

## **Design of reinforced concrete walls in regions of lower seismicity**

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### **ABSTRACT**

The design and detailing of reinforced concrete (RC) buildings in regions of lower seismicity, such as Australia, has historically differed significantly to typical design procedures in regions of higher seismicity, such as New Zealand or the east coast of the US. This is due largely in part to the lack of seismic design that was traditionally performed in these regions and has resulted in an ingrained design methodology that commonly results in structures, while code-complaint, that are very brittle and vulnerable during earthquakes. This paper serves as a primer to a comprehensive research study the authors are performing into the seismic performance of RC wall buildings in regions of lower seismicity. The paper discusses the large scale experimental testing program that has been performed. A first round of observations and recommendations for the design of RC walls in these regions, resulting from this testing, is provided.

### **1. INTRODUCTION**

Seismic design codes in regions of lower seismicity have historically copied or been heavily influenced by codes of practice in regions of higher seismicity. However low seismic regions differ from high seismic regions in two key ways; the first being the intensity of ground shaking between long and short return period events is much more severe and the second being the displacement demands are more modest due to the upper magnitude limit of intraplate earthquakes, characteristic of lower seismic regions. For these reasons, copying design codes and practices from higher seismic regions can simultaneously be overly conservative in some aspects yet inappropriate in others.

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The authors have been undertaking a long term Australian Research Council (ARC) funded research program to assess and reduce the seismic risk and rationalise the seismic design procedures and practices in Australia. While the primary focus is Australia, the research outcomes and findings are relevant to most regions of lower seismicity around the world. This has included research studies that have: lead to the development of the Component Attenuation Model (CAM) (Lam et al., 2000a; Lam et al., 2000b), which lead to the development and implementation of a new response spectrum for Australia (Wilson and Lam, 2003); assessed the seismic performance of unreinforced masonry structures (Griffith et al., 2004; Griffith, Lam and Wilson, 2006); and assessed the seismic performance and drift capacity of soft-storey RC buildings with non-ductile RC columns (Wibowo et al., 2011; Wibowo et al., 2014; Wilson et al., 2015). The most recent phase of this research program is to assess the seismic performance of RC wall buildings in regions of lower seismicity.

Limited ductile RC walls are utilised as the primary lateral load resisting system in the majority low, mid and high-rise multi-storey buildings in Australia (Menegon et al., 2017b), yet in many regards their behaviour is largely unresearched, particularly the post-peak lateral displacement behaviour. Similar methods of wall construction seen in Australia, are also widely used in many buildings in other regions of lower seismicity around the world. This current phase of research was initiated to firstly better understand the lateral displacement behaviour of limited ductile RC walls and secondly, develop guidelines and procedures for accurately assessing their seismic performance within a whole building system.

This paper serves as an interim primer, to a more comprehensive and complete publication currently being produced, documenting the activities and findings of this recent research initiative into the seismic performance of RC wall buildings in regions of lower seismicity. This paper includes a brief summary of the large scale experimental program currently being performed into RC walls and provides some preliminary recommends for the design of RC walls in these regions.

## **2. LOWER SEISMIC REGIONS VERSE HIGHER SEISMIC REGIONS**

Earthquake design of buildings in regions of higher seismicity is typically governed by high magnitude events occurring on tectonic plate boundaries (i.e. interplate earthquakes). This is contrast to regions of lower seismicity where more moderate magnitude earthquakes, occurring away from the plate boundaries (i.e. intraplate earthquakes), govern the design. The frequency content and duration of strong ground motions generated from smaller magnitude intraplate events result in a design response spectrum with significantly lower maximum displacement demand. This maximum displacement demand can be quite modest and comparable to the ultimate displacement capacity of many structures. Whereas in regions of higher seismicity the maximum displacement demand is generally too large to be of any practical importance.

