THE NEXT FRONTIER – IMPROVING THE SEISMIC RESILIENCE OF NON-STRUCTURAL COMPONENTS

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Abstract

The recent earthquakes in New Zealand have illustrated the vulnerability of non-structural elements of buildings as well as the costly consequences of their failure. Impacts on business continuity due to the damage of non-structural elements has been identified as a major issue in the recent earthquakes in New Zealand as well as overseas.

Improvement in the state of practice in structural design for earthquake loads has improved significantly over the years in New Zealand and other developed countries, due in part to increasingly sophisticated seismic design code provisions and robust building construction standards. Building structures designed to these modern codes have generally performed as expected by the code writers in major earthquake events. However, the seismic performance of non-structural components still lags far behind societal expectations, notwithstanding that the structural seismic codes include provisions for the design of non-structural components. The reasons are numerous, including the complexity of many non-structural systems, lack of clarity of design and construction responsibilities for the seismic restraints and the lack of enforcement in the field.

The next big challenge facing engineers and building owners is finding cost-effective and pragmatic solutions to improve the seismic resilience of non-structural elements in order to better meet societal expectations. A further challenge is doing this within the design and construction paradigms buildings are currently constructed in, given the construction industry structure is unlikely to quickly change.

In order to help improve the seismic performance of non-structural elements this paper discusses issues with current design and construction practices that have led to poor performance both in New Zealand and overseas. This paper then explores options to improve implementation ranging from possible enforcement options to possible holistic design approaches. Recent projects illustrate approaches we have taken to provide effective and appropriate seismic bracing for non-structural components.

Introduction

The recent Canterbury earthquake sequence and the more recent Seddon, Lake Grassmere and Castlepoint earthquakes have raised awareness of the risk earthquakes pose to New Zealand from a life safety viewpoint. They have also dramatically illustrated the monetary and societal impacts of large earthquakes. Widespread damage and loss of business continuity from the performance of non-structural components was widely observed and noted [Schouten, 2013; Thomson & Bradley, 2014; Helm, 2014].

An analysis of the losses due to the 1994 Northridge earthquake indicated that of the approximate $6.3 billion of direct economic losses to non-residential buildings only about $1.1billion was due to structural damage [Kircher, 2003]. A similar study completed in 2004 suggested that losses associated with damage to non-structural components and building contents represents 50% of total costs of an earthquake in a developed country [Bachman, 2004].

As buildings become more complex with increasingly sophisticated and extensive building services systems and architectural finishes, an increasing proportion of the building value is dedicated to non-structural components and building contents. The seismic restraint of non-structural components will therefore likely become an increasing area of interest and focus to building owners and tenants who wish to limit damage to buildings and avoid a loss of business continuity. Structural engineers need to identify and implement approaches that improve the current situation.

Issues

Improvement in the state of practice in structural design for earthquake loads has improved significantly over the past 50 years in New Zealand and other developed countries vulnerable to earthquakes with increasingly sophisticated seismic design code provisions and robust building construction standards. Building structures designed to these modern codes have consequently generally performed as expected by the code writers in major earthquake events.

These structural seismic codes include extensive provisions for the design of seismic restraints for non-structural components and they have been in place for many years. Yet, notwithstanding these extensive code requirements, the seismic performance of non-structural components lags far behind the performance of building structures in earthquakes.

California hospitals provide clear evidence that these code requirements are effective in improving the performance of non-structural components if the bracing systems are designed to the requirements of the codes and are implemented. A study of the performance of hospitals in the Northridge earthquake compared those hospital buildings designed and constructed after the State took control of oversight for hospital design and construction in 1973 with those constructed before [Holmes & Burkett, 2006]. The study included consideration of both building structure performance and the performance of non-structural elements in the buildings. This study clearly identified a significant reduction in damage to non-structural components for those buildings designed after the State took control.

