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INTEGRATING SUSTAINABILITY CONSIDERATIONS INTO STRUCTURAL ENGINEERING

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SUMMARY

This paper provides an overview of sustainability opportunities in structural engineering design. It discusses advantages and disadvantages associated with various design choices, to achieve good system sustainability outcomes. Two case studies of recent projects are used to demonstrate the points from the first part of the paper.

INTRODUCTION

The impact of the buildings industry on New Zealand's greenhouse gas emissions has been determined to be in the order of 20% (Thinkstep 2018). Various estimates put the contribution of the physical aspects of the building to be between 20% and 50% (LETI 2020, Thinkstep 2019). This figure will only increase as building services equipment becomes more efficient. Therefore it is disingenuous to suggest that structural engineers can have only a negligible impact on the success of New Zealand's climate target.

Although this paper is not exclusively focussed on 'embodied carbon' – that is, the greenhouse gas emissions associated with the life cycle of the building's physical assets – it will comprise much of the discussion.

Various structural engineering bodies across the globe have taken a stand on climate change, notably through the "Engineers Declare" movement. The Institution of Structural Engineering (IStructE) in the United Kingdom is perhaps the best example of how industry bodies can take up a leadership position. They have created a wide range of resources for structural engineers to be able to undertake meaningful action.

The New Zealand construction industry is not yet as mature as the UK from a sustainability perspective, however, widespread momentum appears to be building in all sectors to consider broader project outcomes. This paper will explore how consulting structural engineers can contribute to this change in direction, and provide examples of good practice.

SUSTAINABILITY FRAMEWORK OVERVIEW

Sustainability has been defined in many ways since the word began to be widely used in its modern sense. One of the most common definitions is "meeting the needs of the present without compromising the ability of future generations to meet their needs" (Brundtland 1987). The various metrics which go into defining what makes something 'sustainable' change depending on who you are talking to and how broadly you define your outcomes. Most will consider time, space and human scales. In order to establish a context for the rest of this paper, some of these sustainability frameworks have been briefly described and explained below.

The triple bottom line (TBL) is an accounting method first developed in the 1980s, to recognise social and environmental costs and benefits alongside financial. This TBL approach was solidified into the 'Three Pillars' framework at the 2005 World Summit on Social Development (Purvis et al 2018). It encompasses financial, social and environmental factors, which are presented pictorially in Figure 1 below. The overarching principle is that 'sustainability' can only be achieved when all three 'pillars' are being adequately considered. As structural engineers, we are typically only drawn into discussions around the 'financial' pillar during the design through the cost estimation and value management processes.

Another sustainability framework used across the globe in the buildings industry comes from the International Living Futures Institute. The Living Building Challenge is described as "A Visionary Path to a Regenerative Future" (ILFI 2019). It is a proprietary framework set up as a standard against which buildings can measure themselves in order to gain certification as a 'Living Building'. What makes a 'Living Building' is determined from a range of 'petals', which extend beyond the basic 'Three Pillars' framework to identify a broader range of metrics against which to measure. These are shown in Figure 1 below. Note these are only two of many such frameworks which attempt to describe sustainability – while the language may differ, all metrics will generally fall under the umbrella terms of the 'Three Pillars'.

