

Comparing New Zealand's Unreinforced Masonry Details with those of Other Seismically Active Countries

by

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ABSTRACT

Unreinforced Masonry (URM) was a very common building material in New Zealand during the later part of the 19th and early part of the 20th centuries, up until the 1931 Napier Earthquake. This paper outlines the prevalence and discusses typical details for unreinforced masonry in New Zealand. These findings are contextualised through comparison with the corresponding information from a selection of other seismically active countries. It has been found that New Zealand shares common URM structural details with Australia, the United States, Portugal and Italy. A lack of positive connection between URM walls and timber diaphragms is the most significant problematic detail common to all countries considered in this paper. The next most common detail was a lack of adequate connection between wall leaves, which can lead to out-of-plane failures under earthquake loading. New Zealand's building practices for URM construction are most closely aligned with those found in Australia and the United States.

1. INTRODUCTION

Unreinforced masonry (URM) is known to perform poorly under lateral loads produced by seismic actions [1-2]. This has been shown countless times in earthquakes such as the 1989 Newcastle earthquake in Australia, and the 1994 Northridge earthquake in California. In New Zealand, URM was a very common building material in the later part of the 19th and early part of the 20th centuries. However, since the 1931 Napier earthquake in which nearly 260 people were killed and most URM buildings in the city were destroyed [3-4], the use of this construction material declined until it was finally banned in 1965, with the introduction of NZS 1900 [5]. Nevertheless many historic URM buildings still exist in New Zealand.

Many buildings of other typologies also exist in New Zealand, such as steel, reinforced concrete and composite mixtures of these materials, and a large research project being conducted between the Universities of Auckland and Canterbury is underway to find retrofit solutions for buildings, which can be identified as needing seismic upgrade. The project is focussed predominantly on multi-storey and non-residential structures, as the majority of single level dwellings in New Zealand are expected to perform satisfactorily in a major earthquake. One of the main concerns of this project is related to the possible differences in construction details and practice in New Zealand when compared to similar building typologies overseas. A strong need to translate and adopt overseas practice in terms of seismic assessment and retrofit of New Zealand's unique building stock, within a general plan of mitigation of the national seismic risk, has been recently recognized. To date, little research has been undertaken in terms of collating and summarizing typical details of unreinforced masonry in New Zealand. As part of the above mentioned "Seismic Retrofit Solutions Project", research is currently underway into assessing the situation in New Zealand in terms of existing

URM building stock. More details of this project can be found on the project website, www.retrofitsolutions.org.nz.

Within the scope of retrofitting URM buildings in New Zealand, it is necessary firstly to establish accurate assessment procedures, so that the most cost effective retrofit solutions can be achieved. Without accurate assessment methods, overly conservative and hence more costly retrofits are required. Before these assessment methods are established it is necessary to ascertain the state of New Zealand URM buildings, in terms of their construction methods, materials and other building details. This research is currently ongoing. It is important that the findings are put in the context of those found in other countries. It has been recognized that those countries with the most similar building practices in the time period in question (1860 – 1960), and whose buildings are also seismically at-risk are Australia, the United States (particularly California), Portugal and Italy. The last two are included to represent European construction in seismically active areas, which would also include Turkey, Greece, Slovenia and others.

2. URM BUILDINGS

Masonry is one of the oldest building materials known to man. The *Bible* refers to the use of bricks and mortar in the construction of the Tower of Babel, thought to have been built around 5,000 years ago. In most civilisations in throughout history masonry has been used in some form for buildings of widely varying sizes and shapes. Masonry construction can be divided into unreinforced and reinforced (including prestressed) masonry. Reinforced masonry, in New Zealand, was defined as containing more than 0.25% of its volume of reinforcing steel [5]. Unreinforced masonry can be broadly divided into either brickwork or stonework masonry. URM buildings exist in different forms and BINDA [6] has identified 4 main typologies, as follows:

- Stand-alone or isolated buildings
- Row residential buildings or shops
- Complex residential buildings
- Religious buildings, palaces and bell towers

Stand-alone URM buildings are usually small, single storey houses, although may sometimes be larger buildings such as large shops or fire stations. URM row buildings often occur in a busy commercial part of a city, such as a shopping district which has evolved over time, with the buildings remaining since the original construction. Complex residential buildings, religious buildings, palaces and bell towers can occur in many different locations and are usually assessed on an individual basis.