Table 1. Performance of all Buildings at 23 California Hospital Sites with one or more Yellow or Red tagged Buildings [Holmes & Burkett, 2006]

Type of Damage	Number (%) of Buildings	
	Pre Act	Post Act
Structural Damage		
Red tagged	12 (24%)	0 (0%)
Yellow tagged	17 (33%)	1 (3%)
Green tagged	22 (43%)	30 (97%)
Non structural Damage		
Major	31 (61%)	7 (23%)
Minor	20 (39%)	24 (77%)
Total Buildings	51	31

The major difference between the Pre Act and Post Act buildings was not that the code requirements for seismic restraint of non-structural components had changed but that the requirements of the codes were implemented and the bracing was installed to meet the requirements of the applicable codes.

Preliminary results from a study currently underway in New Zealand to investigate the extent of seismic restraints present in New Zealand commercial buildings suggest that only a small percentage of non-structural components are braced in accordance with the code requirements [KOA, 2016].

Both these studies indicate the issue of poor performance of non-structural components in earthquakes is largely one of lack of implementation.

Issues with Current Practice Affecting Implementation

Our experience of the New Zealand construction market and industry indicates the following issues affecting the implementation of non-structural seismic restraints:

Cost. The New Zealand construction industry is very cost conscious regarding both design and construction costs. Market cost intelligence used by project managers and estimators to advise clients when planning projects has not traditionally allowed for significant design or construction costs for bracing of non-structural elements.

As non-structural systems become more complex and interconnected it is likely the costs of bracing will rise, exacerbating the issue.

"Just in Time" Design Timing. Proprietary non-structural components are often selected late in the design and construction process, often during the construction phase itself. This "just-in-time" design approach encourages competitive tendering amongst the subcontractors by allowing each tenderer to propose a solution based on the performance specification, generally using proprietary products they have exclusive access to.

This approach is generally seen as providing the best value possible to the owner. However it does result in any design for these elements, including seismic bracing, being completed after the regulatory building consent approvals process has been completed and once the contactor, along with subcontractors, has been selected.

Procurement. The competitive tendering model generally used in New Zealand for the selection of contractors for building projects focusses on initial capital costs. Life cycle costs, including the cost of bracing non-structural elements to improve resilience is inevitably under pressure in such an environment.

In our observation the subcontract tendering and selection process for non-structural systems can result in subcontractors tagging out the seismic bracing in order to provide a more cost competitive tender compared with other subcontractors competing for the work. Sometimes this tag is not made clear or is not recognised by those involved in tender selection resulting in the seismic bracing, noted in the specifications, not in fact being installed.

Without an owner focussed on ensuring that bracing is installed to limit damage and downtime following an earthquake, or some sort of regulatory requirement contractors are obliged to meet, market forces will continue to apply pressure to reduce or remove seismic bracing from the construction contract.

Construction Process and Programme. Non-structural components are typically installed late in the construction process. The structure has been erected and is generally in the process of being made weather tight before any of the non-structural components are introduced to the site for installation.

Generally this means that the structural engineer is no longer visiting the site to inspect key aspects of the construction of the structure at the time the non-structural elements are being installed. If inspections of bracing for non-structural elements are required then these will entail specific site visits.

Engagement of Consultants. The structural engineer's scope of work is traditionally confined to the building structure only, and excludes design of bracing for non-structural components. This is because the focus has traditionally been the design of the primary structure, and often there has not been a request or expectation on the part of the owner, lead design consultant, MEP design engineer, or the proprietary item manufacturer, for structural engineer involvement in the design of the non-structural components.

Also, structural engineering consultants are often looking for ways to keep their fees within the traditionally expected boundaries in order to be competitive and secure the engagement, and so are not seeking to expand the structural scope of work to include non-structural bracing.

Expectations and tradition have meant that structural engineers designing buildings have historically not had significant involvement in the design and construction monitoring associated with non-structural elements attached to the structure.

Code Compliance. NZ society traditionally has had an expectation that the building code requirements will fully meet their needs. Building owners rarely, in our observation, seek to construct buildings that exceed the minimum code requirements. With the New Zealand building codes primarily focused on life safety, damage prevention and limitation has not had the level of focus that it might have.

