ORIGINAL ARTICLE

Incorporating potential environmental impacts in building seismic design decisions

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Abstract

Seismic losses due to earthquakes have been shown to have significant economic, social and environmental consequences. Over recent years, research to predict potential economic and social impact due to seismic risk has been increasing. Recognizing that the traditional philosophy of life safety design can lead to extensive damage and demolition which has a large environmental cost, incorporating environmental impacts associated with the expected seismic damage over a building's life is a key step as the building industry moves towards both sustainable and seismically resilient design. This paper introduces a framework that uses environmental indicators quantifying losses from seismic response that can then be used to advocate for a change in seismic performance objectives. First, existing literature and previously developed approaches for quantifying potential environmental impact due to seismic damage are summarized. Next, performance based earthquake engineering concepts are used to demonstrate a probabilistic approach to quantify potential environmental impacts using a range of environmental and resource use indicators over the life span of a case study building. In addition, a case study is presented to compare different environmental indicators between a Code Minimum building and the same building redesigned for a higher seismic performance. The majority of the composition of the environmental indicator values are from the inclusion of the non-repairable scenario, and from the repair activities, the majority of the impacts are from damage to drift sensitive components including curtains walls, partitions and elevators. For the Code Minimum building the non-repairable scenario contributes to between 8 to 11% the total seismic cost. For the Stronger Stiffer building, the non-repairable scenario contributes around 3% of the initial impact. Neglecting non-repairable scenarios does significantly reduce the potential environmental impacts when analyzing buildings designed for current code minimum structural standards.

Keywords Earthquakes · Seismic losses · Building seismic design · Environmental indicators

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1 Introduction and motivation

The building industry produces significant greenhouse gas emissions, consumes energy, uses raw resources and is therefore identified as a key contributor to climate change. The International Energy Agency (2021) estimates that 37% of greenhouse gas emissions globally correspond to the building sector—of this, the manufacturing of iron, steel and cement is estimated to be responsible for 10.2% of global greenhouse emissions (Ritchie et al. 2020). Emissions produced over the life cycle of a building are typically split between operational and embodied emissions. The breakdown of the building sector emissions is 30% for the manufacturing of construction materials, and 70% from the use of fossil fuels and electricity use in buildings. Traditionally, building operational emissions have been considered the main focus for countries committed to climate change agreements (International Energy Agency 2021), offering the potential to reduce energy consumption (e.g. heating, ventilation) or decarbonize the power supply, for example. However, operational emissions are not the building industry's only emissions. Design guidelines that are emerging worldwide now require (or will soon require) reporting on emissions from building materials, in addition to the operational emissions. To begin to address the construction sector emissions, several countries have begun enacting legislation to mandate the reporting of environmental impacts across the life cycle of buildings. For example, Toronto, Canada has implemented the Toronto Green Standard that requires a whole building LCA from 2022 (Toronto Green Standard 2021). In the Netherlands, a building LCA performed according to the national legislation (MilieuPrestatie Gebouwen—MPG 2021) has been required since 2018. In New Zealand, the Building Climate Change programme was established in 2020 focusing on initiatives to reduce emissions to meet the 2050 net-zero greenhouse gas emission goal (MBIE 2021a) to be aligned with the Climate Change Response Act 2002 (New Zealand Legislation 2021). The objective of those legislations are to align with the reduction of greenhouse gas emissions targets from the construction industry by the following decades.

The environmental impact of building materials has received considerable attention as an opportunity for reducing greenhouse gases (Kayaçetin and Tanyer 2020; Malmqvist et al. 2018). However, this impact traditionally does not incorporate the risk of natural disasters. Li et al. (2022) highlighted the extra environmental burden resulting from unexpected events that can have implications for climate change mitigation efforts. During the last decade, devasting earthquakes have severely damaged buildings resulting in fatalities and significant economic losses. The aftermath of the Canterbury Earthquakes in New Zealand (2010/2011), the L'Aquila earthquake in Italy (2009) and the 2011 East Japan earthquake revealed the considerable losses caused by earthquakes. Gonzalez et al. (2022) investigated the environmental costs of demolitions following the 2010/2011 Canterbury Earthquake and demonstrated the significant consequence of premature demolitions following earthquakes resulting from waste management and construction materials. Wei et al. (2016a, b) questioned whether the building LCA could assess the environmental performance accounting for natural disasters. Recent trends in the last decade have led to a proliferation of studies into the environmental impacts of seismic repair activities e.g. (Chhabra et al. 2018; Huang and Simonen 2020; Welsh-Huggins and Liel 2017).

Investigating the environmental impact of seismicity is a continuing concern and researchers have developed different seismic loss and environmental impact assessment methods. However previous work has demonstrated that a number of these methods are not capable of full and accurate analysis of the environmental performance including

expected seismic damage across a building life-span (Hasik et al. 2018), this is discussed in the next section in more detail. This paper introduces a framework that uses environmental indicators quantifying losses from seismic response that can then be used to advocate for a change in seismic performance objectives. First, the following section summarizes the range of approaches used in previous research to incorporate environmental impacts into loss analysis as well as the available environmental data for analyzing seismic repair activities. Next, a new methodology that can be used to quantify the environmental impacts of buildings over their life span is introduced. This methodology can be used to compare different environmental seismic performance objectives, and this is demonstrated using a case study building designed to both a code minimum and above code standard. The case study building is based on a typical office occupancy type located in a high seismic zone designed in accordance with the New Zealand Building Code B1/VM1 (MBIE 2021c).

2 Literature review

Given the clear worldwide interest in sustainable development, literature on integrating environmental metrics into seismic loss methods has been growing over the last decade. Hasik et al. (2018) provide an extensive review of these approaches and conclude that some approaches are not capable of analyzing the full life cycle of a building. The two main concepts in previously developed methodologies are based on performance-based earthquake engineering (PBEE) and building life cycle assessment (LCA). These two concepts are explained in more detail in Sect. 3. The following subsections review approaches used in previous research in four distinct categories: (1) analysis type, (2) hazard definition, (3) translation of repair activities to environmental impacts (environmental data), and (4) inclusion of collapse and/or repairable scenario.

2.1 Analysis type

Researchers have used different analysis types to understand the value of seismic repair in terms of environmental impact. Structural analysis is used to determine the Engineering Demands Parameters (EDPs) such as storey drift and acceleration. EDPs are related to each floor and for both orthogonal directions. In the case of planar models, EDPs will be the same for both directions assuming a regular building, whereas, in 3D models, EDPs will differ based on direction. The EDPs are used to calculate the potential environmental impacts according to the aleatory damage state estimated in each component. The calculation of potential environmental impacts will highly depend on the building content and distribution of content across the building. Buildings can be modelled as either equivalent to a single degree of freedom (SDOF) system, a multiple degree of freedom (MDOF) system or using a more detailed approach. A higher level of complexity is more computationally expensive; however, simplified models are limited to regular buildings and information on the higher mode effects is lost when a building is represented as a SDOF model. Several authors have used a representation of buildings within a SDOF system (Chiu et al. 2013; Menna et al. 2013). Menna et al. (2013) performed a pushover for the equivalent SDOF system, and potential environmental impacts are assumed to limit states and Chiu et al. (2013) assumed the same repair cost proportions to environmental cost for damage indexes resulting from the maximum deformation response of a SDOF system. The implications of running a

SDOF system for seismic loss estimation is that insufficient information is provided to calculate specific losses depending on building content, and it relies on assumptions of material components needed considering a single metric performance. Planar (2D) models also have been used for structural analysis in some studies (Chhabra et al. 2018; Hossain and Gencturk 2016; Welsh-Huggins et al. 2020; Welsh-Huggins and Liel 2018). Tridimensional models have been used for considering optimal retrofitting of an existing building considering environmental impacts (Clemett et al. 2022). In another recent approach, for example, Gavrilovic and Haukaas (2021) employed finite-element models created from BIM models based on visual damage to determine the cost of environmental damage. This analysis is computationally expensive. However to date, no literature appears to validate model simplifications and/or its impacts on the estimated potential environmental impacts due to earthquakes.

2.2 Seismic loss estimation method

In some of the first studies that included seismic damage in LCA, HAZUS loss estimation tool (Schneider and Schauer 2006) developed by the Federal Emergency Management Agency (FEMA) was used to estimate damage (Comber et al. 2012; Feese et al. 2015; Sarkisian et al. 2011; Wei et al. 2016a, b). In more recent studies, researchers have implemented concepts of PBEE. In comparison to HAZUS, PBEE has been used for more detailed studies that include a configuration of damageable components, including the direction of components and floor location of these components (Chhabra et al. 2018; Clemett et al. 2022; Hossain and Gencturk 2016; Huang and Simonen 2020; Welsh-Huggins et al. 2020; Welsh-Huggins and Liel 2015, 2018). Ramirez et al. (2012) demonstrated that HAZUS could lead to underestimation of damages and losses, compared to using the PBEE's methodology by a factor of 1.6–2.4 times using a concrete building case study. The authors concluded that methods that facilitate quick calculations do not capture individual buildings' structural and non-structural characteristics. A building life cycle assessment provides the option of identification of environmental hotspots (e.g. the main contributor of environmental impact as a function of sensitive or acceleration sensitive components) for a designer to reduce or redesign the building to meet caps or improve the environmental performance over its life span. This is only feasible if the analysis considers individual buildings' characteristics.

Several researchers have performed assessments in terms of environmental metrics considering different scenarios. Loss scenarios can be performed as intensity-based, scenario-based, or time-based. However, when the performance assessment is conducted alongside a LCA, the time-based approach is appropriate when the objective is to represent the life cycle of a building (Hasik et al. 2018). The results from a time-based assessment capture the seismic losses that a building might undergo for a range of seismic records that can be incorporated into a cradle-to-grave life cycle of a building. The intent of intensity-based assessments is to capture a building response to a specific shaking intensity. Scenario-based assessments evaluate a building subjected to a specific earthquake occurring at a specific location. Some researchers have conducted scenario-based assessments (Comber and Poland 2013; Simonen et al. 2015) and risk-based assessments (e.g. time-based, multiple-stripe) (Clemett et al. 2022; Wei et al. 2016a, b; Welsh-Huggins and Liel 2018).

2.3 Environmental data

There are many different documented approaches to select environmental data for LCA. Comber et al. (2012) proposed the use of the Economic Input–Output (EIO) method to translate repair cost to repair environmental impacts. This method uses regional economic and environmental data to map specific environmental impacts on specific industrial sectors to obtain a relationship of environmental impact per dollar spent (Hendrickson et al. 1998). Comber et al. (2012) presented a methodology using the HAZUS methodology and Economic Input–Output (EIO) environmental data for repair activities. This methodology has been used to translate seismic repair activities to environmental impacts in several studies in the US (Comber et al. 2012; Comber and Poland 2013; Huang and Simonen 2020), and it has been implemented in Performance Assessment Calculation Tool (PACT) (Simonen et al. 2018) developed by FEMA. Clemett et al. (2022) implemented the EIO approach and adjusted the US cost consequence to the national context to calculate environmental consequences for repair activities in Italy. In that work, researchers used the approach by Silva et al. (2020) to translate the cost of the seismic repairs to European values and use these economic values to calculate environmental metrics for seismic repairs.

Other researchers have used process-based LCA to calculate the consequence of seismic repair activities. Process-based LCA requires information about the quantity of material, and processing needs for a product or service. This information is used to quantify inputs (material and energy resources), and outputs (e.g. emission and waste to the environment). Some software tools are available to conduct a Process LCA such as SimaPro (PRé Consultants 2015) or GaBI (PE International 2020). Welsh-Huggins and Liel (2017) used process-based LCA to estimate the specific materials needed for seismic repair activities. Other researchers have also used this approach; for example Belleri and Marini (2016) associated embodied carbon dioxide from repair seismic activities using the database provided by Hammond and Jones (2008). Also, Wei et al. (2016a, b) used values from the literature to calculate the environmental impacts of concrete structural components for different earthquake damage states. The authors also calculated the cost ratio and CO2 emission ratio as a relationship between the repair value versus the initial cost/emission from the initial construction. The cost ratio calculated was 18% for a particular damage state, while the CO2 emission ratio is 45%, showing that the relationship between damage states and initial cost/emission values is not the same for economic and environmental metrics. Despite this, several authors have applied the same ratio for both economic and environmental metrics (Alirezaei et al. 2016; Arroyo et al. 2015; Chiu et al. 2013; Feese et al. 2015; Padgett and Li 2016). Other approaches, for example, Caruso et al. (2021), compared the carbon emissions resulting from three different damage conversion approaches, including EIO-LCA, assuming material quantities and using the database by Hammond and Jones (2008), and repair cost ratio applied to repair environmental ratio. The comparison leads to similar results, however, the inventory of damageable components are limited to drift-sensitive components. Säynäjoki et al. (2017) compared results from the process-based LCAs, and the EIO method in the building sector, showing that the two methods deviate considerably from each other, with results from the EIO nearly doubling results from the process LCA method. Säynäjoki et al. (2017) concluded that the EIO approach is preferred for screening LCAs and industry-wide studies while a process-based LCA approach is preferred when specific designs are compared against each other. Sandanayake (2022) recognized the difficulties

in improving the quality of data for building-construction-emissions as a typical issue and identified knowledge gaps.