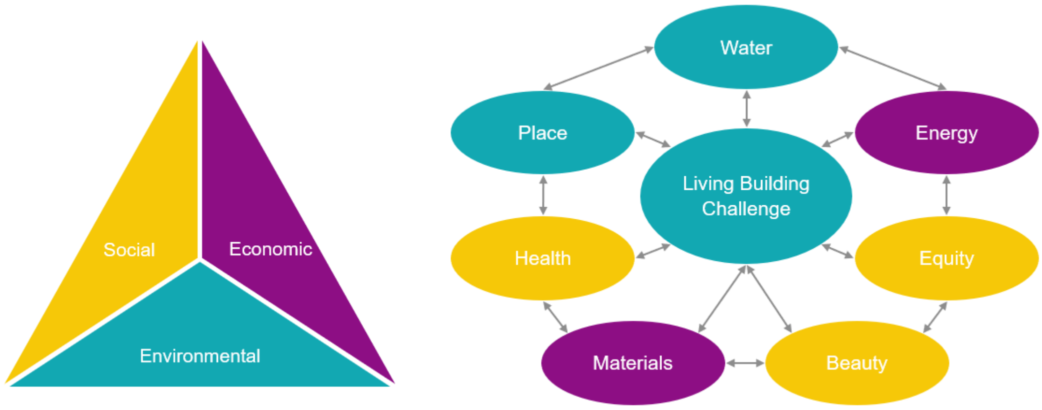

Figure 1: Sustainability frameworks

GENERAL PRINCIPLES OF SUSTAINABLE STRUCTURAL ENGINEERING

For a consulting structural engineer, it may not be immediately obvious where our design can impact some of these areas of sustainability – for example, 'water', 'health', or 'equity'. This is where we need to look beyond our immediate impact and delve further into our wider zones of influence. This section of the paper discusses some ways in which structural engineers can influence sustainability outcomes on a built environment project. It has been framed as a series of points to be considered, which are grouped under relevant sub-headings summarised in Figure 2 below.

The most important questions are the ones asked early on in the consulting process, before design has begun. There is limited scope for change once the design has progressed beyond the preliminary stages.

Figure 2: Structural sustainability options

Material Reduction

This section of the paper primarily deals with embodied carbon, and how to reduce it on a project.

First and foremost, the necessity of building a new asset should be questioned. Clearly, for this sort of question to be asked, we need to be in the privileged position of knowing the long-term built asset strategy of our clients. Once a project has progressed to the moment of appointing a design team, it is often too late to raise this point. By not building a new structure, we effectively negate any carbon emissions which would have been released.

For brownfield sites, investigation into re-use of existing structure should be paramount. This links back to the first point – whether or not a new building is required - and also connects to issues of resilience and holistic design. Case Study 2, University of Auckland B201, gives an effective example for how this can be done well. Not only do you avoid emissions and waste processing associated with the demolition of the existing structure, but less material is required for the creation of the 'new' building. In New Zealand, we have a strong tradition of seismic strengthening of existing buildings. Therefore we are well positioned to argue for retention of built assets.

The determination of grid set outs are typically complex negotiations between architect, client and engineer. If multiple material options are being considered for the primary framing, grid layouts should be proposed which enable the various materials to operate efficiently. In order to reduce wastage, grids should also be set out to accommodate standard manufacturing lengths and sizes. Grid set outs will also determine building use options – consider whether you are precluding other building uses by selecting a particular column arrangement.

Reducing material quantity through efficient design should occur throughout the design process. Any given reduction will proportionally reduce all associated emissions with that material – not including secondary effects such as the impact on foundation size. Although most engineers will typically reduce structural material quantities as the design progresses from concept through to detailed, this is often only looked at from a cost – or space – perspective. We talk of 'rationalisation' of beam and column sizes – which can have benefits of simplicity and wastage reduction from a manufacturing perspective. However it is the role of the structural designer to ensure this is not done to the extent of creating significant material inefficiencies.

Lastly, structural engineers should report on carbon impacts from their decisions in design progress reports and design features reports. Incorporating sustainability outcomes into reporting will require a thorough understanding of how design decisions have impacted carbon emissions. This advice will be increasingly sought after by clients, and we should ensure we have the capability to deliver.

Material Selection

In order to understand the environmental impact associated with a particular material, the environmental product declaration (EPD) is a good place to start. These documents provide a thorough description of a wide range of environmental impacts for that particular product, including the embodied carbon associated with its production. In New Zealand, our 'library' of EPDs is somewhat limited and out of date – which is why it is important that structural engineers continue to request this information from suppliers.

Although the purpose of this paper is not to debate the various merits and deficiencies of steel, concrete and timber – from a climate change perspective, it is apparent that timber provides benefits which are (as of yet) not available from the other two materials in the New Zealand construction industry (BRANZ 2017).

The distance travelled of the material, from source to site, has a direct impact on the up-front carbon emissions for the structure.

No material is perfect for use in all scenarios. Case Study 1 is an example of where each material was used in locations and for functions where their particular properties were of best use.

Material Specification

Through the structural specification, design engineers have the ability to influence material procurement. The processes used in the manufacturing of the material, as well as secondary material streams associated with manufacturing, can be significant in the overall impact.

