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Learning from Christchurch & Structural Design

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Abstract

This paper reflects the thoughts of the author as one who was involved in the structural design of two buildings, of about 10 and 12 stories, in the Christchurch CBD about 40 years ago and describes some of the background then.

The author now understands that there were about 150 taller buildings (exceeding, say, 5 stories) in ChCh at the time of the recent earthquakes. Of these, all but two killed no-one at all. The other two suffered pancake collapses and were responsible for about 60% of the total earthquake fatalities. The visual (television) evidence of pancake collapses in the recent (October 2011) Turkish earthquakes is also noteable.

This leads to 2 inescapabable conclusions:
(1) The direction of structural design for taller buildings for earthquake has mostly been going in the right direction for, say, the last 40 years but …
(2) The death-toll from pancake collapses of taller buildings remains extreme.
Perhaps the two offending buildings were both significantly more than 40 years old?

Tall buildings are usually concrete structures in the sense that concrete is the only 'fire-rated' material suitable for the structural floors and walls. Reinforced masonry is also 'fire-rated' but structurally limited to lower buildings. Unreinforced masonry has not been permitted in New Zealand for many years. The structural frame supporting the concrete floor has also always been concrete in ChCh until recently but structural steel framing is now becoming more common. Clifton et al 2011.

The design of concrete buildings against pancake collapse is a major issue which is, in Australia, addressed by the Earthquake Appendix to AS3600 as well as AS1170.4. Ductile detailing of reinforcing bars is an art that needs to be better understood in Australia, not only for resistance to earthquakes but also for resistance to any abnormal event including accidental explosions, warfare, terrorist attacks and vehicle impact. Ductile detailing of rebar is the way to prevent collapses that are 'progressive' or 'disproportionate'.

Major heritage buildings are a problem with earthquakes anywhere in the world. Italy has had many heritage buildings and much earthquake activity for thousands of years. For heritage buildings, there are established technologies for retro-reinforcing stonework. The damage to the stonework at the Anglican and Catholic Cathedrals seems to go beyond just retro-reinforcing but perhaps they can be rebuilt with some intact existing stonework.

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Learning from Christchurch & Structural Design

There was, earlier this year, a small spate of letters to the Editor of *Engineers Australia* from members perturbed by events in Christchurch, New Zealand and in Japan. They correctly point out that engineers have a responsibility, to their clients and to the community, to learn from events and to do better next time. Alas the writers seem to have some doubt that this process is now working correctly. This note might help them to understand that the process is working as well as can be expected.

The basic problem with major earthquakes is a combination of long return periods, damping with distance, the age and state of repair of most building stock and the fact that building regulation is the outcome of a political process. The human race does not deal well with events with a return period exceeding a normal human life. So it is that world-famous engineers such as Tom Paulay and Bob Park could live out their lives in ChCh as earthquake experts without ever experiencing anything there more than a distant rumble such as 7.1 Inangahua 1968. Nevertheless Paulay and Park were typical of those engineers in ChCh and across New Zealand who devoted themselves and their careers to the rationale of reducing the risk of earthquake damage. Such engineers do have to understand and respect the political process involved in making earthquake-resistance a compulsory process under law and standards. Political will varies in time, with popular support, with the aim of reducing fiscal impacts and in the retrospective light of recent memorable events. Engineers may understand the technology, better now than before, but they never controlled the political process.

Engineers in ChCh are now dealing with a situation that last happened, in New Zealand, in the less populated centres of Hawkes Bay 1931. What may seem surprising is the slow progress in evaluating the extent and the damaged condition of the building stock and reaching definite conclusions. But the same thing seems to be happening in Japan. The process is necessarily slowed by the political/legal system and, in retrospect, one should have expected that to happen in a democracy. It also less surprising after reading the detailed reports in the SESOC Journal for September 2011.

