EARTHQUAKE HAZARD CENTRE
NEWSLETTER
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Contents

REDUCING RISK TO OUR COMMUNITIES

In this issue we run an article about the recent Haiti earthquake. How terrible that almost an entire city was destroyed. The degree of devastation of the built environment is shocking. A New Zealand UN official who lost her husband and two of her three children when their apartment building collapsed describes her journey to the airport to be evacuated as through "the worst devastation one could possibly imagine". She also reported that several months after the quake thousands of bodies were still buried under rubble and that many people were living in tents, and likely to be there in years to come.

Haiti's buildings lacked seismic resistance. Now we have observed what happens when a community like that experiences a moderate to large earthquake. Could this scenario happen to our own cities? What can be done about improving the seismic resistance of existing buildings? How can the risk of building collapse be significantly reduced?

These were some of the questions in the minds of the attendees of a workshop I have just attended. It was for staff of New Zealand City Councils tasked with reducing the number of "earthquake prone" buildings. The 2004 New Zealand Building Act defines "earthquake prone" buildings as those with less than 33% of the seismic strength of an equivalent new building. The Act requires that city councils develop policies to prevent such buildings causing injuries and deaths

during a moderate earthquake. These staff had gathered to share experiences after having implemented their first earthquake prone building policies about five years ago. The Act requires that the policies are reviewed every five years.

It was clear that some city councils are taking quite a proactive approach. They are assessing the strengths of most buildings that are not houses and that were designed prior to 1976. This was the date that the New Zealand seismic design code was updated to include specific requirements that during a large earthquake a building performs in a ductile rather than a brittle manner. In other words, if earthquake shaking exceeds the strength of the building, then rather than the building collapsing, it will just experience damage in non-critical areas of the main structural elements that are specially detailed to be damaged without breaking. In Wellington, for example, the city council has commissioned several consulting engineering firms to undertake a rapid assessment of several thousand buildings. If, on the basis of that assessment, which was developed by the New Zealand Society for Earthquake Engineering, a building is believed to be earthquake prone, the owner is informed. S/he can then arrange for a more detailed assessment by a structural engineer. If the building is still shown to be earthquake prone then the council will require the owner to either demolish it or strengthen it to at least 34% of new building standard. Owners are not expected to take immediate action but are given many years to undertake this work.

Using approaches like that outlined above, the risk of buildings collapsing in New Zealand cities is gradually being lowered. As buildings almost certain to collapse in a moderate to large earthquake are either demolished or strengthened, cities are becoming increasingly seismically resilient. Unfortunately Haiti has left such a campaign too late. Every other city in a seismic zone still has time to lower its risk. It is not easily done. It needs strong political leadership at government and city level. However as demonstrated in Haiti the consequences of not taking action can be horrific.

Virtual Site Visit No. 21 Low-rise concrete and steel frame building

This building is being constructed on the Wellington waterfront. Prior to the foundations being poured the site area, which was prone to liquefaction, was "improved" using a system of densification. Now the building is underlain by many stone columns formed by a vibrating probe compacting the ground as well as creating voids filled with compacted stones.

Fig. 1 shows the foundations. Under columns small reinforced concrete footings are tied together with RC beams. The beams running across the building are also designed to resist bending moments from the base of the cantilever columns in the direction across the building.

The superstructure consists of a series of portal frames spanning across the building (Fig. 2). They support an area of suspended concrete flooring as well as enclosing a large two-storey space to house an historic Maori canoe. The columns of the frames are precast – designed to slip over the vertical reinforcement of Fig. 1 and be grouted to it. Steel rafters are then joined at the tops of the columns to achieve full portal action. Therefore, in the direction across the building seismic forces are resisted by the combined precast concrete and steel portal frames. Along the building length a series of concentrically braced steel frames provide seismic resistance

Fig. 2 Steel portal frames of the superstructure. They support a suspended reinforced concrete floor over a portion of their spans.

Fig. 3 One of several braced bays providing seismic resistance along the length of the building.

Fig.1 Foundation beams and reinforcing starters for columns. After the plastic sheeting under the beams has been protected by cheap sheet material and the excavation has been backfilled the sheeting is bent over and jointed to sheeting providing moisture resistance to the ground floor slab.

SUMMARY OF "LESSONS FOR STEEL STRUCTURES FROM THE 2009 EARTHQUAKE DAMAGE IN PADANG," By Clark W.K Hyland and Sugeng Wijanto, Bulletin for the New Zealand Society for Earthquake Engineering, Vol. 43, No. 2, June 2010.