3. SEISMIC RISK OF URM

Unreinforced masonry has been shown to perform poorly in earthquakes. This is mainly due to its poor capacity to withstand the lateral forces induced when subjected to earthquake loading, and its often brittle behaviour and poor

energy dissipation. Most URM buildings were designed and constructed before modern earthquake code provisions were in place. Indeed, many modern design codes do not permit the construction of unreinforced masonry. The 1931 M7.8 Napier earthquake in New Zealand and the 1933 M6.4 Long Beach earthquake in California proved to be turning points after which the use of unreinforced masonry as a construction material in the respective countries declined until it was no longer used at all [7-8] (see Figures 1 and 2). Other countries such as Australia still permit the construction of URM, provided it falls within the guidelines of the appropriate design code [9-10].

New Zealand is seismically active and lies on the boundary of the Australian and Pacific tectonic plates, and some cities (for example Wellington) lie on the fault line itself. To the east of the North Island the Pacific plate is forced under the Australian plate. Under the South Island the two plates push past each other sideways, and to the south of New Zealand the Australian plate is forced under the Pacific plate. It is estimated that New Zealand has around 14,000 earthquakes each year; most are small, but between 100 and 150 have a magnitude sufficient to be felt. In the past 150 years, New Zealand has had around 15 earthquakes registering over M7.0 magnitude on the Richter scale, with a centre less than 30km deep.

4. URM IN AUSTRALIA

Australia the country most closely neighbouring New Zealand. While Australia's seismic risk is referred to as intraplate, and is not directly associated with deformation at plate boundaries, Australia does experience earthquakes of significant magnitude due to stresses associated with motion of the India-Australian plate being pushed north and colliding with the Eurasian, Philippine and Pacific plates. The largest recorded Australian event was the 1941 M7.2 Meeberrie earthquake. In particular, the 1989 M5.6 Newcastle resulted in extensive damage, with over 3000 buildings affected. See Figure 3. Most damage occurred to unreinforced masonry buildings constructed between 1900 and 1950, and this earthquake raised awareness amongst Australians of their country's seismic risk. This prompted a focus on the need for seismic retrofit of unreinforced masonry buildings in Australia. Before the Newcastle earthquake little attention was given to seismic design, and indeed up until the publication of AS 1170.4 in 1993, Newcastle was deemed to be located in a zone of zero seismic risk, with no seismic design provisions. Consideration of seismic effects when designing for URM is now mandatory in Australia [9-13].

Australia and New Zealand are considered to have had very similar building practices up until the 1931 Napier earthquake. URM construction typical of this era in Australia consisted of clay brick walls, supporting timber floor systems and timber roof trusses with metal or clay brick tiled roofing. The brick walls were typically cavity walls, with no rubble fill, and were supposed to be connected with metal wall ties. The bricks themselves were usually pressed bricks of a regular size. The timber floor/roof systems typically were supported with bearing supports on the inner wythe of the cavity wall without any significant positive connection to the walls. The gable end walls of these buildings were often especially prone to out-of-plane loading and were a common failure mode observed following the 1989 Newcastle earthquake (refer Figure 3). For this class of masonry construction, the weak connection between floor systems and walls also limits the degree to which floor diaphragm action provides effective lateral support to the walls in bending. Where the connections are ineffective, the walls are especially prone to out-of-plane bending failure. A third common failure mode observed in older URM buildings during the Newcastle earthquake was bending failure of the outer leaf of cavity walls, commencing at the top of a building and progressing towards the bottom as if they were "peeled" off the structure. This was mostly due to corrosion of the metal wall ties between the two leaves of brickwork which left the exterior brickwork laterally unsupported over the entire height of the structure [12].

A parametric study of typical design configurations of relatively modern (post-1950) unreinforced clay brick masonry building designs less than 15m tall indicates that, in order of frequency of occurrence, there are 3 common failure modes. Typically, these structures are mostly apartment buildings consisting of brick cavity construction with suspended concrete floor slabs and timber roof structure with either metal or clay tile roof cladding.

For these structures, the first and most common potential failure mode is due to out-of-plane bending of walls. Walls at the top-most storey are the most critical where it is normally assumed for design that the outer leaf is connected to the inner leaf with adequate wall ties so that each wall can be assumed to resist their respective share of the seismically induced inertia load acting in the out-of-plane direction. Combined with the fact that the earthquake induced accelerations are greatest at the top of a building, the external leaf walls have less compressive stress in them. Hence they are the weakest with regard to their flexural strength.



