Non-structural element bracing design and assessment for buildings using automated design

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Formalised by RMIT University into a Graduate Certificate in Design Management, Aurecon Design Academy aims to foster eminence and a human-centred, transdisciplinary approach to design problems, enabling us to serve clients through design excellence and innovation.

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Executive Summary

1 Executive Summary

Past earthquake events have shown that even if the primary structure is intact, building reoccupation is most often prevented by the systemic failure of inadequate non-structural fit-out restraint systems. Improved building performance in large seismic events can be achieved to match owner and tenant expectations of new designs and their reliance on structural building assessments.

Developing an automated design procedure for vertical load support and seismic bracing of non-structural building elements (NSEs) within a 3D Revit model provides a coordinated approach to allow seismic bracing of NSEs to be integrated into the structural engineers design documentation for commercial buildings. This approach can greatly improve design coordination, build quality, building safety and seismic damage reduction.

A building which includes well- coordinated and designed NSEs provides high levels of confidence to reoccupy soon after an earthquake, giving owners and occupiers better chances of business continuity closely following a significant seismic event.

Past earthquake events have shown that suspended services and ceilings are susceptible to damage and collapse which causes significant disruption to building reoccupation soon after earthquake events where primary structure is intact and a building safe for reoccupation. A better approach to design of these elements is possible by integration of the services restraint design into the overall design documentation. An automated design approach can provide coordinated and accurate design at a faction of the effort of traditional sub-contractor design and build methodology.

Detailed seismic assessment of buildings can also benefit from an automated methodology applied to building assessment. The assessment of building services seismic restraint is most often overlooked during building assessment, yet the damage resulting from earthquake can amount to 70% of the buildings value in some cases. It is proposed that seismic assessment of NSEs a logical next step in detailed building assessment.

An approach to automating building seismic assessment of NSEs can be undertaken by integrating an automated design methodology in Revit and Dynamo with comparative as-built conditions discovered with point cloud scanning and structured data of a digital twin enhanced by machine learning.

1.1 Abstract

Following earthquake events in New Zealand between 2010 and 2016 and the subsequent increased awareness of seismic risk, there has been significant interest in the seismic performance of buildings.

A key outcome of building performance is enabling early reoccupation of a building after an earthquake. As New Zealand's earthquake events have proven, immediate reoccupation after a significant earthquake is unlikely, due to the susceptibility of non- structural elements (NSEs) to seismic damage. Vulnerable NSEs include ceilings, claddings, building services' equipment, ducting and piping.

Earthquake occurrences have promoted a shift to resilient building design, which better protects primary structure in new building designs [1] but does little to consider the protection of NSEs.

This paper considers how automated design of seismic restraint to non-structural building elements can be included in the structural design and documentation process, and how this automation may improve the resilience of NSEs to enable early building reoccupation after a large earthquake. This paper also introduces how a new approach, using automated design processes, could be used in the seismic assessment of existing buildings. Seismic assessments ordinarily only assess the primary structure and parts of the building that may have a life safety risk. NSEs are generally overlooked but proven poor performance [4] suggests that building owners, occupiers and insurers could benefit from more comprehensive assessment tools. Techniques for the assessment of NSEs are covered in the New Zealand Engineering Assessment Guidelines Part C10 released in 2017. This document provides guidance for the assessment of secondary structural and NSEs in buildings.

Introduction

2 Introduction

2.1 Resilient Building Design

In New Zealand, structural engineers continue to develop different types of resilient building designs that showcase a variety of resilient design technologies and methods, each offering a different level of seismic protection to the primary structure [1]. But there is obvious focus on the primary structure's protection, rather than paying equivalent attention to the performance of non-structural elements (NSEs) in the building fit out.

Resilient buildings respond similarly to ordinary buildings that are founded directly into the ground. As the ground shakes, the building follows suit and responds with its mass being accelerated. During an earthquake, a building will sway back and forth seeking its natural frequency of response and accelerating all secondary components within the structure. The NSEs are not protected from these accelerations and, as a result, produce their own secondary accelerations and forces, which creates the need for seismic bracing to these elements. The forces can be in the order of 200% of the NSE's own weight. While the actual loads on the restraints can be easily accommodated by normal fixings and braces, as the NSEs are usually relatively light, it is a lack of seismic bracing or incorrect installation that appears to be the main cause of NSE's poor seismic performance [2].

Recent earthquake sequences in Canterbury and Wellington have highlighted that losses from damage to overhead NSEs can be significant. With architectural and building services components accounting for up to 70% of a building's value [3], costs of NSE earthquake damage exceed costs from primary structural damage in some cases. Furthermore, the failure of overhead NSEs can become a significant safety hazard to building occupants during an earthquake and can inhibit business continuity [3].

Non-structural elements are generally not included in the principal structural engineering designer's scope of work. [2]. This leaves the support and seismic bracing design of non-structural elements to be passed on to the main contractor, who is typically a builder and not a designer. The design task is often an afterthought, needing to be designed and installed by an ill-equipped contractor, who will be required to coordinate gravity and seismic restraint locations with structure and multiple layers of services fit out. In some cases, a satisfactory and code compliant restraint solution will be almost impossible to achieve, because the lack of early coordination of service routes and primary structure is now an immovable obstacle. A combination of poor coordination, a poor understanding of required seismic performance and a history of low expectations, has resulted in generally poor seismic performance of NSEs of buildings in New Zealand [3].

Observed performance raises obvious questions about how NSE restraint systems are implemented and what design improvements could be made to increase overall building resilience. This paper investigates how improvements in overall building resilience through the automation of NSE design supports reduced risk of seismic damage from an owner and insurer perspective and improves business continuity soon after a large earthquake.

Methodology

3 Methodology

To investigate the application of design automation in NSEs for both the design and assessment of commercial buildings, a literature review was completed to study the NSE failures documented after significant earthquake events in New Zealand. Those documented failures provide evidence on the contributing factors to the failures of the NSEs. The literature review is extended to include how automated design using Dynamo is integrated with Revit, and how seismic restraint design and assessment for NSEs can be automated.

The review included a detailed analysis of three case studies, an interview with a project manager responsible for preparing a structural engineering request for proposal, an interview with an insurance broker and interviews with design engineering staff within Aurecon who are familiar with Revit software and point cloud surveying.

Case Study 1 provided a recent example of a new build hospital project in Christchurch requiring non-structural element engineering. The study considered the engineer's scope of work, which required the design of NSE restraint.

Case Study 2 investigated one commercially available American automated design tool. The study on this tool provided an assessment of its suitability for NSE restraint. It involved testing the software and forming opinions on its use when applied to design in a New Zealand context.

Case Study 3 introduces the possibilities of automated design used for building assessment. It provides an example of a recent RFP for a hospital requiring the structural engineering scope of work to include the structural assessment of NSEs. The study considers the automated design application in seismic assessment of buildings in New Zealand.

The research ends with an interview with an insurance broker, which assists understanding aspects of insurance and how building resilience may be linked to lower insurance premiums for commercial building owners.

Finally, interviews conducted with Aurecon engineering staff to investigate examples of current day-to-day use of data capture by point cloud scanning, and conversion of unstructured point cloud data, are presented. This information forms the basis of how NSE restraint assessment within commercial buildings could be developed further.

Results and Discussion

4 Result and Discussion

4.1 Defining non-structural elements (NSEs)

All buildings require a network of non-structural elements (NSEs) to function for the overall building to be serviceable for the health and safety of the occupants. NSEs can be broadly defined as suspended ceilings, mechanical, hydraulic and electrical equipment, and fire systems. Each of these elements is distinctly different in structural design and performance.

For the purpose of this paper, the seismic bracing of NSEs was limited to overhead mechanical, hydraulic, electrical services systems and suspended ceilings that may typically be suspended from a floor slab or structure above, and will require vertical support and lateral bracing to resist seismic forces.