The Green Star certification document provides excellent guidance on how to specify a more sustainable outcome for a particular material, under their material credit 19.B (NZGBC 2019). For timber, this focuses on the type of timber treatment adopted for rough sawn and engineered timber elements. For concrete, by nominating minimum mandated inclusions of supplementary cementitious materials, using alternative aggregates, and requiring alternative fuel use at production centres. All these are aimed at reducing the embodied carbon.

For steel, Green Star recognises that the only way to reduce embodied carbon emissions is to reduce the quantity of steel used. If at some point in the future, New Zealand regains its ability to recycle steel domestically, there would theoretically be an opportunity to mandate minimum recycled steel content in steel framing and reinforcing. In the meantime, the steel industry should develop better traceability of steel product at end-of-life to ensure the full life cycle is understood. Shipping scrap steel to Australia will have lower embodied impacts than shipping further afield, and there is demand in the Australian market for high proportion recycled steel.

The same principles can be applied regardless of whether or not a project is undergoing Green Star or other certification. In fact, we don't need to stop at the specification - can we work with the client and builder to source materials from suppliers which treat their effluent water above and beyond the minimum requirements?

Adaptive Re-use

Adaptive re-use, or futureproofing, is one way to thoughtfully incorporate long-term considerations into the design. An example of this is recognising likely future building use requirements when determining load allowances on floors, although this can also have detrimental effects on the up-front building impact. Case Study 1 provides an example of how future flexibility was considered in allocation of space for service reticulation.

Although the scope for designing a flexible space is largely dependent on client briefs, at the very least, designers should take care that decisions are not made which preclude the building being re-purposed at a later date. The best (or worst) example of this is found in scissor deck carpark buildings. The sloping floors make them unsuitable for most other applications, meaning that when they become obsolete or past their usable life, they will require full demolition and replacement.

Another way in which adaptive re-use can be incorporated into the design process is through the provision of redundant load paths. Particularly in shear wall buildings, and in the design of diaphragms, redundancy should be considered not just from a seismic perspective – but from a future user perspective (additional circulation core added, larger duct penetrations required etc).

Resilience

Resilience as a technical topic of structural engineering has been comprehensively covered elsewhere. Here it is briefly described in the context of sustainability. The most sustainable building, from a structural perspective, is the one which has least emissions over its life. Clearly this is dependent on two main factors: the amount of emissions released in its life cycle, and the length of its life. A resilient building is one which has been designed in such a way to have a greater chance of lasting a long time. In the context of New Zealand's seismic landscape, that correlates to a building which has been designed to increase the possibility of re-occupancy after any given earthquake.

Low-damage design considerations are one way in which a building may be designed to be more sustainable from a whole-of-life perspective. This includes both primary structure, and secondary structure supporting non-structural elements. Providing a high level of protection to services and architectural fit-out items contributes to its overall sustainability – particularly for low intensity earthquakes, reducing demolition, waste and replacement emissions.

Maintenance is another, often overlooked aspect of structural resilience. Degradation of the material during its service life, and any ongoing maintenance requirements to keep the integrity of the structure, should always be considered. In particular, structural engineers should consider accessibility for maintenance operations and clearly articulate to the building asset owner time to first maintenance. Whether this is through specification of steel coatings for externally exposed steelwork, or ensuring that areas prone to moisture build-up are easily visible to assess structural impact.

De-constructability and End-of-Life

In some ways, there is very little control over how a building or structure is managed at its end of life stage. Ownership may change along with landlord priorities – and with no current legislation mandating re-use of building components, it can be difficult to justify any sustainability gains expected at the end of life.

Regardless, there are features which can be considered during the design process which will facilitate re-use of materials and minimise structural waste at the end-of-life. Designing for disassembly is one way in which structural engineers can provide for future expansion, relocation, or recycling. Connections which are energy and water intensive to demolish should be reconsidered. The ability of different structural building components to be separated into their respective material streams during demolition is also a factor to consider when designing. For example, composite concrete floor on metal decking is not readily deconstructed (Wang et al 2018). However, it is very efficient and offers significant material reduction (and therefore carbon reduction) in the construction stage. Clearly, full life cycle cost-benefit analyses must be performed to successfully compare options.

