EARTHQUAKE HAZARD CENTRE
NEWSLETTER

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Contents

Editorial: Vulnerability of reinforced concrete shear walls

During the period that this newsletter has been published there have been frequent suggestions that engineers and architects lessen their dependence upon moment frames to resist lateral earthquake loads on buildings. It has been pointed out that moment frames, especially constructed from reinforced concrete, require sophisticated design, detailing, construction and quality control if they have any chance of behaving as ductile structures. To take but one example, if a few ties are missing from a column, then it may well fail in shear before plastic hinges form in the weaker beams.

This advice has been forthcoming as a result of observed damage to moment frames after moderate to severe earthquakes. Moment frames are very commonly used worldwide. In comparison, generally speaking, RC shear walls have performed well. Even if they have suffered severe cracking from flexure or shear, rarely have they collapsed. That is until the M 8.8 Chile Earthquake, 27 February 2010.

Shear walls, often orientated in both orthogonal directions are commonplace in Chile, and so this earthquake provided a serious test of their seismic capability. A summary paper in this newsletter provides the details. In essence, most walls performed well, but some were so badly damaged that buildings collapsed.

This relatively poor seismic performance is a reminder that even RC shear walls are vulnerable to severe damage and collapse if not well designed, detailed and built. The main deficiency highlighted in the article was the lack of confining steel at the ends of walls. These areas undergo huge compressive strains as a result of compression load and bending moments from lateral loads. Not only does concrete spalling occur in these zones, but if walls are too thin, they can also buckle, as some did. In some cases walls suffered badly because of large penetrations near their bases. Given that the bases of walls experience maximum bending moments and shear forces, such configuration weaknesses must always be avoided.

Unfortunately, there are other problems with shear walls that have come to light after the February 22 2011 Christchurch earthquake. They both concern interaction of the deflected wall during a quake. First, as a wall bends, it not only moves laterally, but one end of the wall reduces in height and the other elongates. This vertical movement can induce high shears in beams fixed to the wall which can then lead to dangerously high tensions and compressions in adjacent columns. If a wall is ductile, then during the design earthquake large and wide horizontal cracks form at the wall base as the flexural steel is strained permanently into the inelastic region. These cracks increase in width during an earthquake and the wall elongates, or grows higher, as a whole. Once again, structural elements in the form of beams or slabs connected to the wall will be distorted. They will probably be damaged themselves and they may damage other members, like adjacent columns, as noted above.

As is usually the case, a lot is to be learned from studying earthquake damage. This time we have learnt not to be complacent about shear walls. Overall, most performed well, but there are important lessons to be learnt.

Virtual Site Visit No. 29: Reinforced masonry construction

This site is for a medium-rise mixed development several kilometres away from Wellington's CBD.

The focus of the site visit is upon reinforced masonry walls which create an internal core (Figures 1 and 2) and a perimeter retaining and shear wall (Figure 3).

The masonry units for the ground floor walls of the core have been laid and soon they will be filled with grout. Vertical bars can be seen projecting from above the top course of the masonry units, which conceal the closely-spaced horizontal bars that are necessary to withstand horizontal shear forces.

Figure 2 shows a crucially important construction detail – clean-out ports along the bottom course of masonry units. These ports are provided every third unit to enable reinforcing bars to be tied to the starters projecting from the foundation footings, and just as importantly, to enable the horizontal construction joint between footing and wall to be properly cleaned. During the block laying process, mortar is accidentally dropped down the blockwork cavity.

Fig. 1 Unreinforced masonry walls for the building core.

Fig. 2 Clean-out ports at the wall base to allow the construction joint to be properly cleaned and inspected prior to grouting.

Fig. 3

In order for the grout to bond with the footing concrete, not only does that concrete surface need to be intentionally roughened, but it must be washed or even brushed clean of mortar droppings. Only after a quality control inspection has been satisfied that the joint is clean, should the clean-out port walls be reinstated and the wall grouted.

The rear reinforced masonry retaining wall is shown in Figure 3. Various reinforcing bars are visible. First, one can see the vertical bars which have been bent over to be cast into the floor diaphragm. These bars will enable horizontal seismic shear forces from the diaphragm to be transferred into the shear wall. Secondly, horizontal shear reinforcement protrudes from this section of wall which is detailed to form a vertical crack control joint. These bars will lap with horizontal bars in the next section of wall to ensure adequate wall shear strength in the event of an earthquake. The attached pier has yet to have horizontal ties to confine its vertical reinforcement, and then, after grouting it will be able to receive the end of a horizontal beam and the gravity loads it will transfer.

