Evaluation of Seismically Retrofitted Masonry Substation Buildings

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Abstract

The performance of retrofitted clay brick masonry substation buildings was investigated from a multi-disciplinary perspective that included structural, economic and social considerations. 115 single storey double leaf clay brick masonry substation buildings located within the wider Christchurch region were investigated in detail. Prior to the 2010/2011 Canterbury earthquakes these substation buildings were seismically retrofitted using a system of simple and cost-effective steel elements as part of a natural disaster improvement programme, with an overall cost of NZ$6 million. After the earthquakes, rapid assessment evaluation (Level 1 and Level 2) was conducted with the determination that 82% of the clay brick masonry substation buildings survived with minor damage and 15% had moderate damage, with only one clay brick masonry substation suffered significant damage and two clay brick masonry substation buildings experienced heavy damage. Investment in the seismic improvement programme resulting in cost savings of approximately NZ$60 million and contributed to heritage building preservation.

Keywords: masonry buildings, seismic retrofitting, steel element retrofit, earthquake, substation buildings

1.0 INTRODUCTION

Two devastating earthquakes that occurred in September 2010 and February 2011 hit the Canterbury region with moment magnitudes of M_w 7.1 and M_w 6.3 respectively (Carydis et al., 2012; Giovinazzi & Wilson, 2012), causing severe damage to both buildings and lifelines that served the city. Power distribution was one of the most severely affected networks due to significant ground shaking and deformation that caused faults in underground distribution networks leading to major power outage and loss of functionality to the power distribution system (Giovinazzi & Wilson, 2012; Stevenson et al., 2011). Electrical cables suffered multiple losses from the earthquake events mainly because of liquefaction and lateral spreading However, power was restored to 90% of customers in a single day after the September 2010 event and was restored in ten days after the February 2011 event (Fenwick & Hoskin, 2011; Giovinazzi & Wilson, 2012)

The power distribution in Christchurch is mainly operated by two companies: (1) Transpower, which operates the high voltage nationwide transmission system (220 kV and 66 kV), and (2) the local distributor company, Orion New Zealand Limited (previously known as Southpower). Orion conveys power from Transpower to supply electricity to 191,000 end user clients with low and medium voltage (66 kV, 33 kV, 11 kV and 400 V). The power is supplied via underground cables and an overhead distribution network (Fenwick & Hoskin, 2011; Giovinazzi & Wilson, 2012; Lamb, 1997). In order to distribute the power in cost-effective ways, zone and local network substations act as platforms to transform high voltage into low voltage before reaching customers. The zone substation feed either 66 kV, 33 kV or 11 kV from Transpower substations before conveying 11 kV to the local network substation which in turn provides a 230/400 volt street supply (Lamb, 1997). Most of the zone substation buildings were well designed using reinforced and grout-filled concrete blocks that would most likely be able to withstand a moderate earthquake event. However, most of the local network substation buildings were constructed from the early 1920s using unreinforced clay brick masonry (URM). These vulnerable substation buildings had the potential to be heavily damaged due to earthquake shaking, resulting in power supply interruptions.

There were 314 substations (51 were zone substations and 263 were local network substations) operating in Christchurch prior to the 2010/2011 Canterbury earthquakes. As a result of seismic retrofit work that was undertaken during the mid-1990s on the substation buildings, most of the buildings survived with minor damage and only four of the 314 substation buildings were severely damaged after the earthquakes (Massie & Watson, 2011). Two of the severely damaged substation buildings were constructed of clay brick masonry and were located on St Andrew Hills and on Wakefield Avenue, one of the severely damaged substation building was constructed of concrete block masonry and was located in New Brighton, and the final severely damaged substation was constructed of concrete infill wall and was located on Port Hills Road. These four severely damaged buildings have since been either demolished and replaced or decommissioned and bypassed. Out of the total of 314 substations, 115 substations were identified as double leaf clay brick masonry buildings and are the focus of the multi-disciplinary case study reported herein.