Another difference is seen where studies have used directly calculated single value environmental consequence data (Comber et al. 2012; Feese et al. 2015; Hossain and Gencturk 2016) while others considered the variability in environmental data, across source and level of verification (Chhabra et al. 2018). In seismic losses it has been common to introduce uncertainty beyond the consequence to represent data quality, and knowledge beyond the data (FEMA P-58-1 2018b).

Table 1 summarizes the variety of environmental data used in previous studies. Most of the studies have focused on the US. It is worth noting the range of gaps between the study reporting and the repair data used. Some are between a 5-year gap, and some are up to a 20-year gap. The environmental data is time sensitive as the production of materials or market change over time; usually, Environmental Product Declarations are valid up to a certain period (e.g. 5 years). An Environmental Product Declaration is a third-party verified document containing the output of a LCA of a product or material. The potential environmental impacts of seismic repair activities might happen somewhere in the future. The manufacturing emission of construction materials should be significantly less than manufacturing emissions today, due to the trend to the movement towards zero carbon emissions by 2050. However, the embodied impact data for the materials do not considered future decarbonization due to significant uncertainties about the rate of progress. The use of environmental data of using recent manufacturing and resulting emissions results in conservative results.

2.4 Inclusion of non-repairable or collapse scenario

Including scenarios where a building will no longer be repairable or will face demolition can lead to significant changes in the annualized losses. Welsh-Huggins and Liel (2018) calculated the environmental and economic losses of different building designs showing that the collapse scenario could represent 35% of the total post-earthquake emissions over its life span, considering a threshold of 12% inter-story drift. Chhabra et al. (2018) included the collapse scenario with a threshold of 7% peak interstorey drift, and the repairable scenario was included with either a residual inter-story drift ratio threshold of 1% (median), or a repair cost greater than 40%. Huang and Simonen (2020) have used the PACT database for ten archetype buildings, including a collapse scenario, and concluded that reducing the environmental impact of seismic hazards should focus on avoiding collapse as the highest priority. Including a collapse or non-repairable scenario plays a fundamental role in the environmental annualized risk mainly because the potential environmental impact is considerably higher than the seismic repair activities. The PACT tool allows the user to define non-repairable or collapse scenario through a maximum residual story drift ratio, a monetary threshold and/or using collapse fragility functions (FEMA P-58-1, 2018b). However, to date no previous study has shown how environmental annualized risk can vary with the selection of collapse threshold when including the non-repairable scenario.

2.5 Study recommendations

Based on the review of existing literature, the following was selected for use and/or evaluation in this work, (1) time-based scenario analysis will be used to identify the hazards across the building life span, (2) environmental indicators will be evaluated using a process

Table 1 List of previous studies and environmental seismic repair data characteristics

Authors	Year published	Publisher	Original seismic repair data			Location study
			Geographic region	Year	Type	
Comber et al. (2012)	2012	Structures congress 2012	US		EIO LCA consultant	US
Chiu et al. (2013)	2013	Journal of architectural engineering	Taiwan	2002	% of initial construction	Taiwan
Feese et al. (2015)	2015	Journal of performance of constructed facilities	Athena eco-calculator	2012	% of initial construction	US
Arroyo et al. (2015)	2015	Earthquake spectra	Literature	1994–2011	% of initial construction	Mexico
Hossain and Gencturk (2016)	2016	Journal of architectural engineering	Literature	2004–2012	Process LCA (Other)	US
Welsh-Huggins and Liel (2017)	2017	Structure and infrastructure engineering	Global	2013	Process LCA (SimaPro)	US
Welsh-Huggins and Liel (2018)	2018	Journal of structural engineering (USA)	Global	2013	Process LCA (Simapro)	US
Huang and Simonen (2020)	2022	Journal of structural engineering (USA)	US	2002	EIO LCA US 2002 Purchaser Price Model	US
Clemett et al. (2022)	2022	Engineering structures	US	2013	EIO LCA USEEIO database	Italy

LCA taking into account uncertainties in the environmental data, and (3) the effects of both neglecting and including collapse or non-repairable scenarios on annualized risk will be evaluated.

3 Proposed framework

This section introduces the proposed framework for quantifying potential environmental impacts resulting from probabilistic earthquake damage to a building across its design life. Here, the potential environmental impact is measured using 'Indicators' that encompass core environmental and resource use metrics—Global Warming Potential (GWP), Depletion Potential of the Stratospheric Ozone Layer (ODP), Eutrophication Potential (EP), Acidification for Soil and Water (AP), Formation Potential of Tropospheric Ozone (POCP), Abiotic Depletion Potential (ADP-elements) for Non-fossil Resources, Abiotic Depletion Potential (ADP-fossil fuels) for Fossil Resources, Total primary energy (TPE), divided into Total use of non-renewable primary energy resources (TPE_{nr}) and Total use of renewable primary energy resources (TPE_R) herein these are referred to as the Indicators. The framework has seven steps as summarised in Fig. 1: (1) Goal and scope definition, (2) Hazard definition, (3) Structural Analysis, (4) Damage Analysis, (5) Inventory analysis,

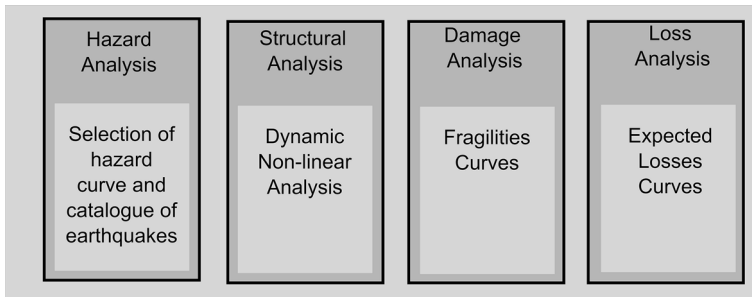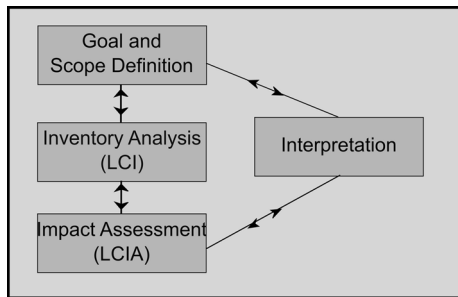**Fig. 1** Framework to include environmental metrics into the PBEE methodology

Fig. 2 PBEE [modified from Moehle and Deierlein (2004)]

Fig. 3 Overview of LCA framework [modified from ISO (2006)]

(6) Loss Analysis, and (7) Annualized Loss analysis and Interpretation. To incorporate the complexity of environmental data requirements and probabilistic seismic loss, the framework uses a traditional PBEE methodology (indicated by green in Fig. 1) and LCA (indicated by blue in Fig. 1). Detailed information regarding each module in the framework is included in the following subsections.

A PBEE method was selected for this framework as it accounts for specific structural and non-structural characteristics of a building and allows design outcomes to be communicated based on simple performance metrics (e.g. environmental indicators in this case) (Moehle and Deierlein 2004). The PBEE method used here measures building performance in terms of potential environmental impacts, using four typical PBEE main steps (illustrated in Fig. 2): (1) hazard analysis, (2) structural analysis, (3) damage analysis and (4) loss analysis. The seismic loss analysis is conducted using LCA, which is a formalized method to identify environmental impacts/resource use indicators across a product or service. ISO (1997, 2006) standardized the LCA framework into four phases as illustrated in Fig. 3: (1) goal and scope definition, (2) life cycle inventory, (3) life cycle impact assessment, and (4) interpretation. Specific standards have been developed for the application of LCA to building and civil engineering works, for example, EN 15978. Subsidiary standards/product category rules (PCRs) have been (and continue to be) developed to provide common rules that should be followed to ensure declared building environmental impacts are consistent and robust. Building LCA is broken into the following life cycle stages: production (modules A1–A3), construction (modules A4–A5), use (modules B1-7), end-of-life (modules C1-4). Additionally, potential benefits/loads beyond the building life cycle may be separately considered (module D). LCA standards (CEN 2021a) provide environmental metrics that should be included.

3.1 Goal and scope definition (LCA)

The goal and scope of an LCA study explicitly states the reasons for carrying out the study and the intended applications of the results (e.g. information about a specific product or comparison between products). Possible applications of LCA in buildings include identifying elements responsible for a large share of environmental impacts (Hollberg et al. 2021) or comparing different structural systems (Saade et al. 2020). In the framework presented here, the objective is to evaluate and compare buildings with the same use, structural system, floor area, and location, but designed for different seismic performance levels. The scope of the LCA includes initial construction materials including structural and non-structural components as well as the seismic repair activities for both structural and non-structural components across the building life span resulting from expected seismic damage, considering possible demolition or non-repairable outcomes.

3.2 Hazard definition

To evaluate seismic losses over a building life span, it is necessary to assess the building performance for a range of possible seismic intensities using time-based scenario analysis. For a time-based scenario analysis, a Probabilistic Seismic Hazard Analysis (PSHA) is performed at the location of interest, considering the local soil conditions and rupture forecast models representing ground motion predictions over a specific time. Recommendations about the selection of record motions can be found in (FEMA P-58-1 2018b). A hazard curve can be developed to represent the distribution of ground motion level per year from all potential seismic sources to estimate the intensities considering local conditions (e.g. soil type, ground fault rupture). A hazard curve is a relationship between ground motion shaking acceleration (Sa) and annual rate of exceedance. For each intensity, a uniform hazard spectrum is developed that is used for scaling the selected seismic records. The scaled seismic records are applied to the structural model to obtain the building performance over a range of scenarios.

3.3 Structural modelling

A structural model is required to obtain the Engineering Demand Parameters (EDPs). Typical EDPs include peak floor acceleration, and inter-story drift. The EDPs are calculated from a model that is capable of capturing non-linear behavior and the dynamic performance of a building in response to representative seismic records. The non-linearity can be included as concentrated, distributed inelasticity (fibre) and/or continuum models. While continuum models' behavior depends on material properties, concentrated non-linearity models are associated with the observed behavior of testing components. Considering the computational efficacy, concentrated plasticity was adopted to obtain EDPs in the case study in the following section, however any validated nonlinear approach can be used. The analysis selected for this framework is non-linear dynamic to obtain the building global performance to identify damage of drift-sensitive and acceleration-sensitive components.

3.4 Damage analysis

Estimating expected damage to structural and non-structural components is required to evaluate the repair and/or replacement activities following an event. A fragility approach to estimate damage is adopted for this framework. The damage analysis module includes the selection of fragilities curves for building components. Fragility curves are developed from experimental data, previously documented earthquake data, engineering judgement, or a combination of all three. The fragility curves represent the probability that a component will exceed a specific damage state at a specific demand (e.g. inter-story drift, or peak ground accelerations). Fragility curves are selected according to the most representative local practice or component characteristic within the building. FEMA contains an extensive library of fragility curves for structural and non-structural components. It is worth noting that the fragility curves are defined by log normal distribution curves using a mean and dispersion values. The dispersion depends on the quality of the data. An inventory of non-structural and structural components is used for the damage analysis with data about the location and directionality of the components. The damage analysis is performed using PACT. PACT uses a Monte Carlo procedure to assess the statistical distribution of component responses to a unique set of EPD (Yang et al. 2009). The number of realizations (on the order of several hundred or thousand) depends to the uncertainties in the defined per example fragility relationships or building model.

3.4.1 Non-repairable scenario

Non-repairable scenario is included in the proposed framework. Previous research has demonstrated that it is important to include this scenario because they can significantly influence the environmental indicators. Environmental repair activities are not likely to exceed the 20% initial carbon construction cost in MCE events (Huang and Simonen 2020), however in a collapse or non-repairable scenario the potential environmental impact is 100% of the initial environmental impacts assuming a similar building replacement. Evaluating the collapse scenario is relatively simple in that collapse can be determined either using a numerical approach that captures the nonlinear building response through collapse or using a collapse fragility function. Determining the non-repairable scenario is somewhat more complex. There is limited research on non-repairable threshold limits such as residual displacements, maximum inter-story drifts, or percentage of loss in lateral strength. Several studies have considered collapse scenario assessments, considering drift threshold for example 5% (Yeow et al. 2018b), or 12% (Welsh-Huggins et al. 2020). Recent work from Murray et al. (2022) suggests that story drift higher than 2% would result in a building that might require major repair for structural safety. In lieu of robust guidance on non-repairable threshold limits, a reasonable value should be used based on characteristics of the structural system and relevant literature. This scenario can be added in the analysis when running the damage analysis in PACT where the outcomes are either repairable or non-repairable scenarios. For repairable scenarios, the repair activities are quantified and defined by a log normal distribution, while in non-repairable scenarios, the total rebuild cost is assumed.

