NEW ZEALAND SOCIETY FOR EARTHQUAKE ENGINEERING
2019 Pacific Conference on Earthquake Engineering
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4 – 6 April | SkyCity, Auckland | New Zealand

Seismic strengthening and uplift of the 1904 Wellington Town Hall

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ABSTRACT

The Wellington Town Hall is a large unreinforced masonry building constructed circa 1904 in Wellington, New Zealand. The building features a large auditorium and forms part of the Wellington City municipal complex. Heritage New Zealand has given the building a Category I rating, the highest possible rating in New Zealand, recognising the building's outstanding historical and cultural significance. The Town Hall predates modern seismic design and has been assessed as vulnerable to even moderate shaking.

Wellington City Council has engaged a team to strengthen and uplift the Town Hall as part of a greater Civic Music Hub initiative. The Town Hall strengthening design is intended to maintain the historic fabric of the building and the outstanding acoustics of the auditorium, while simultaneously preserving the building for another 100 years. This is being accomplished through a series of engineering interventions, including base isolating the building on lead-rubber bearings, re-founding the building on 400+ new piles, and adding new concrete overlay walls. In addition to strengthening efforts, other interventions for uplift purposes were also included in the project scope. These included constructing a new glass atrium, strengthening floors to allow future soundproof "floating" rooms to be built by tenants, and building a watertight basement to accommodate expensive recording equipment.

The paper will describe the various interventions, both strengthening and uplift, from the perspective of using seismic engineering as a way to promote resilience in our historic and urban structures.

1 OVERVIEW

The Wellington Town Hall is a large unreinforced masonry building constructed circa 1904 in Wellington, New Zealand. Figure 1 shows the northern (Civic Square) façade of building. The building features a large auditorium as well as the offices of the Mayor and a Debating Chamber for the City Council, and forms part of the Wellington City municipal complex. Heritage New Zealand has given the building a Category I rating, the highest possible rating in New Zealand, recognising the building's outstanding historical and cultural significance. The main auditorium has been described as having world-class acoustics and was the home of the New Zealand Symphony Orchestra (NZSO) until the Town Hall was closed in 2013. In addition, the Town Hall has been used to record several soundtracks for major films as part of Wellington's burgeoning film industry. Figure 2 shows the main auditorium before the Town Hall was closed.

The Town Hall is located on Civic Square in central Wellington, on reclaimed land and less than 2 km from the Wellington Fault. Figure 3 is a map of the Town Hall's location. In addition to the proximity of the Wellington Fault, which is capable of producing earthquakes up to M8.2, Wellington is located near the Hikurangi Subduction Zone off the east coast of the North Island of New Zealand. This subduction zone is believed to be capable of producing megathrust earthquakes greater than M9. The Town Hall predates modern seismic design and has been assessed as vulnerable to even moderate shaking.

1.1 History of the Town Hall

The Town Hall was originally constructed circa 1904. While no structural or detailed architectural plans are available, watercolour renderings produced at the time show general floor plans, elevations, and building cross-sections. Figure 4 shows the eastern façade of the building, which was once the primary entrance. A large clock tower dominated this façade, as well as a prominent portico entrance and intricate parapet ornamentation.

However, after the 1931 Napier earthquake, which destroyed significant areas of the cities of Napier and Hastings, New Zealanders realised the seismic threat posed by unreinforced masonry (URM), and new measures were adopted prohibiting the use of URM in new buildings and addressing existing URM buildings. As a result, the Town Hall's clock tower, high parapets, and other ornamentation were dismantled, although the URM walls of the Town Hall were not modified at this time.

Figure 1: Northern Façade as it currently stands

Figure 2: Wellington Town Hall Auditorium (courtesy Wellington City Council)

In 1942, two large earthquakes struck the nearby Wairarapa Region, damaging the Town Hall. Repairs were undertaken to cracks in the URM walls, buttressing was added to support the western wall of the auditorium (which heretofore spanned from ground to roof level), and recessed vertical concrete banding was introduced in all of the auditorium and exterior walls. The remaining parapets were, in some places, replaced with significantly shorter reinforced concrete parapets which were doweled into the top of the URM walls.

In the late 1940s and early 1950s, a neighbouring building, the Municipal Office Building (MOB), was built to house various city departments. As part of this construction, a three-storey annex to the MOB was appended to the southwest corner of the Town Hall and made to look like a symmetrical portion of the MOB, although structurally it belonged to the Town Hall. The floor levels of this annex did not correspond to the existing floor levels of Town Hall. A 4 inch (100 mm) seismic gap was left between the MOB Annex and the rest of the MOB.

The most comprehensive intervention to date came in the early 1990s. The project entailed seismic strengthening and significant alterations to the structure, such as the demolition of a double-storey high recital hall and replacement with office space, construction of a small theatre in the southeast corner, creation of a glass-enclosed West Hall between the Town Hall and the MOB, and addition of a mechanical penthouse.

Figure 5 shows a schematic layout of the Town Hall.

