the exterior there were two layers of hollow brick, and sometimes three. It appears that the intensity of the ground motions exceeded design strengths leading to the collapse of non-ductile structures. It is reported that modern RC-frame infill structures performed relatively well – and that although infills were damaged, the RC frames "remained intact". The authors believe that "infill walls may have played a very significant role in preventing many of the damaged non-ductile framed structures from collapsing"

But one of the features of this quake was its short duration - only 5 to 10 seconds of strong shaking, and as a few as three cycles of high intensity excitation. This is seen as the reason that many more non-ductile structures didn't collapse. The authors warn that "a longer duration of shaking could have further deteriorated or completely eliminated the positive affect of infill walls".

So how does this help answer the initial question? It would seem that the answer is "it all depends!" Evidence from this earthquake suggests that infill walls might be helpful in short duration quakes – but who can guarantee that! We also know from the bitter experience of tens of other damaging quakes how infills cause vertical irregularities like soft-storeys. If infill walls aren't distributed evenly up the height of buildings beginning at ground level they are an invitation to collapse.

Where does all this leave us? The authors leave us in no doubt. They recommend against designing RC frames with infill walls, and suggest that structural system, flawed as it may be, should be replaced with ductile shear walls. Such a recommendation is not new. This advice is similar to that given in the 2006 World Housing Encyclopaedia's RC frame tutorial "At Risk – the seismic performance of reinforced concrete buildings with masonry infill walls. " This quite non-technical document can be downloaded from http://www.world-housing.net/. It outlines the problems of infill walls clearly and then suggests methods to overcome them, including using RC shear walls. However it does have other strategies that include structurally separating the infills from the frames – but that is topic of its own!

Virtual Site Visit No. 23. Apartment building with RC shear walls and steel gravity structure.

In this site visit we return to the site of Virtual Site Visit No. 22 where the focus was on the deep beams over piles to support the two transverse shear walls when they are subject to horizontal forces and therefore experience very large bending and overturning moments at their bases.

Now the superstructure construction is well under way. In Fig. 1 the transverse load resisting shear wall reinforcement and the slender gravity-only steel columns are visible. Fig. 2 shows the gravity system in more detail. The precast floor planks are seen loading primary steel beams that are pin-jointed to the steel columns. Precast facia beams that run parallel to the precast ribs carry little load other than their self-weight and the wall cladding to be installed, which is likely to consist of glazing.

The reinforcing cages for the two transverse shear walls are seen in Fig. 3. Their large returns, at each end, provide room for the longitudinal steel that resists the wall bending moments and at the same time prevents any possibility of compression buckling of the wall ends under the combination of gravity and bending compression stress. Close horizontal reinforcement spacing will help carry shear forces within the webs of the walls. In the wall returns, flanges or chords, as they are called, the closely-spaced ties will prevent the longitudinal reinforcement from buckling after any cover concrete spalls off during a major quake. Because the walls are designed to be ductile, there is a high likelihood that they will experience seismic overload and need all this horizontal steel.

Fig.1. The superstructure under construction with transverse shear wall reinforcement and gravity-only steel columns.

Fig.2. Suspended floors consist of primary steel beams carrying precast concrete planks with timber infills supporting 75 mm RC topping.

Fig.3. A longitudinal precast panel shear wall with the two transverse shear walls behind.

The longitudinal resisting system is not so obvious but it takes the form of two shear walls along each side of the building. As seen from Fig. 3 these walls are constructed from many precast concrete panels, joined horizontally and vertically. Vertical starter bars, very short by normal standards will be grouted into the panels to be placed above them using high-strength grout. By being strongly connected to each other the panels will act as one very rigid and strong wall along each boundary line. So this building has its seismic resistance provided by shear walls while a pin jointed steel structure provides the primary gravity support.

Summary of "Recorded Motions of the 6 April 2009 M_w 6.3 L'Aquila, Italy, Earthquake and Implications for Building Structural Damage: Overview" by Mehmet Celebi and others. From Earthquake Spectra, Volume 26, No.3.

