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University of Otago Dental School: Low-damage design for moderate seismicity

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ABSTRACT: Due to the costs incurred by building owners during recent seismic events, there is an increasing desire to design buildings with technology intended to not only increase performance during a seismic event, but also reduce the costs to the building owner in the aftermath. The Replaceable Active Link (RAL) Eccentrically Braced Frame (EBF) is a construction typology that is able to satisfy these goals in a cost effective manner. The new University of Otago School of Dentistry building is located in Dunedin, a region of moderate seismicity, and has been designed to use the RAL EBF system. The RAL EBF system was selected for this building not only because it exhibits excellent seismic performance, but also because the system facilitates rapid rehabilitation of the building following an earthquake, which minimises building downtime. Ductility and damage is concentrated in fusible links, which can be quickly and inexpensively replaced. Furthermore, because the overstrength of the system can be tailored through the design of the RAL, an efficient structural system can be developed. The bolted connections used in the RAL EBF system also enable simplified erection procedures. This paper presents the background, analysis and design of the low-damage RAL EBF system that was developed for the new School of Dentistry building.

1 INTRODUCTION

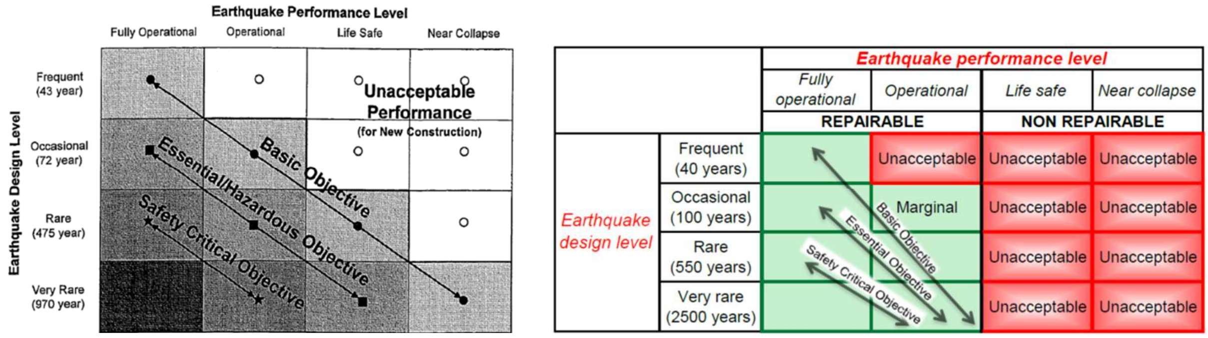
Following the 2011 Canterbury earthquake sequence, New Zealand building owners have become more aware of seismic risk. The risk to a building owner from an earthquake stems not only from the potential damage that may be sustained by the building, but also from loss of rental income whilst repairs are being undertaken and the business interruption that may result to the tenants. Performance-based design, and in particular low-damage design, can be applied to reduce risk to both building owners and occupiers.

2 PERFORMANCE BASED DESIGN

Performance-based design (PBD) is a design philosophy that, instead of using traditional prescriptive methods to describe building performance, places emphasis on achieving a certain level of performance. In this manner, each performance state can be evaluated against both the probability of a loading scenario occurring, which results in a performance state being reached, and the approximate consequences that result. By following this philosophy, a building can be designed to meet better the requirements and expectations of the client.

In the context of building earthquake resilience, Figure 1a presents the relationship between earthquake intensity and the resulting building damage for performance states as broadly defined in current New Zealand Standards (Standards New Zealand, 1997; 2004; 2006). That is, for an Ultimate Limit State (ULS) earthquake intensity a building is designed to protect the lives of the occupants. It is expected, and in some ways encouraged by the current application of capacity design principles, that a building will sustain relatively major damage in response to a ULS intensity earthquake.

