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Importance level 4 structures: Design for seismic resilience and continued functionality. A case-study.

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ABSTRACT

Resilience and continued functionality following an earthquake are imperative requirements for Importance Level 4 (IL4) structures which, by definition, are required to accommodate special post-disaster functions. The failure to perform to this level is associated with serious economic, social or environmental consequences. The new Air Traffic Control (ATC) facility in Christchurch belongs to this category of structure. This facility, and its equivalent in Auckland, can each manage all New Zealand’s air space traffic requirements independently in the event of a natural disaster providing certainty of service. To help to achieve this objective, the ATC facility in Christchurch is supported by a base isolation system – a structural solution which is intended to protect the primary structure from damage and to limit damage to non-structural components via the ability to concentrate a high portion of the building displacement demand within the isolation bearings. In accordance with the American Seismic Isolation Standard for Continued Functionality (SISCF) and ASCE 7 Functionality Criteria, the inter-story drifts have been limited to less than 0.3% and the median floor spectral acceleration limited to 0.4g for a 500-year return period earthquake. Achievement of these limits corresponds to a likelihood of damage less than 2% of the building replacement cost. This is consistent with the REDi Platinum seismic damage limit (Almufti & Willford, 2013). Life-safety was targeted for a 2500-year return period event. For stability and collapse avoidance of the isolation bearings, their displacement capacity has been verified for a return period of approximately 6000 years.

1 INTRODUCTION

The Importance Level 4 (IL4) building considered in this paper is the new Air Traffic Control (ATC) facility located at 20-26 Sir William Pickering Drive, in Christchurch. This facility will be capable of managing all

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New Zealand's air space traffic requirement in case of a natural disaster providing certainty of service. Failure to provide this service may lead to serious economic and social losses.

The cause of most business disruption and downtime is generally associated with damage to non-structural elements such as partitions and ceilings tiles (Almufti & Willford, 2013). To protect these items and ensure continuity of service, the building has been isolated at ground level using Triple Friction Pendulum (TFP) bearings (manufactured by Earthquake Protection System (EPS), San Francisco, California) and tight drift and displacement criteria have been applied during the analysis/design of the main lateral resisting system. In accordance to the American Seismic Isolation Standard for Continued Functionality (SISCF) (Zayas et al., 2017) and ASCE 7 Functionality Criteria (ASCE/SEI 7-16, 2016), the inter-story drifts have been limited to less than 0.3% and the median floor spectral acceleration limited to 0.4g for a 500-year return period earthquake leading to a likelihood of damage less than 2% of the building replacement cost. In accordance with REDi, this corresponds to a Platinum seismic damage limit. Life-safety was targeted for a 2500-year return period event. For stability and collapse avoidance of the isolation bearings, their displacement capacity has been verified for a return period of approximately 6000 years.

2 RESILIENCE REQUIREMENTS FOR ATC FACILITY (CHRISTCHURCH)

Sir William Pickering Drive LP are developing (now under construction) a new Air Traffic Control (ATC) facility for Airways. Airways provided the design brief including resilience requirements to ensure continuity of service in case of natural disaster. The facility is intended to serve Airways tenant under their *One Centre, Two Locations* of operation strategy. The new Airways Auckland facility (by others) and the New Christchurch ATC facility can each independently manage all New Zealand's air space traffic requirements and, in the event of a natural disaster, can provide duplicity and certainty of service. The building is intended to perform as an Importance Level 4 (IL4) facility but with improved resilience compared to their current facilities or other standard buildings and being operational within minutes following a severe earthquake.

3 ATC FACILITY BUILDING

The New Christchurch ATC facility is approximately 1,400m^2 and consists of a services level (ground floor) with generators, plant, data equipment and storage; and an upper level to serve staff accommodation, facilities, offices and the airways operations rooms.

In addition to the structural resilience features (seismic isolation), the building is equipped and supported by standby generators, water and communications/data UPS.

