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Seismic retrofit of historic timber structures: Uncertainties and adaption on site

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ABSTRACT

Existing timber structures, containing more hand-adapted and degradable components than other materials, provide challenges in ensuring your design intent is followed through on site. Often these buildings are flexible with dispersed seismic resistance, and so it is essential that any one component is not made significantly stiffer or stronger than the remainder. This paper uses two recent church retrofits: Old St Paul's and St John’s in the City in Wellington, to give examples of the types of unforeseen issues that can arise. Examples are given of how degradation assessment and repair was addressed, as well as existing damage, unforeseen connection eccentricity, and how modern screw technologies were used to solve difficult issues. The authors recommend appropriate provision of time and expertise required over and above ‘typical’ heritage retrofits.

1 INTRODUCTION

The authors have prepared this paper to share the methodologies that they have successfully used in the seismic retrofit of two historic timber structures. It is hoped that these positive examples can be used as a high-level guide for other teams embarking on similar retrofit projects.

This paper presents a summary of the methodology employed. Two case studies – Old St Paul’s (Wellington) and St John’s in the City (Wellington) – are presented with the experiences during the construction phase.

2 METHODOLOGY

2.1 Briefing and Research

The engineer needs to brief the client and team early on the appropriate approach to design, contingencies, procurement, and construction monitoring. Acknowledge that it is a journey of discovery and the design will evolve as the existing building fabric is untangled. Unfortunately, there will be no such thing as a fixed price contract. Under client pressure the engineer may need to assert the value of their experience: experienced engineers know there will be unforeseen difficulties, which is not a slight on their foresight or design abilities.

The engineer needs to interrogate the existing structure as much as practicable but accept that some things will need to be assumed/unknown and that they will need to 'design around the unknowns' as much as possible. Physical investigations are useful but are unlikely to identify all situations. Step through the history of the building and get assistance from a conservation architect to identify locations of weakness in the weathertightness fabric.

2.2 Assessment and Design

Good heritage timber engineering needs to develop a clear concept for how the building 'works' seismically: where is the strength vs. what needs to be kept flexible. Design out or design around unknowns, and with the contribution of many semi-structural elements to load paths, accept that simplicity is key and accurate analysis is a fallacy. Bracing systems may not be obvious and require some originality in thinking.

Develop robust typical details with clear design intent and retrofit to create non-brittle failure modes. A few well-placed screws that arrest perpendicular-to-grain splitting can provide significant robustness at little cost.

The team should consider Early Contractor Involvement (ECI) for: prototyping typical details; investigation of as built to confirm design assumptions.

2.3 Construction

The relationship with the contractor needs to be a partnership – regular site visits to collaboratively look ahead and identify investigative work are essential because they give engineer/builder time to amend their approach without creating delay. A builder that can assist by sketching out the problem is of significant value. This allows problem solving to be stimulating and the process enjoyable rather than contractual. The way these buildings are hand-built means similar details are all slightly different. It is best to have the contractor on the team's side against the building, not the building's side against the team. Above all, bring the owner/client along on the journey.

