

## PERFORMANCE OF CHURCHES DURING THE DARFIELD EARTHQUAKE OF SEPTEMBER 4, 2010

Myrto Anagnostopoulou<sup>1</sup>, Michel Bruneau<sup>2</sup> and  
Henri P. Gavin<sup>3</sup>

### SUMMARY

This paper focuses on the structural behaviour and types of failure of churches located in the general Canterbury area following the Darfield earthquake of September 04, 2010. Given the variability in architectural styles, structural systems and properties of underlying soils, different patterns of damage were identified including out-of-plane gable failures, collapse of bell towers and cracking due to liquefaction and ground settlement.

An architectural and historical landmark of Christchurch, the Christchurch Cathedral, suffered insignificant damage during the earthquake mainly because of its seismic retrofitting during 2006-2007. However many other church structures required retrofitting and supporting measures to avoid additional damage.

### INTRODUCTION

Like similar buildings designed for large assembly of communities and places of worship, churches are representative of the architectural character of a community. Older church buildings, traditionally built of unreinforced stone or brick masonry, have often suffered damage in past earthquakes. The general modes of failure of unreinforced masonry buildings, repeatedly reported by earthquake reconnaissance teams in the past, typically belong to one of the following categories: (i) lack of anchorage; (ii) anchor failure; (iii) in-plane failure; (iv) out-of-plane failure; (v) combined in-plane and out-of-plane effects; and (vi) diaphragm-related failures [1]. However, newer churches, while often constructed with an architectural expression that simulates traditional construction, are in fact engineered or retrofitted with modern materials with consideration of seismically-induced forces.

During the Darfield 2010 earthquake, several churches in the Christchurch area suffered damage. The identified levels and patterns of damage differ significantly from one case to another. Some intact churches are just a block away from others that suffered significant damage. This variability can be attributed to the differences in architectural styles, structural systems, and the characteristics of local ground excitations (which were close to the level of damage threshold in many cases). The strength and properties of the underlying soils also proved to have a significant impact to the structure's response. A sample of typical church damage is provided here to illustrate some of the notable types of failures observed following the earthquake.

### PERFORMANCE OF CHURCHES

The Christchurch Chinese Methodist Church in Merivale (165 Papanui Rd, 43030'49"S-172°37'19"E) is an unreinforced masonry building with a square tower on top of which rests a pyramidal spire. The building suffered out-of-plane wall failures of its gables, as shown in Figure 1, and was characterized as unsafe to access. In order to facilitate the reconstruction and strengthening of the damaged building, the spire was lifted off its supporting tower with a crane and placed on the ground as illustrated in Figure 2 and Figure 3.



**Figure 1:** *Out-of-plane gable failure, Christchurch Chinese Methodist Church [Photo by M. Bruneau].*

St Mary and St Athanasios Coptic Orthodox Church in St Albans (90 Edgeware Rd, 43°30'49"S-172°38'20"E) is a masonry building. The church suffered significant out-of-

<sup>1</sup> SEESL Structural Engineer, Dept. of Civil, Structural, and Environmental Engineering, University at Buffalo, Buffalo NY

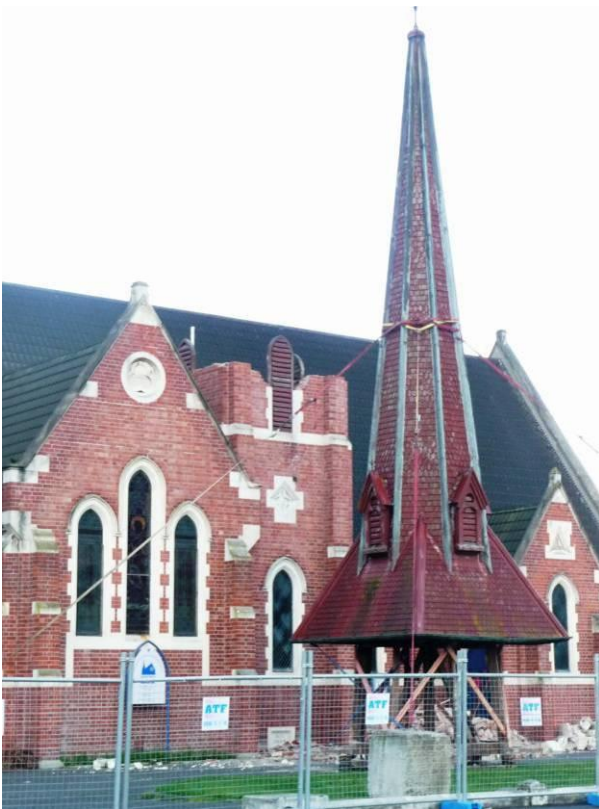
<sup>2</sup> Professor, Dept. of Civil, Structural, and Environmental Engineering, University at Buffalo, Buffalo NY