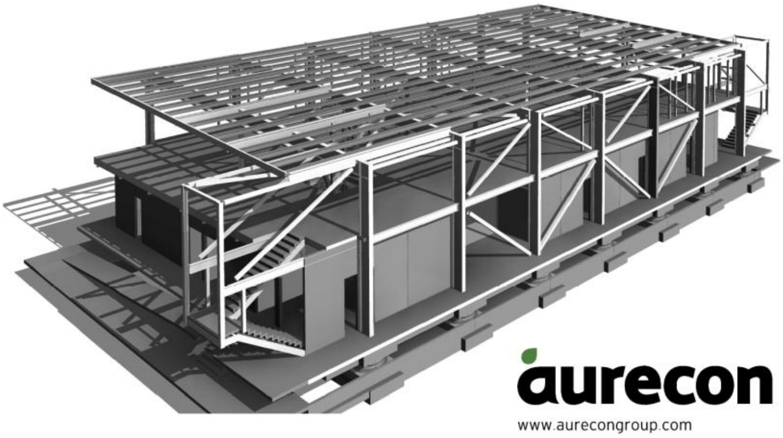


Figure 1: Structural Revit Model of ATC facility (Christchurch)

3.1 Isolation System

TPF bearings have been installed in this building to protect the superstructure and its contents from high accelerations and displacements in case of a significant seismic event. The decision to configure the isolation system in such a way that the building can move laterally above the ground (refer Figure 3) simplifies the details around the building by avoiding the need for special covers for a rattle space required to accommodate the displacement of the building leading to a more economical and resilient solution.

At ground floor the structure is supported by 21 TPF bearings. In addition to gravity load induced stresses, the ground floor concrete beams resist bending moments induced by the lateral displacements of the bearings during an earthquake.

The bearing type specified for this building is provided in the table below:

Table 1: Bearing type for ATC facility

Bearing Type	Displacement Capacity (mm)	Concave Surface Radius (mm)	Design Radius (mm)
FTP15663/12-10R/9-8	1313	3962	7658

Initial resistance to wind loads and small earthquakes is provided by friction within the bearings. Once the friction is overcome and the bearings start to slide, additional resistance is provided by gravity as the slider travels up the curved surface of the bearing.

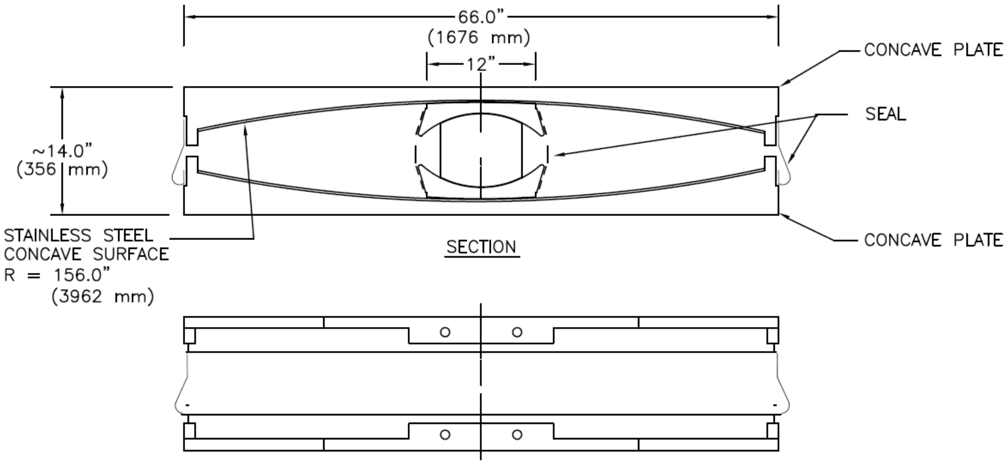
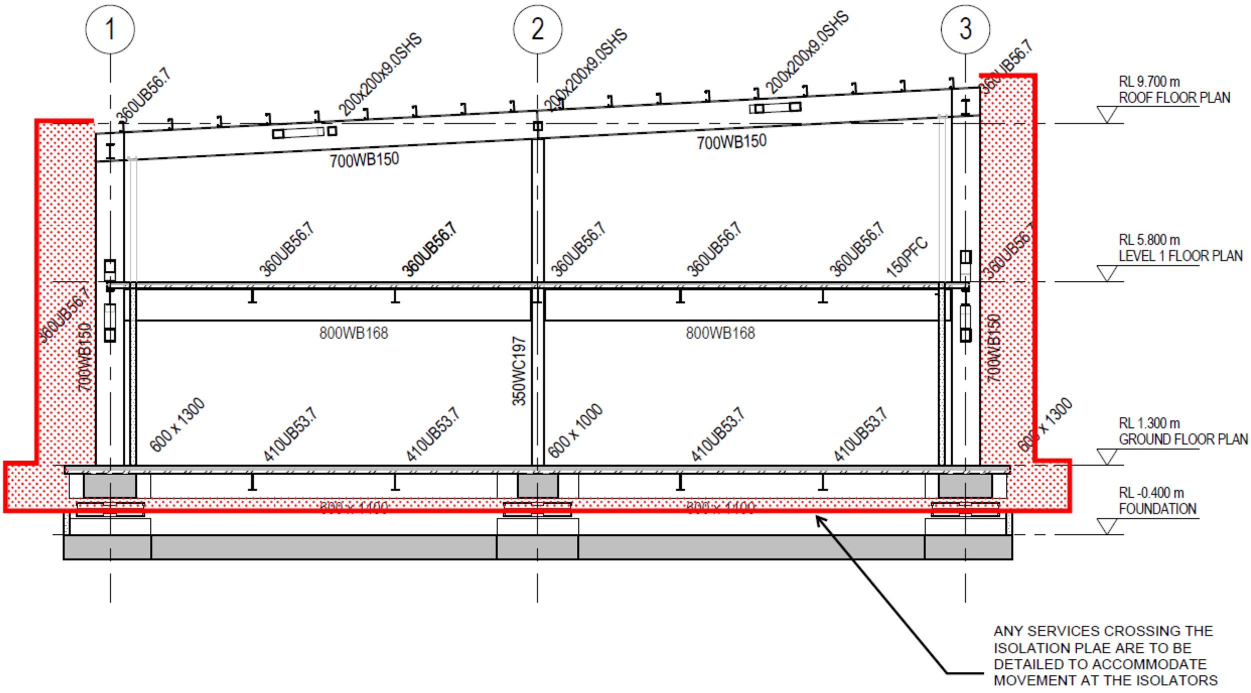


