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CHRISTCHURCH TOWN HALL – POST-EARTHQUAKE REPAIR AND STRENGTHENING PROJECT

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ABSTRACT

The Christchurch Town Hall (CTH) complex consisted of six individual buildings that were originally constructed in the 1970's predominantly from reinforced concrete. During the 2010-2011 Canterbury earthquake sequence, the site experienced significant differential settlement and lateral spreading affects which caused the majority of the structural damage.

The CTH Auditorium is internationally recognised for its acoustics. The complex is listed as a grade one heritage building under the Christchurch City Plan. In 2013, the decision was made by Christchurch City Council to repair and seismically strengthen the CTH buildings to 100% of New Building Standard.

During the design phase, the development of the retrofit and strengthening schemes for each of the buildings involved a combination of: (i) intensive computational modelling and non-linear time history analysis, (ii) investigating the feasibility and design of ground improvement techniques, (iii) the design of a new reinforced concrete raft foundation (typically 600-900mm thick), (iv) the repair and strengthening of the superstructure and the re-levelling of the Limes Room.

The Construction phase for the strengthening and refurbishment project commenced in 2015 and is due for completion mid-2018. This paper describes the project background, an outline of the post-earthquake damage observations, and brief discussion of the analysis and design methods adopted for the strengthening schemes.

INTRODUCTION: A BACKGROUND STORY

The purpose of this paper is to describe the Christchurch Town Hall (CTH) repair and strengthening project. The project was undertaken as a result the 2010-2011 Canterbury earthquakes. Each section of this paper have been kept intentionally brief to provide an overview of the main earthquake-related damage, structural analysis methods and retrofit solutions, and summary of the construction phase.

When it opened in 1972, the CTH was a striking example of what could be achieved through a true collaboration of architecture and structural engineering. The CTH complex consists of a number of existing individual buildings predominately used (and internationally recognised) for entertainment, functions and events. The site is located in the Christchurch City Centre, between Durham and Colombo Streets, with the main northern entrance on Kilmore Street and the south side is bounded by the Avon River.

The **Auditorium** was conceived primarily as a symphony concert hall, but also designed to be suitable for a great variety of public assembly purposes including a lyric theatre mode. It seats an audience of 2,354, an orchestra of 120, and a choir of 400. The **Entrance Foyer** (with conference room above) serves as the focal entry point to the complex and ties the other major spaces together. The **James Hay Theatre** was designed as a traditional drama theatre and concert chamber for similar musical performances. It holds an audience of 1,006. The central buildings provide facilities for public dining, private and civic receptions, conventions, exhibitions and meetings of all kinds. The **Boaters Restaurant** projects over the Avon river bank and has an upper floor containing a 500 seat banquet hall, known as the **Limes Room**. Adjacent was the **Cambridge Room** which is the upper floor of an extension completed in 1976 and includes catering, office spaces and utility rooms on the ground floor.

Figure 1: (Left) interior view of the Auditorium, a venue internationally recognised by the performing arts for its acoustic properties; (Right) looking across the Avon River at the Boaters Restaurant and the Ferrier Fountain.

Despite the intensity of ground shaking during the 2010-2011 Canterbury earthquakes, the overall CTH complex performed remarkably well for a building that pre-dates modern design codes. Its resurrection as a modern building within the original skin has required a repeat of the original collaboration, but with the support of more available technology. At both stages, a significant body of engineering and construction work has been completed.

Before discussing details of the re-engineering of the CTH, the following section describes the original design and construction, and the significance of the Canterbury Earthquakes for the CTH complex.

Historic Overview of Design & Construction (1967-1972)

The original structural design of the CTH commenced in 1967 by Holmes & Wood. This firm commenced work initially as IL Holmes & Partners in Christchurch around 1956, after Lyall Holmes left his lecturing position at the University of Canterbury. By 1967, Holmes was already established as a long-term collaborator with architect's Warren & Mahoney. The two firms had worked together on many projects, but the CTH was their most important public building. Unfortunately, Lyall Holmes died before the opening of the CTH, but his influence was clear in the exposed concrete structure that featured extensive use of precast panels. The original construction was carried out by C. S. Luney Limited for a total cost of approximately $4M.