This is illustrated in Fig. 1, which compares the acceleration-displacement response spectrum (ADRS) of a typical rock site in Australia and New Zealand with a hazard factor of 0.08g and 0.30g respectively. The ADRS curve for the Australian and New Zealand site is constructed using the AS 1170.4 (Standards Australia, 2007) and NZS 1170.5 (Standards New Zealand, 2004) response spectrums respectively. Fig. 1 shows that the site in New Zealand, where the hazard is nearly 4 times greater, has a maximum acceleration demand that is only approximately 2.4 times greater than the Australian site, whereas the maximum displacement demand increases by a factor closer to 9. The larger relative difference between the maximum displacement demands is due to the different second corner period of the Australian and New Zealand response spectrum, which is equal to 1.5 and 3.0 seconds respectively. The second corner period is relative to the maximum magnitude event consider in the respective region, which in Australia has been taken as 7 (Lam et al., 2000a; Lam et al., 2000b) and hence results in a much small second corner period than that of New Zealand, which is a region of high seismicity.

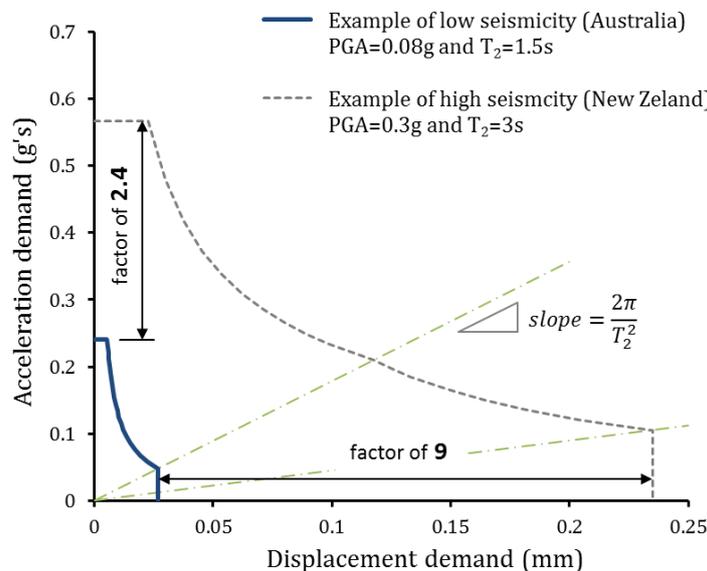


Fig. 1 Difference between regions of lower seismicity and higher seismicity.

The displacement controlled behaviour in regions of lower seismicity can be used to great effect when checking a large existing building stock for seismic compliance. A designer can simply calculate the ultimate displacement of the structure and check it against the corresponding maximum displacement demand for the site. If the ultimate displacement exceeds the associated maximum demand then the building is satisfactory for seismic compliance. This can be a powerful 'first tier' level of analysis in regions of lower seismicity due to the inherent speed and lack of complex calculations.

### 3. RC WALL CONSTRUCTION IN LOWER SEISMIC REGIONS

RC wall construction in regions of lower seismicity differs somewhat significantly from regions of higher seismicity. In regions of higher seismicity walls are typically detailed with high levels of confinement in the end regions of the wall with concentrated vertical reinforcement. The confinement allows for large compressive strains to be developed while also preventing buckling of the vertical reinforcement under reversed cyclic loading. In regions of lower seismicity, such as Australia, walls are typically detailed with a constant spaced grid of vertical and horizontal reinforcement in four layers, two per face. No confinement is typically provided in the end regions, however 'U' bars are usually detailed at the ends of walls and additionally, at wall intersections in non-rectangular walls. Lap splices of the vertical reinforcement at the base of the wall, typically in the plastic hinge zone, is standard practice. The most common type of wall cross section used are rectangular walls and box shaped building cores. The reader is directed to Menegon et al. (2017b) for further details on RC wall construction in Australia.