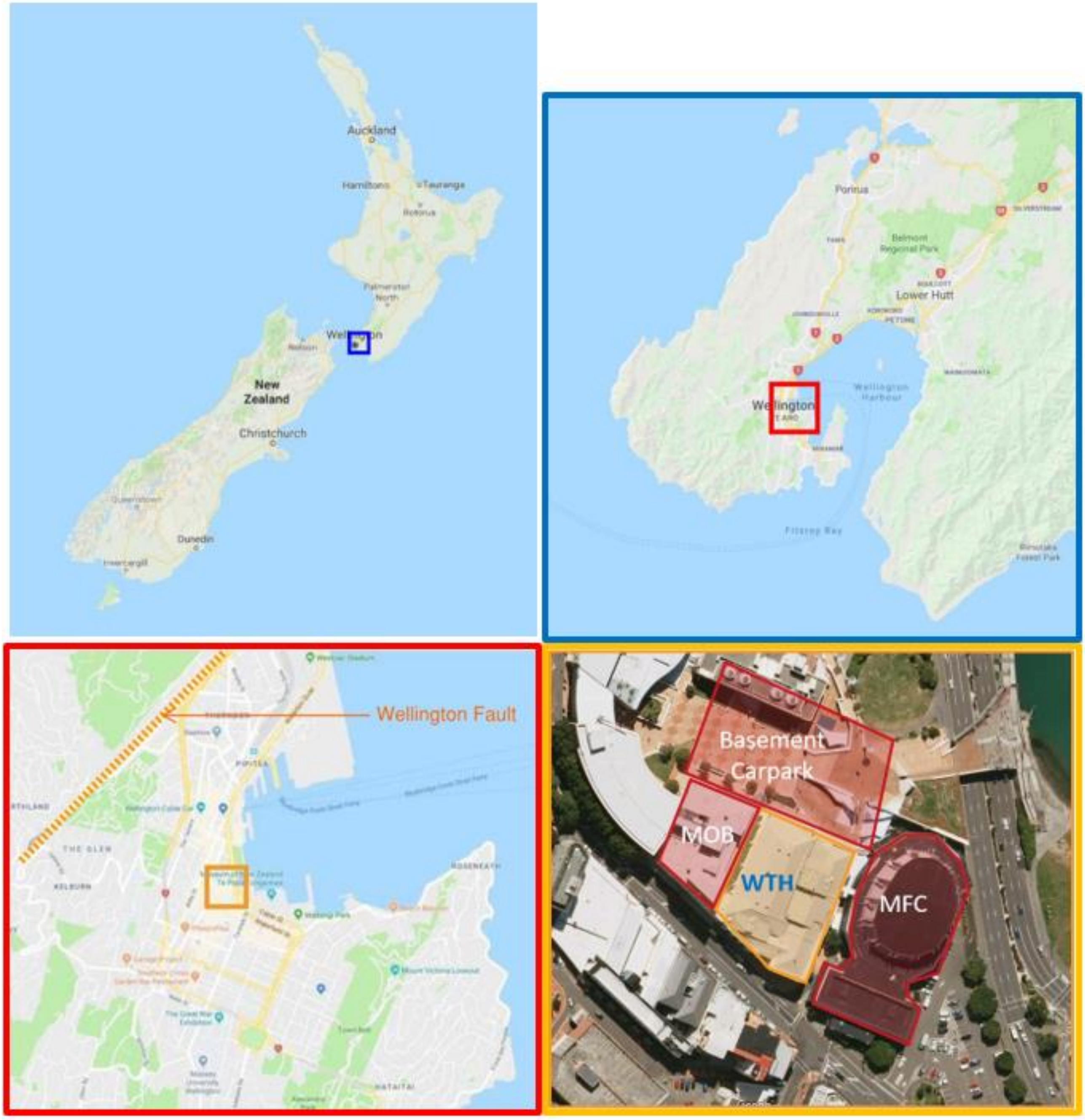

Figure 3: Location of Wellington Town Hall (WTH), adjacent to the Municipal Office Building (MOB), Civic Square Carpark, and the Michael Fowler Centre (MFC)

1.2 Case for intervention

Detailed seismic assessments carried out between 2009 and 2013 determined that the Town Hall was legally considered "earthquake prone," meaning that it had less than one third of the capacity of a structure built to new building standards (as they stood at the time of assessment). This was primarily due to the unreinforced pile foundations and brittle URM walls. Wellington City Council (WCC) closed the Town Hall in 2013 and began investigating options to retrofit the building. Councillors voted overwhelmingly in favour of investing in the project in order to preserve the heritage building and superb acoustics of the auditorium.

The project went through a full design cycle all the way to building consent in 2013 but stalled at that point. In late 2016, a new vision of the Town Hall as a keystone of a new Civic Music Hub was proposed. With buy-in from the New Zealand Symphony Orchestra (NZSO) and Victoria University of Wellington's New Zealand School of Music (NZSM) as major tenants, a revamped version of the project restarted. This version of the project had three tiers:

- base build (seismic strengthening to bring the building to 100% of new building standards),
- uplift (work required to facilitate the creation of the new Civic Music Hub), and
- tenant fit-out (work to meet the performance requirements of the individual tenants).

Currently, the base build and uplift design are complete. Construction of this portion of the work is scheduled to begin in April 2019. The design of the tenant fit-out works is partially complete and will continue during the base build construction period.