Reinforced masonry construction has its place among earthquake resistant construction materials but good performance can only be assured by careful construction and inspection processes. Once grout is cast it is difficult to check quality unless cores are taken.

A continuation of the article in the April 2012 Newsletter; Vol. 15, No. 4.

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 Local branch of Ziraat Bank which was seismically strengthened before the recent earthquakes (photo: Alaluf).

Seismically strengthened buildings

There were several seismically strengthened buildings in the area, three of which were visited by team members The Ziraat Bank building in Erciş survived the earthquake with minor damage (Figure 4). The Kazim Karabekir Primary School in Erciş is a four-story reinforced concrete frame/structural wall building with hollow clay tile walls used as partitions; it had been retrofitted by replacing some of the hollow clay tile infill walls with reinforced concrete structural walls. A survey of the structure revealed that the material quality and the reinforcement detailing in the original framing was inferior. During the October earthquake, there was widespread partition wall damage in the structure. Beams supporting the stairs exhibited damage as well, but it was due to discontinuity in the flexural reinforcement. The existing (original) structural walls of the structure in the N-S direction had a diagonal web of hairline cracks up to the third story. There was separation at the interface between the added structural walls and the perimeter framing, particularly the beam to which the added structural reinforcement was anchored. The damage pattern indicates that the added shear walls did not engage with the existing structural frame right away.

Reportedly, the Van branch building of the Turkish Central Bank had been reviewed for possible seismic strengthening, but that had been deemed unnecessary (Figure 5). This very irregular five-story building has a three-story atrium and wing walls at the perimeter as the primary structural elements of the system. No structural failure was seen in the system except for a crack on one of the beams; however, extensive partition wall failure in the building disrupted services.

Fig. 5 The Van branch building of the Turkish Central Bank (photos: Dönmez).

Government buildings

Structural systems in government buildings varied depending on the age of the structure. The spectrum stretches from stone bearing-wall systems in old structures to RC frames in relatively new structures, but RC frames predominate. They are subject to special regulations depending on the ministry with which they are associated. The Erciş Palace of Justice is an example of the old bearing-wall systems. As shown in Figure 6, cracks formed in the walls and went through concrete lintels within the walls.

Fig. 6 Severe damage to walls of Erciş Palace of Justice (photos: METU group).

The Erciş District Governor's Office, a campus of two- to five-story plus basement modern RC buildings with frame and structural wall systems, sustained no structural damage and only minor damage in nonstructural walls. The main problems were failed water tanks in the basement, collapsed archive support systems (Figure 7), and ceiling tile failure in the conference hall on the top floor.

Primary/secondary education buildings

Primary schools inspected in both Van and Erciş had in-plane and out-of-plane damage to the hollow clay tile infill walls and minor structural damage in some of them. Many schools had cracking at the frame/wall interface, diagonal cracks, through-cracks, and crushing of the infill walls. Out-of-plane gable wall failure was typical in all of the schools that were observed throughout the area. At the Cumhuriyet Primary School (Figure 8), a conglomeration of four-story buildings located approximately 0.5 km southeast of the collapsed building ("Sevgi Apartmanı") that claimed 50 lives in the city center of Erciş, there was only minor damage to the structural system. Except for a corridor in which the infill walls were crushed, minor to moderate damage to the infill walls with cracking at the wall/ frame interface, was observed.

Fig. 7 Archives in Erciş District Governor's Office (photos: İrfanoğlu).

Near the Van pier, a three-story building used as a teachers' residence had out-of-plane wall failure. Above the third-floor ceiling slab, the structure consisted of wood post/beam framing supporting the roof with a story height equivalent to the floors below. The wood-framed portion had wood diagonals placed systematically to provide stability. On two sides of the structure at the uppermost story, out-of-plane wall failure was observed (Figure 9).

Universities

Van Yüzüncü Yıl University, established in 1982 with a population of approximately 18,500 students, is located approximately 20 km from the epicenter of the October earthquake.

Overall, campus buildings performed well from a structural point of view, with most buildings having only minor to moderate damage to the hollow clay tile infill walls. The library, a five-story building with an irregular footprint and obvious inferior concrete quality and reinforcement detailing, sustained the most damage and is currently out of commission. The damage appeared to consist primarily of an out-of-plane collapse at a gable wall and the exterior wall at the exit stair well, heavy structural damage at the stairs and some beams in the structure (Figure 10).