Figure 1 Damage to URM buildings in Napier earthquake 1931 (reproduced from [30])



Figure 2 The collapse of part of Jefferson Junior High School in Long Beach 1933 (reproduced from [31])



Figure 3: Damage to URM school building in the 1989 Newcastle earthquake (reproduced from [32])

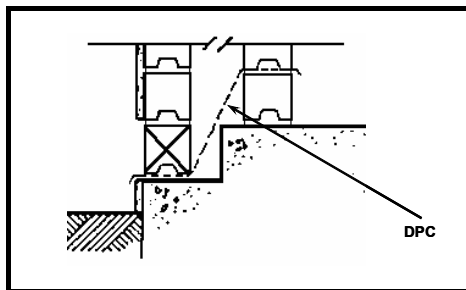


Figure 4 URM wall to ground floor slab DPC connection detail

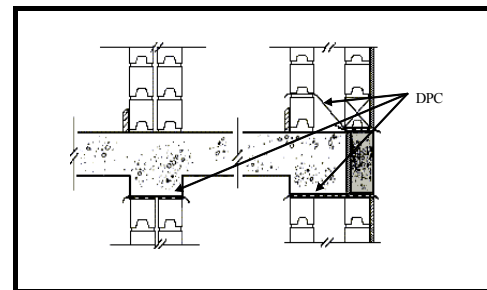


Figure 5 URM wall to inter storey floor slab DPC connection detail

The second most common detail of concern is related to an in-plane sliding shear failure mode at the base of ground storey walls. The use of damp-proof courses (DPC) at the base of URM buildings (see Figure 4), to prevent moisture being sucked up from the ground into the brickwork, means that transfer of seismic shear force at the base of the building is completely due to friction. It is not clear that this failure mode is actually a life-safety issue, given the relatively small amplitude of ground displacements likely to occur in Australia; however, in the current codified procedure it is a strength check which many of the typical buildings do not satisfy. The DPC joints are normally along a constant horizontal plane.

Finally, the third most common potential failure mode is through the wall (thickness) shear failure at the base of exterior walls in the upper levels of a building. This again is due to the use of a DPC or slip joint detail which limits the in-plane stresses induced in a URM wall due to differential concrete slab shrinkage and clay brick growth. However, in URM walls at the top of a building, where the out-of-plane accelerations are greatest, the typical coefficients of friction of about 0.3 are limited in the magnitude of shear reaction in the "through the thickness" direction that they can accommodate. If on average the out-of-plane acceleration is greater than 0.3g, then there can be a problem. See Figure 5.

5. URM IN ITALY AND PORTUGAL

European URM construction consists of all the four building typologies outlined in section 2, and of all the regions investigated in this paper, Europe has the largest stock of

religious buildings, palaces, and bell towers. This is mainly due to the age of much of its building stock, which is substantially older than most buildings in the comparatively later settled countries considered in the current study. URM in Italy and Portugal was considered to be representative of URM construction in seismically active countries in Europe.

In Italy and Portugal a significant portion of the URM building stock is made of stonework masonry. It has been noted by Binda [14] that the performance of URM structures can be understood provided that certain factors are known. These factors include the geometry of the wall, its configuration (e.g. single or multi-leaf construction, connection between leaves) and the characteristics of masonry as a composite material. The strength of masonry structures can be calculated from the components, particularly when new (e.g. 20th century) structures are considered. Older existing brickwork masonry may require material sampling and testing to determine its strength. However the composite and non-homogenous nature of older masonry makes component behavior difficult to predict, and also difficult to replicate in the laboratory [15]. Moreover, it is nearly impossible to perform representative testing of stonework masonry (let alone calculate its strength) due to its high degree of non-homogeneity. The strength and deformability parameters of the components are difficult to extrapolate to determine the global strength and deformability of the structure.

Within stonework masonry, Binda has identified the following critical aspects [16]:

- non-homogeneity, due to the presence of stones, various mortars and other materials

- lack of adhesion between external and internal leaves of the walls
- poor adhesion between mortar and stones
- poor cohesion of mortar in the joints and in the rubble fill
- high porosity of the wall system due to the presence of voids

