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KILMORE STREET MEDICAL CENTRE: APPLICATION OF A POST-TENSIONED STEEL ROCKING SYSTEM

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ABSTRACT

The Kilmore Street Medical Centre is a new three storey building in the Christchurch CBD currently under construction. Tenants include a variety of specialist medical facilities, including four operating theatres, demanding an Importance Level 4 structure and design to the 1/2500 year earthquake at Ultimate Limit State and the 1/500 year earthquake at Serviceability Limit State.

The 2010 and 2011 Canterbury earthquakes have highlighted the need for a wider implementation of a "Damage Control Design" philosophy. Significant downtime and interruption to business has been experienced during the recent earthquakes, and tenants and building owners have developed higher expectations on the seismic performance of new buildings while moving forward into the rebuild of Christchurch.

To meet the design and performance requirements, the Kilmore Street Medical Centre utilises a post-tensioned steel rocking and dissipating (hybrid) system, representing the first application of steel PRESS technology in New Zealand. The lateral load-resisting system consists of coupled steel braced frames (or steel "walls"), vertically post-tensioned by un-bonded high strength steel bars. The frames are able to rock during a significant seismic event, with the post-tensioning providing a restoring force and re-centering characteristics. The design features special detailing at the connections between the floors/diaphragms and the braced frames in order to minimise displacement incompatibilities associated with the uplifting of "wall" systems during the lateral sway (regardless of these walls relying upon a rocking mechanism or not).

The structure is also implementing an "Advanced-Flag Shape" system (AFS) where displacement-proportional and velocity-proportional energy dissipation mechanisms are combined in parallel to the re-centering contribution from the un-bonded post-tensioned bars. An AFS system has been shown to provide robust seismic performance under both far field and near field seismic events. In this particular case, the hysteretic damping contribution is provided by replaceable axially-yielding mild steel fuse-bars while the viscous damping contribution is provided by the High Force-to-Volume lead extrusion devices, developed and tested at the University of Canterbury and implemented for the first time in real practice.

This paper describes several aspects of the steel structural system, outlines the design procedure and describes some of the technical and practical challenges that were faced during the design and, still ongoing, construction phases.

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Introduction

The Kilmore Street Medical Centre is a new building located in the Christchurch central business district. The building is three stories with over 5000m² of specialist medical facilities, including four operating theatres, patient bedrooms and urology, radiology, orthopaedics and fertility clinics. There is over 650m² of plant deck on the roof and a further plant room at ground level. Construction commenced in July 2012 and the building is due for completion later in 2013.



Figure 1: Architectural Render of the Kilmore Street Medical Centre

The 2010 and 2011 Canterbury earthquakes have highlighted the need for a wider implementation of a “Damage Control Design” philosophy (Pampanin, 2012). Significant downtime and interruption to business has been experienced during the recent earthquakes, and tenants and building owners have higher performance expectations moving forward into the rebuild of Christchurch.

To meet the design and performance requirements, the Kilmore Street Medical Centre utilises a post-tensioned steel controlled rocking and dissipating (hybrid) system, the first application of steel PRESSS technology in New Zealand. In addition to the structural design, the building includes features such as a generator, water bore and sewer tank so that the building can be self-sufficient and remain operable following a major event.

Structural Description

The building floor plate is approximately 45m x 40m and consists of a predominantly steel structure. The suspended floors consist of steel-concrete composite slabs with eight sets of coupled steel post-tensioned braced frames located around the perimeter of the building to provide the lateral load resistance. Refer to Figure 2 for a typical floor plan.

A large plant deck covering over one third of the floor plate is located on the roof for the intensive plant equipment required for a medical facility. A single level precast plant room structure is located to the north of the building, which is seismically isolated from the rest of the structure. The lift and stair cores are constructed from precast concrete walls.

The building is clad with curtain wall glazing and the braced frames sit in a frosted glass enclosure, so that they are incorporated as a feature of the building’s architecture.