INTRODUCTION

This paper initially describes general structural response to the earthquake, the importance of an effective building control system to lift the earthquake resisting capability of building stock, and the urgency of seismic strengthening of existing buildings. The performance of steel and concrete moment resisting frames with brickwork infill panels and the challenge they present for design and retrofit are discussed. Other things reviewed are: the design of non-self-centring elements such as upper storey columns supporting pitched rafter roofs: the performance of diagonal steel roof bracing; the connection of concrete and masonry to steel work; falling hazards over egress ways; the need for a structural repair methods guide after an earthquake and the issue of how far a repair should go in terms of allowing a resumption of functionality, or reinstatement to its pre-earthquake strength or improvement of performance.

STRUCTURAL RESPONSE TO THE EARTHQUAKE

The Mw 7.6 earthquake of 30th September, 2009 on the west coast of Sumatra affected a population of 1.2 million people. 1,195 died and there was significant damage to around 140,000 homes and 4,000 other buildings. In Padang 383 people died and 431 were seriously injured as a result of building damage and collapse.

The vast majority of buildings extensively damaged in the earthquake would have been designed and constructed prior to 1987. It would also be expected that buildings designed to 2002 loading levels would have survived the earthquake well, and many of these did perform very well. However some recent structures didn't perform well and these will be discussed in the following sections.

IMPORTANCE OF A BUILDING CONTROL SYSTEM

One of the difficulties in assessing the cause of damage from the earthquake in modern structures in Padang is the

Fig. 4 Collapsed 5 level two-way steel MRF addition to hotel.

lack of a publicly transparent building control system. It is therefore not clear what level of design and construction standard compliance any particular structure achieved. As a consequence it can't be assumed that a structure's performance is necessarily representative of the adequacy or otherwise of the prevailing design and construction standards at the time of its development. The importance of maintaining an effective, knowledgeable and publicly accountable building control system to ensure application of the latest design and construction knowledge and standards is underlined by this earthquake.

THE URGENCY OF SEISMIC UPGRADING

The importance of setting a level of urgency on requiring the upgrading of older building stock to current earthquake design, loadings and material standards, is highlighted by this tragedy. The huge variation in lateral design loadings over the past forty years in Indonesia hasn't translated into seismic upgrading of existing buildings. This meant that the bulk of building stock wasn't prepared to respond safely to the earthquake. Major loss of life and economic disruption has resulted.

THE NEED FOR CONSTRUCTION OBSERVATION BY THE DESIGN ENGINEER

The scope of the structural design engineer's observation of construction of their buildings can vary hugely in Indonesia. While the recommended practice is for weekly observation by the design engineer, this often doesn't occur, particularly for construction in remote locations. Observations may be limited to once a month or less for buildings constructed in locations at some distance from the design office. The consequence of this is that wrong interpretations of the

design drawings can be made. Substitutions and changes are also made without reference back to the original design engineer. The results can be disastrous when events such as an earthquake like this occur.

THE NEED FOR CONTINUING PROFESSIONAL DEVELOPMENT

The level of understanding of engineers in Padang (and it is also believed in other regions) depends mainly on what they have learned while they studied at the university. There is little effort to keep practitioners up to date with new codes, standards and design methods. The exception is for those who are practicing Jakarta and some of the big cities in Java.

MRF WTH INFILL MASONRY PANEL WALLS

Integration of MRF with Unreinforced Brickwork

A commonly observed problem in Padang was the integration of moment resisting frames (MRF) with unreinforced brick infill walls. The majority of these moment frames were reinforced concrete because the use of steel construction is still developing in Indonesia and reinforced concrete is often most cost-effective. However in a few cases structural steel was used for moment resisting frames. Typically the steel columns were concrete encased. The two major collapses of steel MRF involved this form of construction. Also an issue with both cases was the incorporation of the steel MRF structure into older concrete MRF infill structures.

Performance of MRF with Brick Infill

MRF with infilled brick panels in fact performed adequately in cases where there was a regular horizontal arrangement of infilled MRF and vertical consistency of infilling panels up the frames. Where collapses occurred with this form of construction it was typically at ground floor level where infill panels were discontinued, creating a soft storey. This appears to have been one of the causes for the collapse of a new 6 level steel MRF with an infill brick addition to an existing hotel. It is reported that 200 people died in its collapse.

In buildings with good horizontal and vertical regularity of infilled MRF, the infill brick work walls were typically damaged with major diagonal cracking across the panels, but with minor or no damage to the moment resisting frames that confined the brickwork. Few examples of such brick infill panels collapsing out of plane were observed, indicating the general adequacy of the confinement provided by the frame boundary elements.