2 METHODS OF INTERVENTION

2.1 Base build

2.1.1 Foundations

The Town Hall is founded on reclamation fill over beach deposits over alluvium. Bedrock is believed to be at least 45 metres below grade and is not realistically reachable. The reclamation fill and beach deposits are particularly susceptible to liquefaction, although the upper alluvium also has liquefiable lenses. The lower alluvium is considered competent. The existing foundation system is a series of unreinforced concrete piles (founded at varying depths) and a grillage of foundation beams. The existing piles date back to the original 1904 construction and are considered extremely brittle. During the 1990's work, local disturbances to the soil resulted in the shearing of one of these piles at the underside of the foundation beams, necessitating emergency remedial work to stabilise the structure, highlighting the vulnerability of the foundation system to even modest movement.

Figure 4: Original northern and eastern facades with clock tower and parapets

Thus, one of the primary interventions to strengthen the Town Hall is completely refounding the building, vertically and laterally. This is being achieved through the introduction of approximately 450 screw piles, which are to be installed into the lower alluvium. The screw piles are approximately 300 mm diameter grout-filled steel tubes with a steel helix welded to the base, allowing them to be screwed into the ground with minimal ground disturbance, protecting the vulnerable existing foundations. Due to the head-height constraints of working within an existing building, the piles will be installed in sections and spliced in the field. The piles support a heavily reinforced raft slab foundation, typically 850 mm thick.

2.1.2 Base isolation

The other major intervention is the introduction of a base isolation system. Base isolation allows the building to experience far reduced accelerations in a seismic event, significantly decreasing the demand on the brittle superstructure. Without base isolation, any seismic strengthening intervention would have been so intrusive as to destroy any remaining heritage aspects of the building, rendering the project unworkable. By limiting the forces transmitted to the superstructure, the additional strengthening is generally contained to existing elements, rather than requiring the introduction of new lines of vertical resistance or diaphragms.

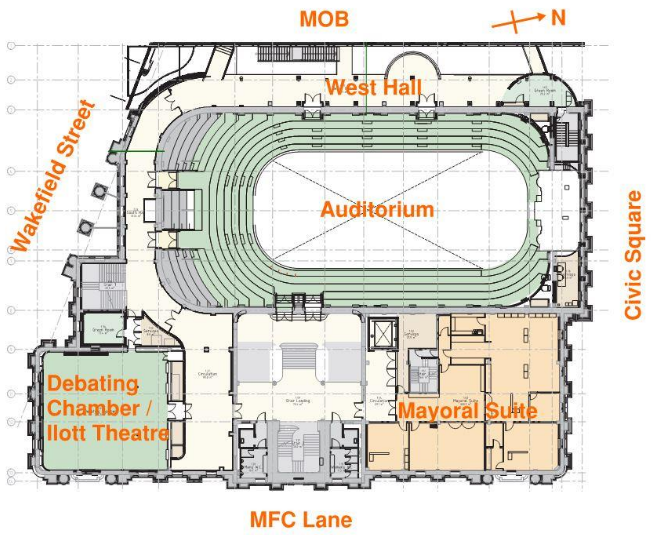

Figure 5: Schematic layout of the Town Hall

The base isolation system consists of approximately 150 lead-rubber bearings (LRBs) distributed throughout the building, as well as 17 slider bearings at locations where it is impractical to place LRBs (such as the tops of cantilevered columns supporting auditorium floor beams). Figure 6 shows the distribution of the LRBs throughout the building. The LRBs are approximately 750 mm diameter and 400 mm high, and are performance-specified to meet assumed damping and displacement properties. The isolation system was modelled as the base conditions for a nonlinear time-history analysis model which informed the design of the bearings as well as the design of elements of the superstructure such as the overlay walls and diaphragm strengthening ties. The analysis model was subjected to a suite of three earthquake records, developed especially for the Wellington region to capture hazard from both the nearfield Wellington Fault as well as the Hikurangi Subduction Zone. Further information on the non-linear time history analysis of the Wellington Town Hall can be found in the paper "Performance-Based Design and Assessment of the Wellington Town Hall" (Oliver, 2018). The records were scaled per the New Zealand Loadings Standard and resulted in a peak ground acceleration of 0.65g at the Ultimate Limit State.