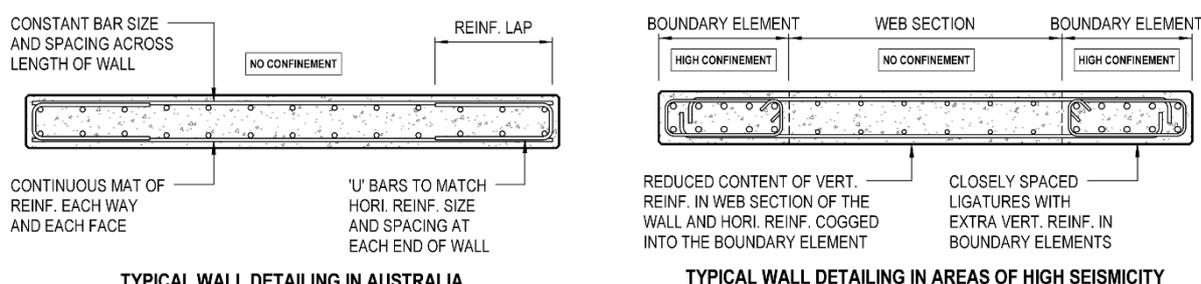


Fig. 2 Right: typical wall detailing in a region of lower seismicity. Left: typical wall detailing in a region of higher seismicity. (Menegon et al., 2017b)

Wall construction of this nature usually results in 'limited ductile' classification to the Australian earthquake code, AS 1170.4 (Standards Australia, 2007) and allows a displacement ductility value of 2.0 to be adopted.

### 4. LIMITED DUCTILE RC WALL TESTING

The authors have recently completed a large scale experimental program of the in-plane lateral displacement behaviour of limited ductile RC walls. The experimental program has included 17 boundary element prism tests (e.g. Menegon et al. (2015b) and Menegon, Wilson and Lam (2015a)) and 5 large scale RC wall tests (e.g. Menegon et al. (2016) and Menegon et al. (2017a)). Both traditional monolithic cast in-situ RC walls and the more recent jointed precast walls were considered in this study. The latter has become an increasingly popular construction option in Australia, particularly for low and mid-rise buildings.

The large-scale wall tests were designed and detailed to best match standard industry practice as identified by Menegon et al. (2017b). The walls were tested under a quasi-static reversed cyclic loading regime with a shear-span ratio of 6.5. The testing was performed using the Multi-Axis Substructure Testing (MAST) system in the Smart Structures Laboratory (SSL) at Swinburne University of Technology. The MAST system is a state-of-the-art test machine capable of applying full six degree of freedom (DOF) loading in mixed-mode, switched-mode, hybrid or a combination therein (Hashemi et al., 2015). The 5 large-scale RC wall tests consisted of 1 rectangular wall and 4 building core specimens. Of the 4 building cores, there was 1 monolithic cast in-situ specimen and 3 jointed precast sections. The rectangular wall was a monolithic cast in-situ element. The cross sections of each specimen can be seen in Fig. 3 and Fig. 4.