3.5 Inventory for environmental indicators

Seismic repair activities result in environmental impacts and use of resources due to the repair process, material replacement and waste management associated with the demolition of the damaged elements. The impacts associated with these activities is quantified considering available local data, or its conversion from available databases. In the traditional LCA of buildings and construction materials, the LCA may use the CEN standard (CEN 2021a), where the quality of environmental data for the construction sector is classified as (1) site-specific, (2) average, or (3) generic data. The quality of the environmental data depends on the objectives of a particular study as well as the quality of the available data sets. Several tools are available to obtain environmental data. Selection of such tools should focus on the study location and geographical coverage. For example, Homestar (NZGBC 2022) recommends some tools over others, considering whether they have tailored their data to be New Zealand specific (NZSGBC 2021). Even though some tools are easier to implement, it is important to account for local characteristics in the data, e.g. the electricity grid differs significantly between countries or regions which can result in different results when considering the production of materials. It is inevitable there will be gaps in the available environmental data (e.g. there is very limited data on the environmental indicators of seismic repair activities). Section 4.5 explains how data gaps were filled in the case study here.

A system boundary defines the processes to be included in the system model, for example a cradle-to-gate system boundary may only include consideration of modules A1 to A5, whilst a cradle-to-grave system boundary would include modules from A to C (and, optionally, D). Figure 4 shows the proposed system boundary for seismic repair activities. The boundary includes the production of materials and transport to products to construction site. The environmental data for the repair activities can be classified by (1) complete replacement of the original, (2) partial replacement of the original, or (3) repair of the original. In cases where replacement of the original is required such as partition damage beyond superficial damage, data for the initial construction material is used. In cases where partial replacement of the original is required, such as an elevator where it might be possible to damage specific components, component material volumes and material data can be used to conservatively estimate the environmental indicators. In this case a sensitivity analysis with alternative data sources should be conducted to evaluate the influence of the results at the building level. Finally in the case where only repair to the original is required, such as a steel beam with buckled elements that needs to be straightened and painted,
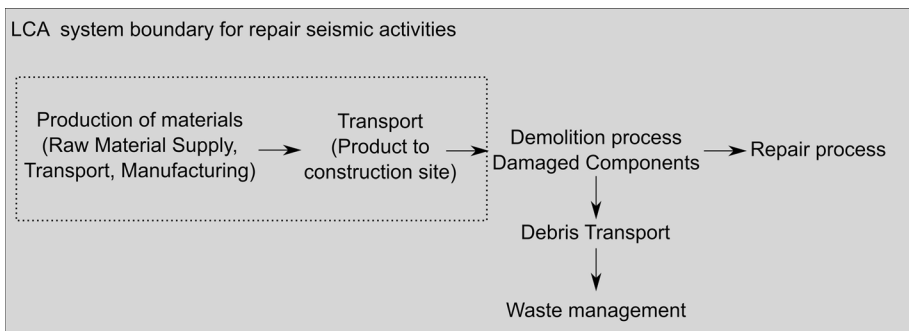

Fig. 4 System boundary for repair seismic activities (Component level)

material quantities used for the repair should be used along with material data to estimate the impacts. The environmental indicators determined for these three repair cases are combined with the dispersion to account for uncertainties in the material data to complete the following phases of the framework. In the non-repairable scenario, the framework assumes a like-for-like replacement of the building. The system boundary for the non-repairable scenario is shown in Fig. 5. The environmental indicators include reconstructing the initial building with the same characteristics, including the impact of the production of materials and their transport to the construction site. The impacts due to initial construction are considered not only for the non-repairable scenarios but also to compare between different building designs and/or weight the seismic repair environmental consequences against initial construction impacts. Waste Managements and Demolition process have not been included in either the repairable or non-repairable scenario, covering the demolition, transport of demolition materials or waste management. Calculating the potential environmental impacts of waste management is complex and requires the spatial distribution of materials, the pathway by which the materials reach their end of life state, and the recycling rates. Previous work has shown that the environmental impacts from this module account for approximately 5% of the total life cycle emissions (Gonzalez et al. 2022), and for this reason have been excluded here, but could be included in future analyses. In cases where comparisons are being made between different structural materials, the inclusion of the recycling process should be included to capture full life cycle impacts, for example the end of life impacts for a steel building considering recycling and waste management could be significantly different than for an equivalent concrete building.

3.5.1 Selection of environmental indicators

The version of EN 15,048:2012 + A2:2013 includes seven core indicators that describe environmental impacts (CEN 2013). The selection of a single environmental indicator when comparing products risks missing other potentially significant environmental impacts. For example, sustainably grown forestry used to supply material for construction timbers and engineered woods can be considered to sequester atmospheric carbon dioxide, which is retained in the products for at least the time they are used in a building. However, wood-based materials may have other impacts, such as eutrophication of waterways or acidification of soil and water
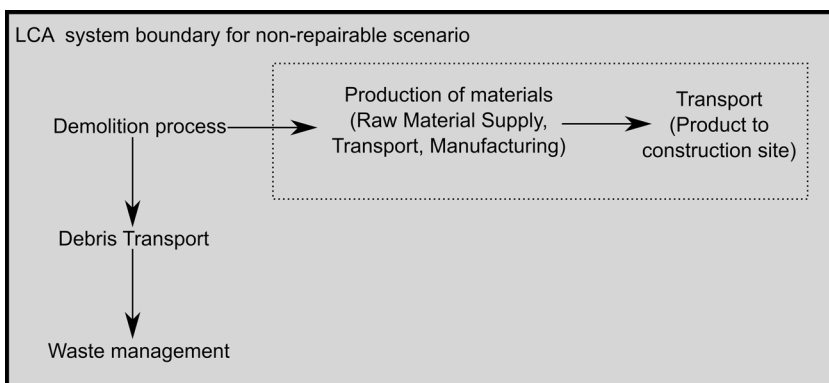

Fig. 5 System boundary for non-repairable scenario

(EPD White Cypress Timber 2022). Several approaches have been proposed to consolidate multiple environmental indicators into a single environmental metric, however, this is voluntary. For example, accreditation for reduction of environmental metrics for Green Star rating in New Zealand (New Zealand Green Building Council 2017) proposes a points based system where points are assigned proportionally to the total percentage of reduction across the environmental indicators. Laurent et al. (2012) mentions the importance of using more than one indicator when evaluating environmental impacts to limit unintentional burden-shifting, where decisions could reduce impacts according to one indicator, but cause larger negative impacts across other indicators. In the case study here (Sect. 4) the seven core environmental indicators and three resource use metrics were evaluated, and different behaviors were observed across the indicators, demonstrating the importance of including various environmental indicators when assessing potential environmental impact.

3.6 Loss analysis

Loss analysis is a representation of a consequence of damage. Here, loss is measured in terms of potential environmental consequences as evaluated using various indicators. Consequence functions are usually represented as log-normal or normal distributions. When developing consequence functions, it is important that local practice is considered. E.g. Fox et al. (2021) developed consequence functions for earthquake damaged steel frame buildings that excluded repair methods not applicable in the New Zealand context such as heat straightening—the same local context must be applied when developing environmental consequence functions. The dispersion used when developing consequence functions should be selected according to the quality of the data. For repair consequence functions, (FEMA P-58-1 2018b) suggests using Eq. (1) to calculate dispersion where $\beta_{r_{ei}}$ is the dispersion for the repair activity, and β_{rc} is the repair cost dispersion. The 0.25 factor is included to account for additional uncertainty associated with environmental impacts. (FEMA P-58-1 2018b) also provides dispersion values according to the quality rating of the data (summarized in Table 2 where lower dispersion values indicate higher-quality data). Fewer realizations are needed to reach convergence when lower dispersion values are needed, and the final results can provide a better certainty about the underlying database used. These consequence functions are used to run Monte Carlo simulations to obtain possible outcomes and posterior fit them in a log normal function. The uncertainty associated to consequence functions include acknowledged variability, labor transportation, material transportation, site energy use and economies of scale and enabling work (FEMA P-58-4 2018).

$$\beta_{r_{ei}} = \sqrt{\beta_{rc}^2 + 0.25^2} \qquad (1)$$

Table 2 Example of dispersion values according to quality rating (FEMA P-58-1 2018b)

	β
Superior quality	0.10
Average quality	0.25
Limited quality	0.40

3.7 Annualized loss analysis and interpretation

The frequency of hazards can help quantify the potential environmental impact/resource use indicators in terms of the annual probability of loss or loss across the life span of a building. These reference values can help stakeholders compare different designs and the probability of losses or return period of investment. The losses can be represented using mean values; however, it is important to consider the dispersion of these values. For example, the upfront cost is guaranteed, however, the seismic risk is a probabilistic value that includes uncertainties in the seismic hazard model, structural modelling, damage analysis, and other local conditions such as post-earthquake cordons or insurance factors that could lead to post-earthquake building decisions.

Realizations from the PACT results can be divided into repairable or non-repairable scenarios. Figure 6 shows the possible simulation outcomes. Figure 6a shows that traditional LCA considers that a building can last its life span assuming a 50-year design life. Figure 6b–d schematically demonstrate the probabilistic environmental impact for ground
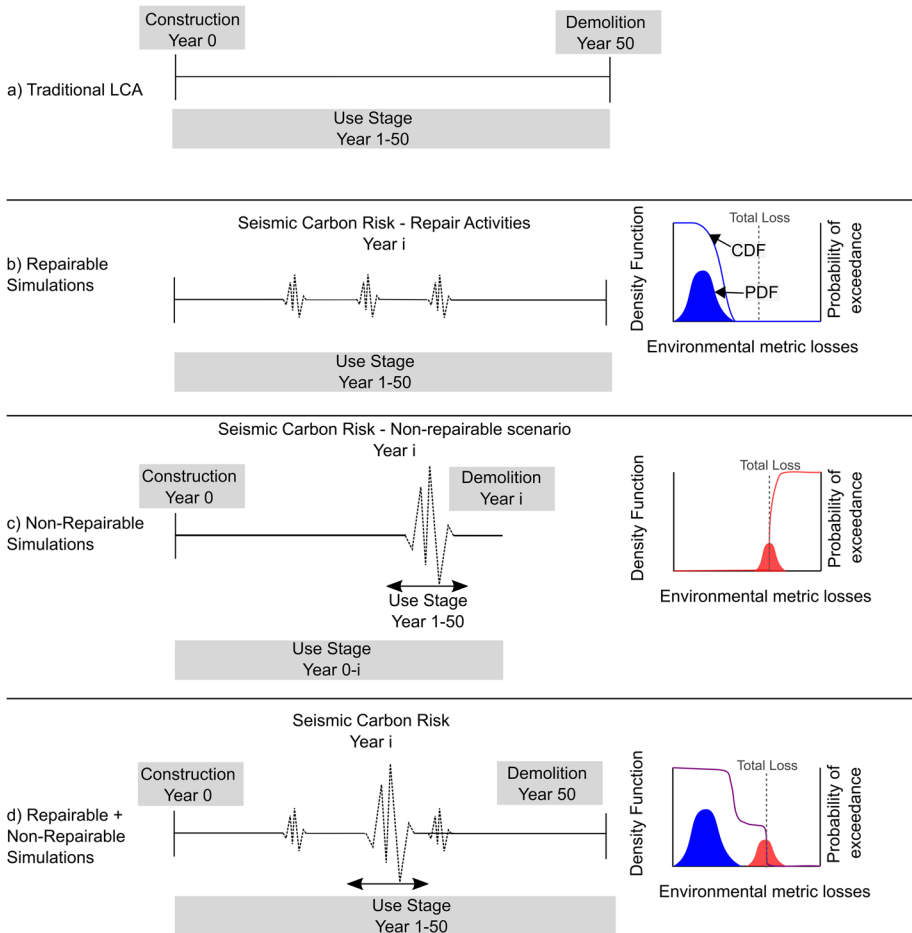

Fig. 6 Scenarios considering seismic hazard

motions scaled to consistent intensity levels where the filled curves represent the lognormal probability density functions, and the lines represent the cumulative distribution functions. Figure 6b demonstrates the seismic losses for a set hazard level for realizations resulting in a repairable scenario, while Fig. 6c demonstrates the seismic losses for a set hazard level for realizations resulting in a non-repairable scenario. When looking at the cumulative distribution function (CDF) in Fig. 6b, it is clear there is a near 0% probability the environmental indicators will exceed the total loss of the building. Conversely, in Fig. 6c it is clear there is a 100% probability the impacts will exceed the total loss of the building. This total loss scenario is a step function, but it is represented as a probability density function (PDF) with a small standard deviation for numerical convenience. Figure 6d represents a case where only some of the simulations result in a non-repairable scenario, which is effectively a combination of the probabilistic loss demonstrated in Fig. 6b, c. The CDF in Fig. 6d is the sum of the CDF from repairable and non-repairable scenarios. The area under the cumulative distribution functions can be calculated to obtain a single environmental value per ground motion intensity considering either mean, median or numerical integration from these functions. Consequently, this value per intensity can be weighted with their probability of exceedance to estimate annual effect and the effect over a building life span.

3.8 Decision making

The environmental indicators from this analysis as measured based on seismic loss across a range of environmental indicators can be used to quantify the environmental implications of different building design decisions. Figure 7 demonstrates a work flow where two or more designs can be compared and their seismic performance quantified based on potential environmental impacts. Within this work flow, hotspots and beneficial changes in materials or systems (e.g. seismic protection for non-structural components) can be identified to optimize a balance between lower environmental impact and resilient design.