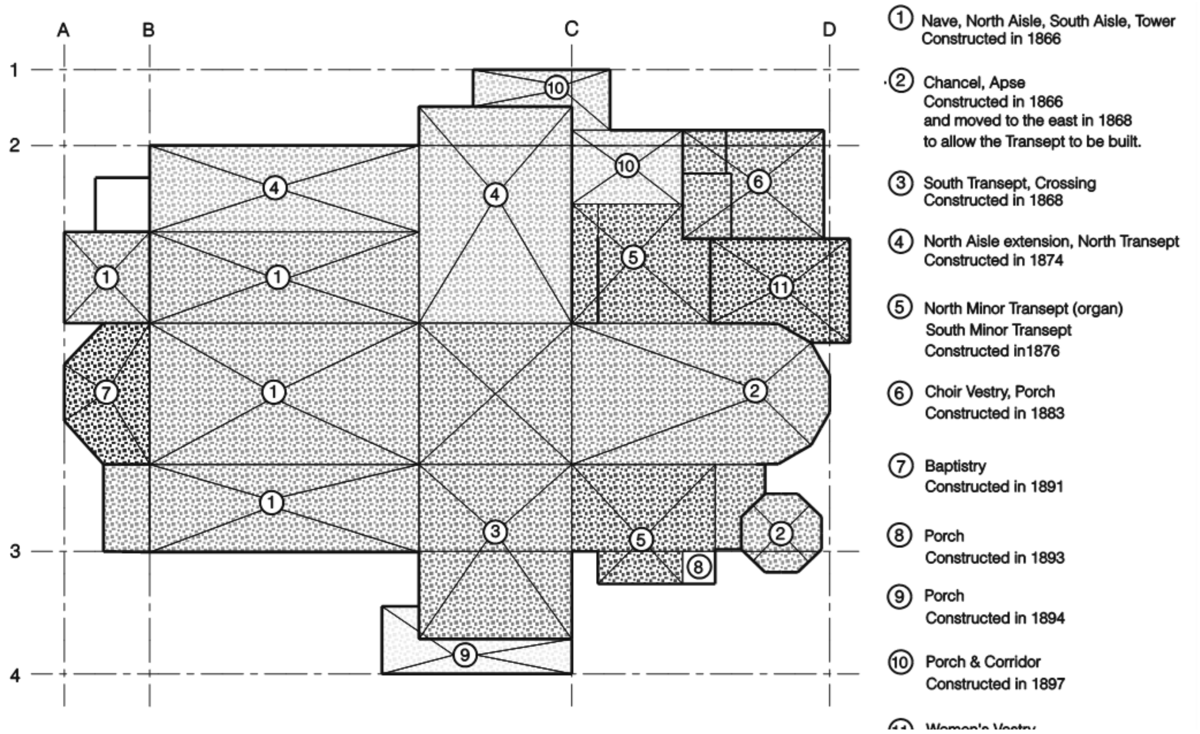


Figure 1: Key plan showing evolution of Old St Paul's

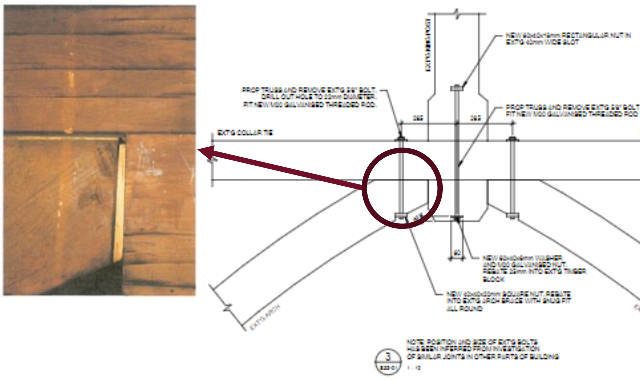
3 CASE STUDY: OLD ST PAUL’S

3.1 Building Details

Old St Paul’s Cathedral is in Thorndon, Wellington and was built in 1866. The building has undergone several alterations and additions throughout its life (Fig. 1). The age of the fabric that makes up the complex structure of Old St Paul’s dates from 1866 through to the present day. A remarkable amount of original fabric, and fabric dating from the time of the major additions, remains in the building, giving it a very high level of authenticity (Cochran et al. 2014).

3.2 Briefing and Research

Dunning Thornton became involved with the building following the 2016 Kaikoura earthquake. Inspections and assessment after the earthquake (Clark 2016) identified that the external walls of the aisles were leaning outwards, and gaps had formed in some connections (Fig 2). The natural period of the nave and aisle structure was reported to be very long relative to other single storey structures and was within the range of periods that experienced high displacements during the Kaikoura earthquake. This theoretical flexibility matched anecdotal data of “the bells ringing themselves on windy days” and the transepts being added shortly after the original construction to mitigate swaying of the building in a northerly wind.