While the appearance of these badly cracked infill panels was disconcerting, it was clear in many instances that the infilled MRF had behaved more as an unreinforced masonry shear wall with reinforced concrete or steel boundary elements, rather than as a MRF. The brick infill walls sustained damage in initial diagonal cracking, but maintained strength using compression field behaviour. The repair of unreinforced brick infill walls is a relatively low cost exercise in comparison with repairing damaged reinforced concrete or steel elements.

Current design and construction of MRF with infill brickwork

The current design code approach in Indonesia does not specifically control the effect of masonry walls on the infilled MRF. Generally, both in design and during construction it is considered that the brick infill panels are non-structural and do not contribute to seismic performance except by increasing the seismic mass. This leads to the frame being analysed for loadings using the natural period of a flexible frame structure rather than the much shorter natural period of a rigid shear wall structure. The frame is also designed for frame action, rather than more correctly as a shear wall, with secondary flexural and shear capacity provided by the frame. No attempt is typically made during construction to isolate the masonry walls from interfering with the lateral movement of the structural frames.

Weak Axis Bending of Steel MRF with Brick Infill

The collapse of a recently built five storey single bay width addition to an existing hotel involved a two way steel moment resisting frame (Fig. 4). The five storey addition totally collapsed under bending failure about the weak axis of what appear to have been concrete encased I-section columns. Brick infill panels are likely to have been incorporated with window openings into the outer wall line. The two way moment connections at the columns appeared to have maintained integrity, so it appears that the frame had not been able to cope with large displacements in the weak axis MRF.

DESIGN OF NON-SELF CENTRING ELEMENTS

Non-self Centring Shake Down Behaviour

Where an out of balance long term design action acts on a structural element which will act in the same direction as an earthquake action, that element will not self-centre if it deforms plastically during an earthquake. The effect of the long term action will be to accentuate the displacement in one direction and prevent it from self-centring as the

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structure seeks to return to equilibrium. Non-self centring shake-down can result in significant repair costs or even collapse if the displacements are high.

Upper Storey Columns Supporting Pitched Portal Rafters

A particular case of this behaviour was found in Pariaman where the upper level reinforced concrete columns supporting a simply supported pitched portal roof with heavy tile roofing had spread outwards at opposing wall faces. If the pitched rafter had been tied then there would have not been any lateral dead load thrust at the column heads to cause the non-self centring behaviour. This would have been architecturally unappealing. The alternative would have been to design the cantilevered columns to act elastically in response to the seismic "parts and portions" actions loads combined with the dead load lateral thrusts imposed by the rafter.

DIAGONAL ROOF BRACING

Failure Hierarchy in Bracing Rods

Diagonal rod roof bracing collapsed in a portal framed warehouse with high masonry walls. The rod bracing had broken free from the rafters after the failure of the weld connecting the rod bracing plate to the rafter (Fig. 5). The weld appeared to be a site weld, raising the issue of how to ensure site welding quality when performed at height. From a design perspective the weld should never be the weakest link in a primary structural member such as a roof bracing rod. The preferred hierarchy of failure is that ductile elongation of the rod itself protects against connection failure at the rod ends. The rod connection therefore needs to be able to cope with the over-strength demand of the rod.

Avoid Hooked Rod Tensioners

Hooked end rod tensioners were found to have jumped free of roof bracing in another building. This reinforces the advice not to use such tensioners, as roof bracing rods can undergo cycles of tension and slackening as an earthquake progresses, allowing the possibility for the tensioner to jump free.

CONNECTIONS OF CONCRETE AND MASONRY TO STEELWORK

Care at Sub-Trade Interfaces

The weakest link in construction can often be found at the interface between where one sub-trade ends and the next starts. The responsibility for quality can be blurred where something is not prepared adequately for the following trade to connect into within their preferred tolerances. Tolerance specifications for the two trades are sometimes contradictory. While this often leads to sub-contract disputed, not seen by the design engineer or client, the true victim is often quality and sub-standard earthquake performance at the interface.

Wall Panel to Roof Steelwork Connections

Concrete masonry panels around the top storey of a three storey office building detached from the roof steelwork in a number of locations around the perimeter of the building. The panels were found to be in danger of falling onto the access-way below. It wasn't clear how the panels had been attached to the roof steelwork which was still in good condition.

FALLING HAZARDS OVER EGRESSWAYS

The example of the detachment of wall panels from roof steelwork discussed previously also highlights the need for special care to prevent falling hazards over safety egress ways in and around the buildings.