<sup>3</sup> Associate Professor, Dept. of Civil and Environmental Engineering, Duke University, Durham NC

plane wall failures of its gables, as shown in Figure 4. As observed in many instances of out-of-plane failures, anchors were present in the walls that failed in order to anchor the masonry wall to its supporting timber frame. A frequently encountered type of archaic anchor is shown in Figure 5. Clearly, these existing anchors provided insufficient restraint against the seismically induced forces, and led to out-of-plane wall failures (Figure 6). This observation is not surprising as these anchors, like many other types of old anchors, were never intended to resist earthquake loads. The façade of the church was decorated by a circular shaped window and two small-size domes that collapsed during the earthquake (Figure 7). The building was determined to be unsafe to access because of the numerous out-of-plane wall failures. (A red tag on the door is visible in Figure 4.)



**Figure 2:** General view of Christchurch Chinese Methodist Church with tower and spire [Photo by M. Anagnostopoulou].



**Figure 3:** Spire supported on the ground, Christchurch Chinese Methodist Church [Photo by M. Bruneau].



**Figure 4:** Front view showing significant gable failure, St Mary and St Athanasios Coptic Orthodox Church [Photo by M. Anagnostopoulou].



**Figure 5:** Characteristic type of anchor, St Mary and St Athanasios Coptic Orthodox Church [Photo by M. Bruneau].



**Figure 6:** Masonry wall failure due to insufficient anchorage, St Mary and St Athanasios Coptic Orthodox Church [Photo by M. Bruneau].



**Figure 7:** Failure of the façade's window and domes, St Mary and St Athanasios Coptic Orthodox Church [Photo by M. Bruneau].

St Paul's Catholic Church in Dallington (17 Gayhurst Rd,  $43^{\circ}31'10''\text{S}$ - $172^{\circ}40'21''\text{E}$ ) was built in 1957 (Figure 8). The building has a rectangular shaped plan view and its structural system consists of concrete portal frames and masonry infill walls [2]. The 2010 earthquake caused an extensive amount of liquefaction and ground deformation in the church's surrounding area (Figure 9). As a result, significant settlement and vertical cracking were observed in the body of the building (Figure 10). Differential settlement across the length of the church separated the lower part of the structure, leaving a wide gap in the roof (Figure 11). The church was determined to be unsafe for occupancy and is to be demolished [2].



**Figure 8:** Front view of St Paul's Catholic Church [Photo by M. Anagnostopoulou].



**Figure 9:** Liquefaction and ground deformation around St Paul's Catholic Church [Photo by M. Anagnostopoulou].



**Figure 10:** Ground settlement due to liquefaction, St Paul's Catholic Church [Photo by M. Anagnostopoulou].



**Figure 11:** Gap in the roof and vertical cracking due to differential settlement, St Paul's Catholic Church [Photo by M. Anagnostopoulou].