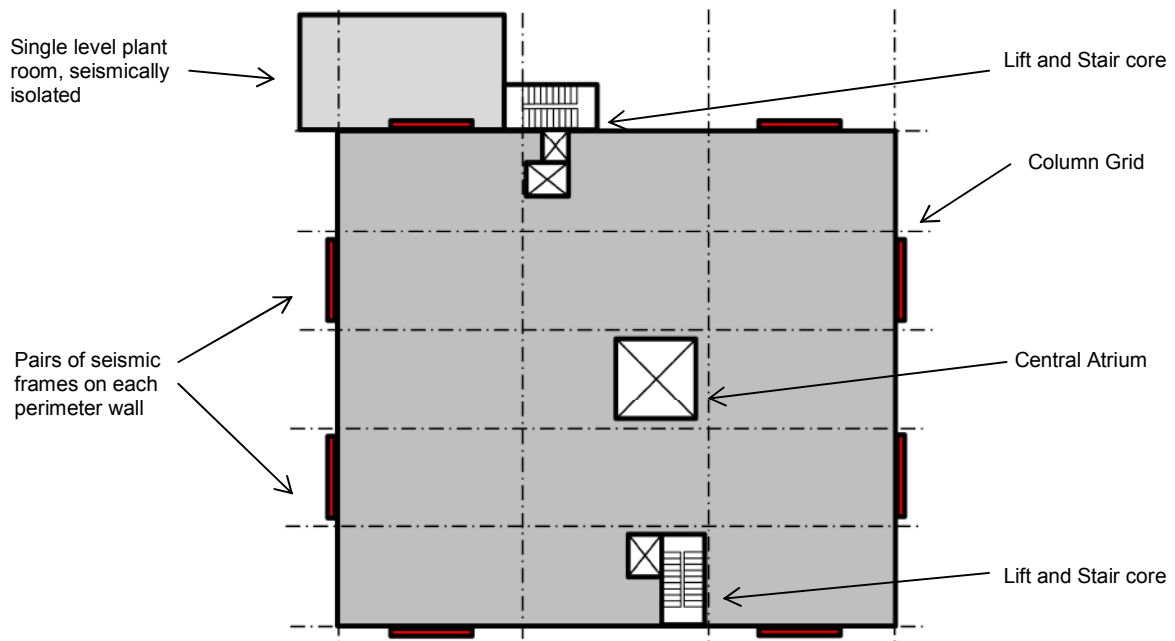


Figure 2: Typical floor plan

Background to PRESSS

The concept of rocking and dissipative (hybrid) self-centering systems was originally developed and tested in the United States (Priestley 1991, 1996; Priestley et al. 1999) using precast concrete, commonly known as PRESSS (Precast or Prefabricated Structural Seismic Systems). It has since been applied in a number of structures around the world and in New Zealand (Pampanin, 2005; Cattanaach and Pampanin, 2008; NZCS, 2010). Recently the concept has been applied using engineered timber, known as PRES-LAM system, with an increasing number of applications in New Zealand (Palermo et al. 2005; Devereux et al. 2011).

A major research programme was carried out by a collaboration of universities in the United States on steel self-centering braced frames, the steel equivalent of PRESSS post-tensioned rocking walls (Roke et al. 2009; Hajjar et al. 2010; Deierlein et al. 2010). The research included large scale dynamic testing at the E-Defence shake table in Japan, and confirmed the technology delivers a high seismic performance.