The Canterbury earthquake sequence has shown that the true cost of earthquake damage is not only that associated with the repair of the physical damage, but also the cost of building downtime to the building owner and tenants; it was not uncommon for the latter cost to be more significant than the former. Building owners, and society in general, were often surprised to learn that these damaged buildings, when assessed against current New Zealand design philosophies, were considered successful designs, and they have begun to expect better performance from buildings. In response to this increased awareness, Buchanan et al. (2011) recommended that the performance objectives of the design Standards be revised to ensure that buildings are not only repairable after a major earthquake, but operational also (Standards New Zealand, 2004). Figure 1b presents the revised performance objective matrix.



Performance objectives relative to current Standards (SEAOC Vision 2000 Committee, 1995). **Performance objectives proposed by Buchanan et al. (2011).**

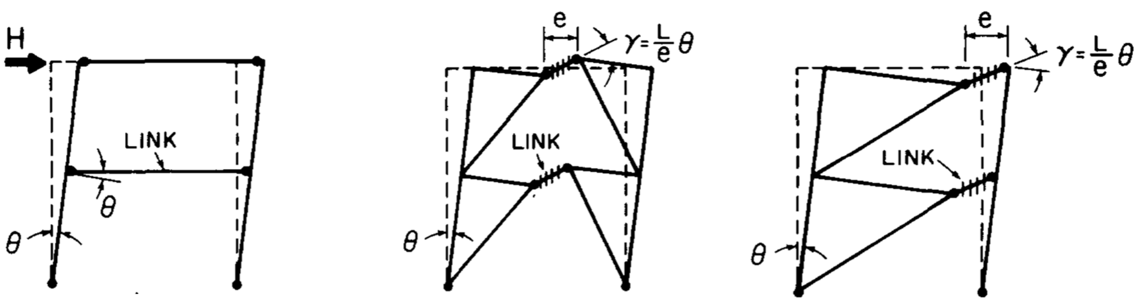
Figure 1. Performance objectives matrices.

Low-damage design (LDD) in its broadest sense is the practical application of PBD. It is a mean by which the performance of a building during an earthquake can be improved, the damage sustained reduced and the building downtime in the aftermath minimised. By applying LDD, a building can be designed to achieve a greater performance level than a comparable design conducted using conventional design philosophy, when subjected to a variety of earthquake loading intensities. In many cases, applying LDD is cost comparable to using conventional design philosophy and provides for significant overall cost savings in the event of an earthquake.

Replaceable Active Link (RAL) Eccentrically Braced Frames (EBF) is a LDD solution that can be implemented within the PBD philosophy to design buildings that exhibit improved performance during an earthquake, and reduced costs in the aftermath, compared to conventionally designed buildings.

3 ECCENTRICALLY BRACED FRAMES

EBF systems were first developed in Japan during the early 1970s (Fujimoto et al., 1972), where it showed promise as a structural system. The concept was subsequently investigated in the United States during the late 1970's and 1980's, principally by Egor Popov (Roeder & Popov, 1977; Popov et al., 1987; Popov & Engelhardt, 1988). EBF systems are conceptually similar to conventional moment resisting frames, where system plasticity is generally provided through the formation of flexural plastic hinge zones at the ends of the beams. In an EBF system, braces are provided between the column and the beam, which has the effect of reducing the shear span of the beam. The shear span is termed an active link. As the shear span is reduced, the deformation mode of the active link gradually transitions from flexural to shear. Shear yielding is very stable and generally the preferred deformation mode in EBF systems. The other elements within the structure are capacity designed to constrain the plasticity in the system to the active link. There are two basic EBF configurations; inverted V-braced and D-braced, as shown in Figure 2b and 2c respectively.