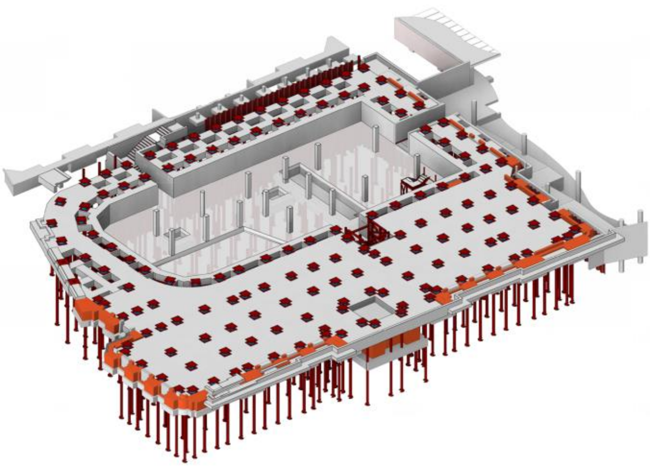

Figure 6: Layout of isolator bearings

The introduction of base isolation to the Town Hall resulted in number of other required interventions, such as the creation of a "rattle space" around the perimeter of the building to allow it to move independently from adjacent structure and ground in a seismic event. The minimum rattle space dimension was set to avoid structure-to-structure contact (pounding) under the Collapse Limit State. Where the Town Hall is adjacent to other structures, the assumed movement from those structures was added to the Town Hall's movement taken from the analysis model. On three sides of the building, the creation of the rattle space required the inclusion of lids to bridge over a gap; on the southern/Wakefield Street frontage, the isolation plane daylights over grade level and thus the building can move laterally over the footpath unencumbered. On the eastern/Michael Fowler Centre (MFC) side of the building, a trench and retaining structure were designed to create the rattle space. On the northern/Civic Square side of the building, two planks of precast hollowcore units will be removed from the adjacent parking garage roof (which forms the walking surface of Civic Square at this location) along the length of the building. On the western/MOB side of the building, the West Hall is bifurcated into structure belonging to the Town Hall and structure belonging to the MOB, and a gap will be left between these two structures corresponding to the required separation noted above.

2.1.3 Wall strengthening

Even after drastically reducing the demands to the superstructure as described above, many of the URM walls were still not strong enough in- or out-of-plane to meet the demands imposed on them. Therefore, several different techniques were designed to strengthen them. The first, and most common, is the introduction of 200 mm concrete overlay walls, reinforced and continuously doweled into the URM walls. A typical overlay wall section is shown in Figure 7. Where an overlay wall isn't practical for architectural or constructability reasons, recessed concrete banding is used. This banding could have been horizontal or vertical, but was chosen to be vertical as cutting a horizontal slot in the wall would have weakened the wall substantially in gravity and would have required more temporary works to support it during construction. A vertical slot only weakens the wall laterally, which was deemed to be acceptable for the construction earthquake.

In addition to the overlay walls and vertical banding, one other major intervention is used to support the URM walls out of plane. At the western wall of the auditorium, only a narrow (~4 m) diaphragm is available to support the wall.

