Turnbull Library: Strengthening for Heritage and Resilience

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ABSTRACT

Turnbull House is a Category 1 Heritage building on Bowen Street in Wellington. It was built in the 1910s as a residence and library, primarily from unreinforced masonry. Although some strengthening was carried out in the 1950s and 1990s, it has been assessed as Earthquake Prone. Dunning Thornton have proposed a seismic upgrade of the building based on the capacity of the existing rocking walls and the 1990s diaphragms, which minimises disruption, cost and intervention to the heritage fabric. It is to be base isolated with Triple Friction Pendulums, with their displacement governed by clearance to surrounding buildings. This approach requires only two new localised lateral load resisting elements in the superstructure. The design is "bottom-up" from the building's existing capacity rather than "top-down" from a target %NBS. This paper will explain the advantages of this approach.

1 BACKGROUND

Turnbull House is an existing 3-storey Unreinforced Mansory (URM) building built circa 1916, situated at 25-27 Bowen Street, Central Wellington. It was originally designed as a private residence and a place to house Alexander Turnbull's substantial book collection.

Different from traditional URM buildings, the in-plane URM capacity is lower than the out-of-plane capacity, primarily due to relatively open spaces (few walls) to the principal rooms.

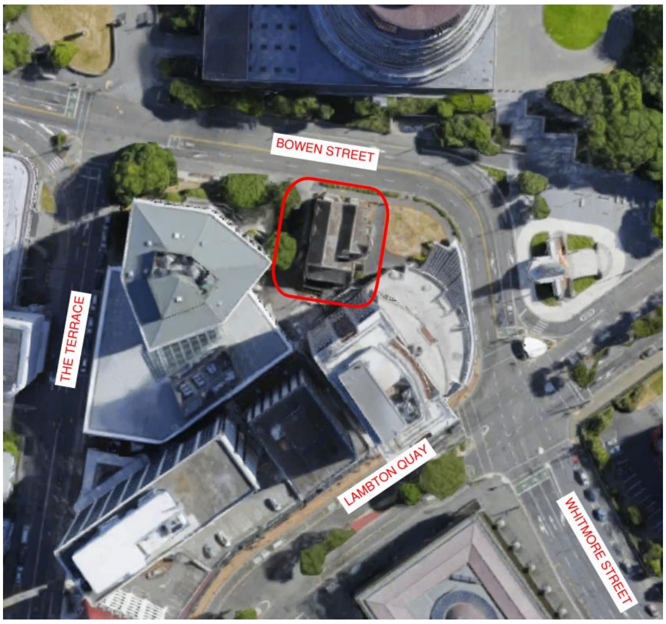

Figure 1.1: Turnbull House Location

1.1 History of the Building

Alexander Turnbull was born in Wellington in 1868, the son of wealthy Scottish merchant. Educated in London, he returned to New Zealand in 1892 to work for the family business, taking it over after his father's death. Always an avid book collector, his wealth allowed him to construct Turnbull House as his residence and library.

To design the building, Turnbull commissioned well known Wellington Architect William Turnbull of Thomas Turnbull and Son (oddly no relation, but himself a legacy also, his father being an early thinker in seismic resilience). It is largely in the Queen Anne style, though has elements of other revivalist styles such as Scottish Baronial (Turnbull House, 2023) Load bearing red brick masonry is typical of the Queen Anne style, as are the formed gables and lancet windows (Turnbull House, 2022). The double storey bay windows and classical style front porch columns are unusual for this style. Floors are typically timber, with a 4-storey concrete stack room for the original book collection. The existing foundations are concrete, and the roof is clad in Welsh Slate. Builders Campbell and Burke completed the building in 1916 for £6,000. A few anomalies occur, potentially reflecting the construction period around WWI. For example, there is no external cavity and wall thicknesses are often increased via timber framing.