2.0 CHARACTERISTICS OF THE BUILDINGS

The 115 single storey double leaf clay brick masonry substation buildings investigated in detail as part of this study were located in the wider Christchurch region as shown in Figure 1. The following suburbs of Christchurch had the highest number of substation buildings (listed in descending order): Christchurch Central Business District (CBD), Riccarton, Burnside, Sydenham, Papanui, Addington, St Albans and Woolston. The majority of the substation buildings had a minimum interior height of 3.65 meters, which was required for switchgear, transformer equipment, and safety clearance. High foundations were implemented to accommodate cables and ventilation ducting, as well as to provide sufficient clearance height for a truck deck for when equipment had to be moved (Hartrick, 2003). The common building footprint shapes are rectangular and most of the buildings were constructed as isolated structures (standalone), although some were attached to other premises (row buildings).

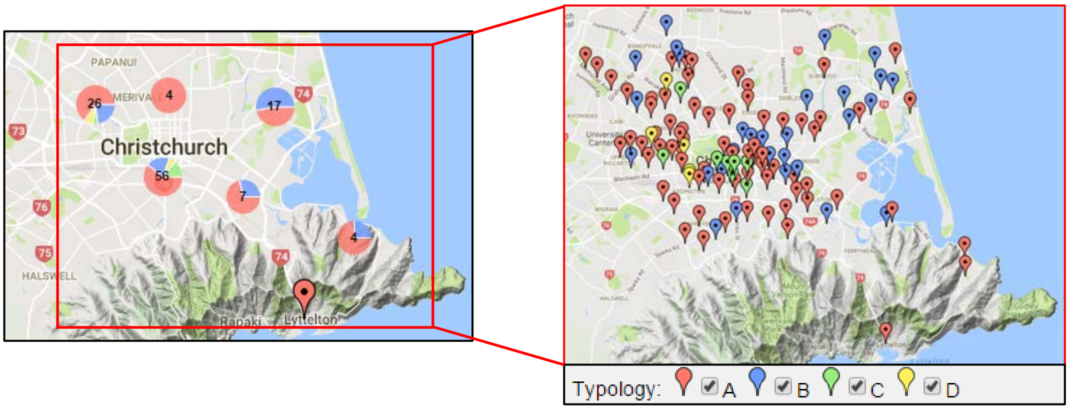


Figure 1: Location of 115 investigated clay brick masonry substation buildings in Christchurch, New Zealand

Of the 115 buildings, 110 are clay brick unreinforced masonry (URM) buildings which were erected between 1920 and 1960, and five are infill masonry buildings which were constructed after 1950. The majority of the 110 URM substation buildings were constructed of solid double leaf brick walls, a concrete floor and flexible roof diaphragm (76 buildings) although 34 buildings had a rigid roof diaphragm (Figure 2). Most of the buildings were observed to contain a concrete perimeter bond beam at ground and eaves level. The presence of reinforced concrete (RC) columns and roof diaphragm in the substation buildings distinguished the infill masonry buildings from the URM buildings, and the existence of air ventilation holes on walls and the use of running bond types of the brick layer suggests that the infill masonry buildings have cavity brick walls. From the data collection, a total of 64 substation buildings appeared to have parapets, and 51 substation buildings had no parapets. In this study, the substation buildings have been classified into four groups of building typologies (i.e. A, B, C, and D) in accordance with the buildings characteristics. The typologies are distinguished according to several factors as presented in Table 1. Figure 3 show examples for each building typology.

(a) Rigid (reinforced concrete slab)

(b) Flexible (timber or steel roof trusses)

Figure 2: Types of roof diaphragm

Table 1: Description of building typology

Typology	Types of masonry building	Building continuity	Parapet	Roof diaphragm	Number of buildings
A	URM	Isolated	Yes/No	Flexible	72
B	URM	Isolated	Yes/No	Rigid	29
C	URM	Row	Yes/No	Rigid/Flexible	9
D	Infill masonry	Isolated	No	Rigid	5

(a) Typology A

(c) Typology C

(b) Typology B

(d) Typology D

Figure 3: Examples of masonry substation building typologies showing exterior and interior of each building example.