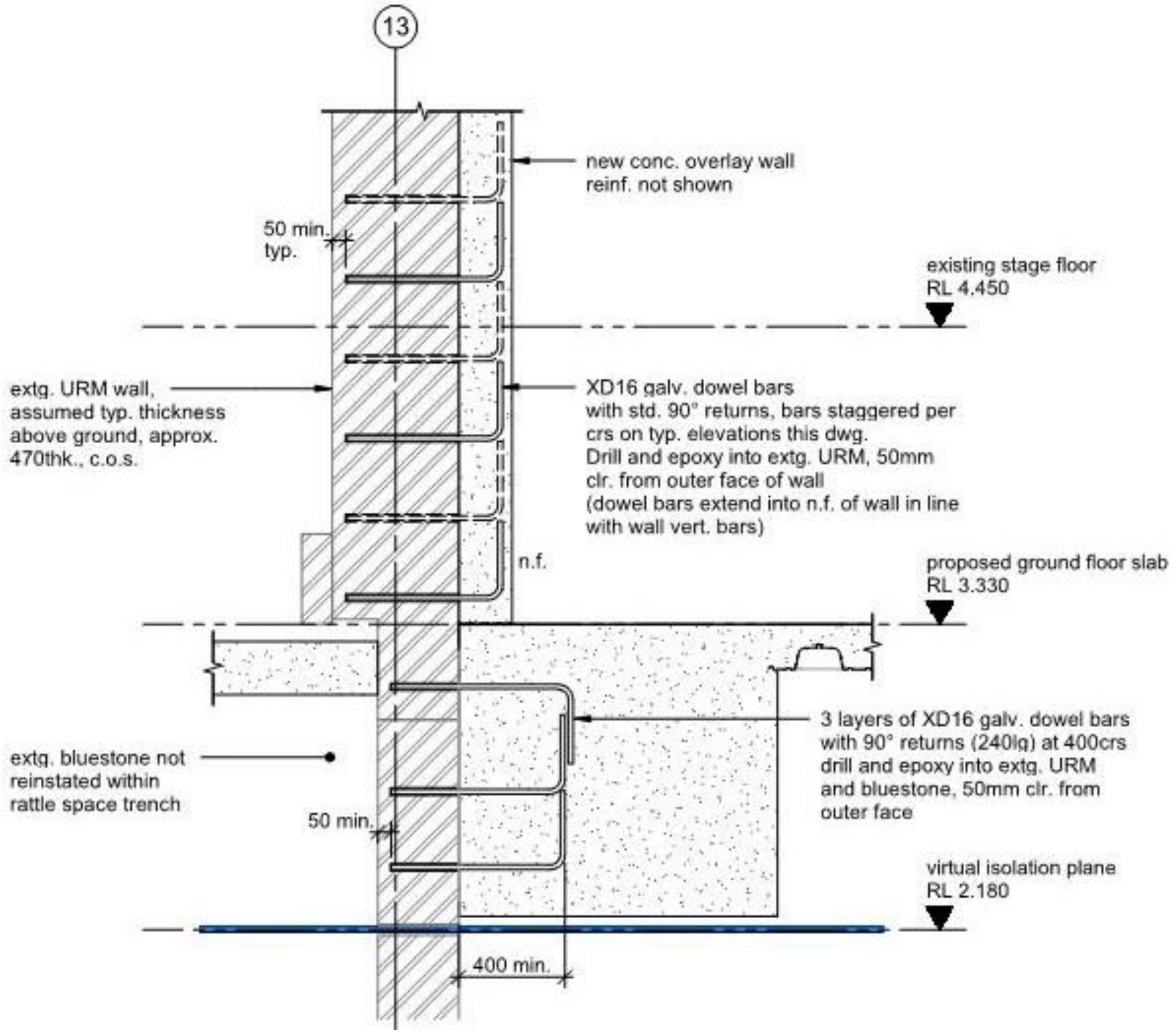

Figure 7: Typical overlay wall detail

The diaphragm alone was deemed to be too flexible to restrain the wall effectively, so six concrete moment frames were introduced. The out-of-plane load from the walls is shared between the diaphragm, which spans back to the perpendicular (east-west) walls of the auditorium, and the six moment frames. An elevation of one of these moment frames is shown in Figure 8. For loads in the north-south direction, the diaphragm is assumed to cantilever back to the auditorium wall. In order to make a more coherent structure, the MOB Annex mentioned previously will be demolished and the West Hall will be re-clad in a more modern aesthetic.

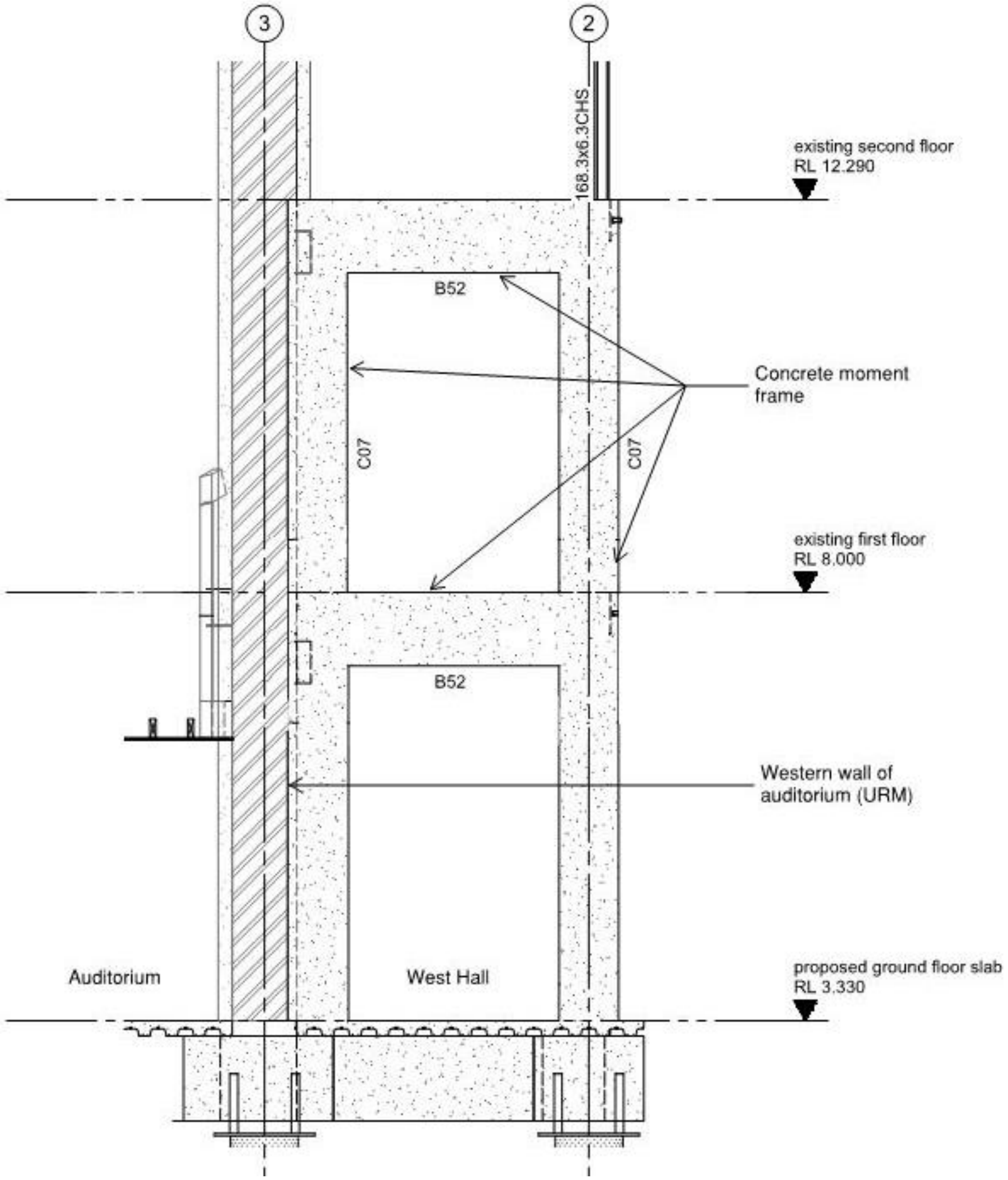

Figure 8: Typical West Hall concrete moment frame

2.1.4 Diaphragms

At locations where the existing diaphragms are required to carry transfer or inertial seismic loads, the shear capacity of the slab as well as the capacity of the connection to the walls were checked. The original 1904 slabs are typically very low strength unreinforced concrete with cast-in rolled steel joists, with the concrete assumed to span between the steel joists with arching action to the flanges. This construction type was assumed to have very low shear capacity and will be typically reinforced with recessed steel plates to provide collector elements capable of transferring the inertial load into the walls. At the roof, where there was no slab but some existing steel work from previous interventions, new steel members will be added to form a complete truss diaphragm.

