Seismic Assessment of Engineering Systems in Hospitals – A Challenge for Operational Continuity

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ABSTRACT: Hospitals are treated as critical facilities which are required to continue functioning after an earthquake event. The expected continued performance of hospitals is greatly dependent on the satisfactory performance of engineering systems surviving seismic demands through their adequate seismic restraints. To understand the potential problems and inadequacies with existing engineering systems within critical facilities, three hospitals in Wellington region were surveyed. The survey focused on ‘essential’ systems required to sustain the operational continuity of hospitals including floor mounted components with rigid and resilient mountings and suspended components. The study revealed that most of the components have been provided with some degree of restraint. However, there were systems with inadequate restraints which could potentially impair their individual functioning requirement or interact with adjacent components resulting in combined failure of the systems. The paper highlights the observations in terms of the vulnerability of the components, the existing scenario of their restraints and their impact on seismic safety. Finally, a brief note is made on the observed current practice within consultancy firms towards the seismic design and installation of engineering systems. In conclusion, the ‘operational continuity’ performance criteria can possibly be achieved through a rigorous framework adopting careful design and installation of components of engineering systems and mainly followed by thorough inspection of all the components considering their interaction effects.

1 INTRODUCTION

Large earthquakes cause damage to buildings and to non-structural components within the buildings, with a larger proportion of loss from the latter. In recent earthquakes, in particular the 1994 Northridge earthquake, the cost of repair and restoration of non-structural components (NSC) has been claimed to far exceed those related to structural framing systems. On the other hand, small to moderate earthquakes could leave the building with minimal damage making it suitable for ‘immediate occupancy’, provided the non-structural components and contents of the building have suffered nil/minor damage so that the functionality of the building is uninterrupted. For example, in the 2001 Nisqually earthquake, which was reportedly a moderate event, many buildings did not suffer major structural damage; however, the damage of non-structural components rendered the buildings unsuitable for occupancy [Filiatrault et. al., 2001]. Typical examples of NSC include architectural partitions, ceilings, exterior cladding, building contents, piping systems, electrical trunking and mechanical and electrical equipment. Engineering systems in a building are non-structural systems that are permanently installed to provide environmental control, water, gas and steam supply, electrical or communication services and active fire fighting systems such as sprinkler pipes.

In AS/NZ 1170.0 [SNZ 2004], critical facilities like hospital buildings are categorised with importance level 4. The code provisions require that the buildings remain operational, particularly under 500 year serviceability limit state (SLS2) earthquakes. Engineering systems become vulnerable when they are not provided with proper anchorage and bracing elements and their failure would practically render the building unusable at the time when it is most needed, particularly after a 500 year return period earthquake. Recently, NZS 4219:2009 [SNZ 2009] was published, providing design guidelines for
better seismic performance of engineering systems.

In California, based on seismic safety law, the Office of Statewide Health Planning and Development (OSHPD), California has developed and expedited an intense program to review and approve hospital retrofit and building plans including the design and installation of non-structural components to ensure that all hospital buildings comply with recognized seismic building codes. The organizational structure of OSHPD is so scrupulous that every stage is verified and inspected and hence the ‘operational continuity’ of hospitals is ensured.

The objectives of the present study are:

(i) Examination of the existing status of engineering systems that are identified to be critical in providing necessary operational continuity in selected hospitals

(ii) Recommendation of simple and effective ways of providing adequate restraints for currently unrestrained equipment in line with NZS 4219:2009 requirements

(iii) Comparison of the current practices followed in New Zealand to ensure operational continuity of hospitals as against California’s OSHPD requirements and facility development.