The lending institutions and insurance companies associated with building projects have not typically recognised with financial incentives, (e.g., reduced insurance premiums or lower lending costs), the considerably reduced risk associated with damage limitation designs

Existing Buildings. Modifications to the services in existing buildings as a result of tenancy changes or other alterations present an additional challenge. Sometimes these modifications are completed without the benefit of a building consent and generally without any oversight to ensure adequate seismic bracing to the non-structural components are installed. As an example, piping added post original construction and installed across existing seismic joints without flexible connections results in a piping network highly vulnerable in an earthquake.

The installation of seismic bracing for non-structural elements requires continued focus and oversight over the course of the life of the building.

Summary

A complex interaction between the design and construction phases for the construction of most buildings and a lack of assigned responsibility for non-structural elements coupled with a competitive procurement selection process that emphasises initial capital costs and speed of construction has resulted in seismic restraints for non-structural components being widely omitted from New Zealand building construction.

EERI conducted a survey of US industry members in 2009 [EERI, 2009] to try and understand people's opinions of changes required to improve the situation surround the poor performance of non-structural elements. This study identified the following key issues:

- Speed of design and construction,
- A requirement to coordinate with many people, across many different disciplines, and between designers, manufacturers and contractors,
- A diffused responsibility matrix,
- The normative effects of individual behaviour where individuals behave as they think others are behaving, and
- Costs involved with provision of non-structural bracing, both design and construction.

These key issues closely align with our observations of the issues associated with current New Zealand practice, confirming that the issues around the seismic restraint of non-structural elements and systems are not unique to New Zealand and are focussed on implementation issues.

Suggested Approaches to Improve the Situation

Based on the key issues identified with current practice surrounding the design and installation of non-structural elements we suggest the following three approaches as ways to improve seismic performance.

Design and Inspection Requirements for Bracing of Non-Structural Elements. Requiring a list of design and inspection requirements for seismic restraint of non-structural elements to be included in the building consent documentation will result in design teams considering who is responsible for these elements. This will prompt discussions with building owners on appropriate design fees for these services along with the identification of appropriate design and inspection responsibilities.

The County of St Louis in Missouri, USA [St Louis County, 2011] have adopted this approach and require a "seismic block" to be included on every set of drawings submitted for building consent. The "seismic block" outlines the non-structural seismic protection required for the building and who is responsible for the design of the seismic restraint systems.

MECHANICAL AND PLUMBING EQUIPMENT COMPONENTS
EARTHQUAKE LOAD RESISTANCE

Occupancy Category ( ) Seismic Design Category ( )

LISTING OF EQUIPMENT AND SYSTEM COMPONENTS	ANCHORAGE TO FLOORS, ROOFS, ETC. (See Note 1 below)		SWAY BRACING (See Note 1 below)		LOCATION OF PROFESSIONALLY SEALED ANCHORAGE AND SWAY BRACING DETAILS			COMMENTS
					ON CONST. DOCUMENTS	SUBSEQUENT SUBMITTAL (See Note 2 below)		
	Not Provided For Project	Provided For Project	Not Provided For Project	Provided For Project	Drawing No. or Spec. Section	Shop Drawings	Separate Permit & Plans	
FIRE PROTECTION, DETECTION & ALARM EQUIPMENT & SYSTEM COMPONENTS: * See Chapter 4, Table 4.1 (List items such as: fire sprinkler system equipment & system components, smoke control & evacuation equipment & system components)								
HAZARDOUS EQUIPMENT & SYSTEM COMPONENTS: * See Chapter 4, Table 4.1 (List items such as: gas piping, piping containing flammable, combustible liquids & gasses or toxic chemicals. Include items such as flammable & combustible tanks, vats & other industrial equipment containing hazardous or toxic liquids, gasses, chemicals, etc.)								
OTHER EQUIPMENT & SYSTEM COMPONENTS NEEDED FOR CONTINUED OPERATION OF OCCUPANCY CATEGORY IV FACILITIES OR WHOSE FAILURE COULD IMPAIR THEIR CONTINUED OPERATION * See Chapter 4, Table 4.1 (List items)								
OTHER GENERAL EQUIPMENT & SYSTEM COMPONENTS (List items such as: boilers, furnaces, AHU's, tanks, heat exchangers and pressure vessels, suspended piping, water heaters, VAV boxes, HVAC ducts, drain, waste & vent piping, pumps, etc.)								