2.1.5 Other elements

Although the high parapets and other decorative elements had been removed in the 1930s, some URM and lightly reinforced concrete parapets still remain. These will be secured back to the roof diaphragm through the use of vertical steel dowels, drilled down up to 7 m into the wall. This reinforcement allows the parapets to cantilever from the level of the roof diaphragm. Steel waler members (typically universal column sections web horizontal) with horizontal dowels into the URM wall then take the load into the steel truss roof diaphragm. On the south/Wakefield Street face of the building, two 12 m tall, 1 m diameter URM columns will be strengthened by post-tensioning with a 50 mm diameter rod.

The auditorium is the most prominent and celebrated space in the Town Hall and one of the main reasons for preserving the building. As such, the auditorium was treated with careful consideration to avoid altering its appearance or acoustics. All strengthening to the walls will be done on the exterior sides (such as the bracing of the western wall with the concrete moment frames mentioned above). A wraparound balcony will be strengthened using plywood diaphragm applied to the underside of the timber trusses supporting the seating tiers. At the front of the auditorium, tiered choir stalls connect the first floor-level balcony and organ loft with the stage level. These choir stalls were deemed to be of heritage value and thus only minimal alterations were allowed. For ventilation purposes, many small grills are being added to the vertical faces of the tiers, diminishing the capacity of the timber structure to carry its own inertial seismic load back to supports. Furthermore, the addition of backstage dressing rooms underneath the choir stalls requires hanging pipes and cable trays from the underside of the choir stall structure. For these reasons, the primary choir stall rakers will be strengthened by sandwiching them with steel channels, and a steel truss diaphragm will be created using flat plates and angles.

The original organ, which is also being refurbished as part of the project, will be braced back to walls to protect occupants in the choir stalls and on the stage. As the organ is an exceptionally complex piece of equipment with over 4000 pipes, this bracing was designed in consultation with the organ company doing the refurbishment to limit impact on the acoustics or maintenance access inside the organ.

2.2 Uplift

To develop the Town Hall as part of the Civic Music Hub, further work is required beyond the basic life safety seismic strengthening. This includes the addition of new performing and support spaces, refurbishment of existing spaces, and connections with adjacent structures.

At the southeast corner of the building, the existing Ilott Theatre sloped down from the ground floor to the basement to achieve a tiered seating area. In the strengthened building, at the ground floor the entire structure will be level to accommodate the creation of a consistent isolation plane. As a result, the Ilott Theatre's space will become level and much shorter in height, creating more of a studio than a recital hall. For the uplift portion of the works, the floor here was designed to accommodate future tenant works, including the addition of acoustic "boxes-in-boxes" (see next section).

Above the Ilott Theatre, at the first floor, the double-height Debating Chamber will be left mostly untouched. One major alteration will be the reframing of a second-floor balcony to improve acoustics and sight lines, and the removal of two cast-iron posts supporting this balcony. The posts require removal as the balcony is being raised and the posts are no longer long enough to serve any structural purpose.

In the northeast corner of the building, the second floor will be strengthened to accommodate a future tenant acoustic box-in-box (see next section), although the actual design of this element is part of the tenant fit-out works.

The auditorium, although deemed to already have superior interior acoustics, was determined to have less than ideal ingress of exterior noise such as heavy rain, traffic, and helicopters. For this reason, the design team's acoustic engineers proposed adding acoustic barriers to the roof in the form of a layer of plywood on the top of the roof trusses and a layer of particle board at the bottom chord of the roof trusses. The existing roof trusses and joists were assessed for gravity load carrying capacity, including testing of the original 1904 joists to determine their strength and stiffness, as little documentation could be found to justify the properties of the historic timber. Although nominally a trafficable floor, the client was advised that the existing roof structure would not be able to carry heavy live loads and access to the space would need to be seriously restricted. (The design floor live load was approximately 1.5 kPa to the joists and 0.8 kPa to the trusses based on guidance given in ASCE 7 for trafficable ceilings and attics without storage.)

Under self-weight, superimposed dead load, rigging loads, and live load, the roof truss members were found to be adequate, although extensive strengthening of their connections was required. The joists were found by testing to have adequate strength and stiffness, although further testing of the existing "bird's mouth" end connections revealed the existing configuration would not have sufficient capacity under the new loads. However, the other option of adding a completely new floor with new floor joists was determined to be more costly than simply supplementing the existing end connections with steel angle brackets, which is the solution that will be implemented.