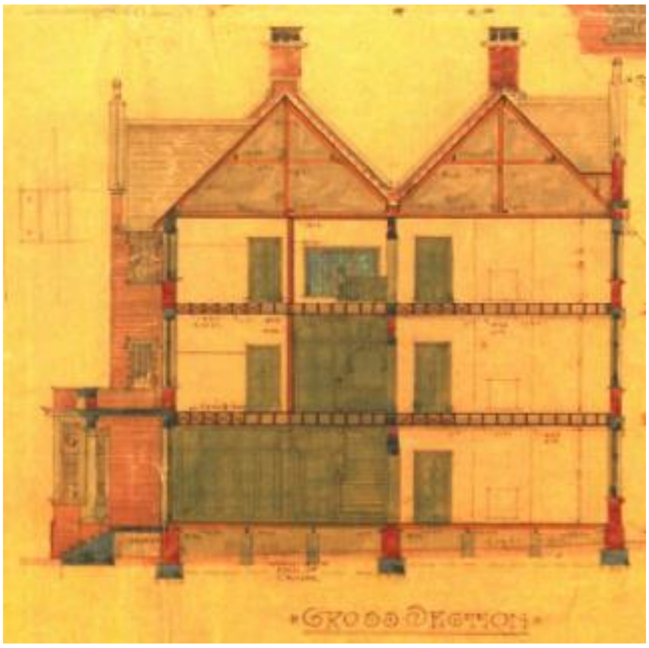

Figure 1.2: Excerpt Original Drawing

Upon Alexander Turnbull's death, his book collection was gifted to the public and formed the backbone of New Zealand's National Library. The government bought Turnbull House from the estate to house the collection. Turnbull House remained a public access library until the construction of a dedicated building in the 1970s. It was saved from demolition in the 1970s to build a motorway, due to public pressure. The building is currently administered on behalf of New Zealanders by Heritage New Zealand Pouhere Taonga (HNZPT) and has a Category 1 listing.

The unreinforced brick masonry, tall piers, bay windows, complex layout, and timber floors create charming architecture, but challenge a seismic engineer. Unreinforced masonry performance in past earthquakes has been highly unreliable, with out-of-plane wall rocking, diagonal tensile failure, and diaphragm flexibility being some of the common weaknesses.

In the 1950s, the Ministry of Works altered the building by demolishing the top stack room level and removing some of the unreinforced masonry gables. The intent was to reduce earthquake risk and remove some foundation loads. In the 1990s, seismic strengthening removed more heritage fabric and replaced solid masonry gables with brick veneer on timber framing. Other heavy fenestrations were removed and replaced with plastered, sculpted foam. Plywood diaphragms were added atop the existing tongue-and-groove floors.

Despite these interventions, the building was assessed as earthquake prone and closed in 2012. To some degree this is unsurprising. Despite the 1990s strengthening work appearing to be a thorough example of practice at the time, one cannot escape the target accelerations were 0.1g in-plane and 0.2g out-of-plane.

Proposed Structural Upgrading

The proposed structural upgrading is to give the building a seismic resistance equivalent to ²/₃ of current code (NZS4203) load capacity. The upgraded building should survive MMVIII intensity earthquake which has a return period of 67 years in Wellington. The building will show significant structural damage after this intensity of shaking. The strengthening proposal meets the requirments of the December 1985 publication by the New Zealand National Society for Earthquake Engineering "Earthquake Risk Buildings: Recommendations and Guidelines for Classifying, Interim Securing and Strengthening".

Figure 1.3: Excerpt 1990s calculations – Note the way strengthening level is communicated.

In 2021, two temporary plywood shear walls and a tie across the front of the building were added to address the weakest building area, knowing that full strengthening was still some way away.

Figure 1.4: View of current building (courtesy of HNZPT (Turnbull House, 2023)).

1.2 Site and Context

The building's northern elevation fronts directly to road reserve (Bowen Street). On its other sides the building is closely bounded by property boundaries and adjoining structures.

To the east, the Kingsway Tunnel passes below the entrance portico. This tunnel connects Bowen House with the parliamentary buildings across Bowen Street. To the south, the main building has a separation of approximately 900 millimetres to an existing boiler house (southwest corner) and the boundary to Bowen House (southeast corner). These constrain the space available for implementing an isolation retrofit.

Bowen House's construction and its associated close boundary may impact the construction of a rattle space retaining wall, potentially requiring an easement.

Figure 1.5 – Block Diagram Showing Adjoining Structures and Approximate Boundaries

Factual and interpretive geotechnical reports have been completed by BECA. These determined that the site consists of loose/soft fill over alluvial materials. The building is likely sited over the former Tutaenui Stream, which carried water from Te Ahumairangi to the harbour. The soils around the historic stream are softer and historic settlement has been observed in the middle of the western façade.

The site's seismic subsoil conditions are complex and industry knowledge suggests there is a steep-sided 'valley' in the bedrock below the site. Adjacent sites have been historically classified as subsoil class C but Turnbull House could fall within a localised area of subsoil class D. This presents uncertainty for assessment and design, so subsoil class D has been conservatively assumed.

Figure 1.6: Historic Map of Wellington Showing Historic Rivers (National Library Collection access via https://natlib.govt.nz/records/22612149).

1.3 Future Use of the Building

Following its disestablishment as a library, Turnbull House had small offices, function rooms and a café. After strengthening, it is intended to be used by both the public (hireable function/exhibition spaces) and private offices. The varied past uses have meant no change of use is required, giving a more open brief to the strengthening level required.