Figure 2: FTP15663/12-10R/9-8 specified for ATC facility (Christchurch). Elevation view.

3.2 Site Conditions and Foundations

The building is founded predominantly on gravel with some sandy and silty inclusions, and the water table is located approximately 5m below the ground level. Soil liquefaction is deemed unlikely at the site.

The site subsoil class considered for the site is soil type D. The foundation structure is a shallow founded grillage of beams on 200mm deep min. compacted hardfill as per geotechnical recommendations.



ANY SERVICES CROSSING THE
ISOLATION PLAE ARE TO BE
DETAILED TO ACCOMMODATE
MOVEMENT AT THE ISOLATORS

Figure 3: Indicative movement space around the building. Elevation view.

3.3 Lateral Resisting System

The lateral load resistance above ground floor is provided by steel Concentrically Braced Frames (CBFs) and steel Moment Resting Frames (MRF). The lateral loads are transferred down through the bearings at the ground floor and at the foundations. The foundation system provides resistance to the lateral load induced bending moments.

3.4 Gravity System

The typical floor structure is formed on Comflor60 at spans which do not require temporary construction propping. The Comflor60 is supported on steel secondary composite steel beams which in turn are supported by the perimeter CBFs, MRF, and by primary and secondary gravity beam elements running internally within the building. The roof is constructed from insulated panels supported on steel purlins which in turn are supported by steel beams. A steel lift shaft encloses the lift and is suspended below the ground floor to accommodate the lift overrun. No internal stairs crossing the isolation plane are present in the building.

A floating floor is present at level 1. This is used as an air plenum and as an area for distribution of the building services across the building/floor plate.

3.5 Generators' encasement structure

The encasement structure for the generators is reinforced concrete blockwork with a concrete lid for fire and acoustic requirements and it has been designed as an independent structure within the structure to avoid damage in case of a significant seismic event. A 50mm clear gap between main and secondary structure has been provided to achieve this separation.

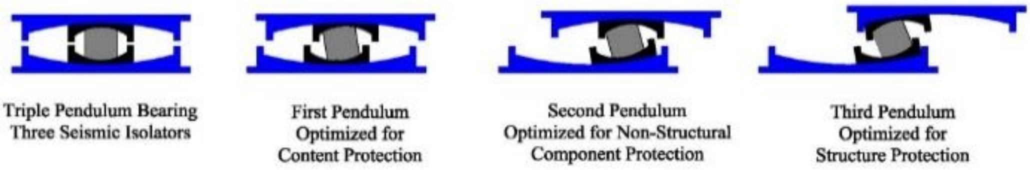
Piped and cabled building services

The piped and cabled services of this building have been designed by eCubed (Auckland). The services crossing the isolation plane are design to accommodate the potential displacement of the isolators with no significant damage.