St. John's Anglican Church in central Christchurch (234 Hereford St,  $43^{\circ}31'56''\text{S}$ - $172^{\circ}38'35''\text{E}$ ) is a stone masonry building built in the late 1800s. According to the Christchurch City Libraries catalogue [3], it is one of the city's heritage buildings. The church's masonry bell tower, which was characterised by different architectural styles and structural elements along its height [4], collapsed during the 2010 earthquake as shown in Figure 12 through Figure 14. The tower collapsed away from the main church building avoiding any consequent damage. Vertical fracture of the tower over its remaining height was visible, and damage revealed the rubble infill of the stone walls (Figure 13). Moreover, out-of-plane movement of the gable left it separated from the building. This separation spread to the connection with the church's lateral walls, resulting in vertical cracking along the building's height (Figure 16). The horizontal gap at the top of the façade's gable was approximately eight centimetres. In order to prevent the church's façade from suffering more damage or collapsing into a busy thoroughfare, a heavy steel reaction frame was installed 10 days after the main shock as shown in Figure 15 and Figure 16.



**Figure 12:** Collapse and vertical fracture of bell tower, St. John's Anglican Church [Photo by M. Bruneau].



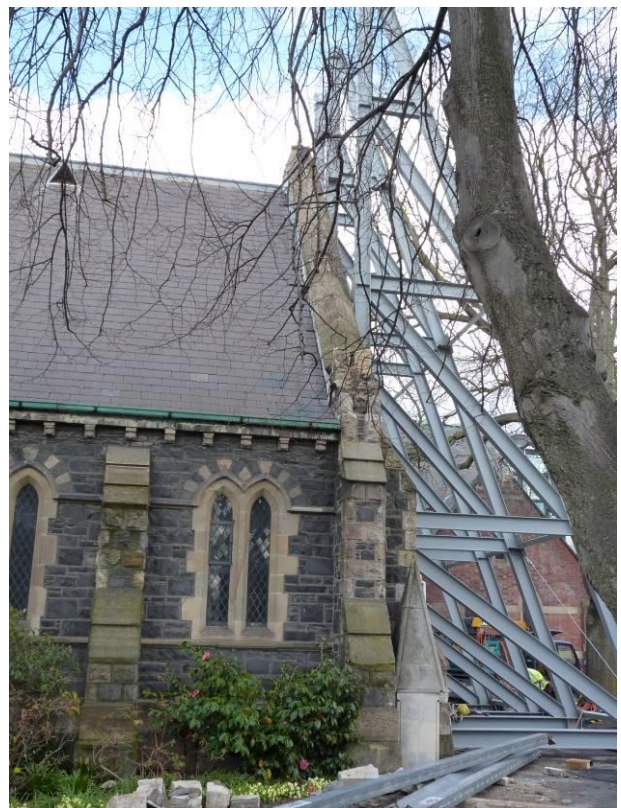
**Figure 13:** Vertical fracture of bell tower, St. John's Anglican Church [Photo by M. Bruneau].



**Figure 14:** General view and bell tower failure, St. John's Anglican Church [Photo by M. Anagnostopoulou].



**Figure 15:** Reaction frame at façade's gable, St. John's Anglican Church [Photo by M. Bruneau].



**Figure 16:** Separation of façade's gable from building and steel reaction frame, St. John's Anglican Church [Photo by M. Anagnostopoulou].

The Knox Presbyterian Church in central Christchurch (28 Bealey Av, 43°31'16"S-172°37'43"E) was built in 1964 [5]. The building's masonry gables were significantly damaged due to lack of anchorage to their supporting timber diaphragms, as shown in Figure 17 and Figure 18. The church was tagged to permit restricted access and restoration work started the week after the earthquake.