The project will also improve accessibility, with the inclusion of a new lift, accessible bathrooms and ramp for level access. Warren and Mahoney Architects have furthered the scope, with reinstatement of heritage features and improving watertightness performance. Russell Murray is the heritage architect who has found a careful balance of pragmatism and conservation. .

1.4 Prior Assessment

As there has been an intention to (re)strengthen since at least 2011, a full DSA has never been completed, as it was felt unnecessary once at least one element was established as <33%NBS. This has had project implications, as the contractor expected a full DSA to inform site safety procedures.

2 STRENGTHENING METHODOLOGY

2.1 Typical Practice

Common solutions to suppress out-of-plane wall failure are external strengthening (e.g. steel, timber, or concrete strongbacks) or internal strengthening (post-tensioning, bonded reinforcing etc).

Conventional strengthening of Turnbull House would need new lateral load-resisting elements to improve URM wall behaviour, a redo of plywood diaphragms, improving wall to floor connections and out of plane behaviour.

2.2 Our Design Philosophy

The overarching design philosophy is to strengthen the building to substantially improve its seismic performance whilst minimising intervention, lifetime budget and loss of heritage fabric. Colloquially, we are setting out to achieve "bang for buck", rather than a specific strengthening target. This means the building's baseline achievable strengthening level is governed by the capacity of 'hard to strengthen' elements.

The project's funding 'floor' rating of "67% NBS" is another example of "%NBS" being absorbed into the vernacular with its use going far beyond the original intended purpose. Its intended purpose is to compare existing buildings to each other, in order to identify the weakest, i.e. Earthquake Prone, buildings (NZSEE, 2006). It was not conceived as a tool to communicate the performance of strengthened existing building. As the building is heritage listed with original fabric intact, the strengthening seeks to preserve as much heritage fabric as possible. Particularly focusing on:

1. Minimal intervention to the existing structure
2. Preserving the primary room proportions

This philosophy is achieved by base isolating the building such that loads from the existing masonry are reduced and can be primarily resisted by the existing structure without major intervention. Construction work associated with forming a base isolated platform is concentrated below the ground floor, which is not an area of significant heritage value.

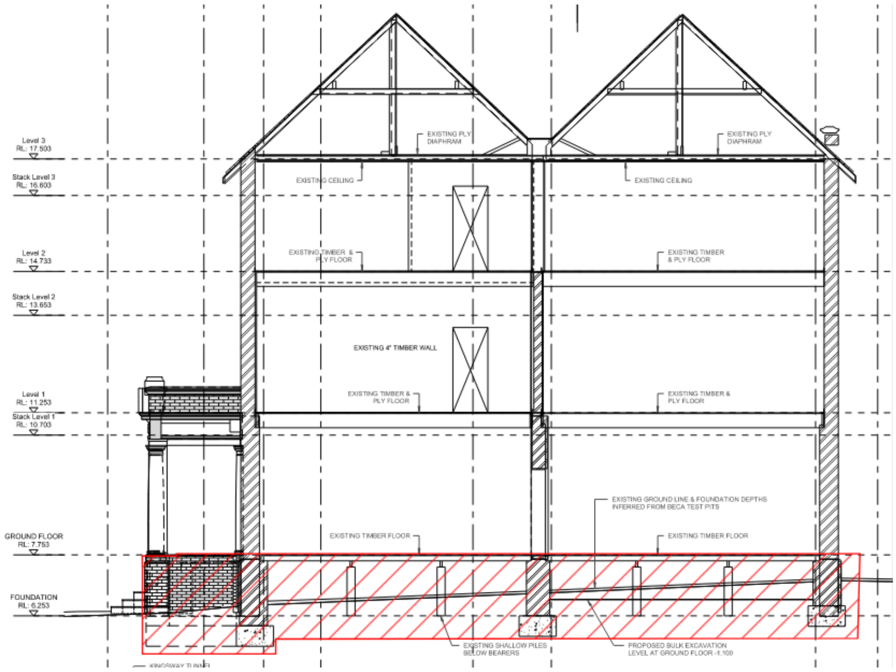

Figure 2.1:- Cross Section Showing Area Most Affected by Strengthening Works (Hatched Red)

The available clearance for a rattle space limits the displacements the base isolation system can achieve. This constrains the achievable strengthening level without significantly more intervention scope to the upper heritage building structure. For this project, higher value was placed on a long-term strengthening solution which reduced the likelihood of damage to heritage elements in smaller seismic events, rather than targeting an arbitrary %*NBS*.