3.0 ARCHITECTURAL HERITAGE

The substation buildings are important pieces of the Christchurch city's architectural and social history because of their construction in the early to mid-1900s. Some of the substation buildings are listed in the City Plan as Group 4 heritage buildings (metropolitan or local significance) (Hartrick, 2003) due to their age, pleasing appearance and social significance. The traditional European decorative style which was brought to New Zealand from Victorian England (Hartrick, 2003) had great influence on the architectural design of these buildings. In this study, the substation building styles are grouped into two construction periods: 1920-1940 and post-1940.

The main three classical styles for the 1920 – 1940 building exteriors are neo-Georgian pavilion (Figure 4a), the guise of the classical temple known as 'Temples of Electricity' (Figure 4b) and Art Deco (Figure 4c). A style influenced by Frank Lloyd Wright's Chicago was used for a small number of substations (Figure 4d). While the design of the 1920-1940 buildings focused on decoration and architectural appearance, the post-1940 buildings' design emphasized seismic resistance. Most of these buildings had additional reinforced concrete perimeter beam at eaves level.

(a) Neo-Georgian pavilion of Woodham Road Substation

(b) Temples of Electricity of Seddon Street Substation

(c) Art Deco Moderne of Retreat Road Substation

(d) Frank Lloyd Wright's Chicago of Dyers Pass Road Substation

(e) Griffith's modernism of Office Road West Substation.

Figure 4: Decorative styles of substation buildings (Photos taken from Hartrick, 2003).

Christchurch experienced a significant loss of heritage following the 2010/2011 Canterbury earthquakes when Canterbury Earthquake Recovery Authority (CERA) listed at least 104 heritage buildings as approved for demolition (Heather, 2011). Consequently, the substation buildings have since gained increased heritage status within the community.

4.0 RETROFITTING SCHEMES

The Risk and Realities improvement programme, initiated in the early 1990s by Christchurch Engineering Lifelines Group, led to the initiation of an ongoing seismic retrofitting programme of the substation buildings. This programme commenced in 1996 and progressed systematically annually for fifteen years (Fenwick & Hoskin, 2011). The objective of this plan was not only to reduce exposure to risk from natural hazard but also to comply with life safety requirements. Therefore, measures to mitigate earthquake risk had been undertaken by strengthening the substation buildings. Buildings were retrofitted by bracing the buildings at roof level and bolting steel members to appropriate position. The bracing system provided structural ribs and reduced face loads to the substation buildings (Lamb, 1997). The use of steelwork was found to be a cost-effective way to retrofit the substation building that provided a long-term plan due to its reversibility (Robinson et al., 2000). The retrofitting work was implemented on two individual elements of structural components of the substation buildings: walls and roofs.