SUMMARY

The normal-faulting earthquake of 6 April 2009 in the Abruzzo Region of central Italy caused heavy losses of life and substantial damage to centuries old buildings of significant cultural importance and to modern reinforced concrete- framed buildings with hollow masonry infill walls. Although structural deficiencies were significant and widespread, the study of the characteristics of strong motion data from the heavily affected area indicated that the short duration of strong shaking might have spared many more damaged buildings from collapsing. It is recognized that, with this caveat of short duration shaking, the infill walls may have played a very important role in preventing further deterioration or collapse of many buildings. It is concluded that better new or retrofit construction practices that include reinforced concrete shear walls may prove helpful in reducing risks in such seismic areas of Italy, other Mediterranean countries, and even in United States, where there are large inventories of deficient structures.

THE EARTHQUAKE: GENERAL INFORMATION

A significant normal-faulting earthquake shook the Abruzzo Region of Central Italy on 6 April 2009. The magnitude of the earthquake was M_w=6.3 and the hypo-central depth was 9.5 km. As of early May 2009, 305 people lost their lives and over 1,500 people experienced injuries in the earthquake. A significant amount of losses in terms of lives (approximately 134 people) occurred in a few reinforced-concrete buildings (about 1% of the whole reinforced-concrete construction stock). L'Aquila, the largest town in the area with a population of 66,813, was devastated by the earthquake.

TYPES OF STRUCTURES AND DAMAGE

Reinforced concrete (RC) shear walls are not commonly used in construction in this earthquake region. Very few steel structures exist. Hence, the dominant types of construction in the region can be classified as:

Older buildings or historical buildings, considered as "cultural heritage," are mainly constructed of stone or brick masonry. A significant percentage of such structures (including historical churches), especially those with poorly maintained walls and without strengthening devices (e.g., tie rods), were damaged. In general, historical masonry construction is of poor quality (e.g., lack of connections, poor mortar, etc.). Steel or wood ties have improved the behaviour avoiding in various cases local and global collapses and the overturning of facades.

Typical Mediterranean type of construction of low-rise (two to four stories) to mid-rise (five to eight stories) buildings of reinforced concreted (RC)-framed structural system with hollow clay masonry infill walls and with various architectural and structural vertical and in-plan layout designs. Due to a desire to provide weather insulation, there are commonly unreinforced infill walls, almost all built with hollow bricks at least two and sometimes three layers thick. This type of reinforced concrete building was constructed in large numbers following World War II and most after 1960.

Industrial buildings (precast panels, similar to tilt-up buildings in the United States, and a few of steel construction).

In general, recently constructed RC-framed structural systems with infill walls performed better. In many cases, the more recent RC-framed buildings with infill walls were also damaged, but the damage was usually limited to nonstructural components while the framing system remained intact. Not surprisingly, older and nonductile or less ductile buildings suffered the heaviest damage. Very few soft-story or pancake-type collapses were observed. The variation of the vulnerability characteristics of reinforced buildings is significant. As observed in many cases, many collapsed buildings are very close to buildings that survived the earthquake with minor damage. Due to the variability of the buildings' vulnerability and the variability of the ground motion and site effects, the observed damage distribution is significantly irregular.

TYPES OF DAMAGE

In this earthquake, as well as in other earthquakes, structural damage can be generalized to be caused by three main reasons:

Structural deficiency: Caused by design or construction process and/or age, lack of ductility, deficient materials (e.g., use of smooth instead of deformed reinforcing bars, even though smooth bars were permitted by law at the time of construction of many of the existing building inventory) and/or workmanship, deficient shear and/or longitudinal reinforcement, deficient detailing of joints. Most damaged RC-framed buildings with infill walls had poor detailing and insufficient shear reinforcement (stirrups and cross-ties) with larger than requisite spacing and insufficient diameter and/or vertical reinforcement. Concrete quality was questionable in most buildings that collapsed or suffered heavy damage. Most of the damaged buildings would not meet what is known as Hassan index which stipulates that there must be a minimum percentage area of lateral force-resisting elements (columns and walls) on the ground floor compared to the total floor area of a building in order to improve its performance.