Even if a structure is designed such that the materials are readily separated, recycling of those materials is not guaranteed. There are very few locations in New Zealand, for example, where concrete can be processed to produce recycled aggregate (Gjerde 2003) – and those processing plants require the concrete to be thoroughly cleaned prior to arrival, requiring more use of water resources. Scrap steel from demolition cannot be recycled within New Zealand since the closure of Pacific Steel's Otahuhu mill in 2016, and needs to be sent overseas for reprocessing (SMRANZ 2017). Treated timber has limited options for recycling (or downcycling) into other products due to the health and safety risks associated with the treatment chemicals (ECAN 2013).

In many cases, waste material will end up in landfill. The actual decomposition of timber in landfill has been estimated to be anywhere between 1%-50% over 20 years (Ximenes et al 2007; Milke et al 2010). Therefore timber end-of-life scenarios should be carefully considered when comparing the life cycle carbon footprint against a steel or concrete option.

<u>Social Licence</u>

It can be too easy to delegate the responsibility of social considerations to the client, or in some cases the architect. Engineers are not removed from community, therefore we should acknowledge our impacts – both positive and negative – on those communities. This includes communities which we are directly involved with during the design process, and communities which we impact through our projects.

In New Zealand, the Treaty of Waitangi steers the relationship between Māori and the Crown – as well as all bodies associated with and subject to the Crown. In most cases, our projects are undertaken on behalf of parties who belong under the umbrella of the Crown. We may hear the architect, client or project manager talk of 'iwi engagement', or discussion with tāngata whenua. It is very rarely that we become involved in those discussions or form a deeper understanding of how mana whenua can be considered during the design and construction process.

The structure will be situated within an existing local community. When designing, the human and material capital available in that community can be considered when selecting construction materials, or in the construction methodologies we assume. To some extent, this is already performed, in particular for remote or isolated communities where transport of people and objects is difficult or costly. Supporting local business is one of the main themes which came out of the COVID crisis in New Zealand. This should equally apply to the procurement of products and services associated with the buildings industry.

Social procurement also needs to consider worker conditions. Whether or not those people associated with the design and construction will be paid the living wage is one such factor which should be queried. This includes sub-contractors, support staff, and employees at manufacturing facilities at the source of material production. Health and safety is another incredibly important aspect of social sustainability. The impact that consultants can have on health and safety culture during construction should not be underestimated. This can be projected beyond the construction phase, to also consider the wellbeing of building occupants or asset users. This may be through considering materiality alongside the architect, and understanding accessibility requirements for outdoor or landscaped areas, to give two examples.

Holistic Design

This final section covers structural design aspects which primarily impact other design disciplines, and how we can improve holistic sustainability considerations.

Thermal mass is a concept which relates to the ability of an object or space to effectively self-regulate its temperature, by storing heat energy. The higher the thermal mass, the greater the temperature equilibrium. This is particularly important in building design, where ongoing operational efficiencies can be achieved through the provision of adequate thermal mass. Concrete as a material is a very effective heat sink, therefore generally does not require additional thermal mass provisions. Mass timber buildings often require additional material to provide sufficient thermal mass for buildings service engineers to achieve high levels of operational efficiency in heating and cooling of the building.

Fire engineering is a contentious issue in the buildings industry, as evidenced by recent publications from both timber and steel industry bodies (Andisheh 2021, Buchanan 2021). Steel primary framing will either require intumescent paint or layers of protective lining to achieve necessary fire protection requirements. Concrete framing is the most straightforward from a fire perspective, requiring minimal design consideration. Mass engineered timber framing requires careful consideration and detailing to design for a fire scenario. From a sustainability perspective, the impacts of the combined systems should be compared – which can be approximated by calculating the quantity of materials involved and assessing each material's impact. This can be done for carbon emissions as well as other environmental impacts, if the EPDs are available.

Acoustic and vibrational performance is yet another factor in determining system sustainability outcomes. One example of where increasing acoustic performance can lead to more adverse sustainability outcomes is with the example of a lightweight timber floor. Creating a composite system through the addition of concrete topping may address acoustic issues, however this significantly increases the floor weight, carbon intensity per square metre, and reduces the de-constructability of the system.

SUSTAINABILITY NOW VS SUSTAINABILITY FOR THE FUTURE

At the end of the IStructE Gold Medal Address in 2020, I posed a question to the presenter Dr Mike Cook (who has led their response to the climate emergency).