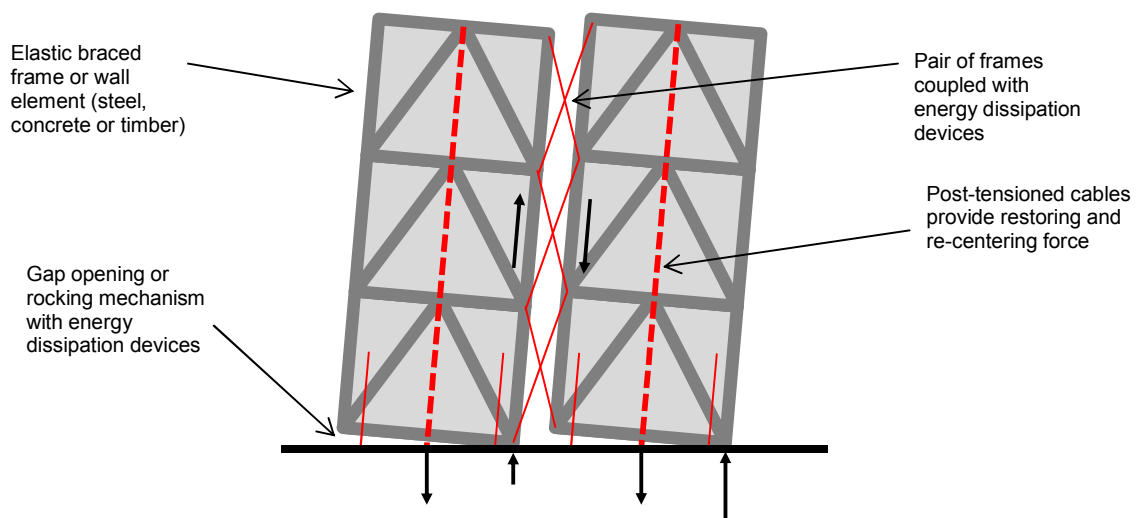


Figure 3: Schematic of PRESSS technology, using coupled walls (or frames)

The concept of these systems is to allow controlled rocking of the structure to reduce damage to the primary structural elements themselves. Refer to Figure 3 for a schematic of a typical PRESSS coupled-wall system. Un-bonded post-tensioned tendons or bars provide a restoring and self-centering force. Energy dissipation occurs at the rocking interface, and can be provided in many different forms. Pairs of braced frame or wall elements can be coupled together with further energy dissipation devices to provide additional strength and stiffness. The braced frames and post-tensioned bars are designed to remain elastic, while the energy dissipation devices accommodate the inelastic demand and can be replaced if necessary.

This type of hybrid system has a unique hysteresis loop referred to as a “flag shape” hysteresis; refer to Figure 4. The hysteretic behaviour can be modified by adjusting the various contributions of the post-tensioning and the energy dissipation devices.

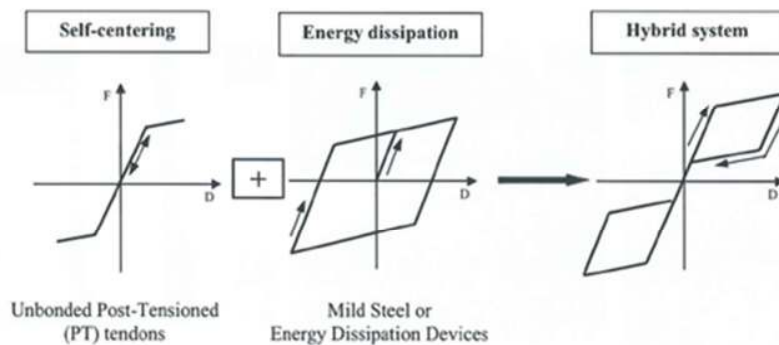


Figure 4: Flag shape hysteresis behaviour for hybrid system (Source: NZCS, 2010)

A second generation of self-centering/dissipative high-performance systems, referred to as “Advanced Flag-Shape” systems (AFS), has been recently proposed and tested at the University of Canterbury. AFS systems combine alternative forms of displacement-proportional and velocity-proportional energy dissipation in parallel with the re-centering mechanism. As a result, it is possible to achieve an enhanced and very robust seismic performance, under either far field or near field events (high velocity pulse), as demonstrated by numerical investigations (Kam et al. 2010) as well as shake table testing (Marriot et al. 2008).

Steel Braced Frames or “Walls”

The seismic resisting system at the Kilmore Street Medical Centre consists of pairs of concentrically braced frames (CBF’s) coupled together, representing the equivalent of the concept of coupled post-tensioned and dissipative “walls” using structural steel.