Notes:

1. It is the basic intent of this Code Block to declare whether or not anchorage and sway bracing is being provided on the project. If so, to declare whether or not the details are shown on the plans or will be shown on a subsequent submission. If seismic restraint of a component is not required by code this should be stated in comments. If seismic restraint, which is not required by code, is being provided due to owner/designer requirements this should also be stated in the comments.
2. Shop drawings need to be submitted to the County a minimum of two weeks prior to the planned installation to allow for plan review and distribution to the inspector. Additional time may be needed if such submissions are deficient.

Figure 1: St Louis "Seismic Block"

The presumption behind this approach is that implementation will improve if clarity is provided as to who is responsible for the design of the seismic restraint of the various non-structural systems.

Non-Structural Seismic Coordinator. Adding the role of non-structural seismic coordinator to the design team provides a designated person responsible for considering the seismic protection of non-structural elements. This role ensures the responsibility for the design of the bracing systems for non-structural elements is appropriately assigned within the design and construction team and that the construction documents contain provisions for protection, such as anchorage or bracing, that are clear, coordinated, and practical to implement. During construction the non-structural seismic coordinator's role is to monitor implementation of the seismic protection systems reporting non-compliance to the client.

The role was first introduced for the construction of Stanley Hall at University of California Berkeley and is now a requirement for the construction of California Courthouses [California Judicial Council, 2011].

Include Seismic Restraint of Non-Structural Elements as Part of A Holistic Design Approach. A possible alternative, or additional, approach is to incorporate considerations of non-structural seismic restraint directly into the building design right from the start of concept design as part of a holistic design approach.

A challenge in this approach is the requirement for coordination across the design disciplines during the design stages and across the many trades during construction. The benefits are resilient buildings where the non-structural components are restrained for seismic loads.

Three examples are provided below where we have adopted this approach on several of our recent New Zealand projects.

AUT ETD Building – Service Support Frames / Service Racetrack

The Auckland University of Technology Engineering, Technology and Design (AUT ETD) Building contains a mixture of laboratory and teaching space, making it more heavily serviced than a typical commercial building. The building is to be used for subjects relating to Engineering, Technology and Design (ETD), so it was the architect's desire to leave as much of the structure and services exposed as possible to assist the student's learning by being able to see elements of the building. This requirement to expose both structure and services, along with the high level of service reticulation led to the need to develop a strategy for the seismic restraint of building services to ensure a tidy, efficient solution was achieved.

