Section 4:

Techniques for seismic improvement of unreinforced masonry buildings

The purpose of this section is to describe recognised techniques that are available for the seismic improvement of unreinforced masonry (URM) buildings. Typical failure modes are presented in Section 4.1 with reference to the observed performance of URM buildings in the 2010/2011 Canterbury earthquake swarm as documented in Section 3. A brief description of both well proven and recently developed techniques that have been implemented successfully in Christchurch for seismic improvement of URM buildings is presented in Section 4.2. Photographic evidence is provided to illustrate both successful and unsuccessful examples of retrofit techniques that had been installed in Christchurch URM buildings before the 4th September 2010 Darfield earthquake.

4.1 Typical earthquake failure modes in URM buildings

Decisions on whether to seismically retrofit a URM building or to demolish and rebuild a replacement structure that complies with current earthquake strength criteria depend upon the desired building performance as well as the associated costs. In this section, a generic retrofit strategy is described that begins with the most basic, and important, items to address with the primary aim of ensuring public safety. Additional retrofit measures may be taken beyond these to further improve building performance in order to minimise damage to the building and contents, with the highest performance target conceivably being to have the building and its contents suffer no damage and be immediately functional following the considered earthquake event.

Unmodified URM buildings usually have a number of inherent structural features which make them prone to earthquake forces. Many of these features can often be addressed without significant alteration to the building fabric, resulting in a relatively large increase in strength (Robinson & Bowman, 2000). The overarching problem is that New Zealand's URM building stock were simply not designed for earthquake loads, and whilst these buildings can be made to perform adequately in an earthquake, they lack a basic degree of connection between structural components to allow all parts of the building to act together. Therefore, the basic philosophy followed here is to first secure non-structural parts of URM buildings that represent falling hazards to the public (eg, chimneys and parapets) followed by improving the connections between the structural elements (roof, floors and walls), strengthening of specific structural elements, and possibly adding new structural components to provide extra support for the masonry building. In the rest of this section, the most commonly observed failure modes are described and possible retrofit strategies for each are given.

Chimney and parapet failures

Chimneys and parapets are parts of URM construction that project above the roof of the building. When subject to seismic actions, they act as cantilevers which rock on their supports at the roof line. If sufficiently accelerated by the earthquake, they will topple over (see Figure 3.6 and Figure 3.8). The simplest way to prevent earthquake failure of these elements is to brace them back into the roof structure (see Figure 3.6(d)). Implementation of this bracing is comparatively straightforward and inexpensive.

Gable end wall failures (missing or inadequate ties/anchorage)

Gable end walls sit at the top of walls at the end of buildings with pitched-roofs (refer to Figure 3.7). If this triangular portion of the wall is not adequately attached to the roof, the gable end section of the wall will rock as a cantilever (similar to a chimney or parapet) and is similarly vulnerable to outward collapse. An example of a building that was undergoing gable wall retrofit at the time of the February Lyttelton earthquake is shown in Figure 4.1 where the retrofitted gable walls had survived whereas the one gable wall remaining to be anchored to the roof truss failed. Other examples of gable end walls that performed poorly in the Canterbury earthquakes are shown in Figure 3.7 whilst examples of URM buildings that performed adequately due to the presence of anchor plate connections between the gable wall and the roof structure are shown in Figure 3.14.

Out-of-plane wall failures

Unreinforced masonry walls are weak in out-of-plane bending and therefore are susceptible to out-of-plane failures as shown previously (see Figure 3.10). The earthquake vulnerability of a URM wall to out-of-plane bending is predominantly dictated by its slenderness. Cavity walls (e.g. two single brick thick walls separated by a 75 mm gap that are connected by small metal ties) that are missing wall ties or have wall ties that are badly deteriorated are especially vulnerable (refer to Figure 3.12).

Solid walls can also be vulnerable but they have the advantage of being less slender. Examples were observed of out-of-plane failures of solid walls. The addition of wall-to-diaphragm anchors serves to reduce the vertical slenderness of a wall as well as make the building work together as a whole, rather than as independent parts.

**Figure 4.1 Example of a secured gable end that survived earthquake loading
and a companion failed gable end that was not secured**

Floor and roof diaphragm failures (excessive deformation)

In some cases the floor and roof diaphragms, which are typically constructed of timber, were excessively flexible. This flexibility resulted in the walls that were connected to these diaphragms undergoing sufficiently large out-of-plane deflections to cause major wall damage and collapse. A number of successful diaphragm stiffening retrofits were observed, with details presented in the following section.

