Australian Earthquake Engineering Society 2013 Conference, Nov 15-17, Hobart, Tasmania

Seismic Design Principles and Methodology for the New Royal Adelaide Hospital

McBean P

Director, Wallbridge & Gilbert, Adelaide South Australia 5000
Email: pmcbean@wgeng.com

Abstract

When completed in 2016, the $1.85b new Royal Adelaide Hospital will be Australia's newest and most advanced major hospital, and one of the most complex building infrastructure projects delivered in the country.

As a critical post disaster facility designed to meet BCA Importance Level 4 criteria, the structure is required to deliver the dual earthquake design performance objectives of collapse prevention for an earthquake with an annual probability of exceedance of 1:1500 , together with maintaining full operational capability following a serviceability earthquake with an annual probability of exceedance of 1:500. The earthquake serviceability performance design criterion was introduced for Importance Level 4 structures in the 2007 edition of AS1170.4. The new Royal Adelaide Hospital is one of the first major structures designed to comply with these new provisions.

This paper outlines the engineering design processes and strategies adopted for the project to address both the collapse prevention and serviceability earthquake requirements.

Keywords: Post disaster, Importance Level 4, serviceability, earthquake

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Director, Wallbridge & Gilbert, Adelaide South Australia 5000
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1. INTRODUCTION:

The new $1.85b Royal Adelaide Hospital is the biggest building infrastructure project in South Australia's history and when completed in 2016, will be Australia's newest and most advanced major Hospital.

The new 800 bed facility will have an initial capacity to treat 85,000 admissions per year, whilst the 10 hectare green field site provides sufficient space to accommodate future expansion needs anticipated during the 100 year design life of the facility.

Figure 1 – 3D Structural Model showing 3 Storey underground carparking and basement retention system

In the event of a major earthquake in the Adelaide region, the new Royal Adelaide Hospital will be required to provide immediate tertiary clinical care for large numbers of casualties. A critical aspect of the design brief required that the Hospital survive such events and retain a high level of operational capacity to deliver post disaster services. This paper outlines some of the structural design methodology used to achieve this goal.

2. POST DISASTER FUNCTION:

As noted above, the Facility is required to provide a high level of immediate post disaster response. The majority of the Facility has been designed to meet or exceed the requirements for an Importance Level 4 (IL4) structure in accordance with Building Code of Australia (BCA) 2010, together with additional technical requirements of the State Government.

The 2007 edition of AS1170.4 referenced in the BCA introduced for the first time new performance criteria for IL4 structures requiring that they be designed for two distinct earthquake events:

2.1 Life Safety Design Earthquake

This design event simulates a major earthquake with an annual probability of exceedance of 1:1500. That is, a low probability, high consequence event for which the primary design objective is to preserve the lives of building occupants and those near the structure. It is envisaged that both the structure and its contents will suffer extensive damage during such a severe event, however collapse is to be prevented. Structural design strategies used to ensure this design objective is achieved concentrate on detailing of structural elements to accommodate relatively large lateral displacements without significant loss of lateral resistance, and importantly to maintain integrity of the structure to support gravity loads.

2.2 Serviceability Design Earthquake

The serviceability earthquake models a statistically more frequent event with less intense ground motion, after which the Hospital is required to remain operational for immediate use. During such an event some minor damage is permitted provided it is easily repairable and would not interfere with the ongoing operation of the Hospital. Consistent with the requirements of AS1170.4-2007, an event with an annual probability of exceedance corresponding to that which would ordinarily be required for an Importance Level 2 structure has been adopted, that is, a 1:500 year event.

To satisfy this performance requirement, the structural design has focused on controlling storey drift and limiting overall building displacements to ensure vulnerable non-structural components such as ceilings, services, partitions and alike remain intact and suffer only superficial damage.