Structural layout: Architectural defects such as large eccentricity or layout with respect to nearby structures. These effects can cause significant shaking variation that may include significant torsion, pounding, short columns, soft stories (Fig. 4).

Actual ground shaking that exceeds design levels: In other words, larger demand than capacity of structures. The larger shaking can sometimes be caused by site effects including basin and topographical effects. Also, possible pulse effects due to directivity can add additional demand to structures for which enough capacity could not have been designed for (e.g., Fig. 5).

Fig. 4 (a) Condition of Hotel Duca Degli Abruzzi in L'Aquila before the earthquake as obtained from Google Maps Street View and (b) the post-earthquake condition observed from the ground. It is possible to observe the presence of a significant irregularity in elevation between the ground and the first floor. (c) Before and (d) after earthquake condition of another collapsed building (irregularity in elevation at intermediate floor) in L'Aquila assessed by similar methods.

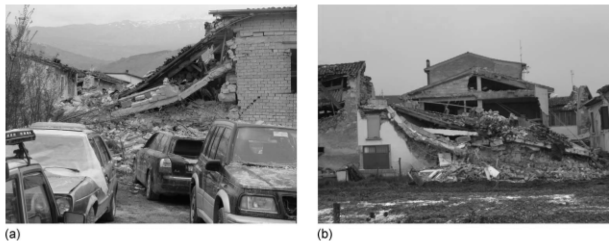

Fig. 5 A majority of buildings in Onna - mostly older, poor, nonductile masonry and un-engineered - suffered heavy damage or collapsed.

STRUCTURAL CHARACTERISTICS

A significant majority of nonductile, non-engineered and unreinforced masonry buildings (including historical structures), and a significant percentage of reinforced concrete buildings with limited ductility and deficient strength due to design and/or construction practices most likely did not have the requisite capacity to resist the level of shaking experienced without damage. Hence, it is possible that during the short duration, high-frequency and large-amplitude shaking, the majority of the deficient structures were damaged each to some degree (and some pancaked) within only a few cycles. In other words, the shaking motions did not contribute to damage patterns expected from sustained or prolonged large displacement cycles. This is a likely explanation for why so few (approximately two dozen) of the damaged engineered structures collapsed. It is reasonable to speculate that if a larger-magnitude earthquake similar to that in 1915 (M_w 7.0) had occurred, the expected longer duration of strong shaking would probably exhibit different statistics on collapsed buildings as displacement demands would have been higher and a greater percentage of the deficient structures might be expected to collapse. It is strongly stated that infill walls may have played a very significant role in preventing many of the damaged nonductile framed structures from collapsing ("shoring" and/or "diagonal strut" effect) by dissipating the imparted input energy, even though the infill walls themselves may have been damaged. A large amount of infill walls provide additional shear resistance to such buildings, even though the quality of infill is often questionable. However, this positive help of infill walls was sufficient to prevent many collapses only because of the relatively short duration of strong shaking, that is, a longer duration of shaking could have further deteriorated or completely eliminated the positive effect of infill walls. In addition to some other factors cited, lack of ductility in older buildings (historical or otherwise) or newer buildings (but built according to the pre-2003 code) played a significant role in the collapse of, or heavy damage to, a majority of these structures.

In summary, it is reasonable to conclude that in general, it was surprising that many more of the damaged structures did not collapse at such high levels of seismic demands.

As mentioned before, this might be attributed to the short duration of strong shaking. If the duration had been longer and at higher levels of accelerations, displacement demands would have been higher, possibly causing many more buildings to collapse. Another way to improve lateral load capacity of the typical buildings in the region (RC-frame with infill walls) is to construct the infill walls with reinforcement integrated with the frame system, effectively turning them into shear walls.