**Figure 17:** Gable failure, Knox Presbyterian Church [Photo by M. Bruneau].

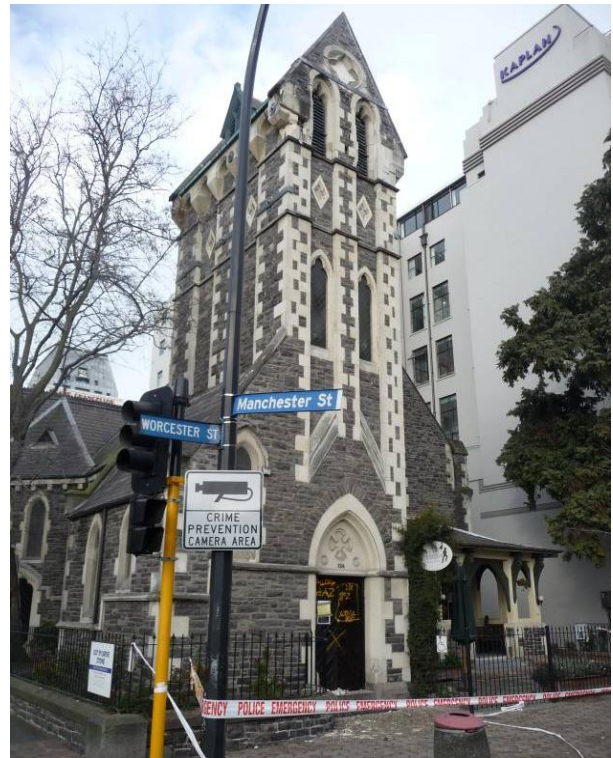


**Figure 18:** Damage in masonry gables and restoration, Knox Presbyterian Church [Photo by M. Anagnostopoulou].

The Trinity Congregational Church in central Christchurch (124 Worcester St, 43°31'52"S-172°38'22"E) was built in 1874 and has a Gothic style [6] (Figure 19 and Figure 20). Recent retrofitting and strengthening of the building, including several anchor ties (Figure 21), appears to have reduced the damage from the 2010 earthquake. Minor cracking, spalling of the building's thick stone walls, and damage in the tower were observed (Figure 22). The building will reopen as soon as repairs are completed [7].

St. Peter's Anglican Church in Upper Riccarton (23 Yaldhurst Rd, 43°31'54"S-172°34'12"E) was constructed in stages from 1858 to 1929 [8]. The oldest existing portion of the church, the chancel, was completed in 1876 and most of the existing stone work was completed in 1929. Damage to St. Peter's was typical of many heritage structures. In the September 4<sup>th</sup>

earthquake the peaks of transept parapets fell (NS direction) and peaks of quire parapets fell (EW direction) in subsequent aftershocks (Figure 23).



**Figure 19:** General view of Trinity Congregational Church [Photo by M. Bruneau].



**Figure 20:** Side view of Trinity Congregational Church [Photo by M. Anagnostopoulou].



**Figure 21:** Anchor ties installed at building's tower, Trinity Congregational Church [Photo by M. Bruneau].



**Figure 22:** *Damaged tower, Trinity Congregational Church [Photo by M. Bruneau].*



**Figure 23:** *Fallen quire and transept parapets, St Peter's Anglican Church [Photo by H. Gavin].*

The Cathedral of the Blessed Sacrament in central Christchurch (122 Barbados St,  $43^{\circ}32'17''\text{S}$ – $172^{\circ}38'46''\text{E}$ ) has a basilica form and is constructed of poured concrete between walls of large limestone blocks [9]. The wall thickness is 1.2 meters. “The Basilica” was built over four years and opened in 1905. Seismic upgrades in 2004 included strengthening of the drum below the dome (Figure 24), the bell tower, the mezzanine floor, and the roof above the mezzanine. The drum was strengthened with cast concrete ring beams above and below the windows which were joined by pilaster columns. Spandrel beams and cross bracing were added inside the bell towers. The 2010 earthquake caused little in the way of horizontal shear cracks at construction joints in the walls or in the retrofitted portions. Repairs to cracks around the keystone of window arches and in the mezzanine floor above the sanctuary require that “the Basilica” remains closed for at least a year (Figure 25).