A few buildings were deemed to require further investigation, while others had only a little nonstructural damage with some cracking at the wall/frame interface.

The Medical School of the university is not on campus but in Van, with seven main blocks interconnected to each other. Four of these blocks were built 60 years ago. The other blocks were built in the last 15 years.

All of the blocks are RC structures with two-way slab systems. Even though the overall construction quality was not good, no structural damage was observed in the buildings after the October earthquake. However, due to medium to heavy nonstructural damage, the university hospital was out of service. The nonstructural elements and contents that rendered the hospital inoperable were partition walls, molded gypsum ornaments at the ceilings, wall panels on top of partition walls, and laboratory glassware and hardware. The university was closed until February 2012. .

Fig. 8 Cushed infill walls in Cumhuriyet Primary School in Erciş (photo: İrfanoğlu).

Fig. 9 Teachers' housing in Van near the pier (photo: Hernandez).

Fig. 10 Library building at Van Yüzüncü Yıl University (photos: Dönmez).

A summary of "the M8.8 Chile Earthquake, 27 February 2010"

from the *Bulletin of the New Zealand Society for Earthquake Engineering*, Vol. 44, No. 3, September 2011, pages 123-147 by Hugh Cowan, Graeme Beattie, Katherine Hill, Noel Evans, Craig McGhie, Gary Gibson, Graeme Lawrance, John Hamilton, Penny Allan, Martin Bryant, Mike Davis, Clark Hyland, Claudio Oyarzo-Vera, Patricio Quintana-Gallo and Peter Smith.

Fig. 11 Residential home in Concepción incorporating lower storey of reinforced masonry and upper storey of plywood and timber frame. (Photo: Hugh Cowan).

T H E 27 FERUARY 2010 CHILE EARTHQUAKE AND TSUNAMI

The Earthquake

On Saturday, 27 February 2010 at 0334 hours local time, a magnitude M_W 8.8 earthquake struck the central south region of Chile, with its epicentre at the coast in the region of Maule. The earthquake was an inter-plate subduction event, along the boundary between the Nazca Plate and the South American Plate. The rupture initiated at a focal depth of about 35 km and extended in a north-south orientation over an area about 600 km long and 100 km wide. Warping of the ocean floor resulted in a destructive tsunami that swept into several coastal settlements, including the naval base and shipyard near Concepción.

The rupture duration was more than 140 seconds with ground shaking exceeding 0.05g in some areas for more than two minutes and a maximum acceleration of 0.65g recorded at one site in Concepción. More than 12 million people or 72% of the national population experienced intensity VII or stronger shaking, with 521 deaths reported overall.

The damage to housing and infrastructure included about 200,000 dwellings damaged or destroyed including a number of multi-storey buildings, greatly surpassing in economic terms the losses caused by the 1960 Valdivia earthquake of magnitude 9.6 - the largest ever recorded worldwide - and the 1985 Valparaiso earthquake of magnitude 7.7.

PERFORMANCE OF BUILDINGS AND RELATED STRUCTURES

Individual Dwellings

While there is a predominance of multi-storey apartment and commercial buildings in the major cities of Chile, some incorporating advanced seismic energy dissipation systems there are still many low-rise, stand-alone, single-family dwellings. Our contacts informed us that (in central-south Chile) the predominant means of construction of house structures traditionally has been either adobe and, confined masonry. Confined masonry is a system of lightly reinforced concrete columns and beams with an infill of masonry blocks and has been used in Chile since the 1930s. Generally, the columns and beams are cast after the blocks have been laid, and the first floor is also constructed of reinforced concrete, effectively distributing forces to the lower storey walls.

We did see examples of confined masonry, however, where subdivisions of identical houses with a confined masonry lower storey and light steel frame upper storey were observed to have performed well. Similarly good performance was observed in up-market suburbs with reinforced concrete lower storey homes and timber-frame upper storeys (Figure 11). Several homes situated adjacent to minor waterways on the alluvial floodplain nearby, however, suffered severe deformation as a result of localised lateral spreading beneath the floor slab.

Historic buildings

The majority of buildings of historic significance are in the central city areas and include public assembly buildings, churches and early administrative buildings. Typically these buildings are of brick or lowly reinforced concrete construction. The facades are often heavily penetrated on the street façade. Other walls to internal boundaries have few if any penetrations. These buildings often suffered significant structural cracking, but few suffered collapse.