Figure 5: Pair of steel braced frames assembled in the workshop with dampers



Figure 6: Overview of steel braced frames assembled in the workshop

Each CBF is a single fabricated element and is vertically post-tensioned to the foundation with two 75mm high strength Macalloy bars. The frame consists of a 400mm deep double-webbed I-section, which was used to enable the post-tensioned bars to pass through the middle of the frame and to reduce the unsupported length of the flanges. The frames sit in a base “shoe” which acts as a shear key under horizontal loading.

Axially yielding mild steel fuse rods provide hysteretic damping and are located at the base of the frames at the rocking interface and between the two frames to provide coupling between them. Similarly, University of Canterbury-developed High Force-to-Volume lead extrusion dampers (Rodgers et al. 2008; Rodgers 2009) provide viscous damping, and are also located at the base and between the frames.

A feature of the design includes special detailing at the connection between the floor diaphragms and the lateral load-resisting system in order to minimise the effect of the displacement incompatibilities associated with the uplifting of “wall” systems during the lateral sway (regardless of these walls relying upon a rocking mechanism or not). A steel tongue plate protrudes from the floor structure and fits through a slot in the seismic frame; refer to Figures 7 and 8. The tongue plate is able to slide up and down within the seismic frame to accommodate the vertical movements experienced by the frames as they rock.



Figure 7: Seismic frame collector beam with slot for tongue plates



Figure 8: Tongue plate protruding from floor structure that slots through the seismic frame

Lateral loads are transferred via bearing of the steel plate onto the frames. Brass shims are used within the frame to reduce the friction whilst still providing the necessary bearing strength. Steel columns are provided within the floor structure at these connection points to resist the friction-induced vertical forces. Out-of-plane restraint is provided to the columns of the seismic frames at each floor level via a simple tension tie and compression bearing system. These are designed to accommodate the movements experienced by the frame as it rocks, and are isolated from the horizontal load transfer system.

The use of steel provided a number of advantages for this type of system, particularly for resolving the floor diaphragm-to-seismic frame connections. Significant forces are required to be transferred, which lends itself to the use of steel which is capable of sustaining high bearing forces. In addition, the use of steel enabled the connection to be designed so that it could develop a ductile mechanism in the event of overload.

Mild Steel Fuse Rods

The rods consist of a mild steel round bar which is designed to yield in axial tension and compression to dissipate energy. This type of system is also known in more general terms as a buckling restrained brace, and has been modified and adapted for the specific use as part of a key component of rocking and dissipative post-tensioned rocking systems in recent years. The bar has a reduced diameter over the central region to create a fuse where the yielding can be concentrated. The length of this fuse was determined based on the expected total elongation (stroke) required and material strain limits.

The bar is restrained from buckling by a larger outer tube, which is filled with grout, and is de-bonded to prevent it acting compositely with the grout. One end of the rod is fixed to the outer core and the other end is free to allow for the relative extension and compression. Figure 9 shows some of the rods under fabrication.



Figure 9: Mild steel fuse rods under fabrication and prior to being encased and grouted



Figure 10: Mild steel fuse rods assembled with the braced frames in the workshop

The end regions of the rods are welded to a stiffened plate which connects to the structure with high strength pins. The brackets are bolted to the braced frames which provide tolerance, as shown in Figure 10.

Floors

The floor structure consists of a concrete-steel composite floor system, as shown in Figure 11. The slab is 150mm thick with a 60mm profiled metal deck. The secondary beams span approximately 14.7m, which provides large open spaces and maximum flexibility for the use of the space. Holes are provided in the webs of the floor beams to allow for services to pass through the beams.

The beam-column joints were designed as “top hinge” connections to minimise any displacement incompatibilities from lateral deflections and to limit damage to the concrete floor slab. The connections consisted of a double web cleat welded to the column, which bolted to the web of the beam in double shear. Slotted holes were provided to the lower bolts to allow the beam to pivot about the floor slab as the building displaces laterally.