Suspended ceilings in commercial buildings typically consist of a cold formed steel grid in which ceiling tiles sit, suspended from the main structure. Mechanical and hydraulic services, typically consisting of Heating Ventilation and Air Conditioning (HVAC) ducts, pipes and equipment, which are often suspended from steel rods fixed to the structure above. Some mechanical units and large hydraulic services pipes can be of considerable weight, and require detailed consideration for support and seismic restraint. [2]

4.2 Current NSE bracing design methodology and importance levels

The structural design for seismic bracing for NSEs is outlined in NZS1170.5 Section 8 – Parts. Ceilings, partitions, claddings and building services plant are included in this section. Reference must also be made to AS/NZS1170.0 when evaluating seismic risk, and the importance levels required when designing to the Ultimate and/or Serviceability Limit States (ULS and/or SLS) for seismic bracing.

Seismic bracing criteria for NSEs are also specified in NZS4219, so either document may be used for designing seismic restraint.

NSEs or Parts classifications in NZS1170.5 are grouped into seven categories, which represent different levels of seismic risk with associated ultimate limit state or serviceability limit state design criteria. Category P5 is the only category that applies to Importance Level 4 buildings.

These groupings are described as follows:

P1 – Claddings and glazing (ULS)

P2 – Heavy plant, ceilings and heavy partitions in auditoriums (ULS)

P3 – Heavy plant and partitions (ULS)

P4 – Egress stairs, partitions and ceilings etc whose failure would affect the function of emergency egress/lighting, life support systems and rescue systems (ULS)

P5 – Ceilings, partitions, cladding, plant and other parts of structures with post disaster functions, medical emergency facilities etc. (SLS2)

P6 – Parts for which the consequential damage caused by its failure are disproportionately great – e.g. pipework over valuable contents (SLS1)

P7 – All other ceilings, partitions and other parts (SLS1)

When determining the seismic restraint loads, the magnitude of the part's coefficient used to obtain the design load is dependent on:

- Parts classifications
- Building's importance level
- Hazard class associated with its location
- Subsoil class
- Near fault factor (for long period structures)
- Building height
- Height of the part within the structure
- Natural period
- Ductility of the element and its fixings
- Its structural performance factor

A ductility of 1.0 is adopted when assessing the serviceability limit state for NSE bracing design, and for the ultimate limit state connections are typically designed for a ductility of 1.25.

4.2.1 NSE sample bracing calculation

The sample calculation below derives the seismic bracing demand for an air ventilation duct in a hospital located in Christchurch. The hospital needs to be capable of continuing to provide essential services after an earthquake, so is classified as an Importance Level 4 building.

The gravity load support failure represents a falling hazard in relation to life safety, and is classified as Seismic risk category P3 for ULS loads.

The seismic bracing is essential for operational continuity of the hospital functions, and is classified as Seismic risk category P5 for SLS2 loads.

Earthquake load demand is determined from the higher risk factor between life safety (P3) and operational continuity (P5).

The duct parameters are:

W = operating weight of the duct (150 kg or 1.472 KN)

Ch = floor height coefficient; 3.0 above ground floor and 1.0 at or below ground floor (3.0) Cp = performance factor (0.45 from Appendix C in NZS 4219)

Rc = component risk factor (1.6 for IL4 and P3 from Table 5 in NZS 4219) Z = zone factor (0.3 for Christchurch)

C = lateral force coefficient = 2.7 ChZCpRc ‹ 3.6

= 2.7 x 3 x .3 x 0.45 x 1.6

= 1.75

The lateral force on the duct is:

F = CW

= 1.75 x 1.472

= 2.58 KN

Assuming the lateral force represents the seismic bracing demand, ignoring the bracing geometry, when comparing the seismic bracing demand of 2.58 KN to the pullout and shear capacity of a single M12 expanding anchor, it is observed that an M12 anchor can easily accommodate this bracing demand:

M12 pullout capacity = 20 KN ›› 2.58 KN

M12 shear capacity = 13.6 KN ›› 2.58 KN

This basic calculation demonstrates that standard fixings into concrete will easily provide excess capacity over demand for services restraint. Conventional fixings can provide the necessary protection against premature failure to ensure continued functionality for buildings of any importance level. This raises the question, what is the cause of observed NSE bracing failures?

4.3 Coordination between design consultants for non-structural elements

In order to clearly understand the relationship between structural engineers and building services engineers for new building projects, Beattie [2] completed a survey of four consulting engineering firms in 2000. The level of cooperation between the two disciplines was found to be similar across the four firms. In the final design stages, the structural engineer usually provided design forces for the equipment restraints and the expected inter-storey displacements required to be accommodated. It was common for the building services engineer to require the installation contractor to design and certify the restraint systems for the equipment that they are installing because they may be utilising plant from a different manufacturer that satisfies the mechanical performance specification, but which has quite different physical characteristics. It was observed at this point that the contractor tended to use a rule of thumb established through experience, rather than employ the services of a structural engineer.

Beattie [2] identified that it was often a matter of no allocated design fee and a lack of coordination between the structural and building services engineers, whereby no responsibility was taken for the design of the services restraints. The building services contractor was often relied on to provide bracing using his experience of 'what looks right', with no engineering input.

Beattie [2] also conducted building audits which showed there was generally an effort made to provide restraint to building services, although there were often overlooked components in the load path, whose failure could still cause the whole system to fail.

Beattie typically found there was no mechanism for integrating the seismic bracing design for non-structural building elements in the design process before tender. Construction of building services fit out above ceilings can be complex due to the extent of vertical and bracing support for multiple layers of building services. The complexity requires detailed coordination and adequate provision of space for the installation of bracing elements. This requirement was found to be often overlooked by the principal design consultants during the design phase.

The challenges were further compounded due to different subcontractors being used for both the restraint design and installation of the different services installations. Subcontractors will typically develop a design and build a tender bid without the opportunity to coordinate the design with other subcontractors. Services are installed on a 'first-in-first-served' basis, which can lead to seismic restraint bracing clashes, resulting in bracing elements and fixings being missed. In some cases, 'best fit' workarounds are invented at the workface by subcontractors in an effort to get the job done at no more effort or material cost than their tender price allowed. Despite the best efforts of the contractor, matters are made more difficult by the fragmented nature of the different installations and limited design standards for NSEs, in addition to different standards for different elements.

Moreover, current standards have in some cases proven ineffective in preventing significant damage during earthquakes in New Zealand during 2010 to 2016. [5]

4.4 Post-earthquake Reconnaissance in Wellington after the 2016 Kaikoura earthquake

Recent earthquakes in New Zealand between 2010 and 2016 have caused significant damage to NSEs, which is a reoccurring post-earthquake observation. Damage observations have shown collapsed suspended ceiling grids, collapsed suspended services such as HVAC, electrical and pipework, while failure of suspended services almost always caused secondary damage to the suspended ceiling grids.

Extensive damage to suspended services and suspended ceilings was observed after the February 2011 earthquakes in Christchurch. Figure 1 shows the aftermath of the damage within the Aurecon Christchurch Office caused by severe earthquake shaking and inadequate seismic restraint of services and suspended ceilings.

Fig 1: Aurecon Christchurch Office after the February 2011 earthquake showing extensive damage to suspended services and ceiling grid, (Image courtesy of Lee Howard, Aurecon Christchurch office)

The effectiveness of non-structural seismic restraint was also evident during the post-earthquake Reconnaissance of Wellington commercial buildings after the 2016 Kaikoura earthquake [4]. It was observed that where seismic bracing, or seismic restraint of overhead services was present, there was often no visible damage to the NSEs. The inspection was not detailed at a sufficient level that the seismic bracing could be assessed for compliance with NZS4219:2009.