In-plane wall failures (piers and spandrels)

When out-of-plane failure mechanisms are prevented, the building is able to act as a complete entity and in-plane wall failure mechanisms can occur. It should be noted that when in this condition, building strength is often not far off the full design strength requirements. Strengthening of piers and spandrels can result in further increases in overall building strength. The seismic retrofit strategy for a building in this condition might be to improve the building's displacement capacity, rather than institute any further increase in strength. This intervention could be achieved by locally reinforcing the masonry spandrels and/or piers. Alternatively, ductile steel or concrete frames can be inserted internally to provide the in-plane shear strength needed, whilst also becoming responsible for some or all of the gravity load carrying function of the masonry walls. In effect, the introduction of a new internal structure converts the URM building into a frame structure with masonry veneer cladding.

Return wall separation

This failure mechanism (see Figure 3.21) is undesirable because it allows a wall over the entire building height to fall outwards. This failure mode can be prevented by the use of anchors installed along the vertical intersections between walls.

Pounding failures

This failure mechanism only occurs in row type construction where there is insufficient space between adjacent buildings so that they pound into each other when vibrating laterally during an earthquake. Widespread examples of pounding damage to URM buildings were observed in the recent Canterbury earthquakes (see Figure 3.22).

4.2   Techniques for seismic improvement of URM buildings

4.2.1   URM material stabilisation (poor maintenance)

Aim: Ongoing building maintenance should be undertaken to ensure that the masonry elements (walls, parapets, chimneys, and facades), and the timber roof and floor elements are in sound condition. Deterioration of the fundamental building elements compromises the ability of the 'as-is' connections between elements to share the seismic forces generated during an earthquake.

The bricks and particularly the mortar used in URM buildings deteriorate in the environment over time. Occasionally this deterioration will result in local failures and cracking which affect the overall effectiveness of the building. Various external actions such as dampness, subsidence, earthquakes, and impacts can also cause cracking and damage in the masonry elements. Deterioration similar to that shown in Figure 4.2 can often be remedied by reinstatement and repointing of mortar[7], but sometimes more substantial measures are required. There are various techniques for the repair of cracks, securing of lintels, and reinstatement of damage. Bonding agents such as grout or epoxy can be injected into the mortar and there are also several metal-based types of inserts, such as shaped dowels or reinforcing bars, which can be used to reinstate and strengthen the brickwork (Croci, 1998). The visual impact of reinstatement and strengthening can be minimal if done carefully, and the result is potentially far superior to a cracked and broken façade. However such measures are often irreversible, and care needs to be taken with colour matching and the concealment of holes drilled for inserting rods. Lintels and arches will sometimes require strengthening, particularly when these elements are constructed from URM. One of the best ways to achieve this intervention is by using drilled and inserted rods which are grouted or epoxy anchored into place. These rods provide the requisite tensile strength to the structural element while having little visual impact.

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[7] Lime mortars should always be repointed with new lime mortars. Mixing lime and Portland cement mortars can cause numerous problems.

Figure 4.2 Severely degraded bricks and mortar due to moisture ingress

4.2.2   Parapets and other falling hazards

Aim: Secure or remove falling hazards. The greatest threat to public safety posed by URM buildings is that of falling masonry. This hazard can be due to chimneys that fail by rocking, usually at the roof line, and fall through the building's roof or over the side of the building. Parapets that are not properly secured to the building can fail similarly. Because of their location along the front and sides of commercial buildings, and because they typically fall outwards towards the footpath/street, parapets pose a very high danger to the public. Many of these failures were seen during both the 4 September 2010 and 22 February 2011 earthquakes, where parapets not only fell towards the street/footpath but they mostly fell onto the building's awning or canopy that projects above the pedestrian access, and resulted in collapse of that element as well. In cases of multi-storey (two or three) buildings with parapet failures, the parapets fell across the footpath and well into the street, crushing cars and buses and in several instances killing the occupants of those vehicles. Gable end walls are another version of this out-of-plane failure mechanism and similar to parapets, gable walls almost exclusively fall outwards. Where the gable walls are adjacent to public spaces, they also pose extreme danger to the public.

The basic strategy to eliminate these falling hazards is to fasten them to the rest of the structure, normally through use of ties or anchors back to the roof structure. Many examples of successful chimney, parapet and gable wall retrofits were observed.

URM buildings will often feature numerous decorative elements built with brick and plaster which are important parts of the building's architectural character, such as parapets, chimneys, gable walls, and other, smaller, decorative features. In the past, some buildings have had these elements removed wholesale, rather than the elements being strengthened or secured. Parapets and chimneys are usually the first parts of a building to fail in an earthquake due to their low bending strength and high imposed accelerations (FEMA 547, 2006). Parapets in particular are comparatively simple to strengthen. Generally a continuous steel section running horizontally along the length of the parapet which is fixed back to the roof structure behind is a suitable technique, if a little crude. The back of a parapet is not often seen, which makes the visual impact of

this method low, and the steel section is bolted to the URM, which also has good
potential for reversibility.