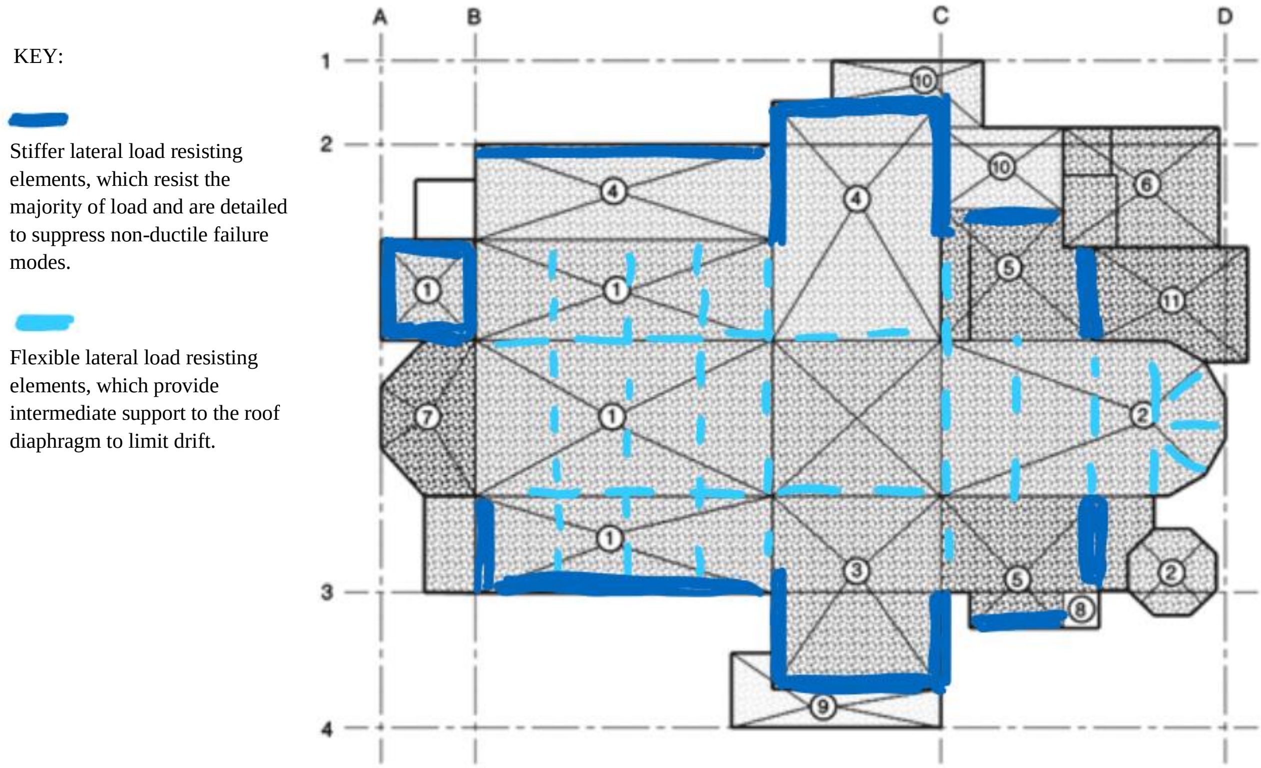
An important part of the project was to help the client appreciate that the need to harmonise with the authenticity of the building’s 19th century detailing meant that many aspects of the project were going to be bespoke and therefore difficult to estimate and programme in the conventional manner. Fortunately, another church retrofit project was under construction at the time and the client was able visit the site and view the specialist skills that need to be applied.

Figure 2: Opening of joint

3.3 Assessment and Design

A major part of the assessment and design process was investigation of the existing structure. Old St Paul’s has been subject to many additions and alterations throughout its life, including strengthening by the Ministry of Works in the second half of the 20th century. Detailed measurements of some key connections had been completed by others and the style of these connections was assumed to apply throughout the building. Within the existing connections, the load transfer mechanisms were primarily timber-to-timber bearing with nominal bolts. Assessment of the existing connections generally found that they had high strength in compression and shear but little tension strength, which is consistent with a structure that was only detailed for gravity loads.

As noted in the previous section, and described in Figure 3, the building is generally very flexible in the central areas (the nave, aisles, crossing, and apse). The walls in the north and south transepts and bell tower had historically been retrofit with diagonal timber bracing to reduce sway in the wind. This meant there were parts of the building with higher stiffness, excepting that the connections of the diagonal bracing typically had negligible tension capacity.


KEY:

▬ Stiffer lateral load resisting elements, which resist the majority of load and are detailed to suppress non-ductile failure modes.

▬ Flexible lateral load resisting elements, which provide intermediate support to the roof diaphragm to limit drift.

Figure 3: Schematic of lateral load resistance mechanism

The seismic retrofit approach adopted a design intent that complemented the existing building characteristics, and included the following key works:

- Installing steel bars parallel to existing timber braces to add tension capacity to the brace connections in the transept walls and bell tower.
- Increasing the available lateral strength of the transept walls and bell towers by adding mass to the foundations to increase the overturning resistance, but still maintaining a strength hierarchy where overturning/rocking occurs before failure of non-ductile timbers/connections.
- Adding tension capacity to connections in the nave, apse and aisles to improve their lateral strength, while maintaining flexibility/resilience through detailing to a hierarchy that favoured local crushing of timber and yielding of dowel-type fixings.
- Adding a small number of horizontal tie rods to mitigate plastic dilation of timber arches.
- Creation/verification of secondary gravity load paths in the crossing to make it resilient to differential displacements from surrounding structural elements.
- Adding subfloor bracing between existing shallow piles.