Like many collaborations between Warren & Mahoney and Holmes, the CTH's structure was an integral part of the architecture. There is a clear expression of form and function which required careful structural design, in an era when slide rules and drafting boards were the tools of engineers and draughtspersons. The sculptural and irregular form created many design challenges that required judgement and skill to resolve. While complex structures can be modelled precisely using modern computer analysis, those techniques were not available at the time. Engineering judgement and approximations were required to simplify the analysis.

The CTH was designed in an era that crosses the boundary between the early seismic design provisions of Chapter 8 of NZS1900:1965 (SNZ, 1965), and the effective fore-runner of the modern standards which codified ductile design, NZS4203:1976 (SNZ, 1976). Despite this, the reinforcement detailing reflects an advanced level of knowledge of ductile design that was based on seminal research being conducted at the University of Canterbury (by Professors Park and Paulay). Other aspects of the design were less positive, particularly insufficient allowances for displacement compatibility. These allowances are important as the CTH is a complex of six different buildings. Seismic joints were provided between some of the separate parts to allow building movement, but these joints were designed for earthquake-induced displacement that are significantly less than the current seismic loadings standard, NZS1170.5:2004 (SNZ, 2004).

Despite the above mentioned challenges, the original designers produced a credible design which shows an impressive clarity of thinking. Although many structural elements would not meet current standards, a review of the CTH suggests the overall building performance would have been remarkable if founded on good ground.

Fortunately, most of the original records (calculations, specification and drawings) had been retained by Holmes and were scanned prior to the earthquakes. These records have proved invaluable during the repair and strengthening project.

WHAT HAPPENED: 2010-2011 POST-EARTHQUAKE ASSESSMENT

A detailed description of the 2010-2011 earthquake sequence is not provided in this paper as the impacts on the wider built environment of Canterbury, along with lessons learnt for modern engineering practise, have been well documented elsewhere (CERC, 2012). The most significant ground shaking in Christchurch occurred from the following earthquake events:

- Darfield earthquake, 4th September 2010
- Christchurch earthquake, 22nd February 2011
- The aftershocks of 13th June 2011, and 24th December 2011.

The Darfield earthquake caused relatively minimal damage; immediate measures were taken to stabilise the Cambridge Room building and other areas of localised damage. The Christchurch earthquake was most damaging. The severity of damage was immediately evident, and access to the CTH was immediately suspended, pending further engineering evaluation and major post-disaster decision making. Liquefaction had occurred, which could be expected based on the underlying soils and being located alongside the Avon River. The liquefaction meant damage evaluations were more challenging as ground movements beneath buildings continued well after the earthquake, and subsequent aftershocks added to the total residual settlement and lateral spread.

The most significant damage included:

- Liquefaction of soils caused significant settlement and lateral spread of the upper soil layers towards the Avon. There was up to 350mm of differential settlement beneath the structure, causing parts to twist and move. In the worst case the ground floor fell 350mm from corner to corner across the **Auditorium**. The Auditorium also moved towards the river, although the extent of the lateral movement is almost impossible to quantify accurately.
- The individual buildings that make up the CTH complex moved differently, in some cases pulling apart, and in others, crashing together.
- The **Cambridge Room** was undergoing refurbishment and structural alteration at the time of the earthquakes. The building was crippled due to failure of the temporary propping that was designed for lower levels of earthquake shaking. The building was

demolished and will be rebuilt in a different structural form, albeit to maintain similar architectural and functionality requirements.

- Varying degrees of damage occurred above ground, resulting in concrete cracking, tearing apart of elements, and even dislodgement of some elements from their supports. In some cases, the extent of this damage only became evident as the repair works proceeded and the elements could be fully exposed.

Tonkin and Taylor was engaged to review the geotechnical aspects of the site. Significant volumes of liquefaction ejecta had forced its way into the building through damaged slabs and basement walls. The southern landscaped area in front of the Avon River was the most spectacularly damaged as it was uplifted and tilted out of shape as shown in Figure 2.

Figure 2: Southern landscaped area damaged. Left: facing the Auditorium, taken 2011, Right: 2013 from Wikipedia.

