(a) unstable front wall

(b) return wall separation

Figure 3.30 Christchurch Anglican Cathedral – front façade damage

3.2.2 Damage mechanisms in stone masonry buildings and churches

Many examples of earthquake induced damage mechanisms to stone masonry buildings were observed, with a detailed description of the most recurrent mechanisms presented below.

<u>Out-of-plane failure mechanisms</u>

As expected for buildings having architectural features typical of the Gothic Revival style (long span façades, flexible floor diaphragms and weak connections between walls), partial or global overturning or instability of the façades was reported for most of the structures inspected, with damage ranging from moderate to severe and in some cases reaching collapse. Examples are shown in Figure 3.30 to Figure 3.32 relative to the main façade of the Anglican Cathedral (now partially collapsed after the June 2011 earthquake and aftershocks), the Rockvilla dwelling that experienced complete collapse of the north and east façades, and the former Old Boy's High building in which the north façade was propped to avoid collapse due to out-of-plane failure. 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 (Figure 3.31).

Figure 3.31 Rockvilla dwelling with complete collapse of the north and east façades

Figure 3.32 Christchurch Arts Centre (former Old Boy's High building), with severe damage due to instability of the façade at the second storey

Many of the 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. 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 3.33).

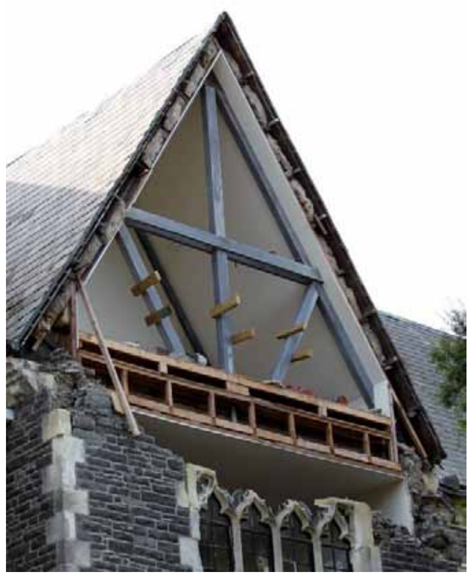


Figure 3.33 Cramner Court, showing complete collapse of a gable

<u>In-plane response of walls</u>

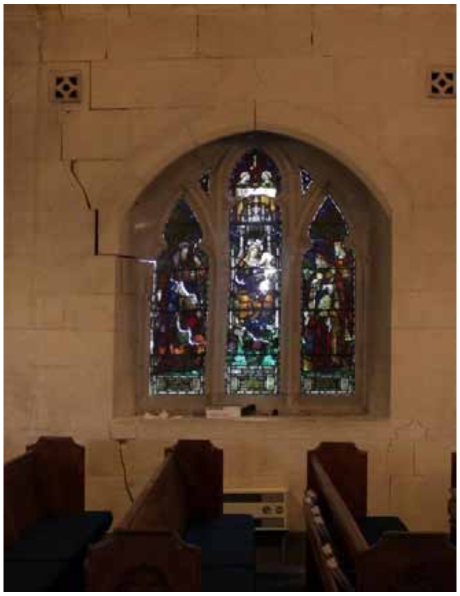
Because the predominate direction of the 22 February 2011 earthquake was in the east-west direction, and because the buildings in the CBD are primarily oriented in the same direction, evidence of in-plane wall damage in the east-west running walls (see Figure 3.34 and Figure 3.35) was reported in conjunction with overturning of façades oriented in the orthogonal direction (see Figure 3.30).

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

Figure 3.35 Canterbury Provincial Chambers - diagonal crack through entire south façade of the east annex

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 (see Figure 3.36 and Figure 3.37).



(a) Interior view

(b) Exterior view

Figure 3.36 St. Barnabas' Church, showing interaction between the nave and the bell tower

Figure 3.37 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. Figure 3.38 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 their separate foundations.

(a) Distant view

(b) Close up view

Figure 3.38 Interior views of Old Boy's High (part of the Arts Centre Complex, 2 Worcester St), showing interaction between adjacent buildings

Diaphragm and roof seismic response

The influence of both inadequate and adequate securing of walls and diaphragms using wall-diaphragm anchors was observed. 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 sufficiently closely spaced to resist lateral loads, the overturning of gables and other portions of walls was prevented.

(a) overturning of the front façade gable

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

Figure 3.39 Former Trinity Church, showing details of gable ended out-of-plane wall failure

Two cases are presented to show the different behaviour induced by the presence and effectiveness of anchoring. Figure 3.39(a) 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 Figure 3.39(b) illustrates how the anchoring was insufficient in size and spacing to secure the wall in place. Figure 3.40 shows some examples of successful wall-to-roof anchoring in the Arts Centre building.

(a) former Old Girl's High

(b) former Canterbury Engineering Department

Figure 3.40 The Christchurch Arts Centre, showing successful use of wall-diaphragm anchorages

In the case of churches, hammering of roof trusses was reported as for the case of St. James' Church shown in Figure 3.41.

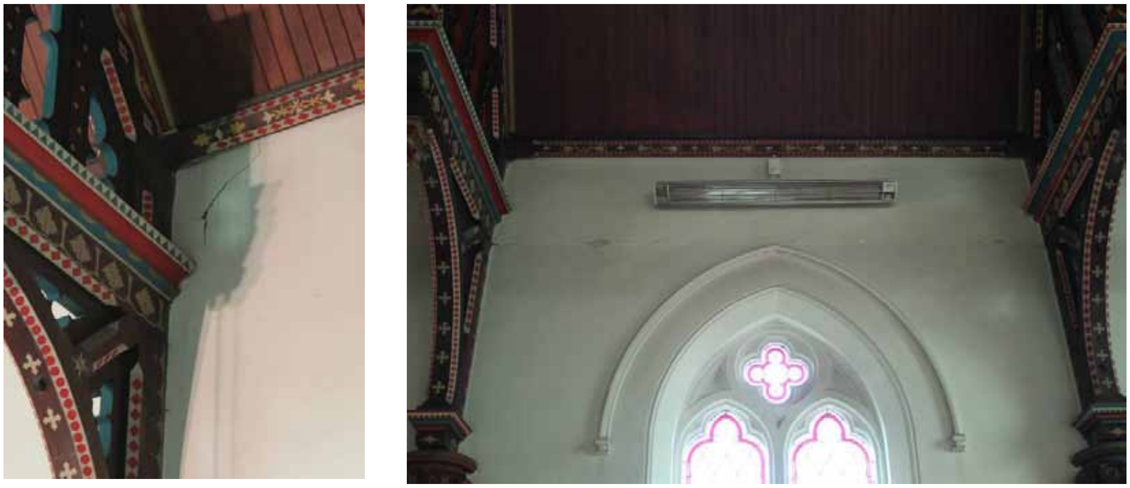


Figure 3.41 St James' Church, hammering of roofing elements on the walls of the nave

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 lead to poor earthquake response. Examples of such behaviour include the Holy Trinity Church in Lyttelton, one of the oldest constructions in Canterbury, and St. John's the Baptist and the Time Ball station, as represented in Figure 3.42 to Figure 3.44.

Figure 3.42 Lyttelton Holy Trinity Church. Damage induced by hammering of the roof

Figure 3.43 St. John's the Baptist Church. Local collapse of material

It has been reported that after the 13th June 2011 earthquakes, the remaining of these two buildings, and several others in Lyttelton that were in a similar state of damage, completely collapsed.

Figure 3.44 Time Ball Station. Damage in the Time Ball tower