Several examples of unsuccessful parapet retrofits were observed following the recent
Canterbury earthquakes. These failures provide an important opportunity to identify
aspects that need to be considered when formulating best practice examples for use in
future retrofit designs. Figure 4.3 shows two examples where discontinuous horizontal
elements were installed at the rear of the parapet. In Figure 4.3(a) the distance between
the braces securing the parapet to the roof structure was too large and in Figure 4.3(b)
and (c) the horizontal element that was used to secure the parapet was discontinued
adjacent to the corner of the building.

(a)   Roof level view of failed parapet restraint

(b)   Exterior view of failed parapet at corner   **(c)   Roof level view of failed parapet at corner**

**Figure 4.3 Failed parapet where the securing was discontinuous at the corner
of the building**

Equally important has been the widespread observation that many steel fixings that
were installed inside URM buildings to internally secure gable walls and prevent out-of-
plane wall failure have failed due to two companion failure modes:

- There has been a significant number of observed failures of adhesive anchors,
  where the anchor has withdrawn from the brick (see Figure 4.4(a)). This failure

mode is of major significance as this securing technique has been used widely internationally. Recognising the significance of these observations, an international study between the University of Minnesota and the University of Auckland is currently underway in Christchurch to obtain reliable data on the pull-out strength of this class of anchor[8].

• There are many examples where the adhesive anchor has held the brick to which it was secured, but that brick has detached from the masonry structural element and only an individual brick is retained (see Figure 4.4(b)). This failure mode demonstrates the need for application of a continuous supplementary structural element to the surface of the masonry to secure the structural element as a single component.

| (a) Failure of a steel fixing due to anchor withdrawal | (b) Failure of a steel fixing due to both anchor withdrawal and brick detachment |

Figure 4.4 Examples showing failure of adhesive anchors

Chimneys contribute to the architectural form of a building and often help define its roofscape, and as such should be preserved if possible. The securing of chimneys is more complex than the securing of parapets and gables, but can usually be achieved by fixing them to the building diaphragms at each level and either strengthening the projecting portion or bracing it back to the roof structure with steel members similar to the methods used for parapet restraint, or fixing steel sections to the sides to provide flexural strength. A number of strengthening solutions are available for bonding to the surface of masonry elements and may be appropriate where the exterior has been plastered. Two such techniques used to strengthen chimneys are shown in Figure 4.5.

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[8] Professor Arturo Schultz from the University of Minnesota is the Principal Investigator of this project, with funding provided by the US national Science Foundation: Grant #CMMI-1138614, 'Data Collection on the Performance of Adhesive Anchor Retrofits in Unreinforced Masonry Buildings during the February 2011 Christchurch, New Zealand Earthquake'.

Other elements that constitute falling hazards, such as decorative plaster features on the face of a wall, can be effectively fixed with a single bolted connection. Less secure elements, such as plaster finials or balusters, can be secured with a single adhesive anchor connected to a strand of stainless steel wire, to mitigate the falling hazard. However, more complex strengthening work may be appropriate in some cases.

(a) **Vertical Near Surface Mounted (NSM) Fibre Reinforced Polymer (FRP) strip strengthening of chimneys**

(b) **Fibre reinforced shotcrete applied to the exterior surface of a chimney**

Figure 4.5 Examples of earthquake strengthened chimneys

4.2.3 Wall strengthening to restrain out-of-plane bending

Aim: Prevent out-of-plane failure of walls by increasing their flexural strength or reducing the vertical and horizontal distance between their supports.

URM walls are weak when subjected to forces other than compression. Even when fully secured to floors at each level, out-of-plane forces can cause significant wall bending that is governed by the ratio of the height between levels of support to the thickness of the wall (Derakhshan, 2011; Rutherford & Chekene, 1990). Some walls have sufficient thickness or have cross-walls or buttresses which enable them to withstand these out-of-plane forces without modification, however many walls will require seismic improvement. There are a number of approaches to combat this problem as described below.

Brick Cavity Walls – (Outer leaf fixing)

The outer leaf of a cavity wall is problematic as it is particularly susceptible to failure by peeling off outwards. The steel ties which were commonly installed to connect this layer to the more robust wall behind are subject to deterioration and sometimes missing, requiring attention during retrofits (Russell et al., 2006). One approach to this problem has been to fill the cavity with reinforcing steel and a cementitious grout, which has the

dual benefits of bonding the outer leaf to the inner leaf and also forming a reasonably strong shear wall which is hidden from view. However, this approach fails to consider the purpose of a ventilated, drainable cavity. When a cavity is filled, not only is the ventilation route blocked but water penetrating the outer leaf is transferred directly to the inner leaf via the grout fill, which results in moisture penetration into the building. This moisture can directly cause the decay of timber components built into the structure, as has been seen in an early URM building at one of three schools in Auckland (Auckland Girls Grammar School) which in the early 1990s had their cavities filled with a cementitious grout. As a consequence, dry rot developed in timbers such as door and window frames and skirtings, causing extensive damage. While a filled cavity may seem to be an excellent strengthening solution, it is the ventilation and drainage functionality of a cavity that is the overriding priority.