"*Is it better to design a high-carbon structure which lasts hundreds of years, or a low-carbon structure to reduce emissions urgently now? In the context of NZ's highly seismic arena where we often aim for low-damage design*." (Phoebe Moses, 2020)

His response was as follows:

"*The answer doesn't take long really. It's far better that we address the emergency now, and **we cannot afford to be creating very high carbon-intensive buildings**… and we have to think really hard about that. The main principle for the vast majority of engineers has to be to think very hard about our emissions now, that happen right up front in the construction of new buildings, and if at all possible, to look at how you re-use old buildings*." (Dr Mike Cook, 2020)

In short, the climate emergency is now. Actions which we take in the next ten years will determine the outlook for future generations. Therefore the construction industry cannot rely on future building resilience or re-use in order to achieve what will be asked of us. We need to be designing structures which have low up-front, 'locked-in' carbon emissions, rather than relying on hypothetical future savings (Craig 2019).

CASE STUDY 1: A1 BUILDING (AUT)

Project Overview

AUT A1 has been designed as a four-storey rectangular building, with post-tensioned LVL frames in the transverse direction and concentric timber bracing in the longitudinal direction. The building sits on a deep raft foundation due to poor soil conditions on site. The floors are proprietary Potius system, which consists of LVL joists with plywood decking to form T-sections. There is a large atrium connecting the new building to the existing AF teaching building, which is also being strengthened as part of the overall project. Figure 3 below is an architectural render of the atrium between A1 and AF.

Figure 3: AUT A1 Atrium (Jasmax 2020)

From the beginning of pre-concept design, the client (AUT) made it clear to the design team that sustainability was to be one of the overarching key performance indicators of the new 'Heart of the Campus' building on Auckland's North Shore.

During pre-concept design, we created a sustainability report which aimed to acknowledge AUT's overall sustainability roadmap in the context of this project. This report formed part of the structural response, and detailed how the design team were going to contribute towards AUT's nominated UNSDGs (United Nations Sustainable Development Goals, 2017) throughout the building's life cycle, from design through to demolition. Figure 4 shows an example of how this was presented.

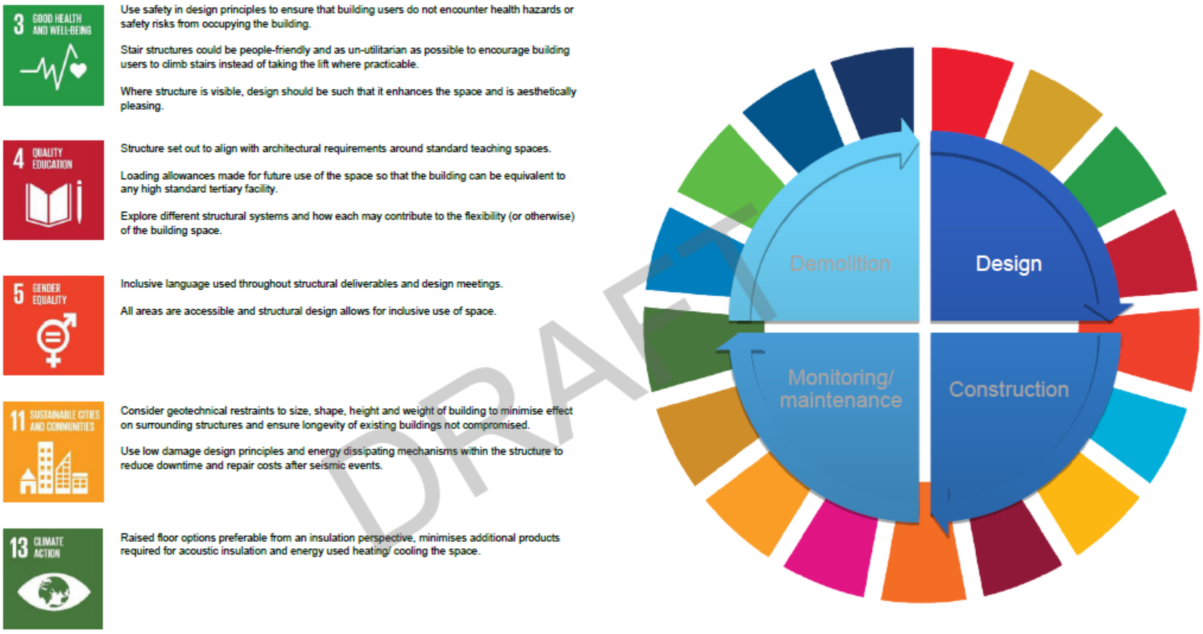

Figure 4: Example review of design against UNSDGs

Material Selection

AUT's sustainability goals for the project were further defined in the 'Sustainable Design Brief', which outlined multiple specific goals across a wide range of disciplines. Many of the goals were specific to energy and water performance requirements, including façade performance. AUT noted a strong preference for New Zealand locally manufactured materials and equipment, particularly for materials which have high embodied energy – to make the most of our renewable grid.

