The seismic performance of unreinforced stone masonry buildings during the 2010-2011 Canterbury earthquake sequence

I. Senaldi
ROSE School, IUSS, Pavia, Italy)

G. Magenes
University of Pavia and European Centre for Training and Research in Earthquake Engineering (EUCENTRE), Pavia, Italy

J. M. Ingham
The University of Auckland, Auckland, New Zealand

SUMMARY
The sequence of earthquakes that has affected Christchurch and Canterbury since September 2010 has caused damage to a great number of buildings of all construction types. Following post-event damage surveys performed between April 2011 and June 2011, the damage suffered by unreinforced stone masonry buildings is reported and different types of observed failures are described. A detailed technical description of the most prevalently observed failure mechanisms is provided, with reference to recognised failure modes for unreinforced masonry structures. The observed performance of existing seismic retrofit interventions is also provided, as an understanding of the seismic response of these interventions is of fundamental importance for assessing the vulnerability of similar strengthening techniques when applied to unreinforced stone masonry structures.

Keywords: Unreinforced stone masonry, seismic response, Canterbury earthquake

1. INTRODUCTION

In the early morning of 4th September 2010 the region of Christchurch, New Zealand, was subjected to a magnitude Mw 7.1 event, located near Greendale, 40 km west of Christchurch at a depth of 10 km (GeoNet, 2010). This main event was followed by a considerable number of aftershocks, of magnitude Mw 3.0 or greater, including several damaging events. A severe aftershock occurred on 22nd February 2011, with a magnitude Mw 6.3 at a depth of 5 km and epicentre located 10 km south-east of Christchurch that produced accelerations greater than those measured during the 4th September 2010 earthquake and caused structural damage that affected all building types (GeoNet, 2011). In addition, two other aftershocks of magnitude Mw 5.7 and Mw 6.2 respectively happened on 13th June 2011 and a magnitude Mw 6 occurred on 23rd December 2011, causing further damage to the weakened structures of Christchurch. Fig. 1 represents the epicentres of the four seismic events with magnitude greater than Mw 6.0 that occurred between September 2010 and December 2011 and the location of epicentres of the events of the Canterbury aftershock sequence.

Starting from April 2011, the seismic performance and the damage that occurred to unreinforced stone masonry buildings and churches in Christchurch was assessed and documented in order to compile an accurate damage statistics database and to provide a detailed technical description of the most prevalently observed failure mechanisms, recognizing that unreinforced stone masonry buildings constitute an important component of New Zealand's heritage architecture. The damage assessment inspections identified 90 unreinforced stone masonry buildings in Christchurch, including churches, many of which are included on the New Zealand Historic Places Trust register of heritage buildings.

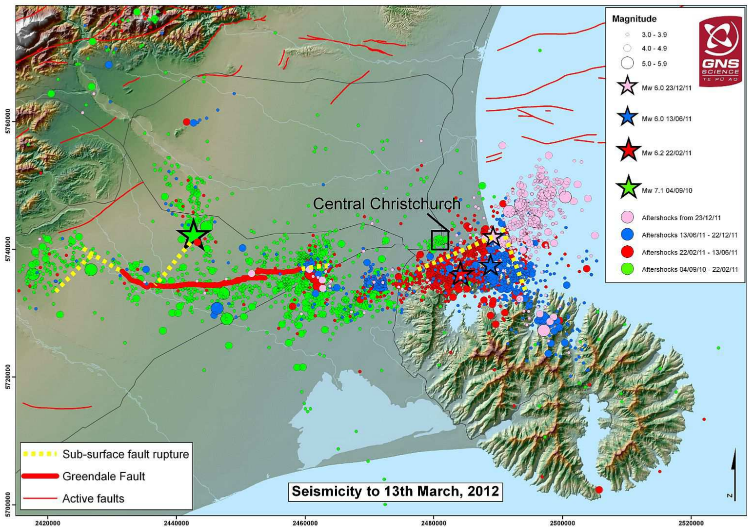


Figure 1. Seismicity of the Canterbury region to March 2012 (GeoNet, 2012)

2. UNREINFORCED STONE MASONRY BUILDINGS IN CANTERBURY

Most of the stone masonry buildings in Christchurch tend to have similar characteristics both from an architectural and from a structural perspective. These similarities derive from the fact that many buildings were constructed in a relatively short period of time, between 1850 and 1930, and were designed by the same architects or architectural firms. Significant examples, including the Canterbury Provincial Council Buildings and the former Canterbury University College that is now referred to as the Christchurch Arts Centre, are the masterpieces of important architects such as Benjamin Mountfort, Cecil Woods and John Goddard Collins and are examples of the Gothic Revival style.

