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Balancing seismic resilience and lean design to reduce the embodied carbon of buildings

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ABSTRACT

The building and construction sector needs to make big changes to reduce greenhouse gas emissions if New Zealand is going to meet the legally binding targets of the 2019 Zero Carbon Act, and its commitments under the Paris Agreement.

Emissions in building and construction come from both the operation of buildings, and the materials and products that make up buildings, known as embodied carbon. In 2020, the Ministry of Business, Innovation and Employment (MBIE) launched the Building for Climate Change programme, which sets out a bold vision of how to reduce these emissions. The Whole-of-Life Embodied Carbon Emissions Reduction framework proposes to make reporting of embodied carbon mandatory, and eventually require that all new buildings meet a cap on embodied carbon to obtain a building consent.

Embodied carbon can be reduced by improving the efficiency of construction material use, and reducing the carbon intensity of those construction materials. However there are also significant benefits in ensuring buildings are designed to achieve their full life potential: by being adaptable and resilient, emissions are avoided from extensive building repairs, and new builds in the future.

There is a perceived trade-off between material efficiency and resilience in order to minimise whole-of life carbon, particularly in the design of structural frames. These have significant embodied emissions and, in New Zealand, are heavily influenced by seismic performance considerations. Further research work is required to draw attention to the carbon impacts of design decisions that consider resilience and lean design principles.

1 CLIMATE CHANGE AND EMBODIED CARBON

1.1 Introduction

Embodied carbon, operational carbon and whole of life carbon are not terms that most structural engineers in practice today were familiar with at the start of their careers. Engineers however are likely to be aware of our changing climate, the threats it poses to future generations, and the direct link between the effects of climate change and global emissions of greenhouse gasses.

Greenhouse gas emissions from buildings are generally put into two groups: operational emissions and embodied emissions. Operational emissions occur only during the use stage of a building's life and are from the energy and other resources used when operating the building. Embodied emissions are from the materials and products that form the building and can occur right across the building's life cycle.

The resilience of a building will determine the amount of repair and replacement that a building will need to undergo throughout its operational life, and so will directly impact the embodied emissions over the building's life cycle.

This paper uses a range of international and New Zealand sources to investigate the balancing act between seismic resilience and material efficiency (lean design) to optimise embodied emissions for the seismic risk context of building design in New Zealand.

1.2 Why carbon?

Note that the terms 'emissions, 'carbon emissions' and 'carbon' are used here as shorthand for all greenhouse gas emissions: this includes Carbon Dioxide (CO_2), but also all gasses that have a warming effect on the climate. Quantities are measured in units of Carbon Dioxide equivalent, or kg CO_2-e.

Carbon emissions are not the only environmental impact of buildings. Others environmental impacts that can be measured include energy and depletable resource use, acidification, eutrophication, ozone depletion etc. Despite the diverse nature of potential environmental impacts, when they are assessed, there is a close correlation between carbon and most other environmental impacts, hence carbon can be considered a proxy for the assessment of overall environmental impact. (Simonen et al 2018)

1.3 What are embodied and operational carbon emissions?

Operational carbon emissions are those directly and indirectly attributable to the operation of buildings: essentially emissions from the use of energy (for heating, cooling, hot water, lighting, ventilation, appliances etc.) and water.

Embodied carbon emissions are those attributable to the building itself, i.e. the construction materials and products across the life cycle of the building. This includes emissions across the full supply chain of construction materials and products, construction processes (and the waste arising), repair and maintenance, and processes at the end-of-life of a building.