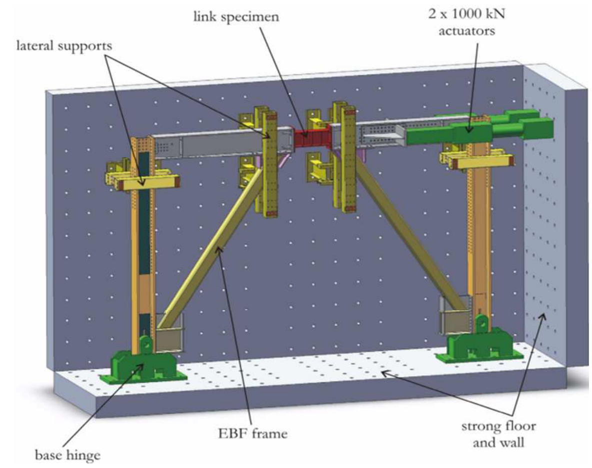
(a) Moment resisting frame. **(b) Inverted V-braced EBF.** **(c) D-braced EBF.**

Figure 2. Deformation modes of different structural framing systems (Popov & Engelhardt, 1988).

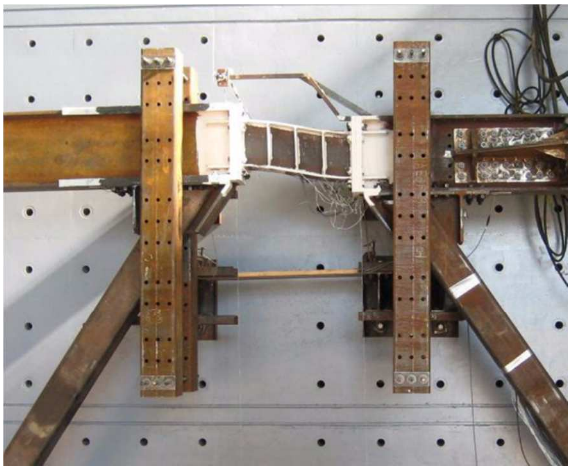
EBF systems are able to provide a dependable ductile mechanism during response to ULS earthquake intensity; however, the active link undergoes significant inelastic deformation, which may completely exhaust its low-cycle fatigue capacity. Replacing the active links in a conventional EBF system is invasive, complex and time intensive, which may result in repair of the building being economically unviable.

3.1 *Replaceable Active Link EBF*

EBF systems with Replaceable Active Links (RAL) are a relatively recent innovation, with the first specific investigations into RAL EBF systems conducted in the early 2000's (Stratan & Dubina, 2004). These early experimental investigations showed the potential of the system; however, there remained issues with the detailing. Mansour (2010) subsequently developed the RAL EBF system through an extensive experimental and analytical investigation. Figure 3 presents the experimental setup for, and deflected shape of, Mansour's (2010) EPM-11A RAL EBF test. Mansour (2010) showed that the RAL EBF system, if well designed, exhibited comparable seismic performance to a conventional EBF system. The New Zealand Heavy Engineering Research Association (HERA) undertook finite element analyses (FEA) to verify the performance of the RAL EBF system (Mago, 2013). The FEA investigation showed that EBF systems that used a bolted procedure for the RAL constrained inelastic behaviour to the RAL.



(a) Experimental setup.

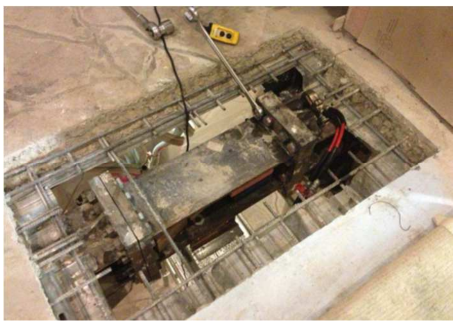


(b) Sample EPM-11A at 1.7% drift.

Figure 3. Research conducted in Canada on RAL EBF (Mansour, 2010).

During the rebuild in Christchurch, following the 2010-2011 earthquake sequence, the RAL EBF detail has been implemented in both new build and retrofit applications. Figure 4a shows a rendering of Project 365, in which RAL were used within the EBF system. Figure 4b shows a RAL being retrofitted into an existing EBF system that was damaged during the Christchurch earthquake sequence. RAL EBF systems have been shown to be able to be designed and constructed effectively within the New Zealand construction environment. Besides facilitating rapid and economical rehabilitation of a building following an earthquake, using a RAL EBF system affords several other benefits, which are discussed in Section 4.