Within brickwork masonry, it has been identified that several problematic details are common in Italian URM. Magenes and Calvi [15] have identified that damage to brickwork buildings observed as out-of-plane failures of URM walls was often caused by excessive deflections in the floor or ceiling diaphragms, and the insufficient connections between them. Often URM walls are pierced by windows and doors, leaving the wall effectively as a series of piers between the openings. Often these piers provide some resistance to lateral loads, although the behaviour of such components differs greatly from other frame-type structures or reinforced concrete walls. Magenes and Calvi have also identified that if the method of failure is due to in-plane loading, the principal mechanisms of failure are likely to be either rocking failure, shear cracking or sliding [15]. Rocking failures are usually due to the poor bed joint strength and as the bed joint cracks in tension due to the lateral force or displacement demand, failure is caused by overturning of the wall. When inclined shear cracks form, the two failure modes observed are to follow either the path of bed and head joints, or through the bricks. This depends on the relative strength of mortar joints, the brick-mortar interface and the bricks themselves. When low levels of vertical load are present, for example in low-rise buildings, sliding may occur on the cracked bed joints, due to the formation of tensile horizontal crack in the bed joints, when subjected to reverse seismic loading.

In Portugal, Lourenço and Ramos have undertaken extensive research into ancient masonry structures, and especially churches [17-19]. A comprehensive analysis of the church of Saint Christ in Outeiro (Bragança), in the North of Portugal, which was constructed between 1698-1738 has also been conducted [20-21]. A significant number of structures referred to as ancient masonry in Portugal are stone masonry and were constructed in the order of several hundred years ago. Referring to the church of Saint Christ in Outeiro in the North of Portugal, Lourenço states, "the structure is mostly made of local shale stone and thick lime mortar (rubble masonry), [and] regular masonry (granite ashlar and dry / thin joints) was used in doors / windows frames and the façade...The structure is of moderate size (38 × 22m² for the plan view, 13m height for the nave and 22m height for the towers)... The façade [has a] cladding [of] granite." [17]. This church is representative of a significant number of unreinforced masonry buildings in Portugal, constructed of stone masonry. Little has been documented on brickwork masonry in Portugal, built between 1860 and 1960.

6. URM IN THE UNITED STATES

Before the Long Beach earthquake in 1933, unreinforced masonry construction in California was representative of construction throughout The United States. Due to the widespread damage suffered to public schools in Los Angeles in that earthquake, by the end of 1933 the City of Los Angeles and many other cities had already outlawed all unreinforced masonry wall bearing construction. Subsequently in California and other west-coast states, unreinforced masonry became an unused and archaic building construction type. Nevertheless, California retained a considerable inventory of existing unreinforced masonry

buildings, estimated at nearly 25,000 in 1991, and it was estimated that in 2003 about 3000 still did not meet the minimum standards recommended by legislation. Construction of unreinforced masonry buildings continued freely in other parts of the United States, including seismically at-risk areas, for roughly another 40 years. In California, most URM buildings house commercial uses, and in San Francisco about 38% are residential. In the Bay Area in Northern California about 20% of URM buildings are designated historic [8,22-23].

It was recognised by Bruneau [8,24-25] that during the M6.7 Northridge earthquake in 1994 most damage to URM buildings was related to diaphragms and their connections to walls. It has been found that the use of unreinforced masonry walls with timber diaphragms for floors or roofs was commonplace in pre-1945 construction in America, although less so in California (see Figures 7, 8 and 9). Timber diaphragms typically consist of three components; sheathing, framing and chords. It was found that in buildings constructed before 1945, sheathing was made of straight members, nailed onto the framing, rather than plywood, as would be expected in current practice. Occasionally iron wall anchors were used to connect the diaphragm to the wall, but only on about every 4th joist. Usually joist-to-wall anchors were designed without taking seismic forces into consideration. Such connections have been observed to fail in three ways; the iron anchor itself fails, the connection pulls out of the masonry or shears out of the framing member at the other end. In general there were insufficient connections between diaphragms and perimeter masonry walls. Most often there was a complete lack of positive anchorage of the floors and roof to the URM walls. Often joists were supported by pocket holes in the URM wall, with a very small bearing area, even as small as 75mm deep. Sometimes the joists or beams were simply supported on special corbels, but most often the URM wall was constructed around the supported beam, either with bricks tightly fitting around the beam, or with a weak grout used to fill the oversized cavity housing the supports for the beams [24]. With inadequate connections between the diaphragms and URM walls, the exterior walls behave as cantilevers, extending from the ground up to the top of the building. This increases the risk of wall out-of-plane failure. It also means that the floors or roofs are free to pull out of the wall during an earthquake, contributing to global collapse of the building.

Another vulnerable detail was the lack of chord members along edges of the diaphragm. HAMBURGER and MCCORMICK [26] observed that in the Northridge earthquake a major source of damage was due to failure of out-of-plane connections between masonry walls and panelised plywood roofs.