This process and the outcomes will be useful for aligning with national carbon thresholds. Currently in New Zealand embodied carbon caps for new builds are still in the planning phase, with mandatory reporting targeted to be in place by 2025, and phased lowering of caps in 2026–2029. The New Zealand Ministry of Business, Innovation & Employment (MBIE) is responsible for delivering New Zealand's response for the built environment to ensure the country meets its commitments under the Paris Agreement. To this end, MBIE has established a long-term Building for Climate Change work programme (MBIE 2021b), aimed at reducing emissions from construction and operation of buildings, and to make sure buildings are prepared for the future effects of climate change. As part of this programme, MBIE has stated its future aims to (i) require a carbon footprint to be calculated to obtain a building consent and, (ii) require that a calculated building carbon footprint is below a provided cap, which will be lowered in phases over a period of years.

The results of a building LCA empowers the decision making process and facilitates best practice of sustainable design principles at early stages of design (Najjar et al. 2017; Vandenbroucke et al. 2015). Currently, without any accepted national threshold limits, stakeholders involved in design (including the building client) must decide if a building design is justified, especially when some environmental metrics may be reduced while others are increased. In the case of evaluating seismic damage impacts, it is important to consider that the initial construction of a building is in the near future and more certain, however, the impacts from seismic repair activities are an estimation over a building service life, which can occur over a long timeframe and with less certainty, requiring additional

Fig. 7 Methodology for selection
of building design
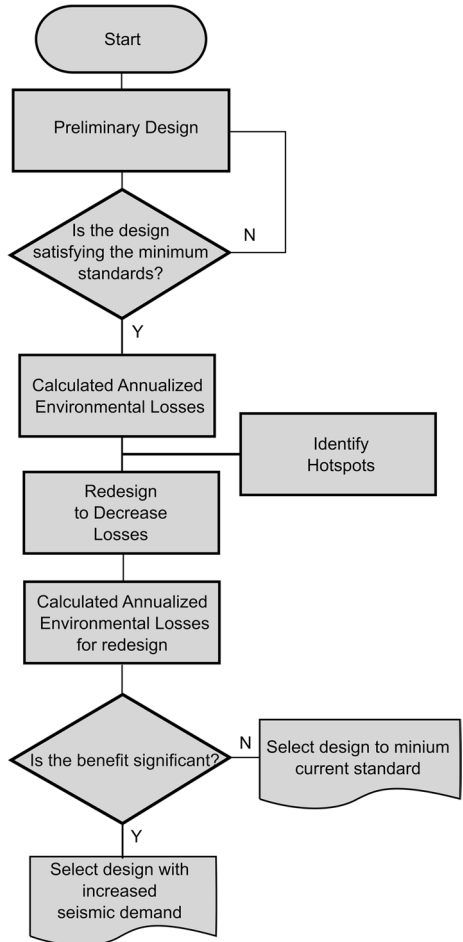
assumptions and analysis beyond a traditional LCA (e.g. building modelling, seismic hazard, expected seismic repair activities). Ultimately, designing and occupying buildings that are more seismically resilient compared to the status quo, provides a potential strategy that needs investigation to help New Zealand achieve its zero carbon goal by 2050.

4 Case-study example

This section uses a hypothetical case-study building to demonstrate the proposed the methodology, compare different insights according to the environmental indicators and compare the lifecycle environmental performance of buildings designed for varying performance objectives. The selected 4-story building was designed by researchers with industry input regarding typical design and geometry of commercial buildings in New Zealand (Yeow et al. 2018b). The building was designed to the code minimum 'life safety' structural standard ("Code Minimum"). The floor plan is 24 by 40 m with bays every 8 m, totaling in a floor area of 960 square meters. The lateral system consists

of perimeter steel moment frames. The Code Minimum building was designed for the seismic hazards in Christchurch, New Zealand, for a service life of 50 years. Additional detail regarding the design of the case study building as well as drawings of the non-structural fitout can be found in Yeow et al. (2018a).

The Code Minimum building was redesigned using increased lateral demands to develop a case-study building designed for higher seismic performance ("Stronger Stiffer"). This was accomplished by simply doubling the earthquake design loads used in the original case study and resizing the members to create a stronger and stiffer building. The Code Minimum building was designed for an earthquake load factor of 14% of the seismic weight, and the Stronger Stiffer building was designed for a factor of 27%. The Stronger Stiffer building has a fundamental period of 1.14 s, compared to 1.47 for the Code Minimum building. The columns and beams for the seismic frame in the Code Minimum and Stronger Stiffer buildings are shown in Table 3.

4.1 Goal and scope definition

The goal of this case-study is to identify the environmental indicators of earthquake damage considering seismic repair activities and upfront cost across the life cycle of two buildings: one designed to the code minimum performance level in New Zealand and one designed for a higher seismic performance. This will demonstrate the trade-offs between up-front environmental costs and environmental costs that result from potential earthquake damage across a 50 year service life of buildings in moderate and high seismic regions. The environmental parameters were analyzed using the EN-15804:2012 + A1:2013 (CEN 2013) assessment method, including the environmental impact indicators: GWP, ODP, EP, AP, POCP, ADP-elements, and ADP-fossil fuels recommended by EN-15084 standards (CEN 2013). Furthermore, three additional resource use metrics are included, these being: TPE divided into TPE_{nr} and TPE_R. The authors recognize that EN-15804 has been updated in 2019 with a change to some environmental indicators and expansion to include others (CEN 2021b). However, at present, most Environmental Product Declarations and databases include data which is based on the 2013 version of this standard. The use stage is excluded from this case study as this would be identical in both versions of the building. The boundaries in this study include the initial construction, seismic repair activities and non-repairable scenarios (e.g. total loss) including structural and non-structural components in the building.

Table 3 Seismic frame sections for code minimum and stronger stiffer building

	Code minimum	Stronger stiffer
Columns - Floor 1-4	900WB218	900WB282
Beams - Floor 1	610UB125	700WB150
Beams - Floor 2	610UB113	700WB150
Beams - Floor 3	530UB92.4	610UB125
Beams - Floor 4	410UB53.7	460UB82.1

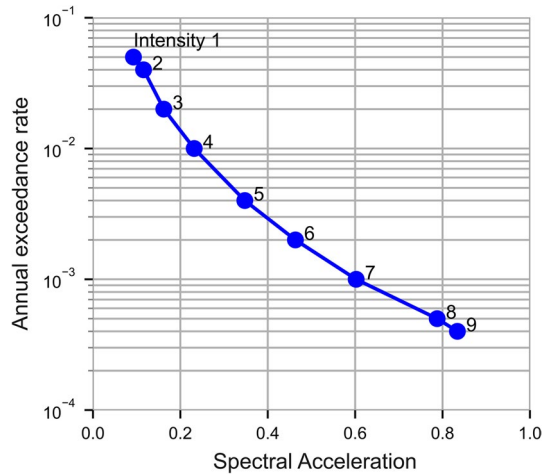**Fig. 8** Seismic hazard curve (according to NZ 1170.5:2004 for $T = 1.47$ s)

Table 4 Probability for occurrence in fifty years and annually for each intensity

Intensity	Probability of occurrence in 50 years (%)	Annual probability of occurrence
1	250	1/20
2	200	1/25
3	100	1/50
4	50	1/100
5	20	1/250
6	10	1/500
7	5	1/1000
8	3	1/2000
9	2	1/2500

4.2 Hazards analysis

The ground motions were selected from Yeow et al. (2018a). These records were selected for Christchurch (43.53°S, 172.64°E) at a shear wave velocity of 450 m/s to 30 m depth from a probabilistic seismic hazard analysis conducted using OpenSHA (Field et al. 2013). The hazard analysis used specific New Zealand rupture forecast models (Stirling et al. 2012) and attenuation relationships (Bradley 2013). Additional information about selected records can be found in Yeow et al. (2018b). These seismic records were conditioned to the design hazards in NZS 1170.5 (2004) at the fundamental period of the structures (1.47 and 1.14 s). The conditional mean spectrum (CMS) provides the mean response from a selection of ground motions that are conditioned on a target spectral acceleration at the period of interest (Baker 2011). Figure 8 shows the hazard curve for a period of 1.47 s; 9 intensities were selected with a return period ranging from 20 to 2500 years. Table 4 shows the probability of occurrence for each intensity annually and over a 50-year time frame. Figure 9 shows the 40 seismic records conditioned to the fundamental period of the Code Minimum building and 2.5th and 97.5th
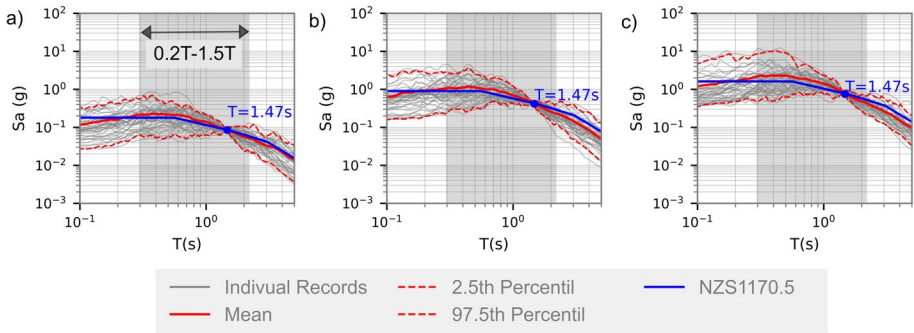
Fig. 9 Seismic hazard curve conditioned to $T = 1.47$ s return period **a** 20, **b** 500 and **c** 2500 years for code minimum building

percentiles for intensity 6 and 9 (return periods 500 years and 2500 years respectively). The shadow areas show the period range of interest from 0.2 to 1.5 T recommended by ASCE/SEI 41-17 (2017).

4.3 Structural modelling

The buildings were modeled using a 2D approach in OpenSeesPy (Zhu et al. 2018). An overview of the model geometry is shown in Fig. 10. The lateral frame was modelled including the non-linear behavior of the columns, beams, and panel zone hinges. The non-linear hinges were modeled using zero length elements with "Bilin" material for column and beam elements and "MultiLinear" material for the panel zone within the parameters obtained from ASCE/SEI 41-17 (2017). The "Bilin" material uses the modified Ibarra-Medina-Krawinkler deterioration model with a bilinear hysteretic response, while the "MultiLinear" material allows for user defined post-yield stiffness degradation. The contribution of out-of-plane seismic columns and gravity columns were included. P-delta effects were included for vertical elements to consider geometric non-linearity. The flexibility of the base was modelled based on the recommendation of the New Zealand Steel Structures Standard NZS3404 (NZS 3404 1997).
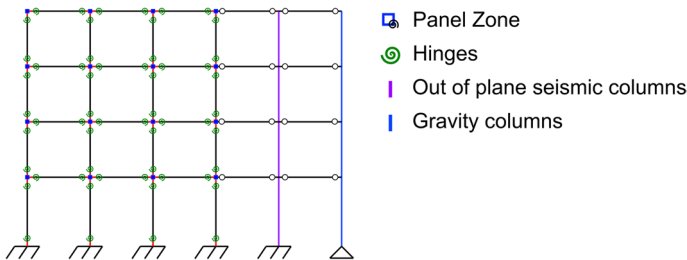

Fig. 10 Numerical modelling drawing

4.3.1 Structural response

The EDPs selected for this study were the inter-story drift and total floor acceleration. Figure 11 shows the peak response across all ground motions, the mean of the peak response, and the 16th and 84th percentiles for the Code Minimum building at return periods of 20, 500 and 2500 years. The mean values are used to estimate damage states.

4.4 Damage analysis

The quantities of the structural and nonstructural elements considered in the damage analysis are available in Yeow et al. (2018a) and have been summarised in Appendix (Table 5). Fragility functions were used to estimate damage based on the realizations from the Monte Carlo Simulation. Each realization contains for each component a specific damage state. Each realization final result is the sum of the consequences of all components. Damage to both structural and nonstructural elements was considered. Pact fragilities were generally used, except where New Zealand specific fragilities were available. Appendix (Table 6) shows the fragility functions for each component. The inventory and consequence functions underlying environmental data are explained in more detail in Sect. 4.5.