Project 365 - New build with RAL EBF system (Ramsay et al., 2013).

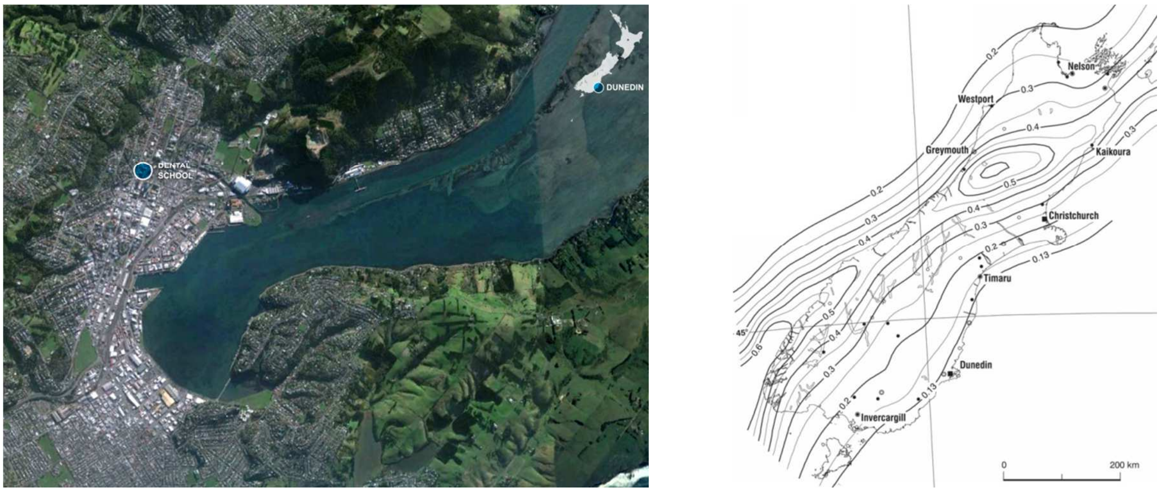


Pacific Tower - Retrofitted building with RAL EBF system (Gardiner et al., 2013).

Figure 4. Structures in Christchurch using RAL EBF.

4 UNIVERSITY OF OTAGO: SCHOOL OF DENTISTRY

The University of Otago School of Dentistry is located in Dunedin, New Zealand on the corner of Frederick and Great King Streets, as shown in Figure 5a. The existing School of Dentistry complex consists of the West Wing and the Walsh building. The West Wing is to be demolished to allow the new School of Dentistry building to be constructed. The Wash building is a Category 1 listed building, noted for being an outstanding example of international style Modernist architecture, and is to be retained and redeveloped. Dunedin is a region of moderate seismicity, with a seismic hazard factor of 0.13 as defined by the New Zealand Loading Standard, as shown in Figure 5b (Standards New Zealand, 2004). The seismicity in Dunedin is approximately a third of that in Wellington, and is comparable to some regions of Australia.



(a) School of Dentistry location (Jasmax, 2014). **(b) Dunedin seismicity (Standards New Zealand, 2004).**

Figure 5. Location of new building and seismicity.

Due to the restrictions of the site, the new School of Dentistry building must be situated in close proximity to the heritage listed Walsh building; hence, the architecture had to be sympathetic to the existing building. However, the project brief required a modern clinical and teaching environment, supported by generic teaching spaces that are up to date with modern changes in education. A rendering of the redeveloped School of Dentistry site is presented in Figure 6; the new School of Dentistry building is to the right of the existing Walsh building.

Figure 6. Architectural Rendering of new Dental School building (Jasmax, 2015).