In this case, the selection of LVL as the primary framing and floor material served multiple purposes. It not only met AUT's vision for sustainable buildings, but due to the poor soil conditions on site, also enabled an additional floor level to be constructed (when compared with an equivalent steel frame and concrete floor building) due to the reduced weight. This also provided an opportunity for the architect to enhance the aesthetics of the space through exposed mass timber. The LVL is proposed to be sourced locally through Nelson Pine manufacturers.

Holistic Design/ Adaptive Re-use

The introduction of a raised floor allowed for a displacement ventilation system to be adopted, which generally achieves higher operational efficiencies than other systems. It provided a ready opportunity to incorporate additional acoustic insulation layers in the floor build-up. The raised floor also gives future flexibility for changes in space use, meaning services will be able to be easily altered to suit. AUT's sustainability brief also noted the requirement for the building to have a predominantly open floor plan, enabling flexible future use, and internal staircases which are "irresistible to use". The provision of a 'social stair' connecting the A1, AF, library and atrium was a key method of achieving this outcome.

Although internal thermal mass is not as critical for a displacement ventilated building (Craig 2019, Mustakallio 2010), it was considered prudent to specify additional material (in this case, aluminium wall finishes) in the building design. This is because mass timber does not provide as effective a heat sink as concrete or metal (Craig 2019).

End-of-Life/ Deconstruction

AUT's sustainability brief required all primary timber components to be de-constructible. This was achieved through careful detailing of the post-tensioned moment frames and braced elements.

CASE STUDY 2: HUMAN SCIENCES BUILDING B201 (UNIVERSITY OF AUCKLAND)

Project Overview

This project is the extensive refurbishment and strengthening of an existing building complex on Symonds Street in central Auckland. There are two reinforced concrete moment frame towers sitting on top of a basement podium structure, all designed and built in the early 1970s. Originally, the project scope was limited to seismic strengthening and internal refurbishment of selected areas. There had been some historic durability issues with the precast façade cladding, and the intent was to remediate these to allow the building to continue to be occupied for at least another 15 years.

However, during the initial design process, the client (University of Auckland) reassessed their approach. It was recognised that the existing buildings had the ability to become a long-term asset to the University, and that significant sustainability achievements could be targeted. Further discussions with the design team highlighted areas which would need to be addressed in order to make the building suitable for a renewed 50 year design life. The most significant aspect to this was the replacement of the precast façade, which limited the building from a seismic and durability perspective. This also meant that the ongoing operational efficiency of the building could be better controlled through the new envelope. The building is targeting a high level of Green Star certification, and is shown in Figure 5 below.