Underneath the auditorium floor, a new basement will be dug to accommodate a high-end recording suite, storage facilities, practice rooms, and dressing rooms. Many of these facilities require acoustic isolation, which will be achieved through acoustic "box-in-box" construction (see next section) as part of the tenant fit-out works. Given the requirements of the recording suite, the basement was expected to be consistently dry, even though it was well below the water table. To that end, a two-prong waterproofing system was designed. Structurally, the basement walls were designed to be as watertight as possible though the use of hydrophilic waterbars and backstops at construction joints, tightly spaced reinforcement, and a concrete mix design specified to reduce shrinkage. Even with all these measures, some water ingress is expected. Therefore, inside the basement a drained cavity system was specified by the architect, which will allow any water to drain to sumps without intruding into habitable spaces.

The West Hall, between the Town Hall and the MOB, will be completely reframed. As discussed previously, a concrete slab and moment frame system will be added to brace the auditorium walls. Across the seismic joint, a glass roof supported on a steel structure will cantilever laterally from the MOB and rest on a concrete corbel on the Town Hall side. A modern glass, brass, and aluminium façade will enclose the West Hall on each end, creating a passageway between Wakefield Street on the south end and the Civic Square on the north end.

2.3 Tenant fit-out works

The last design stage of the project is the design of the tenant fit-out works. There are three proposed primary tenants: the WCC and Mayor, the NZSO, and the NZSM. Structurally, the fit-out works for the

WCC and Mayor require little to no design. The NZSO and NZSM works both involve the creation of acoustically isolated "boxes-in-boxes."

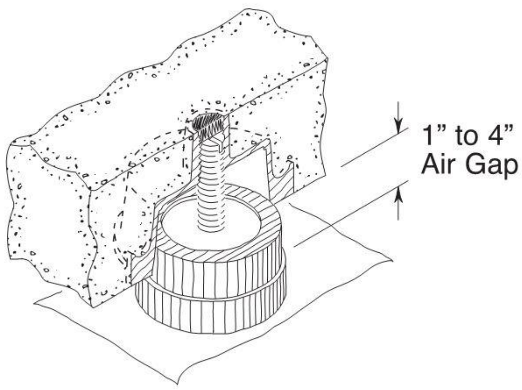

Figure 9: Typical acoustic slab jack (courtesy Mason Industries)

A box-in-box is designed to limit structure-borne noise by isolating the room from the rest of the structure as much as possible. The acoustically isolated box-in-box is achieved typically by casting a slab on top of another slab. The upper slab has a screw-jacking system cast into it, which is used to raise the upper slab up 25-100 mm above the lower slab after the upper slab has achieved sufficient strength to span between jacking points. Figure 9 shows a typical jack. On top of this slab, a set of walls and a ceiling are built, creating a "floating" box with minimal contact with building structure.

The intentional lack of contact with base structure creates significant challenges in restraining the boxes seismically. Any connection with the structure has the potential to transmit noise, so careful detailing is required to limit this transmission. Some strategies that have been considered include using the jacks as lateral load resisting elements (which works for small loads only), bracing the boxes up to diaphragms above with acoustically resilient buffers at steel-to-steel connections, and employing snubbers designed to only make contact during a seismic event.

3 CHALLENGES

The Town Hall was an extremely challenging project to design and will continue to be challenging to construct.

The piecemeal nature of the existing building created difficulties in designing coherent and consistent load paths through the building. Furthermore, much of the original structure was undocumented, and even the 1990's work did not have complete structural drawings. This caused significant challenges in designing retrofit solutions and required extensive on-site investigations. Even with many investigations during the design phase of the project, further discoveries are expected during the construction phase which may have impacts on the solutions as currently designed.

Another challenge was the emphasis on preservation of the heritage fabric of the exterior of the building, restricting all the remediation works to the inside only. This inhibited several solutions and required considerable creativity in achieving the desired outcome. For instance, all of the exterior URM walls are supported from the inside only, through the use of dowels into overlay walls which are supported on sizeable concrete beams hugging the inside face of the walls. These beams span to the LRBs. At URM pier locations, perpendicular beams cantilever out from the LRBs and underneath the pier to support the heavier wall gravity load as well as the boundary-element reactions from the seismic forces in the walls. Figure 10 shows a typical pier location with the cantilevering stub beam.

As discussed previously, in the interior of the building, highest importance was placed on the preservation of the auditorium in its current form. One of the big construction challenges there will be the support of the historic balcony and choir stalls during the demolition of the auditorium floor, the excavation of the basement, and the installation of the screw piles.

The site itself imposes many challenges as well. As discussed previously, the poor soils required extensive intervention to the foundation system. The site's proximity to the Wellington Harbour mean a high water table as well as the consideration of aggressive soils and brackish water. In addition to the already high