Significant damage to URM buildings observed in the 1989 Loma Prieta Earthquake was due to in-plane and out-of-plane failures. In-plane shear failures were common in walls, spandrels and short piers between those spandrels; these shear cracks often appeared as double-diagonal cracking. Flexural failure usually occurred in slender URM columns, where the cracking at both ends of the column transformed them into rigid bodies with no further lateral-load resisting capacity [24]. Out-of-plane failure tends to be sudden and brittle. If there are sufficient connections between the joists and walls, then the walls behave as one-storey high panels excited at each end by the floor diaphragms. If the connections between the walls and floors are inadequate, then the walls have a tendency to topple, rather than explode, and the floors will simply collapse, leading to total global failure of the building.



Figure 6 New Zealand multi-leaved wall with change in wall thickness at floor level



Figure 7 Cross-section of brick masonry wall in The United States (reproduced from [33])



Figure 8 Connection between floor joists and URM wall in US (reproduced from [34])

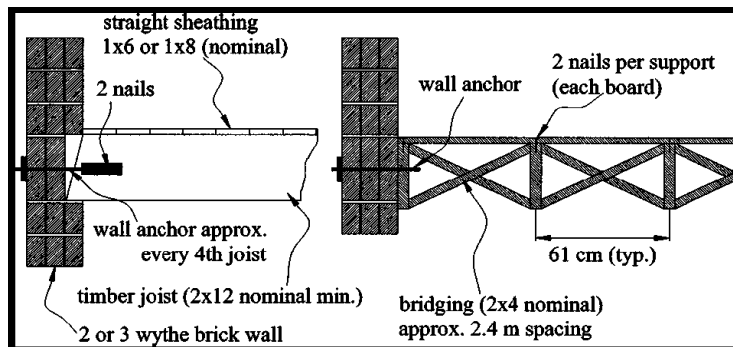


Figure 9 Typical floor connection details in pre-1950s URM buildings in US (reproduced from [25])

7. URM IN NEW ZEALAND

In the late 19th century and the early part of the 20th century, when New Zealand was growing rapidly due to European settlement, URM was a common construction material, and was used to build most commercial buildings [27]. After the 1931 Napier earthquake it became apparent that unreinforced masonry was insufficient in providing the strength which buildings required to withstand earthquake forces, and this construction practice began to decline. Nevertheless, the use of URM as a construction material remained common right through until the late 1940's. After World War II no large buildings were constructed with unreinforced masonry and in 1965, with the introduction of NZS 1900, this construction practice was prohibited.

A significant number of URM buildings still exist in New Zealand, and of those, many are administered by the Historic Places Trust, a heritage agency set up to preserve and maintain New Zealand's heritage places and buildings. Buildings administered by the Historic Places Trust must not be demolished, but often require retrofit.

Existing URM buildings in New Zealand are typically large stand-alone buildings, for example the Auckland High Court, constructed between 1865 and 1868, and the Auckland Chief Post Office, built between 1909 and 1912 [28]. However, URM buildings also often exist in the typology of a block of individual shops or residential dwellings, such as in Queen Street, Auckland's main retail area. Small single-storey isolated URM houses still exist in New Zealand, but most are not protected by the Historic Places Trust, and are more likely to be demolished than retrofitted. Unique structures also exist, such as the 40m high chimney originally part of Auckland City's rubbish destructor, and now part of Victoria Park Market, a popular shopping complex. The distribution of URM buildings is roughly proportional to population density; significant buildings tend to occur in more highly populated areas, such as Auckland and Wellington, although a number of large URM buildings were present in Napier before the earthquake in 1931. Smaller buildings are located around the country according to the population at the time of construction.

Most URM in New Zealand is brickwork masonry, although some stonework masonry does exist, often for façades but also for structural purposes, particularly in the South Island, (mainly Christchurch and Dunedin), with the use of Oamaru sandstone and Otago granite.

Unreinforced masonry buildings in New Zealand can be of either one- two or multi-leaf construction. Figure 6 shows a double leaf wall. Usually the outer leaf is simply for weather proofing, and serves little structural purpose, while the inner leaf is structural. In external walls, it is important that the leaves are connected adequately to combat out-of-plane accelerations in the façade or outer leaf. It has been identified that in many instances these ties were never put in place as part of the original construction, or if they were they are now completely rusted out. Also, due to erosion of the building, the mortar in the walls is often now in poor condition. Wire ties were often placed in the mortar between

bricks rather than in the bricks themselves, and hence pull out more easily in an earthquake than if they were embedded in the bricks.