**Figure 24:** *Dome and drum of the Cathedral of the Blessed Sacrament [Photo by H. Gavin].*



**Figure 25:** *Cracks around keystones in the Cathedral of the Blessed Sacrament [Photo by H. Gavin].*

As one of the city’s most famous landmarks, the Christchurch Cathedral (Cathedral Square,  $43^{\circ}31'51''\text{S}$ – $172^{\circ}38'13''\text{E}$ ) is a masonry structure built in the second half of the 19<sup>th</sup> century. Although the 1848 Wellington earthquake gave the Cathedral's original designers reason to consider seismic effects, the design ultimately selected utilized columns of locally-quarried stone rather than the kauri logs from Auckland as initially proposed [10, 11]. Nonetheless, timber scissor trusses were selected for the vaults of the nave, transept, and apse. Damage to the stone spire from the earthquakes of 1881, 1888 and 1901 led to the current spire design of a timber frame with copper cladding. Seismic retrofit in 2006-2007 involved installation of a steel truss in the inclined aisle roofs with cast concrete anchoring the steel chords to the outer aisle walls, steel channel sections strengthening the ordinary wall buttresses between the clerestory windows (Figure 26), custom arched steel sections sandwiching the timber vault arches, and new shear walls at each end of the aisle. This retrofit provided a continuous load path from the scissor trusses of the nave, through the nave arch, into the buttresses, along the aisle roof into shear walls.

Because of these renovations, the structure suffered insignificant damage during the 2010 earthquake (Figure 27). The only damage was to ornamental stone details. The Cathedral remained closed until September 22 due to the risk of falling debris during aftershocks. Careful and repeated inspections of the Cathedral revealed no significant structural damage.



**Figure 26:** Steel channels along the ordinary buttresses, Christchurch Cathedral [Photo by H. Gavin].

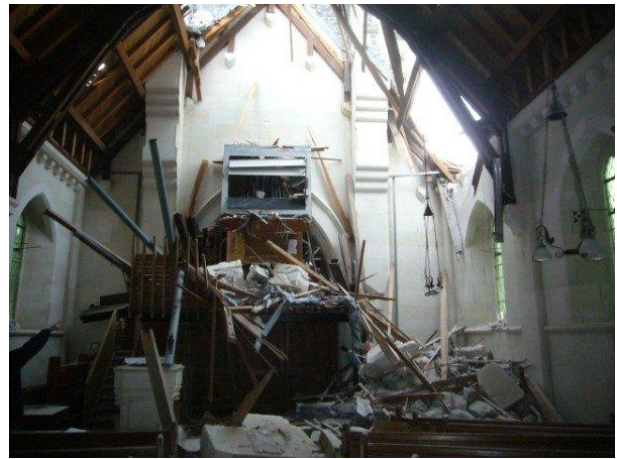


**Figure 27:** General view of Christchurch Cathedral [Photo by M. Anagnostopoulou].

St John's Hororata Church in Darfield ( $43^{\circ}31'08''\text{S}$ - $171^{\circ}56'46''\text{E}$ ) was built in the early 1900's and is considered a heritage building [12]. It is a masonry structure located only a few kilometres away from the epicentre. During the 2010 earthquake, the church's tower collapsed causing significant damage to the west end of the nave as well as to the church organ (Figure 28 and Figure 29).



**Figure 28:** Collapsed tower, St John's Hororata Church (Retrieved October, 2010, from <http://geoconger.wordpress.com/category/anglican-church-news/anglican-church-of-aotearoa-new-zealand-polynesia/>).



**Figure 29:** Damage in the interior of the church and organ, St John's Hororata Church (Retrieved October, 2010, from <http://www.hororataparish.co.nz/st-johns-hororata-gallery.php>).

St Joseph's Catholic Church in Darfield (Telegraph Rd,  $43^{\circ}29'32''\text{S}$ - $171^{\circ}06'32''\text{E}$ ) is a masonry structure located only a few kilometres away from the epicentre (Figure 30). During the 2010 earthquake, the church suffered cosmetic wall cracks as illustrated in Figure 31.



**Figure 30:** General view of St Joseph's Catholic Church [Photo by M. Bruneau].



**Figure 31:** Cosmetic wall crack, St Joseph's Catholic Church [Photo by M. Bruneau].

## ACKNOWLEDGMENTS

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