The unreinforced stone masonry buildings in Christchurch have similar characteristics as regards the details of their construction. The vast majority of these structures, and in particular those constructed in the Gothic Revival style, are characterized by structural peripheral masonry walls that may be connected, depending on the size of the building, to an internal frame structure constituted of cast iron or steel columns and timber beams or to internal masonry walls that support flexible timber floor diaphragms and timber roof trusses. However, there are a few commercial buildings in the Christchurch Central Business District (CBD) that are characterized by slender stone masonry piers in the front façade with the other perimeter walls constructed of multiple leaves of clay brick. These buildings are typically two or three stories in height, with two storey buildings being most common, and may be either standalone or row type buildings (see Russell & Ingham (2010) for further details of URM building typology).

Several types of masonry wall cross-sections were identified during the damage assessment surveys. The most representative types present the following characteristics:

- three-leaf masonry walls, with dressed or undressed basalt or lava flow stone units on the outer leaves (wythes) while the internal core consists of stone rubble fill (Fig. 2a);
- three-leaf masonry walls, with the outer layers in Oamaru sandstone and with a poured concrete core, such as for the Catholic Cathedral of the Blessed Sacrament (Fig. 2b);
- double-leaf walls, with the front façade layer being of dressed stone, either dressed basalt or bluestone blocks, or undressed lava flow units, and the back leaf constituted by one or two layers of clay bricks, usually with a common bond pattern, with the possible presence of a cavity or of poured concrete between the inner and outer leaves (Fig. 2c).

(a) Cramner Court; 3 leaves with rubble fill

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

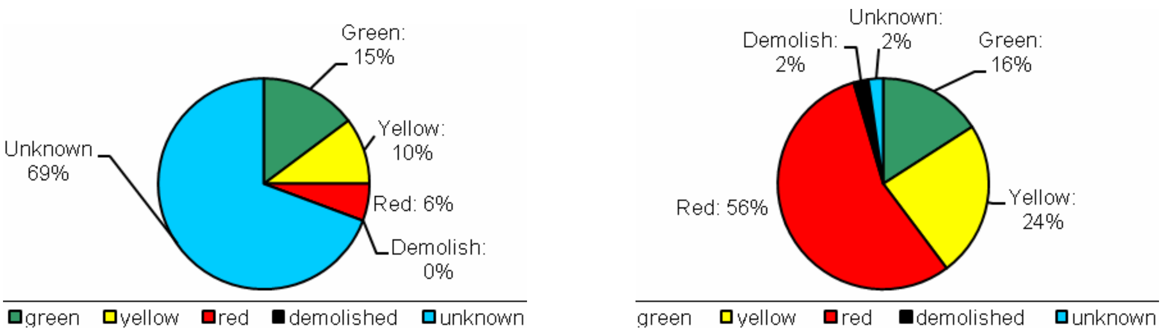
(c) St. Luke's Anglican Church; stone front façade with clay brick interior leaves

Figure 2. Representative examples of wall cross-sections for Christchurch stone masonry buildings.

3. POST-EARTHQUAKE ASSESSMENT AND DAMAGE STATISTICS

As required by New Zealand legislation, a building safety evaluation process was activated immediately after the declaration of the State of Emergency following the earthquakes of September 2010 and February 2011. Green placards were assigned to structures that were deemed to be safe to re-enter and required no further intervention; yellow placards were applied to buildings whose accessibility was restricted due to minor damage; and red placards were applied to buildings that were considered unsafe and likely to have a moderate to severe level of damage.

The seismic performance of stone masonry buildings was initially identified by considering the safety assessment data collected during the building safety evaluation process. Fig. 3(a) and Fig. 3(b) show the different percentages of building safety assessments after the 4th September 2010 and 22nd February 2011 earthquakes, respectively. From these figure it can be seen that there was a significant escalation of damage due to the continuing earthquake activity in the Christchurch region, although 69% of the 90 stone masonry buildings in Christchurch were not assessed after the September earthquake. At the time of the study reported here, several buildings had been demolished already because of the hazard associated with their damage state after the February 2011 event.



(a) After September 2010

(b) Data updated 07 June 2011

Figure 3. Distribution of safety evaluation placards applied to stone masonry buildings.