Brickwork supported on steel lintel beams broke free under face loading over exit ways in many cases and could have been a cause of serious injury to those escaping the buildings.

STRUCTURAL REPAIR METHODS GUIDE

The development of some recommended repair concepts for reinforced concrete and steel structures in a guide able to be used immediately post-earthquake would help structural engineers and quantity surveyors to quickly identify appropriate repair strategies and cost budgets, to quickly achieve a return to economic and social functionality of damaged structures.

Fig. 5 Collapsed roof-level rod bracing in warehouse.

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Summary of "The Mw 7.0 Haiti Earthquake of January 12, 2010: Report #2", from EERI newsletter, May 2010, Vol. 44, No. 5.

INTRODUCTION

On January 12, 2010, at approximately 5 p.m. local time, Mw=7.0 earthquake struck approximately 17 km west of Port-au-Prince, Haiti, along the Enriquillo fault. The effects of the earthquake were felt over a wide area. The metropolitan Port-au-Prince region was hit extremely hard.

Over 1.5 million people (approximately 15% of the national population) have been directly affected by the earthquake. The Haitian government estimates over 220,000 people lost their lives and more than 300,000 were injured in the earthquake. It is estimated that over 105,000 homes were completely destroyed and more than 208,000 damaged. Approximately 1,300 educational institutions and over 50 medical centres and hospitals collapsed or were damaged; 13 out of 15 key government buildings were severely damaged.

Unreinforced Masonry (URM): Unreinforced masonry construction predominates among buildings constructed between the late 1800s and the 1920s, often combined with the timber construction.

The failures we observed generally ranged from diagonal cracking in wall sections to absolute collapse; modes of failure included 1) lack of brick ties or brick headers between brick withes, 2) lack of adequate steel reinforcing, 3) weak stone masonry where it was necessary for structural support, and 4) poor mortar quality due to poor aggregate quality, inadequate cement or lime, or poor maintenance.

Reinforced Concrete: Many turnof-the-20th-century structures built in the manner prevalent in Europe at the time were precursors to what is now the most common form of construction in Haiti. At the time these were built, it was unique to construct an entire building with poured-in-place concrete. This building type included two of the best known landmarks in Haiti, the National Presidential Palace and the National Cathedral (Fig. 6), both of which collapsed catastrophically. According to our observations, the following are possible primary modes of failure: poor weight and wall distribution for seismic loading; corroded steel reinforcement as a result of aged carbonated concrete; and inadequately ductile concrete members to sustain repetitive stressing.

Fig. 6. Collapsed roof, interior of National Cathedral, Port-au-Prince (photo: Martin Hammer).

Fig. 7 Reinforced CMU wall from a hotel in Pentonville (photo: Amanda Lewis).

ENGINEERED BUILDINGS

Given the absence of building codes and record keeping, and the widespread practice of uncontrolled construction, it was not always possible to establish whether a specific building was engineered. We decided that "modern engineered buildings" were those with regular structural framing layouts, estimated to be built after the 1950s, and deemed to have received some degree of care by a structural engineer during design and construction. "Engineered" does not mean designed for seismic loading. While modern commercial, industrial, and essential buildings are the most likely structures to be engineered, several low to mid-rise office, residential, and school buildings were also considered

to be engineered.

Since the 1950s, reinforced concrete has been the material of choice and many construction practices that do not consider seismic loads were established at that time. Concrete is usually hand-mixed on site for smaller engineered buildings and is typically of poor quality. There is only one Haitian contractor who uses ready-mix concrete consistently; no information is available about the practice of international contractors. In older engineered buildings, smooth reinforcing bars were used, and transverse reinforcement was observed to be 5-6mm diameter wires with unacceptably large spacing, particularly in columns. In newer construction, deformed bars were also observed.

Reinforced Concrete Buildings: Reinforced concrete buildings with moment-resisting frame structural systems (RCMRF) and unreinforced hollow concrete masonry unit (CMU) infill walls dominate the engineered buildings (Fig.7). A small number of dual-system buildings with RC MRF and structural walls were also observed. The typical floor system is RC slab with beams. RC dual systems are observed to have sustained less damage, on average, than the RC-MRF buildings. In several buildings recently constructed, seismic design guidelines such as those provided in U.S. design codes and ACI-318 were followed. However, the application of seismic design principles was due to individual initiative and not because of consensus or governmental action.

Critical structural damage was mainly due to absence of proper detailing in the structural elements, with failure of brittle columns as the main cause of collapse. Some structures had soft-story issues.