This author went to Christchurch in 1972 for the structural design of two CBD buildings of about 10 and 12 storeys designed in association with local Christchurch Consulting Engineers. The project was a response from an Australian-based developer to the then Christchurch City Council policy on clearing older earthquake-risk buildings from the CBD after, and in the light of, the Inangahua event.

Having previously only practiced, as a structural engineer, in NSW, the author then knew little of earthquakes. There had just been a large Los Angeles (San Fernando 1971) earthquake and there was a ‘1-year later’ EERI Conference in Los Angeles February 1972. The author was sent to that Conference by his employer and then spent some months talking to engineers on the America west coast and as far east as Chicago. International air travel in 1972 was then more expensive (say 6 to 12 months salary) and took several days including stop-overs in Fiji and Honululu. By the time the author reached ChCh in July 1972, he had some understanding of the SEAOC Blue Book and of the changes then proposed to that following the San Fernando quake. The Blue Book largely controlled structural design on the Pacific Coast of America (‘west of the Rockies’) and had some influence in British Columbia.

It was, in a sense, a good time to get started in a new field. The San Fernando shake brought down numerous freeway bridges and fly-overs as well as buildings and, along with earlier events in Alaska, made it clear that the field of earthquake engineering then needed major re-invention.

TALL BUILDINGS IN SYDNEY

Sydney had a tall buildings boom from the early 1960s following the repeal of legislation that prohibited construction above the height of a fireman’s ladder, say about 14 storeys. Most/All of the new Sydney buildings had concrete shear-cores and, indeed, the author thinks this is still true of most/all new tall buildings in Australia, perhaps because of expertise developed for the construction of wheat-silos in the 1930s. On the other hand, shear-core and shear-wall buildings (there is a difference) were then somewhat rare in New Zealand and in Los Angeles and that may still be true.

The San Fernando site visit during the 1972 trip provided graphic evidence of the superior performance of shear-core and shear-wall buildings in earthquakes. Shear-core/shear-wall buildings were re-occupiable within a few weeks. Ductile frame buildings were much more flexible and suffered very extensive damage which, while mostly non-structural, nevertheless took longer to repair. The then brand-new 4-storey Olive View Hospital main building of about 4 storeys, had a soft but very ductile bottom storey (circular spirally-reinforced columns) and finished the earthquake with more than a half-metre of drift in that bottom storey but did not collapse!

Slide-rules were then (almost) the only structural design office computing resource but they were replaced a year or two later by pocket calculators. Computers barely existed. The author’s Sydney employer had just installed a terminal which produced punched paper tape and connected over a modem to a main-frame in America that produced output a day or so later. There was a programming language which one programmed to calculate concentric rectangular spread footings. Indeed an elementary exercise but there are, perhaps, a hundred of them under a then Sydney CBD project and they are all somewhat different. There were no structural analysis packages yet and it was at UC Berkeley that the author came across an early package: still strictly limited and 2-dimensional but much better than days of moment-distribution with a slide-rule!

DUCTILITY

Ductility is, of course, the key to all successful earthquake engineering as, indeed, it is for any other abnormal event such as Ronan Point 1968, the Oklahoma City Federal Building 1995 and the attack on the World Trade Center 2001.

Nevertheless the author thought then, and still thinks that the role of ductility has nevertheless still been under-estimated. Ductility is indeed directly related to displacement capacity. The author thinks that the forced displacement analysis invented by Nigel Priestley is a major step in the right direction but that it seeks to impose Nigel's 'best-available' guess as to mode shape. (The author uses the term 'mode' somewhat loosely here). The author would prefer to see mode shapes emerge as a conclusion of the analysis rather than as an input because he has a hunch that thereby we would learn much more. This is not just an elastic issue. Some 'mode' shapes might be specific, say, to the maximum rotation demand at some given group of plastic hinges for a given energy input. One can, indeed, think of rigid-plastic collapse mechanisms as collapse shapes and one could then seek to view that in a dynamic situation.

