The performance of unreinforced masonry buildings in the 2010/2011 Canterbury earthquakes

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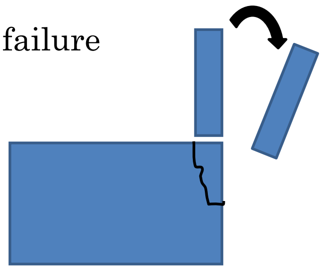
Part 3: Earthquake failure modes and strengthening techniques for URM buildings

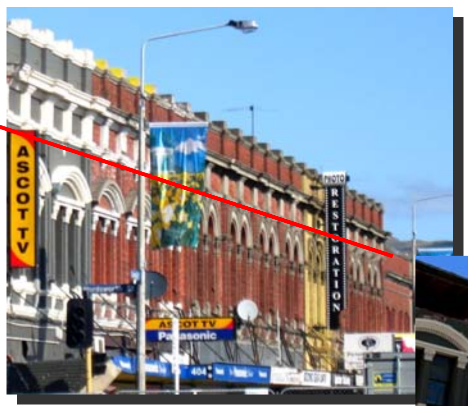
Purpose:

To clarify the types of failure modes and the range of techniques used in Christchurch to earthquake strengthen URM buildings

URM earthquake failure modes

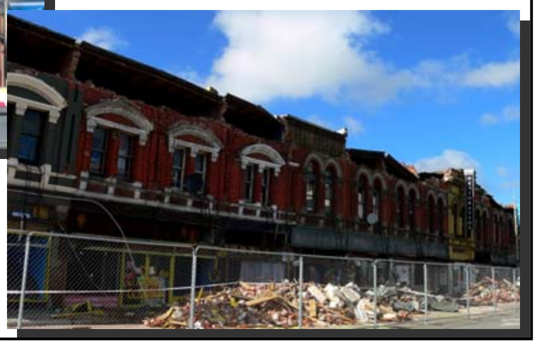
Parapet and chimney failure



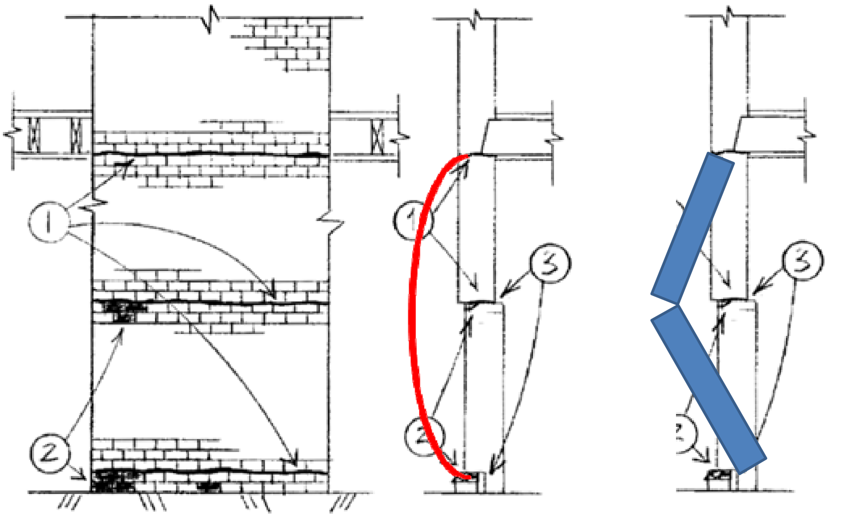


Before

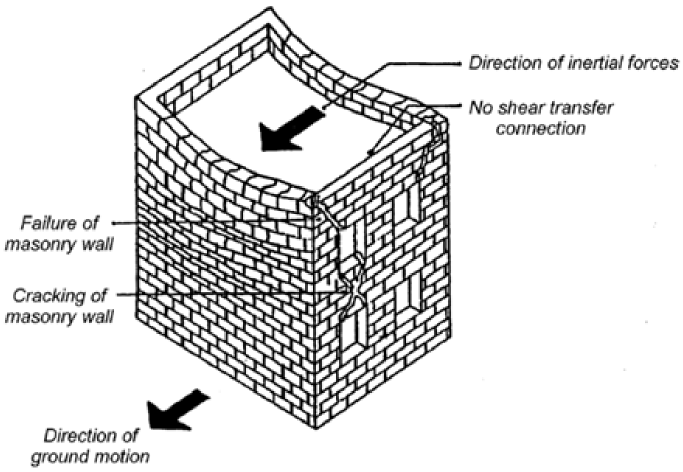
After



FEMA 306 classification of damage due to one-way bending failure (FEMA, 1999a)



Return wall separation and two way out-of-plane failure (FEMA, 1999a)



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Return wall separation (after Darfield earthquake)

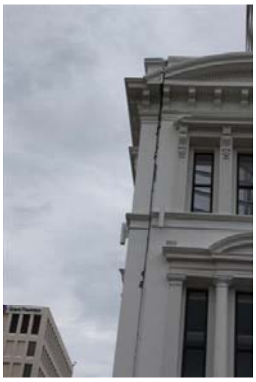

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Figure 3.33 Cramner Court, showing complete collapse of a gable