Holmes carried out approximately 20 site visits to evaluate the damage to the building after each significant earthquake, along with monitoring crack gauges during the demolition of the adjacent Crowne Plaza building (in the background of Figure 2). The majority of structural damage was recorded, and temporary propping installed and "no go" areas identified. Overall the complex was in relatively good condition after being forced to deform significantly to take up the new shape of the warped ground beneath the foundations.

WHAT TO DO? INVESTIGATIVE ANALYSIS & DESIGN OF STRENGTHENING CONCEPTS

Phases of concept work for the repair and strengthening started in 2011 and continued for the next two years. Various structural schemes and levels of strengthening were investigated with many stakeholders. Non-linear time history analysis (NLTHA, herein referred to as 'the analysis') was completed for each of the CTH buildings. A sample of the analysis models are illustrated in Figure 3.

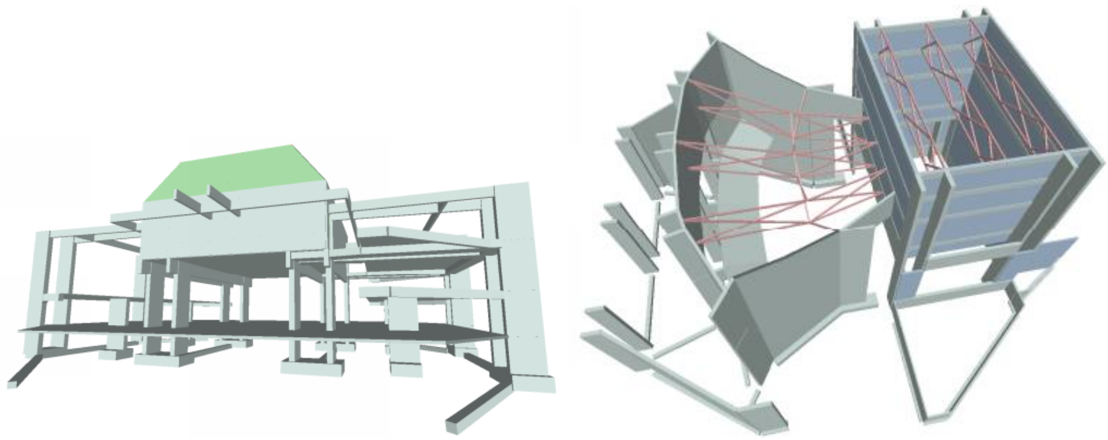

Figure 3: Computational models of two of the Christchurch Town Hall buildings used for Non-Linear Time History Analysis. Foyer/Entrance block (left) and James Hay Theatre (right).

The purpose of the analysis was to evaluate the performance of structural components in accordance with the criteria set out in ASCE41-06 (ASCE, 2006). ASCE41-06 was followed as the NZSEE guidelines (NZSEE, 2006) did not provide adequate information on overall building resilience and contained some errors.

The analysis identified deficiencies in each building to varying degrees and complexity, some of which is described further in this paper. Overall, the performance of the **Auditorium** and **Kitchen** buildings was relatively good, with targeted localised strengthening being adequate to achieve 100% New building standard (%NBS). The **Foyer** and the **Limes Room** however required significantly more work. The **James Hay Theatre** required reasonably extensive structural steelwork to the fly-tower to achieve both 100%NBS and the functionality requirements of a newly refurbished theatre.

In the **Foyer** building, the analysis reported that the strength capacity and stiffness of the original RC columns was a deficiency which needed to be addressed. Following consultation with many stake holders it was decided that rebuilding the columns using modern seismic detailing was the preferred solution, particularly because alternative options would be highly detrimental to the functionality and aesthetics of the entrance building.