It would have required significant investigation of all existing connections to create a full set of details that could be used for a traditional fixed-price tender approach to procurement. The physical works associated with such investigation would increase the risk of damage to heritage fabric and disrupt the venue. The design was instead documented using a suite of typical details for each area of the building and an early contractor involvement (ECI) process was used to build mock-up existing connections. By applying the typical details to the mock-ups, it was possible to refine costs, quality control procedures and train staff on new techniques. This could then be extrapolated to develop a budget and programme with an appropriate contingency for atypical connections and the unforeseeable, e.g., repairs to rotted material.

3.4 Construction

One of the genuine pleasures of the construction phase was the trusting relationship that developed between client, engineer, and contractor. This allowed challenges to be discussed frankly and solutions could be found through sharing ideas of capacities and interventions – true collaboration.

Weekly walk-throughs on site with the contractor provided a crucial look-ahead to identify where non-typical details might be required and to plan early access to allow the joint to be sighted and amended details to be developed. As construction progressed, the suite of typical details was annotated with 'rules' that the contractor could apply when they came across different variations of the joint.

Figure 4: Clockwise from top left: new steel bars in transept wall; new transverse tie rods in aisle; new longitudinal tie rods in north aisle extension; new bearing plate in centre of crossing; repaired column in aisle.

Plywood templates, mocked up joints and drilling jigs were used extensively by the carpenters/joiners to finalise installation angles of dowels and self-drilling screws. This allowed Dunning Thornton to effectively pre-inspect the work and led to negligible construction defects. This sure and steady approach was especially valuable when discovering unexpected existing conditions, such as:

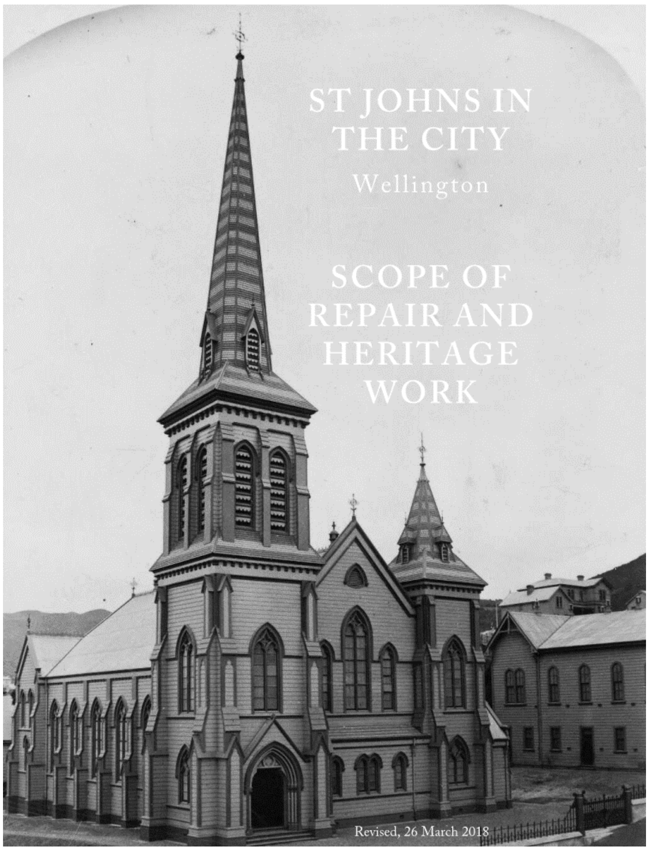
- Two ruptured columns in the nave.
- A transept column that had been historically hollowed out to accommodate electrical cabling.
- Historic dilation and splitting of timber arches in the crossing.

Developing a solution for these issues took significant time and consideration of multiple alternatives until a solution was found that was buildable, architecturally authentic and structurally compliant. The contractor appreciated the subfloor bracing scope during this time because it used traditional detailing and provided a lower risk scope for pricing and a fall-back work front. This highlights the importance of maintaining a balanced design that doesn't overplay innovative/complex detailing.

3.5 Acknowledgements

The authors wish to acknowledge: Heritage New Zealand Pouhere Taonga (Client); Russell Murray (Conservation Architect), and; Maycroft Construction Ltd (Builder), particularly Tim Hefford who sadly passed away a few months after completion of the project.

4 CASE STUDY: ST JOHN'S IN THE CITY



ST JOHNS IN THE CITY
Wellington

SCOPE OF REPAIR AND HERITAGE WORK

Revised, 26 March 2018

Figure 5: Photograph of the church circa late 1880's extracted from heritage Architect's documentation, courtesy Alexander Turnbull Library PA Col 8215.