4 DESIGN RATIONALE

As previously mentioned, to achieve the Airways project brief and resilience objectives, the building is supported by a base isolation system. This system acts to improve building performance for life safety, reduce structural and non-structural damage by limiting seismic demands imposed on the superstructure, and lessen the likelihood of business interruption in case of small and moderate events.

The isolators achieve this accommodating large displacement at the isolation plane, where a steel puck slides on a coated surface between four curved dishes.


Triple Pendulum Bearing
Three Seismic Isolators

First Pendulum
Optimized for
Content Protection

Second Pendulum
Optimized for Non-Structural
Component Protection

Third Pendulum
Optimized for
Structure Protection

Figure 4: Triple Friction Pendulum (TFP) bearings mechanism of movement. Courtesy of EPS.

The bearings used for the ATC building in Christchurch are TPF bearings. The TPF bearings allow the supported building to slide laterally in any direction up to the movement capacity of the bearing (in this case approximately 1300mm). The magnitude of movements depends on the size of the earthquake and relative ground acceleration, its duration, depth of the fault rupture, distance to site, interaction with the ground and other parameters which are inherently variable in nature. Above the isolation system, the structure is designed as a rigid/stiff box. This reduces inter-story drift (i.e. inter-floor movements) above ground level and forces most of the displacement (energy) demand into the isolators below which are devoted to dissipating seismic energy in the form of movement and heat.

To ensure structural reliability of these devices, all the 21 bearings installed in the Christchurch ATC facility have gone through a thorough quality control testing regime to ensure alignment with the design parameters for displacements up to the design level (i.e. a 2500-year return period event). Moreover, destructive prototype capacity testing was performed on two additional bearings to validate the maximum displacement and shear capacity of the bearings.

Figure 5: One of the bearing after destructive prototype testing.

Figure 6 shows one of the bearings after the destructive prototype testing. The shear force required to break the retainer rings corresponds to 0.48g at a displacement beyond 1400mm. Fracture of the ring is considered ductile as observed during the testing.

As previously mentioned, in order to achieve the resilience level required for this type of structures, the superstructure has been designed following tight drift and displacement criteria. In accordance to the American Seismic Isolation Standard for Continued Functionality (SISCF) and ASCE 7 Functionality Criteria, the inter-story drifts have been limited to less than 0.3% and the median floor spectral acceleration limited to 0.4g for a 500-year return period earthquake leading to a likelihood of damage less than 2% of the building replacement cost. In accordance to REDi, this correspond to a Platinum seismic damage limit. For the first time in New Zealand, Sir William Pickering Drive LP, in collaboration with EPS and Aurecon, are working toward the official certification for this facility, testifying the achievement of the targeted Platinum resilience level.

4.1 Seismic Demands and TPF Bearing Properties

4.1.1 Seismic Hazard

The hazard at the site has been established from the requirements of AS/NZS 1170.5. For Christchurch the zone factor is 0.3.

The interim GNS spectra for Christchurch produced for a site class D that has a ‘bump’ in the spectra in the 2-4 second range has not been used. This spectrum is noted to have the normal random excitation of an earthquake along with more systematic excitation associated to the resonance of the alluvial basin. When spectra are combined at damping levels higher than code standard 5% damping it is found that higher damping reduces the response by much more than the empirical relationships normally used to estimate the benefits of damping (Whittaker & Jones, 2013).

Displacement spectra modified removing the 3s corner period has been considered to define displacement demand at the bearings.

4.1.2 Seismic Loading

In accordance with the New Zealand Standard NZS1170 and American Seismic Isolation Standard for Continued Functionality (SISCF) and Guideline for the Design of Seismic Isolation Systems for Building (2017, in draft), four design events have been considered for the superstructure:

- Collapse Avoidance Limit State (CALS) event which has an approximated return period of 1 in 6000 years.

- The Ultimate Limit State (ULS) event which has a return period corresponding to the ULS load criteria appropriate to the importance of the structure. For an importance level 4 structure such the ATC Centre this is a 1 in 2500-year event
- Serviceability Limit State 2 (SLS2) which has a return period of 1 in 500 years.
- Serviceability Limit State 1 (SLS1) which has a return period of 1 in 25 years.

