Seismic assessment and strengthening of the Auckland International Airport Control Tower

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ABSTRACT: This paper summarises the seismic assessment of the Auckland International Airport Control Tower and outlines the strengthening schemes implemented. Due to the multiple construction types and significantly different lateral force resisting systems present with the Control Tower, a modal response spectrum analysis was conducted to determine the distribution of lateral forces throughout the tower. The Control Tower's main tower concrete shaft, service level concrete moment frames and cab level steel moment frames were analysed. Particular attention was focused on the interaction between the service level's moment frames and the cab level access stairs since the access stairs were built integrally with the service level's moment frames and floor slab. Two strengthening schemes were devised to address the earthquake prone cab level access stairs and the seismically deficient cab level steel moment frames. Finally, contractor issues related to the implementation of the retrofit schemes are discussed.

1 INTRODUCTION

1.1 Background

In 2011, *Airways New Zealand Limited* appointed *Opus International Consultants Limited* to carry out a detailed seismic assessment of the air-traffic Control Tower located at Auckland International Airport. *Opus* was also asked to provide strengthening options to improve the Control Tower's seismic performance, with a target of meeting at least 67% of the New Building Standard (%NBS) for an Importance Level 4 (IL4) structure with a 50 year design life.

2 CONTROL TOWER CONSTRUCTION

2.1 General description

Constructed in 1963, the Control Tower structure is located west of the south end of Fred Ladd Way at the Auckland International Airport. The Control Tower stands 29m high and is comprised of two elevated levels atop of a main reinforced concrete tower. The upper levels are constructed from reinforced concrete, structural steel, and timber. At an elevation of 22.4 metres above the foundation base, the lower of the two elevated levels functions as a service floor. At an elevation of 26 metres above the foundation base, the upper of the two levels functions as a control cab.

The hollow circular concrete main tower shaft has a 4.4 metre outer diameter, a 205mm wall thickness and is 22.4 metres tall from the base to the top of service floor slab. A 152mm thick cone-shaped wall extends out from the face of the shaft's circular wall to the underside of the service floor slab atop the shaft.

Atop of the main tower shaft is the elliptical-shaped service floor, the lower of the two elevated levels. The service floor major and minor axis dimensions are 12.8 metres and 10.4 metres, respectively. The service level floor slab is a 229mm thick concrete slab supported by the main tower shaft circular wall at the interior of the slab and by the main tower shaft's cone-shaped wall at the exterior of the slab.

Cantilevering up to 1.9 metres beyond the cone-shaped wall, the service level slab supports the service level exterior and interior timber framed walls, the service floor concrete roof, and the cab level concrete frame. As part of the exterior wall framing, horizontal steel angle trusses support the precast concrete panels at the lower half of the walls and vertical steel angle trusses support the stainless steel cladded mansard parapets at the upper half of the walls. Vertical steel angles and horizontal channels support the parapet's vertical trusses and the precast panel horizontal trusses. Half of the service floor's concrete roof is supported by these angles and channels within the exterior walls of the service level. The other half of the concrete roof is supported by the cab's concrete frame.