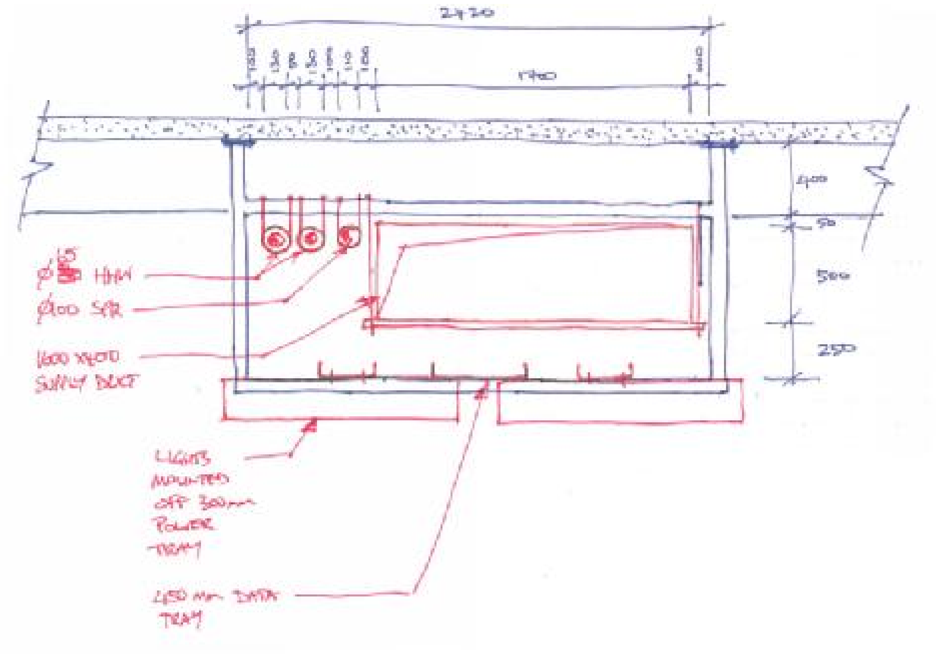

Figure 2: Service Support Frame for AUT ETD

The concept of a system of inverted frames forming a "services racetrack" hung from the floor above and exposed within the laboratories and teaching spaces supporting the various services was developed very early in the design process, refer Figure 2.

Adoption of such a scheme requires coordination between the structural engineers, building services engineers and the architect much earlier than for a typical project. Once the strategy was established and all parties were happy with the general location of the service racetracks, the structural engineer sized the frame based on the weight of services and the spacing of frames. The architect then placed these frames in their model and the services engineers subsequently modelled in the services around each frame, as shown in Figure 3 below.

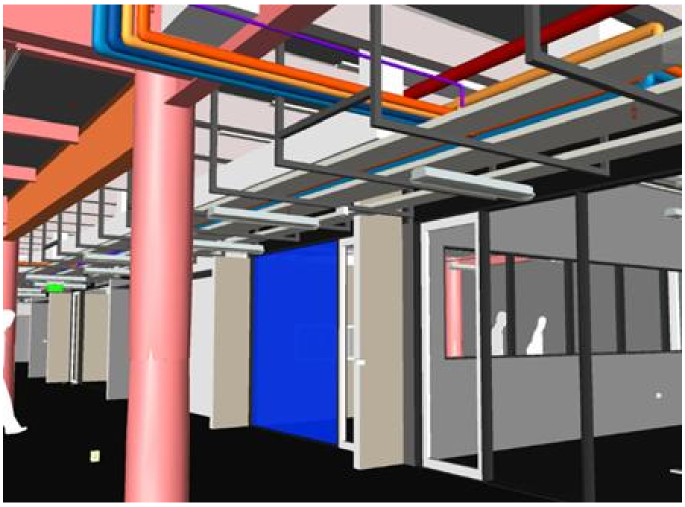

Figure 3: Services Support Frame, Auckland, New Zealand

Wellington International Airport

The architect's vision for the recently constructed extension to Wellington airport was to incorporate passenger way finding directly into the building design rather than just as added signage. The ceilings feature large timber beams orientated in the direction passengers walk to the airline gates as part of the directional messaging.

The challenge was to support these large timber beams (more than 1m deep) and associated perforated ceiling panels along with myriad building services components at the ceiling level in the large open space of an airport terminal, in a manner that would prevent these elements all moving relative to each other in the event of an earthquake. The solution was to create a rigid framework at the ceiling level using specially introduced transverse steel trusses. The timber beams directly support all ceiling elements and associated building services (refer Figures 4 and 5 below). The large ductwork runs are directly supported and fixed to this steel sub frame.

The end result is an intricate ceiling system where all the various elements are directly supported on the rigid steel supporting frame located immediately above so they are well supported and braced and are not able to move relative to each other.