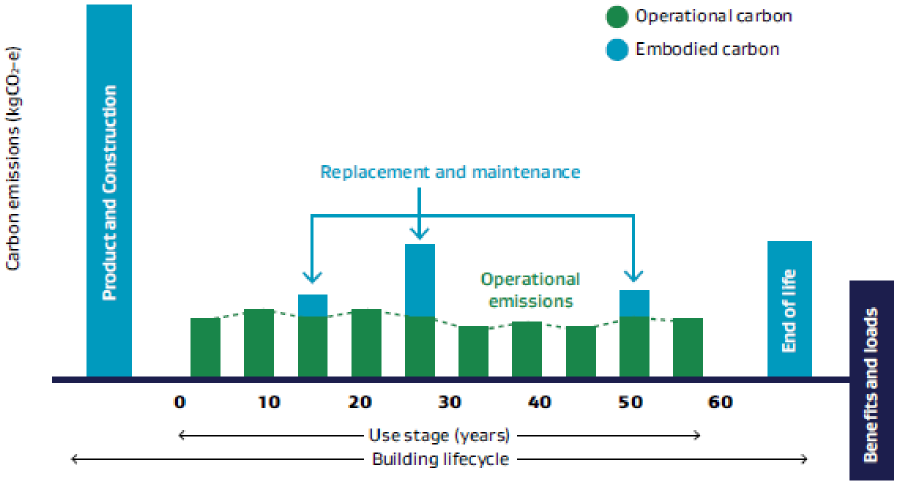

Figure 1: Operational and embodied carbon emissions over a building lifecycle (MBIE, August 2020)

Although a large proportion of embodied carbon emissions occur at the material production and construction phase, prior to the building coming into use (sometimes termed 'upfront embodied carbon'), as seen in figure 1, embodied emissions occur at other lifecycle stages too: during the building's use when elements of the building are maintained and replaced, and when the building reaches its end-of-life. When elements of the building are reused or recycled for use in other buildings, these processes will have emissions but may also result in savings of embodied carbon, if it offsets the use of other materials. These are reported as loads and benefits beyond the system boundary.

Most assessments of carbon emissions from buildings are based on the principles of Life Cycle Assessment (LCA). International standards for LCA in construction define life cycle stages according to a module framework, as shown in figure 2:

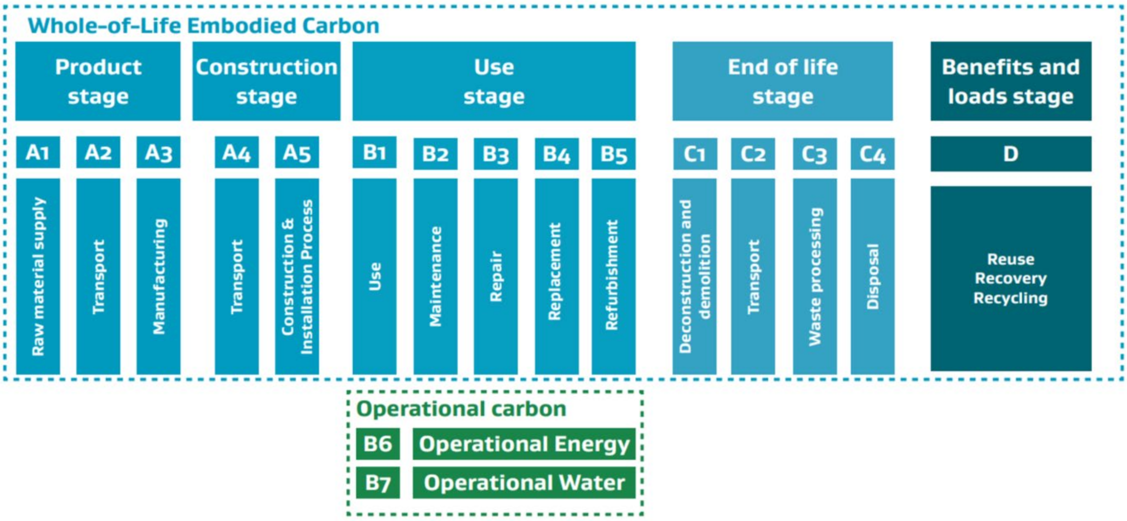

Figure 2: Module framework for assessing whole-of-life carbon for a building (MBIE August 2020)

Note modules B6 and B7 are the operational emissions due to the use of energy and water. However modules B1-B5 also occur during the 'Use' life cycle stage, and are a result of the use, maintenance, repair, replacement and refurbishment of physical elements of the building. Any repair or replacement to building components following seismic damage are therefore accounted for in these modules. Improvements to the seismic resilience of a building will reduce the emissions at these stages after a seismic event, and hence reduce whole-of-life embodied carbon.