The filling of a cavity with cementitious grout does not take into account the incompatibility between rigid cementitious mortars and grouts, and the weaker lime mortars that historic (mainly 19th Century and early 20th Century) buildings are constructed of. These materials are incompatible in terms of both strength and permeability, with the difference in permeability potentially leading to a number of detrimental effects on the original performance of the building fabric. The softer, permeable materials, such as bricks and the lime bedding mortar, will become prematurely sacrificial in the weathering process, as the cementitious materials trap water against the more porous, softer elements. As a result, extensive erosion of soft brickwork leads to the loss of original fabric due to the need for brick replacement, as occurred at Auckland Girls Grammar School.

Efflorescence can also develop in structures as a consequence of changing the way that moisture is transferred through a building, and by introducing cementitous grouts and mortars containing soluble salts. This efflorescence can cause extensive damage to both external brickwork and internal plaster finishes.

The current preferred approach to re-attaching the outer leaf is to use a series of proprietary corrosion resistant ties at regular centres which are drilled through the face layer and are epoxy anchored into the structure behind, as shown in Figure 4.6. This technique is effectively a retrofit of the steel ties which have either deteriorated or were omitted in the original construction. The visual impact of these ties is minimal, although care needs to be taken when concealing drilled holes. These ties are irreversible, but their presence is visually negligible.

Figure 4.6 Use of drilled ties to fix external leaf to internal leaf

Inter-Floor Wall Supports

A series of vertical steel sections can be bolted to the inside face of the wall at sufficient spacing to ensure that the width of wall between supports is capable of resisting the out-of-plane forces (see Figure 4.7(a)). These sections act in bending to transfer wall loads to the adjacent floor diaphragms, essentially breaking up a large planar wall into a number of buttressed segments. This simple method may be appropriate in, for example, an industrial building, where visible steel bolted to the walls is in keeping with the character of the building, or in other buildings where the steel can be made to be architecturally appealing. In some other situations it may be less appropriate but less intrusive than other techniques. If there is existing internal framing with space behind for these columns, and no historic material is lost during installation, then it is a perfectly acceptable method. Sections generally fix to the historic material with bolts only, which allows a high degree of reversibility.
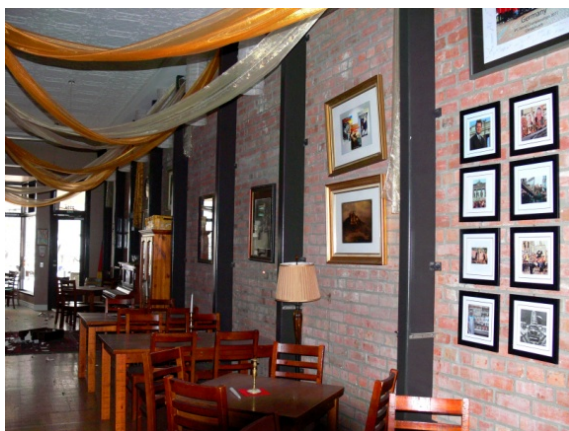
(a) Internal strong backs to restrain out-of-plane wall failure
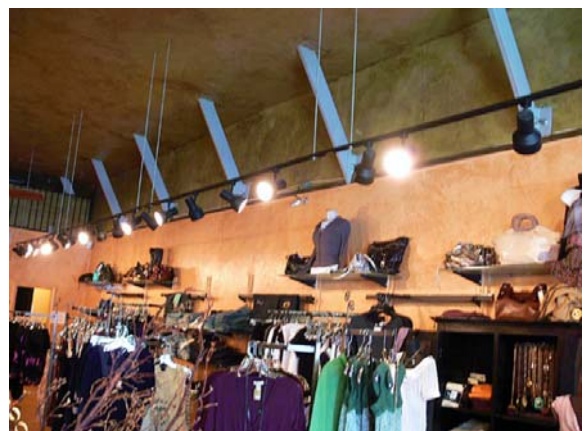
(b) Struts from the floor above to improve out-of-plane performance

Figure 4.7 Techniques available to increase wall stability against out-of-plane failure