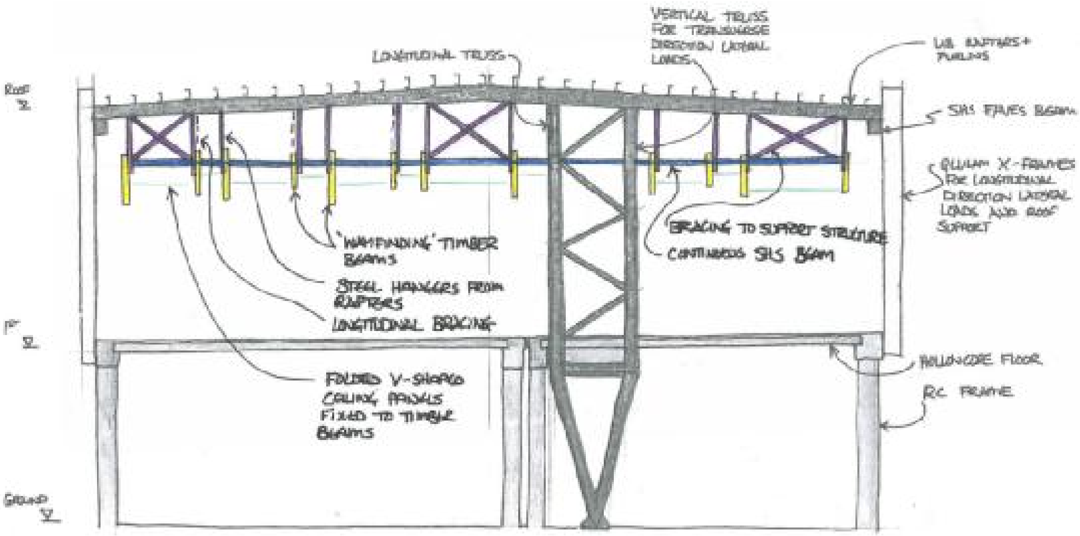

Figure 4: Cross Section of Wellington International Airport

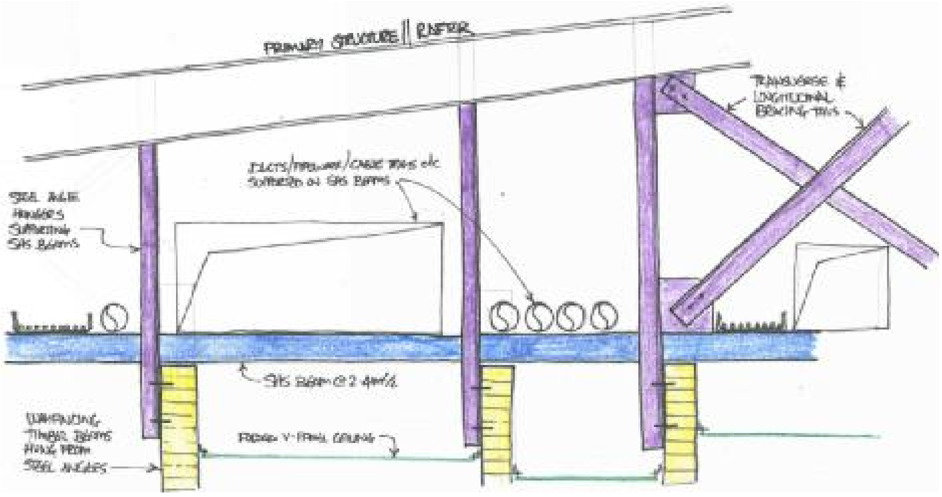

Figure 5: Detail of non-structural services support system

Victoria University Faculty of Architecture Refurbishment.

Victoria University, Wellington, wished to repurpose one of its buildings and introduce several offices into a space that was not heavily serviced. The introduction of offices required additional services to each office and subsequent lateral restraint. The solution adopted was to construct the offices as mini structures within the existing building. The office walls and ceiling were used to create a rigid box structure supported on the floor within the existing building, with no connection to the floor above and separated from all building columns (refer Figure 6 below). This allowed the pods to remain rigid and move with the floor supporting them and allowed the main building structure to move independently without causing damage to the pods.