Figure 1: Control Tower elevation

Figure 2: Close-up of service and cab levels

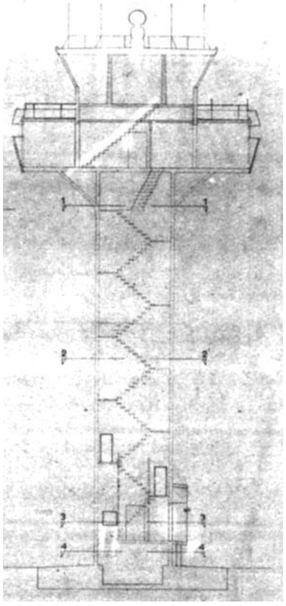

Figure 3: Cross section of Control Tower

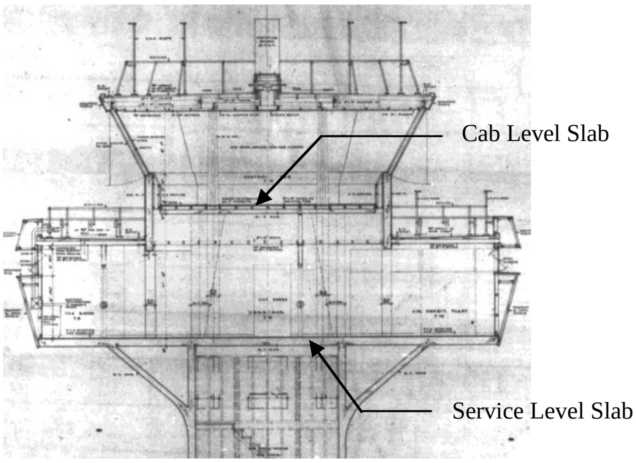

Figure 4: Cross section of service and cab levels

The control cab roof consists of timber and steel framing supported by a steel moment frame. Serving as the lateral resistance for the cab's roof, the steel moment frame is constructed with angle and channel section beams and double angle columns. The angle beams at the base of these frames, the angle and channel beams at the top of these frames and the double angle columns frame out the windows at this level of the Control Tower. Supporting the roof moment frame, the cab's concrete frame consists of 2.1 metre deep spandrel beams, a 125mm thick concrete floor slab, and eight tapered concrete columns. At the base, the column dimensions are 255mm by 355mm. At the top of the columns (the bottom of the spandrels), the column dimensions are 255mm by 760mm. The cab's roof and floor frames are supported by the 230mm thick concrete service floor slab.

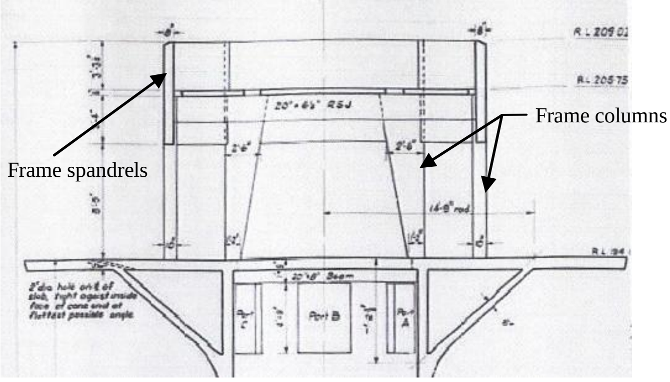

Figure 5: Cross section of service level slab and cab reinforced concrete frame

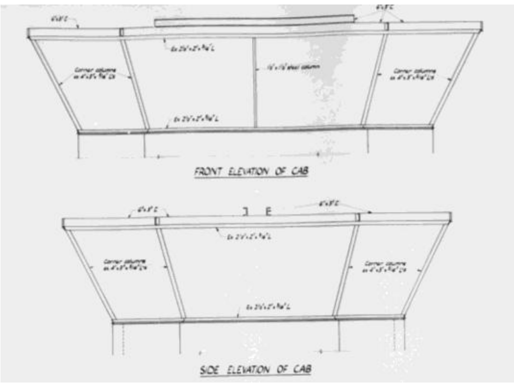

Figure 6: Cab roof steel frame elevations

2.2 Foundations and local geotechnical conditions

The Control Tower is supported on a cast in-situ concrete raft slab and prestressed pile foundations. The concrete raft slab is 10.7 metres in diameter and is 1.2 metres thick. Piles are 380mm square and protrude 685mm into the raft slab. The depth to which the thirty piles are driven is unknown.

Neither a desktop nor full geotechnical investigation has been performed for the site. Site geology consists of Puketoka alluvial material for the first 20-30 metres of soil. The Puketoka alluvial material is comprised of silts and sands with peat at some locations. Below this layer lies the Kaawa formation comprised of weak yellow pumiceous sandstone underlain by a shelly calcerous sandstone layer. There is low isolated liquefaction potential with minimal-to-no potential of lateral spread at the site.