4.1 Building Details

The Category 1 Historic Place dates from 1885 and was designed by Thomas Turnbull. Although fabricated completely from timber (except for a few minor subfloor walls in the basement under the altar), it has a traditional form with buttresses along each side, to the corners, and to the towers (Fig. 5). The primary framing uses large native timbers of 150-300mm principle dimensions, to form roof trusses, vertical framing to the towers, all buttressing, and beams within the mezzanine and choir stalls floors. Between these timbers the walls are infilled with large studs, 25-50mm diagonal bracing let into the studs, inner match lining, and outer sarking overlaid by weatherboards. Metalwork is limited to wrought iron tie rods, small cast iron columns supporting the mezzanine, and plate straps at the truss crossovers. Connections of the large timbers generally rely on notching and housing, pinned in place with bolts. The remainder of fixings are nails.

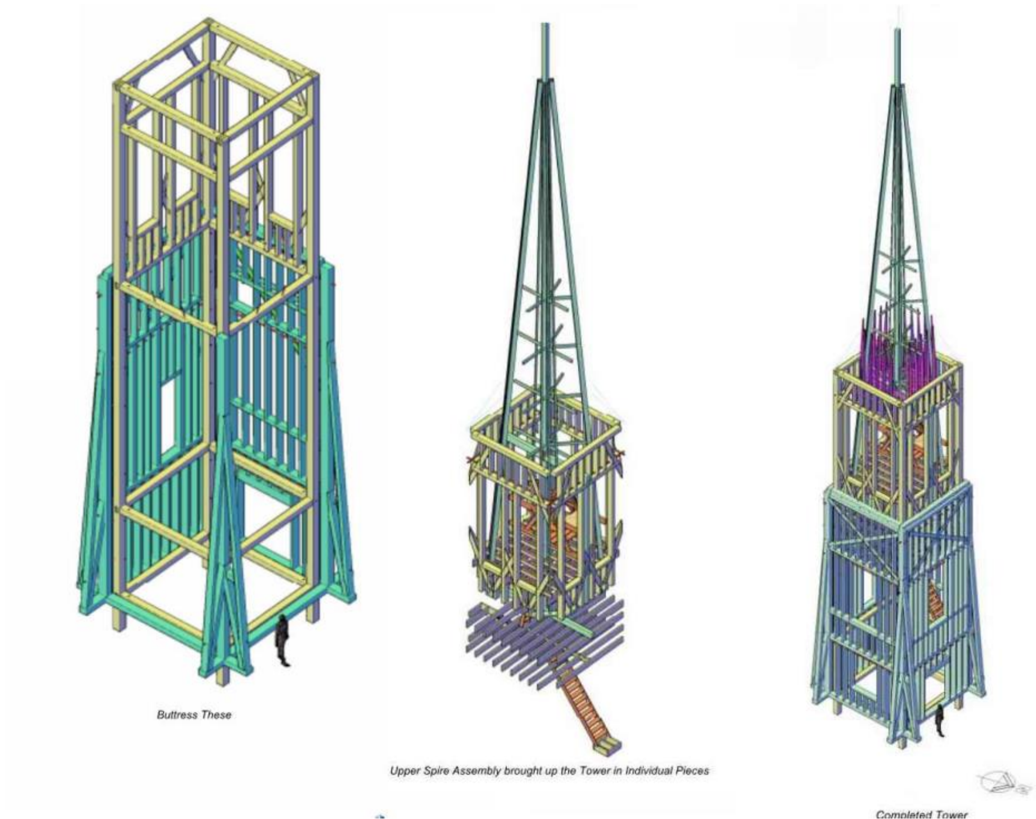


Figure 6: Drafting assumed construction sequence to understand layers of framing in the towers.

4.2 Briefing and Research

Following Wellington City Council's seismic assessment programme in the late 2000's, Dunning Thornton carried out a Detailed Seismic Assessment in 2012 using the (brief) timber guidance in the 2006 guidelines. Our work was based on some detailed plans prepared by Chris Cochran heritage architect, plus non-intrusive measure-up and investigations in the bell towers, roof space, and subfloor. Investigative and deductive work by Senior Draftsman Martin Williams made sense of what appeared to be double-frames in the towers by simulating the way it could have been built and buttressed (Fig. 6) in stages, given the equipment available in the 1880's.

For both shear walls, and more so the buttresses, capacity was limited by overturning (hold-down) capacity. The perimeter of the building was re-piled in the 1980/90's using only slightly larger and deeper domestic piles, with scant regard for tension or lateral demands.