4.4.1 Non-repairable scenario

The non-repairable scenario was calculated using a peak drift threshold of 2.5% which corresponds to the maximum allowable drift limit in the New Zealand seismic design standard (NZS 1170.5 2004). This threshold was selected based on discussions with practicing engineers as there are no robust recommendations for non-repairable drift thresholds for steel moment frame buildings. The analysis uses the percentage of number of realizations that exceed this threshold value (Fig. 12a) to develop a non-repairable fragility function. Figure 12b shows the normal logarithm function with a median value of 0.51 and a dispersion of 0.256. The components to calculate the upfront potential environmental impacts (which correspond to the replacement cost and total loss in a non-repairable scenario) are detailed in Appendix (Table 8). The software used to calculated the environmental upfront cost was
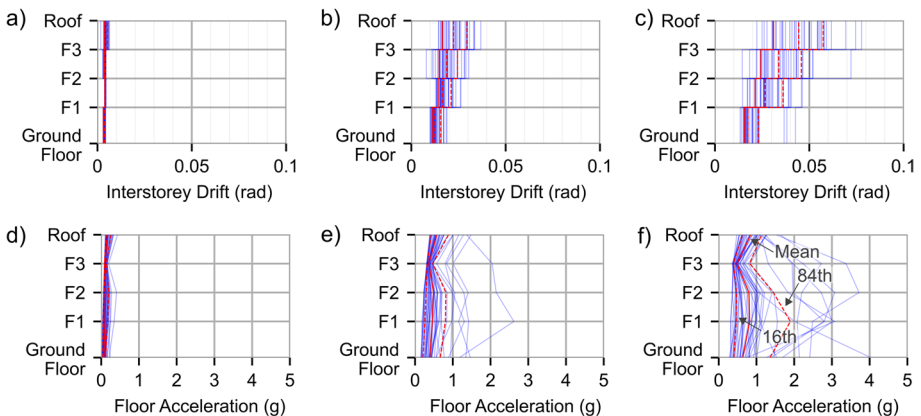

Fig. 11 Floor Acceleration (g) return period **a** 20 years, **b** 50 years, **c** 2500 years and Interstorey Drift (rad) return period **d** 20 years, **e** 50 years, and **f** 2500 years
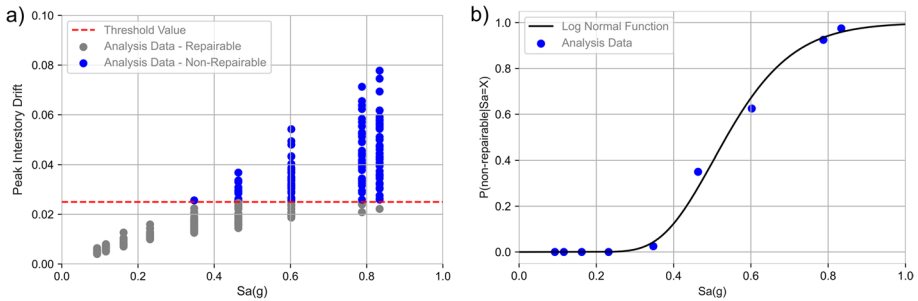
Fig. 12 Non-repairable scenario for Code Minimum building **a** analyses that exceed the threshold values and **b** log normal function for analysis data

LCAquick V3.5 (BRANZ 2022) and the quantity of materials were obtained from a BIM model into Revit software (Autodesk 2022).

4.4.2 Damage analysis

The seismic damage assessment was conducted using the Performance Assessment Calculation Tool (PACT) based on (FEMA P-58-1 2018b) formulation applying the mean EDPs obtained from the structural analysis. 5000 realizations were used to ensure the damage assessment would not depend on the number of realizations. Each realization provided a specific damage state per component, where a damage state corresponds to a unique repair action which has associated cost and material quantity.

4.5 Environmental indicators

The damage states of each component were used to quantify the losses based on the aforementioned indicators to evaluate probabilistic environmental consequences. Appendix (Table 7)details the consequences functions for each component. A Monte Carlo simulation was used to assess the ten environmental indicators by using consequence functions for the resulted damage states across the different building components using Python 3.8. The consequence functions were determined for each component based on the median values and dispersion. There were some limitations regarding a lack of environmental data for some components in the building. In these instances, conservative values were assumed for the component based on the primary material of the component and its weight. If the building-level environmental indicators were not significantly influenced in cases of missing data, then the analysis was considered complete. The building level influence of each component depends on how many components are in the building, their location, and their vulnerability. The take-off materials for each damage state for each component are in Appendix (Table 9). The environmental data for the materials were taken from LCAQuick V3.5 (BRANZ 2022). Dowdell et al. (2020) details the supporting data for this New Zealand Database. The building service data were obtained from Bullen and Dowdell (2022).

Here it is worth mentioning a limitation of the proposed methodology, which concerns the timing of normal replacement of components with service lives less than the building service life (50 years), and the need to replace those components when damaged due to a seismic event. Taking carpets as an example, they may be replaced every

20-years. If there was a scenario where significant earthquake damage occurred in year 19 which required replacement of the carpet, the methodology would consider this as a seismic loss despite the fact that the carpet has neared the end of its service life. This has not been incorporated into the probabilistic approach proposed here, but is being considered for future iterations of the methodology.

4.5.1 Contribution of components

The contribution of individual building components to the overall environmental impact as estimated using the ten indicators is shown in Fig. 13 for the Code Minimum building, where darker colors indicate a higher contribution. The contribution of each component depends on the environmental impact/resource use indicator value, the sensitivity to acceleration or drift, and the quantities and location across the building. One interesting note—at different intensity levels, different components become key contributors to each indicator. E.g. at lower intensities the primary contributor is elevators (which are commonly damaged in very small events), while at higher intensities there is a more significant contribution from curtain walls, glazing and stairs across most indicators. Further, the contributions do vary over the different environmental/resource use indicators. Elevators have the highest contribution to ADP_{ff} across all hazard levels, despite having almost no contribution in any other indicators in cases of larger seismic intensity.

4.6 Loss analysis (results)

A log normal distribution was fitted from the results from all the realizations. The log normal distribution provides the environmental repair consequence at each intensity considering the contribution of all components in the building. In addition, the simulations can result in a non-repairable scenario as discussed above. Here, it was assumed that the building would be replaced like-for-like in the non-repairable scenario, so the environmental indicators were equal to the upfront environmental costs. Figure 14 shows the functions resulting from repair activities (blue), and non-repairable scenarios (red line) for GWP for the Code Minimum building as an example. The sum of both distributions results is the black line, which incorporates both repair and non-repairable scenarios. This combined cumulative distribution function was used to calculate a mean loss value for each intensity using numerical integration. The numerical integration was conducted using the Eq. (2) which was taken from FEMA P-58-2 (2018), where $\overline{PM}$ is the mean value, obtained from the total sum of dividing the function into strip of values $P(i)$, that is multiplied by the central value within each strip PM_i. This mean value is used to evaluate the probable environmental performance of a building over the life span considering the probable frequency of each seismic intensity.

$$\overline{PM} = \sum_{i=1}^{k} P(i)PM_i \tag{2}$$
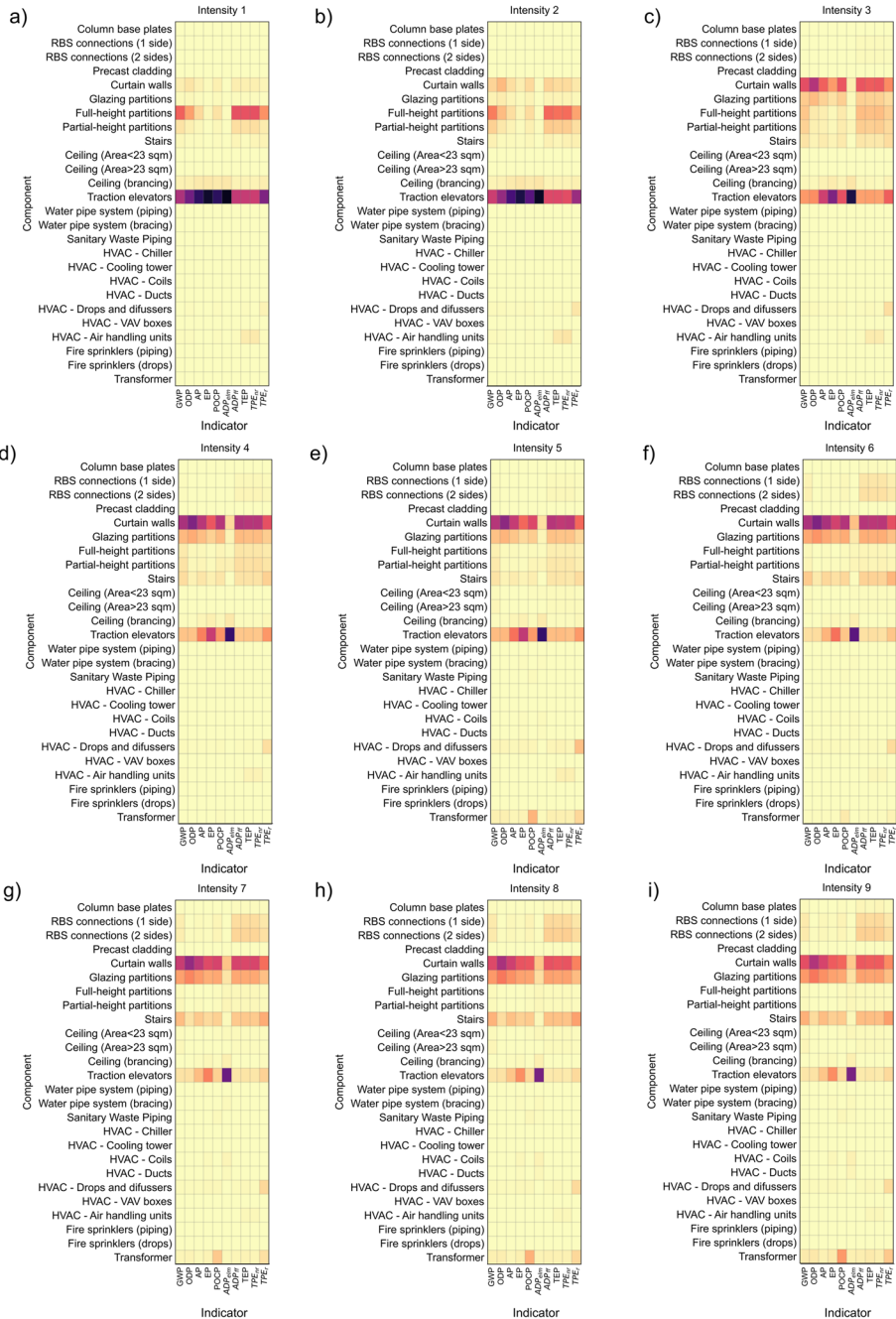
4.6.1 Expected loss over building life span

The expected loss over the building lifespan was evaluated for the ten environmental/
resource use indicators for both the Code Minimum and Stroger Stiffer building. Figure 15a
and 16a show the expected mean annual exceedance of loss for each indicator for the Code
Minimum and Stronger Stiffer building, respectively, as a percentage of the initial building
cost. These plots were developed simply by combining the hazard curve and the mean loss
value for each intensity calculated following the procedure discussed in the last section.
The data was fitted to a log-normal distribution defined by a mean value and a disper-
sion. It is worth noting that many of the environmental/resource use indicators have similar
expected mean annual exceedance values for both buildings, however, ADP-elements is
clearly higher in both cases. The mean values for each log–normal function were multi-
plied by 50 to calculate the seismic loss across the lifespan of the building. In addition, a
lower bound of 5% and upper bound of 95% were calculated from the log–normal function
for each indicator. Figures 15b and 16b show the lifecycle losses standardized by the initial
cost for each environmental metric for the Code Minimum and Stronger Stiffer building
respectively. The initial cost is the quantification of potential environmental impacts due
to initial construction of the Code Minimum building. Detailed information about the cal-
culation of initial impacts is explained in Sect. 4.4.1. Note that the values in Fig. 16b have
been normalized to the upfront costs of the Code Minimum building to allow for a direct
comparison. The dispersion values are around 0.7 for the Code Minimum building. The
Stronger Stiffer Building dispersion values are between 0.7 and 1.7.

The seismic loss for the baseline building ranges from 6 to 9% of the upfront costs for
different environmental/resource use indicators, while the seismic loss for the redesigned
building ranges from 2 to 3%. Note that the larger up-front cost in the redesigned build is
due to larger material quantities in the structural components. The data points in Fig. 15a
and 16a were used to calculate the expected annual cost for each indicator, and these val-
ues were multiplied by 50 to calculate the seismic loss across the lifespan of the building.
Figure 17 shows the reduction for the ten environmental/resource use metrics between the
original and the redesigned building. The Stronger Stiffer building has a reduction ranging
from 3 to 8% across the assessed indicators. GWP has a reduction of 4.7%. The higher ben-
efits are for ODP, AP and EP. The lowest reduction is for POCP.

One interesting note is that the magnitude of potential environmental impact differs
from typical economic losses as a function of upfront building costs. Economic losses from
seismic damage in a repairable scenario could exceed 40% of the initial cost (Bradley et al.
2009); however, the environmental repair cost varied from 2 to 11% for the Case Study
buildings.