It is envisaged that reinforced concrete elements could develop some minor cracking during the serviceability earthquake, but without significant yielding of reinforcement or crushing of concrete. A review of drift limits consistent with this performance standard was undertaken. Eurocode 8, EN1998-1:2004 recommends a damage limit state for in-plane drift of 0.5% for brittle non-structural elements and 0.75% for ductile non-structural elements. Priestley's latest text "Displacement Based Seismic Design of Structures", indicates that serviceability limit state drift limits appropriate to ensure ongoing building functionality are material dependent and suggests that the most restrictive drift limits are in the order of 0.5% and associated with masonry infill walls. Damage to mechanical equipment would not be expected at such low levels of drift. A serviceability drift limit of 0.5% was therefore adopted for the project.

Interestingly, the recently introduced serviceability design event governed the structural design and heavily influenced the design and detailing of all non-structural parts and components.

3. SITE EARTHQUAKE HAZARD:

To better understand the earthquake risk for the site, the State Government commissioned an independent site specific Probabilistic Seismic Hazard Analysis (PSHA). The analysis was undertaken by Environmental Systems and Services (ES&S) and provided estimates of Peak Ground Acceleration (PGA) together with Uniform Probability Response Spectra for Return periods of 500 years, 1000 years and 1500 years. Site specific models of ground surface motion were provided based on geotechnical models consisting of firm rock (Vs 30 = 1000 m/s) and for soil profiles containing very soft sediments (Vs 30= 275 m/s) overlying rock. These later spectra incorporated soil amplification effects based on shear wave velocity measurements taken nearby at Government House, Adelaide, which had the effect of increasing the surface ground motion experienced during an earthquake. Later measurement taken on the actual site indicated that the soils were marginally stiffer than initially assumed with average shear wave velocities between 330 m/s to 435 m/s. A review of the site specific response spectrum was subsequently undertaken by Golder Associates based on the updated shear wave data. The analysis was conducted using the computer programme SHAKE, and considered local geology and more accurate models of the site soil conditions.

The acceleration response spectra produced by the SHAKE analysis were found to match reasonably well with the ES&S spectra. The more severe of the two site specific spectra were used for structural analysis, taking the higher acceleration from each of the spectra across all period values. A comparison of the resultant site specific PSHA used for design, and AS1170.4-2007 derived spectra is provided in figure 2 below.

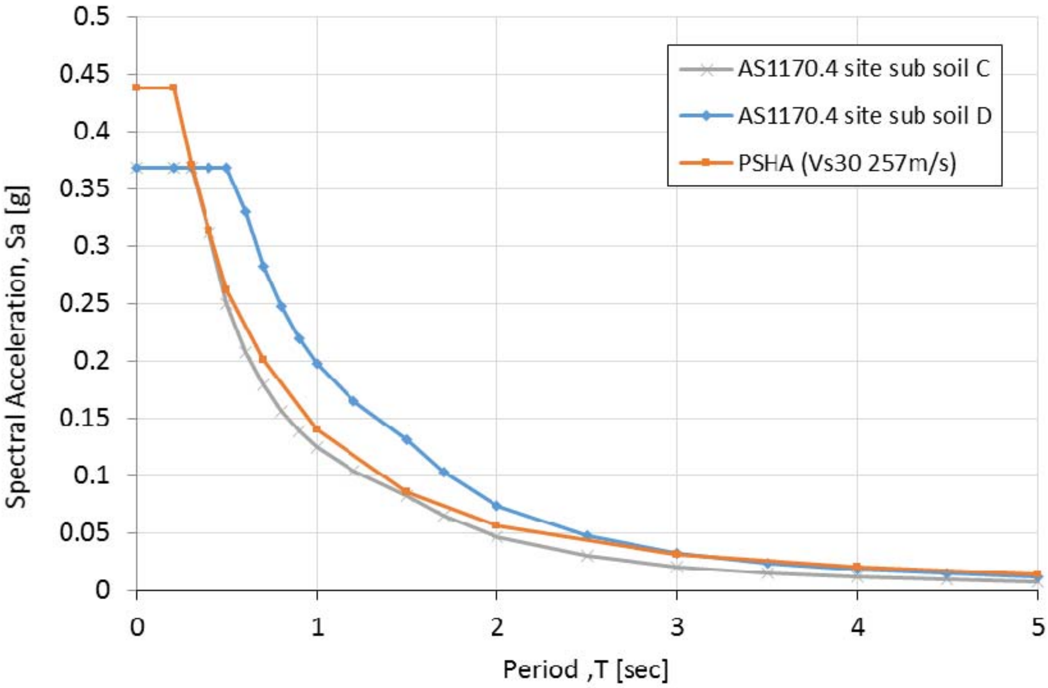


Figure 2 – Comparison of 1:500 annual probability of exceedance PSHA spectra with AS1170.4-2007 spectra for C_e and D_e soil classifications.