The structure is designed to withstand the forces generated by the ULS event remaining in its elastic range. It has then been checked that both superstructure and isolation system are stable during a 6000yr CALS event. Further to these two design cases, the displacement under an SLS1 level event with a return period of approximately 25 years has been considered for element response checks and the detailing of any minor sacrificial elements. Operational continuity after SLS2 earthquake is verified as part of the design.

The seismic forces acting on the structure have been derived from the response spectra provided by NZS 1170.5:2004 (with corner period removed as noted in the previous section) using the following parameters (Table 2):

Table 2: Design parameters in accordance to NZS1170.5:2004

Item	**Value**
Hazard factor Z	0.30
Soil conditions	Class D
Near fault factor N(T, D)	1.0
Return period factor R	
- 2500yr EQ (ULS)	1.8
- 6000yr EQ (CALS)	2.25
- SLS2 EQ	1.0
- SLS1 EQ	0.25
Structural performance factor S_p	1.0 (ULS and CALS).
Ductility	1.0 (all limit states)
Accidental eccentricity	5%

Accidental eccentricity equal to 5% is in accordance with ASCE7-16 and Guideline for the Design of Seismic Isolation Systems for Building (in draft).

4.1.3 Bearing Properties and Demands

The bearing selection determines the magnitude of the forces that the structure is required to resist. Following the results of the prototype testing of the isolators, the coefficients of friction shown in Table 3 have been considered for design purposes.

Table 3: Coefficients of friction considered for design purposes.

Friction	**f_1**	**f_2**	**f_3**
Average from Testing	0.02	0.08	0.10

The design of the foundation and of the super-structure has been designed allowing for a coefficient of friction of 0.095 (average between f_2 and f_3 + 0.05 for aging effects). The derived design parameters are summarized in Table 4:

Table 4: Derived design parameters.

Limit State	Acceleration	Horizontal Displacement (mm) – no torsion	Vertical Displacement (mm)
SLS2 (1/500yr)	0.120g	220	Approx.25
ULS (1/2500yr)	0.163g	510	50
CALS (1/6000yr)	0.187g	691	100

The distribution of the seismic forces along the height of the building has been assumed triangular in agreement with ASCE/SEI-7-10 Methodology and Guideline for the Design of Seismic Isolation Systems for Building (2017, in Draft). NZS1170.5 spectra have been considered for the definition of accelerations/displacements. As previously noted, no spectral corner period has been considered on the definition of the isolator displacement.

4.2 Building Demands and Movements

The building is divided into two types of structure above the isolators (main structure and the generator/fuel store encasement structure as a secondary internal structure), separated by seismic gaps. A minimum seismic separation between the secondary generator structure and the surrounding building of 50mm has been provided.

The building movements considered in the design of the ATC building are summarized in the table below:

Table 5. Design clearances between main and secondary structures

Parameter	Clearance (mm)
Clearance between the main structure and the generator/fuel store encasement structure.	50
Vertical clearance between non-load bearing walls and floor/beams above.	25
Horizontal clearance between lightweight non-structural elements and primary structure (i.e. timber walls).	25
Horizontal clearance between heavyweight non-structural elements and primary structure (i.e. blockwork/precast walls).	50

5 PLATINUM SEISMIC DAMAGE LIMIT

To meet the requirements necessary to achieve a Platinum seismic damage limit, EPS and Aurecon have conducted several numerical analyses on both the building and the isolators. Non-Linear Time History Analyses have been performed by both parties to ensure that the inter-story drift and the floor acceleration experienced by the building during an ULS event are within the REDi limits.

The analyses performed show that the expected drift of the superstructure for both directions of loading is smaller than 0.3% and the spectral floor acceleration was found to be below 0.4g for a seismic event with a return period of 500 years.

6 CONCLUSIONS

This paper presents an overview of the design approach followed for the new ATC facility in Christchurch to achieve stringent resilience requirements. The new ATC building is an IL4 building with isolation system installed at the ground floor to protect the building from a severe shaking induced by a significant earthquake and ensure post-earthquake continued functionality of this facility. Achievement of the requirements for Platinum seismic damage limits has been proven through several numerical analyses on both the building and the isolators.

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Any opinion, findings and conclusion or recommendations express in this paper are those of the authors and do not necessarily reflect those of Aurecon New Zealand Limited, Sir William Pickering Drive LP, and Airways.

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