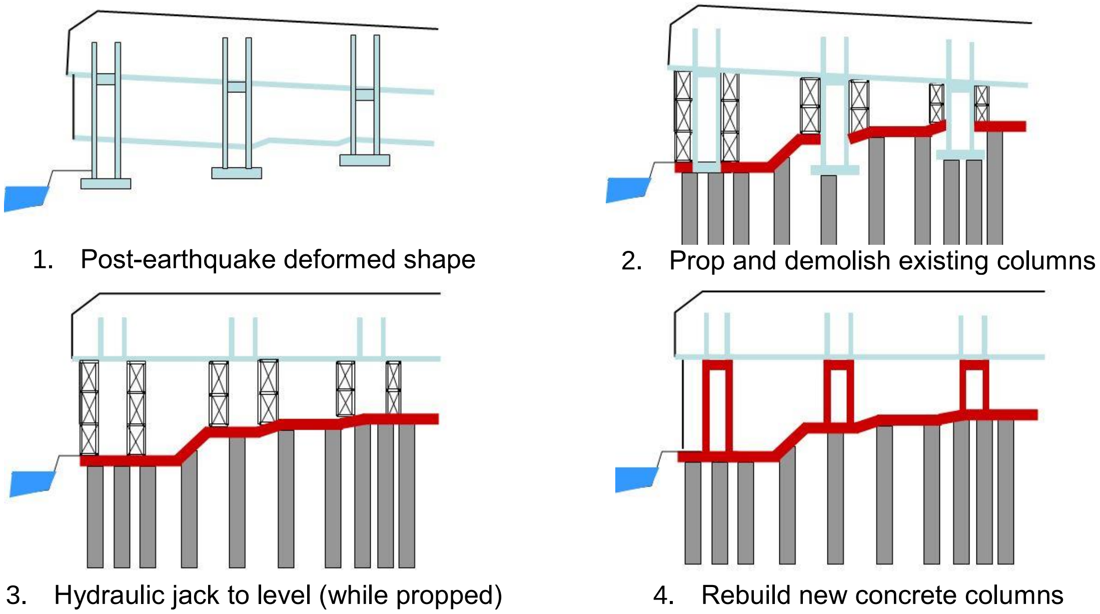

Figure 4: Limes Room building, adjacent to the Avon River - a schematic illustration of the re-levelling and temporary propping and rebuild sequence.

The **Limes Room** building experienced significant residual ground movement. The ground movement behaved as a slip circle, moving towards the Avon River. The slip circle caused the southern end to be tilted upwards, as illustrated in Figure 4 above. The decision to re-level the building was made in tandem with the rebuilding of the columns to achieve strengthening targets. Figure 4 shows the sequencing required to construct the new raft slab (shown in red) on the ground improvement, before temporarily supporting the Limes room to allow the original RC columns to be demolished. The building is re-levelled using hydraulic rams, to lift the floor in some locations, and lower it in others. The rebuilding of the new RC columns is undertaken on completion of the re-levelling. The Limes Room columns were identified as having a similar deficiency to the Foyer columns, with insufficient strength and stiffness. In this case however, the options for strengthening the Limes Room were less limited by its building function. The retrofit has adopted new Buckling Restrained Braces (BRB's) inserted between the pairs of rebuilt RC columns.

In parallel with the structural analysis and retrofit concepts for the structure, the geotechnical engineers at Tonkin and Taylor were working through foundation improvement strategies. Following review of various techniques, the two most feasible options for supporting the building at foundation level included either: a) piling coupled with new reinforced concrete (RC) ground beams; or, b) jet grouted columns with new RC raft foundations. Both of these options were conceptually schemed, with option b) being identified as preferred.

DECISION MADE: DETAILED DESIGN TO REPAIR AND STRENGTHEN

In 2013 the Christchurch City Council made the decision to progress the repair and strengthening project through to detailed design. The project team was assembled as follows:-

Structure and Civil Engineering Consultant	Holmes Consulting
Architects	Warren and Mahoney
Geotechnical Engineer	Tonkin and Taylor
Mechanical Engineering Consultant	Aurecon
Electrical Engineering Consultant	Cosgroves
Fire Engineer	Holmes Fire
Quantity Surveyor	Rider Levett Bucknall
Project Manager	Christchurch City Council

The design progressed from west to east (Auditorium to James Hay Theatre) and was initially focussed on the ground floor areas. The existing ground floor slabs were damaged and needed to be removed prior to installing the new raft foundation. Structurally, the raft foundation needed to be continuous throughout, and so levels of the new raft were worked through in close consultation with the Architect.