In the past, rather than only supporting the URM walls for out-of-plane actions, these inter-floor wall support systems have been conceived as a method to support the floors in the event that the walls fail and collapse (Cattanach et al., 2008). A technique that is similar to the installation of vertical steel members is to provide a horizontal steel member at the mid-height of the wall and brace this with diagonal struts up to the floor or ceiling diaphragm above, as shown in Figure 4.7(b). This technique might be more suitable than the installation of vertical members if there is a cornice part way up the wall which needs to be conserved, or which can be used to disguise the steelwork. However care needs to be taken to ensure that the struts are visually unobtrusive. Both of these techniques can also be undertaken with the steel substituted with concrete, where this is more appropriate visually, or less commonly with timber. Steel struts can also be recessed within the width of the wall. Recessing the members results in an irrecoverable loss of material and may result in other complications such as cracking, although recesses may be preferable if used beneath a plastered surface, as there it will not affect the interior space. Concrete sections will have larger cross section geometries than will steel sections and will therefore be more intrusive. Also, once cast, concrete is difficult to remove without significant damage, particularly from a porous and naturally coloured material like clay brick. The installation of in-situ concrete is a comparatively permanent measure, so any activity which requires concrete to be cast against brick should be given careful thought before being undertaken.

Post-tensioning

Post-tensioning is an extremely effective method for increasing the out-of-plane strength of URM walls. The post-tensioning may be applied externally as shown in Figure 4.8(a) or be installed internally (see Figure 4.8(b)) by drilling vertical cores through the middle of a URM wall and then inserting steel rods into these cores. The rods may or may not be set in grout, and are then tensioned, which provides an additional compressive force in the wall. This loading modifies the stress behaviour of the URM in bending (i.e. the result of out-of-plane loading). Instead of bending instantly and causing tensile forces, to which URM has little resistance, the wall remains in compression (Ismail et al., 2011). This modification of the material properties also results in an increase in the shear strength of the wall, making post-tensioning an attractive strengthening solution.

Internal post-tensioning has little visual impact, although its installation may be unsuitable in some buildings, as access is required to the top of the wall, and walls need to be of a certain minimum thickness. Drilling cores involves some loss of historic material from the holes, though compared to some methods this is a minor impact. If the bars are fully grouted in place, post-tensioning is essentially irreversible, although this does not necessarily have to be done. The presence of post-tensioning bars is not likely to result in any negative effects to the historic material should their function no longer be required, provided care is taken with all core reinforcement to ensure that it is adequately protected from corrosion. This problem can be completely avoided by using plastic coated steel or FRP bars.
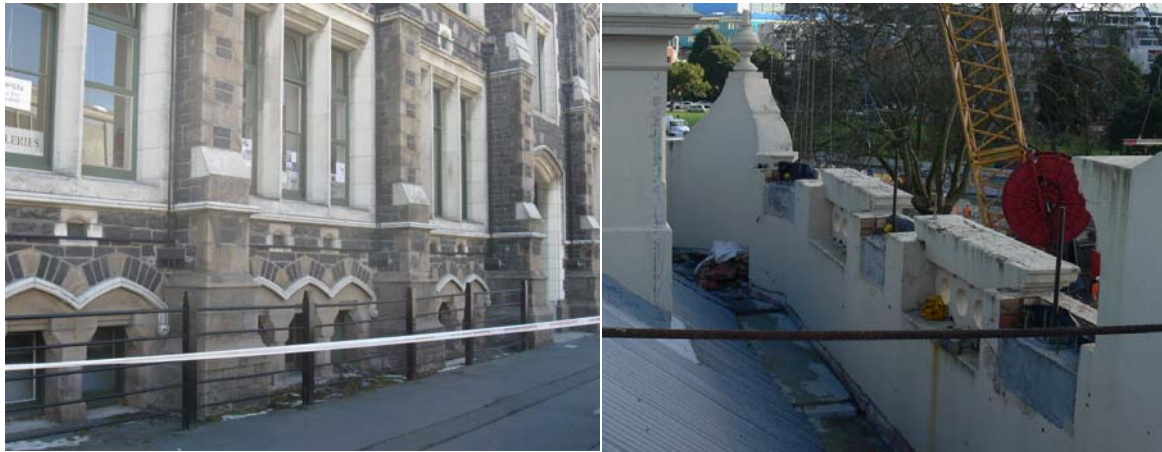
(a) **External post-tensioning used in the Christchurch Arts Centre (photo taken after 22 February 2011 earthquake)**

(b) **Internal post-tensioning bars used in the Birdcage hotel, Auckland**

Figure 4.8 Post-tensioned seismic retrofits of URM buildings

There are other methods of core reinforcement, with the most common being non-stressed steel bars set in grout, where the steel reinforcement only becomes stressed when the wall is loaded laterally. The visual impact and reversibility of these methods are the same as for fully grouted post-tensioning, although they are less effective structurally.