3 DESIGN ELEMENTS

3.1 Existing Loads and Capacities

The first step was to determine the capacity of the existing structure and the associated load demands. The building mass and weight at each level was determined. A load take-down for each wall line provided axial loads for determining the URM wall in-plane and out-of-plane capacities, and the inputs for the new raft slab design. The URM wall capacities were assessed using 2017 Assessment Guidelines C8. The acceleration capacities of the URM walls in and out-of-plane provided a target base isolation acceleration at which the URM walls required no strengthening. These accelerations were used to formulate a preferred isolator, then were provided to EPS (isolator supplier) to inform the triple pendulum design and selection.

Figure 3.1: Overview of the Existing Structure and URM Walls.

Some walls remain more vulnerable and it is proposed to strengthen these with galvanised stressbars. This increases the compression, and thus rocking capacity. Stressbar loads are limited such that rocking still governs, rather than bed joint sliding or diagonal tensile failure. These will be dry cored to preserve heritage finishes, which adds cost but has less disruption to the heritage fabric.

3.2 Base Isolation

The proposed base isolation system uses triple pendulum sliders, designed, manufactured, tested, and supplied by Earthquake Protection Systems (based in the USA). This hardware allows the isolation system to traverse large displacements at lower forces. This limits the acceleration demands on the existing masonry elements. Alternative isolation hardware, like lead rubber bearings, do not have the same large displacement capacity at low seismic forces, thus difficult to implement with minimal superstructure interventions.

The triple pendulum isolation dissipate energy through friction on sliding stainless surfaces and storing gravitational energy as it moves up the curve of the isolator dish. The effective period of the structure is increased by sliding on the different surfaces once excited by a ground motion acceleration. Triple pendulums achieve low transfer forces to the superstructure by achieving large displacements. Under large earthquake forces, the isolator displacements increase and the effective pendulum length and the effective damping increase to absorb the larger seismic accelerations. The available horizontal displacement for Turnbull House is up to 875mm.

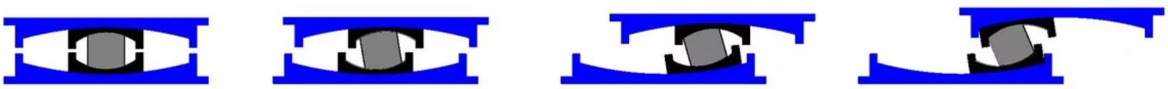

Figure 3.2: Schematic Showing Horizontal Displacement of Triple Pendulum Slider (courtesy Earthquake Protection Systems Ltd.)

Chapter 17 of ASCE/SEI 7-22 “equivalent lateral force procedure” was used to determine the initial parameters of the triple pendulums. Pendulum radii (Ri), heights (h_i) and surface frictions (μ) were assumed, and a displacement estimated. The initial estimated displacement was iterated until the isolation acceleration and the spectral acceleration (C(T)) from NZS1170.5 converged. The effective damping, period and acceleration of the isolation system were also calculated for each displacement. This final converged displacement (D_m) provided the expected COM displacement for the isolation system. Lower and upper bound displacements were determine based on different isolator surface frictions (μ values) for CALS, ULS and SLS load cases. The ULS case was taken as 70%NBS and the CALS case was taken as 1.5xULS as per the draft Seismic Isolation Guidelines. The final system displacements and damping ratios were plotted against the NZS1170.5 design spectra.

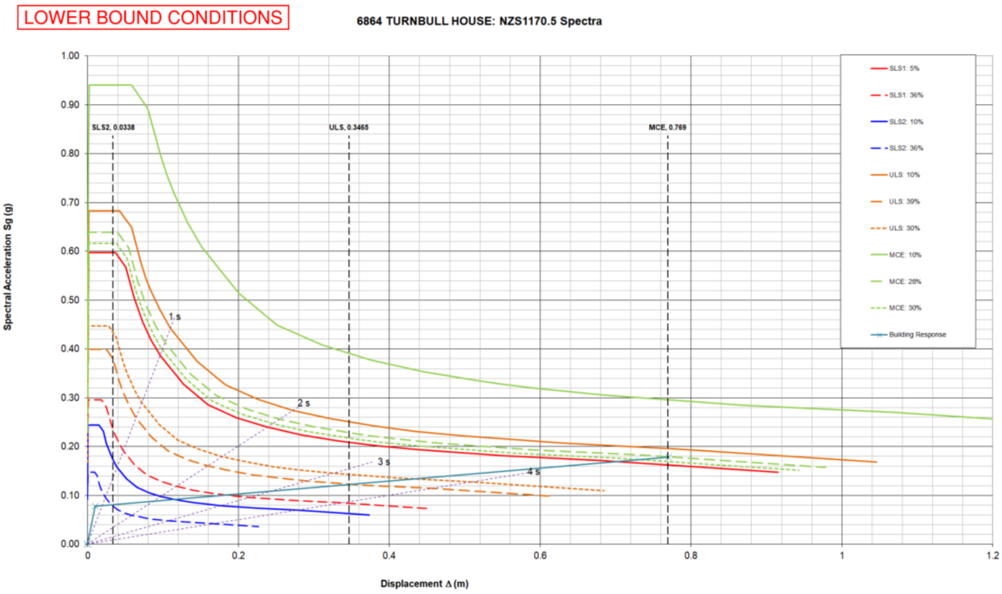

Figure 3.3: Isolator displacements for DTC isolator design to NZS1170.5 design spectra.