1.4 What is resilience?

The ISO definition of resilience is “The capacity to absorb and adapt in a changing environment” (ISO 2017). In the New Zealand context, a major part of any resilience discussion will inevitably revolve around the impact and consequences of seismic events. Seismic events are short term shocks, but any holistic assessment of resilience should also look to assess longer term stresses such as climate change adaptability, material degradation, potential for integration of new technologies, flexibility for change of use etc. Not all of these resilience considerations can or should be driven by the structural engineer. The appropriate level of resilience for any given building will vary according to the function of the building and the risk tolerance of the building owner or occupier (Field 2020). Providing the required level of resilience will require a well-co-ordinated multi-disciplinary approach from the design team and robust conversations with the building owner/occupier throughout the design process.

A basic level of resilience is incorporated into all building designs in New Zealand, either by the codified requirements for resilience, the safety margins in the probabilistic basis of many design standards or via the allowances made by designers for the risks, uncertainties and assumptions inherent in any design process e.g. material properties, loads, ground conditions, modelling uncertainties etc.

1.5 What is ‘lean design’?

The Institution of Structural Engineers defines ‘lean design’ as “creating more value with fewer resources” (Field 2020). Lean design is not simply about taking spare capacity out of the structure, but focusses on maximising material efficiency and optimising what is provided to what is required. Questions for a lean design process could include (Watson 2020):

- Have structural utilisation ratios been optimised?
- Are the serviceability criteria fully understood? Is there scope to challenge façade deflection limits, can localised exceedance of deflection or dynamic criteria be accepted? etc.
- Are the loading criteria representative of real requirements, or have conservative preliminary design assumptions been carried forward?
- Does it make sense to construct for future flexibility now or can this be efficiently built-in later?

Similar to resilience, achieving a lean design requires a well-co-ordinated multi-disciplinary approach from the design team and robust conversations with the building owner/occupier throughout the design process. Achieving a lean yet resilient design will require both issues be considered concurrently as part of a well-integrated design process.

2 NEW ZEALAND REGULATORY CONTEXT

2.1 Carbon emissions from buildings

The Climate Change Response (Zero Carbon) Amendment Act 2019 (known as the Zero Carbon Act) commits New Zealand to net zero carbon emissions as a nation by 2050. It provides a framework by which New Zealand can develop and implement clear and stable climate change policies that contribute to the global effort, under the Paris Agreement, to limit the global average temperature increase to 1.5° Celsius above pre-industrial levels.

The Zero Carbon Act also establishes a system of emissions budgets to act as stepping stones towards the 2050 targets. A new, independent Climate Change Commission has been established to provide expert advice and monitoring to help keep successive governments on track to meeting long-term goals.

In response, the Building System Performance (BSP) Branch of the Ministry of Business, Innovation and Employment (MBIE) launched the Building for Climate Change (BfCC) programme in 2020. This programme is intended to drive transformational changes, including new regulations, to deliver emissions reductions from the building and construction sector. In August 2020, the BfCC programme launched a public consultation on the two frameworks that set out how the operational and embodied carbon of buildings can be reduced.

The Whole-of-Life Embodied Carbon Reduction Framework (MBIE August 2020) set out proposals for building projects to report and subsequently meet a cap on embodied carbon emissions at building consent stage. A similar approach was adopted for operational emissions but implemented on different timelines.