Wall reinforcement (FRP and other materials)

There are a number of other methods that may be used to provide out-of-plane stability of unreinforced masonry walls, such as the use of strips of fibre reinforced polymer (FRP) fitted into vertical saw cuts in URM (Dizhur et al., 2010; Dizhur et al., 2011). This technique is known as near surface mounting (NSM). NSM is a relatively recent technique which involves epoxying FRP into saw cuts in the surface of the URM and covering the cut with a grout mixed with brick dust (see Figure 4.5(a)). This technique would have some visual impact in naked brick, but little if done within an existing grout line, and none if installed in plastered walls being repointed. This technique can be a particularly effective and non-intrusive method of strengthening, although the finishing of this system is noticeable and work needs to be done to conceal the inserts.

4.2.4 Floor and roof diaphragm stiffening

Aim: Increase in-plane stiffness of horizontal diaphragms (floors and roof) so the seismic forces can be efficiently transferred to masonry shear walls.

Diaphragms are useful because they provide a layer through which lateral forces can be distributed from their source to remote resisting elements, and also act to bind the whole building together at each level. A building which acts as one rigid body rather than a number of flexible panels is far more likely to survive an earthquake. Tying floors to the outer walls (see Figure 4.9(a)) is generally required regardless to ensure that joists are not dislodged (Robinson & Bowman, 2000).

Timber floor diaphragms consist of three main elements; chords, sheathing material, and supplementary structure. To form a diaphragm in a typical URM building, chords need to be established, and mechanical fastenings added to take shear and tensile loads (Rutherford & Chekene, 1990). Several secondary fastenings between the chord and the floor or roof may also be required depending on the technique used. Some tensile ties will penetrate to the outside of the building and others will be drilled and epoxied in place. Existing historic sheathing may prove inadequate and require strengthening or an additional layer of more rigid material (see Figure 4.9(b)).

(a) **Steel sections added to stiffen and secure the floor diaphragm**   (b) **Steel strapping for floor stiffening**

Figure 4.9 Examples of floor diaphragm stiffening

Ties to the outside of walls may require metal load spreaders which visually impact the exterior. Many New Zealand buildings display these, and they seem to have become somewhat accepted as part of the strengthening process. Nevertheless, care needs to be taken when considering their visual impact and invisible solutions may be preferable. Much of the additional required work can be hidden within the floor space, but if this is exposed or the connections are extensive, special attention will be required to preserve the visual character of the inter-floor space.

Diaphragm strengthening may have some visual impact if new sheathing material is required. Historic flooring material is often a significant contributor to the character of a place and ought to be retained in view whenever possible. If the existing sheathing is inadequate, a ceiling diaphragm below, or stiffening the existing material might be preferable to covering it. Another approach is to remove the existing sheathing and install a structural layer beneath it. This exercise requires extreme care; firstly because existing sheathing, particularly tongue and groove, is very easily damaged during removal; and secondly, care needs to be taken to restore the boards in the correct order.

Diaphragms which are formed using mechanical connections have a high degree of reversibility; where ties are epoxied into walls there is less reversibility, but minimal visual intrusion. Additional sheathing may damage or alter the nature of the historic timber below, making it less desirable as a solution, although this can be mitigated. Occasionally, pouring concrete over an existing timber floor is considered. This solution

can greatly increase the stiffness of the building, but in turn increases its weight and therefore the forces acting upon it. Further, it completely changes the material of the floor and is not a reversible action, because even if it can be removed, the concrete would essentially destroy the character of the underlying timber. This procedure is therefore not recommended except in exceptional circumstances.

Roof diaphragms where the structure is exposed are slightly different, as the inclusion of a plywood diaphragm *above* timber sarking is generally acceptable if this area can be accessed, for example if the roofing is being replaced. This installation can also help to protect the sarking beneath. Roofs with suspended ceilings can be made to accommodate cross bracing, struts, and more innovative solutions, as they can be hidden within the ceiling space. In instances where the roof provides little diaphragm action, or the forming of a diaphragm is uneconomical or impossible, a horizontal load resisting member at the level of the top of the walls can be used to provide stability to the walls under out-of-plane loads. However, this member needs to be fixed to stiff elements at regular intervals to transfer horizontal loads, and these stiff elements may need to be introduced to the building if other structure cannot perform this task.

4.2.5   Connection of structural elements

Aim: ensure adequate strength of roof-to-wall, floor-to-wall and wall-to-wall connections. Good connectivity between the walls and the floor and roof diaphragms will ensure that the walls only deflect outwardly over the height of one storey of a building. This reduces the out-of-plane displacements that lead to wall collapse. Similarly, good connectivity along the vertical intersection of walls meeting at corners of a building (or internal walls meeting with an external wall) will ensure that the building responds as a single structural system and not as separate, isolated components. Much better performance can be expected in an earthquake when the building responds as a single system.

