Building and Environment 241 (2023) 110512

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Integrating energy retrofit with seismic upgrades to future-proof built heritage: Case studies of unreinforced masonry buildings in Aotearoa New Zealand

P. Besen [a,c,*], P. Boarin [b,c]

[a] *Huri te Ao School of Future Environments, Te Wānanga Aronui o Tāmaki Makau Rau - Auckland University of Technology, 2 Governor Fitzroy Place, Auckland, 1010, New Zealand*

[b] *Te Pare School of Architecture and Planning, Faculty of Creative Arts and Industries, Waipapa Taumata Rau University of Auckland, 26 Symonds Street, Auckland, 1010, New Zealand*

[c] *Future Cities Research Hub, Te Pare School of Architecture and Planning, Waipapa Taumata Rau University of Auckland, 26 Symonds Street, Auckland, 1010, New Zealand*

A R T I C L E I N F O

Keywords:
Energy retrofit
Unreinforced masonry buildings
Integrated retrofit
Seismic strengthening
Heritage adaptation
New Zealand heritage

A B S T R A C T

Deep energy retrofit can improve historic buildings' indoor environmental quality and protect them from decay and obsolescence while reducing their energy use and related greenhouse gas emissions. Although this practice has been growing internationally, in Aotearoa New Zealand there are currently no policies or initiatives to encourage energy retrofit in historic buildings and no substantial examples of projects. Most retrofits currently focus on much-needed earthquake strengthening, due to high seismic risks and national policies which mandate all existing earthquake-prone buildings to be either structurally retrofitted or demolished over the next decades. As seismic upgrade projects are widespread, this study explores the potential of applying energy retrofit concurrently with seismic strengthening, with a focus on unreinforced masonry (URM) – the main type of earthquake-prone historic construction in the country. The research investigates three case studies of listed heritage URM buildings using Post-Occupancy Evaluation and simulation. Their current performance was investigated, and retrofit scenarios were analysed through energy and hygrothermal simulation, utilising the EnerPHit standard as a guide. The energy models demonstrated a potential reduction of up to 92% in heating demand when comparing the most comprehensive retrofit scenario with the baseline in the coldest climate. The potential energy savings from each intervention were balanced against their heritage impact, based on the standard EN16883:2017. The study provides a methodology for balancing several considerations in integrated retrofit to make historic buildings more resilient not only to seismic threats, but also to a changing climate, while keeping a respectful approach to heritage.

1. Introduction and background

The relationship between built heritage and sustainability has been highlighted by several initiatives in recent decades, such as the inclusion of cultural heritage protection in Sustainable Development Goal 11, which recognises its critical role in the achievement of the new humanistic and ecological paradigms of sustainable cities [1–3]. Several studies have investigated the environmental benefits of reusing existing and historic buildings instead of building new constructions, demonstrating the significant potential to reduce embodied carbon emissions [4–8]. Moreover, heritage conservation researchers and organisations increasingly acknowledge the need to retrofit historic buildings to reduce their environmental impact and to adapt to climate change, ensuring that heritage sites are safeguarded for future generations [9–14].

In Aotearoa New Zealand, built heritage plays an important role in making history visible in cities and in creating vibrant, diverse, and sustainable urban environments. The country possesses a unique collection of places of cultural heritage value relating to Māori and more recent peoples, a blend of European and Indigenous architectures of

* Corresponding author. Huri te Ao School of Future Environments, Auckland University of Technology, Auckland, 2 Governor Fitzroy Place, Auckland, 1010, New Zealand.

E-mail addresses: priscila.besen@aut.ac.nz (P. Besen), p.boarin@auckland.ac.nz (P. Boarin).

https://doi.org/10.1016/j.buildenv.2023.110512
Received 5 April 2023; Received in revised form 1 June 2023; Accepted 7 June 2023
Available online 8 June 2023

distinctive value that have accrued meanings over time [15,16]. The adaptation of historic buildings to current and future needs is of high importance in New Zealand, as the country has had many examples of lost heritage [17,18] due to earthquakes, fire, lack of maintenance, and decay related to inadequate indoor environmental conditions and neglect. Nowadays, there are additional complexities to the management of built heritage in the country, as new regulations came into force in 2017 for earthquake-prone structures, which set up timeframes for all existing buildings to either be retrofitted to minimum structural standards or face demolition [19,20]. Existing buildings need to be strengthened to the minimum required New Building Standard (%NBS) rating, which is based on an assessment of the expected seismic performance relative to the minimum that would apply under the Building Code to a new building on the same site with respect to life safety [21]. As a result, there are many earthquake strengthening projects taking place, especially in Unreinforced Masonry (URM) buildings – a widespread historic type of construction identified as one of the most vulnerable in the country due to significant seismic risks [22–25]. Although timber construction prevails in historic buildings in New Zealand, URM buildings remain New Zealand's most earthquake-prone class of building [22,26].