However, it was possible to inspect whether the bracing appeared to be appropriate for the elements being restrained. Several instances were observed where the seismic bracing appeared to have been lacking. It was apparent that when seismic bracing was installed, it had performed well, often with no visible damage. This result suggests that typical seismic bracing solutions do work and that even when a perfect bracing solution may not be achievable, the adage ‘something is better than nothing’ seems to hold true for seismic bracing of NSEs.

4.5 Case study 1 – non-structural elements engineer

In a recent request for proposal (RFP) on a hospital project in New Zealand, the RFP was written with the intention to change the business-as-usual approach that design consultants preferred to take when submitting design services. Consultants typically avoid the design component for services restraint and prefer to allow performance specifications for subcontractor design and build solutions. The consultant documentation is typically coordinated for services and structure clashes but pays little regard for the provision of services support or seismic bracing.

In a hospital project with many suspended services and often little space to work, the space allocation required to allow the contractor to complete a design and build solution is often overlooked by consultants. This makes the contractor's design and build solution difficult and sometimes impossible, leading to non-compliant contractor workarounds or omission of bracing components because they could not be installed. In turn, it leads to high risk of failure and significant NSE damage when the support system is required to perform its function in a large earthquake. [4]

To address this issue, in a recent Hospital RFP the author of the RFP proposed to create a new role "Non-Structural Elements Engineer". The intention of the RFP was to engage a consultant who held design responsibility for the NSEs from the outset, reducing the risk of non-compliant contractor design and build solutions.

The RFP was designed to achieve:

- Clearly defined responsibilities and better demarcation between the consultant team and contractor design responsibilities
- An NSE specification that could be used by all proprietary and contractor design engineers
- Improve the level and extent of consultant documentation detail provided, to enhance the coordination of the project's overall design and construction
- A single individual in the consultant team to have oversight of these contractor designs, to allow relationship development and dialogue between contractor designers throughout the project
- Design consultants thinking ahead to allow physical space in their designs and capacity at junctions to main structure for load paths from contractor design into the main structure.

The key purpose to achieve a coordinated solution between structure and services, so the contractor could install bracing without a major redistribution or repositioning of services routes from that designed and documented by the consultants

The exact wording of the RFP included the following clause:

Working with your Non-Structural Elements Engineer; extract and determine in consultation with the other Consultants, the Client's Project Representatives and Stakeholders the extent of secondary supporting and fixing structure that will be Consultant designed and documented for major building services reticulation corridors and plantrooms, also including equipment mounting, proprietary external façade support or some other specific function or requirement. This includes the necessary seismic bracing for such secondary supporting structure. These elements are to be identified, designed and included within the Structural Engineering documentation package(s).

The extent of Consultant design and documentation for services support and seismic bracing should include designing and documenting the support structure for main services reticulation route corridors, plantrooms and risers. Include for span or height reducing mid-grid supports when appropriate, additional specific structure under lightweight roof structures (such as supporting structure able to accommodate partition bracing, patient hoisting, imposed loading allowances to steel purlins and the like), span reducing supports provided for façade fixing and so on. Consultant design should also include for all overhead secondary support structure as is typically necessary for medical plant or equipment.

(RFP Extract courtesy of Gordon Morrison – Proj-X Ltd)

This alternative approach to the design for NSEs appears to be a step towards reducing the risk of NSE damage and improving the quality of building fit out, as it is generally regarded that the current norm doesn't really work for anyone. The author of the RFP had observed problems, frustrations and arguments on other projects, which prompted this alternative approach.

The outcomes for this project are yet to be seen, as the project is currently in the construction phase. However, the intention to have a better coordinated approach between consultants and contractors should result in less non-compliant services fit out, improved seismic performance giving less risk of seismic damage, and provide a higher probability for business continuity soon after a large earthquake.

4.6 Aspects of insurance risk – assessment of existing building portfolio

4.6.1 The underwriter

We held comprehensive discussions with an insurance broker representing one of the largest insurance brokerage companies in the world. The discussions were targeted at understanding the interest and potential commercial opportunities with underwriters, insurance brokers and building owners for the possible benefits from improved seismic resilience of NSEs, or assessment of non-structural building elements from a seismic damage risk perspective.

Seismic risk to building stock is only a small part of the overall risk exposure for insurance covers. The discussion in this paper was limited to seismic risk. However, in earthquake risk countries it makes up a large portion of the work and risk being assessed by insurers. Underwriter insurance coverage for a large building or a portfolio of building stock is based on risk models and the assessment of a variety of risk. The models for buildings cover earthquake risk, weather, fire, age, design typologies and include many years of historic data, all supporting an insurer's assessment for the risk acceptance.

The goal of the insurer is to spread risk, so that they may hedge exposure to claims. In this way, an insurer may accept taking on risk in high seismic areas but may also hedge that against taking on risk in non-seismic areas offering lower exposure to seismic risk. Insurers work with a wide range of statistical and probabilistic methods for the modelling of risk, including short-term risk modelling, model-based pricing and risk-sharing. It is fair to say that insurers are very risk aware organisations and rely on trusted methods of modelling and historical data records for commercial viability and decision making.

From an individual building perspective, there is a significant challenge in gaining interest or acceptance of an insurer for improved NSE resilience or bespoke assessment of NSEs, despite the seismic risk reductions that can be demonstrated. This is because insurance risk is embedded in statistical modelling and years of reliable historical data. Challenging the insurer modelling with bespoke design or assessment, would pose a significant education process for underwriters and is more likely to pose further unknown risk, not quantifiable in their risk assessment methods. It would appear a different approach is required, as stepping outside of what the insurance model predicts is possibly a leap of faith an insurer may not have the risk appetite for.

4.6.2 The insurance broker

Insurance brokers are specialists in insurance protection having independence from the underwriter and having an in-depth working knowledge of the insurance market. The broker's task is to support clients in obtaining insurance, and insurers in identifying the risks that a building owner may be exposed to. When arranging insurance, an insurance broker will canvass the insurance market to obtain the best insurance protection at a competitive price. The broker then arranges the insurance policy and documentation.

Insurance brokers undertake the detailed discussions and negotiations on insurance matters with underwriters. They will review policies ensuring that the policy is appropriate, and that a client is well protected. A broker may suggest amendments to the policies in the light of market changes. Their expertise is aimed at saving insurance costs and improving the effectiveness of the cover.

There appears to be better potential for the insurance broker to negotiate on behalf of the building owner for insurance cost savings, if an existing building was to be supported by engineering assessment evidence of lower seismic risk. This is especially true for a building owner holding a large portfolio of buildings, which provides economies of scale.

4.6.3 The building owner

The greatest potential for the assessment of NSEs would appear to be the building owners of large building portfolios. Bespoke buildings of high value, such as national museums, art galleries, hospitals and other national buildings of significance may also benefit. Insurance cost reductions can possibly be gained by working with insurance brokers and building owners, either private, institutional or government, using robust building assessment tools and legislated building assessment guidance documents providing evidence of low seismic risk.

Discussions with an insurance broker identified that the recurring areas of maximum insurance risk are:

- Water damage after fire
- Gas fire after earthquake
- NSE damage during and following earthquake shaking

Discussions also pointed to a hardening insurance market, making it tougher for some buildingowners to obtain insurance. There would appear to be further avenues for the assessment of NSEs, in addition to building assessment of primary structures, to support building owners facing the scenario, whereby insurers are more risk averse and unwilling to consider different risks without such targeted non-structural building assessments.

(Discussions with the insurance broker were facilitated by Tarek Taher, Aurecon Melbourne office)

4.7 Considerations of automated design and assessment of NSE restraint

Previous studies have shown how building designers can incorporate automated design into the design and documentation processes for new building design. [6]

Nezamaldin [6] illustrates the possibilities of incorporating parametric and custom design applications using Revit and Dynamo design software. The study demonstrates the huge potential of parametric design and the development of custom design applications for Revit.