IMPLICATIONS FOR OTHER COUNTRIES

It is also reasonable to conclude that the design and construction practice of not using ductile reinforced concrete shear walls (or a combination of walls and frame structural system) in highly seismic areas, rather than continuing the dominant practice of design and construction of the typical reinforced concrete frame system with infill unreinforced masonry walls, may not sufficiently reduce the risk from future earthquake hazards. Seismic risk to RC-framed buildings with masonry infill walls is described in detail, along with appropriate retrofit solutions including the implementation of RC shear walls in a recent World Housing Encyclopedia publication (Murty et al. 2006). In many other countries with serious seismic hazard (e.g., Chile, Argentina, and the United States), a considerable percentage of the plan areas of buildings are designed with reinforced concrete shear walls. Following the 1999 Izmit, Turkey, earthquake, there have been some proposals for retrofit of RC-framed buildings with masonry infill walls by strategically replacing some of the infill walls with RC shear walls. The vulnerability of RC-framed buildings with infill walls was originally related to the cross-sectional areas of lateral force resisting elements (columns and walls). Hassan and Sozen (1994) proposed that buildings with lateral force resisting elements of ground floor with approximately 0.35-0.4% of the total building floor area exhibited better performance during earthquakes. Gülkan and Sozen (1999) related vulnerability of reinforced concrete buildings with or without infill walls to column and masonry infill wall ratios of the total dimensions (area) of a building. Recently, Canbolat et al. (2009) presented results of studies leading to recommendations indicating that approximately 1.5-2% shear wall index (defined as the area of shear wall per story floor area) provides excellent performance and constrains drift ratio - and therefore the damage vulnerability - of a building. Thus, there are many studies that may be used in the assessment of vulnerabilities of suspected deficient buildings.

Summary of "Learning from Earthquakes: The M_w 7.1 Darfield (Canterbury), New Zealand Earthquake of September 4, 2010."

From EERI Special Earthquake Report – November 2010.

INTRODUCTION

In the early hours of Saturday morning on September 4, 2010, people in Christchurch and the surrounding Canterbury region were jolted awake by the most damaging earthquake in New Zealand since the deadly M_w7.8 Hawke's Bay (Napier) earthquake in 1931. This time there was no loss of life and only two serious injuries. The low casualties can be attributed in part to the time of the M_w7.1 earthquake at 4:36 am, as well as to the moderate level of shaking in the most populated areas of the Canterbury region. New Zealand also benefits from a modern structural code and rigorous code enforcement. Regional planning had been undertaken to reduce critical infrastructure and lifelines vulnerability to natural hazards about 15 years ago (Centre for Advanced Engineering, 1997), with improvements in local government and utilities preparedness, as well as the retrofitting of bridges and other lifeline facilities.

Christchurch is the largest city in the South Island of New Zealand, and the country's second-largest urban area, with a population of 375,000. While New Zealand has strict seismic building codes for new construction, Christchurch was not considered a high-risk area and had a passive retrofit policy for its unreinforced masonry buildings. The damage to nonretrofitted URM buildings from the moderate shaking is an important object lesson for other regions with large inventories of URM buildings. Unprecedented residential losses due to liquefaction and lateral spreading represent a considerable portion of the total losses, estimated at $4 billion NZ ($3 billion US). Even for buildings that performed well structurally, there was extensive nonstructural damage to both building components and contents.

GEOTECHNICAL EFFECTS AND LIFELINES

Liquefaction and lateral spreading were pervasive in portions of Christchurch and neighboring communities (Fig. 6), causing extensive damage to buried utilities (water and wastewater pipelines), residential housing, and other building structures. To a lesser extent, roads, railroad embankments, and levees were also affected. According to a 2004 liquefaction susceptibility study in Christchurch, approximately 50% of Christchurch residential areas are vulnerable to liquefaction (Environment Canterbury, 2004). Between 5% and 10% of residential properties in the Christchurch area were actually affected by liquefaction. By far one of the greatest impacts of this earthquake on the residents in the Canterbury region was the lateral spreading and post-liquefaction differential settlement that damaged numerous residential and other structures (Fig. 7).