The building services associated with the pods were generally routed up through the walls and supported directly on the pod ceiling structure. Where services were required to be routed from the hung services supported on the floor above the pods, flexible dropper type connections were provided to allow movement of the services between the floors of the main structure. These services were then directly supported on the ceiling of the pod mini structure in a rigid manner.

This approach provided a simple system to provide seismic restraint to non-structural elements and prevent interaction between the non-structural elements and the main building structure.

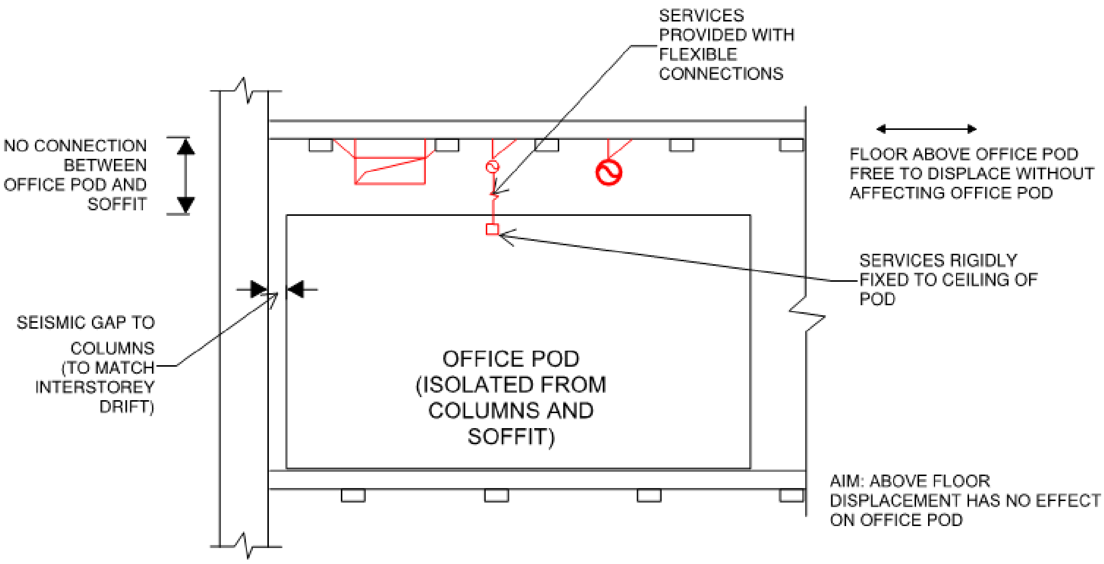

Figure 6: Victoria University Office Pod Concept

Summary

The first two approaches proposed encourage the provision of seismic restraints for non-structural elements by focussing on improving visibility for the implementation of non-structural seismic bracing within the design and contractor teams as well as the regulatory authorities.

The third approach proposed is different. It aims to improve the provision of seismic restraints for non-structural elements by taking a holistic design approach for the building right from the start of concept design. We are finding this approach requires considerable coordination both at the design and construction phases. The subcontractors in particular have to coordinate the installation of each of the services elements between the trades which can be challenging but it is resulting in structures where the resilience of the non-structural elements is considerably improved compared with the traditional approach.

Conclusions

A combination of a lack of focus on the seismic performance of non-structural elements by structural engineers and other designers as well as constructors and a history of low expectations, has resulted in generally poor performance of non-structural elements.

It is becoming clear that seismic design in the future will be driven, at least in part, by the need to improve the seismic performance of non-structural systems. Post-earthquake functionality and operability will not be delivered until effective strategies are devised to improve the resilience of non-structural elements.

Key to improving the resilience of non-structural elements is improving implementation of non-structural seismic restraints during building construction. Improving visibility of the responsibilities for design and installation of the systems will help as will considering the design of building in a holistic manner so that seismic restraint considerations are included right from concept design and are designed into the building.

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