Parametric design can be compared to a spreadsheet in e.g. Excel. One can add equations, constants and variables. Changing one parameter changes the results that are connected to that particular parameter and as a process can be applied to geometry. The method of parametric design is to make the geometric parameters interrelated.

Parametric design is a process of creating a hierarchy of geometrical and mathematical relations to create a model that can be manipulated by changing certain parameters. The benefits of this process are in being able to automate design and repeat several tasks with no possibilities of human error.

These tasks can be repeated multiple times as parameters are varied, without reproducing the entire calculations each time.

The process can perform a design function, or alternatively can be used as a building assessment function.

4.8 Revit and Dynamo – software used for automated design

Revit is an application created by Autodesk and provides 3D modelling software that allows users to model building elements, so that the engineer can visualise the structure before it is documented into 2D drawings. Revit is used by architects, landscape architects, structural engineers and building services engineers. A Revit model can be built up among all project consultants and shared for the purpose of including the design components associated with each discipline, allowing easy visual coordination.

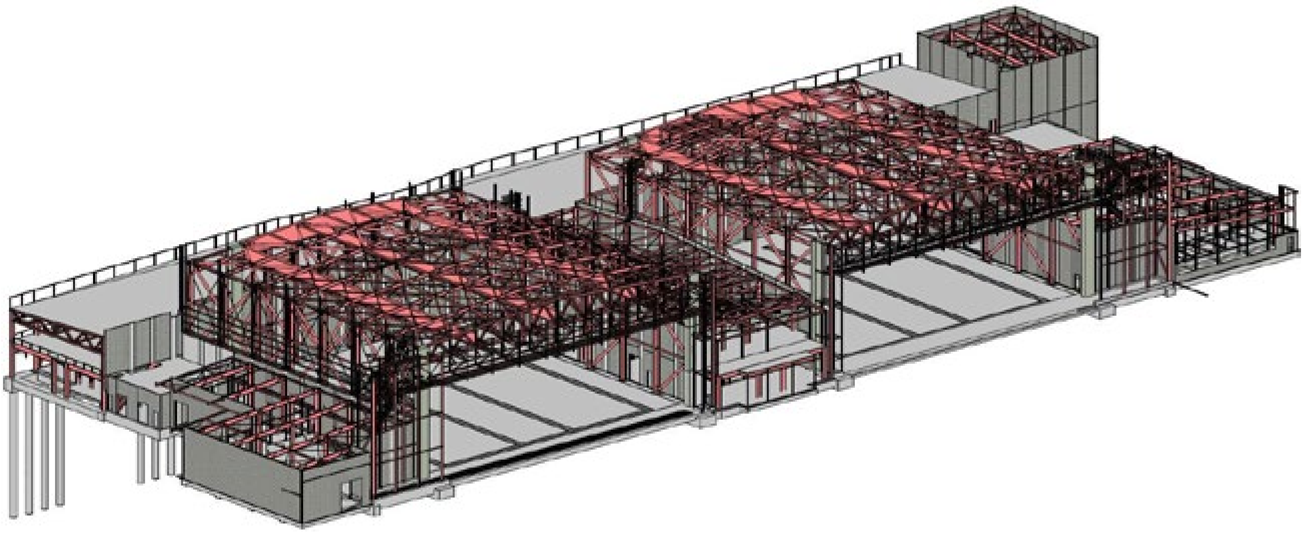


Fig 2: Example of a structural Revit model (Image courtesy of Gary Stapleton, Aurecon Wellington office)

Dynamo, also created by Autodesk, can be used as a Revit plug-in to act as a graphical (or visual) programming tool for documenting design tasks. Dynamo and Revit edits update in real time with changes in Revit being simultaneously reflected in Dynamo.

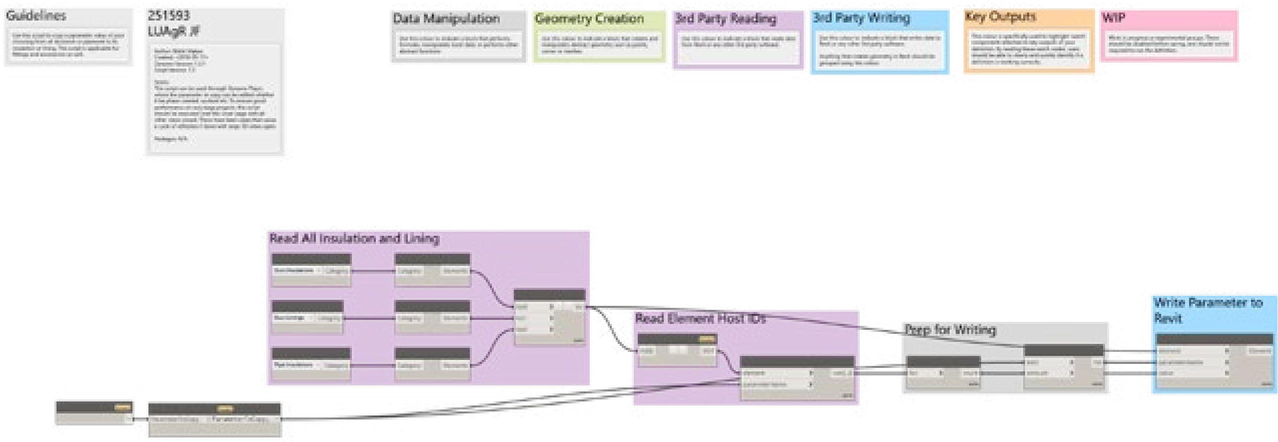


Fig 3: Example of visual scripting used in Dynamo (Image courtesy of Nikhal Makan, Aurecon Christchurch Office)

An example of parametric design using Revit and Dynamo would be a designer or modeller changing the position of a mechanical services duct, or perhaps the location of suspended plant in Revit, and then Dynamo automatically redesigns the fixings and sizes, plus hanger and restraint locations.

A study by Perrone and Filiatrault [7] [8] demonstrates the effectiveness of using automated design within a Revit environment for the seismic design of NSEs. A simple tool was developed to perform the automatic seismic design of sprinkler piping systems. The design tool extracted the piping layout from the model and automatically performed the seismic design of sway bracing according to certain criteria. This paper is an illustrative example of how an effective design tool can be adapted for automated design of seismic bracing systems for multiple building services runs within a new building.

Embedding an automated design procedure within a BIM environment for support and bracing on non-structural building elements enables coordinated approaches to gravity support and seismic bracing for NSEs. The quality of the build process is improved, assisting the installing subcontractors, improves building safety for occupants, reduces building seismic risk to insurers, ensures high levels of confidence to reoccupy soon after an earthquake, and providing owners and occupiers business continuity soon after a significant seismic event. [7]

This could be particularly important for strategic facilities such as hospitals and other public buildings that need to remain operational in the post-earthquake emergency response. The introduction of the 3D Revit modelling software has already significantly enhanced several aspects of the planning, design and construction processes, along with numerous aspects of the project management.

Layering this with automated design functionality represents the next step in the seismic design of NSEs, through offering dramatic improvement in coordination between structure and building services, and the performance of the completed fit out.