2 ENGINEERING SYSTEMS IN HOSPITALS

The Wellington region has a population of 400,000 and with a very high risk of experiencing damaging earthquakes of magnitude 7.4 or greater. A 6.8 magnitude earthquake occurred in Gisborne in December 2007. Despite its size, it was centred off the coast of the country and the effects on the land were therefore reduced. There was evidence of failure of non-structural components but these were mostly architectural elements, including some suspended ceilings. There were very few instances of mechanical or electrical system failures. However, to gain a better understanding and appreciate the current status of engineering systems particularly in hospitals, audits were carried out in three Wellington hospitals. During the audit, attention was given to mechanical and electrical equipment, air supply systems, suspended components and communication and data-handling units. The status of the components was compared with the mandatory requirements of NZS 4219:2009 and comments and suggestions for retrofit, if needed, were given with regard to the component under consideration.

2.1 Mechanical and electrical equipment

The mechanical and electrical equipment is classified into two main categories: (i) equipment and systems required to remain operable following an earthquake; and (ii) other supporting systems. The first category includes mainly active electrical and mechanical equipment such as switch gear, air-handling units, air conditioning units, emergency power supply systems. These components are referred to as ‘designated systems’. The second category includes systems like sterilizers, motors and motor operators and vacuum pumps which are referred as ‘rugged systems’ as they may not play a significant role in operational continuity. In order to ensure ‘operational continuity’ after any earthquake event, the OSHPD framework requires all the systems within the first category to have a product certification by an approved testing laboratory or agency. On the other hand, the framework systems under the second category do not require any special testing certificate.

From the Wellington survey, it is very clear that there is no indication of product certification attached to the ‘designated systems’ of mechanical and electrical equipment. The components are identified to be either proprietary systems from overseas or locally assembled parts. However, NZS 4219:2009 includes a clause (Clause 2.4) specifying that all the proprietary components manufactured in New Zealand or overseas need to be verified for the performance level required (i.e. to be operational under serviceability level earthquake for hospital buildings).

In this section, all the systems that are floor mounted are grouped and discussed with regard to their mounting types. The mechanical and electrical equipment is generally floor mounted with rigid fixings or with resilient mountings to prevent the transfer of mechanical vibrations to the floor. Rigid mounted
components that generally have no moving parts, such as motors, are usually bolted directly to the floor. On the other hand, if there is a potential for the equipment to induce vibrations in the supporting structure, often such equipment is supported on resilient mounts. The following list of equipment encountered in the surveyed hospitals includes both types:

(1) Air handling units (AHU) (rigid and resilient)
(2) Chiller (resilient)
(3) Switch boards (rigid)
(4) Boilers (rigid)
(5) Generators (standby power supply units) (resilient)
(6) Pressure vessels (rigid)
(7) Oxygen storage tank (rigid)
(8) Air-conditioning inverters (resilient)

NZS 4219:2009 further divides the resilient mounted equipment into two types. Type 1 mounts provide sufficient strength and stiffness to restrain the equipment against earthquake motions while the Type 2 mounts require snubbers to be included to resist seismic forces and displacements. Typical examples of restraint systems provided in floor mounted components are discussed below.

2.1.1 Rigidly mounted components

(a) Air handling units: These units were found to be usually stable against overturning because of their squat shape and they were mounted directly on the floor. Because there is a fan in the unit, there is a potential for it to impart vibration into the structure and therefore a resilient bearing pad has generally been installed under the feet of the unit (Figure 1). Depending on the floor types where the units were placed, the fixing system varied. In general, it was observed that the fixing was made with an angle bracket fitted between the leg of the AHU and the floor, as shown in Figure 1. Such a connection provides a positive resistance against sliding in one direction but in the orthogonal direction there is a possibility that the bracket will rotate on the single bolt fixing it to the leg of the AHU if the unit was to slide, possibly levering the screw out of the floor at each leg. Figure 1 shows an air-handling unit located on a timber floor and a Type 17 screw fixing to the floor. There is a potential for the screw to be ripped out of the floor should the AHU slide in an earthquake. A coach screw would have been a more appropriate solution provided it was fitted into timber framing beneath the flooring. Alternatively, the addition of a second bracket on the adjacent face of the AHU leg, with a second screw into the timber floor would alleviate the potential to slide.