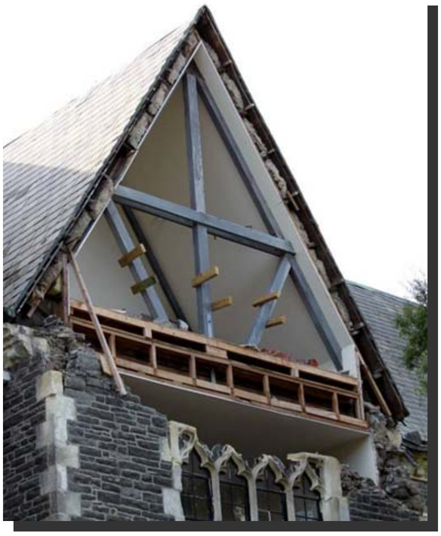

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Figure 3.30 Christchurch Anglican Cathedral – front façade damage

(a) unstable front wall

(b) return wall separation

Figure 3.11 Failure mechanism comparisons – observed earthquake damage versus experimental simulation

(a) Wall damage at 140 Linchfield Street

(a) High speed photograph of a dry-stacked masonry wall failing during a tilt test

Cavity wall construction

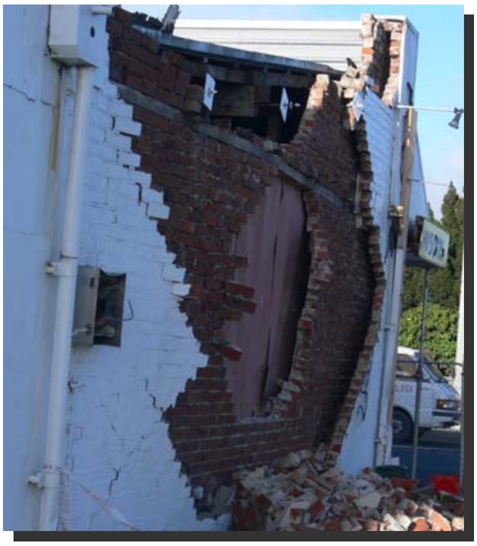


Figure 3.27 Representative examples of wall cross-sections for Christchurch stone masonry buildings

(a) Cramner Court - 3 leaves with rubble fill.

(b) Cathedral of the Blessed Sacrament - Oamaru stone with poured concrete.

(c) St. Luke's Anglican Church - stone front façade with clay bricks back layers.

Failure of exterior leaf of dressed stone

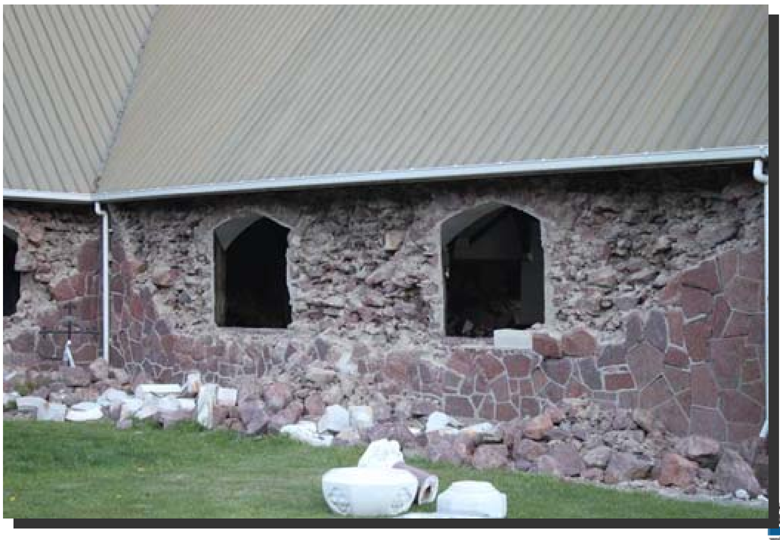
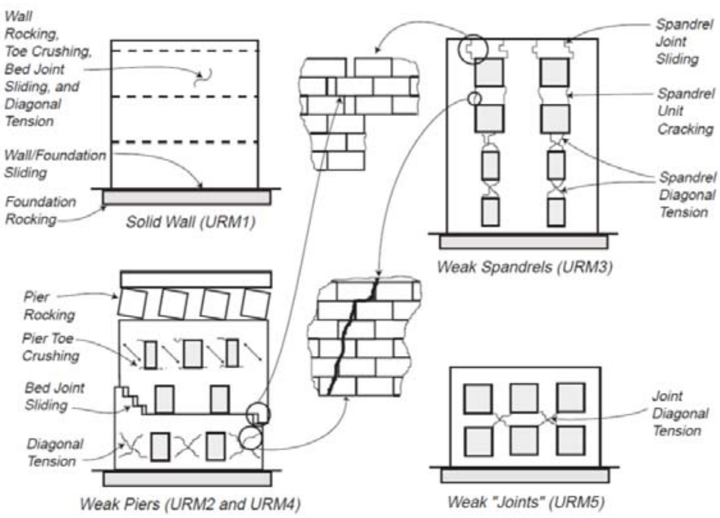