The initial isolator design was provided to Earthquake Protection Systems (EPS) to evaluate against their isolator designs. They proposed an isolator with a lower friction, which imparts less acceleration to the superstructure, and different friction for outer surfaces, giving lower parts acceleration. To analyse the isolation system behaviour, an ETABS model was created with 10 triple pendulum isolator links, and additional masses to represent the building weights. Non-linear time-history analysis was used to determine the parts spectra, considering geometric and mass parameters and triple pendulum properties (for both the DTC and EPS designs). Suitable earthquake records for the non-linear time history analysis were selected and scaled to the ASCE 7-16 method. A 3-mass model was created with a ground level slab mass and the superstructure mass split into in-plane walls and total OOP wall/floor mass. Links to represent in-plane walls, or OOP walls/floors stiffnesses connected the masses.

The parts acceleration spectra for each mass were taken from an average of all earthquake records. The acceleration behaviours were investigated by varying the link stiffnesses, damping, and further splitting masses. This led to 4-mass and 6-mass models with different OOP masses and link stiffnesses. See Figure 3.4 below for an illustration of each model iteration. The advantage of this process is that it allows us to build up knowledge of how the building behaves, and test the sensitivity to changes in element properties, an essential step in understanding a building with so many moving parts.

Further splitting the OOP masses with varied link stiffnesses, reduced the acceleration drag effects of the upper masses on the slab mass response. The average parts accelerations for each mass were plotted to compare responses. Figure 3.5 gives an example output for the 6-mass ETABS model at 5% damping. The slab mass (green) follows the isolator behaviour whilst the upper OOP masses have higher acceleration peaks depending on their mass and stiffness, ranging from 0.35g to 0.59g. Figure 3.6 shows the mass responses from the different models used to derive a parts spectra.

The base isolator design (with original DTC and proposed EPS) were compared against NZS1170.5 (subsoil class D) demands, an average of time history records, EPS spectra, and an approximate NSHM spectra (estimating V30 parameters based on available published maps.). The simplified parts spectra (black line on Figure 3.6) is used for assessing and designing superstructure elements, including existing diaphragms and bracket connections.

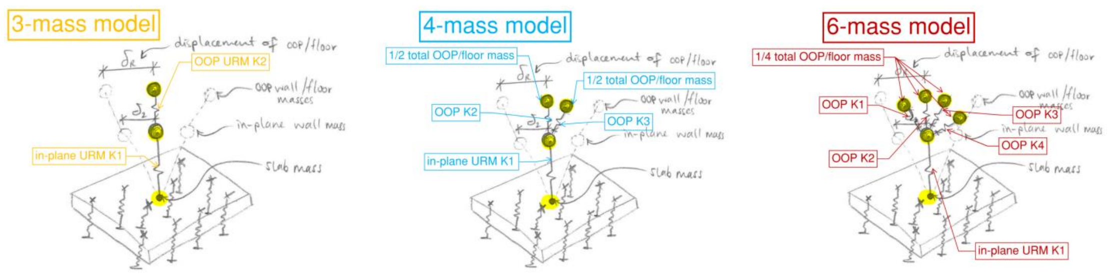

Figure 3.4: Illustration of ETABS base isolation model evolutions used to refine the parts spectra response.