The period range of particular interest for the structural design of the Hospital lies between 0.5sec and 2.0sec. In that range, the PSHA design spectra is very similar in shape to the AS1170.4 spectra for class C_e soil conditions with a hazard factor of 0.11g. Highly weathered rock is encountered on the site at depths of around 75m which would have otherwise categorised the soil class as D_e.

4. STRUCTURAL OVERVIEW:

4.1 Building Sectors and Seismic Movement Joints

The Hospital's structural frame is constructed primarily from reinforced concrete, utilising two-way post tensioned concrete floor plates. Unlike regular office or commercial buildings, the Hospital function and use varies widely both across the site, and vertically throughout the building, leading to considerable diversity in the type of structural systems required. Much of the floor plate design is governed by stringent vibration performance requirements associated with medical imaging and robotic surgery equipment, with these areas often requiring very stiff and heavy floor systems.

The Hospital varies in height between five and ten storeys and covers a footprint of more than 350 metres x 150 metres. The large building footprint has necessitated subdivision of the Facility into separate smaller independent building sectors. This is done in order to manage the cumulative long term movements associated with concrete shrinkage, creep, elastic shortening, and thermal effects. Typically, the maximum building length constructable in Adelaide using locally available concrete aggregates (with associated shrinkage and creep values above National averages), is in the order of 90 metres. Permanent seismic movement joints have been strategically positioned across the Hospital footprint so as not to exceed 90 metres in any direction, whilst simultaneously achieving the following aims:

- To create floor diaphragms with favourable aspect ratios and inherent structural integrity;
- To minimise the overall use of movement joints throughout the Facility which are both expensive and problematic from a functional planning perspective; and
- Where possible, to locate movement joints along partition lines and to avoid high traffic areas.

The seismic movement joints structurally isolate each sector from its neighbours and ensure that lateral earthquake design actions are independently resolved within each sector. Figure 3 illustrates the sector subdivision across the site. It can be seen that articulation naturally arising from re-entrant corners and atria located throughout the floor plate has led to a logical network of seismic joints.