Fig. 6. Structures damaged by lateral spreading and post-liquifaction differential settlement. Above: Residential structure in Spencerville. Below: St. Paul's Church in Dallington.

ENGINEERED STRUCTURES

Newer engineered buildings generally performed well, but preliminary indications are that the ground shaking was below the design response spectra for shorter-period buildings (periods less than about 2 seconds). The majority of larger and multi-story buildings in the affected area are located in downtown Christchurch and on the University of Canterbury campus. Reinforced concrete construction is prevalent, with older buildings being typically reinforced concrete moment frames. A number of these older buildings also had masonry infill walls, but we observed very limited structural damage to these structures. This is likely attributable to the lower-than-design-level demands that are suspected to have been imposed on the shorter-period structures. One of the most visible exceptions was an eight-story building consisting of reinforced concrete frames with a double cavity wall of unreinforced masonry bricks around the building. Severe shear cracks were visible in the masonry on both the exterior and interior of the building.

SCHOOLS

Most schools in the Christchurch (171 schools, 59,736 students), Selwyn (30 schools, 7,818 students), and Waimakariri (25 schools, 6,618 students) districts opened one week after the earthquake. The oldest schools have heritage buildings — typically multi-story unreinforced masonry structures almost a century old. Newer school campuses typically contain timber-frame single-story structures with unreinforced slab-on-grade foundations. Nine schools remained closed beyond one week for further structural evaluations and repairs.

While very few schools sustained significant losses to contents, 75% of them required minor repairs (rearranging toppled contents, repairing broken windows, replacing ceiling tiles). Most schools reopened after 50 person-hours or less of work in each one, but about 20% of them required 200 person-hours or more to make necessary repairs.

HOSPITALS

Immediately following the earthquake, all area hospitals remained operational, including the Christchurch Hospital Emergency Department. Backup generators for Christchurch and Burwood Hospitals were operational

Fig.7. Above: Large lateral spreading like a rupture passed through the foundation near Courtenay Drive in Kaiapoi. Below: This house slid more than 1.2 m and tilted significantly (near Courtenay Drive in Kaiapoi) (photos: Lai).

within 15 seconds of losing power, and full power to these facilities was restored within 80 minutes.

HOUSING

Almost all housing in the Christchurch region is single-family woodframe, most of it one story. Many of the older homes had unreinforced masonry chimneys, highly vulnerable to earthquake damage, and to date there have been more than 14,000 claims for damaged chimneys. The homes are predominantly concrete slab on grade with a light perimeter grade beam, as opposed to the US approach of using woodframed first floors over crawl spaces.

Although crawl spaces create their own earthquake vulnerability, such a system is probably better under severe liquefaction conditions, because the wood floor is more tolerant of slight differential settlements and the crawl space can be used to raise and/or relevel the superstructure.

UNREINFORCED MASONRY BUILDING PERFORMANCE

New Zealand's building stock resembles that of the western part of North America. With the shaking intensity in Christchurch varying between VII and VIII, the Central Business District had severe damage in some unreinforced masonry (URM) brick commercial and stone institutional buildings. The Canterbury Region has 958 URM buildings; of the 595 URM buildings assessed after the earthquake in Christchurch (apparently concentrating on the CBD), 21% received red "unsafe" placards, and 28% received yellow "restricted use" placards. Over 160 buildings suffered more than 10% damage and many of these have since been demolished (Ingham and Griffith, 2010).

Stair-step and X-cracking in the plane of walls was observed in two seven-story URM buildings in the district, but was only rarely noted in the low-rise URM buildings. Many of the severely damaged buildings had relatively low mortar strength. Throughout the city, loose masonry fell from unbraced parapets and gable walls (Fig. 8). In a large number of cases, entire parapets and upper walls not adequately attached to roofs fell onto streets, sidewalks, and adjacent smaller buildings.