Figure 11: Concrete-steel composite floor structure under construction



Figure 12: Sliding Hinge Joint for secondary frames during construction

The internal beam-column joints (Fig. 12) implement the “Sliding Hinge Joint” solution (MacRae et al., 2010) to provide a secondary moment resisting frame system. This system can accommodate the lateral displacements required for displacement compatibility with the main seismic resisting system, while providing additional redundancy to the lateral system and stability to the building during erection and after a fire.

The Slab Panel Method (HERA, 2006) was used to determine the extent of fire rating to the floor steelwork. Using this method it enabled every third secondary beam to be fire rated with the remaining secondary beams left unprotected. Primary beams and columns were also protected. The fire rating was provided by intumescent painting.

Deflection and vibration criteria governed the design of the floor. Due to the type of occupancy, the building contained several vibration-sensitive areas, in particular the operating theatres and the patient bedrooms. Steel Construction New Zealand (SCNZ) was engaged to perform a vibration analysis on the floor system using their Oasys GSA finite element software. Based on the SCNZ analysis, the floor under the operating theatres was stiffened slightly to meet the required vibration acceptance criteria.

Stair and Lift Cores

The stair and lift cores consist of precast walls, which are detailed to pivot and rock about the centre of the wall to minimise any displacement incompatibilities with the primary steel braced frame structure. Precast walls provide the required fire rating as well as being stiff enough to limit distortions between floors that can damage non-structural elements and, importantly, affect the operation of the lifts.

Foundations

The site presents a significant liquefaction hazard. The foundations consist of 168 steel H piles driven to a typical depth of 24m; refer to Figure 13. Steel H piles were the preferred solution due to the ability to drive through intermediate dense layers, reduced post-liquefaction negative skin friction and the inherent ductility capacity so that lateral movement can be accommodated by the piles.



Figure 13: Steel H-piles being driven to approximately 24m

Concrete foundation beams span between piles. The post-tensioned Macalloy bars are anchored near the bottom of the foundation under the seismic frames. The bars are encased in a steel box and baseplate assembly so that the bottom nut and washer is accessible from the side of the foundation. The assembly is grease-filled to provide protection from corrosion.

Seismic Design Procedure

A direct displacement-based design (DDBD) procedure (Priestley et al. 2007) was adopted for the design of this structure, in conjunction with design guidelines available in New Zealand for similar systems

(NZCS, 2010), and a procedure to modify the DDBD to allow for the contribution of the viscous dampers (Marriot, 2009).

Due to the type of occupancy, this building was considered an Importance Level 4 (IL4) structure, requiring design to the 1/2500 year earthquake at the Ultimate Limit State (ULS), along with Serviceability Limit State (SLS1/SLS2) checks at the 1/45 year and 1/500 year earthquakes. In addition, specific checks were made at a level larger than the 1/2500 year earthquake to represent the Maximum Considered Event (MCE).

A preliminary DDBD was used to determine the initial sizes of the steel frames, post-tensioning, energy dissipation and foundation requirements. A moment-rotation analysis at the rocking interface was carried out using principles of equilibrium. A non-linear static analysis was used to carry out the detailed design. A capacity design procedure allowing for overstrength and dynamic effects was implemented for individual elements and the system as a whole to ensure that that it performs as intended and undesirable mechanisms are avoided. Material strain limits were checked or used as the basis of the design as appropriate.

Following the detailed design, non-linear dynamic analysis was used to verify the static design assumptions and general system performance. This showed that under a range of earthquake excitations, the system delivered a high seismic performance.

Further details and discussion on the seismic design and analysis of this building will be presented in future publications.

Design and Construction Issues

Design Challenges

A project of this nature utilising a new innovative structural system presented several challenges to the design. Considerable background research and review of available literature was required before commencing the project, and along with the more in-depth analysis required, the overall design effort required was considerably greater than if a traditional structural system was used.