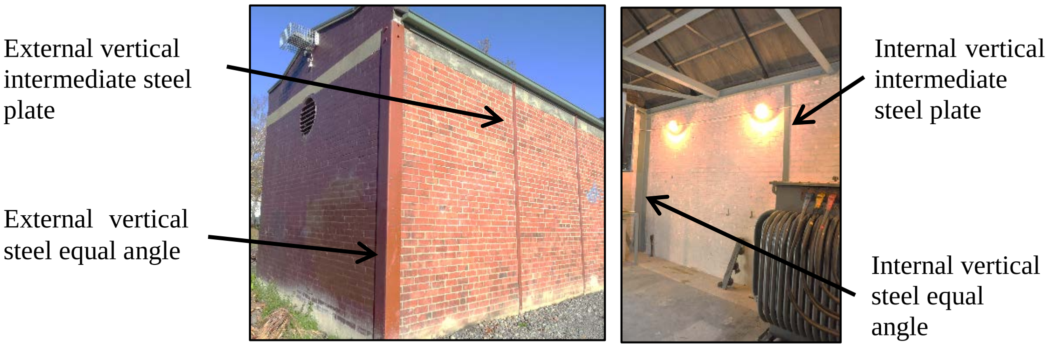
4.1 WALLS

Traditional retrofitting methods of reinforcement, braced steel frame, and anchored steel ties were used for walls retrofitting work. The braced steel frame consists of vertical and diagonal steel members. These members were installed at corners of the substation buildings and walls either externally, internally or a combination of the two. These buildings contain a large number of equipment such as switch gears, transformers etc. thus, retrofitting members were positioned in the most convenient places. Priority was given to interior but where accessibility was not possible, the steel members were installed externally. The vertical steel angles were common at the corners and intermediate walls of the buildings (Figure 5a) while diagonal steel members were generally mounted at the entrance and the rear walls (as seen in Figure 5b). The intermediate vertical steel plates improved out-of-plane behaviour of URM by effectively reinforcing the walls as tension members and also by holding down the concrete perimeter bond beam at eaves level and the strip foundation to confine the URM walls. Meanwhile, the diagonal steel plates were added to improve both the out-of-plane strength of the masonry walls and to provide reliable in-plane shear strength to the front of the overall building. Fasteners known as bugle head countersinks (Figure 5c) were epoxy set to connect the diagonal steel plates to the masonry walls. Both steel members (vertical and diagonal) provided additional confinement to the masonry walls of the substation buildings.

The use of anchored steel ties assisted in reducing the chance of out-of-plane failure of the outer walls from earthquake shaking. As described in Section 2.0, most of the walls of the substation buildings were constructed with double leaves. These leaves generally are not connected resulting in a high risk of collapse of the outer walls. Figure 5d shows an example of a substation building retrofitted with steel anchored ties.

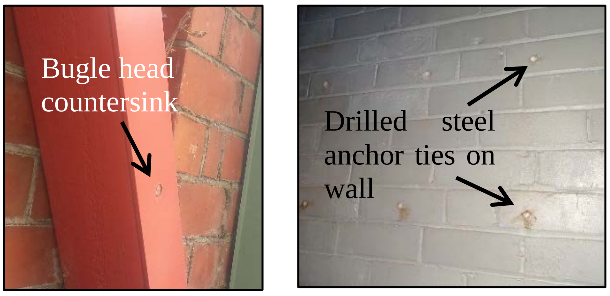
4.2 ROOFS

Three methods were applied to retrofit the roof elements: (1) installation of additional structural elements (steel bracing across the roof diaphragm); (2) bolting steel brackets at purlin; and (3) mounting steel plates on perimeter beam at eaves level. The steel bracing is commonly observed in substation buildings with flexible diaphragms (Figure 6a). This technique aided in transferring lateral loads from roof to walls, and reducing the risk of roof damage. In addition, steel brackets were bolted to purlins (Figure 6b) to improve roof connections of the substation buildings. The mounted steel plates were common for rigid diaphragms and usually could be found externally or internally, or externally and internally to the perimeter roof beam (Figure 6c).



(a) Vertical steel equal angles and intermediate steel plates

(b) Diagonal steel plates



(c) Diagonal steel plate was connected to masonry walls with bugle head countersink.

(d) Epoxy set steel anchor ties

Figure 5: Walls bracing with steel elements as part of seismic retrofit

The retrofit method of the substation buildings was classified into several groups as shown in Figure 7. 67.8% (78) of the substation buildings received retrofits to both the walls and roof, while 22.6% (26) and 1.7% (2) received retrofits to only the walls or to the roof respectively. 7.8% (9) substation buildings showed no retrofitting system.