However, the other significant challenge for historic buildings is to keep high levels of indoor comfort in a changing climatic context while minimising energy consumption and respecting heritage values [27–33]. In general, historic URM buildings have poor energy performance and inadequate indoor environmental conditions, due to the characteristics of their thermal envelope [34,35]. Lack of insulation, air leaks, draughty windows with single glazing, poor ventilation, and inadequate heating systems are commonly found in these buildings [28, 36–38]. Climate change can add additional pressure to historic buildings since they will need to withstand more extreme weather conditions and still provide liveable indoor conditions without requiring excessive energy input as New Zealand transitions to a low-carbon future [39]. Although energy retrofit is not mandatory in current regulations, this would be a crucial measure to ensure that URM buildings can continue to serve a useful purpose in a low-carbon future and be safeguarded for generations to come. So far, energy considerations have not been extensively included as parameters in retrofit projects either in existing national policies or in practice [40], except for the mandatory upgrade of selected residential rental properties [41]. There are very limited data on their current energy performance – comprehensive studies have investigated energy use in existing commercial buildings [42], but no in-depth studies have focussed specifically on such historic buildings. Major seismic strengthening works that are currently taking place in URM buildings allow access to important elements of the building envelope that can be improved for better thermal performance, so there is now the unique opportunity to include energy retrofitting in these projects [39].

Internationally, research about the potential benefits of integrating energy and seismic retrofit in historic building adaptation has been expanding in recent years. The links between energy and seismic retrofitting are important for the overall sustainability of built heritage: energy efficiency retrofit is useful for structural protection by minimising temperature variations for structural elements [39], while structural strengthening prevents the environmental impacts and required energy associated with damages, repairs, or reconstruction.

In Italy, La Greca and Margani [43] reviewed seismic and energy renovation measures and pointed out that combined seismic and energy retrofit represents a prevention action that is necessary to increase the sustainability level of towns, allowing very relevant benefits at environmental, social, and economic levels. Calvi et al. [44] proposed an integrated assessment of energy efficiency and earthquake resilience, according to which environmental and seismic impact metrics are translated into common financial decision-making variables. Following the 2009 earthquakes in Italy, there were proposals to turn the recovery process into an opportunity to improve the energy performance of historic buildings as part of an integrated energy and seismic retrofit approach [45]. The proposed strategies included passive energy retrofit actions on building envelopes and structural interventions aimed at improving seismic performance, together with the integration or addition of HVAC plant systems powered by renewable energy such as photovoltaics [46]. De Berardinis et al. [33] identified suitable energy solutions for earthquake-damaged masonry buildings that could improve their energy performance by over 50% [35]. More recently, Mistretta et al. [47] suggested solutions that consider economic and ecological costs of several retrofitting solutions taking into account thermal and seismic capacity demand of the construction site in existing masonry buildings.

A few studies have proposed integrated systems for the external insulation and structural upgrade of existing buildings [48–50], however there is a need for internal solutions to keep historic façades intact. Examples of potential internal seismic-energy upgrading solutions include integrated systems utilising cross-laminated timber (CLT) panels and Rock wool insulation [51], glass fiber-reinforced polymers reinforced jacketing [52], and plastering of building using Fabric Reinforced Geopolymer Mortar [53]. In general, researchers have identified that most building retrofit interventions tend to focus on either energy efficiency or seismic resilience techniques, and point out to the need for more integration and understanding across both fields [44,48,54,55]. Therefore, there is a gap in the knowledge concerning the integration of energy and seismic upgrades, not only in New Zealand but also internationally.

Another critical aspect for energy retrofitting historic masonry buildings is hygrothermal risk [56]. Several studies have pointed out that internal insulation of the envelope results in colder façades and the drying potential of walls is reduced, which can lead to mould growth in the interface between the interior insulation and the brick wall [57–59].