2.3 Lateral force resisting systems

Three significantly different lateral force resisting systems are present with the Control Tower, with one at each level. These lateral force resisting systems are the main tower shaft, the cab level reinforced concrete moment frame, and the cab roof steel moment frame. The cab roof moment frame is constructed atop of the cab level concrete moment frame and the cab moment frame is supported by the service level floor slab atop of the cantilevered main tower shaft.

The Control Tower's most prominent lateral force resisting system is the 4.4 metre diameter circular hollow concrete main tower shaft. As mentioned previously, the tower shaft has a wall thickness of 205mm. It is 22.4 metres tall and cantilevers from the concrete raft slab and prestressed pile foundation.

Supported by the service level floor slab, which is constructed at the top of the main tower shaft, the cab level reinforced concrete moment frame consists of eight tapered columns, eight 2.1 metre deep spandrel beams and a 125mm thick concrete slab. The eight columns, four in each orthogonal direction, are pinned based and extend through the bottom half of the spandrel beams and terminate at the bottom of the cab level floor slab. Built integral to the service and cab level floor slabs and to the cab level spandrels, the cab level access stair inadvertently acts as part of the lateral force resisting system at this level.

Built atop of the cab level moment frame, the cab roof steel moment frame is constructed of ten outwardly slanted steel columns, eight unequal angle-C section upper beams, and eight single unequal angle lower beams. The upper and lower beams are at column tops and bases, respectively. Eight of the frame columns are 100mm x 75mm x 8mm double angles and the remaining two are 40mm square hollow steel sections. The double angle columns are seam welded along their leg edges to form a diamond shaped section. The upper beams consist of lower 65mm x 50mm x —8mm angles and upper 150mm x 75mm C sections. Sizes of the lower beam angles are the same as the upper beam angles.

3 SEISMIC ASSESSMENT

3.1 Methodology

Due to the multiple construction types and significantly different lateral force resisting systems present with the Control Tower, a modal response spectrum analysis was conducted to determine the distribution of lateral forces throughout the tower's three lateral force resisting systems. The tower was modeled in Microstran and the results from the response spectrum analysis were utilised in assessing each of the three lateral force resisting systems individually. LUSAS was utilised to assess the stresses in the main tower shaft and service level floor slab.

3.2 Summary of seismic performance

A summary of the Control Tower's assessed structural performance of each major structural element/system below 100%NBS is reported below in Table 1. Only the critical structural elements/systems were analysed, as these effectively define the building's seismic capacity. Elements/systems below 67%NBS are considered further in the following sections when developing strengthening options. Elements/systems less than 33%NBS are elements that classify the structure (or portion of the structure) as earthquake prone in terms of the Building Act, and hence need to be strengthened before other elements above 33%.

Table 1: Summary of seismic performance

Structural System	Governing Action	Failure Mode	% NBS
Main Tower Shaft at Base	Bending	Fracture of longitudinal reinforcement	90%
Main Tower Shaft at Door	Bending (door side in tension)	Fracture of longitudinal reinforcement	91%
	Bending (door side in compression)	Crushing of concrete	80%
Service Level Floor Slab	Bending	Crushing of concrete	85%
	Shear	Shear failure of reinforced concrete section	82%
Cab Access Stair	Transverse (in-plane) Bending	Fracture of longitudinal reinforcement	23%
Cab Access Stair Support Beam	Bending	Crushing of concrete	66%
Cab Roof Steel Moment Frame	Columns - all actions	Yielding of columns	45%

3.3 Evaluation of results

The seismic performance of the Control Tower's main tower shaft is governed by bending of the core column at the door. The main tower shaft's longitudinal reinforcement has the potential of fracturing after peak capacity is reached. This potential of fracturing is due to a low reinforcement ratio. There is also minimal confinement of the longitudinal reinforcement when the shaft is in compression from bending. Any amount of damage at the door might make the door inoperable.