The framework proposals received broad public support: over 360 consultation responses were received, and 74% of respondents supported a cap on embodied carbon (MBIE January 2021). The next steps will be to finalise a methodology for embodied carbon to be assessed in New Zealand, and identify how the new requirements will be implemented through regulation. The methodology will cover how, and if, whole-of-life embodied carbon that have not yet occurred at building consent stage will be reported, such as those at end-of-life, and repair and replacement of building components during the ‘Use’ stage,

2.2 Seismic resilience

Achieving a balance between resilience and lean design is not just a question of minimising embodied carbon, but is also critical for informing broader conversations around the future of seismic risk and building performance in New Zealand. Triggers for these conversations include the imminent update of the National Seismic Hazard Model (NSHM), covering advances in earthquake science and experience gained from earthquakes that have occurred over the last few decades. In response to these triggers, MBIE commissioned a group of experts, the Seismic Risk Working Group, to provide advice on how the updated NSHM could be applied within the Building Code (MBIE November 2020). In response to the advice received, MBIE is currently developing a Seismic Risk Work Programme (SRWP) to ensure;

- Policy/risk settings are clear and transparent,
- Seismic design provisions contribute to consistent building performance,
- Seismic loading provisions are appropriate, considering the uncertain nature of earthquakes.

Successful delivery of the SRWP will rely on input from key stakeholders, such as the structural engineering community, and resilience and lean design will be important considerations for any solutions developed.

2.3 Seismic risk and ‘carbon risk’

Seismic risk drives the structural design of most buildings in New Zealand. Seismic risk is unique among the design loadcases in that we are generally accepting of some level of damage before the Ultimate Limit State (ULS) design case is reached. By contrast, if a storm event occurs that does not involve winds in excess of the ULS design state, we would not expect roofs to lift off or facades to be damaged. This dichotomy is not unique to New Zealand. There are many reasons for this approach to seismic risk but these are beyond the scope of this paper. The key point to note here is that this leads us to take a different approach to how we consider the seismic component of embodied carbon and the risk that seismic events pose to the whole of life carbon impact of a building.

In New Zealand, it is likely that at some point within the lifetime of any building it will be affected by a seismic event. Few large modern buildings in New Zealand are designed to respond elastically to ULS seismic events. In general terms, the risk of a ULS seismic event is low while the risk of an SLS (or slightly larger) seismic event is much higher. Hence, if we are to minimise whole-of-life embodied carbon of a building, it is reasonable to make some assessment of the likelihood of damage to a building at a range of seismic events. The carbon impact or ‘carbon risk of seismic events could be considered alongside the financial, operational and safety considerations for seismic events.

There are tools available to support the assessment of likely damage in different seismic events, such as the Performance Assessment Calculation Tool (PACT) and Performance Estimation Tool (PET) developed by the Federal Emergency Management Agency (FEMA) in the US (FEMA P-58). These allow different scenarios to be assessed to support designers when conserving resilience issues. These are likely to only provide ‘ball-park’ estimates of the damage that may occur but they are useful for the purposes of comparison and identifying critical elements that contribute to damage and impacts such as cost, carbon or repair time etc.

3 WHERE IS THE EMBODIED CARBON IN A BUILDING?

3.1 New-build construction

There are many variables that affect how much embodied carbon is in the different components of a building. Figure 3 shows a breakdown of embodied carbon by element for three different building types in the UK, over the ‘Product’ stage (modules A1-A3 in the LCA framework).