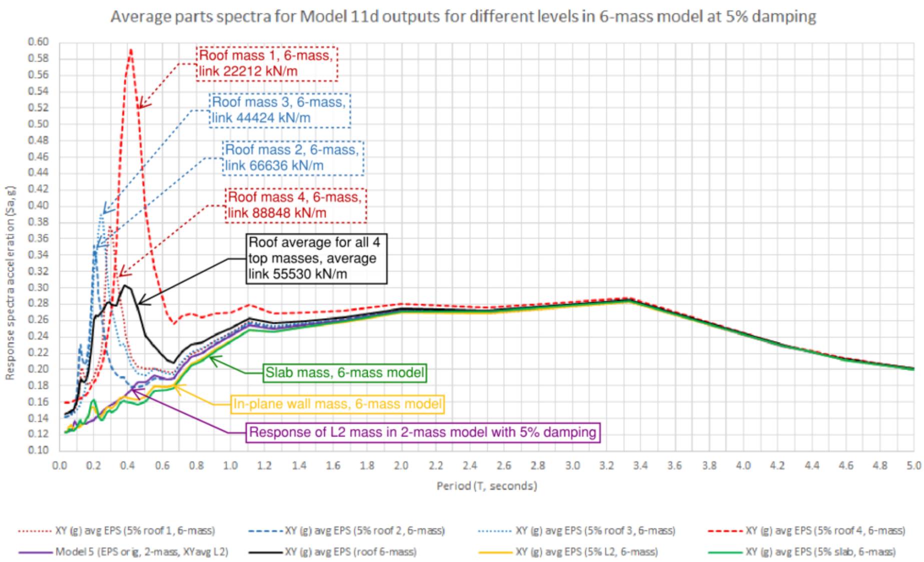

Figure 3.5: Parts spectra response for each mass in the 6-mass ETABS model to compare stiffness effects on accelerations and single level isolation model (green line).

It should be noted how well isolated the building is, with a very flat floor spectra.

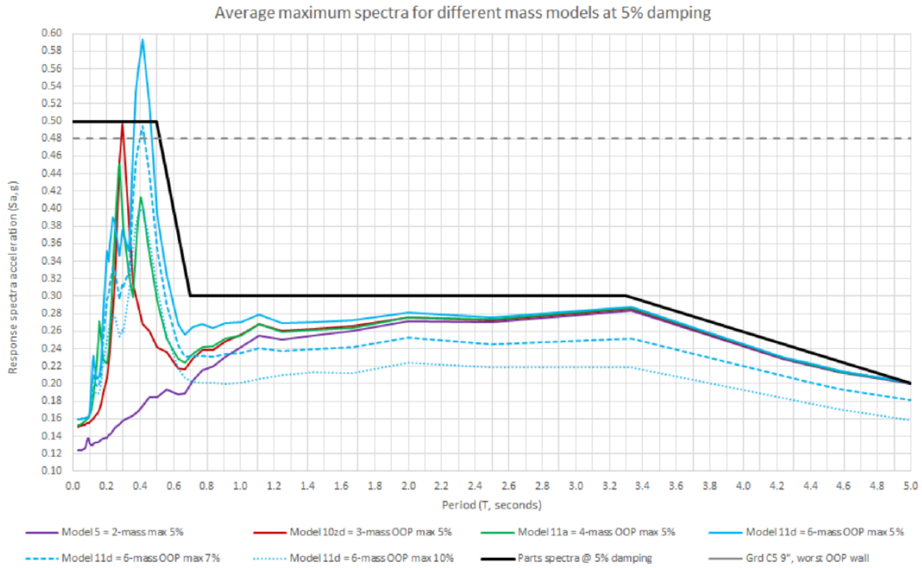

Figure 3.6: Derived parts spectra for isolated structure (black line) based on the averaged out-of-plane mass responses from the ETABS models (3-mass, 4-mass, and 6-mass models).

3.3 New Bracing Elements

To increase the seismic lateral capacity of the existing structure, two new concrete bracing elements were added: a frame longitudinally and a shear wall parallel to Bowen Street. The required capacities of these elements were determined from achieving a suitable global acceleration for base isolation while also balancing the building's torsional response.