(a) Typical roof bracing of flexible diaphragm

(b) Steel brackets bolted at purlin

(c) Steel plates mounted on perimeter beam

Figure 6: Seismic retrofitting at roof level

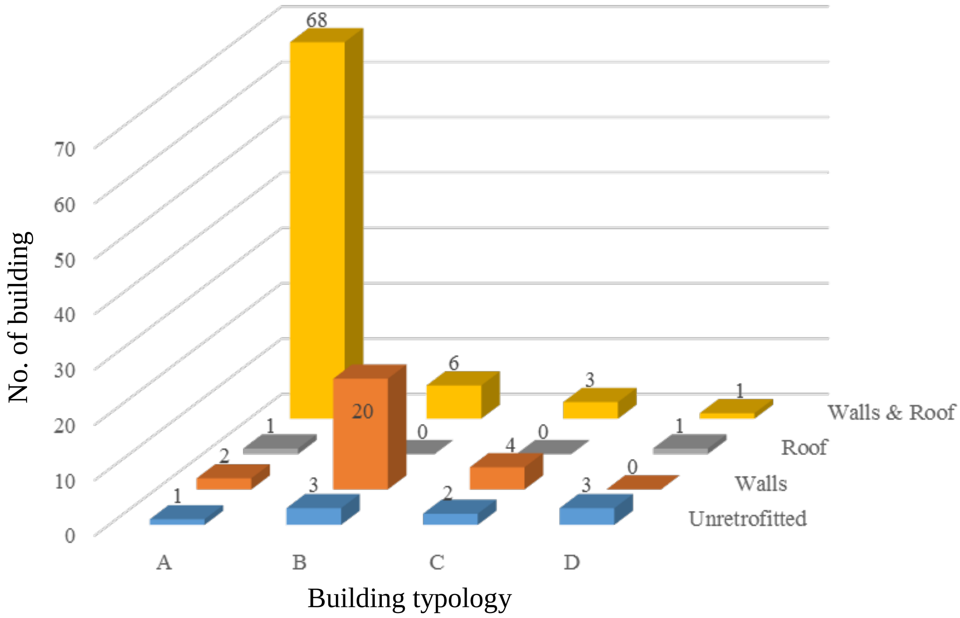


Figure 7: Number of retrofitted substation buildings

5.0 ECONOMIC APPRAISAL

Under the seismic improvement programme as discussed in Section 4.0, a total of NZ$6 million was spent over a period of fifteen consecutive years for the seismic retrofits of the substation buildings (an average of $NZ 400,000 per year) as a staged process of safety improvement (Fenwick & Hoskin, 2011). The estimated cost of retrofitting each building was NZ$21,408 including the retrofitting materials (steel members and grout) and labour costs (installation of steel members and building fixing works). As a result, Orion saved approximately NZ$60 million in direct asset replacement cost (Orion New Zealand Limited, 2012).

6.0 POST-EARTHQUAKE ASSESSMENT

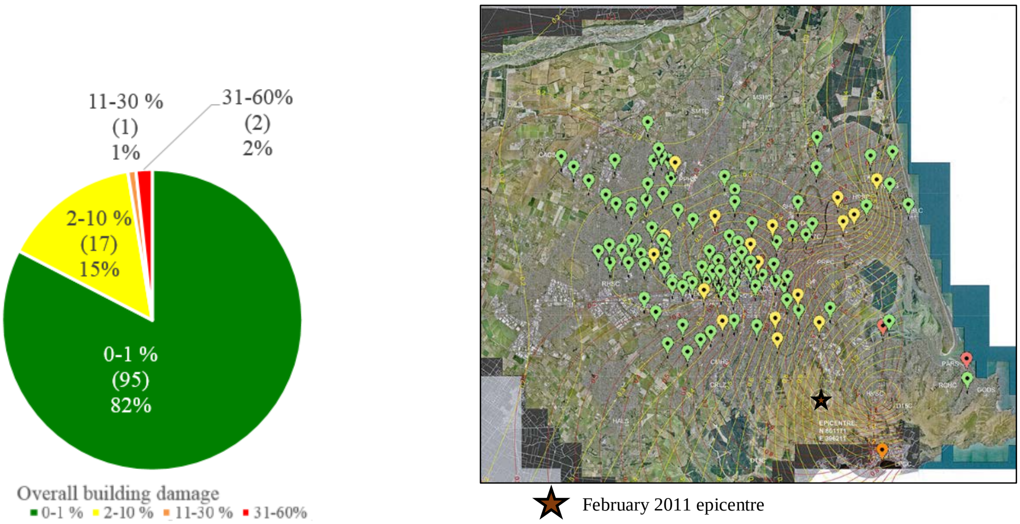
A post-earthquake assessment team was immediately formed in Christchurch as an emergency response to the 2010/2011 Canterbury earthquakes. The team was assigned to examine the substation buildings for safety and structural performance. The building evaluations were carried out in three phases as recommended by New Zealand Society for Earthquake Engineering (NZSEE), i.e., overall damage survey, rapid building assessment and detailed engineering evaluations (NZSEE, 2009). The overall damage survey phase was conducted by emergency services personnel and local authority staff while professional engineers undertook the rapid assessments. The detailed engineering evaluations were only carried out if required (NZSEE, 2011).