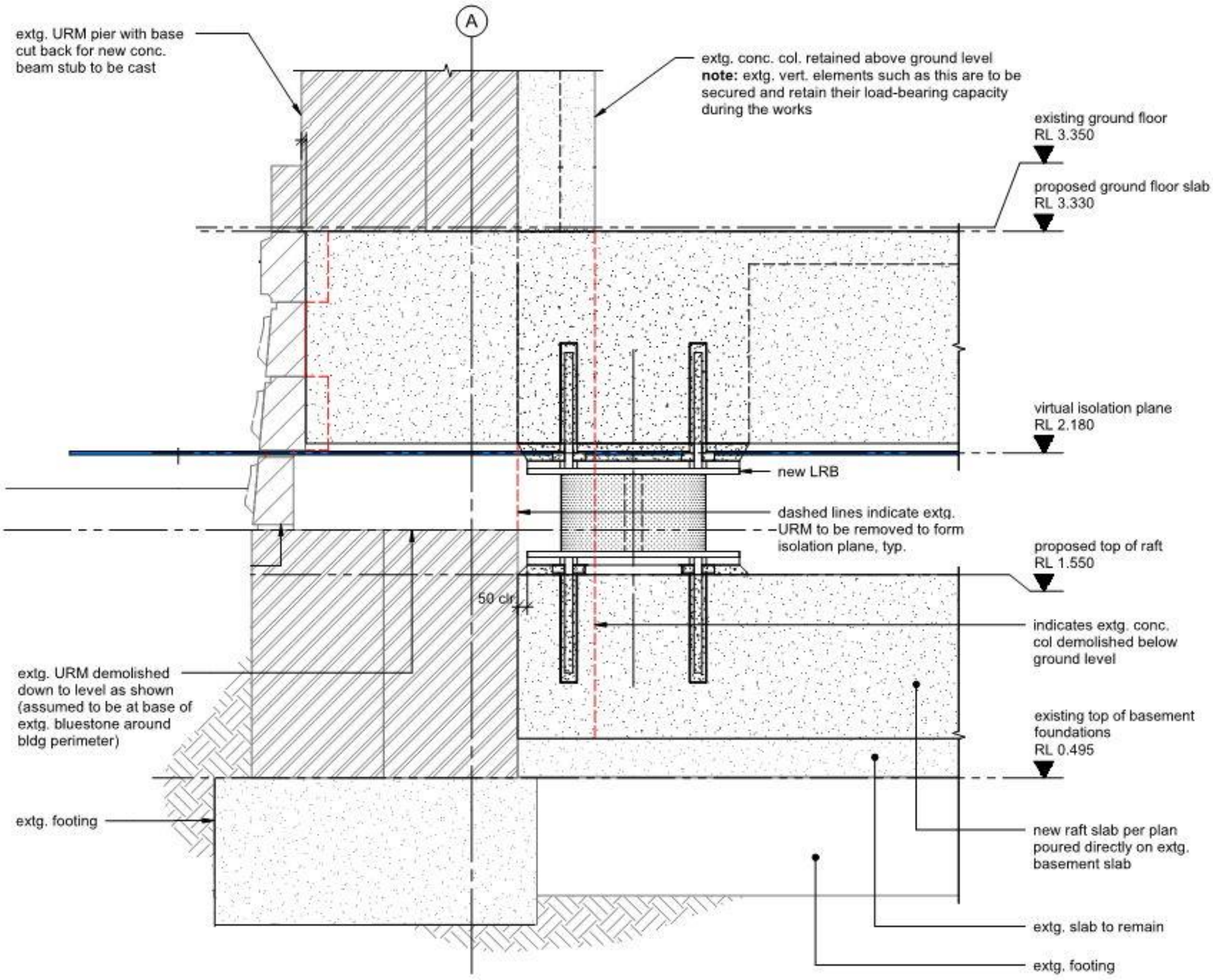

Figure 10: Typical stub beam cantilevering off LRB to pick up URM pier

water table, seasonal inundation and global sea level rise were required to be considered in the design, bringing the design water table up to the top of the basement. During the construction phase, the constrained nature of the site, with buildings on three sides, will create many challenges for access into the building. As currently conceived, the only access to the building for heavy equipment will be through the south entrance to the West Hall (after the demolition of the MOB Annex). All equipment, including the equipment required for excavation, sheet piling, screw piling, and jet grouting, will need to be brought through this entrance and then driven into various locations throughout the building. This will require careful consideration and sequencing from the contractor.

In addition to the constrained access to the building, the temporary works and stabilisation requirements during construction will be major challenges for the contractor. While the design was developed to simplify the construction process where possible, sequencing constraints and temporary works are still substantial. The excavation of the basement will be particularly challenging, as the installation of temporary retaining structure (typically sheet piling) could create differential settlement in the adjacent auditorium URM walls, which could potentially damage or irreparably destabilise them. The creation of the isolation plane requires careful design of temporary support for the fragile existing URM structure throughout the building. Furthermore, the creation of the isolation plane will need to be carefully sequenced and managed to avoid prematurely disconnecting the building from its foundation or excessively weakening the structure.

Additionally, where URM walls and columns are disconnected from existing diaphragms, temporary bracing will need to be supplied to maintain the structural integrity of the building.

4 CONCLUSIONS

The Wellington Town Hall, having been deemed to be of important heritage and civic value, is being strengthened and uplifted to provide an anchor for a Civic Music Hub in central Wellington. This is achieved through seismic strengthening to bring it up to current building code standards (including refounding of the building and the introduction of a base isolation system) and uplift of the existing facilities to promote its use as a centre for performing arts. As part of the tenancy agreement with several entities, the building will also be upgraded to include high end performance and recording spaces. The owners of the building have invested considerable resources into the restoration of this historic building, maintaining the heritage fabric of the city while also creating new performance spaces for future generations.

REFERENCES

Oliver, S., McKenzie, H. & Makan, K. 2018. Performance-based design and assessment of the Wellington Town Hall, *Proc. 16th European Conference on Earthquake Engineering*.