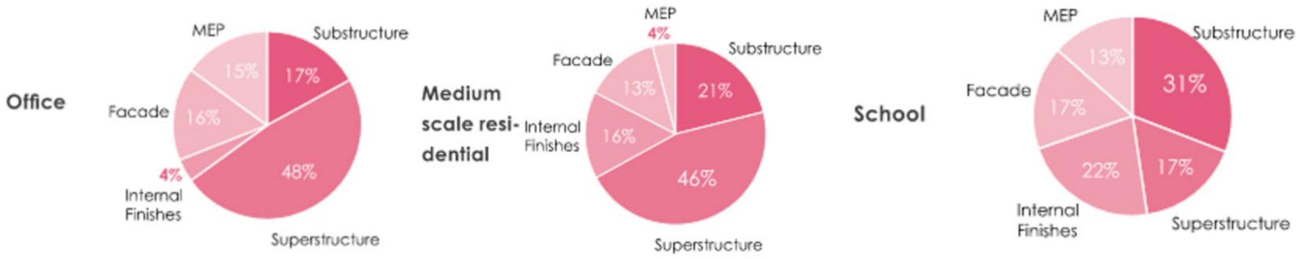

Figure 3: Breakdown of embodied carbon in UK buildings by element: product stage (LETI 2020). Note: MEP = Mechanical, Electrical and Plumbing elements, i.e. building services equipment

A similar analysis has been done by MBIE for ten non-residential building projects in New Zealand, using data from projects assessed using the eTool methodology and software tool, see figure 4. It should be noted that this analysis includes replacement of components over the lifetimes of the buildings, their end-of-life impacts and subsequent potential loads/benefits (modules A1-A3, B3-B4, C1-C3 and D in the LCA module framework).

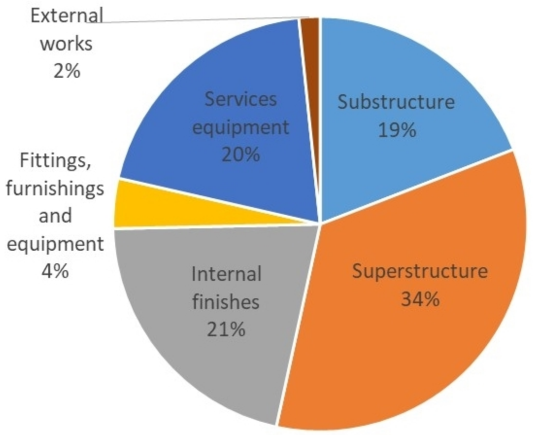

Figure 4: Breakdown of the embodied carbon of 10 New Zealand buildings by element, multiple LCA stages

All building designs will be unique, but across all building types, it is clear that the primary structure represents a significant proportion of the total embodied carbon in many buildings. It also highlights that non-structural elements such as internal finishes, façade, fittings and building services equipment also contribute significantly, especially when their replacement due to normal wear and tear during the lifetime of the building is factored in. Any damage to these elements incurred during a seismic event will therefore result in greater emissions in modules B3 and B4, due to additional repair and replacement work.

It follows that, whilst every effort should be made to incorporate lean design principles in the design of the primary structure to reduce embodied emissions from these elements, since the behaviour of the structure will determine the level of damage incurred by the building, including non-structural elements, this must be carefully considered as part of a design process to reduce whole-of-life embodied carbon.

3.2 Seismic repairs

As noted previously, the PACT and PET tools (FEMA P-58) can provide 'ball-park' estimates of the seismic damage that may occur in different seismic events.

FEMA have also conducted studies into the impact to embodied carbon of repairs required after seismic events (Huang & Simonen 2019). An extract from a key graph is reproduced in figure 5. A key finding of this study is that the carbon impact of seismic damage is heavily weighted towards the non-structural components of the building. The embodied carbon of glass and gypsum products is greater than for many other products (Simonen et al 2018). When considering 'carbon risk', the impact of the high embodied carbon of glass and gypsum products is exacerbated by their fragility and likelihood of damage during seismic events. Choosing a structural system that limits damage to non-structural components could have a significant impact on reducing the risk of substantial embodied carbon emissions after a seismic event.