4.6.2 Contribution of components to life cycle environmental indicators from seismicity

Figure 18 shows the contribution of components to the potential environmental impact/
resource use indicator over the building life span when considering non-repairable and
repairable scenarios for both buildings. Note that the values of Fig. 18 are the results

a) Intensity 1 · b) Intensity 2 · c) Intensity 3 · d) Intensity 4 · e) Intensity 5 · f) Intensity 6 · g) Intensity 7 · h) Intensity 8 · i) Intensity 9

GWP Global Warming Potential
OPD Depletion Potential of the Stratospheric Ozone Layer
AP Acidification for Soil and Water
EP Eutrophication Potential
POPC Formation potential of tropospheric ozone

ADP_{elm} Abiotic Depletion Potential for Non-fossil Resources
ADP_{ff} Abiotic Depletion Potential for Fossil Resources
TPE Total use of renewable and non-renewable energy resources
TPE_{nr} total use of non-renewable primary energy resources
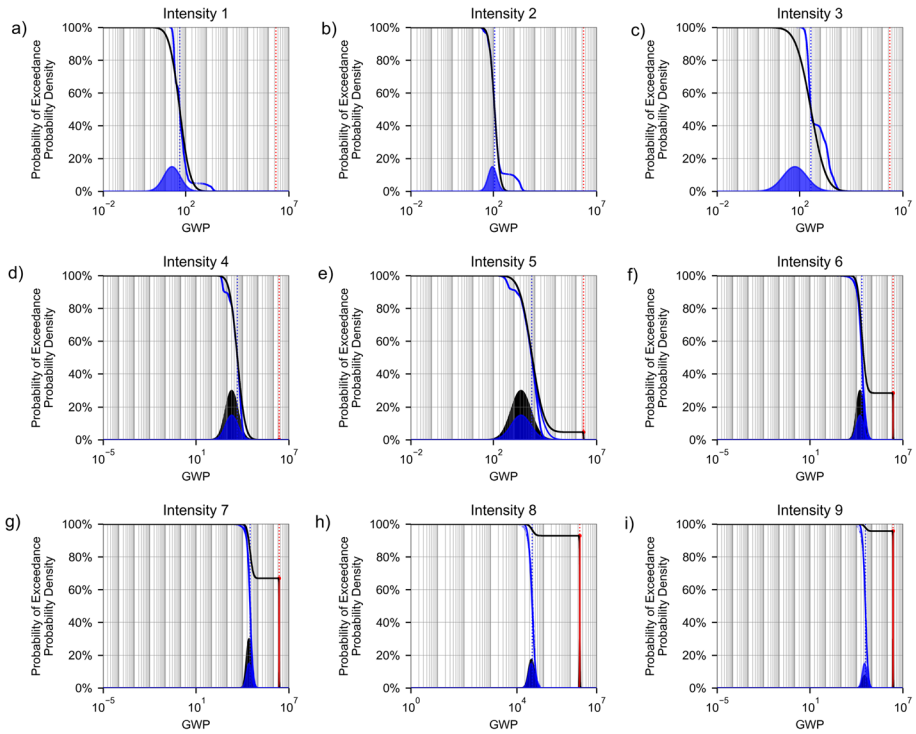TPE_R Total use of renewable primary energy resources

Fig. 14 Loss analysis for GWP for return period of **a** 20, **b** 25, **c** 50, **d** 100, **e** 250, **f** 500, **g** 1000, **h** 2000 and **i** 2500 years for the Code Minimum Building. Blue points analysis data, blue line (log normal curve fit for repair data), red line (total cost), black line (combination of repairable and non-repairable scenarios)
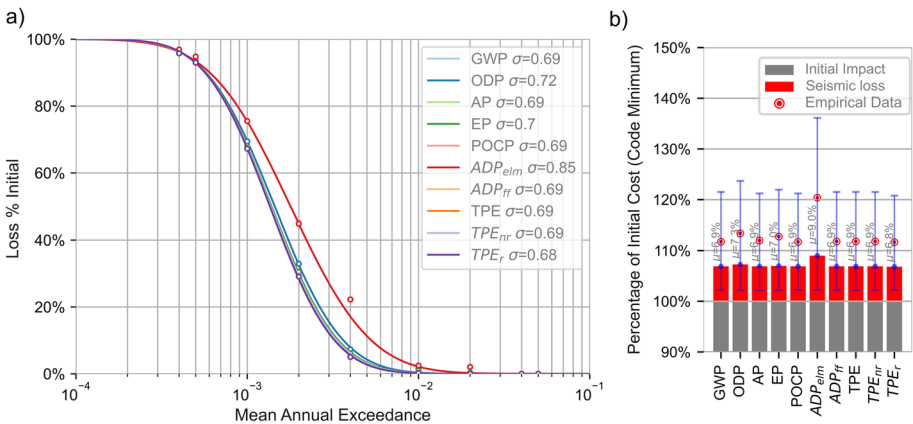

Fig. 15 a Mean annual exceedance in terms of percentage of loss in terms of initial impacts and **b** Total loss over the life span of the Code Minimum building

from the data points in Fig. 15a and 16a. These data points were used to calculate the expected annual cost for each indicator, and these values were multiplied by 50 (life span building) resulting in the empirical data points in Fig. 16a, b representing
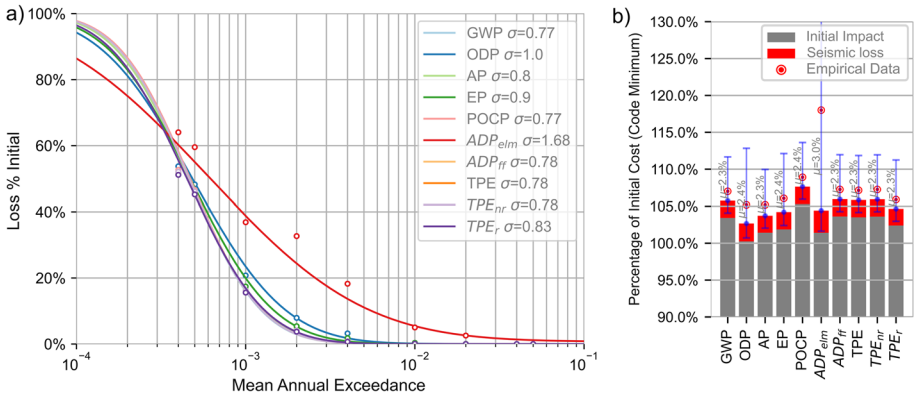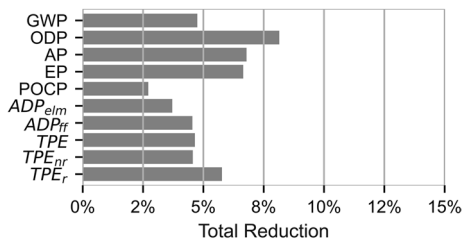
Fig. 16 **a** Mean Annual Exceedance in terms of percentage of loss in terms of initial impacts and **b** Total loss over the life span of the Stronger Stiffer building. NB **b** is normalized to Code Minimum building initial impact

Fig. 17 Reduction of potential environmental impacts/resource use indicators of Stronger Stiffer building design

the seismic loss across the lifespan of the building. The influence of specific components for the final value is difficult to predict at the beginning of collection of data due to dispersion values, different locations of components, local seismic hazard, and so on. The identification of principal contributors helps to identify hotspots. The highest contribution is from the non-repairable scenarios for nine of the ten assessed indicators. The highest contributions from repair activities for the majority of indicators are from curtains walls, glazing partitions, and sanitary waste piping. The GWP is reduced from 11.3% for the Code Minimum building to 3.4% to the Stronger Stiffer building. The highest contribution from repair activities for GWP are from curtain walls, glazing partitions, and traction elevators. For the ADP_{elem}, the elevators are the main contributor to the total seismic cost. In this example, environmental damage data for the elevator has a high uncertainty as the values are provided by estimation for material and weights of components to be replaced. Rodriguez et al. (2020) mentions the lack of environmental data for this type of components. It is worth to notice than there are some components that their repair activities consequences are similar between both design. Per example, the traction elevator is an acceleration-sensitive component, and located on the ground floor. A thoughtful design could be to reduce the vulnerability of traction elevators than increase the resistance of the whole building.
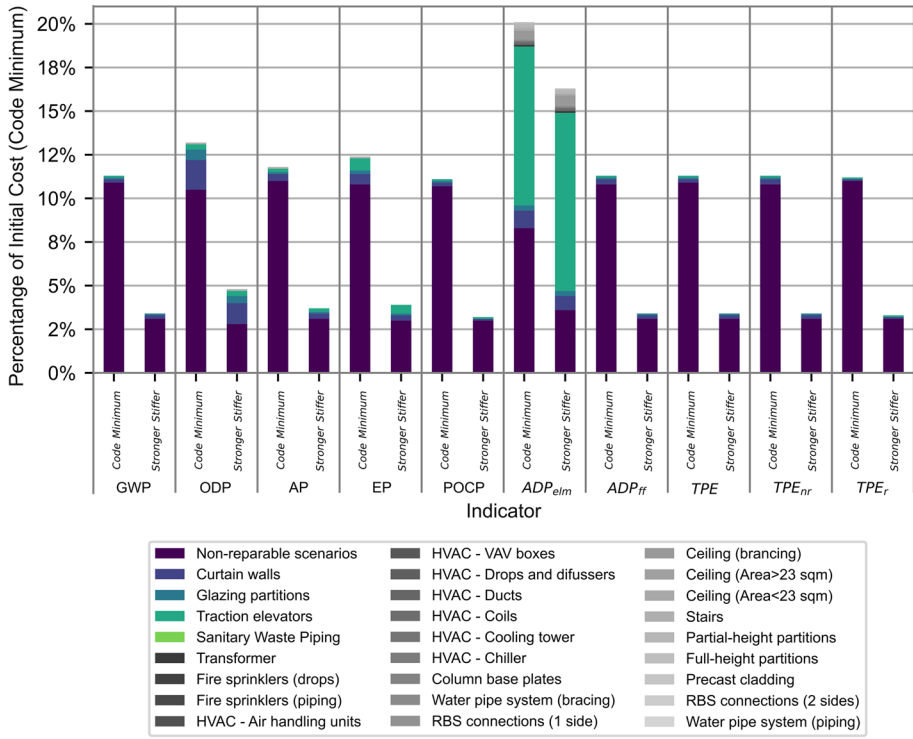
Fig. 18 Contribution of components from repair activities to potential environmental impact/resource use indicators for Code Minimum building and Stronger Stiffer building using empirical data points
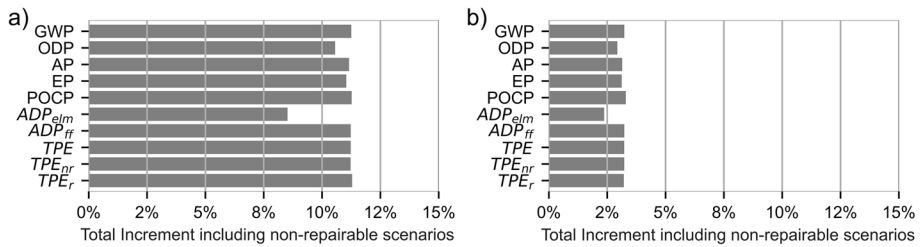
Fig. 19 Increment to seismic losses due to non-repairable scenario **a** code minimum and **b** stronger stiffer building

4.6.3 Influence of non-repairable scenarios

Including non-repairable scenarios can lead to significantly different results for building type and environmental/resource use indicator. Figure 19 shows the contribution of the environmental seismic lifecycle cost across the indicators for the Code Minimum and Stronger Stiffer buildings normalized according to the upfront costs of the Code Minimum building. For the Code Minimum building the non-repairable scenario contributes

Fig. 20 Comparison of buildings excluding non-repairable scenario **a** Code Minimum Building, **b** Stronger Stiffer Building and **c** Reduction of potential environmental impact in Stronger Stiffer building

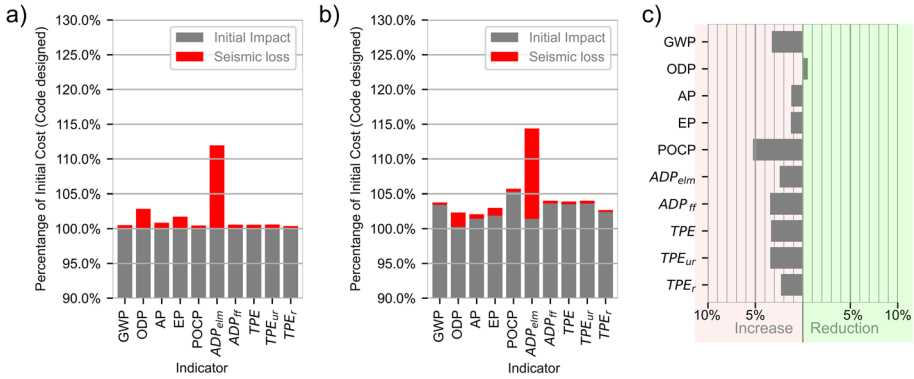to between 8 and 11% the total seismic cost. For the Stronger Stiffer building, the non-repairable scenario contributes around 3% of the initial impact.

In the case where the non-repairable scenario is not included the lifecycle seismic environmental implications when comparing the two designs differ significantly from the cases where the non-repairable scenario is included. Figure 20a, b, shows the potential environmental impacts/resource use indicators when non-repairable scenarios are neglected for the Code Minimum and Stronger Stiffer building, respectively. Figure 20c shows the reduction across environmental metrics between the Code Minimum and Stronger Stiffer building. From this figure, it is clear that when the non-repairable scenario is neglected, the Stronger Stiffer building performs worse than the Code Minimum building across nearly all indicators. This is because the initial environmental impact is higher for the Stronger Stiffer Building, and any benefit across the building life does not exceed this additional upfront impact. The benefit of increasing the stiffness of this building is not captured if the non-repairable scenarios are not taken into account.