The raft foundation design was done using RAM concept, a finite element software package by Bentley. For the NLTHA analysis, the raft slab had been modelled using a grid of beams and gap elements at the existing column foundation pads. The force results at these gap elements were extracted from the NLTHA and applied as loads on the raft slab in RAM Concept, which was then used to design the new raft foundation. A snapshot of analysis stress results are shown in Figure 5(b). The flexural reinforcement is designed within RAM Concept, whereas for the design of reinforcement to resist punching shear was done outside of RAM, instead using Section 12 NZS3101:2006 for combined moments and shears. Wood-Armer moments are incorporated into the RAM Concept software and generally resulted in more raft slab reinforcement required.

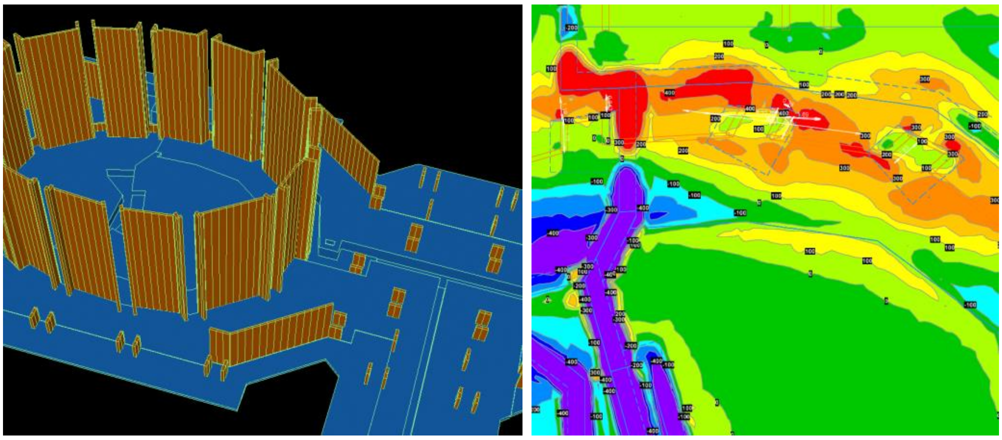

Figure 5: Ram Concept: 3D model view (Left); Stress analysis used for design of raft flexural reinforcement (Right).

The analysis (NLTHA) was progressed from the concept stages with more detail added to the computational models, including the foundation flexibility and interaction effects with the improved soil. The added foundation flexibility changed the behaviour of some of the buildings, and changed the targeted strengthening in some cases.

In the **Auditorium building**, the analysis reported shear capacity deficiencies in the concrete beams that support the promenade floor. To address this deficiency, the adopted retrofit strategy was to selectively weaken the beams by cutting some of the beam flexural reinforcement at the beam-column interface, and to wrap the potential plastic hinge zone (PPHZ) with FRP carbon fibre to for additional shear strength. The selectively weakened beams are shaded red in Figure 6 below. The reduced beam flexural strengths were updated in the model and the analysis was repeated to re-assess the structural performance.

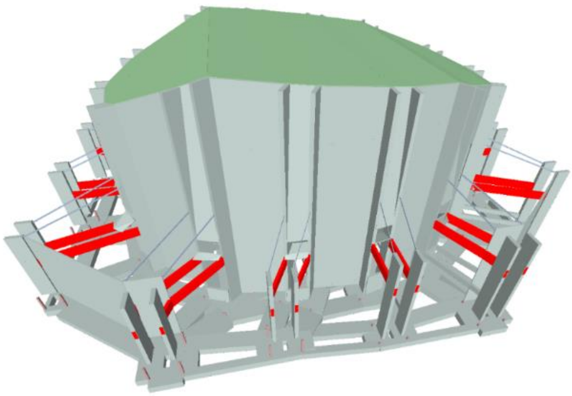

Figure 6: Selectively weakened beams in Auditorium. The promenade floors are hidden for clarity in this figure.

In the **James Hay Theatre**, the fly-tower around the stage area had inadequate out-of-plane lateral restraint of the original 190mm masonry walls. The approximate vertical span of the most critical eastern wall is 18metres and 20metres long. Due to the Heritage status of the building, all strengthening needed to be concealed on the inside the building. New vertical and horizontal steel beams (610UB and 530UBs) are fixed to the wall at regular spacing and span between new steel roof bracing of the fly-tower and to the back of house area. Figure 7 from the Revit model illustrates the extent of new structural works being carried out inside the fly-tower and on the eastern side.