In terms of AS1170.4, ductility is just a number that one picks out of AS1170.4 in order to calculate the design load. Often, particularly in Australia, engineers can pick a low value for ductility implying a higher load and a brittle structure because the load is still quite low. The author thinks that this is quite wrong. Ductility is the big issue and the design (collapse) load should be an outcome of that. With wind there is an upper-bound on events in the sense that a 1000- or 2000-year wind is not too much larger than a 500-year event. This seems not to be true with earthquakes.

The author has suggested, in a paper published in America (Gurley 2008), that the quality of ductile-detailing of rebar be related to the rather more extensive ASCE list related to building importance.

BUILDING TYPES IN AUSTRALIA & NEW ZEALAND

And performance in the light of the ChCh 2010 and 2011 events:

- Single/two-storey houses
- Medium-density walk-up housing up to 3 storeys without a lift.
- 3-storey commercial buildings
- Taller framed buildings with a lift more than, say, 5 storeys
- Major heritage items such as the Christchurch Anglican and Catholic Cathedrals

There is a huge asset in old (including 'heritage') single/two-storey houses which are probably not too much of a problem in earthquakes simply because of low density of occupation (say > 30 m^2 per person) and because the collapse of timber upper-floors and roofs are less likely to kill people than the collapse of concrete floors supported on unreinforced masonry. In Australia most/many of these are occupied by owners who will oppose any interference through the political system and probably win. Why is that wrong? There is much more of a problem, in Australia, with houses in bush-fires, floods, and cyclones. But bush-fires, floods and maybe cyclones are a town-planning problem; we do know which sites are prone to those problems and we do not seem to choose to do much about that. It is, incidentally, absurd/ridiculous that Australian planning authorities can refuse steel ('Colorbond') roofs which are the only non-trafficable roofs able to withstand hail attacks at a time when the carbon problem makes it clear that those attacks will become more intense and more numerous soon enough. There was a hail attack in south-east Sydney (Maroubra) within the last 10 years that took most of the Australian roofing contractors more than a year to repair with tarpaulins over all of the roofs in the meantime. We do have short memories!

3-storey walk-up home-unit blocks are still being built in major Australian centres in large numbers using concrete slabs (for fire and acoustic separation between units) supported on walls of 110 (intra-unit walls) and 230 or 270 (inter-unit walls) unreinforced brick. This has been illegal in all of New Zealand for many years since long before the author went there in 1972. The ChCh February 2011 event at 6.3 might be considered an intraplate earthquake although it has been suggested that it is in a zone influenced by movements along the tectonic plate boundaries. Nevertheless, no one can say that that a 6.3 intraplate event is impossible in Australia. The Housing Industry of Australia is a very effective political lobby group and, presumably, very interested in 3-storey walk-ups.

There were numerous 2 and 3-storey commercial (shops, offices) buildings with floor-areas ranging up to hundreds of square metres on the approach roads immediately outside the ChCh CBD and some inside. Many of these use unreinforced load-bearing masonry and many have been lost in the recent events. Is this an engineering failure? These buildings would have to have been built before, say, 1960 and in many/most cases, before WW2. The only criticism can be that local government was not aggressive enough in seeking to demolish old buildings that had been first recognized as hazardous only several decades after they had been built. Almost all old buildings in New Zealand and in Australia, particularly including large heritage buildings are hazardous to some degree. Moon et al 2011 do, however identify several cases in which retro-strengthening was successful in ChCh. One would like to see detailed reports of these successes.

Be clear that, in ChCh before the recent earthquakes, removal of all hazardous buildings would have required some extensive areas of block-by-block demolition as is happening now! Would there have then been the political will to do that before any major ChCh shake? And would the Christchurch City Council have survived the next election and the numerous legal battles through the courts? It was not true that Christchurch City Council did nothing. It did encourage that Australian-based developer of 1972 with whatever incentives it then took to persuade the then owners to sell hazardous buildings to a developer prepared to demolish and rebuild. No doubt this was typical of Council's policies at that time.