Fig. 21 Push-over curve for code minimum building. Red points represent yielding hinges
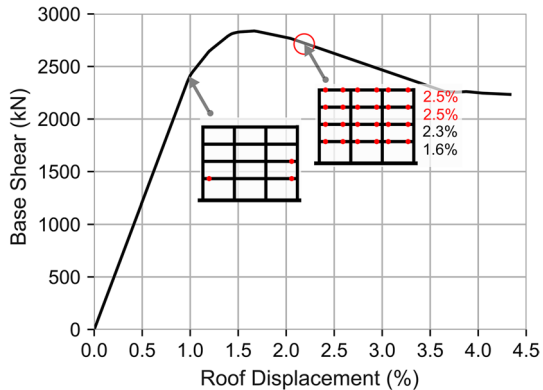
4.7 Comment on non-repairable thresholds

For the case study building the results showed that the non-reparable scenario is the main contributor to the annualized potential environmental impacts. For the case study building, the results showed that the non-reparable scenario is the main contributor to the annualized potential environmental impacts. To evaluate the appropriateness of the 2.5% story drift threshold that was used in this study, a nonlinear pushover was conducted on the code-minimum building. The results of the pushover (shown in Fig. 21) demonstrate that at the 2.5% threshold, the building has developed significant plastic hinging and is in the post capping region of the global pushover curve. This indicates that for this structure, 2.5% is not unreasonable as a non-repairable threshold. However, there still exists significant uncertainty on what the non-repairable threshold value should be more broadly, and additional work is planned to quantify the influence of the selected value. Based on evidence from Christchurch demolition data, this parameter is not necessarily tied to structural performance, but is influenced by other factors including insurance cover, building functionality and fitout, neighboring building performance and surrounding infrastructure.

5 Conclusion

This study presented a detailed framework to quantify the environmental impacts/ resources across indicators of seismic building damage. The framework was demonstrated using a case study building designed for two seismic performance objectives, Code Minimum and Stronger Stiffer. Based on the results of the case study, the following conclusion are reached:

- The relative potential environmental impacts from seismic damage vary depending on the indicators used to assess loss.
- Neglecting non-repairable scenarios can significantly influence the loss estimates especially when comparing the performance of two buildings with respect to environmental impact. In this case, the building designed for a higher seismic performance (Stronger Stiffer) performed worse than the Code Minimum building when the non-repairable scenarios were neglected.
- It is clear the magnitude of potential environmental impact differs from the economic losses as a function of upfront building costs. Economic seismic losses due to repair activities could exceed 40% of the initial cost; however, the environmental repair cost varied from 2 to 11% for the Case Study buildings.
- The GWP was reduced from 11.3 to 3.4% from the Code Minimum building to the Stronger Stiffer Building. This results are exclusive to this building. Additional research is needed for different structural lateral systems to explore environmental indicators performances.

Appendix

See Appendix Tables 5, 6, 7, 8 and 9.

Table 5 The inventory of components used for the seismic loss

Component type	Quantity[a]	Unit[a]	Sensitive	Quantity per direction		Floor
				X	Y	
Column base plates	1	Unit	Drift	8	8	1
RBS connections (1 side)	1	Unit	Drift	4	4	1–4
RBS connections (2 sides)	1	Unit	Drift	4	4	1–4
Precast cladding	3.8	m length	Drift	–	12	1–4
Curtain walls	2.8	m^2 area	Drift	104	0	1–4
Glazing partitions	2.8	m^2 area	Drift	16	5	1–4
Full-height partitions	1.2	m length	Drift	14	35	1–4
Partial-height partitions	1.2	m length	Drift	18	34	1–4
Stairs	1	Unit	Drift	1	1	1–4
Ceiling (area < 23 m^2)	1	Unit	Acceleration	6		1–4
Ceiling (area > 23 m^2)	1	Unit	Acceleration	3		1–4
Ceiling (bracing)	1	Unit	Acceleration	34		1–4
Traction elevators	1	Unit	Acceleration	3		Ground
Water pipe system (piping)	305	m length	Acceleration	2		1–4
Water pipe system (bracing)	305	Piping m length	Acceleration	2		1–4
Sanitary pipe system (bracing)	305	Piping m length	Acceleration	1		1–4
HVAC—chiller capacity 100–350	1	Unit	Acceleration	1		Ground
HVAC—cooling tower capacity 100–350	1	Unit	Acceleration	1		Roof
HVAC—coils	10	Unit	Acceleration	5		1–4
HVAC—ducts < 6 ft2	305	m length	Acceleration	1		1–4
HVAC—drops and diffusers	10	Unit	Acceleration	10		1–4
HVAC—VAV boxes	10	Unit	Acceleration	2		1–4
HVAC—air handling units 10,000–25,000 cfm	1	Unit	Acceleration	2		Roof
Fire sprinklers—pipes	305	m length	Acceleration	2		1–4
Fire sprinklers—drops	10	Unit	Acceleration	10		1–4
Transformers 100–350 kVA	1	Unit	Acceleration	1		Ground

[a]This quantity and unit refers to unit of measurement of a component used for the fragility and consequence functions

Table 6 The fragility functions used for the seismic loss

Component type	Sensitive	Fragility functions			
		DS1	DS2	DS3	DS4
Column base plates	Drift	B1031.011a[a]			
RBS connections (1 side)	Drift	B1035.001[a]			
RBS connections (2 sides)	Drift	B1035.011[a]			
Precast cladding	Drift	0.42 (0.4)[b]	0.75 (0.4)[b]		
Curtain walls	Drift	B2022.001[a]			
Glazing partitions	Drift	B2023.001[a]			
Full-height partitions	Drift	C1011.001a[a]			
Partial-height partitions	Drift	C1011.001b[a]			
Stairs	Drift	C2011.011b[a]			
Ceiling (A < 23 m^2)	Acceleration	C3032.001a[a]			
Ceiling (A > 23 m^2)	Acceleration	C3032.001b[a]			
Ceiling (bracing)	Acceleration	0.72 (0.4)[c]			
Traction elevators	Acceleration	D1014.011[a]			
Water pipe system (piping)	Acceleration	D2021.013a[a]			
Water pipe system (bracing)	Acceleration	D2021.013b[a]			
Sanitary pipe system	Acceleration	D2031.013b[a]			
HVAC—chiller capacity 100–350	Acceleration	D3031.013e[a]			
HVAC—cooling tower capacity 100–350	Acceleration	D3031.023e[a]			
HVAC—coils	Acceleration	D3041.001c[a]			
HVAC—ducts < 6 ft2	Acceleration	D3041.011c[a]			
HVAC—drops and diffusers	Acceleration	D3041.032c[a]			
HVAC—VAV boxes	Acceleration	D3041.041b[a]			
HVAC—air handling units 10,000–25,000 cfm	Acceleration	D3052.013e[a]			
Fire sprinklers—pipes	Acceleration	D4011.023a[a]			
Fire sprinklers—drops	Acceleration	D4011.033a[a]			
Transformers 100–350 kVA	Acceleration	D5011.013e[a]			

NB There are cases where there are two values. The first value is the mean value, and the number on the brackets is the dispersion value

[a]Pact library code

[b]Baird (2014)

[c]Dhakal et al. (2016)

Table 7 The consequences functions used for the seismic loss

Component Type	Damage State	GWP	ODP	AP	EP	POCP	ADP$_{elm}$	AD$_{fi}$	TPE	TPE$_{nr}$	TPE$_r$
Column Base Plates	1	1.41E+02	1.22E−06	3.75E−01	4.43E−02	4.31E−02	3.50E−04	3.35E+03	3.62E+03	3.48E+03	1.42E+02
Column Base Plates	2	1.26E+03	3.98E−06	3.39E+00	3.02E−01	4.69E−01	1.18E−03	1.50E+04	1.57E+04	1.53E+04	4.43E+02
Column Base Plates	3	1.26E+03	3.98E−06	3.39E+00	3.02E−01	4.69E−01	1.18E−03	1.50E+04	1.57E+04	1.53E+04	4.43E+02
RBS connections (1 side)	1	7.55E+01	3.50E−07	1.93E−01	2.08E−02	2.36E−02	1.06E−04	2.32E+03	2.52E+03	2.42E+03	9.83E+01
RBS connections (1 side)	2	1.33E+02	5.28E−07	3.53E−01	3.38E−02	4.69E−02	1.57E−04	2.25E+03	2.40E+03	2.32E+03	8.16E+01
RBS connections (1 side)	3	1.33E+02	5.28E−07	3.53E−01	3.38E−02	4.69E−02	1.57E−04	2.25E+03	2.40E+03	2.32E+03	8.16E+01
RBS connections (2 sides)	1	9.05E+01	4.78E−07	2.33E−01	2.54E−02	2.82E−02	1.42E−04	2.68E+03	2.91E+03	2.80E+03	1.14E+02
RBS connections (2 sides)	2	1.18E+02	1.29E−06	3.23E−01	3.02E−02	3.19E−02	1.94E−04	3.05E+03	3.33E+03	3.20E+03	1.32E+02
RBS connections (2 sides)	3	1.18E+02	1.29E−06	3.23E−01	3.02E−02	3.19E−02	1.94E−04	3.05E+03	3.33E+03	3.20E+03	1.32E+02
Precast cladding	1	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Precast cladding	2	7.74E+03	4.69E−04	6.98E+01	7.49E+00	4.11E+00	2.53E−02	8.09E+04	8.75E+04	8.27E+04	4.87E+03
Curtain Walls	1	1.04E+03	8.32E−05	1.04E+01	1.15E+00	6.05E−01	4.55E−03	1.13E+04	1.21E+04	1.16E+04	4.97E+02
Curtain Walls	2	1.04E+03	8.32E−05	1.04E+01	1.15E+00	6.05E−01	4.55E−03	1.13E+04	1.21E+04	1.16E+04	4.97E+02
Glazing partitions	1	4.17E+02	3.33E−05	4.17E+00	4.62E−01	2.42E−01	1.82E−03	4.54E+03	4.86E+03	4.66E+03	1.99E+02
Glazing partitions	2	4.17E+02	3.33E−05	4.17E+00	4.62E−01	2.42E−01	1.82E−03	4.54E+03	4.86E+03	4.66E+03	1.99E+02
Glazing partitions	3	4.17E+02	3.33E−05	4.17E+00	4.62E−01	2.42E−01	1.82E−03	4.54E+03	4.86E+03	4.66E+03	1.99E+02
Full-height partitions	1	1.64E+00	6.84E−08	6.00E−03	0.00E+00	0.00E+00	9.52E−09	2.22E+01	2.67E+01	2.55E+01	1.18E+00
Full-height partitions	2	1.13E+01	2.11E−07	3.33E−02	3.57E−03	2.81E−03	3.90E−05	1.51E+02	1.61E+02	1.55E+02	7.14E+00
Full-height partitions	3	3.06E+01	1.64E+00	9.60E−02	9.85E−03	1.33E−02	9.74E−04	3.69E+02	3.88E+02	3.77E+02	1.77E+01
Partial-height partitions	1	1.64E+00	6.84E−08	6.00E−03	0.00E+00	0.00E+00	9.52E−09	2.22E+01	2.67E+01	2.55E+01	1.18E+00
Partial-height partitions	2	1.13E+01	2.11E−07	3.33E−02	3.57E−03	2.81E−03	3.90E−05	1.51E+02	1.61E+02	1.55E+02	7.14E+00
Partial-height partitions	3	3.06E+01	1.64E+00	1.73E+00	1.65E+00	1.65E+00	1.64E+00	3.49E+02	3.63E+02	3.53E+02	1.82E+01
Stairs	1	1.59E−01	1.68E−15	1.62E−04	3.39E−05	2.74E−05	2.50E−08	3.22E+00	3.16E−01	3.33E+00	3.16E−01
Stairs	2	1.59E−01	1.68E−15	1.62E−04	3.39E−05	2.74E−05	2.50E−08	3.22E+00	3.16E−01	3.33E+00	3.16E−01
Stairs	3	1.52E+03	3.91E−05	1.13E+01	1.11E+00	6.79E−01	1.75E−03	1.45E+04	1.61E+04	1.46E+04	1.41E+03
Ceiling (A <23 sqm)	1	3.24E+00	4.85E−08	9.16E−03	1.21E−03	9.51E−04	1.33E−05	4.35E+01	4.55E+01	4.37E+01	1.82E+00
Ceiling (A <23 sqm)	2	5.37E+01	2.91E−07	1.63E−01	1.84E−02	2.43E−02	1.29E−03	6.46E+02	6.74E+02	6.51E+02	2.32E+01

Table 7 (continued)