To understand the impact of the Canterbury earthquake sequence on the population of Christchurch it should be noted that most of the buildings considered in the study belong to the cultural heritage of the region and are used for a variety of public functions ranging from churches to public offices, schools and colleges, and incorporating both commercial and cultural activities. The 56% of stone masonry buildings that were red tagged after the February 2011 earthquake were essentially churches or were used for cultural and commercial purposes.

4. DAMAGE MECHANISMS OF STONE MASONRY BUILDINGS AND CHURCHES

Many examples of earthquake induced damage mechanisms to stone masonry buildings were observed and have been classified according to the catalogue of mechanisms originally developed by D'ayala and Speranza (2002) and successively revised and applied in the inspection forms used by the Italian Civil Protection Department for the damage assessment of churches (Lagomarsino and Podestà 2004), palaces (Italian Civil Protection Department, 2006) and residential buildings (Italian Civil Protection Department, 2008). The most recurrent failure mechanisms are described in detail in the following sections, with examples of damaged buildings also illustrated.

4.1 Damage induced by poor quality of construction materials

The quality of construction materials played a key role in the response of stone URM buildings. As previously described, one of the typical features of stone URM buildings in Christchurch is the different types of stone and mortar quality present in structures built with three-leaf walls. The use of soft limestone, such as Oamaru stone or the red tuff extracted in the Banks Peninsula, in conjunction with the use of low strength lime mortar, often led to poor earthquake response. Examples of such behaviour, frequently caused by hammering of the roofing system on the walls, include the Holy Trinity Church in Lyttelton, which is one of the oldest buildings in Canterbury, and St. Cuthberts Church as represented in Fig. 4.

Figure 4. Lyttelton Holy Trinity Church (left) and St. Cuthberts Church in Governor's Bay (right).

(a) Out-of-plane wall failure (b) Damage to the octagonal tower

Figure 5. Damage in the Time Ball Station tower.

The Time Ball Station in Lyttelton is another example of poor performance during a seismic event, due to the very weak mechanical properties of the local scoria and Oamaru stone used for its construction. The lack of connection between the stone walls is shown in Fig. 5. It was reported that after the 13th June 2011 earthquakes, the remaining parts of the Time Ball Station and of Lyttelton Holy Trinity Church completely collapsed as did several other unreinforced masonry buildings in Lyttelton that were in a similar state of damage (Ingham and Griffith, 2011, Appendix C).

4.2 Damage due to geometric irregularities

Damage that was attributable to plan irregularity was frequently observed, particularly for stone churches, due to interaction between adjacent structural elements at the intersections between walls. In most churches where the bell tower or low annexes are connected to the nave, damage developed at the intersection of the different structures (Fig. 5).

Figure 5. (a) St. Barnabas' Church, internal view. (b) St. Mary's Anglican Church: detachment of the bell tower from the nave

Another distinct example of damage due to plan irregularity in association with differential foundation settlement was observed at the former Old Boy's High building in the Arts Centre. Fig. 6 shows the vertical crack that formed at the intersection between two buildings constructed in successive phases, attributable to the lack of connectivity between the structural walls and to their separate foundations.

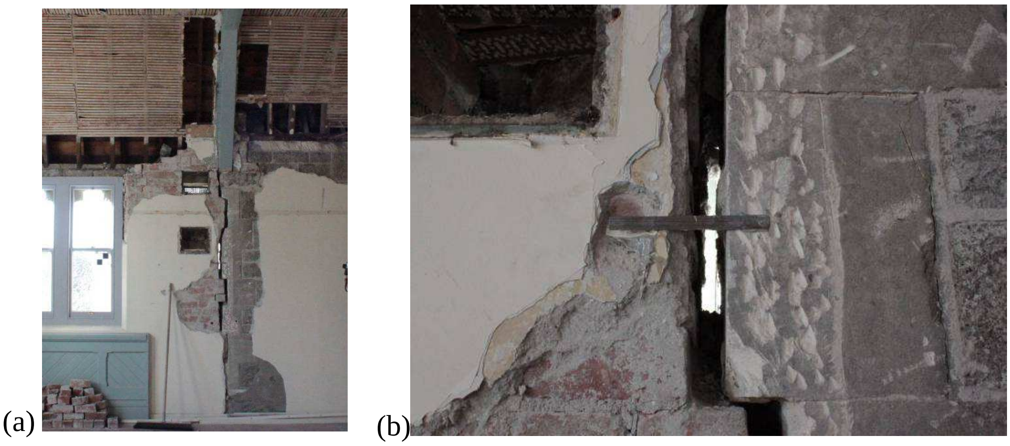


Figure 6. Interior views of Old Boy's High, showing interaction between adjacent buildings: (a) distant view, (b) close up view.