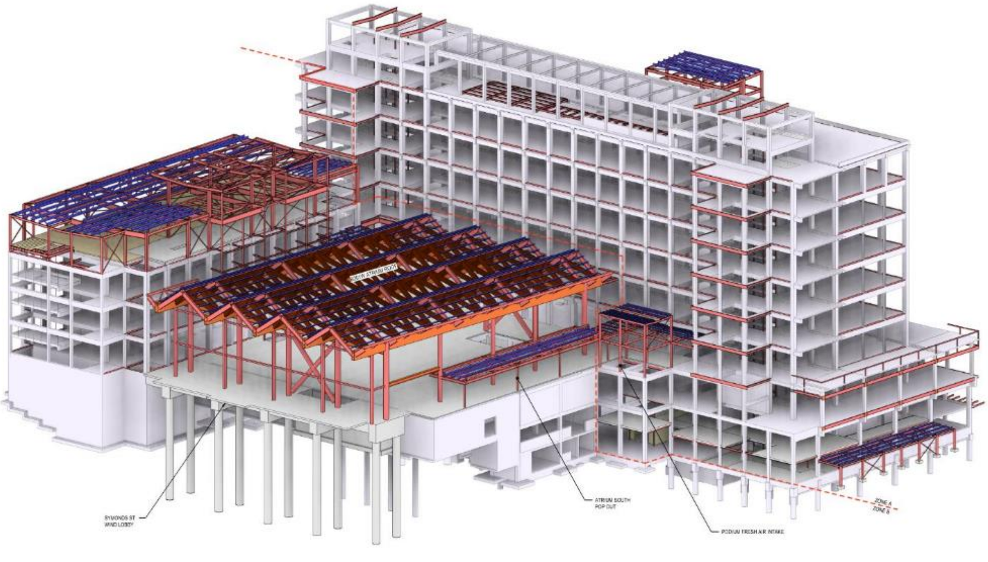

Figure 5: UoA B201 building

Material Reduction

Retaining the majority of the existing structure had significant environmental benefits described previously, reducing the embodied carbon that would otherwise be associated with the construction of a new building.

As part of the Green Star certification, the University of Auckland opted to undertake a Life Cycle Assessment (LCA). The aim of an LCA is to quantify the environmental impacts of a building against an industry benchmark. For this project, we completed the LCA using E-Tool

LCD – a proprietary software which meets the Green Star requirements for a certified practitioner. Through this process we were able to identify 'hot spots' of carbon within the building, as well as celebrate the significant benefits which were achieved compared to a benchmark.

Resilience

The current building already meets minimum legal requirements for seismic resilience. Therefore the resilience of the new building, compared against its current state, has been improved on multiple fronts.

Thanks to the replacement of the facade, the seismic mass of the building has been reduced, significantly improving the overall performance of the building. Strengthening has been targeted to elements in several key locations which will increase the level of seismic shaking in which they remain elastic. This lessens the likelihood of damage in a given seismic event, reducing the level of post-earthquake repair required.

The façade, ceilings and partitions are being fully replaced with gravity and lateral support systems designed to current standards. Therefore the likelihood of these elements requiring repair after a serviceability level event is significantly reduced.

Material Specification/Social Licence

The structural specification included a specific section dedicated to sustainability requirements, in particular those required for Green Star.

All new concrete in this project has been specified to include minimum 10% fly-ash as an alternative cementitious material. This not only reduces the embodied carbon per volume of concrete used, but also improves the durability compared with a standard Portland cement mix. Given the limited amount of new concrete on this project, this was not done for the purposes of gaining a point for Green Star, but adopted into the structural specification as good practice. This was done following initial conversations with two major concrete suppliers in NZ who verbally advised there would be negligible cost difference for supply of a 10-15% fly ash mix. This has yet to be confirmed as the contractor has not yet received quotes for the supply.

All timber treatments and coatings used on the project will be required to conform to the specifications laid out in the Green Star certification. This means there will be improved wellbeing through construction and occupation, achieved through low volatile organic compound concentrations.

The structural specification also laid out requirements for responsible procurement and sourcing of structural steel and all timber. All timber is required to be sourced locally from forests which attain Forest Stewardship Council (FSC) certification. Note the majority of timber supplies in New Zealand have FSC certification, however very few have environmental product declarations. The majority of steel is required to be fabricated by a current member of the New Zealand Sustainable Steel Council (SSC). Note there are difficulties with achieving sustainable steel procurement, as the mills from which fabricators receive their material do not often have the required level of sustainable certification, such as is looked for by Green Star.

CONCLUSIONS

There are many ways to incorporate sustainability considerations into the structural engineering design process. Although some of the concepts may seem unrelated or unfamiliar, a holistic viewpoint will enable structural engineers to consider a wide range of consequences and implications. Design choices can have unintended repercussions in spheres beyond the immediate context of the project, which may not be clear until later in the life cycle of the building or structure. Having a foundational understanding of the main areas of sustainable design will enable better choices to be made at an early stage.

Although it may be difficult to achieve good outcomes on all fronts of sustainability, the case studies shown have demonstrated how multiple aspects can be considered simultaneously, and how outcomes are often interconnected. Both the AUT A1 and UoA B201 buildings are examples of what can happen when the client and engineer are motivated to make sustainable decisions together.

From a carbon emissions perspective, structural life cycle emissions reductions should focus primarily on the immediate up-front life stage in order to help New Zealand achieve its climate change commitments and limit global warming. Structural engineers should understand the carbon impacts of different design decisions, and report the outcomes alongside the other design features.

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