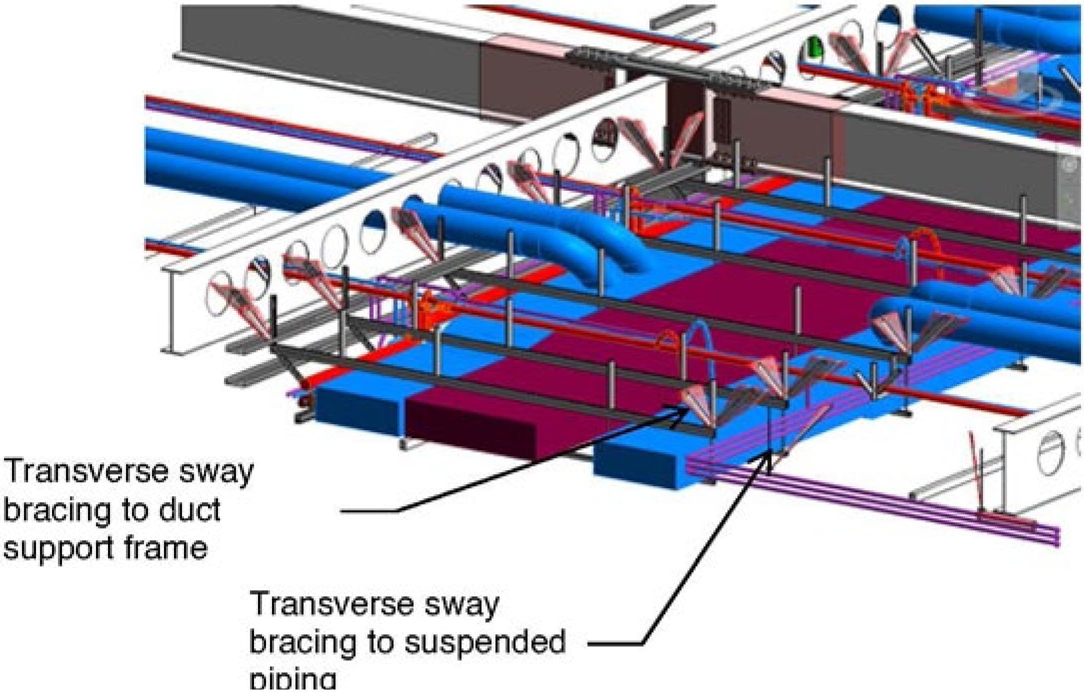


Fig 4: Example of possible design automation for seismic bracing for NSEs included in a BIM model (Image courtesy of Cherry Man, Aurecon Wellington Office)

Figure 5 below represents a proposed design process using Dynamo to perform automated design processes:

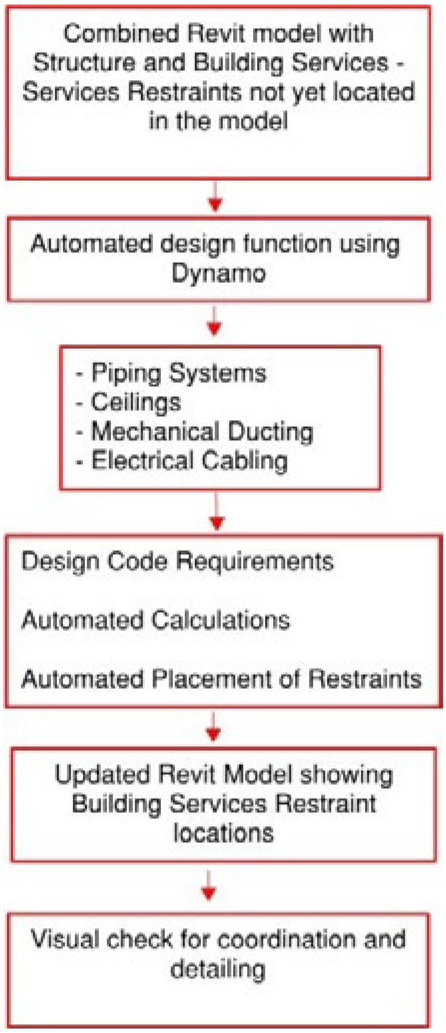


Fig 5: Example of an automated design process using Revit and Dynamo for design and documentation of NSEs [8]

This leads to a discussion about who should be responsible for the integration of structural and non-structural seismic design and installation. As discussed previously, until now there has typically been no mechanism for integrating the seismic bracing design for non-structural building elements in the design process by the consultant design team, before tender.

Structural engineers are often not interested in the design of NSEs and believe this issue is not inherently their responsibility and will not wish to include such secondary design scope in their design fee, which is often set on a competitive basis. From these considerations, it appears evident that a new profession called "non-structural elements engineer" could be introduced to the building professions. This idea was proposed on a recent New Zealand hospital project, as discussed in the case study above.

In terms of specific competencies, the only professional with expertise in seismic design within the scope of a building project is usually the structural engineer, so it makes sense for the structural engineer to develop design solutions for NSE restraint. The structural engineer often has a good understanding of architecture, mechanical, electrical and hydraulic services requirements. In this context, combining the knowledge of the structure with a senior structural modeller's skills in Revit, automated design functionality using Revit with Dynamo could be very useful to identify NSEs requiring seismic bracing. It could also identify the more common typology, location and configuration of non-structural bracing elements installed in buildings.

A simplistic representation of ‘before’ and ‘after’ an automated design process is shown in Figure 6 below:

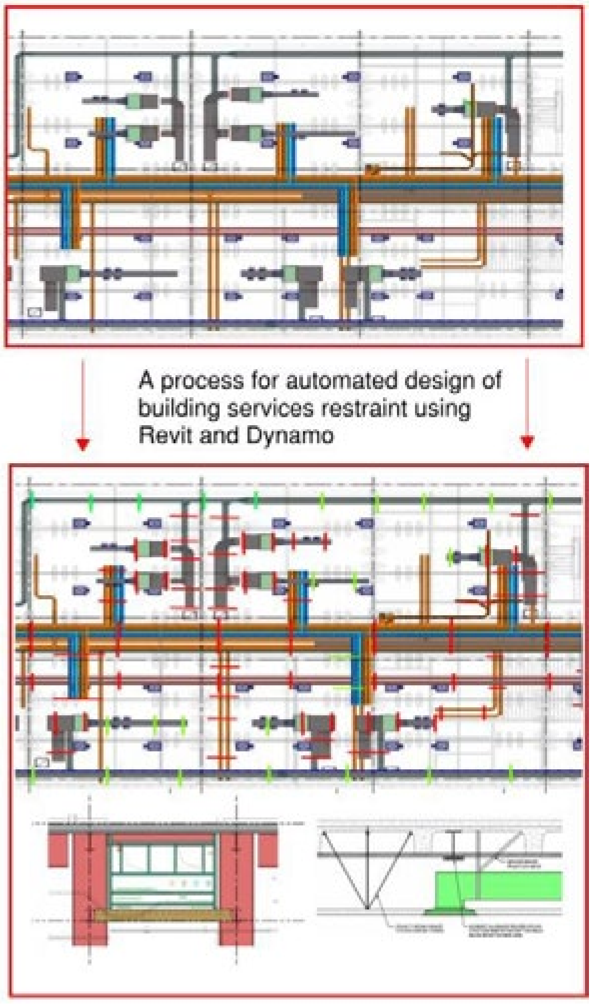


Fig 6: A simplistic example of a before and after automated design process for design and documentation of NSEs

4.9 Case Study 2 – DeWalt Hanger Works automated design software

A commercially available automated design tool is DeWalt HangerWorks [9]. This software is also a plug-in for Autodesk Revit and purports to be a tool that automates the placement and design of hangers and seismic bracing for building services systems such as pipe, duct, conduit, and cable trays. Engineering calculations are built into the tool that enable it to size hanger assemblies based on the weights of the services system including contents (water, wire, air), and determine hanger locations based on building code requirements and user-defined project standards.

To test the functionality of this software, the author and several Aurecon design engineers conducted a case study using DeWalt HangerWorks as an option for automating the design and modelling of seismic bracing of services on several projects. The output report and details were provided to a senior structural engineer for review.

The case study showed the software was difficult to use in terms of obtaining meaningful information. In all cases, it was necessary to revert back to manual methods to complete deliverables.