Following the 22 February 2011 earthquake (NZSEE, 2009) damage data for the substation buildings was collected using the Rapid Assessment Form (Level 1 and Level 2). After the Level 1 rapid assessments, substation buildings were posted with short term indication placards (i.e. green, yellow and red). If a building was inspected and no safety issues were highlighted then the buildings was assigned a green placard, but if there was a safety concern then a yellow placard was assigned and the building could only be entered for restricted use. The red placard was only assigned if a building was no longer safe and no access was permitted (NZSEE, 2009). 97% (112) of the substation buildings were tagged as green, 1% (1) was labelled as yellow placard and 2% (2) were marked as red.

The Level 2 rapid evaluation procedure can only be performed by professional engineers with broad technical experience and these assessments were used to estimate a percentage range of overall building damage as described in Table 2. Of the 115 clay brick masonry substation buildings, 95 buildings were estimated to have 0-1% damage, 17 buildings experienced 2-10% damage, one substation building in Simeon Quay had significant damage, and two substation buildings located at Wakefield Avenue and at St Andrew Hills suffered from 31 – 60% damage.

Table 2: Description of the extent of damage

Damage level	Definition	Description
0 – 1 %	Minor	Observation of none to very light structural damage such as hairline cracks. No immediate repair works are required
2 – 10 %	Moderate	Minor to moderate structural damage with no significant effect on building structures. Prompt repair work is required
11 – 30 %	Significant	Damage significantly affects building performance. Immediate remedial work is required
31 – 60 %	Heavy	More than 30% failure of building structure. Demolition of building is possible



(a) Analysis of observed buildings damage

(b) Location of masonry substation buildings on PGA map

Figure 8: Building damage observations

Buildings with a damage estimation rate of 0–1% represented buildings with none to very minor damage (Figure 9) and these buildings could be immediately occupied as no safety concerns were highlighted. 62% (59) of the 95 buildings with minor damage were labelled with green placards, G1 (no immediate further investigation required) while 38% (36) were tagged with G2 (repairing works are required). Minor to moderate damage buildings was about 2–10% (Figure 10) and labelled with green placards (3 and 14 buildings with G1 and G2 label respectively). Most of the buildings assessed with this damage level experienced ground movement or settlement that caused foundation settlement and floor damage (Figure 10c). Re-levelling works had to be performed to those buildings having noticeable foundation movements. Damage that was associated with parapet also could be observed by the parapet movement. Repair works included the provision of addition steel rods for restraining the parapet from collapse.

(a) Hairline cracking of floor

(b) Hairline cracking of masonry wall

Figure 9: Observations of minor damage

A substation building in Simeon Quay was located at the base of a clay cliff and suffered significant damage due to rock fall from a landslide (Figure 11) that damaged the rear part of the building and caused significant damage to the roof. The strengthened walls performed well with only minor damages being observed.

(a) Mortar dropped out from the parapet

(b) Cracking of concrete foundation

(c) Cracking of floor

Figure 10: Examples of moderate damage. Note that (b) and (c) damage were due to ground settlement.

(a) Rock fall from a landside hit the rear part of Simeon Quay Substation

(b) Precautionary propping of Simeon Quay after a severe landslip

Figure 11: Significant damage to Simeon Quay substation building

Two substation buildings in Wakefield Avenue and St Andrew Hills suffered heavy (31-60%) damage (Figure 12). Both buildings were close to the epicentre of the February 2011 Christchurch earthquake, with an estimated PGA of 1.2g (Figure 8b). The damage to the Wakefield Avenue substation building was attributed to boulder damage that caused collapse to approximately 50% of the substation building, resulting in the substation building being decommissioned and bypassed. Nevertheless, due to seismic retrofitting, the front portion of the building remained intact. The St Andrew Hills substation building suffered diagonal shear failures and partial collapse of the north and east URM walls due to significant earthquake shaking, although the seismic retrofitting system of the building held the roof up (Figure 12) and the transformer remained operational while demolishing works were undertaken. The building has since been demolished and replaced with a steel kiosk.

(a) Wakefield Avenue substation boulder damage

(b) Large diagonal shear crack at the entrance of St Andrew Hills Substation

(c) Installation of vertical steel elements kept the roof up after the earthquake.