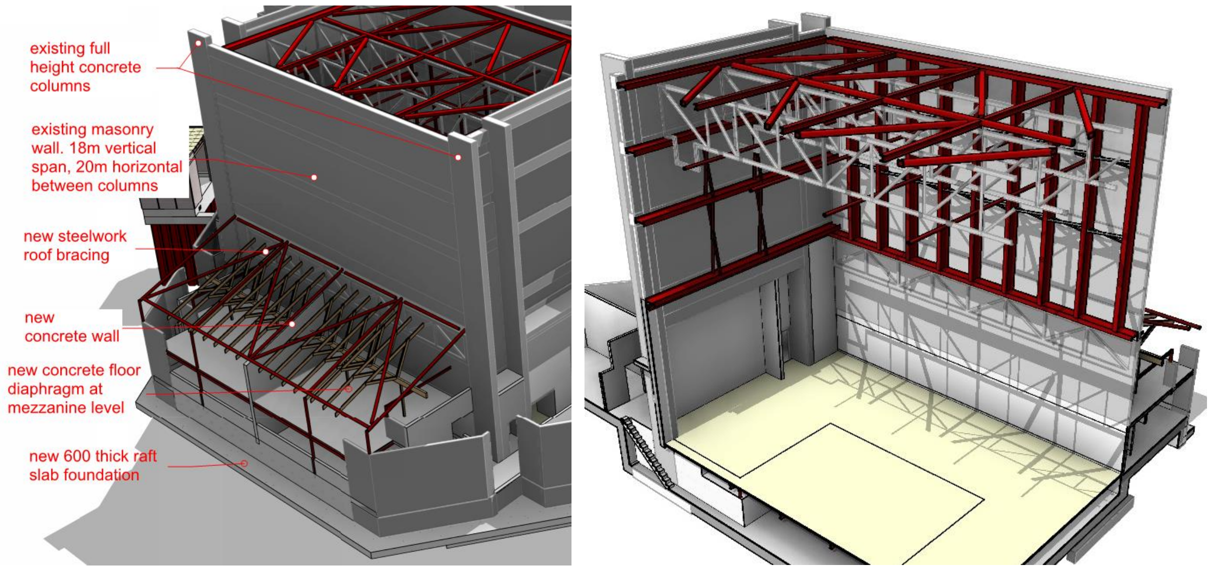

Figure 7: 3D Revit perspective views of James Hay Theatre fly-tower. Left: south-west facing the back of house; Right: North-east facing, inside the fly-tower. (Note dark grey elements show existing concrete and masonry).

The analysis of the **James Hay Theatre** also reported that the existing masonry walls in the fly tower had excessive shear strains at lower level. This is illustrated in Figure 8 showing these wall elements failing the Collapse Prevention (CP) criteria defined in ASCE 41-06. An important clarification of the CP criteria is that this is not a state of collapse, but rather a state which collapse is unlikely to occur, although the damaged structural elements has little residual strength.
This was considered a critical structural deficiency as these masonry walls provide lateral restraint to the full-height concrete columns. The shear strains in the masonry walls were reduced by the addition of new RC wall in-fills around the perimeter of the fly-tower structure, from ground to mid-height.

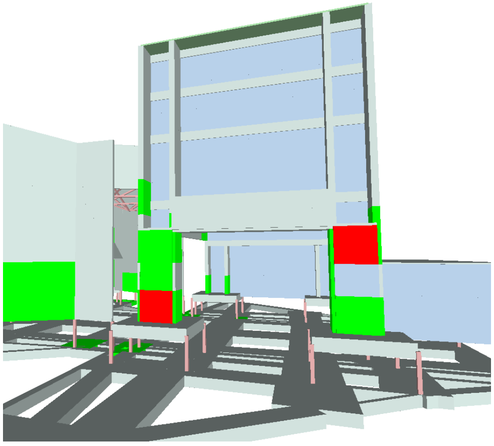

Figure 8: NLTHA output of the fly-tower elements at the Collapse Limit State (CLS).