The senior engineer’s review of the basic output of calculations and details found that the report was poorly formatted and in imperial units and based on American standards not relevant to New Zealand and Australian codes. However, the data and engineering seemed sound and could be developed further into something useful.

After using the software on three projects, the author and the Aurecon design engineers found many design and detailing issues that could not be resolved. The author did not manage to get to a point where a meaningful report could be produced that was better than the initial basic report given to the initial senior structural engineer for review.

A sample of the design issues register created during the case studies is shown in Figure 7.

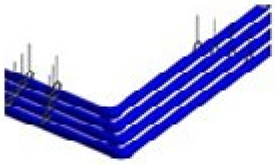
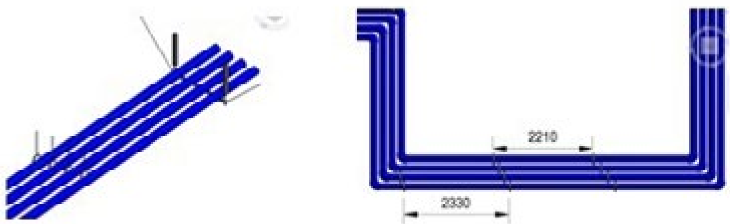
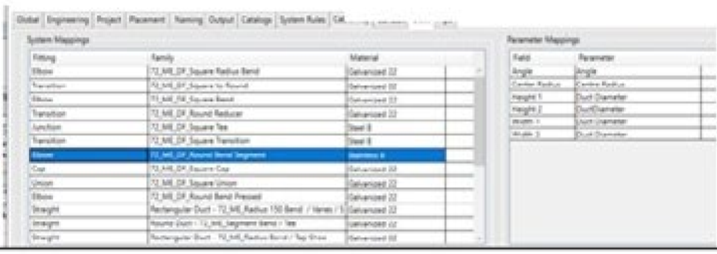
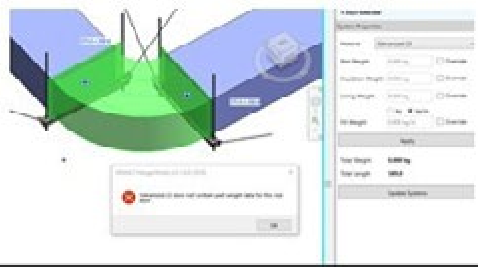
REF	CATEGORY	ISSUE	IMAGE
1	PIPEWORK	CLEVIS HANGER IS INSERTED AT WRONG DIRECTION ON SOME LENGTHS. RIGHT DIRECTION FOR SOME LENGTHS WRONG FOR OTHERS.	
2	PIPEWORK	SOFTWARE USING TRAPEZE BRACING FOR HANGERS ON END OF PIPEWORK BUT NOT ON OTHER AREAS. GUESSSING THIS IS A DEFAULT SELECTED HANGER TYPE ISSUE? FURTHUR INVESTIGATION SHOWS THIS ONLY HAPPENS WHEN THERE IS BENDS IN THE RUN PRESENT I.E WONT HAPPEN ON ONE LONG RUN OF PIPEWORK ITS AS THOUGH SOFTWARE DOES NOT CONSIDER THE 4 PIPES ONE SYSTEM. IS THERE ANY WAY FOR DEWALT TO CONSIDER EACH RUN WITH THE SAME START POINT SO IT PLACES A TRAPEZE	
3	DUCTWORK	HOW DOES THE PARAMETER MAPPING WORK FOR ROUND DUCTOWORK? DOES IT MATTER WHAT HxW SHOULD BE SET TO? IS IT MEANT TO BE SET TO THE DIAMETER SINCE THIS IS TECHNICALLY THE HEIGHT AND WIDTH OF THE DUCT.	
4	DUCTWORK	ALL OUR DUCT FITTINGS FAMILIES ARE COMING UP WITH NO WEIGHT DUE TO THE FOLLOWING ERROR FOR ALL MATERIALS. GUESSING IT HAS TO DO WITH THE FAMILY PARAMETER IT USES TO CALCUALTE THE SIZE? IS THERE A WAY TO VIEW WHAT SIZES DEWALT HAS ASSOCIATED WITH EACH MATERIAL TYPE? THIS ISSUE DOES NOT HAPPEN ON PIPEWORK FITTINGS	

Fig 7: A sample of the design issues register form using DeWalt HangerWorks. (Image courtesy of Mike Greisen, case studies completed by David Elliott and Mike Greisen, Aurecon Christchurch office)

This case study provides evidence of software being developed to automate the placement of seismic restraints for NSEs. It appears that the software has its limitations for use, but undoubtedly can be improved to suit a New Zealand application.

Our case study determined at this time it was more practical to model the hangers manually based on engineering and details provided by our structural engineers, rather than the reverse workflow using DeWalt Hanger Works.

4.10 Case Study 3 – Possibilities for automated design for seismic building assessment

Seismic assessment of buildings in New Zealand is of significant interest to building owners, tenants and structural engineers due to the recent occurrence of earthquakes and the perceived safety hazards multi-storey buildings may present during an earthquake. This was most recently highlighted by two building collapses that occurred in Christchurch during the February 2011 earthquake. In July 2017,

the New Zealand Guidelines for the detailed seismic assessment of building were issued. [10] These guidelines assist engineers in building evaluation. The guidelines are broad ranging and cover the assessment of building structures of different design typologies, including foundations. Specifically, Part C10 considers the techniques for the assessment of NSEs.

The release of these assessment guidelines has increased interest by building tenants and government bodies in reviewing the seismic capacity and safety of buildings they currently occupy. In one recent example, this interest has extended to the evaluation of NSEs within a hospital.

A District Health Board in New Zealand has recently issued a request for proposal (RFP) for a detailed seismic assessment of six buildings designed between 1965 and 1986. In addition to the regular seismic assessment of the structure, the RFP requests the seismic assessment of the NSEs. An extract from the RFP is shown below:

- Recording and assessing the compliance of Non-Structural Elements (NSE's) other than those required in the OSA guidelines, to current code requirements f or fixings or flexibility, as circumstances require, including at seismic joint locations to adjacent buildings. This is limited to NSE's from the services main distribution points in each building.
- Concept design of seismic strengthening schemes in the- event a building is rated at less than 67% NBS. Concept scheme p la n s and short descriptions would be expected in the report.
- Concept design of seismic restraint, flexibility in the event that NSE's are rated at less thancompliant with current relevant codes.

Fig 8: Excerpt from a recent RFP for a New Zealand district health board (Extract from the RFP supplied by Sara Broglio, Aurecon Christchurch office)

The structural assessment of building services restraint compliance is usually overlooked in engineering building assessments as the structural engineers typically focus effort on the primary seismic resisting structure and foundations, passing over the NSEs in terms of detailed assessment. [11] However, as evidenced by the recent RFP, building owners are recognising the need for the seismic assessment of building services. In the case of hospital buildings with complex building services fit out, the assessment of NSEs would be a difficult and time-consuming task if undertaken manually and made more complex if complete as-built drawings are not available. [12] Making matters more difficult for the engineers is that between 1965 and 1986, the design codes have changed, making it inevitable that there will be different levels of non-compliance for buildings of different design eras.

A potential solution to this issue would be to use an automated design process for locating compliant building services restraint by reverse engineering. In building assessment terms, the design automation would involve the detection and location of building services, i.e. ducting, piping, cable trays suspended ceilings, and then a process of identifying the specific service run with specific identifying attributes to enable 3D modelling in Revit. Reverse engineering using a Dynamo automated design process could set out the required services restraint and support locations, which can then be compared with the existing restraint conditions.

4.11 Using a point cloud scan for locating building services

The example in Figure 9 below has been provided by the Aurecon Wellington office, which shows the use of a point cloud survey to detect and locate piped services associated with a tank farm. The point cloud includes several items of interest: pipe runs, support points, pumps and valves. This example shows how an unstructured point cloud survey can be used detect the location of services' pipes, plant and support conditions, and highlights the general opportunities for the automated detection and location of existing services runs.