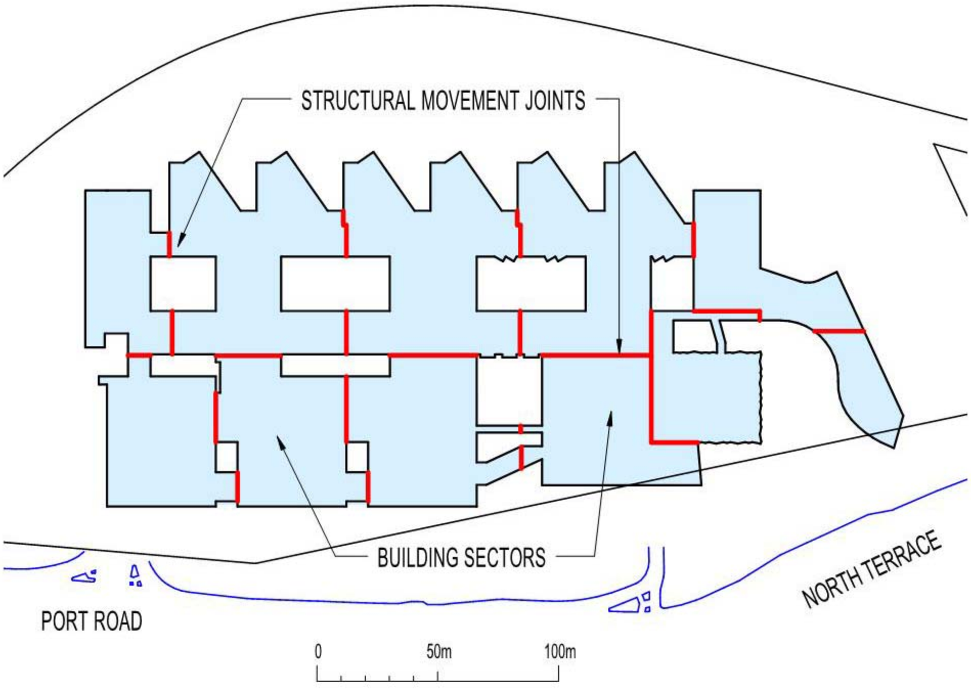
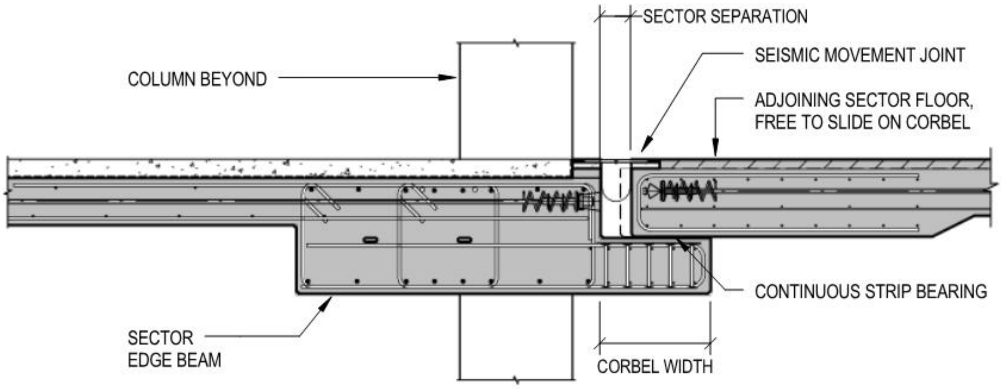
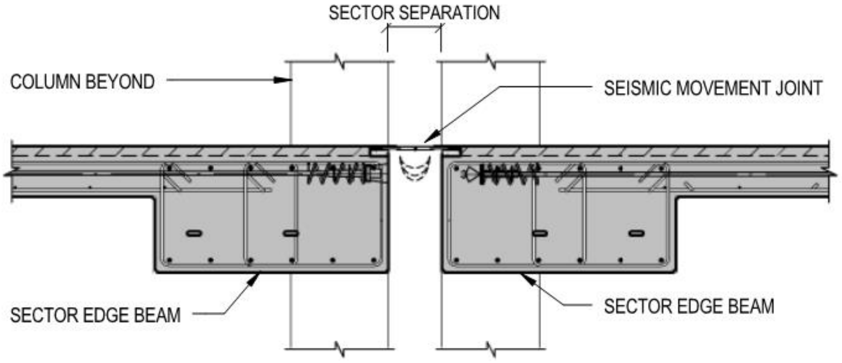


Figure 3 – Site Plan Indicating Sector Boundaries

A clear gap constructed between adjoining sectors has been sized to prevent pounding based on the calculated drift demand determined for an earthquake with an annual probability of exceedance of 1:1500.
The floor surface trafficable seismic movement joints have been selected to accommodate the serviceability earthquake drift demands based on modelling of the 1:500 event.
Adjoining sector drift maxima have been combined using the "square root of the sum of the squares" method to determine overall seismic joint demand.
Two construction approaches have been adopted at sector boundary seismic movement joint locations. Where functional planning of the Hospital permitted, each sector was given its own column and edge beam creating a traditional double column arrangement. Such column pairs are founded on a common piled footing to limit differential vertical movement. Alternatively, where planning needs dictated that only single columns could be accommodated, one sector was used to vertically support the neighbouring floor slab on a continuous "corbel" which cantilevered from the sector edge beam. The supported slab is free to slide on a continuous strip bearing fixed to the corbel. Both arrangements are shown below in Figure 4.



SECTION THROUGH TYPICAL SLAB CORBEL JOINT



SECTION THROUGH TYPICAL DOUBLE COLUMN JOINT

Figure 4 – Typical Movement Joint Details

Corbel connection geometry varied across the project primarily and was proportioned to avoid pounding whilst accommodating:

- Full earthquake movement of each floor plate tending to open the joint (not combined using the square root of the sum of the squares method) to conservatively prevent corbel unseating.
- Floor plate movement due to shrinkage and creep effects.
- Movement due to thermal effects.