In the New Zealand context, there has been a limited number of studies investigating energy and thermal retrofit of listed heritage buildings. The first investigations were conducted by the authors of this article, who analysed the status quo in the energy retrofit of built heritage in New Zealand by first investigating existing policies, current challenges, and future opportunities [39,40,60]. Paschoalin and Isaacs [61] explored the application of international guidelines in historic building retrofit in New Zealand by utilising a case study of a typical historic timber-frame house. Quantitative assessments and qualitative interviews in the study highlighted both the national and stakeholders' demands for appropriate guidelines for renovation projects that deal both with conservation and technical aspects of typical constructions. Their study highlighted that adopting country-specific guidelines would benefit practice. Due to the limited literature on heritage-listed non-residential buildings, some insights can be gained from studies focused on retrofitting existing residential buildings. Lloyd et al. [62,63] showed the limitations in improving the thermal performance of residential buildings by retrofitting only ceilings and floors – the only upgrades available in a government-sponsored residential energy efficiency upgrade programme. They stated that the solution to future proof housing will likely need a combination of more intensive fabric upgrades with wall insulation and improved glazing, as well as incorporating improved space heating. Other studies have investigated the thermal retrofit of New Zealand's 1930s–1950s Labour Party State Houses [64] and the application of Passive House retrofits to state housing built in the 1940s–1960s, demonstrating that it would be possible to achieve over 90% savings in heating demand with comprehensive retrofit packages [65].

In summary, in Aotearoa's context, there is limited literature about energy retrofit of heritage listed buildings, there is a knowledge gap on energy upgrades of URM construction, and there are no existing studies on the integration between energy and seismic retrofit. Internationally, few articles presented comprehensive case studies that demonstrate holistic approaches to balance energy performance, seismic resilience and heritage conservation. Therefore, this study investigates how energy upgrades can be integrated into the seismic retrofit of historic URM buildings in New Zealand in a heritage-sensitive way, by utilising case study buildings selected in different cities and climate zones. The aims of the research are.

1) To utilise selected case studies to investigate current performance and potential energy savings that can be achieved through energy retrofit applied in combination with seismic strengthening;
2) To investigate the relationship between proposed energy retrofit and structural upgrading;
3) To explore the suitability of different materials to be applied when considering hygrothermal risks in historic URM buildings; and
4) To assess the impacts of the proposed interventions on heritage fabric, while discussing the need to balance energy performance improvements with the safeguarding of existing historic features.

The study provides a framework that can be replicated to the retrofit of other URM buildings in Aotearoa New Zealand and abroad, especially in earthquake prone countries which face similar seismic and energy upgrading needs. The study proposes steps to move from a "reactive" retrofit approach [66] to a proactive one, which considers not only urgent issues but also future needs, moving towards positive-energy buildings. The main originality of the study sits in its multidisciplinary approach that considers energy performance, seismic resilience, and heritage conservation aspects in an integrated way to safeguard built heritage for future generations. The research also contributes towards closing the knowledge gap on energy upgrades of historic URM construction in New Zealand.

2. Methodology

The research utilised case studies to explore the potential benefits and challenges of energy retrofitting historic URM buildings in New Zealand, and conducted a Post-Occupancy Evaluation (POE) and simulation process including.

1) Quantitative analyses, i.e., energy consumption data collection, on-site temperature measurements, and energy and hygrothermal simulation of the case study buildings; and
2) Qualitative investigations including literature review, archival research, visual inspection of buildings, building occupant questionnaires, and a retrofit impact assessment.

Due to the limitations in existing knowledge about energy retrofit in New Zealand, the case studies were of exploratory and illustrative character [67]. The use of three case studies allowed the exploration of the possibilities of energy retrofit and the evaluation of potential risks and benefits in different climatic contexts in New Zealand to a level of detail that provided adequate accuracy for the study. The selected number of case studies provided a balance between allowing a comparison between different buildings and climates, and enabling an in-depth investigation of each study. The illustrative character of case studies focused on demonstrating how energy retrofit projects should be proposed and evaluated for URM buildings, taking into account heritage conservation and seismic resilience considerations.

The assessment of case study buildings and proposal of energy retrofit scenarios were guided by the European standard EN 16883:2017 *Guidelines for improving the energy performance of historic buildings* [68]. As this standard does not provide specific methods, targets, or modelling parameters for energy retrofit, the study also utilised the EnerPHit standard developed by the Passive House Institute [69] as a reference for specific technical requirements for the energy retrofit. EnerPHit was selected because it provides a reliable, performance-based methodology to improve energy performance and thermal comfort in existing buildings [70–72].