To utilise unstructured data from a point cloud into an automated design application, a tracing of the point cloud has to be made using Revit to create a digital twin of the services network. A manual process of assigning physical attributes to the digital twin services components is then completed by the digital modeller. The assigned attributes provide the information required to enable an automated design process in Revit using the Dynamo plug-in. A comparison between the initial point cloud 3D image with the completed automated designed restraint locations included for the services network enables a visual comparison to check compliance of the existing services restraint. This can be an effective assessment tool for building services restraint compliance.

Furthermore, new technology is being developed by Clear Edge 3D, a US software company that has developed software for feature extraction and automated modelling technologies to automatically identify pipe, conduit and round ducting from laser scan point clouds. This software is used in an industrial application with an 80% reliability accuracy. The technology integrates directly with Revit, saving manual modelling time.

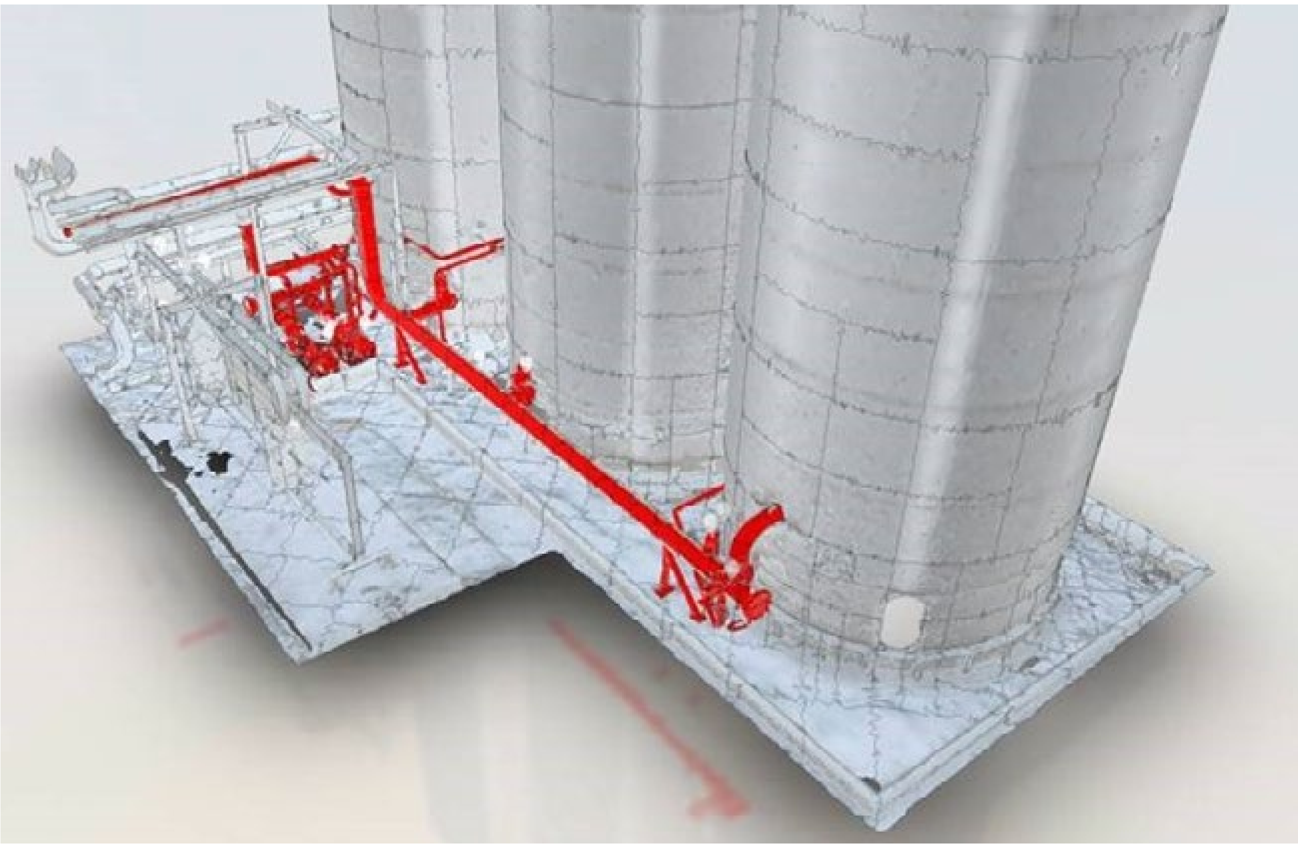


Fig 9: Example of a point cloud survey used for automated design of pipe supports (Image courtesy of Matt Randell, Aurecon Wellington office)

Extending this concept to a commercial building environment, ceilings often cover and obscure the locations of the building services. (The following examples were provided by the Aurecon Christchurch office.) In these examples, point cloud scans are taken from multiple locations and combined to form a single unstructured point cloud scan for the area of interest. For use in a commercial office environment, ceiling tiles can be removed, or holes cut in fixed ceilings to position the scanning equipment. The digital modeller then creates the digital twin and manually assigns the physical attributes to each of the services' network. After the creation of the digital twin model updated with structured data, the model can be used in design or building assessment.

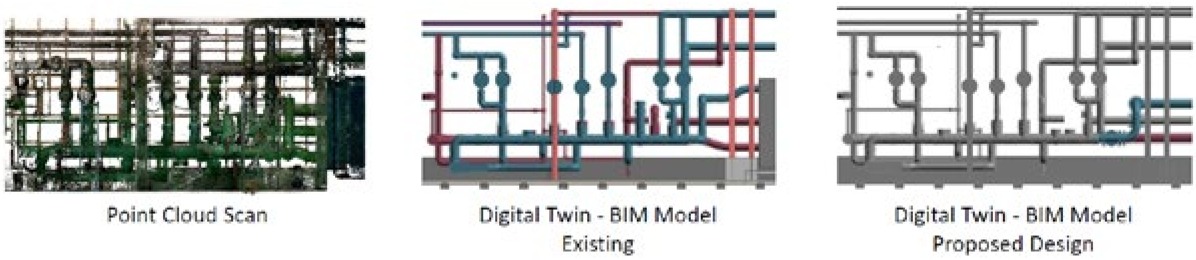


Fig 10: Example of a multiple location point cloud survey used to create a digital twin (Image courtesy of Nikhil Makan, Aurecon Christchurch office)

Fig 11: Example of a single location point cloud survey combined with a 360-degree image used to create a digital twin (Image courtesy of Nikhil Makan, Aurecon Christchurch office)

When a point cloud scan is taken from a single point location, a 360-degree image is taken which provides colour definition and clarity to the point cloud, making the digital twin process and structuring the data significantly easier.
At this stage, the combined use of 360-degree images and point cloud scanning is only possible where single point scanning is undertaken, as the 360-degree image matches the point cloud data. Scanning at multiple locations means the 360-degree image will not match the point cloud data, although the 360-degree image is useful for interpretation of the point cloud.

4.12 Design Fees

In a New Zealand context, the design fee applicable for the scope of design for building services restraint is in the order of 1.0%–1.5% of the building services cost. In the case of a hospital, this will represent a significant fee budget. (Information sourced from Aurecon NZ Auckland office). By comparison, structural design fees in New Zealand typically range between 1.2%–1.6% of the construction cost for a new building of approximately NZD30M build cost.

As discussed above, the principal structural consultant typically chooses to avoid this work, which then requires secondary consultants to provide design solutions for the subcontractors who are undertaking the services installation. From a principal design consultant's perspective, the design and coordination of non-structural element restraint is seemingly too complex, time consuming to resolve, and requires ongoing coordination well after the documentation is issued.