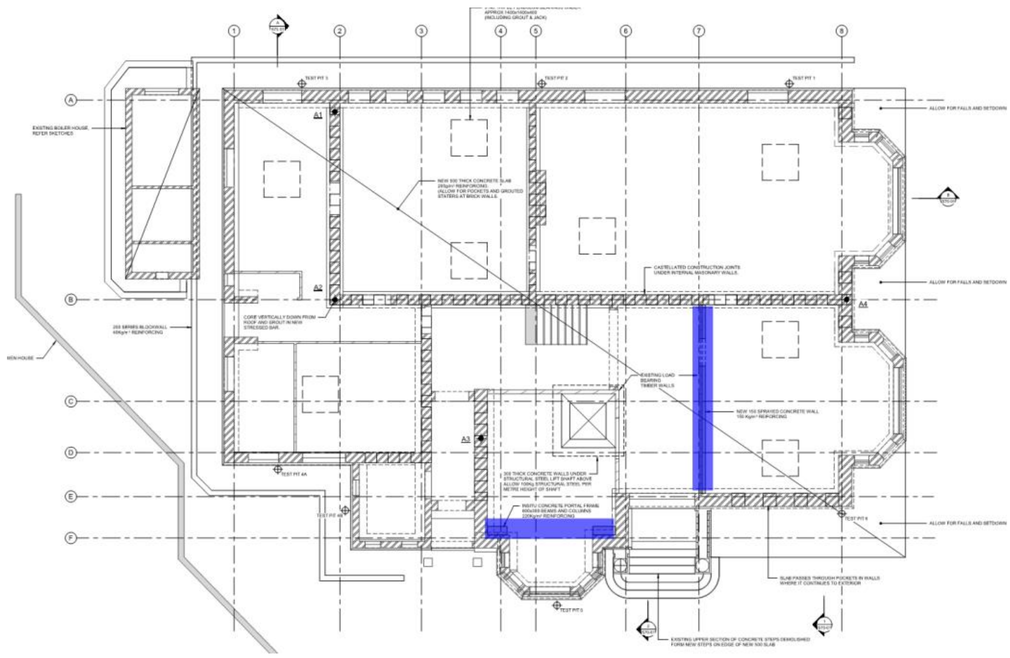

Figure 3.7: .Main Structural Interventions Highlighted

3.4 New Raft Slab:

The main strengthening intervention is re-supporting the URM building on base isolators, with a new ground floor concrete slab to transfer the loads from the walls to the isolators. A beam grillage of 1m wide x 0.5m deep strips was created in SpaceGass. Loads representing Gravity (G) and Live loads (Q) were applied to represent wall lines and slab weights. Localised point loads were distributed at wall ends to represent earthquake-induced wall overturning loads. The isolator layout was also determined from this model, and iterated to both balance vertical isolator reactions, and limit slab deflections. Slab deflections were checked to ensure URM walls above remained stable under static and earthquake load cases. Slab penetrations and subfloor access hatches were added in least loaded areas. The SpaceGass model (with artificially low torsion capacity) represents a lower bound capacity, verses a more complex SAFE/ETABS model, whilst also being easier to interrogate.

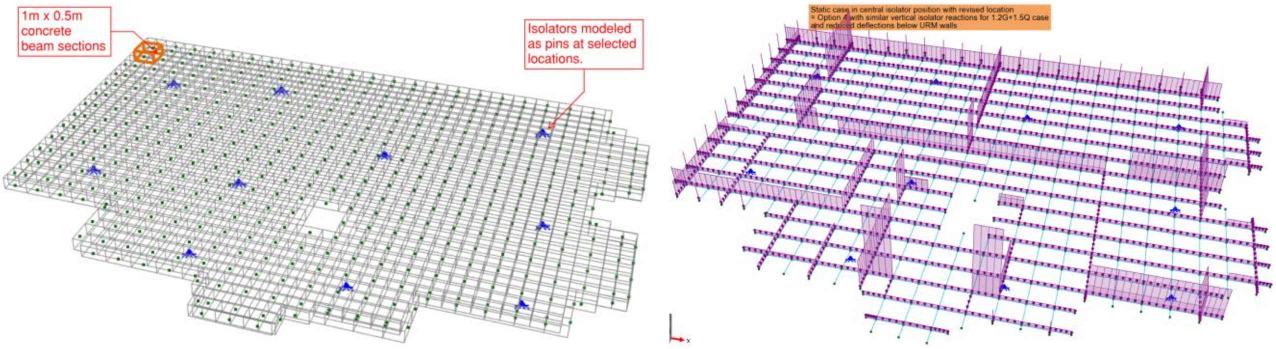

Figure 3.8: Snips from Grillage Model

The existing ground floor tongue-and-groove floorboards will be salvaged and re-laid over the new concrete slab. The slab is set down to provide 100 mm to the finished floor level for cabling, floor boxes, and the salvaged boards to help preserve the heritage feel of a timber floor.

3.5 Diaphragms

A further advantage of base isolation is the reduced diaphragm demands. This allows much more of the 10mm 1990s plywood to remain, with the aim to limit stresses so the existing diaphragms are sufficient, minimising re-work. Some remediation is required, particularly around the new lift where additional steel straps are proposed. For the time, the diaphragm angles to the URM walls were good, with deep epoxy anchors (see Figure 3.9).

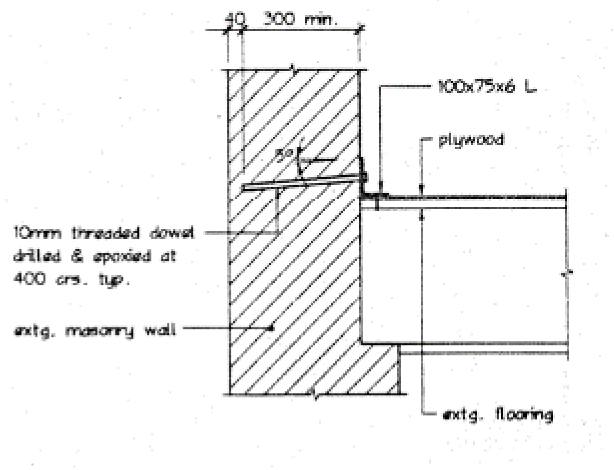

Figure 3.9: Excerpt From 1990s Strengthening Drawings

However, there is evidence of heavy corrosion to some of these angles, after less than 50 years. With more major watertightness interventions needed (see below), most of these angles are to be removed and replaced by new brackets.