Figure 1. Unit and its fixing on a timber floor

Figure 2 shows an AHU fixed to a concrete floor. It can be seen that the unit is positively fixed to a steel channel which is in turn bolted to the floor with proprietary anchors. It is believed that the anchorage system will hold the equipment in place in a large earthquake.
Figure 2. Unit and its fixing to a concrete floor

Figure 3 shows one AHU placed on top of another. The bottom unit is fixed well to the floor. However, the top unit is restrained only in the transverse direction and not in the longitudinal direction. In a large earthquake, the top unit could slide a sufficient amount to sever its supply connections. A simple detail similar to the one provided in the transverse direction would provide adequate restraint.

Figure 3. Units placed one top of the other – inadequate restraint in longitudinal direction

(b) Boilers: Figure 4 shows a vertical boiler which is tall and therefore prone to overturning under lateral earthquake motion. To prevent this, the boiler has been braced back to wall at about the 1/3 height and at top levels with a flat strip fixed to the Unistrut system, which is in turn fixed to the wall. The supporting system provided would prevent the boiler from moving perpendicular to the wall direction and would probably prevent most movement parallel to the wall.

Figure 4. Vertical boilers supported at top and 1/3 levels height with flat strip fixed to the Unistrut system on the wall.
2.1.2 Resilient mounted systems

Different types of isolator systems were in place for some components. Figure 5 shows 4 specific types observed during the audit. Figure 5(a) shows the steel equipment base frame (blue colour) attached to the concrete pad with cork blocks. In this case the cork is glued to the frame and the concrete. While vibration isolation is thus achieved the cork is not likely to provide sufficient strength against lateral motion. Rather, the weak cork is likely to shear through. Figure 5(b) shows an open coiled spring with a threaded rod inserted through the middle. This rod is expected to limit the movement in the vertical direction through tension as the nuts make contact with the spring seats and in the horizontal direction also through tension as the spring tilts sideways. Corrosion of the rod has potentially weakened the “snubber”.

Figure 5(c) is one of several spring isolators used under an air-handling unit. The unit was mounted in a steel frame which was isolated using these springs. The springs are placed between the plates with three short steel pegs on each plate so that the springs are held in place against sliding on the plates. This arrangement provides adequate vibration isolation of the AHU. However, the frame was not provided with any snubbers, and under large lateral displacements the springs could “roll over” and disengage from their end supports. It is recommended that angle shaped snubbers be provided to prevent this eventuality. In Figure 5(d), the resilient mounting of an extract and supply fan system is shown. The system is mounted on a steel plate frame through small compression springs placed within rings welded to the plate and the underside of the fan unit. There appeared to be no central tie rod to resist large displacements and no other snubbers are provided. Also, the steel plate frame did not appear to be fixed to the floor. It is recommended that the frame be coach screwed to the timber floor and that some type of snubber is provided to prevent excessive lateral displacement of the fan.

![Figure 5. Different types of resilient mounts observed](image)

2.2 Medical gas storage

Invariably in all the hospitals, there is a ‘standard’ practice of securing the medical gas cylinders to the wall with chains only near the top of the cylinders as shown in Figure 6a. It is important for the hospital to be able to remove and install cylinders without having to lift them over any retaining plinth at the base. It is recommended that a second row of chains near to the base would perform the function of maintaining the bottles in the correct orientation during an earthquake but would allow
them to be easily exchanged when empty. However, in new hospitals, there was evidence of an improved restraint system (Figure 6b).

![Medical gas cylinders](image)

**Figure 6** Medical gas cylinders:

(a) chained only at top;                       (b) chained at top and bottom

2.3 **Suspended components**

For suspended components, NZS 4219 recommends adequate restraints in the longitudinal and transverse directions apart from gravity support. In all hospitals considered in this study, the gravity supports to the suspended components were of little concern. However, there were some instances of a lack of transverse or longitudinal support. In some cases, the vertical hangers were too long to provide any lateral restraint on their own, potentially allowing the components to swing and interfere with other equipment.