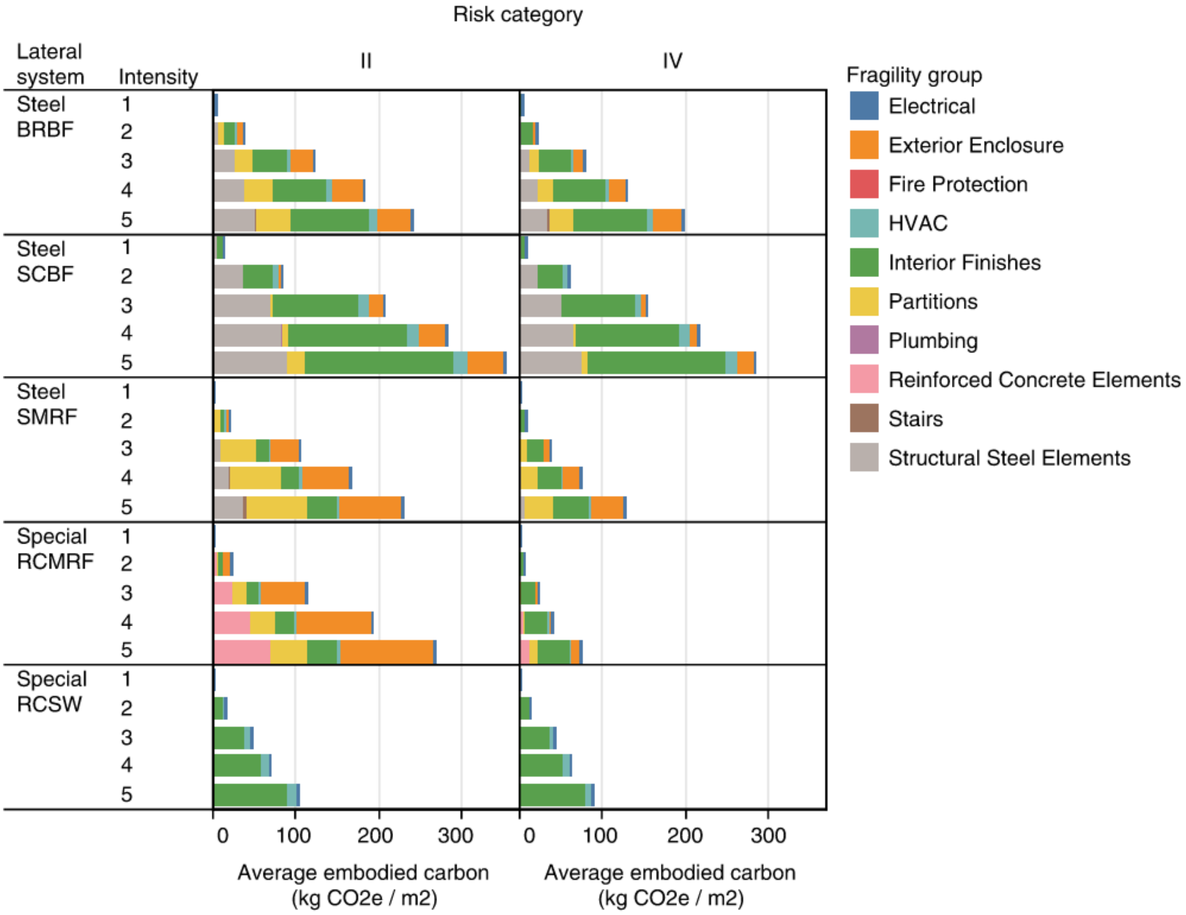

Figure 5: Average carbon emissions of repairs for a number of different seismic scenarios (1-5 in increasing intensity) and structural frames. (Huang & Simonen 2019). Note: BRBF – Buckling Restrained Braced Frames, SCBF – Special Concentric Braced Frame, SMRF – Special Moment Resisting Frame, RCMRF – Reinforced Concrete Moment Resisting Frame, RCSW – Reinforced Concrete Shear Wall; Risk Category II and IV are approximately equivalent to NZS1170.0 IL 2 and 4

It is important to note that the figure 5 is only presented for the purposes of highlighting potential locations of carbon risk. The actual relationship between seismic damage and carbon risk will vary greatly from building to building. For example, warehouses with minimal fit-out and services are unlikely to have such a significant contribution from cladding and internal finishes, but there may be key high value/carbon components such as generators, chiller units, server rooms etc. where limiting the risk of seismic damage may significantly reduce embodied carbon.