Once a strengthening scheme was devised, one buttress was investigated to confirm connections of the raking member into the vertical member, plus possible degradation at the steps in the external cladding. Unfortunately, as it turned out, the buttress investigated was in particularly good condition and not a representative sample.

4.3 Assessment and Design

The building's lateral load capacity comes from a combination of the buttressing elements, and the multiple layers of sarking acting as shear panels. The time between the initial assessment and the detailed design allowed research into historic timber diaphragms and the updated C9 chapter (MBIE, 2017) to assist with generally greater capacities and an ability to benchmark higher damping or structural performance factor (S_p).

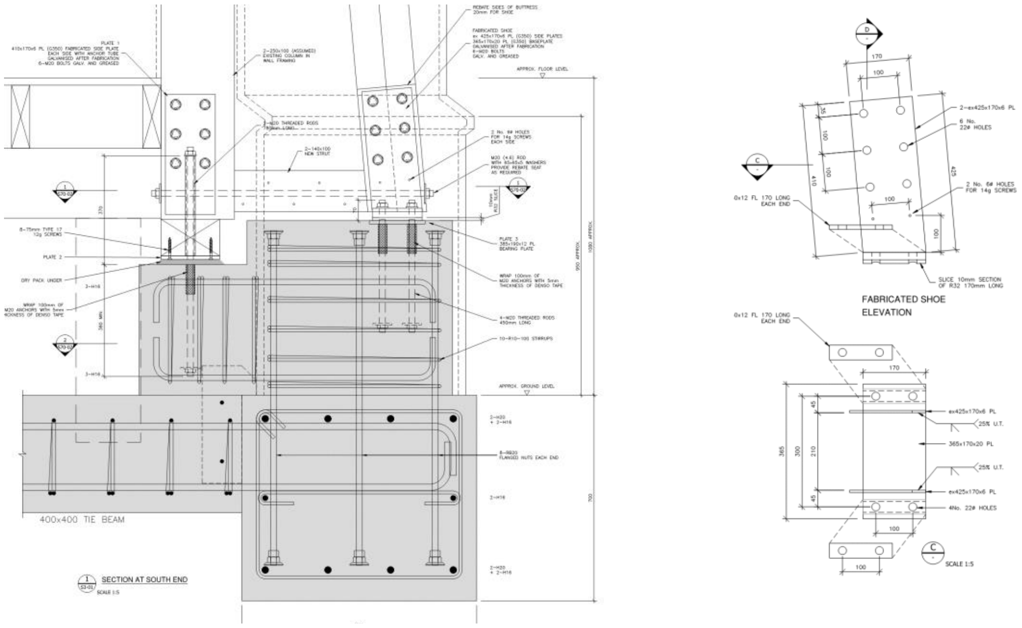


Figure 7: Ductile connection between brace and new foundation. The baseplate to the raking member can yield in two-point bending, and the hold down bolt positions are stiffened with half rounds to allow for this movement.

The philosophy was to retain the flexibility of the sarked elements and anchor their chords. This involved thinking about the interaction between studs, sarking and weatherboards which provided adequate longitudinal bracing. In highly stressed areas of the towers these were augmented by additional plywood elements.

For the buttresses, connections were strengthened, and the bases anchored to new foundations (Fig. 7). As gravity loads were typically supported by the inner vertical elements, the outer raking members were connected to new foundations with a ductile element.

L.T. McGuinness provided ECI input with investigations and pricing, including deferred maintenance related to re-painting and resolution of some previous leaks.

4.4 Construction

Construction was commenced late 2018 following a long fundraising period and subsequent building consent in early 2018. Significant engineering input was required to deal with arising degradation (including borer) and variation in alignments and connections throughout, lessons from which are noted below.