2.3.1 **Pipes and ducts**

Figure 7 shows typical examples of suspended systems observed during the audit. Figure 7(a) shows a series of trapeze hangers supporting a pipe. Lateral braces are provided at regular intervals. Figure 7(b) shows long vertical hangers supporting the pipes and with no observed lateral bracing. Figure 7 (c) shows well restrained pipes with short hanger rods from the ceiling.

![Suspended systems for pipes and ducts](image)

(a) Braced trapeze system          (b) Long vertical hangers         (c) well restrained pipes

**Figure 7** Typical suspended systems for pipes and ducts
2.3.2 Operating theatre rooms

Operating theatre rooms are equipped with components such as: (i) operating theatre lights (suspended from the ceiling as shown in Figure 8 (a)); (ii) free moving racks with brakes and partial arrestors (Figure 8 (b)); and (iii) free standing racks with no wheel arrestors (Figure 8 (c)). In an earthquake event, a theatre room might look like what is shown in Figure 8 (d), showing anchorage failure of the theatre lights hanging from the ceiling and electronic components spread on the floor. In this case, the components had been supported on a hanging work station. As theatre lights are very large and heavy, care should be taken in the design and installation of the fixings for such components.

(a) operating theatre lights

(b) Partial restraints around the wheels

(c) free standing racks

(d) Damaged components within operating theatre room (Nisqually earthquake, 2001; obtained from website)

Figure 8: Components in operating theatre room
2.4 Interference between components

(a) Pipes well supported to avoid interference
(b) Potential impact of pipe with nearby Invertor

Figure 9: Typical interaction effects

In hospitals, many of the engineering systems are placed on the roof and all the systems have to be configured so that adequate gaps are provided between the components to accommodate any displacements each component would undergo during an earthquake. Figure 9 (a) shows a typical restraint system which prevents interference between the pipes. However, sometimes, due to lack of space and coordination between trades, some components are placed close to one another without realising the potential damage that may be caused by one impacting the other. Figure 9 (b) shows a typical example where a pipe swinging in its transverse direction can potentially be damaged when it hits against the inverter which are usually supported on resilient mountings. Similarly, the impact from the pipe may cause failure of the inverter.

2.5 Communication, data and network systems

NZS 4219 recommends that items under the communication and network category have a latching mechanism that restrains the item against a force of twice its own weight against sliding. During the audits, it was observed that computer network items were simply placed in the rack without any restraint and the rack was often not adequately braced to the wall. This observation was consistent across all three hospitals. It appears that no or little consideration is given to the provision of adequate seismic restraints for the equipment (Figure 10), probably because it has not been pointed out to the installers what could be the consequences in a major earthquake. If a hospital is reliant on an electronic system for its patient records, without proper consideration of the required restraints, it is very likely that after a severe earthquake the hospital will have to revert to the keeping of paper records for new patients. With the computer network inoperative, records for existing patients may no longer be accessible.

Figure 10 Unrestrained communication data system and racks
3 MITIGATION OF SEISMIC RISK WITH ENGINEERING SYSTEMS

The operational continuity of hospitals in a post-earthquake situation should be possible if seismic safety provisions required by building standards are adopted and essentially followed up by onsite inspection to ensure proper implementation. In this regard, California’s OSHPD organization features a well-defined organizational structure for the construction of hospitals. It includes various departments and/or accredited agencies to review the plans and design of the building and to approve the installation of equipment and non-structural components. Unfortunately, in New Zealand there is not such a thorough organizational structure to ensure an adequate seismic performance. However, for most new major projects, efforts are made by the structural engineers to ensure that the code provisions are adopted, followed by the assignment of a field engineer to perform an on-site inspection once the equipment is installed.