TALL OFFICE BUILDINGS

Tall office-buildings are an entirely different ball-park. The structural floors and structural walls are both always concrete and the supporting framework may be concrete or structural steel. Clifton et al 2011. This is for protection against fire and, of course, fires do usually follow earthquakes and other abnormal events. Tall office-buildings are occupied at a density which can be 10 m^2/person. Tall residential buildings are similar but less dense. The death-toll from a pancake collapse is very high. It is probably possible to design an 'earthquake-proof' concrete tall building that will survive anything except only a major ground-rupture directly below. The safety of tall concrete buildings is entirely a matter of the quality of rebar-detailing. One does see this as a/the major issue.

The author is aware of an experimental residential building of about 6 stories of glue-laminated timber panels for floors and walls recently built in London. It will be some , perhaps many, years before such construction is generally accepted.

WHAT THEN OF TALL BUILDINGS IN THE CHRISTCHURCH CBD?

Greg McRae, writing in the SESOC New Zealand Journal of April 2011 notes that: *"Buildings designed and constructed after the 1976 code changes generally satisfied their life safety design objective under the severe level of shaking experienced. Unfortunately there were some notable exceptions"*. McRae relates this to the 1976 code change threshold but those changes were generally known and had been discussed since about 1972.

We have all seen television footage of the 2 fatal tall building collapses in ChCh along with whatever else is available on the internet. For the buildings that collapsed there will be searching enquiries hopefully to be published in the technical press assuming that the reports are not with-held on legal advice. The age of these two buildings is definitely an issue; before or after 1971/72 when code changes began to be discussed in response to San Fernando 1971. Some current NZ thinking seems to be that buildings designed before about 1982 or even 1992 may be regarded as suspect.

It does seem clear that:
(1) Very few tall buildings collapsed mostly because most tall buildings were fairly recent and generally used more recent (and better) structural rebar detailing but
(2) The two tall building pancake collapses inevitably killed many people including more than half of the death-toll at ChCh.

Clearly there are some tall buildings that did not kill anybody but are still badly enough damaged to require demolition. There is some speculation about buildings that may look alright but may have gone through several cycles of yielding of rebars. All buildings should, of course, be subject to very careful and detailed inspections.

After the Northridge Earthquake 1994, the cladding of some tall buildings was stripped to permit detailed inspections of field-welds; the cost of stripping the cladding was high and some owners decided to demolish without such inspections. Los Angeles was then (and still may be) a city in which structural steel beams and columns were predominant and the contractural arrangements and the responsibilities for the quality of field-welds were not then well allocated and unambiguous. The American Institute of Steel Construction (Chicago) has, since then, taken a major interest in this issue.

ChCh was, at least until recently, a reinforced concrete city so the problems are not the same as at Northridge. Concrete structures are usually able to be inspected with less removal of cladding. If a careful and detailed inspection finds no significant evidence of damage why then consider a partial demolition for the purpose of looking further?

Nevertheless, it is true that the level of safety to be provided, more particularly in new buildings, is a matter for political negotiation. It is reasonable now for engineers to negotiate a higher level of safety than would have been politically acceptable the day before the first ChCh quake. Nevertheless we need to be careful to ensure that this will be money that will all be well spent because it is as technically correct as we can make it at this time. This should involve a lot of engineering debate.

Clifton et al 2011 report the recent construction of new tall buildings using composite metal-deck floors and/or eccentrically-braced structural steel frames. All of these seem to have suffered only minor repairable damage. One can imagine that the composite metal-deck floors have adequate fire-rating and are probably better, as a diaphragm, than many precast concrete floors. There was concern, after the attack on the World Trade Center, that the spray-on asbestos then used for fire-rating steel members did not stay stuck after the aircraft impact. Other spray-on materials are now used but the author has not yet seen experimental evidence to prove that these stick better.