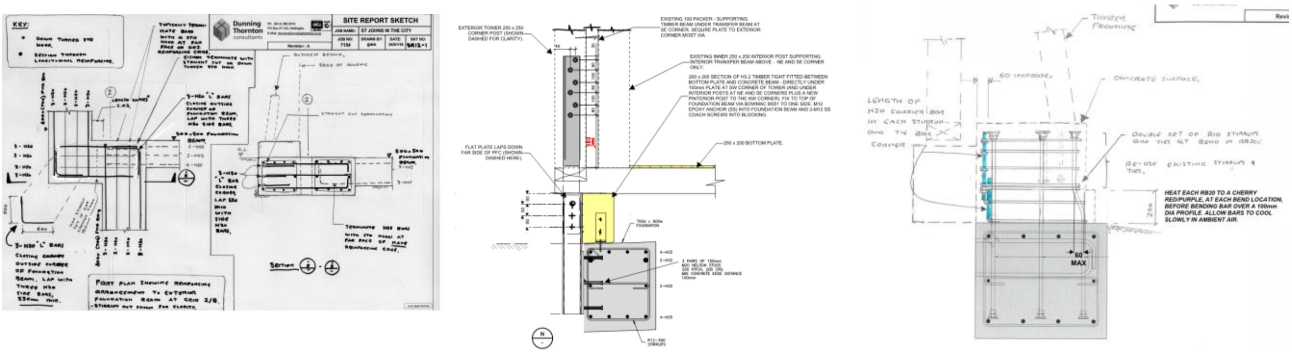


Figure 8: Examples of site remedial details increasing torsion demands on foundations.

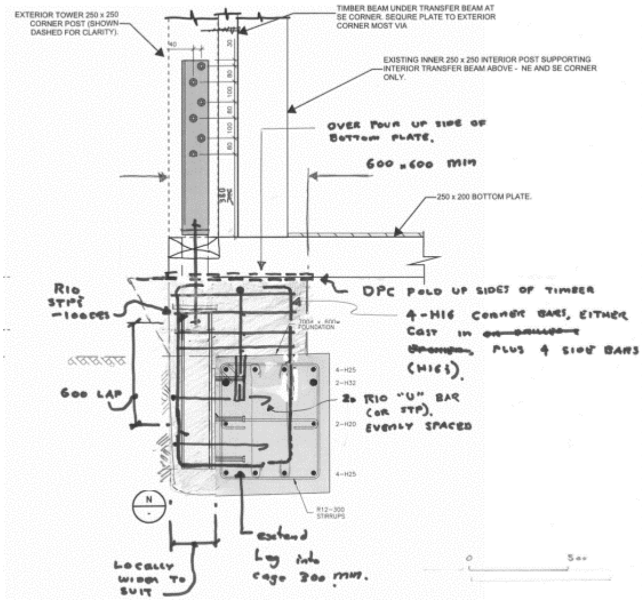


Figure 9: Example foundation rot remedial details

4.4.1 Foundations

To achieve hold-down to piles spaced off the existing buttresses, new foundations beams were designed to work in torsion (Fig. 8). The high torsion capacity provided became invaluable to resolve many different eccentricities for the arising positions of supporting posts and tension hold-down bolts. Corbels off the main beams could be provided to resolve difficulties in access/fit-up of connection brackets. Ensuring all foundations have torsional capacity and torsion-resolving return elements is recommended.

4.4.2 Foundation rot

Landscaping around the North end/entrances had reduced the subfloor ventilation. Significant rot was present in both stud framing and in the larger baulks. Timbers were cut out and replaced with LVL to match strength and stiffness: deft detailing was required to maintain load paths (Fig. 9).

4.4.3 Borer

Borer was found around the gutters and internal corner details, especially towards the south wall. These were current, or more often previous, leaks where moisture content had increased sufficiently to allow borer attack (Fig. 10).

These were typically cut out and replaced where degradation was bad. Where borer had been previously treated or leaks had been fixed allowing the timbers natural dry resilience to return, core samples were taken from the wood to measure loss of density. This relatively cost-effective technique allowed the contractor to get a “feel” for assessing degradation and what areas needed to be brought to the engineer’s attention.

4.4.4 Sheathing edges

Although the sheathing with alternating angles of inner, outer sarking and weatherboards was robust, often discontinuities existed at posts, floor levels and architectural features. Many inventive back-blocking details were required.