The clinical and teaching nature of the new School of Dentistry building required large open spaces and intensive services reticulation. Braced structural steel framing was best suited to satisfy the functional and architectural project objectives. An efficient structural design was an important project objective, which meant allowing for ductility during ULS earthquake loading. Furthermore, the new School of Dentistry building interfaces with the existing Walsh building via walkways at each level across a glazed atrium between the two structures. An EBF framing system provided relatively open spaces for egress between the buildings, while being capable of providing a dependable inelastic mechanism. A D-braced EBF system was required to allow large enough openings in the exterior frames for the required egress paths. The building site slopes naturally from west to east and soil retaining structures were required to enable the ground floor level of the new School of Dentistry building to match that of the existing Walsh building. Instead of providing separate retaining structures, it was decided that it would be more economical to use reinforced concrete walls in the ground floor of the structural system to both retain the surrounding soil and effectively found the EBF system at the first floor level. A rendering of the structural system is presented in Figure 7.

Figure 7. Structural rendering of new School of Dentistry building (Walsh building in background).

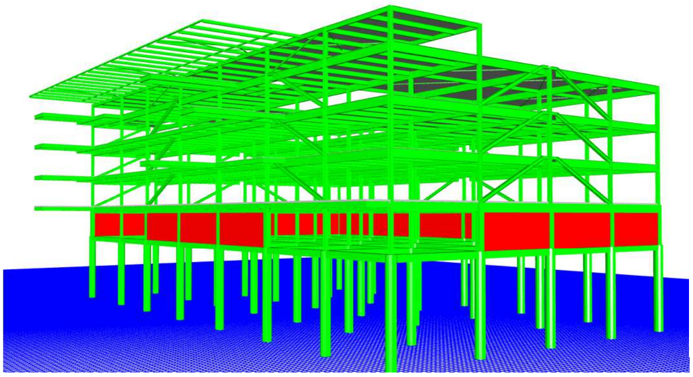
Following the lessons learnt in the aftermath of the Christchurch earthquake sequence, it was recommended that the principles of PBD be considered in implementing a LDD system; however, due to the commercial nature of the project, the structural system utilised had to be justifiable economically also. It was due to the ability of the RAL EBF system to facilitate the latter that it was implemented to achieve the former. The new School of Dentistry building is the first RAL EBF building in Dunedin, and the first known example in a moderate seismicity region of New Zealand.

In high seismicity regions, bay lengths are generally shorter than would be provided in a comparable building in a moderate seismicity region; shorter bay lengths generally simplify the design of the braces and collector beams. In a conventional EBF system, the active link section is the same as that of the collector beam; hence, the strength of the system is influenced by the depth of the section required for the collector beam. Longer span lengths generally used in moderate seismicity regions necessitate deeper beam sections to resist the greater gravity flexural demands, which results in higher capacity active links than required and correspondingly large overstrength factors. The high overstrength factors, often larger than required by an elastic analysis, result in the other structural elements in the system being comparatively overdesigned and uneconomic.

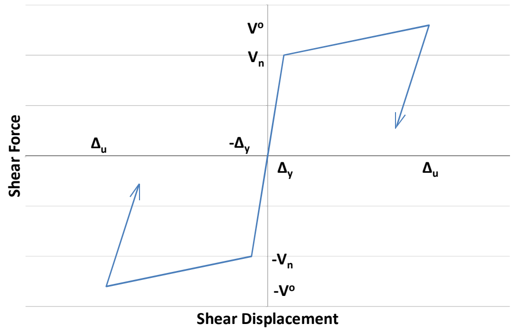
The RAL EBF system allows the strength, and hence overstrength, of the system to be decoupled from the size of the collector beams. Hence, the collector beams can be sized to resist gravity and seismic actions, and the RAL can be 'tuned' to minimise the system overstrength and provide as efficient structural system as possible.

In addition to enabling a more efficient structural design, improving seismic performance and facilitating quicker rehabilitation following an earthquake, the RAL EBF system provides constructional benefits also. The bolted connections used in the RAL means that the system is well suited to a high degree of prefabrication. Prefabrication enables the structural steel components to be manufactured under controlled conditions, which allows high quality components to be fabricated. High fabrication quality is especially important for the RAL, which is typically assembled from hot rolled plate using full penetration butt welds due to the inelastic demands that it is subjected to during a design level earthquake. Prefabrication can also enable faster building erection, not only because the prefabricated components can be quickly and simply bolted together onsite, but also because parallel work streams can exist onsite and in the in the manufacturing yard.