4.2 Structural Shear Walls

Ductile reinforced concrete structural walls have been adopted as the primary lateral load resisting system for all building sectors. Such walls have proven themselves repeatedly as providing a reliable method of both limiting drift and preventing structural failure in major earthquakes around the world.

Having earlier established the sector configuration and seismic joint layout, the primary functional arrangement of vertical reinforced concrete elements including lift shafts, stairs and plant risers were reviewed for efficiency and adequacy. Additional strategically located structural “shear” walls were added to improve the torsion response and ensure a good distribution of lateral resistance was provided in all directions to all sectors.

The size and thickness of concrete shafts and walls was then adjusted and refined until the serviceability earthquake drift limit of 0.5% was achieved. In some instances where drifts were found to be unnecessarily low, larger cores were re-planned and uncoupled from one another to increase lateral flexibility and sector period with associated reductions in base shear and element demand. The walls are proportioned and detailed in accordance with AS3600 Appendix C together with the additional recommendations proposed by Paulay and Priestley, 1991, and Priestley, 2007, to ensure adequate ductility is achieved at calculated limit state curvatures.

All structural walls and cores are founded on piled footings.

4.3 Structural Design Strategies

The following principles have been incorporated into the structural design to improve inelastic response and prevent collapse:

- Use of redundant lateral and vertical loads paths together with continuous edge beams to improve structural resilience
- Use of direct vertical load paths throughout the building without resorting to the introduction of transfer structures which can create irregularities leading to concentrations of plastic demand, and potential collapse. A number of transfer failures were observed first hand by the author in Christchurch 2011
- Preservation of vertical continuity for lateral bracing systems, again avoiding concentration of plastic demand at discontinuities
- Columns have been proportioned to work comfortably without requiring the use of high strength concrete (ie not greater than 50MPa) and designed with reserve capacity to accommodate drift induced moments and shears arising from both frame action and $P\text{-}\Delta$ effects
- All beam/column and slab/column joints have continuous anchored bottom face bars passing through the joint to provide post failure resistance to punching shear via dowel action
- Avoidance of plan irregularities and the adoption of a uniform distribution of lateral bracing elements and mass in order to control torsional response of each building sector
- Avoidance of ‘soft-storey’ structural performance
- No unreinforced masonry has been permitted within the Facility
- Attention to detailing with a focus on the proper anchorage of reinforcement; adequate confinement of concrete in hinge zones and the use of appropriately proportioned boundary elements to structural walls in plastic hinge regions to prevent bulking
- Careful detailing to prevent structural interaction with stiff ‘non-structural’ components such as infill partition walls and precast cladding.

5. SEISMIC MODELLING AND ANALYSIS:

Consistent with the requirements of AS1170.4-2007 earthquake design Category III, each sector of the Hospital has been separately modelled dynamically in 3D using the finite element analysis package ETABS. All sector mathematical models used during the dynamic analysis incorporated the following characteristics:

- Full three dimensional analysis to more accurately identify torsional modes and model diaphragm behaviour.
- Floor diaphragms modelled as semi rigid to include appropriate diaphragm flexibility.
- Stiffness properties of cores and walls modelled to account for cracking and inelastic degradation consistent with the limit state under consideration. The adopted stiffness were chosen to reflect the level of axial load, bending demand, and percentage of element reinforcement. Wall and core stiffnesses have been based on referenced work by Fenwick and Bull, together with Priestley and Paulay. A lower bound stiffness value has been used for determining drift performance, and an upper bound stiffness used for strength calculations.
- Pile cap rotational stiffness at the base of shear wall elements has been seperately modelled using PLAXIS, a finite element analysis package which incorporates soil/structure interaction. The modelling provided lower bound pile cap stiffness values which were then incorporated into the ETABS dynamic model. Drift estimates were observed to increase by approximately 10% when this effect was included in the analysis, suggesting that ignoring this effect would have led to non-conservative sector separation gaps and an increased likelihood of pounding. Pile cap rotational stiffness values obtained from PLAXIS were doubled to provide an upper bound for strength analysis.
- The minimum mass participation of 90% is achieved as required in AS1170.4 -2007 for dynamic analysis.
- Sector response has been based on combined model analysis using the complete quadratic combination method.