Only some of the URM buildings appeared to be partially or fully retrofitted prior to the earthquake. Parapet bracing was apparent in some, often only on walls over busy streets. Because Christchurch was considered to be in a region of moderate seismic hazard, the regional government had encouraged voluntary retrofits of collapse-prone buildings. Although statistics are not available at this time, anecdotal evidence indicates that retrofitted or partially retrofitted URMS performed well compared to similar unretrofitted buildings nearby. Various techniques were used for retrofitting URMs: through-bolts, adhesive anchors, fiber reinforced polymers, grout injections, added steel moment frames and braced frames, concrete moment frames and walls, new roof diaphragms, and external steel rods, angles and plates. These retrofit methods appeared to preclude collapse and did not exhibit systematic vulnerabilities to the particular ground motions of the earthquake. However, there was minor damage in several retrofitted buildings, as would be expected. Efforts to document the performance of retrofitted buildings are particularly relevant to U.S. and Canadian practice, since New Zealand's methods are quite similar to those in North America.

Fig.8. Blackwell's Department Store on William Street in Kaiapoi suffered extensive structural damage (photo: Arendt)

NONSTRUCTURAL LOSSES

Much of the nonstructural damage at universities and in office, commercial, and warehouse buildings was removed before the EERI team arrived, but discussions with engineers and news reports suggest that there was significant nonstructural damage to both building components and contents. Storage racks for food supplies at two regional distribution centers collapsed during the earthquake, losing a month's food supply for Christchurch. To compensate for the lost storage, food shipments by truck and train were undertaken from the North Island down the transportation corridor of Highway 1 along the South Island east coast.

Damage to industrial storage racks was observed at many locations after the earthquake. Such damage, especially with respect to the food supply, illustrates the importance of nonstructural mitigation for secondary building systems and contents. The disruption of transportation routes to Christchurch illustrates the effects of multiple natural hazards on critical lifelines. To dispose of the food lost by storage rack collapse, a new cell was opened in the city landfill to expedite removal and thereby avert a health hazard. The University of Canterbury is the 2nd oldest in New Zealand. The original campus is now the downtown "Art's Centre," and the current campus (with about 13,500 students) was built in the 1950s-1970s on the west side of Christchurch. The building stock is predominantly 3-12 story concrete construction. University staff had done excellent earthquake preparedness planning and immediately organized safety inspections and detailed building assessments. About one third of campus buildings had some nonstructural damage, while 75% had contents damaged (files and shelves overturned, books off shelves, fallen lab equipment, broken beakers). The nonstructural damage was primarily to stairs, finishes at seismic joints, ceilings and elevators. Some sprinklers were set off by ceiling movement, and one eightstory building had an open water tank on the roof. The water sloshed out of the tank and caused water damage in labs.

ISSUES FOR FUTURE SCRUTINY

The earthquake was notable for three main reasons:
1) serious liquefaction and lateral spreading damage to homes (as well as schools and other low buildings) located on soft soils and sand;
2) considerable damage to nonretrofitted URM buildings, many of which are historic structures; and
3) widespread nonstructural damage to both building components and contents, even in buildings with little structural damage.

Effects in each of these areas will require considerable expense to repair. For homes, the universal insurance provided by the EQC will fund a portion of the repairs, but URM losses and nonstructural repair and clean up costs will exceed coverage when the costs are fully estimated. The damage leaves the city of Christchurch and the region with a number of major planning and engineering questions regarding residential neighborhoods on soft soils and rebuilding the downtown. In addition to structural and geotechnical lessons, the earthquake will provide instruction in the longterm efficacy of the recovery and policy decisions made in the next few months.

Earthquake Hazard Centre
Promoting Earthquake-Resistant Construction in Developing Countries

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Director (honorary) and Editor: Andrew Charleson, ME.(Civil)(Dist), MIPENZ
Research Assistant: Samantha McGavock, 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: quake@arch.vuw.ac.nz

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