The most problematic deficiency in URM construction is inadequate connection of diaphragms to walls (FEMA, 2006), as failure of these connections can potentially lead to global collapse of the building. The addition of a network of small ties can substantially increase the strength of the building by fixing the walls to the floor and roof diaphragms (Robinson & Bowman, 2000). These ties need to resist two actions: shear from the diaphragms trying to slide across the walls; and tension from the diaphragm and wall trying to separate. If these ties are missing, the walls will be acting as a cantilever from the ground level under lateral loads, and floors and roofs are far more likely to be dislodged from their supports, which is the most common mode of failure for URM buildings in an earthquake. This failure mode is shown in Figure 4.10.

Figure 4.10 An extreme case in the 2010 Darfield earthquake where inadequate connections have resulted in wall collapse (Welstead House, 184-188 Manchester Street)

The use of simple metal anchors to connect the walls to the floor and roof diaphragms is relatively straight forward and was observed in many buildings that survived both earthquakes (see Figure 3.14 and Figure 3.15). Recently, some proprietary systems have become available that use steel reinforcement to connect walls to the floor and roof diaphragms, and to provide wall-to-wall connection at corners and other wall intersections. Typically, the reinforcement is placed in horizontally cored holes that pass through the entire building at each floor level and at the roof level. The reinforcement is then post-tensioned and grouted in order to clamp the walls to the floors and roof and to each other.   In some applications, vertical reinforcement, sometimes with post-tensioning, is also used to increase the compressive stress in the wall which results in an improvement to the walls earthquake strength when subjected to horizontal loads.

4.2.6 Shear walls

Aim: Provide additional storey/base shear strength; this could be through strengthening existing walls or by construction of additional shear walls.

Most URM walls are required to transfer some degree of shear loading along their length. If a building has insufficient shear capacity in a particular direction, then capacity of existing walls can be increased instead of inserting additional structure. There are various methods for achieving this strength increase which generally involve the application of an additional layer of material bonded to the surface of URM to increase its strength, although there are some measures which involve altering the wall itself, such as post-tensioning, as described above. Most of these measures involve a plane of extra independent structure being applied over the surface of the URM, effectively forming new shear walls, which are described below.

The presence of openings in a shear wall renders that section less stiff than the surrounding full height walls, meaning that the wall above and below, or between closely spaced openings, will likely be the first areas to fail in the event of an earthquake. Infilling the openings will eliminate this problem by making the wall continuous, and has been advocated as a valid solution in the past. Problems with altering the character of the building and matching brick and mortar colours mean that this approach should

only be used as a last resort and even then preferably not in visible areas. Infilling openings is likely to be somewhat reversible if done with brick, but not completely, and visual impact will depend on the location. If in-filled with concrete, the work will be less reversible and the ductile behaviour of the wall may be affected due to incompatible stiffnesses. Localised steel cross bracing near openings is another technique which can prove effective, but again this system is likely to be highly visible and should only be undertaken when it does not detract from the character of the building.

Shear walls are used to increase the strength of existing URM walls or are added as new elements. Materials which resist shear loads can be added to the surface of the URM; these might include gypsum plasterboard, particle board, plywood, or plate steel (Robinson & Bowman, 2000), and are generally fixed to the URM wall with bolts via a supplementary structure. This approach leads to the surface of the URM wall generally being covered which may interfere with decorative elements on walls and openings, although this interference can be alleviated by using stronger materials such as plate or strap steel. They can also increase the thickness of the wall, which is not particularly desirable as it can reduce the scale and area of the interior. For these reasons shear walls can be visually detrimental if used indiscriminately. Stand alone shear walls, which are independent of URM walls, can be introduced, although these can be detrimental for similar reasons. Despite these negatives, shear walls are a practical and efficient method for strengthening and are commonly used. All of these materials can be easily removed in the future, which makes them good solutions for shear walls in two to three storey buildings with moderate horizontal loads.

The shotcreting of shear walls was a common strengthening technique during the 1980s. This technique involves spraying concrete onto the surface of a URM wall to essentially cast a new wall against the existing wall, as shown in Figure 4.11(a). This technique provides plenty of additional strength to the wall, both in-plane and out-of-plane, but is now largely regarded as unacceptable unless absolutely necessary. The technique causes a significant increase in wall thickness and it is very difficult to remove the concrete, and even more so to restore the wall behind to any semblance of its character prior to concreting. Furthermore, the installation of shotcrete generally requires the building to be gutted, which results in the loss of much heritage material and creates an essentially new interior (Robinson & Bowman, 2000).

| (a) Shotcrete applied to a former URM building | (b) Surface bonded FRP applied to the exterior of a URM wall |

Figure 4.11 Examples of strengthened masonry shear walls

Another technique for forming strengthened shear walls is the addition of surface
bonded fibre reinforced polymer sheets is in Figure 4.11(b). These sheets do not require
the same invasive installation as shotcrete walls, but generally are equally permanent,
and have potentially limited application, although new technology may soon change this.
If it is possible to provide out-of-plane strength using FRP inserts, coupled with an FRP
surface layer for shear, then this solution could be far superior to shotcrete from an
architectural perspective. An important consideration with the use of sheets of FRP is
that it is impermeable, which can lead to problems with water trapped within the
building resulting in damp and mould issues, and potential de-bonding of the epoxy.

| (a) Exterior view of retrofitted building | (b) Close up view of surface application |

Figure 4.12 Textile reinforced render as retrofit

4.2.7 Insertion of internal frames

Aim: Provide alternative structural system to resist the seismic loads.