3.3 Refurbishment and seismic strengthening work

Building resilience is also about being flexible to adapt to future uses. For many buildings, particularly commercial ones, it is assumed there will be a number of refurbishments and fit-outs before they are demolished. The embodied carbon emissions associated with these refurbishments is an important consideration for the whole of life carbon of the building, and is captured in module B5 of the LCA framework. For new buildings, an estimation of the impact of refurbishments can be made at the design stage to assess whole-of-life embodied carbon for the building. For existing buildings, assessing whether a refurbishment is an efficient use of embodied carbon is more complex, as it needs to consider the carbon risk from seismic damage.

Retrofitting a building to seismically strengthen it can be assumed to reduce the risk of the building needing to be replaced due to seismic damage. There will be an embodied carbon cost associated with this work, which can be significant, especially if it involves work to the foundations.

In addition, if an old building is to remain in use for longer, it may be pertinent to consider the operational carbon impacts of this decision. Older buildings are unlikely to be optimised for energy efficiency. The operational carbon costs of continuing to occupy an energy inefficient building can outweigh the embodied carbon benefits of extending its life. Conversely, improving the energy efficiency and reducing the operational carbon impact of an older building may not benefit whole-of-life carbon impacts if the building is prone to seismic damage and this is not addressed (Belleri & Marini 2015). Balancing the carbon cost of refurbishment and seismic strengthening to get an overall net benefit may require assessing a number of different scenarios.

4 USING RESILIENCE AND LEAN DESIGN TO REDUCE EMBODIED CARBON

The Building for Climate Change Whole-of-Life Embodied Carbon Reduction Framework proposes 3 objectives to achieve reductions in embodied carbon (MBIE August 2020):

- Use new buildings efficiently: make the size and quantity of new buildings proportional to the need, upgrade existing buildings so they can be used effectively, and increase the longevity of new buildings to reduce avoidable new build in the future,
- Increase material efficiency of buildings: use less material, reduce waste and minimise replacement over the building's life cycle,
- Reduce the embodied carbon of materials: by driving wider use of low carbon building materials.

Improving resilience contributes to the first and second of these objectives, because by making buildings last longer, we reduce what we build in the future, and also reduce the need to replace building elements over the lifecycle. Adopting lean design principles addresses the second objective, by only using as much material as is necessary. There can be a perception of a trade-off between resilience and lean design.

A successful balancing act between seismic resilience and lean design needs to consider the carbon impact of resilient design decisions. Figure 6 is an extract from the RICS methodology for embodied carbon (Lockie & Berebecki 2012). This is an example of the impact that measures including incorporating lean design principles can have on the total embodied carbon. However, it is noted this is for a building in a non-seismic area. Analysis of seismic damage scenarios and consideration of whole-of-life carbon may well lead to some cases where a higher embodied carbon option for the foundation or frame may be justified, in order to protect and reduce the 'carbon risk' to secondary or non-structural components that would otherwise be prone to damage.