Figure 12: Heavy damage to Wakefield Avenue and St Andrew Hills substation buildings

7.0 CONCLUSIONS

The performance of the seismic retrofitting system adopted for 115 clay brick masonry substation buildings that utilised steel elements was assessed from a multidisciplinary viewpoint considering structural, economic and social attributes. The characteristics of the buildings and the retrofit features were discussed and it was established that the provided steel bracing system was cost-effective and effectively restrained the substation buildings during the 2010/2011 Canterbury earthquakes. Of the 115 buildings studied, 82% and 15% were rated with minor and moderate damage respectively. Although three substation buildings were classified as receiving significant and heavy damage, the retrofitting system was identified as having generated cost savings in direct asset replacement of up to approximately NZ$60 million whilst the preservation of architectural heritage was also achieved.

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REFERENCES

Carydis, P., Lekkas, E., & Kritikos, T. (2012). The Mw 7.1 Sept 4 2010 and Mw 6.3 Febr 22 2.11, New Zealand Eqs . Comparison of EMS 1998 and ESI 2007 Data. *In Proceeding of the 15th World Conference on Earthquake Engineering, Lisbon Portugal (15WCEE),* (February).

Fenwick, T., & Hoskin, K. (2011). *Resilience Lessons : Orion ’ s 2010 and 2011 Earthquake Experience* (Independent Report). Retrieved from http://www.oriongroup.co.nz.

Giovinazzi, S., & Wilson, T. (2012). “Recovery of Lifelines” following the 22nd February 2011 Christchurch Earthquake : successes and issues. In Proceeding of *2012 New Zealand Society for Eathquake Engineering Conference (NZSEE),Christchurch, New Zealand, (090)*, 1–15.

Hartrick, E. (2003). *The architectural heritage of Christchurch 10, Pavilions, temples & four square walls : Christchurch pump houses and substations*. Retrieved from http://christchurchcitylibraries.com/Heritage/Publications/ChristchurchCityCouncil/ArchitecturalHeritage/PavilionsTemplesFourSquareWalls/1877313092.pdf

Heather, B. (2011, June 8). Life ebbing for heritage buildings [Press article]. Retrieved from http:// http://www.stuff.co.nz/the-press/news/christchurch-earthquake-2011/5111994/Life-ebbing-for-heritage-buildings

Lamb, J. (1997). *Risks & realities a multi-disciplinary approach to the vulnerability of lifelines to natural hazards: report*. *Centre for Advanced Engineering, University of Canterbury*. Retrieved from http://ir.canterbury.ac.nz/handle/10092/11544

Massie, A. & Watson N. R. (2011). Impact of the Christchurch Earthquakes on the Electrical Power System Infrastructure. *Bulletin of The New Zealand Society for Earthquake Engineering, 44 (4)*, 425 - 430.

New Zealand Society for Earthquake Engineering. (2009). *Guidelines for Building Safety Evaluation During a State of Emergency. Guidelines for Territorial Authorities*. Retrieved from http://www.nzsee.org.nz/Guidelines/BuildingSafetyEvaluationAug09.pdf

New Zealand Society for Earthquake Engineering. (2011). Building Safety Evaluation Following the Canterbury Earthquakes. *Report to the Royal Commission of Inquiry into Building Failure Caused by the Canterbury Earthquake*, (September), 1–49. Retrieved from http://canterbury.royalcommission.govt.nz/

Orion New Zealand Limited. (2012). *Annual Report 2011 Orion New Zealand Limited*. Retrieved from http://www.oriongroup.co.nz/assets/Company/Corporate-publications/OrionAR11-WEB.pdf

Robinson, L., Bowman, I., & Bowron, G. (2000). *Guidelines for earthquake strengthening.* Wellington: NewZealand Historic Places Trust, c2000.

Stevenson, J. R., Kachali, H., Whitman, Z., Seville, E., Vargo, J., & Wilson, T. (2011). Preliminary observations of the impacts the 22 February Christchurch earthquake had on organisations and the economy: A report from the field (22 February - 22 March 2011). *Bulletin of the New Zealand Society for Earthquake Engineering, 44*(2), 65–76.