The seismic performance of the Control Tower's service level slab is governed by the slab bending and shear capacities. Service slab shear failure would be attributed to high axial, shear and bending forces from the cab level access stair loading the service level slab. When the stair fails, the lateral loads in the stair would shift from the stair to the cab level concrete moment frame, hence increasing the chance for punching shear failure at the cab frame columns.

The seismic performance of the Control Tower's cab level concrete frame is governed by the capacity of the cab level access stair. The cab level access stair is unable to resist the displacement demands imposed on it. Since the stairs are built integral to the cab and service level floor slabs, the cab level access stair is inadvertently part of the lateral resisting system of the Control Tower cab. The stairs were not designed to resist such demands and as a result will be severely damaged in a 1-in-2500 year event (the IL4 design level event). The stair will thus be inoperable after this event. With regard to the stair support beam having a %NBS of 66%, once the cab level access stairs have been remediated, the capacity of this beam will be above 100%NBS.

The analysis of the cab roof steel moment frame has identified the columns as the governing element. Since the cab roof columns are slanted outward, they have a reduced capacity when compared to typical vertical columns of the same section. The interaction between these P-delta effects, the level of axial load and the biaxial bending induced from seismic loading causes these elements of the cab roof moment frame to govern the frame's capacity. Since the cab roof frame is quite flexible, P-delta effects from the cab frame deflections also increase the bending forces in the columns. Moreover, since the cab roof frame is highly flexible, there is a high probability that after the 1-in-2500 year event the windows in the cab will be shattered because of excessive deflections in the moment frame.

Under the 1-in-500 year event (the Serviceability Limit State (SLS2) event), the cab roof steel frame has deflections well outside of the serviceability limit. When considering the SLS2 event the capacity of the cab roof steel frame is at 81%NBS and the cab level access stairs has a capacity of 41%NBS. All structural elements discussed in this report have a capacity over 100%NBS for the SLS2 event.

The prestressed foundation piles have not been assessed due to the lack of design information provided. Capacity of the raft foundation exceeds the capacity of the main tower shaft, thus, with this consideration, global performance of the Control Tower is governed by the performance of the main tower shaft. Rocking of the raft foundation is minimal.

4 REMEDIATION AND STRENGTHENING SCHEMES AND IMPLEMENTATION

4.1 Cab access stair remediation methodology

The remediation methodology chosen for the cast in-situ concrete access stair was to disconnect the stair from the cab's lateral force resisting system (the cab's concrete moment frame) at the stair's base. This was accomplished by removing the bottom in-situ concrete step and replacing it with a new steel step. Only allowing for vertical support of the stair, the new steel step would be mechanically connected to the top of the service level slab. A Teflon pad would be placed between the bottom of the existing concrete stair and the top of the new steel step, effectively disconnecting the access stair from the cab's lateral force resisting system. Installing the Teflon pad allows for the access stair to slide across the top of the steel step during a seismic event. Because the Teflon pad disconnects the access stair from the cab's lateral force resisting system, the only forces present within the stair at all times are gravity forces. Disconnecting the access stair also removed the lateral forces in the cab access stair support beam, eliminating the need to retrofit this cab structural element.

4.2 Cab access stair remediation implementation

Implementation of the cab access stair remediation required removal of the bottom step of the cast in-situ stair. Upon removal of the bottom concrete step, the new steel step was slid into place and attached to the service level concrete floor slab with post-installed mechanical anchors. Reference Figure 7 and Figure 8 below for cab access stair construction prior to and after remediation, respectively.