Chile also has many 1930 to 1970 early reinforced concrete buildings. These buildings generally performed well in the earthquake. Many of these buildings were also constructed without seismic separation and there was minor damage caused by pounding. Buildings that adjoined buildings of the same height with similar storey heights, suffered only minor harmful affects of pounding on the primary structure of the buildings.

There were some exceptions where differences in the height of buildings and offsets between floor levels resulted in pounding which was detrimental to the structure of one or both buildings.

Apartment buildings

In general, engineered buildings subjected to intensive earthquake motions in Chile performed well. The greatest damage in this earthquake was suffered by tall buildings built on deep saturated sediments. Similar structures built on dry soils or rock foundations appeared to have been largely unaffected.

The most significant damage occurred to medium to high-rise apartment buildings Prior to the 1985 earthquake apartment buildings were typically under 15 storeys in height and had almost all apartment walls as thin reinforced concrete gravity and lateral load resisting elements. The satisfactory performance of these buildings in the 1985 earthquake resulted in the industry extending this form of construction into taller buildings, typically up to 25 storeys in height.

These buildings typically had reinforced concrete shear walls in each direction, often with structural discontinuities at the lower floor.

Detailing of these walls is understood to have been in accordance with pre 1995 ACI requirements. Typically the tension and compression reinforcement was inadequately confined and wall thicknesses of 200 mm were used for 16 storey and 250 mm were used for up to 25 storey buildings. These lightly reinforced walls were often constructed without the horizontal shear and confinement steel being anchored into the core.

These walls typically failed in flexure with horizontal cracking below first floor level. The failure mechanism demonstrated the potential for buckling of the vertical reinforcement to cause spalling of the cover concrete. With the cover concrete spalled and the compression reinforcement ineffective due to buckling, there was a significant reduction in the area of concrete left to resist the compression load and the concrete core remaining being unconfined, resulted in progressive failure of the remaining concrete core resulted in a vertical failure of the wall. Where the outer edge of transverse walls were supported on lightly reinforced columns, the significant load induced under overturning of the shear wall above resulted in column failure.

A large number of multi-storey apartment buildings inspected in Chile had thin shear wall elements that suffered significant damage in the lower storeys. Flexural-compressive shear wall damage was commonly observed at the lower levels of multistorey apartment buildings affected by the earthquake. In one case in Vina del Mar a shear wall had crushed and collapsed completely, leading to the portion of the building supporting it dropping over 600 mm. In another spectacular case the use of columns with a low level of confinement under the outer edge of alternate shear walls led to the total overturning collapse of a 13-level apartment building in Concepción (Figure 12). The principal reasons for the poor performance appeared to be the inadequate confinement of the main vertical steel and the core concrete in relatively thin section lightly reinforced concrete shear walls.

In some locations where shear wall or column failures had occurred, brittle fractures in flexural reinforcing steel were also evident. These appeared to be linked to localised cyclic buckling and partial re-straightening of the reinforcing steel. This occurred where confining steel had failed to fulfil its function of retaining the core concrete in place or where the tie spacing was perhaps too large relative to the diameter of the bar being confined. The long duration of strong cyclic ground motion in this earthquake may have been a factor in causing this mode of damage.

Significant damage occurred to apartment buildings, which lacked regularity of structural form, emphasising the importance of avoiding irregularity of structural form, especially in the lower floors of taller buildings. The challenges posed in providing car parking facilities in the lower floors of apartment buildings where the inter tenancy walls to the apartments are used as the structural system above the car parks creates excessive demand on the lower structural system.

The ability of many substantial apartment buildings with shear walls in both directions to remain standing with the structural failures present in the primary structural walls highlighted the inherent resilience of these buildings against structural collapse.

The need for shear walls to be detailed to prevent buckling of tension and compression reinforcement in areas where inelastic deformations are expected and to confine the core concrete that must provide an essential part of the compression resisting structure was amply demonstrated in the structural failures in Chile.

Many of the buildings incorporated LT or T shaped walls, which perform in an asymmetric manner under lateral loading with the steel in the T or L shaped leg rarely yielding while the tension at the end of the thin wall yielding in most cycles. This action is thought to have resulted in high compression forces in the in-situ floors between walls, actions, which are not considered in the analysis of some buildings.

Fig. 12 Catastrophic failure of the multi-storey "Alto Rio" apartment block in Concepcion. (Photo: Hugh Cowan).

Fig. 13 Shear wall failure, Plaza del Rio, Concepción. (Photo: Peter Smith).

Earthquake Hazard Centre
Promoting Earthquake-Resistant Construction in Developing Countries

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