Figure 3.7 FEMA 306 Classification of in-plane failure modes (FEMA, 1999a)



Diagonal tension failure

Figure 3.34 Christchurch Anglican Cathedral - diagonal cracks in the south façade piers

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Spandrel failure

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Diagonal tension failure and spandrel failure

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Toe crushing due to rocking

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Toe crushing

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Rocking slender URM pier

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Bed joint sliding (due to pounding)

Bed joint sliding

Bed joint sliding

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Building pounding

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Building pounding

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Duration of shaking:

After Sept 2010 After Feb 2011

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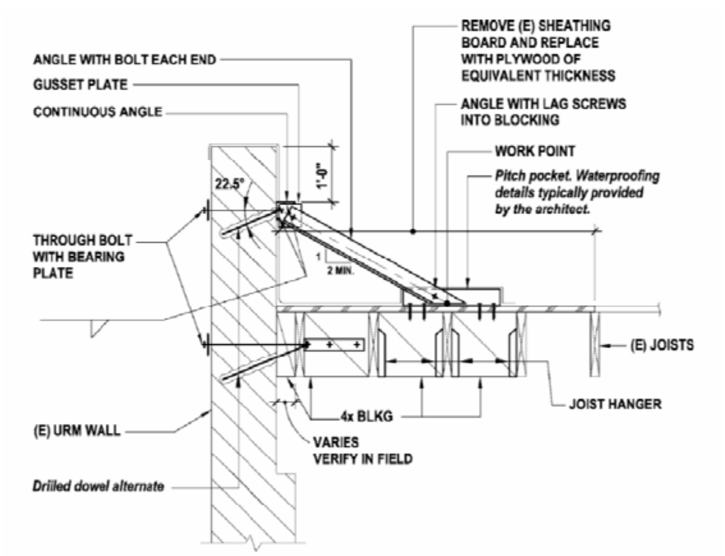
3/10/2010

25/03/2011

14/06/2011

Earthquake strengthening techniques for unreinforced masonry buildings

Figure 2.2 Parapet restraint and wall diaphragm anchorage detail (FEMA 547, 2006)



Parapet restraint using rigid steel braces connected to a continuous steel section

Gable restraints
Also called 'anchor plates', 'washers', 'rosettes' when circular

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Failed parapet restraints

(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

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Figure 4.4 Examples showing failure of adhesive anchors

(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 7.3 Adhesive anchors installation quality

(a) Poor installation of adhesive anchors

(b) Recovered adhesive anchors that performed inadequately

Figure 4.5 Examples of earthquake strengthened chimneys

(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 4.9 Examples of floor diaphragm stiffening

(a) Steel sections added to stiffen and secure the floor diaphragm

(b) Steel strapping for floor stiffening

Examples of roof diaphragm stiffening

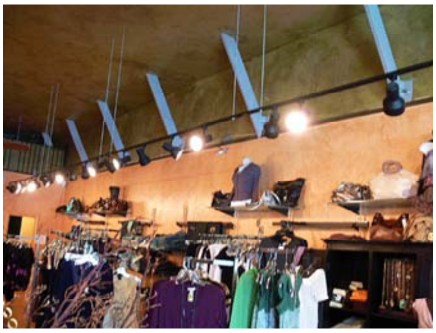
(a) Roof diaphragm improvement using steel brace frames

(b) Roof diaphragm improvement using steel braces

Install new cavity ties

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

(a) Internal strong backs to restrain out-of-plane wall failure



(b) Struts from the floor above to improve out-of-plane performance

Figure 2.5 Addition of strong-backs for increased out-of-plane wall capacity

(a) Installation of steel moment frames and steel strong-backs, San Louis Obispo

(b) Addition of internal strong-backs and extensive anchorage of masonry, San Louis Obispo

Figure 4.8 Post-tensioned seismic retrofits of URM buildings

(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 4.11 Examples of strengthened masonry shear walls

(a) Shotcrete applied to a former URM building

(b) Surface bonded FRP applied to the exterior of a URM wall

Figure 2.7 Shotcrete rehabilitation technique in San Francisco

(a) Internally applied shotcrete to a URM building located in San Francisco

(b) Shotcrete applied to a URM building located in San Francisco

(c) Externally applied shotcrete to a URM building located in San Francisco

Figure 4.13 Internal moment frames installed as seismic retrofits

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

(b) Reinforced concrete moment frame retrofit

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

(a) Eccentric bracing in a walkway

(b) Eccentrically braced core

Figure 2.6 Addition of lateral resisting systems

(a) Steel k-brace frames used in a multi storey URM building in San Francisco

(b) Steel moment frames used in a multi storey URM building in San Francisco

(c) Reduction of window opening to increase in-plane wall capacity