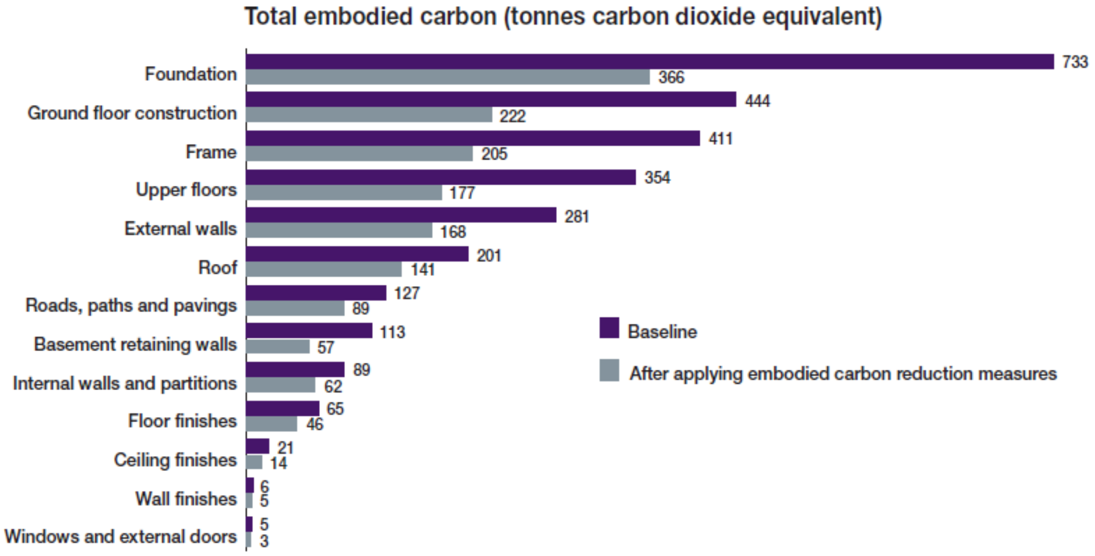

Figure 6: Effect of carbon reduction measures on embodied carbon of a building (Lockie & Berebecki 2012)

The challenge for today's building designers is to find a 'sweet spot', where a building is resilient enough but lean enough to minimise embodied carbon. Designers need to be aware of the impacts of both resilience and lean design on whole-of-life embodied carbon to enable them to make informed design decisions about the 'carbon risk'.

Further work is required to understand the reality of the perceived trade-off between resilience and lean design. 'Low damage' buildings that are specifically designed to be seismically resilient (by, for example, concentrating damage from seismic loads into replaceable components for the sake of reducing damage to other structural and non-structural building elements), may also be materially efficient when compared to other buildings. Such design solutions, that offer both materially efficient and resilient buildings, should be explored for their potential to be reproduced widely, to reduce whole-of-life embodied emissions.

5 CONCLUSIONS

The operational and embodied carbon emissions of buildings are significant in New Zealand, and there is growing pressure on the building and construction sector to find ways to reduce them. The design of primary structural elements in a building impacts the whole-of-life embodied carbon, as it represents a significant proportion of the 'upfront' embodied carbon, but also determines the level of damage to both structural and non-structural elements in a seismic event, and therefore impacts subsequent emissions due to the repair and replacement of these elements.

The Building for Climate Change programme is developing a methodology which will determine how whole-of-life embodied carbon will be assessed at building consent stage. ‘Lean design’ principles should result in reduced embodied carbon at the product stage, due to high material efficiency, but the emissions from potential repair and replacement of building elements due to seismic damage also need to be considered. There is evidence to show these emissions are disproportionately from fragile, non-structural components, and tools exist to assess these potential emissions, or ‘carbon risk’.

Achieving a resilient and lean design requires a well co-ordinated multi-disciplinary approach from the design team and robust conversations with the building owner/occupier throughout the design process. The ‘carbon risk’ posed by seismic events to the whole-of-life impacts requires a similar approach to the consideration of seismic risk. This could be considered alongside the financial, operational and safety considerations in making decisions about material efficiency that impact resilience.

Balancing the carbon cost of seismic repairs, refurbishment work and seismic strengthening to get an overall net benefit may require assessing a number of different scenarios. Designers need to be aware of the impacts of both resilience and lean design considerations on embodied carbon to enable them to make informed design decisions about the carbon risk and find the ‘sweet spot’ where the embodied carbon is minimised.

Further work is required to understand the reality of the perceived trade-off between building resilience and lean design. Design solutions may exist that are resilient and lean may exist, and these should be exploited as a way of reducing the whole-of-life embodied carbon of buildings in New Zealand.

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