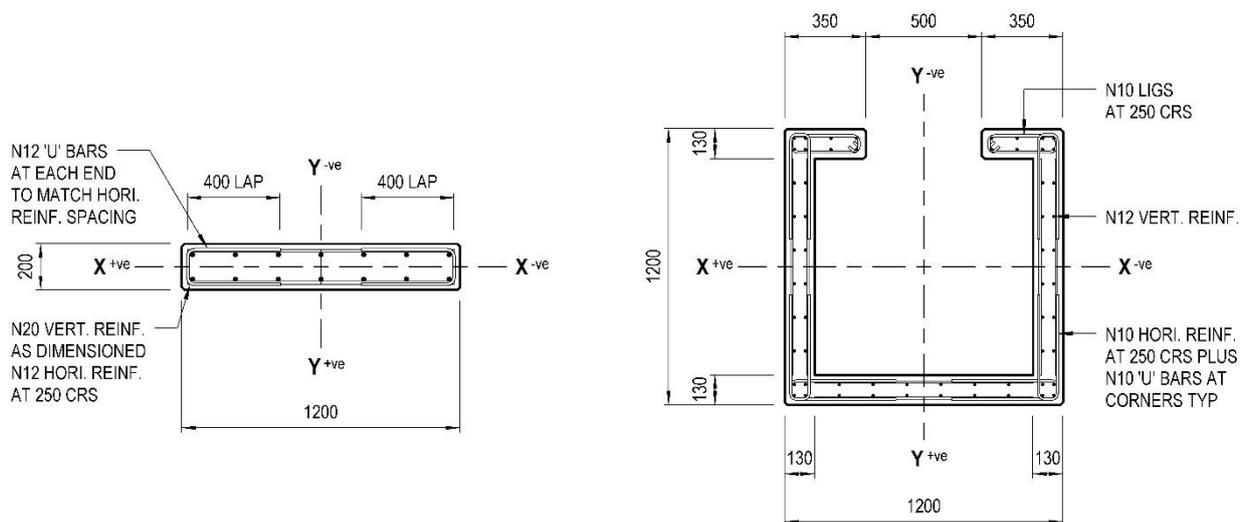


Fig 3. Cast in-situ rectangular wall and building cores specimens.

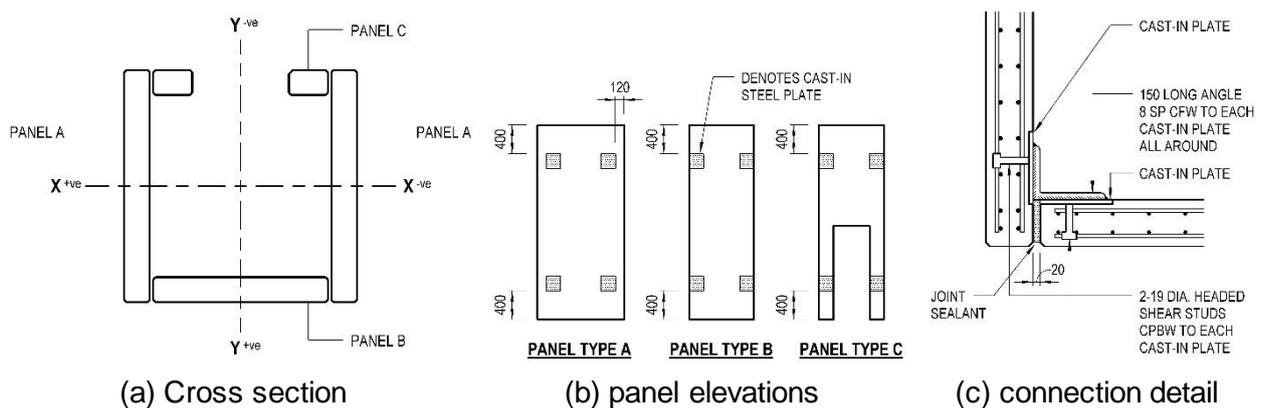


Fig. 4 Typical cross section and connection detail of a jointed building core specimen.

One of the key findings of the large scale experimental program was the atypical plastic hinge behaviour that was observed in the test specimens. This behaviour was a result of the lap splice at the base of the wall. Typically in RC wall testing – when no lap splice is at the base of the wall – the wall develops one of two plastic hinge models. The first being the typical plastic hinge model which has distributed cracking extending

some length up the height of the wall with the inelastic tension strain distributed somewhat evenly across these cracks. The second being a single crack plastic hinge, where the wall is detailed such that only a single crack develops at the base of the wall with all the inelastic tension strain being concentrated in this one location, resulting in a significantly reduced lateral displacement capacity compared to the former. This behaviour usual occurs in under reinforced cross sections where the cracking moment of the wall is greater than the ultimate moment capacity of the wall. These models are depicted in Fig. 5(a) and 5(b) respectively.