Fig. 8. Typical construction of a residence, showing a rock rubble foundation, confined masonry construction technique, and reinforced concrete slab. Note blocks added to the top of the walls and reinforcement emerging from the slab, ready for construction of another level (photo: Anna Lang).

Fig. 9. Typical out-of-plane failure of an infill masonry construction (photo: Anna Lang).

The quality of concrete varied from weak (typical) to good (rare), verified by preliminary tests. Both smooth and deformed reinforcing bars were observed in structural elements exposed due to damage.

LOW-RISE BUILDINGS AND HOMES

The most prevalent building type in Haiti, particularly in the Port-au-Prince region, consists of non-engineered, lightly reinforced concrete frame structures with concrete masonry block infill. They are constructed with unreinforced concrete block walls framed by slender, lightly reinforced concrete columns. Other types of masonry, including fired clay brick, are not used.

Floors and roofs are reinforced concrete slabs, typically four to six inches thick with a single layer of bi-directional reinforcement. Concrete blocks are commonly cast into the slab to minimize the use of concrete. Corrugated steel or fiber glass over a sparse wood frame is also a common roofing method.

These buildings are used for single family dwellings and small businesses, and are usually one or two stories, though three stories are not uncommon. The familiar soft-story design, whereby the ground level is dedicated commercial space and upper floors are residential apartments, is not prevalent in Haiti, as most people live and work in different geographical areas. Soft stories are a problem, however: large openings for windows and reduced wall area caused numerous floor collapses, both at the ground level and at floor levels above.

Construction Materials and Procedures:

Concrete masonry blocks are commonly manufactured at or near the construction site. Portland cement is used for all construction elements, including masonry blocks, foundation and wall mortars, roof and floor slabs, and columns and beams. Concrete mix proportions regularly

Fig. 10. In foreground, new wall under construction shows staggering of blocks within the column cavity; this mechanically locks the masonry wall to the columns, causing them to act as a unit. In background, a typical one-story CM residence (photo: Anna Lang).

lack sufficient cement and have high water content for workability and reduced cost (Fig. 8).

Masonry walls are typically 2.5 m high with a single-wythe staggered block arrangement. Walls are constructed directly on top of a finished foundation or floor slab; no mechanical connection is made. Typical block dimensions are 40 cm long, 18.5 cm high and 14.5 cm wide.

Column depth is no less than the masonry unit width. Longitudinal reinforcement usually consists of four 10mm or 12mm bars; transverse reinforcement is typically 6mm bars, spaced between 150-300mm with no decrease in spacing at column ends. Transverse ties are not bent beyond 90 degrees and smooth or ribbed reinforcement is used.

Poured-in-place concrete is not typically consolidated, so there are large air pockets and a lack of bond with the reinforcement. Further, the lack of sufficient cement in the concrete mix reduces bond strength.

Roof and floor slabs are commonly poured after the wall panels are already constructed and, regrettably, the walls are typically not assembled to the full height of the roof or floor. Rock or masonry debris is added later to fill in the gap between the top of the walls and the bottom of the slab. Subsequently, masonry walls are typically not load-bearing — gravity load is carried only by the slender concrete columns. For future construction of additional levels, longitudinal reinforcement of the columns commonly extends through the slab thickness, but without additional connection detailing.

Performance of Infill Masonry:
When these building types were excited during the earthquake, lateral load transfer primarily occurred at the column-slab connection. The walls are typically not load-

bearing, and their strength capacity was reduced by a lack of friction between the blocks. Interaction between wall panels and columns resulted in localized damage, notably in the columns. Lateral capacity of the slender columns was generally insufficient to resist acceleration demands on the structure. P-delta effects ensued, proliferating collapse. Overturning and out-of-plane failures of wall panels were common place and caused the majority of complete structural collapses (Fig. 9). Even when they didn't contribute to building collapse, these out-of-plane wall failures caused innumerable injuries and deaths.

Performance of Confined Masonry:
Confined masonry structures generally sustained little or no damage during the earthquake (Fig. 10). A seemingly minor variation in the construction sequence resulted in very different behaviour. The confined masonry construction technique is similar to infill masonry, but walls are assembled first and then used to form the columns. If masonry blocks are staggered within the column cavity, a secure connection develops between the masonry wall and the columns. Instead of two structural systems acting independently, confined masonry performs as a singular system whereby lateral load is transferred from the column-slab connection to the walls directly. Though the walls are not load-bearing and therefore do not develop full capacity, they still contribute to the lateral resistance of the overall structure through the mechanical connection with the columns. Though of poor quality, this connection was sufficient to develop one-way bending and arching of the wall, greatly reducing out-of-plane failures during the earthquake.