The design of the floor diaphragm-to-seismic braced frame connection was a particularly challenging aspect of the design. The connection had to be capable of transferring large horizontal forces while allowing the seismic frames to uplift relative to the floor. This criterion was required due to the building function and to be consistent with a “Damage Control Design” philosophy. The floor also had to support the seismic frame and the columns out-of-plane.

A number of different options were considered, and several iterations of the connection were developed before establishing the final solution. It was necessary to find a solution that was technically adequate, was sufficiently robust, whilst being relatively straightforward to fabricate and erect. Tables 1 and 2 describe some of the options that were considered during the design process.

Table 1: Options for main floor diaphragm to seismic frame connection considered during design

Option	Schematic	Comments
Single pin in slotted hole		<p>Allows for uplift and rotations</p> <p>Contact surface of a round pin on a straight surface is small giving a very small bearing area</p> <p>Difficult to achieve tolerance</p>

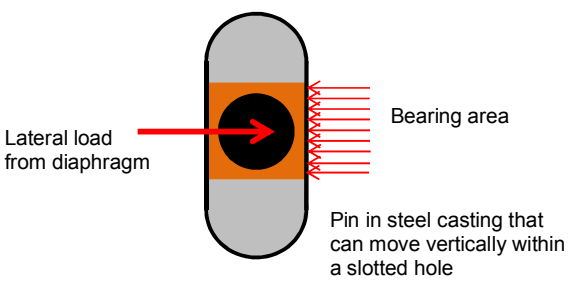
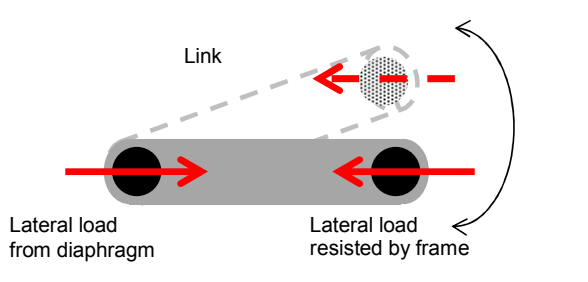
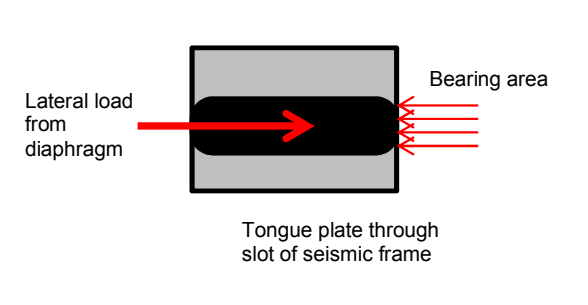
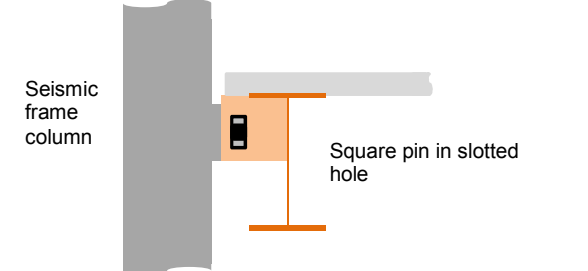
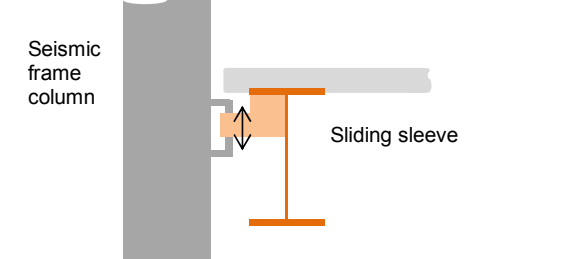
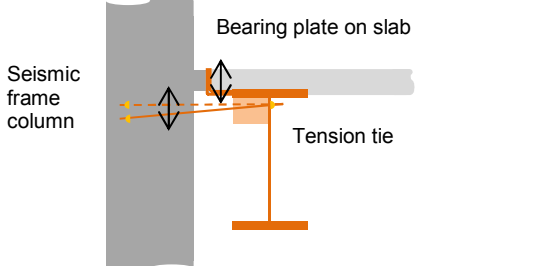
<p>Single pin in a round hole within steel casting within a slotted hole</p>	 <p>Lateral load from diaphragm</p> <p>Bearing area</p> <p>Pin in steel casting that can move vertically within a slotted hole</p>	<p>Allows for uplift and rotations</p> <p>Larger bearing area</p> <p>High friction may prevent vertical sliding</p> <p>Potential for uneven bearing of casting on seismic frame surface</p>
<p>Link system with two pins</p>	 <p>Link</p> <p>Lateral load from diaphragm</p> <p>Lateral load resisted by frame</p>	<p>Allows for uplift and in-plane rotations</p> <p>Relatively uniform bearing of the pins</p> <p>Difficult to accommodate out-of-plane displacements</p>
<p>Protruding tongue plate</p>	 <p>Lateral load from diaphragm</p> <p>Bearing area</p> <p>Tongue plate through slot of seismic frame</p>	<p>Allows for uplift and rotations</p> <p>Bearing area can be controlled</p> <p>Friction may prevent vertical sliding however can be minimised by design</p> <p>Ductile yielding mechanism in case of overload</p>