The walls in this experimental program were detailed with a lap splice at the base of the wall in the plastic hinge region, which is standard practice in Australia, and as such developed a different plastic hinge model to both of the aforementioned. The lap splice resulted in a region of overstrength at the base of the wall, allowing only hairline cracks to develop across the lap splice and forcing the development of two major cracks, one above and one below the lap splice. The majority of the inelastic tension strain was concentrated in these two cracks resulting in a two-crack plastic hinge model (Fig. 5(c)). A variation of the two-crack plastic hinge model was observed in some specimens, where instead of one major crack being developed above the lap splice, multiple cracks developed (Fig. 5(d)). The type c and type d plastic hinge response is dictated by the ratio of the applied moment at the base of the wall to the applied moment at the top of the lap splice, which is in turn dependent on the shear-span ratio of the wall (i.e. slenderness) and overall length of the lap splice.

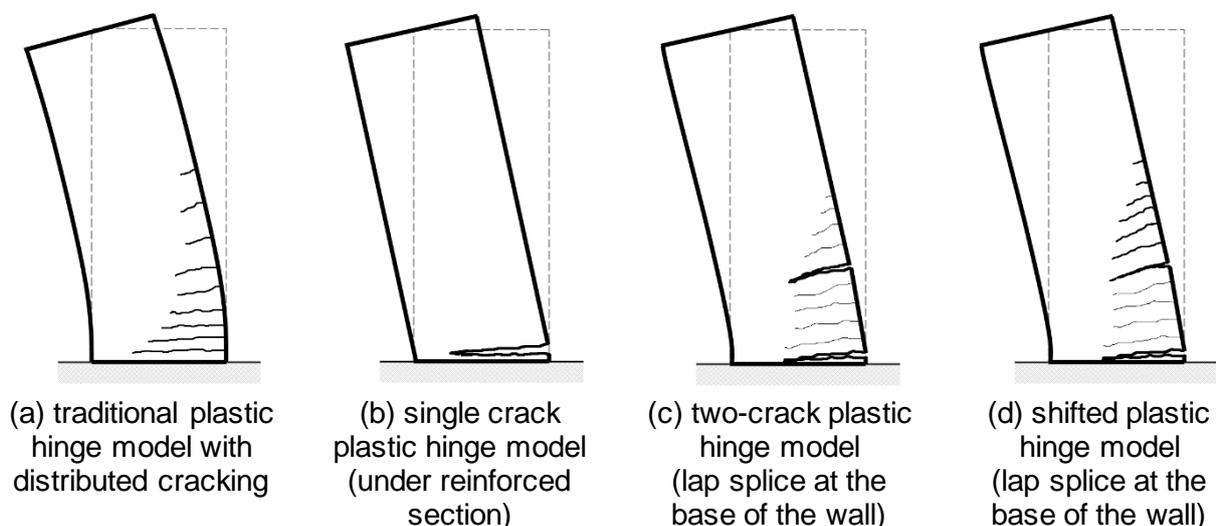


Fig. 5 Plastic hinge models for RC walls (Menegon et al., 2016).

## 5. DETAILING OF RC WALLS IN LOWER SEISMIC REGIONS

In regions of lower seismicity, such as Australia, for many years the seismic design of buildings was not performed nor required by building codes. It has only been in more recent times that designers in these regions have had to undertake seismic design and analysis of structures. This lack of attention to seismic design over many years has resulted in many misconceptions and a low level of education surrounding seismic design and its inherent assumptions, particularly with regards to the concept of trading strength for ductility. Force-based seismic design allows the structure to absorb part of the energy imparted by the earthquake via inelastic plastic deformation of its elements. This is accounted for in design by the force reduction factor (e.g.  $R_f$ ), which is used to reduce the equivalent elastic design earthquake loads on the structure. The force reduction factor consists of two components, the first being overstrength ( $\Omega$ ) and the second being displacement ductility ( $\mu$ ), and is equal to the product of these two components, i.e.  $R_f = \Omega\mu$ . Standard detailing in accordance with the main body of the Australian concrete code, AS 3600 (Standards Australia, 2009) allows designers to adopt an overstrength value of 1.3 and a ductility value of 2.0, resulting in a force reduction factor of 2.6.