An automated design process, as previously mentioned, introduces the opportunity for a significant reduction in engineering labour cost with improved accuracy and documentation, while the fees available for this service remain at reasonable values. An automated process enables multiple design iterations, while minimising labour-intensive rework to achieve a coordinated design.

There would appear to be three opportunities for the principal structural engineer to engage in this design process, and to achieve market fees for these services:

a. In a traditional sense, the structural consultant can sub-consult to the subcontractor and provide the services restraint design for the subcontractor-designed mechanical, electrical and hydraulic services. The structural consultant may also provide restraint designs to the suspended ceiling subcontractor or other non-structural fit-out trades. Conflict of interest issues may need to be considered further, but this would appear to be no different than the structural consultant completing structural steel shop drawings after issuing construction drawings to a successful tenderer. Noting that the Aurecon NZ Wellington office, until recently, provided a shop drawing service for their own designed buildings.

b. Assuming the principal structural engineer is not also the consultant, he/she could respond to opportunities for the 'non-structural elements engineer'. This role can be delivered by an automated process if the Revit building model is provided. Design automation processes can then be applied, and deliverables could be a package of services restraint design calculations and documentation, which can be issued for building consent or for construction.

c. Assume the principal structural engineer delivers the primary structure and then proceeds with the secondary non-structural bracing element design, which can be possible on the basis that the building services are fully designed and specified by the principal designers. If changes to the design are proposed by subcontractors after tender, then updates to the building services restraint design can be reprocessed by the principal consultant under a simple variation agreement with the subcontractor.

4.13 Future considerations

The process of moving from an unstructured point cloud to a structured digital model would be very useful as an automated process. Machine learning to classify objects within a point cloud is not new and could be applied to NSEs, which is an area of future research. If we continue creating digital twins with a point cloud and producing a corresponding digital model, theoretically we are building a training data set that could be used at some point to train a machine learning algorithm to partially automate this process. US company, Clear Edge 3D, has developed software for feature extraction and automated modelling technologies to automatically identify features for industrial applications.

The feature extraction technology integrates directly with Revit, saving manual modelling time. Further specific development into NSEs and restraints appears to be within reach.

(Information on Clear Edge 3D sourced from discussion with Simon York, Aurecon Christchurch office)

Conclusion

5 Conclusion

While engineers focus on the design and seismic assessment of primary structures, past earthquake events have shown that even if the primary structure is intact, the building reoccupation is most often prevented by the systemic failure of inadequate non-structural fit-out restraint systems. Designers need to address this issue if improved building performance is to match owner and tenant expectations of new designs, or their reliance on structural building assessments.

Incorporating an automated design procedure for support and seismic bracing of non-structural building elements within a 3D Revit model will provide a coordinated approach to allow seismic bracing of NSEs to be integrated into the design documentation for commercial buildings. Design automation of this type improves the design coordination, build quality, building safety for occupants, and reduces risk of seismic damage for owners. It also provides leverage for insurance brokers to obtain lower insurance premiums for large portfolio owners. A building which includes well- coordinated and designed NSEs provides high levels of confidence to reoccupy soon after an earthquake, giving owners and occupiers better chances of business continuity closely following a significant seismic event.

Automated design processes can also extend to the seismic assessment of existing buildings which often only focus on the primary structure and perceived high-risk elements. The assessment of building services seismic restraint is most often overlooked during building assessment, yet the damage resulting from earthquake can amount to 70% of the buildings value in some cases. [3]

This paper has identified three viable uses of an automated design process for NSEs:

- New design using the automated design functionality of Revit and Dynamo
- Building assessment using point cloud surveys and the creation of digital twins enhanced by machine learning to structure point cloud data
- Building assessment identifying existing NSE restraint compliance by comparing a digital twin with a compliant automated design

5.1 Next Steps in Research

To achieve a tangible outcome from this research, a first step would be to develop a working automated design process using Revit and Dynamo for designing NSE restraint, specifically for a mechanical ducting ventilation system. This may include duct runs of different sizes and suspended plant to ensure different design parameters and bracing details. Completing this work only for the mechanical services ducts and suspended plant is deliberate, to keep the automated design manageable and targeted. It could be completed as a 'bench test' study to check on automated design functionality with the output, including design calculations and NSE restraints, positioned in the MEP model. The work could be carried out on an existing design or undertaken on a relatively simple new design. It would provide some clear indications of the usefulness of the automated design process and how commercially viable this consulting service offering may be.

A further step is the assessment of existing building services restraint. This will necessitate a multi-location point cloud survey above a suspended ceiling grid. The significant challenge and unknown when undertaking this work are the reliability of the access and shadowing of existing services ducts, which may prevent full point cloud coverage and obtaining continuous reference points. This can be mitigated by using a handheld BLK2GO scanner, which will provide reference points above and below a ceiling in spite of limited access. The point cloud can then be used to create a digital twin of the building services.

As part of the point cloud scanning application that extends this body of work, further research should also be focused on a deeper understanding of available software used with point cloud scanning. Software developers such as Clear Edge 3D have developed software plug-ins compatible with Revit for similar assessment uses on industrial piping, which includes reliable object identification. Further investigation and discussions directly with these suppliers should be progressed to assess the opportunities for specific software development in the assessment of NSE restraint.

A future extension to this research would be investigating the concept of real-time reconstruction. This concept is a step further than point cloud scanning, which requires post processing to structure the data with the element attributes which allows for automated design or assessment. Real-time reconstruction conceptually uses devices such as smart phones or tablets to scan duct runs in real time, with the capability of identification and live feedback to Revit for MEP model development and automated design applications. This concept could be used as an on-site assessment tool providing instant results.

Bibliography

6 Bibliography

[1] Hogg, S.J. (2015). *Seismically Resilient Building Technology: Examples of resilient buildings constructed in New Zealand since 2013*. Proc. 10th Pacific Conf. Earthq. Eng. Build. An Earthquake-Resilient Pacific, no. 190, p. Paper No: 190.

[2] Beattie,G.J. (2000). *The design of building services for earthquake resistance.*

[3] Ferner, H., Wemyss, M., Baird,A., Beer, A., & Hunter, D. (2014). *Seismic Performance of Non-structural Elements within Buildings*. Nzsee.

[4] Baird, A.& Ferner, H. (2017). *Damage to non-structural elements in the 2016 Kaikōura earthquake*. Bull. New Zeal. Soc. Earthq. Eng., vol. 50, no. 2, pp. 187–193.

[5] Banks, G.N. & Dunbar, A.J.M. (2015). *Seismic design of interior overhead non-structural elements*. 2015 NZSEE Conference.

[6] Nezamaldin, D. (2019). *Parametric design with Visual programming in Dynamo with Revit: The conversion from CAD models to BIM and the design of analytical applications*. No. 467, p. 84.

[7] Perrone, D., & Filiatrault, A. (2019). *Use of building information modelling for the seismic design of non-structural elements*.

[8] Perrone, D., & Filiatrault, A. (2017). *Automated seismic design of non-structural elements with building information modelling*. vol. 84, no. September, pp. 166–175. Autom. Constr.

[9] Loads, P., & Bracing, S. (2019). *Automate the placement and design of MEP hangers and seismic bracing*.

[10] *The Seismic Assessment of Existing Buildings Technical Guidelines for Engineering Assessments: Draft for Sector Briefings June 2016. Part A : Assessment Objectives and Principles*. NZ Society for Earthquake Engineering.

[11] MacRae,G., Pampanin, S., Dhakal, R., Palermo, A., Baird, A.& Tasligedik, S. (2012). *Review of Design and Installation Practices for Non-Structural Components*.

[12] Uma, S.R.,& Beattie, G.J., (2010). *Seismic assessment of engineering systems in hospitals: A challenge for operational continuity*. New Zealand Society for Earthquake Engineering Conference.

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