Table 2: Options for out-of-plane restraint of seismic frame considered during design

Option	Schematic	Comments
<p>Sliding square pin</p>	 <p>Seismic frame column</p> <p>Square pin in slotted hole</p>	<p>Provides out-of-plane stability while allowing for vertical uplift of column</p> <p>Difficult to accommodate rotational distortions</p>
<p>Sliding sleeve</p>	 <p>Seismic frame column</p> <p>Sliding sleeve</p>	<p>Provides out-of-plane stability while allowing for vertical uplift of column</p> <p>Rotational distortions can be accommodated</p> <p>Complex fabrication and erection</p>

<p>Tension tie and compression bearing plate</p>	 <p>The diagram illustrates a structural connection between a seismic frame column and a slab. A bearing plate is shown on the slab, and a tension tie connects it to a steel beam below. Arrows indicate lateral movement of the column and vertical uplift of the column.</p>	<p>Provides out-of-plane stability while allowing for vertical uplift of column</p> <p>Rotational distortions can be accommodated</p> <p>Simple fabrication and erection</p>
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Another challenging aspect of the design was the integration of the architectural and building services. Considerable efforts were made to ensure the expected seismic lateral displacements were adequately communicated to, and understood by, the designers of the glazing and cladding systems, to ensure the building will have a high seismic performance as a whole.

Review and Consent Process

A quasi-independent peer review process of the seismic design was carried out by Dr Stefano Pampanin, Associate Professor from the Civil Engineering Department of University of Canterbury and Director of PRESSS Ltd. This mechanism allowed for the review to be commenced at very early stages of the project, with significant benefits in terms of regular availability and critical feedback throughout the design.

This type of structural system and the use of DDBD is not covered by a verification method to the New Zealand Building Code (NZBC). Instead the design required an alternative solution, which involves specific justification and evidence that the performance requirements of the NZBC are achieved. The Christchurch City Council (CCC) was familiar with the design of rocking and dissipative systems, a DDBD procedure and the quasi-independent review process adopted in this project. There were no specific issues raised by CCC related to the structural design and the alternative solution. However it is the authors' recommendation that further research is carried out to develop comprehensive design criteria for this type of steel post-tensioned braced frame system into design codes and an associated design handbook, similar to Appendix B of the Concrete Structures Standard, NZS3101:2006 and the NZ Concrete Society PRESSS-Design Handbook, respectively.

Construction Challenges

As for the design, this project presented a challenge for the contractor, Fletcher Construction, and steelwork sub-contractors, John Jones Steel in conjunction with D&H Steel. While many aspects of the design were conventional, there were aspects of the steel system that were new to the contractors. ARCL has worked closely with the contractors to help them understand how the system works and the critical aspects of it.