Component Type	Damage State	GWP	ODP	AP	EP	POCP	ADP$_{elm}$	AD$_{ff}$	TPE	TPE$_{nr}$	TPE$_{r}$
Ceiling (A<23 sqm)	3	1.94E+02	9.71E-07	5.99E-01	6.58E-02	8.54E-02	4.62E-03	2.34E+03	2.52E+03	2.39E+03	1.33E+02
Ceiling (A>23sqm)	1	8.00E+00	1.20E-07	2.26E-02	2.98E-03	2.35E-03	3.28E-05	1.07E+02	1.12E+02	1.08E+02	4.50E+00
Ceiling (A>23sqm)	2	8.22E+01	7.17E-07	1.36E-01	1.79E-02	1.41E-02	1.97E-04	6.44E+02	6.74E+02	6.47E+02	2.70E+01
Ceiling (A>23sqm)	3	4.48E+02	2.39E-06	5.08E-01	6.40E-02	5.13E-02	9.86E-04	2.33E+03	2.52E+03	2.38E+03	1.46E+02
Ceiling (Bracing)	1	1.13E+01	6.68E-07	2.73E-01	7.19E-02	1.29E-02	2.15E-03	1.24E+02	1.43E+02	1.29E+02	1.41E+01
Traction elevators	1	1.79E+02	3.00E-05	2.06E+00	4.76E-01	1.10E-01	5.31E-02	9.42E+02	1.09E+03	9.84E+02	1.03E+02
Traction elevators	2	5.30E+02	3.13E-05	1.28E+01	3.37E+00	6.04E-01	1.01E-01	5.85E+03	6.74E+03	6.08E+03	6.62E+02
Traction elevators	3	7.45E+02	4.40E-05	1.80E+01	4.74E+00	8.49E-01	1.41E-01	8.21E+03	9.46E+03	8.53E+03	9.27E+02
Traction elevators	4	1.16E+02	2.52E+01	2.80E+00	7.45E+00	1.32E-01	4.19E+00	1.28E+03	1.47E+03	1.33E+03	1.44E+02
Water pipe system (piping)	1	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Water pipe system (piping)	2	2.6E+00	4.6E-11	2.2E-02	7.7E-04	1.9E-01	0.0E+00	3.1E+00	0.0E+00	0.0E+00	0.0E+00
Water pipe system (bracing)	1	1.13E+01	6.68E-07	2.73E-01	7.19E-02	1.29E-02	2.15E-03	1.24E+02	1.43E+02	1.29E+02	1.41E+01
Sanitary pipe system (bracing)	1	1.58E+01	6.68E-07	3.12E-01	7.33E-02	3.51E-01	2.15E-03	1.30E+02	1.43E+02	1.29E+02	1.41E+01
HVAC- Chiller capacity	1	1.13E+00	2.82E-07	5.49E-03	6.51E-04	3.54E-04	1.80E-04	2.14E+01	2.54E+01	2.04E+01	4.98E+00
HVAC- Chiller capacity	2	4.56E+02	5.19E-06	4.73E+00	1.35E-01	3.37E-01	1.34E-02	5.04E+03	5.61E+03	5.29E+03	3.22E+02
HVAC- Chiller capacity	3	5.31E+03	6.04E-05	5.51E+01	1.57E+00	3.93E+00	1.56E-01	5.87E+04	6.54E+04	6.17E+04	3.76E+03
HVAC – coils	1	1.13E+00	2.82E-07	5.49E-03	6.51E-04	3.54E-04	1.80E-04	2.14E+01	2.54E+01	2.04E+01	4.98E+00
HVAC – coils	2	2.29E+01	1.65E-06	3.91E-01	3.81E-01	2.42E-02	7.91E-03	3.31E+02	4.16E+02	3.81E+02	3.53E+01
HVAC – ducts <0.55m^2	1	1.13E+01	6.68E-07	2.73E-01	7.19E-02	1.29E-02	2.15E-03	1.24E+02	1.43E+02	1.29E+02	1.41E+01
HVAC – ducts < 0.55m^2	2	5.87E+01	3.25E-06	1.00E+00	2.55E-01	5.20E-02	6.53E-03	7.66E+02	8.78E+02	8.04E+02	7.44E+01
HVAC – drops and diffusers	1	8.58E+01	5.34E-06	7.59E-01	1.27E-01	6.32E-02	1.69E-04	8.14E+02	1.29E+03	8.34E+02	4.56E+02
HVAC – VAV boxes	1	1.13E+00	2.82E-07	5.49E-03	6.51E-04	3.54E-04	1.80E-04	2.14E+01	2.54E+01	2.04E+01	4.98E+00
HVAC – VAV boxes	2	2.29E+01	1.65E-06	3.91E-01	3.81E-01	2.42E-02	7.91E-03	3.31E+02	4.16E+02	3.81E+02	3.53E+01
HVAC – air handling units	1	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
HVAC – air handling units	2	2.91E+02	8.69E-06	1.14E+00	1.12E-01	1.30E-01	1.89E-03	3.30E+03	1.81E+04	1.79E+04	1.82E+02

Table 7 (continued)

Component Type	Damage State	GWP	ODP	AP	EP	POCP	ADP_{elm}	AD_{ff}	TPE	TPE_{nr}	TPE_r
Fire sprinklers—pipes	1	7.28E+00	2.88E−09	1.80E−02	1.56E−03	2.73E−03	4.90E−06	7.38E+01	7.62E+01	7.45E+01	1.74E+00
Fire sprinklers—pipes	2	3.64E+01	1.44E−08	8.99E−02	7.78E−03	1.36E−02	2.45E−05	3.69E+02	3.81E+02	3.73E+02	8.69E+00
Fire sprinklers—drops	1	1.66E+00	6.56E−10	4.10E−03	3.55E−04	6.21E−04	1.12E−06	1.68E+01	1.74E+01	1.70E+01	3.96E−01
Transformers	1	1.04E+04	7.04E−04	5.96E+01	1.36E+01	3.86E+01	1.12E−01	1.04E+05	1.34E+05	1.12E+05	2.18E+04

*Dispersion values were assigned to 0.4 for all,

Table 8 Building inventory

Element	LCAquicK v3.5 Code	Quantity (Code Minimum Building)	Quantity (Stronger Siffer Building)
Steel, universal column (UC), structural section, unpainted, 97×99 mm to 327×311 mm, imported (Liberty Primary Steel, Australia)	PR_20_76_51_12_1_12_4_1	7.92 m³	9.66 m³
Steel, universal beam (UB), structural section, unpainted, 150×75 mm to 612×229 mm, imported (InfraBuild and Liberty Primary Steel, Australia)	PR_20_76_51_12_1_11_3_1	23.49 m³	24.66 m³
Reinforced concrete, 35 MPa, in-situ, inc. 200 kg/m3 steel reinforcing, (OPC)	PR_20_31_16_5_2_4_1	729.38 m³	729.38 m³
Reinforced concrete, 35 MPa, in-situ, inc. 150 kg/m3 steel reinforcing, (OPC)	PR_20_31_16_5_2_3_1	162.18 m³	162.18 m³
Masonry wall, incl. concrete block 20 series (17.5 MPa OPC), grouted 22 MPa (OPC), inc. steel reinforcing	PR_20_93_85_13_1_2	555.99 m³	555.99 m³
Particleboard (floor) [from unsustainable forest management practices, don't ensure or won't ensure from sustainable forestry], with galvanised fixings, imported	PR_25_71_97_60_1_B	1.11 m³	1.11 m³
Window/door, IGU, glazing (float glass), for use with PVC—U joinery	PR_25_71_33_42_5	18.57 m³	18.57 m³
Door, interior, MDF [from unsustainable forest management practices, don't know or won't ensure from sustainable forestry], unpainted, imported	PR_30_59_23_97_1_B	169.88 m²	169.88 m²
Reinforced concrete, 25 MPa, composite floor decking, trapezoidal deck Section 75 mm deep troughs at 300 mm ctrs, 125 mm thick in-situ slab, inc. 100 kg/m3 steel reinforcing, (OPC)	PR_20_85_14_10_1_1_1_1_1	3714.14 m³	3714.14 m³
Reinforced concrete, 30 MPa, precast, inc. 50 kg/m3 steel reinforcing, (OPC)	PR_20_31_16_4_3_1_1	14.56 m³	14.56 m³

Table 9 Take-off of materials for repair activities

Component	Damage State Description	Repair Activity
RBS CONNECTION 1 SIDE (each connection)	DS1: Yielding first at the flange	Replace floor finishes, and gypsum partitions. Section repainted
	DS2: Local Buckling	Replace floor finishes, and gypsum partitions. Remove and replace section from the column face to beyond 300 mm from the reduced beam section
	DS3: Fracture	Replace floor finishes, and gypsum partitions. Remove and replace section from the column face to beyond 300 mm from the reduced beam section
RBS CONNECTION 2 SIDE (each connection)	DS1: Yielding first at the flange	Replace floor finishes, and gypsum partitions. Section repainted
	DS2: Local Buckling	Replace floor finishes, and gypsum partitions. Remove and replace section from the column face to beyond 300 mm from the reduced beam section
	DS3: Fracture	Replace floor finishes, and gypsum partitions. Remove and replace section from the column face to beyond 300 mm from the reduced beam section
Steel Column base (each base)	DS1: Cracking initiation between the column flange and the base plate weld	Replace floor finished, and gypsum partitions. Re-welding the fracture
	DS2: Propagation of brittle crack into the column and base plate	Replace floor finished, and gypsum partitions. Re-place of a portion of the column or base plate
	DS3: Complete fracture of the column and dislocation of it	Replace floor finished, and gypsum partitions. Re-place of a portion of the column or base plate
Partitions Full-Height (Area:2.88m^2)	DS1: Superficial damage to the walls	Re-paint walls
	DS2: Local damage of gypsum wallboards and/or steel frame components	Partial replacement of wall and fasteners. Re-paint walls, and steel frame
	DS3: Severe damage to walls,	Complete replacement of wall and fasteners. Paint walls, and replace steel frame

Table 9 (continued)

Component	Damage State Description	Repair Activity
Partitions Full-Height (Area:2.88m^2)	DS1: Superficial damage to the walls	Re-paint walls
	DS2: Local damage of gypsum wallboards and/or steel frame components	Partial replacement of wall and fasteners. Re-paint walls, and steel frame
	DS3: Severe damage to walls,	Complete replacement of wall and fasteners. Paint walls, and replace steel frame
Partitions Interior Glazing (Area:2.88m^2)	DS1: minor cracks in glass	Replace glass
	DS1: major glass cracks, and sealants are dislodged	Replace glass
	DS1: complete glass cracked, and sealants are dislodged	Replace glass
Exterior Glazing (Area:2.88m^2)	DS1: crack in glass	Replace glass
	DS2: glass falls from frame	Replace glass
Precast Cladding (3.8 m length)	DS1: chipping corners in cladding units	No action
	DS2: units damaged	Replace Units, and re-inste contents adjacent to damaged area (windows and walls)
Precast Stairs (unit)	DS1: concrete spalling	Use of epoxy and concrete finished
	DS2: extensive concrete cracking, concrete crushing and buckling of rebar	Use of epoxy, and concrete
	DS3: Extensive concrete crushing	Replace precast stairs
Ceiling	DS1: 5% of damaged tile	Replace damaged tiles
	DS2: 30% of damaged tile	Replace damaged tiles, and light fixtures
	DS3: 100% of damaged tile	Replace ceiling, and light fixtures

Table 9 (continued)

Component	Damage State Description	Repair Activity
Elevator (unit)	DS1: replaced of failed components	Fail: Controller anchorage, machine anchorage, motor generator anchorage, Governor anchorage and Rope guard
	DS2: replaced of failed components	Fail: Rail, intermediate bracket, Counterweight bracket, car bracket, car guide shoes, Counterweight guide shoes, counterweight frame, and tail sheave dislodged
	DS3: replaced of failed components	Fail: Cab stabilizers bent, cab walls and cab doors
	DS4: damaged cab ceiling	Replace cab ceiling
Water pipe system (300 ml)	DS1: minor leakage	One joint (Only labour)
Sanitary pipe system (300 ml)	DS1: pipework damage	Replace pipe, and new supports
HVAC–Chiller (unit)	DS1: Unit moves, damage in connections	Replace electrical cables
	DS2: Component damage	Replace compressor
	DS3: Unit not suitable for repair	Replace Unit
HVAC—Tower (unit)	DS1: Unit not suitable for repair	Replace CT
HVAC—DUCTS (300 ml)	DS1: Support fails	Replace supports
	DS2: Several support fails and ducting sections falls	Replace supports, ceiling and ducts
HVAC—DIFUSSERS (10 units)	DS1: Diffusers falls	Replace diffuser, and ceiling
HVAC—COILS FANS (Unit)	DS1: Partial damage	Repair power supply
	DS2: Unit falls	Replace unit
HVAC—AIR HANDLING (unit)	DS1: Unattached connections	Only labour
	DS2: Unit is not longer repairable	Replace Unit
Fire Sprinklers—drops (10 units)	DS1: dripping leakage at drop joints	Replace sprinkler head (dropper)
Fire Sprinklers – pipes (300 ml)	DS1: Leakage at joints	Replace sprinkler pipe
	DS2: major leakage	Replace sprinkler pipe
Transformer (1 unit)	DS1: Unit Replaced	Replace Unit

Declarations

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