Moment frames

Moment frames are a common method of gaining additional horizontal resistance which can also be used as a local strengthening solution. The advantage of this system is that it is comprised of beams and columns, so is fully customisable, and there is space between the vertical and horizontal elements. Moment frames allow full visual and physical access between each side of the frame, and minimal spatial disruption. In building façades with numerous openings, some form of moment frame can often be fitted to the masonry piers on the inside or outside (or both) depending on the effect on the architectural character. Moment frames can be a particularly effective solution, especially where the frame is tailored to the character of the building. Care needs to be taken with steel frames in particular to ensure stiffness compatibility with the existing structure (Robinson & Bowman, 2000). Steel is a ductile material, but URM is not, meaning that under earthquake loads the added stiffness of the steel might not come into effect until a load is reached where the URM has already been extensively cracked.

Moment frames can be an excellent strengthening technique, either to supplement an existing wall or as a new, stand alone element. If a steel frame is erected against an existing wall where weakness exists, the frame needs to be fixed either directly to the URM using bolted connections into the wall or to the diaphragm (see Figure 4.13(a)). Installing concrete frames is a more complex undertaking, as these will often be constructed by thickening existing piers, although a concrete frame which is separate from the existing structure is possible (see Figure 4.13(b)). In both situations it is important that architectural character is retained, and historic material conserved. Some considerate and artful design strategies may need to be undertaken to achieve this.

Steel moment frames have a high degree of reversibility, as again they rely on mechanical connections and relatively small ties to connect to the existing structure. Concrete frames are generally far less reversible, but can sometimes be better concealed when this is a requirement. Figure 4.13(b) shows a large new moment frame which is expressed as a new element. Some recent buildings have very effectively used precast concrete load-resisting elements which are separate from the URM walls, solving the problem of reversibility (Cattanach et al., 2008).

(a) **Post-earthquake condition of a
URM building having an internal
steel frame retrofit**

(b) **Reinforced concrete moment frame retrofit**

Figure 4.13 Internal moment frames installed as seismic retrofits

Braced frames

Braced frames are available in various configurations: concentric, tension only concentric, eccentric, and 'K' bracing. The key functional difference between braced frames and moment frames is that due to the diagonal braces, braced frames prevent physical continuity between spaces on either side of the frame. Braced frames are also generally constructed from steel rather than concrete, and are much more rigid than moment frames.

Braced frames are a very efficient method of transferring horizontal forces but have significant setbacks. Their use in façade walls is usually precluded by the presence of windows, as diagonal braces crossing window openings are generally considered to be poor design. It is also difficult to get a braced frame to conform to an existing architectural character; however they can be used to very good effect within secondary spaces, and can be made to fit architecturally in some situations with careful consideration. Figure 4.14 shows braced frames in use. Generally speaking, steel braced frames have a good degree of reversibility and can provide excellent strengthening when used appropriately.

| (a) Eccentric bracing in a walkway | (b) Eccentrically braced core |

Figure 4.14 Eccentrically braced steel frame retrofits (photos courtesy of Dunning Thornton Consultants)

4.2.8   Removal of mass and/or geometric/stiffness irregularities

Aim: Reduce the seismic forces through reduction of structural mass or structural irregularities.

Another approach to seismic improvement of URM buildings derives from its weight. Seismic actions are directly proportional to the mass of the building, so if mass is reduced, so are the forces acting upon the building. A lighter building requires less lateral strength and therefore less additional strengthening. Reducing the mass of a building may seem at face value to be a sensible approach; however past experience has shown this to not be so. The mass must be removed from somewhere, and the higher up the mass is, the stronger the forces upon it and the more difficult it is to strengthen, so the top of the building is the first place which has been looked at. Historically this logic has led to the ad-hoc removal of decorative elements such as parapets, gables, chimneys, and occasionally whole towers (Robinson & Bowman, 2000). These elements will almost always significantly contribute to heritage value and character, and their retention is essential to preserving these attributes. Indeed, it is often desirable to replace these features if they have been removed from buildings and still exist. While reduction of weight may be achieved in more minor ways, such as removal of internal URM partitions or the removal of plant loads, the wholesale removal of decorative elements is strongly discouraged.