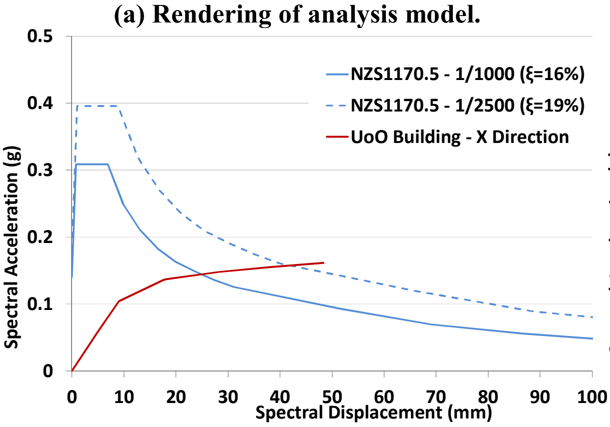
The analysis of the RAL EBF system developed for the new School of Dentistry building was conducted using the ETABS structural analysis suite (Computers and Structures, 2013). A rendering of the analysis model of the building is presented in Figure 8a. The foundation system, which was modelled with a system of horizontal and vertical springs, was included to capture load redistribution between column lines. The soil spring properties were assigned based on subgrade modulus data collected during the geotechnical investigation. The floor diaphragms, which are a one-way Comflor system, were modelled using semi-rigid membrane elements. The reinforced concrete walls at ground level were modelled using elastic shell elements. A RAL EBF system can be analysed in an identical manner to a conventional EBF system using either force-based or displacement-based methods. A ductility of three was chosen for the design of the new School of Dentistry building, this is the maximum recommended for EBF systems in interim design guidance issued by the Structural Engineering Society of New Zealand (SESOC, 2013). The modal response spectrum method was used to determine design actions because, given the geometry of the structure, it enabled a more efficient solution to be developed. The fundamental translational periods in each orthogonal direction were approximately 0.6 seconds.



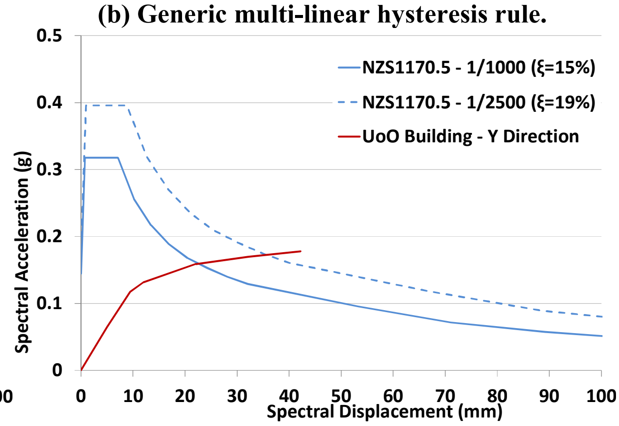
(a) Rendering of analysis model.



(b) Generic multi-linear hysteresis rule.



(c) ADRS for x direction (north-south).



(d) ADRS for y direction (east-west).

Figure 8. ETABS analysis parameters.

To validate the design of the building, which was undertaken using force-based methods, an inelastic pushover analysis was undertaken. Because the structure was capacity designed, the plasticity in the system is constrained to the RALs in the EBF bays. The RALs were modelled using an inelastic link element and assigned a multi-linear hysteresis, as shown schematically in Figure 8b. The computed building response was transformed to an equivalent single degree of freedom system to enable the force-displacement response to be compared to the design spectra specified in the Standard (Standards New Zealand, 2004). The building response in both principle directions was plotted against both the spectral displacement and acceleration on an Acceleration-Displacement Response Spectrum (ADRS) plot, as presented in Figure 8c and Figure 8d. The equivalent viscous damping was determined using recommendations by Priestley et al. (2007). The displacement demand for a ULS earthquake (1/1000 year return period) was approximately 2.7. The RALs began to exceed the shear strain limits prescribed in the Steel Structures Standard during a Maximum Credible Event (MCE) earthquake, which corresponds to a 1/2500 year return period (Standards New Zealand, 1997).