In multi-leaved walls, it has been found that header bricks are used about every five to seven courses. It has also been found that when subjected to lateral loads many bricks simply pull out of the wall as their strength depends on the strength of the mortar. In the case of lime mortar the bricks hold together, but sometimes where cement mortar is used the bricks themselves tend to tear apart as the strength of the mortar exceeds that of the brick [29].

In the building typology of a long block of individual dwellings, the walls dividing the dwellings (usually shops or residential flats) are mostly a single solid wall and not a double skin. In these cases, often the floor levels in neighbouring dwellings are at different levels, and this can cause pounding of the dividing wall from the diaphragms during earthquake loading.

Another common problem in New Zealand URM has been identified as the configuration of unreinforced brick walls with timber floor and ceiling diaphragms. Often there is no positive connection between the walls and diaphragms, and the building cannot hold itself up under earthquake loading as the lateral loads cannot be effectively transferred. If an effective connection is put in place between the diaphragms and walls, the strength of the walls can be mobilised and the building can then be expected to have a reasonable amount of capacity during an earthquake. Figure 6 shows a wall with the thickness of the wall stepping down at the upper storey. It has been found that this configuration is common, and the floor diaphragms are simply bearing on the top of the lower wall, and are not embedded in the brick at all. Frequently there is also a lack of effective chord members along the edge of the diaphragm, so that even if there was an adequate connection to the wall, the diaphragm itself could tear apart at the edges. In addition upper floor levels and parapets lack strength and require some method of bracing.

Sometimes instead of timber diaphragms, reinforced concrete diaphragms were used, and in this case the mass is much greater, causing higher lateral accelerations under seismic loading.

Another critical issue in New Zealand URM structures is to address their propensity for in-plane rocking of piers between wall openings. Although in-plane rocking and pier behaviour between openings does enable some energy dissipation, the interaction of in-plane and out-of-plane behaviour is not well understood.

Where URM buildings contain extensive openings in the form of doors and windows, often at the front of a shop and normally confined to the bottom storey, the building has very poor torsional capacity. In this case there are usually adequate walls in one direction (perpendicular to the shop front window) and the back wall may have a relatively small opening in the form of a door. When subjected to seismic loading, the building may have sufficient strength in the direction of the long walls, but not in the perpendicular direction, and as earthquake loading never occurs in one direction only, the building will have very poor torsional strength.

8. CONCLUSIONS

Italy and Portugal exhibit all four main building typologies, and URM buildings range from small isolated houses to complicated residential dwellings to large cathedrals and bell towers. New Zealand, Australia and The United States exhibit a smaller range of building typologies and URM construction tends to be isolated buildings (from small houses to large fire stations and railway stations) and only a few unique structures such as tall brick chimneys.

Italy and Portugal, with considerably older URM construction, have a significant amount of stonework masonry, whereas in New Zealand, Australia and The United States, while stonework masonry does exist, the majority of URM buildings tend to be of brickwork. Brickwork masonry in Italy and Portugal does exist, and newer URM structures are often constructed using this material.

It has emerged that New Zealand shares some URM details with other seismically at-risk countries. The most notable is the connection between URM walls and timber floor or ceiling diaphragms, which is common to New Zealand, Australia, Italy and Portugal and The United States. Usually a positive connection between the wall and timber diaphragm is insufficient or completely lacking. This prevents an effective transfer of load from the diaphragm to the wall.

Another detail which is shared by New Zealand, Australia and The United States is a lack of adequate connection between URM wall leaves. The wire ties which were intended to connect the leaves are either corroded or not present at all. In Italian stone masonry, it has been identified that there is a lack of adequate adhesion between internal and external leaves of the walls.

It has been identified in The United States, Australia and New Zealand that frequently there are poor connections between leaves and between walls and diaphragms, and this often leads to a poor out-of-plane response of the URM wall.

Italy and Portugal have old non-homogenous stone masonry walls, and large tall stone masonry churches, both of which are not common in New Zealand.

During the 1989 Newcastle Earthquake in Australia, some URM walls exhibited in-plane sliding shear failures, due to the presence of damp-proof courses at the base of the wall. The use of a DPC in this way occurred in post-1950 Australian URM buildings, and by then URM construction in New Zealand was seldom used. This detail does not occur in existing New Zealand URM buildings.

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