Within the design community in Australia there is currently a widespread lack of appreciation and understanding of the fundamental assumption of force-based seismic design where strength is traded for ductility. As a result, many dubious detailing practices are often adopted when designing and detailing RC walls, which in turn greatly reduce and in some cases, eliminate the displacement ductility capacity of the system. To many, these detailing practices have been accepted as pseudo industry standards. Assuming some level of ductility when determining the earthquake actions on the building (e.g.  $\mu = 2$ ), but then detailing the structure in a manner that results in little or no ductility, is obviously contradictory. The following detailing practices, which are widely observed in Australia, particularly in jointed precast structures, significantly reduce the displacement ductility capacity of a system and their use is cautioned:

1. Detailing RC walls with a single central layer of vertical and horizontal reinforcement.
2. Detailing RC walls using low ductility reinforcement (usually comes in the form of welded wire mesh).
3. Detailing RC walls using low percentages of vertical reinforcement.
4. Detailing dowel connections in precast wall panels such that the area of the dowel reinforcement is less than the area of the main vertical reinforcement in the wall panel.

While the authors are not advocates of any of these practices, it is appreciated that due to various project constraints it may be desired that they be adopted. If this is the case, it is recommended that a displacement ductility factor of 1.0 (i.e.  $\mu = 1.0$ ) be adopted in the design.

A common argument for allowing the use of these poor detailing practices, while still assuming some level of ductility when determining the earthquake forces, is that the central core is taking all the lateral load and the exterior or peripheral RC walls

(often precast) are 'load bearing only elements' and as such, it only matters how the central core is detailed. It would be a false assumption to assume these walls are load bearing only elements as an earthquake will distribute load based on the strength, stiffness and ductility of the elements in a system regardless of how one describes them during the design.

When performing lateral analysis, it may appear that the central core takes all the lateral load (when the forces are distributed using initial or effective stiffnesses), however the real force distribution that would occur if the overall systems inelastic displacements were taken into consideration would likely be very different. The ductility class assumed for the building should be that of the least ductile element within the lateral load resisting system of the building.

## **6. AXIAL LOAD RATIO**

Reducing the axial load ratio on an RC element can be the simplest and more effectively method for increasing the maximum displacement capacity of the element. The axial load ratio is taken as the design load on the element (e.g. column or wall) divided by the product of the gross cross-sectional area of the element and the concrete strength. Using a recent study by Wilson et al. (2015) it can be shown that increasing the axial load ratio from 10 to 30 per cent can decrease the maximum drift capacity of an RC column by a factor greater than 2. The displacement capacity of RC columns is of particular importance in torsional eccentric buildings with external gravity frames. While the gravity frame may be assumed to take none of the lateral load, it may in fact be subject to large displacements due to the large deformations the core will have to undergo to develop the assumed level of ductility in the design. Designing gravity frames with high axial load ratios in these scenarios is not recommended.

## **7. CONCLUSIONS**

This paper has discussed and presented portions of the current component of a long-term research project by the authors to reduce the seismic risk and rationalise the seismic design procedures and practices in Australia. This component is looking at the seismic performance of RC wall buildings in Australia and other regions of the lower seismicity. It has included a large experimental testing program consisting of 17 boundary element prism tests and 5 large scale RC wall tests. The latter are discussed within.

This paper discusses a number of poor detailing practices observed in RC wall construction in Australia that will result in the overall structural system of the building having limited or no displacement ductility capacity. These detailing practices include the use of centrally reinforced walls, walls with minimum percentages of vertical reinforcement and walls detailed using low ductility reinforcement. When any of these practices are adopted, it is recommended that a displacement ductility factor of 1.0 be adopted when calculated the earthquake design loads for the building. The ductility classification should be selected based on the least ductile component in the building.

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