At the time of writing, only part of the building structure has been erected. A particular challenge for the contractors has been erecting a building in a seismically active zone. Additional bracing and propping has been required to allow pouring of the floor slabs in sections, and to reduce the risk to the contractors working on site as well as damage to the structure in the event of a significant aftershock.

Material Compliance

The New Zealand Steel Structures Standard, NZS3404:1997, provides a list of material standards that all structural steel must comply with to be within the scope of the Steel Structures standard. Structural steel that does not conform to one of the listed standards is outside the scope of NZS3404 and its role as a verification method to the NZBC. Table 3 lists the joint Australian / New Zealand material standards given in NZS3404. In addition to compliance with the relevant material standard, the material also needs to meet requirements that ensure brittle fracture is suppressed.

Table 3: Australian / New Zealand Structural Steel Material Standards

Standard	Latest Revision	Title
AS/NZS 1163	2009	Structural Steel – Hollow Sections
AS/NZS 3678	2011	Structural Steel – Hot-rolled Plate, Floorplates and Slabs
AS/NZS 3679.1	2010	Structural Steel – Hot-rolled Bars and Sections
AS/NZS 3679.2	2010	Structural Steel – Welded I-sections

The latest revisions of these standards outline the minimum requirements for test reports and test certificates. One of the key requirements that is consistent across all of the standards in Table 3 is that all tests carried out for the purpose of establishing compliance with the material standard must be performed by a laboratory accredited by signatories to the International Laboratory Accreditation Corporation (ILAC) through their Mutual Recognition Agreement (MRA), in the field and class of testing that they have undertaken. In Australia, the ILAC (MRA) accredited body is the National Association of Testing Authorities (NATA) and in New Zealand is the International Accreditation New Zealand (IANZ). This requirement ensures that test certificates can be acceptably relied upon.

The contractors and ARCL have made considerable efforts to ensure all materials used on this project comply with the required standards. Many sources of steel supply were excluded as they did not comply with the requirements. It was particularly challenging for the contractor to source large hollow sections. A process was adopted whereby the contractor submitted all material certificates to ARCL prior to fabrication for review to ensure that all material was compliant.

The NZBC and the updated materials section of NZS3404 allows the use of alternative material specifications via an alternative solution on the basis that acceptable evidence is provided to show that the performance requirements of the NZBC are met. Specifically, NZS3404.1:2009 allows other internationally recognised standards to be used if they are approved by a qualified metallurgist or materials engineer as being equivalent to the cited standards. It would be beneficial for further work to be carried out on this and the list of acceptable alternative standards increased if possible, so that a greater number of sources of steel supply are available to the contractor.

Fabrication Quality Control

A high degree of quality control was required for this project. A comprehensive quality control plan was adopted by the contractor which ensured full traceability of materials and workmanship throughout the project. All materials were stamped and traced back to their material certificates. All welds were stamped with a welder identification number, which could be linked to their qualifications and the weld procedures used. The welder and welding supervisor had to formally sign off on each weld.

Southern Quality Assurance was engaged to carry out an independent review and non-destructive testing (NDT) of the welding and fabrication. Critical welds were identified which were given more rigorous review and NDT testing. The procedures adopted by the contractor along with the independent testing regime have ensured that a high quality end product is produced.

Conclusions

The Kilmore Street Medical Centre utilises post-tensioned steel rocking and dissipating braced frames to deliver a system with high seismic performance, consistent with a “Damage Control Design” philosophy, whilst meeting demanding seismic design criteria. The project is under construction and is generally within budget and on schedule. It has shown that this type of system is viable for future developments.

The client, design team and contractor have supported the use of this innovative steel structural system and shown enthusiasm about the project and the use of the technology. The contractor has shown commitment to achieving a high standard of workmanship.

Further development and research, in conjunction with designers, contractors and academia, would be beneficial for this type of system, with an aim to further optimise the design and construction of these types of buildings.

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