THE SITUATION IN AUSTRALIA

AEES has written, and published, a Commentary on AS1170.4. This is good of itself. However, in the process it may have lost sight of AS3600 and the Earthquake Appendix therein. The author believes that this is more important to the survival of tall buildings in an Australian earthquake than AS1170.4. There is very little 'how-to-do-it' on the art of ductile-detailing in AS3600 as compared to NZS3101 and ACI-318-Ch21. Remember that FEMA 277 (1996) thought that rebar detailing to SEAOC standards at the time of original construction, would have increased the cost of the Oklahoma Federal Building by 1%-2% and reduced the extent of damage (and presumably the 167? fatalities) by 80%.

Alas Australian Concrete Codes have increased in the author's working lifetime from about 30 x A5 pages in 1958 to 200 x A4 pages in 2009 plus about the same again in the separate Commentary. One has some doubt that the quality and clarity of our concrete codes has increased in the same proportion. Perhaps part of this problem is a tendency to treat codes as detailed textbooks. There is no present mechanism that fosters an on-going written conversation about code details and code interpretation.

One does notice that AS3600:2009 directs Australian engineers to NZS3101 if they want an advanced code for the design of concrete structures for earthquakes in Australia or elsewhere. This seems to have been a last-minute change in that, as the author remembers, the AS3600 Draft referred Australian engineers to ACI-318-Ch21. As a retired consulting engineer, one does not have access to the latest current, foreign codes. The author did have the experience of designing the shear-core of a tall Australian building (> 30 storeys) for earthquake resistance to NZS3101 in 1986. In more recent years, NZS3101 seems to have become a good deal more complicated as compared to ACI-318-Ch21.

WHAT THEN OF HERITAGE BUILDINGS IN CHCH?

Particularly including the Anglican and Catholic Cathedrals.

There are established high-tech Italian and German methods for retro-reinforcing such heritage buildings.

The author visited Naples in 1983 in an unsuccessful attempt to persuade the late Dr Fernando Lizzi, then Chief Engineer of Fondedile SpA, to tender on work in Auckland. Fondedile was then, and may still be, a large Italian piling company with a large UK subsidiary. Lizzi had invented micro-piling and then extended that to the retro-reinforcing of large stone monuments and buildings. Italy has, perhaps more heritage buildings than the rest of the world and many of them are several thousand years old. Fondedile has an established record for retro-reinforcing such buildings in Italy and in the UK.

More recently, our colleague Bill Jordan, Consulting Engineer of Newcastle NSW was responsible for retro-reinforcing the brick Newcastle Anglican Cathedral (coincidentally named ‘Christchurch Cathedral’) following the 1989 Newcastle earthquake using German technology. The German technology seems to improve on the Italian method by using a long sock in the drill-holes to better control grout-leakage. Bill seems to have occupied a role which combined the normal role of a consulting engineer with that of a construction superintendent. The construction experience, in this hemisphere, may be more valuable than design skills which are quite widely available. The work did, incidentally, discover earlier damage from, at least, one earlier earthquake. The earlier earthquake had been reported in the local press but been forgotten.

Bill’s work restored the Newcastle Cathedral pretty much to its original appearance and it now looks better than ever. This may not be possible in Christchurch (the City) because the damage to stonework is often much more extensive. My own view of an engineering design approach would be to:

(1) Remove collapsed stonework and sort it with a view to establishing a maintenance resource and/or to construct a new separate/detached memorial obelisk on the same site. Further remove such in-place stonework as cannot be dealt with as below.
(2) Brace the existing structure with a clearly new steel(or concrete)-and-glass structure that would take all future earthquake loads from the stonework down to the ground whether externally and/or internally. The new structure should make a major architectural statement in its own right. There should be no attempt to conceal it. Perhaps it could emulate the outline of the original tower at the Anglican Cathedral.
(3) The new structure should be sufficient to guarantee that a large future earthquake might cause some localised further damage but not a catastrophic general collapse.
(4) Consider clearly and carefully the necessity for fire-rating the new structure.
(5) Use retro-reinforcing to take the loads on the existing stonework back to the new steel(or concrete)-and-glass structure so as to minimise the extent of future damage.

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