The detailed design was conducted in accordance with the HERA design guidance for EBF, P4001:2013, and the New Zealand Steel and Concrete Structures Standards (Standards New Zealand, 1997, 2006; Clifton & Cowie, 2013). The project faced several challenges unique to the application of the RAL EBF system in a moderate seismicity region.

As discussed above, bay lengths are generally longer in moderate seismicity regions. This issue was exacerbated by the need to use a D-braced EBF system to satisfy architectural requirements. The combination of a D-braced EBF system and long bay lengths, which necessitates shallow brace angles, results in large design actions. It was possible to use heavy hot rolled sections for the braces; however, due to the combination of large axial seismic demands and gravity demands in the collector beams, custom welded sections were required. Standard welded sections were not able to be used because the narrow width of them caused detailing issues at the interface between the beam and the brace. Furthermore, the section geometry requirements of §12.5 of the Steel Structures Standard could not be satisfied with standard welded sections (Standards New Zealand, 1997).

A further consequence of the geometry was that, compared to an inverted V-braced EBF or a system with shorter bay lengths, the induced rotation angle of the RAL was increased and the overall frame stiffness decreased. With fixed geometry, the primary means of increasing the stiffness of the frame is to decrease the RAL length; however, decreasing the RAL length increases the rotation angle for a given building displacement. Hence, the length of the RAL was determined iteratively to achieve a stiffness that was sufficient to ensure that overall building displacements were within limits imposed by maximum allowed RAL rotation angles, which are prescribed by §12.11.3.3.1 of the Steel Structures Standard (Standards New Zealand, 1997).

Due to architectural requirements, the two D-braced EBFs on the eastern face could not be adjacent to each other. Hence, the shear demands from the RALs were not equilibrated by an adjacent RAL, instead the shear demands manifest in column axial demand. When the overstrength derived column axial demands were combined with the gravity derived axial demand, which was significant due the large tributary areas created by the long bay lengths, the column axial design forces became very large. To satisfy the axial force requirements of §12.8.3 of the Steel Structures Standard, heavy hot rolled sections were required (Standards New Zealand, 1997). If the EBF overstrength factors had not been able to be minimised by using RAL, then custom welded columns would have to have been specified.

The University of Otago School of Dentistry redevelopment project is currently in the Detailed Design phase; construction is scheduled to begin in 2016.

5 SUMMARY

The design of the new University of Otago School of Dentistry building, which forms part of the School of Dentistry redevelopment project, was presented. LDD was introduced within the broader context of PBD, and the development of the RAL EBF was briefly described.

The analysis of the new School of Dentistry building was conducted using the modal response spectrum method and its performance verified using an inelastic pushover analysis. Design challenges unique to the application of the RAL EBF system in a moderate seismicity region were discussed.

The RAL EBF system has been shown to be effective in high seismicity regions; however, the design of the new School of Dentistry building has shown that it is effective also in regions of moderate seismicity. The RAL EBF system was selected for the new School of Dentistry building for several reasons.

- The RAL EBF is a LDD solution that, when implemented within the PBD framework, can be used to design a building with excellent seismic performance; lower earthquake induced damage; and reduced repair costs and minimised building downtime in the aftermath of an earthquake.
- The RAL EBF can facilitate a very efficient structural system by allowing a designer to minimise the overstrength of the RAL, and hence the size of other related elements in the system.
- A RAL EBF system is well suited to a high degree of prefabrication, which enables high quality components to be fabricated and enables rapid erection onsite.

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