3.1 Current Practices in NZ consultancy firms

Our investigations have shown that what happens in New Zealand in consultancy practices can vary markedly because of the lack of coordination between structural and mechanical engineering disciplines. However, as the size of the project increases or the importance of the completed structure to the community increases (i.e. a hospital versus an office building) there appears to be more coordination. It is often the fee structure for the project that determines the level of design and checking that is undertaken on the seismic restraint of building services and non-structural components. If no fee allowance has been made for signoff at completion of the installation then it is not likely to get done (Beattie, 2000).

The latest issue of NZS 4219 is not currently referenced in the New Zealand Building Code clause B1 Structure. However, NZS 4219:2009 states that it is intended to provide a means of compliance with B1.3.1 and B1.3.2 for loads from B1.3.3 (f), (m) and (p), that is, for loads arising from earthquakes and earthquake actions. All building projects should therefore make use of this standard to ensure the compliance of the building services contained therein with the seismic provisions of the Building Code.

For a major new hospital project a coordinated process has been observed. This involved:

- Preparation of a specification document by the structural engineers for the services subcontractors
- Requests by the structural engineers that design details for the seismic restraints for the services were documented
- Requests by the structural engineers for Producer Statements (PS1, PS3 and PS4) to be provided by the subcontractors to show that the requirements of the specification had been met
- Assigning a structural engineer in the field to verify the installation process.

With regard to installation of engineering systems and other non-structural components, OSHPD requires an inspection certificate for every important component to be issued by an approved agency. In connection to testing of the component and fixings, Code Application Notice (CAN) from OSHPD suggests the adoption of the AC 156 shake table test protocol and AC 193 for testing of mechanical anchors in concrete elements. Similar to this, product certification has been addressed within the NZS 4219 provisions by suggesting that for “unverified” equipment (such as systems imported from non-seismic countries), the product should be tested in accordance with NZS 4219 and reported. However, this is a static test only and therefore will not qualify components that are acceleration sensitive. The testing may either be done in-situ or in a test laboratory. However, there is also a concern among engineers, how seriously this requirement will be enforced by the supplier or manufacturer of the equipment, particularly if there is no inspection by the structural engineer on completion of the installation.

In the opinion of the authors, it may not be feasible or practicable to follow the structure adopted by OSHPD in California because the number of hospitals in New Zealand is far less than in California. However, given the importance of seismic qualification of equipment and plant, on-site inspection of the installed equipment may be more feasible at a reasonably small additional cost in the practice.
SUMMARY

A survey has been undertaken of three hospital facilities in the Wellington region. The aim of the survey was to determine the level of seismic restraint provided to critical plant and equipment in these existing facilities.

The design standard for seismic restraints, NZS 4219, has recently been updated to align with the new earthquake loadings standard, NZS 1170.5. In reviewing the facilities, an attempt was made to determine whether the restraint system, if in place, would satisfy the requirements of the new standard. Because the details of the mass distribution in much of the equipment could not be accurately determined by visual inspection, qualitative assessments were made of the suitability of the provided restraint systems. On most occasions the restraint systems appeared to be suitable (either by default or by design), however, there were some instances where the restraint was clearly not sufficient. This particularly applied to vibration isolated systems where there was a lack of snubbers to prevent excessive movement in an earthquake and also to computer systems, where servers, CPUs and other equipment were located on insecure shelving and/or not restrained in place on the shelf. Retrofit solutions have been suggested for poor installations.

The implementation of a system similar to the OSHPD system in New Zealand has been considered but discounted as being too onerous for a small country. However, it is hoped that the introduction of the up to date and simple to use NZS 4219 standard will encourage greater care taken towards restraining plant and equipment in new hospital buildings. It is noted that for new major hospital facilities there has been greater cooperation between the mechanical services engineers and structural engineers in an effort to provide resilient systems.

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