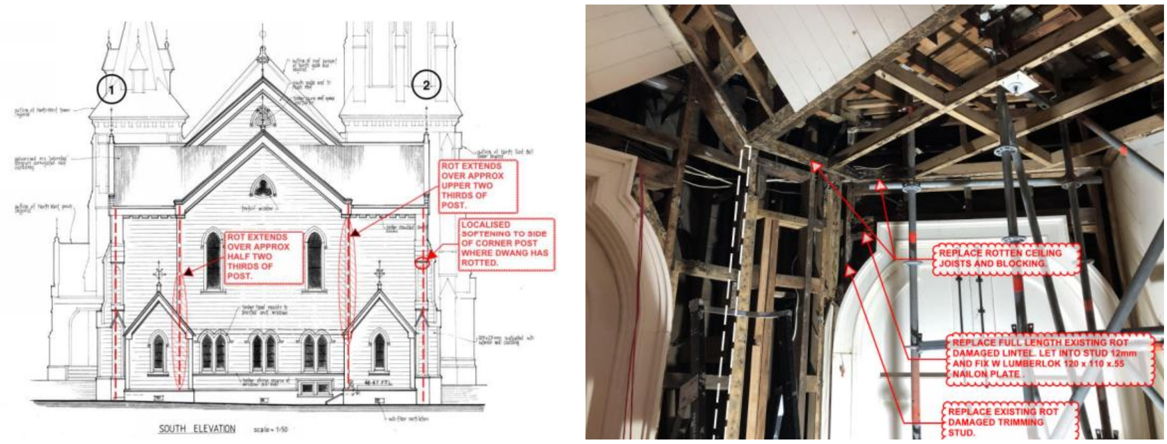


Figure 10: Example investigations and repairs

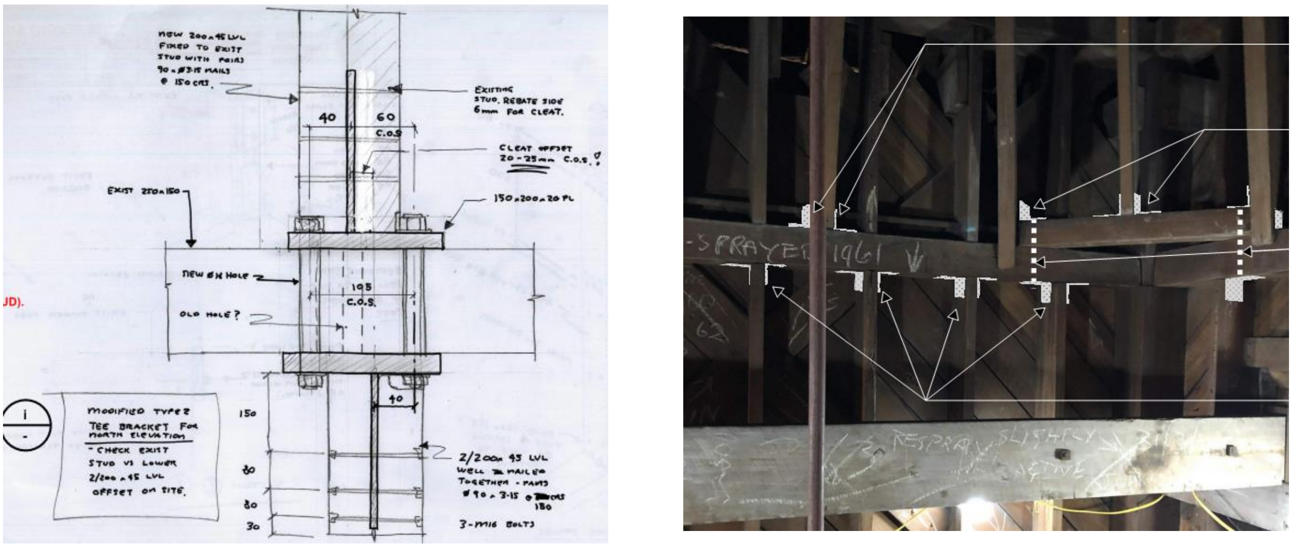


Figure 11: Example hold down alignment details.

4.4.5 Hold-down alignments

The original carpenters were careful to align gravity load-paths for downward loads. However, load paths taking hold-down tensions, especially around windows and doors, were mixed. Again, many inventive details were required for solving these (Fig. 11), as well as a critical eye on site to spot where those discontinuities could exist where still covered.

4.5 Acknowledgements

St John's in the City (Client); Beca (Quantity Surveyor and strategic advisor to client); LT McGuinness (Builder), and; Russell Murray (Conservation Architect).

5 CONCLUSIONS

From our collective experience on these case studies, the authors believe the following are key points to carry forward to future projects:

- Brief the client early on the appropriate approach to design, contingencies, procurement and construction monitoring.
- Learn the building's history and establish clarity of thought regarding the seismic response.
- Design robust details that are adaptive and suppress brittle failure modes.
- Develop trusting relationship with contractor and client.
- Expect the unexpected!

6 REFERENCES

Cochran C., Murray R. and Kelly M. 2014. Old St Paul's 1866: Conservation Plan. *Report Prepared for Heritage New Zealand Pouhere Taonga*.

Clark W. 2016. Old St Paul's: Structural Assessment and Proposal for Retrofit. *Report Prepared for Heritage New Zealand Pouhere Taonga*.

Ministry of Business, Innovation and Employment (MBIE) 2017. The Seismic Assessment of Existing Buildings: Technical Guidelines for Engineering Assessments

Professional photography of Old St Paul's courtesy Paul McCredie