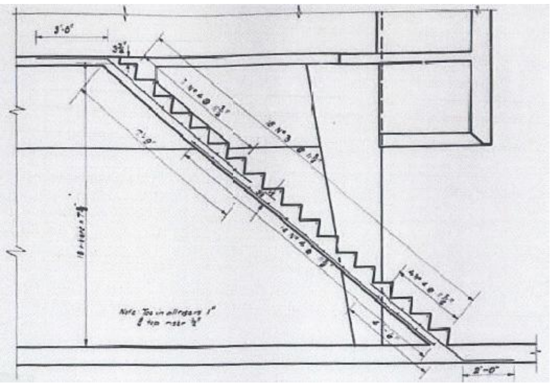

Figure 7:Cab access stair prior to remediation

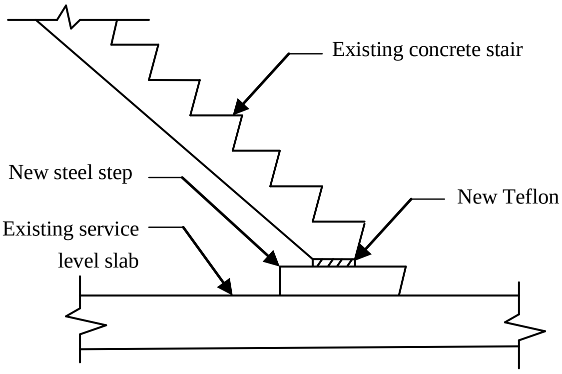

Figure 8: Cab access stair after remediation

4.3 Cab roof moment frame strengthening methodology

Since the steel frame columns need to be stiffened and strengthened and considering how the frame was constructed, the best strengthening strategy for the cab roof moment frame was to screw steel plates to the sides of the eight double angle columns. Replacing the columns would be costly and logistically unwise since the Control Tower needed to be constantly in operation except for a few early morning hours during the beginning of the week. Another issue that prevented the columns from being replaced was that the cab roof downpipes passed through the inner void of the double angle columns. The two steel square hollow section columns were not strengthened as it would be difficult and costly to retrofit them. Plus, the strengthening and stiffening of the roof moment frame could be accomplished by only retrofitting the eight double angle columns. Reference Figure 9 and Figure 10 below for the locations of the cab roof moment frame columns and for the double angle column retrofit, respectively.

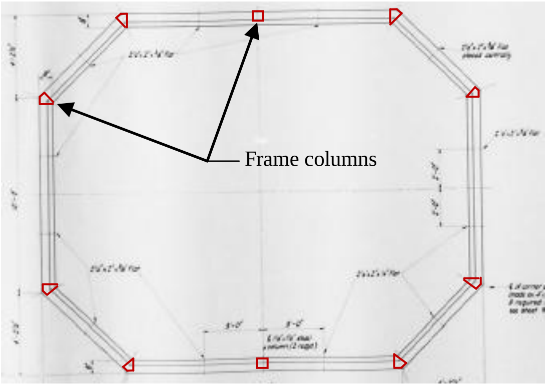

Figure 9: Cab roof moment frame column locations

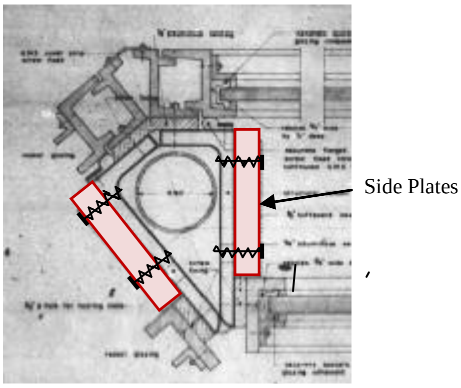

Figure 10: Double angle column retrofit

4.4 Cab roof moment frame strengthening implementation

Implementation of the cab roof moment frame strengthening highlights another advantage of installing side plates versus replacing the frame columns. The side plates were easily installed by accessing the service level roof, opening the cab windows and then screwing on the plates. Minimal amount of window frame architectural linings and steel surface preparation needed to take place. No window frame hardware needed to be removed.