THE CONSTRUCTION PHASE: 2015-2018

After a comprehensive tendering process, Hawkins Construction was selected to repair and strengthen the CTH in 2015. This appointment of the Contractor did not represent an end for the design team, as the complexity of the project meant that significant input would be required during construction. As successive work-fronts and operations opened up, the design team needed to be on hand to work closely with the Contractor.

The sequence of works to rebuild the new foundations was somewhat repetitive, albeit with different constraints in each location around the site. Core-drilled holes through the existing foundations were done first to allow the machine equipment to inject the jet-grout. After ground improvement was completed in a given area, the existing foundations were partially demolished to enable the construction of the much thicker new RC raft slab foundation. Figure 9 below illustrates the preparation work being done in the Auditorium to allow the new 900mm deep raft slab.

Figure 9: Inside view of Auditorium in preparation for the new raft slab foundation (photo dated May, 2016).

The stability of all buildings under gravity and lateral loads was important for sequencing the construction. Portions of the existing structure had to be carefully demolished in a piecemeal manner to allow for the construction of the new raft slab, along with new columns and walls. The temporary stability of the buildings has been tested during the construction. The most noticeable of these tests occurred following ground shaking in Christchurch from the 14th February 2016 earthquake, and the longer duration of shaking from the magnitude M_w7.8 Kaikoura earthquake on 14 November 2016.

At the time of writing this paper, the following major works had been carried out:

- **Jet-Grout ground improvement:** Across the footprint of the site, the jet-grout columns were installed within 12months. At times, the jet-grout machinery had to work in relatively tight spaces.
- **New RC raft foundation:** The new RC raft foundation is largely complete. From the quantity surveyor's measure, there are: 1069 new jet grout columns and approximately 5,500 m^3 of concrete in the new raft slab with 667 tonnes of steel reinforcement.
- **Auditorium:** the main structural works are completed and the remaining work relates to the refurbishment and Architectural fit-out.
- **Foyer:** the majority of the existing Foyer columns have been demolished with 16 of 20 new columns re-built to be both stiffer and higher strength. A temporary steel cross-braced frame supported the central conference room for several months. The temporary frame was disassembled on completion of the new columns.
- **Limes Room:** is currently supported on a temporary steel cross-braced frame structure, part way through the column rebuilding works in the last illustration of Figure 4. Following this, eight new BRB's are to be installed between the new columns. The BRB's have been delivered to site, with some of their gusset plates cast into the new RC columns and raft slab.
- **Kitchen block:** mostly refurbishment works, along with adjusting the concrete floor and stair structures which link to the re-levelled Limes Room in its new position.
- **James Hay Theatre:** As shown in Figure 10, the upper portion of the eastern wall of the fly-tower is supported by a combination of temporary and permanent structural steelwork. In the west end of the theatre, adjacent to the Foyer, the architectural fit out is progressing for the ticket booths and toilet areas.

Figure 10: James Hay Theatre back of house area. (Taken August, 2017).

CONCLUSIONS AND ACKNOWLEDGEMENTS

This paper provided a background story of the Christchurch Town Hall (CTH) which required repair and strengthening works following the 2010-2011 Canterbury Earthquakes. Extending back to the original design and construction, the CTH is a legacy of the designers and a proud example of high-quality concrete construction of its time.

The earthquakes caused permanent ground movements which forced each of the different buildings to deform differently and the existing foundations were damaged. A new RC raft foundation was built over top of the jet-grout columns which provided ground improvement. This paper provides examples of how detailed structural analysis was used to identify deficiencies and provide a targeted repair and strengthening strategy for each building.

Overall, the project has been complex due to the intensive structural analysis, the various strengthening methods adopted, and generally achieving the heritage requirement that all strengthening work is done inside the original skin of the building (aside from 8 new exposed Buckling-Restrained Braces). Much like the original CTH project, the post-earthquake repair and strengthening project has been a major collaboration between the architects and engineers, the client Christchurch City Council, and the contractor Hawkins Constriction.

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Wikipedia Commons Photo, taken 31 August 2013 by User Schwede66 https://commons.wikimedia.org/wiki/File:Christchurch_Town_Hall_486.JPG