4.3 Out-of-plane failure mechanisms

One of the most recurrent damage mechanism reported for most of the structures inspected was the partial and global overturning of the façades, with damage levels ranging from moderate to severe and in some cases reaching collapse. Because most of the buildings were designed following the architectural principles of the Gothic Revival style and hence were characterized by long span façades, flexible floor diaphragms and weak connections between walls, those types of damage mechanisms are expected to occur.

Examples of out-of-plane failures are shown in Fig. 7 and Fig. 8 relative to the main façade of the Anglican Cathedral (now partially collapsed after the 13 June 2011 earthquake and aftershocks), and the Rockvilla dwelling that experienced complete collapse of the north and east façades. All of these buildings appeared to have poor connections between the walls at their corners, leading to return wall separation and subsequent out-of-plane failure of entire walls, as in the case of the Rockvilla house (Fig. 8).


(a) unstable front wall (prior to June 13)


(b) return wall separation

Figure 7. Christchurch Anglican Cathedral: out-of-plane overturning of the front façade

Figure 8. Rockvilla dwelling with complete collapse of the north and east façades

Many of the stone masonry buildings that were constructed in the Gothic Revival style sustained partial damage to their gable ends, with many cases of complete collapse of the gable. As shown in Fig. 9, the absence of significant gravity loads and inadequate connection between the gable and roof trusses are primary contributing factors to this failure mode, along with increased accelerations experienced at the top levels of the structure.

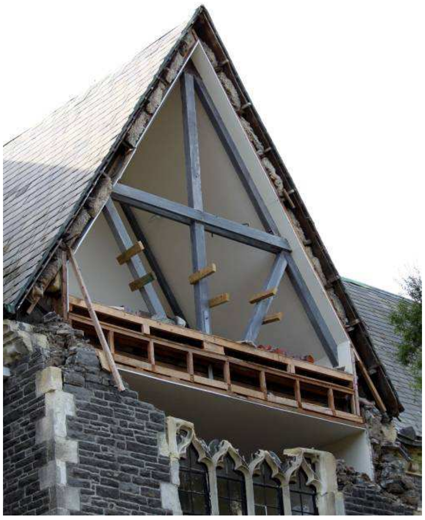


Figure 9. Cramner Court, showing complete collapse of a gable

In some cases, when the façade span was rather wide and internal bearing walls exerted almost no restraining action, a horizontal arch mechanism occurred. In the example presented in Fig. 10, where the north-west façade of Strange's Building in High Street is pictured, it is clear that the formation of a cylindrical hinge along the floor level of the top storey and the complete lack of proper connection between the perimeter wall and the roof structure resulted in a trapezoidal portion of the façade plane overturned around the cylindrical hinge.

Figure 10. Strange's Building at the corner of High street and Lichfield Street

4.4 In-plane response of walls

Because the 22 February 2011 earthquake was predominant in the east-west direction, and because many of the buildings in the CBD were primarily oriented in the same direction, evidence of in-plane wall damage in the east-west running walls was reported in conjunction with overturning of façades oriented in the orthogonal direction. An example of a recurrent damage pattern is shown in Fig. 11a, where masonry piers of many of the stone masonry churches exhibited a shear type of response, evident by diagonal cracks that in some cases involved the buttresses. Also, a rocking behaviour was exhibited by the masonry piers (Fig. 11b). Light to substantial damage to masonry spandrels was also reported, such as diagonal cracking due to shear (Fig. 11b) but also a flexural type of response such as for the Cramner Court buildings.

(a)  (b) 

Figure 11. (a) Christchurch Anglican Cathedral: diagonal cracks in the south façade piers.
(b) Canterbury Provincial Chambers: diagonal crack in the top spandrel and horizontal cracks of the left pier in south façade of the East annex

4.5 Diaphragm and roof seismic response

A close inspection of buildings that suffered out-of-plane wall failures revealed that in many instances some anchors were present in the walls that failed, or that the inadequate securing of walls and diaphragms using wall-diaphragm anchors could not prevent portions of walls from overturning. In some cases anchors were either absent or were spaced too far apart to prevent bed joint shear failure of the masonry at the location of the anchorage. In those cases where anchoring had been seismically designed, or were sufficiently closely spaced to resist lateral loads, the overturning of gables and other portions of walls was prevented. Different examples could be given of a seismic response of a structure that was highly influenced by the effectiveness of wall-to-floor connections. For instance, Fig. 12a shows the damage resulting from overturning of the gable of the main façade of the former Trinity Church in the Christchurch CBD while the detail in Fig. 12b illustrates how the anchoring was insufficient in size and spacing to secure the wall in place.