3.6 Foundations

The building will be re-founded on shallow reinforced concrete pads below the isolators. The building will be cut from its original wall footings once the isolators are installed. Detailed ground investigations are required at each isolator location, as initial investigations highlighted variable ground conditions across the site. It is likely that some pads will require ground improvement. Options for pre-compression to accelerate any settlement below the pads are being considered.

3.7 Roof Structure and Reinstated Gables

The Welsh slate roof is in poor condition and needs replacing. A like-for-like replacement was anticipated with the same tile style and thickness. Unfortunately, the current thin slate tile is not available, only a heavier replacement option, leading to an assessment of the existing roof trusses being required. The existing sarking is also in poor condition and will be supplemented with new plywood. This also appeases the contractor from a health and safety perspective.

The roof trusses are to be modified to improve attic access via much larger access hatches. Again, this results in larger demands on some existing trusses. As expected with a building of this era, the connection between framing elements are the weakest link. The 1990s ceiling diaphragm restricts access to the trusses so these connection improvements will be designed during construction once they can be sighted.

Additional walls will be constructed in the roof space in line with some existing URM walls, to connect the new plywood roof diaphragm to existing wall lines below. There would be the opportunity to line these walls with fire-rated plasterboard (over plywood bracing layer) to compartmentalise the roof space and improve fire performance.

The 1990s gable reconstruction is considered poor architecturally, particularly regarding watertightness. It is proposed to reconstruct these gables with single wythe bricks supported on timber framing and cavity ties.

3.8 Boiler Room

The boiler room to the south of the main house has been treated as a separate structure and is not base-isolated. It will be conventionally strengthened with steel mullions to 67%NBS (IL2, Subsoil class D). A new roof and wall extension will reinstate the original steep roof pitch. The wall extension will be treated similarly to the reinstated gables on the main building. The decision was made to not isolate this outbuilding, partly due to the added complexity of supporting two structures on a single raft and there being insufficient clearance between buildings to separately isolate

4 BUILDABILITY AND OTHER PROJECT CHALLENGES

4.1 Rattle Space / Height Under Raft

To limit the extent of underpinning to the existing shallow strip footings, the height of the subfloor space has been minimised as much as possible. There is an inherent tension between providing more space to aid constructability (particularly with the need to access and jack isolators as part of the installation) and limiting the excavation and resulting underpinning.

4.2 Services Installation

Intertwined with the space available under the new ground floor slab, is the installation challenges of below slab services and the careful sequencing required.

4.3 Watertightness / Joist Rot

Late in the design phase, a soak test was carried out. This showed major water ingress through the brickwork, likely exacerbated by the lack of cavity. This poor result, combined with evidence of corrosion to the 1990s steel angles fixed to the external walls, led to the engagement of a moisture management specialist who tested timber for rot. The pocketed joists were found to have been absorbing moisture from the walls, rotting the ends. It is now proposed to cut away all external joists ends and install new brackets, which both re-support the joists and provide the diaphragm connection to the external walls. Cutting back the joists also allows a new cavity to be formed, with a new (non-load bearing) timber framed wall on the internal side. This has been a huge (ongoing) challenge as the watertightness aspiration is diametrically opposed to the structural necessity of connection between the floor and the external walls.

4.4 Tunnel

The original 1990s tunnel indicate a cut-and-cover construction method that involved installing horizontal soil anchors below Turnbull House. The tunnel was designed for two loading conditions, one stronger section under Bowen Street, and a lesser capacity section adjacent to Turnbull House. Unfortunately, this has had site implications for access, construction traffic, delivery of materials as well as final landscaping options. In hindsight, the potential saving in reinforcing was potentially not fully considered with regards to the opportunity cost regarding future above ground use over the tunnel.

4.5 Small Nature of the Footprint

The small footprint of the building is challenging, as it is very complex project in terms of temporary works, base isolation, re-founding, etc, but on the budget of the project is naturally constrained by the size of the building. That is, medium-sized projects of this nature have neither the advantage of small domestic scale, nor the repetitive nature of large buildings.

5 CONCLUSION AND THANKS

We thank HNZPT for the opportunity to work on this interesting project. Our thanks also to fellow members of the design team, contractor Naylor Love, and our peer reviewer Miyamoto.

In conclusion, Turnbull House provides a good example of practical considerations for strengthening important historic buildings, balancing intervention and " targets."

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