4.5 The effects of remediation and strengthening

After the cab access stair remediation was implemented, the Control Tower no longer had any earthquake prone structural elements. Table 2 summarises the pre- and post-remediation %NBS of each major structural system of the Control Tower upon implementation of the cab level access stair and cab steel moment frame remediation.

Table 2:Pre- and post-remediation/strengthening %NBS (50 year design life)

Structural System	Pre-Remediation/Strengthening %NBS	Post-Remediation/strengthening %NBS
Main Tower Shaft at Base	90%	90%
Main Tower Shaft at Door	80%	80%
Service Level Floor Slab	82%	82%
Cab Access Stair	23%	>100%
Cab Access Stair Support Beam	66%	>100%
Cab Roof Steel Moment Frame	45%	81%

4.6 Control Tower replacement

It is projected that the Control Tower will be replaced within the next ten years. With this in mind, expensive retrofit strategies would not be economically feasible. Hence simple and inexpensive retrofit solutions were devised and implemented in communication with the client and contractor. Also since the Control Tower needs to function as an IL4 structure, since it is near the end of its design life and because of earthquake insurance issues, the client requested that the Control Tower be assessed as an IL4 structure with less than a twenty-five year remaining design life. Assessing the Control Tower as such places the post remediation/strengthening Control Tower %NBS above 100%.

5 IMPLEMENTATION OF RETROFIT SCHEMES AND CONTRACTOR RELATED ISSUES

For the cab access stair, the engineer’s proposed implementation strategy involved propping the stairs, removing the bottom concrete step, sliding in the steel step, attaching the steel step to the service level floor slab and then, lastly, placing the Teflon pad between the steel step and the existing stair. The contractor proposed a modification to this implementation strategy, which involved jacking the existing stair roughly 5mm to allow for the installation of the steel step. This modification was reviewed by Opus and determined to be a feasible modification to the implementation strategy. Reference Figure 11 for the jacking setup. Reference Figure 12 for the installed steel step.

The first contractor related issue involving the implementation of the cab access stair remediation was related to the difficulty of removing the bottom cast in-situ concrete step. Opus proposed utilising a concrete cutting chainsaw to remove the bottom step, which, when utilised with a jig, would allow for a relatively easy removal. But because of the cost of obtaining this type of speciality saw, the contractor ended up utilising a typical concrete saw and jack hammer.

The second contractor related issue involving the implementation of the cab access stair remediation was related to the steel step being fabricated too tall. This forced the contractor to remove more of the underside of the existing stair and to increase the jacking amount to roughly 10mm.

At the time this paper was being written, the implementation of the cab roof moment frame strengthening was not yet completed. Despite this, no contractor related issues have been foreseen.

Figure 11: Cab access stair jacking

Figure 12: Cab access stair steel step (without thread plate)

6 CONCLUSION

The seismic assessment of the Auckland International Airport Control Tower determined that the Control Tower cab access stair was earthquake prone since it was inadvertently part of the cab's lateral force resisting system. The assessment also highlighted the structural inadequacy of the Control Tower's cab roof steel moment frame. All other major structural systems were above 67% NBS and hence at low seismic risk.

Due to the seismically deficient cab access stair and the cab roof moment frame and due to the relatively inexpensive cost to retrofit these items, cab access stair and cab roof moment frame retrofit schemes were devised and implemented.

The cab access stair remediation strategy consisted of disconnecting the cab access stair from the cab level lateral force resisting system. This involved removing the stair's bottom cast in-situ concrete step and replacing it with a new steel step and Teflon pad. The cab roof moment frame strengthening consisted of installing steel side plates at eight of the ten cab roof moment frame double angle columns. These side plates not only strengthened the cab roof moment frame but also stiffened it, reducing its Code exceeded deflections.

7 ACKNOWLEDGEMENTS

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