(a) Overturning of the front façade gable

(b) Detail of failed wall-to-roof anchorage

Figure 12. Former Trinity Church, showing details of gable ended out-of-plane wall failure

(a) Pounding of roof truss

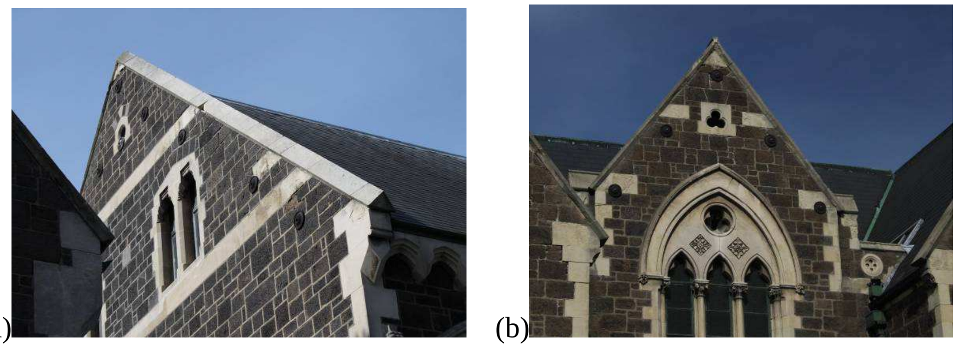
(b) Horizontal crack above arched window

Figure 13. St James' Church, showing pounding of roofing elements on the walls of the nave

In the case of churches, pounding of roof trusses was reported as for the case of St. James' Church shown in Fig. 13.

4.6 Seismic performance of retrofitted structures

One of the main objectives of the damage surveys of stone masonry structures was to investigate the response of structures that had been seismically retrofitted or strengthened at the time of the September 2010 earthquake. As previously illustrated one of the most common factors that contributes to the vulnerability of unreinforced masonry structure is the lack of connection between walls and diaphragms. However, a proper design of anchoring and the insertion of steel tie rods at floor and roof level helped reducing the likelihood of local failures due to out-of-plane collapse of walls and gables. Fig. 14 shows some examples of successful wall-to-roof anchoring in the Arts Centre building complex, showing respectively the former Old Girl's High (Fig. 14a) and the former Canterbury Engineering Department (Fig. 14b).



(a) (b)

Figure 14. The Christchurch Arts Centre, showing successful use of wall-diaphragm anchorages

Different types of strengthening techniques were also applied to enhance the global response of buildings and to restrain the activation of possible local failure mechanisms. For instance, the use of steel moment frames as a retrofit strategy proved to be efficient in the case of the former Lawrie and Wilson Auctioneers Building (Fig. 15a). Considering instead the former Chemistry Department that is now part of the Christchurch Arts Centre complex, the insertion of vertical post-tensioned tendons in collaboration with buttresses and of horizontal tie rods in collaboration with floors improved the global response of the structure (Fig. 15b.) Nonetheless, the building was badly damaged because of the partial collapse of the tower that was not retrofitted.

(a) (b)

Figure 15. (a) Former Lawrie and Wilson Auctioneers building. (b) Former Chemistry Department, Christchurch Arts Centre.

6. CONCLUSIONS

The damage assessment database is based on surveys undertaken between April and May 2011. Consequently the results regarding the seismic performance of unreinforced stone masonry buildings in Christchurch refer to the observation made at that time. The conditions of damaged heritage stone masonry buildings continued to deteriorate after the earthquakes that occurred on the 23rd June 2011 and 23rd December 2011, after which more cases of partial and complete collapse were reported.

The observed poor seismic performance of unreinforced stone masonry buildings in Christchurch is a reminder of the necessity of retrofitting heritage buildings in an earthquake prone country such as New Zealand. Suggestions for appropriate strengthening principles and techniques should be gathered from the experiences accumulated by researchers and practitioners in other seismic areas of the world having stone masonry buildings with similar characteristics, such as European or North American countries. In particular, retrofit strategies should be aimed at reducing the main factors contributing to the vulnerability of unreinforced masonry buildings, addressing also issues related to the sustainability of the intervention and its compatibility with the existing structure. A global type of response should be ensured by means of improvement of the wall-to-floor connection and enhancement of the mechanical properties of the masonry and strengthening of structural elements whenever possible, in order to prevent the occurrence of local failure mechanisms.

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