Drift estimates were independently obtained using the displacement based principles outlined by Wilson and Lam, 2006. The PSHA acceleration design spectra was first transformed into Acceleration – Displacement Response Spectra (ADRS) format using the approach in the commentary to AS1170.4-2007. A 1500 year maximum response spectrum displacement (RSD max) of 95mm was obtained which corresponded to a 1.5 second T_2 corner period. Torsional amplification was accounted for using procedures outlined by Lumantarna et al, 2008, incorporating a two-way asymmetric torsional amplification factor Γ_{DD} of 1.7 giving a conservative estimate of peak drift demand PDD = Γ_{DD} RSD max = 160mm

6. SERVICEABILITY DESIGN EARTHQUAKE SPECIAL STUDY:

One of the most challenging aspects of the Hospital design has been assisting our architectural and services engineering colleagues to understand and comply with seismic design requirements relevant to their respective disciplines.

As the new Royal Adelaide Hospital is one of the first Australian buildings to be rigorously designed to the new serviceability earthquake requirements of AS1170.4-2007, it is fair to say that for many of our allied professionals, this project has been their first direct exposure to earthquake design concepts.

Fortunately there are a number of very useful publications to assist, such as FEMA577, a freely available design guide which discusses strategies for improving Hospital safety during earthquakes and other natural disasters. That particular publication explains in simple clear language the concepts of strength vs ductility, interstorey drift, and design accelerations, together with the importance of regular configuration, direct load paths and appropriate material selection. Whilst written for a North American audience, the principles and language are directly transferable into the Australian context and greatly assisted in the communication of important concepts to architects and planners early in the project design phase.

After an initial period of education and adjustment, everyone involved in the project quickly appreciated the all encompassing nature of seismic design and the direct effect it had on their design, detailing and equipment selection. Particular focus was placed on ensuring that non-structural parts and components remained functional and operational after the serviceability earthquake. To demonstrate this, each sector was structurally modelled on ETABS for the 1:500 event using a ductility factor, $\mu = 1.0$ and a structural performance factor, $Sp = 0.77$, these factors being consistent with an essentially elastic response whilst taking into account available material over strength. Such analysis provided estimates of drift demand, seismic joint movement, and floor design accelerations. These actions and displacements were applied to the specification and design of ceilings, partitions, ductwork, piping, equipment and alike. Particular care has been taken to ensure adequate articulation is provided to ceilings, partitions and services crossing seismic movement joints.

The selection of mechanical anchors for the project has been restricted to those suitable for use in cracked concrete under seismic conditions. Cast in anchors have been designed to ACI 318 Appendix D, and post fixed anchors are required to comply with ACI 355.2 or equivalent international testing standards.

In addition, emergency power generators have undergone shake table testing; ceiling systems tested under seismic conditions; full scale inplane façade racking tests have been undertaken, and a Building Management System installed which, on the detection of P-waves arriving ahead of the main ground motion will automatically stop all 48 lifts at the nearest floor and opens all lift car doors to avoid entrapment.

7. CONCLUSION:

The new Royal Adelaide Hospital is one of the largest and most complex building infrastructure projects ever delivered in Australia, and is also likely to be Australia's most seismically resistant building. As one of the first major projects to rigorously apply the new post disaster serviceability earthquake provisions of AS1170.4-2007, the design process required resolution of issues which are not routinely addressed by designers in the Australian context. Lessons recently learnt in Christchurch have been incorporated into the design, together with alternative analysis methods involving displacement based approaches.

8. ACKNOWLEDGEMENTS:

The author would like to thank Prof. John Wilson of Swinburne University of Technology for his expert advice and input throughout the project. The author also wishes to thank SA Health Partnerships and the Hansen Yuncken – Leighton Contractor Joint Venture for permission to present this material.

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