The study was structured into the following five main phases.

1 Literature review investigating URM building stock in New Zealand, and current issues and opportunities in integrating energy retrofit into seismic upgrade projects. Investigation of current retrofit practices through questionnaires and interviews with professionals working in this field.
2 Selection and analysis of case study buildings, including an assessment of technical and historical aspects, as well as energy performance and indoor environmental quality, guided by EN 16883 [68].
3 Hygrothermal simulation to determine suitable materials to be utilised in the proposed energy retrofit.
4 Development of retrofit scenarios through energy simulation, and assessing the possibility of achieving the EnerPHit standard according to the criteria released in 2016 [69], which are still applicable to the new version released in 2023 [73].
5 Assessment of impact of retrofit scenarios on heritage conservation, based on EN 16883 [68].

Phase 1 has already been presented by the authors in previous publications [39,40,74], therefore this article focuses on stages 2–5. Sections 2.2 to 2.5 present more details about the methodology applied to each stage.

2.1. Scope and limitations

Although it utilised a multidisciplinary approach, the main focus of this study was on energy performance considerations through addressing the thermal envelope of buildings, as this is connected to structural work that is mandated by New Zealand regulations [19]; this was also highlighted as the main gap in existing practice [40]. Other energy retrofit strategies, such as upgrading HVAC plant systems, lighting, and equipment, were not included in this study. All structural drawings were obtained from existing as-built plans or concept design drawings provided by engineers who worked on the projects. The study aims to adapt energy retrofit interventions to seismic upgrade techniques that are common in New Zealand; therefore, it considered the structural elements as they were built or designed without proposing modifications to the systems utilised. Due to the location of case studies in different cities, property management restrictions to avoid disruption to building occupants, and covid-related lockdowns, there were limited in-situ measurements. Other measurements, such as U-value measurements and blower door testing, would have benefitted the study, but were not possible due to the reasons mentioned above. Additional assessments, such as cost considerations through pay-back time calculations and life-cycle analysis, were outside the scope of this research.

2.2. Selection and analysis of case studies

To consider the country's different climatic conditions, one building was selected as a case study in each of New Zealand's three climate zones, according to the classification indicated in NZS 4218 [75]. Although a recent update to the New Zealand Building Code clause H1 has provided new classifications with six different climate zones [76], the analysis was conducted based on the zones available at the time of the study. All buildings selected are of URM and represent a range of different typologies, construction techniques, and architectural styles typical of the historic URM building stock in New Zealand [22]. Isolated or stand-alone typologies were selected as case studies because their thermal envelope is more affected by the surrounding climatic conditions when compared to attached buildings.

University buildings were selected as case studies due to the availability of building management systems, accessibility of a wide range of data through property management departments, and the similarity of building use and occupation patterns amongst these buildings across all regions of New Zealand. Other criteria were the availability of occupants to participate in questionnaires and the public character of these buildings. In addition, universities in New Zealand are ahead of the private sector in terms of seismic strengthening, with many of them having policies to complete upgrades beyond minimum requirements and well before the deadlines defined by government [77]. However, their work on energy upgrading has not been significantly explored, so this study can provide an opportunity to investigate this field.

All case study buildings are or were considered seismically vulnerable by the local Councils – buildings A and B had already been seismically strengthened and building C was in the design process for seismic upgrading at the time of the study. The seismic strengthening strategies are different in all buildings, demonstrating the range of possible structural systems currently being utilised in New Zealand. All buildings are scheduled in the Heritage New Zealand list, with buildings B and C listed as Category 1 (i.e., outstanding historical/cultural value), and building A listed as Category 2 (i.e., historical/cultural value). Alterations to these buildings require approval from local Councils and from the national authority Heritage New Zealand Pouhere Taonga, since New Zealand's Heritage Policy relies on centralised and decentralised frameworks [39,78]. Table 1 summarises the information about the case studies that is relevant to the building simulation and development of retrofit scenarios further discussed in this paper.

The designs of the case study buildings reflect different architectural styles of the time and the original intended use of the buildings. Case study A was originally a house, built with Italianate and 'arts and crafts' features which were common in residential architecture at the time. Buildings B and C were built for university uses and were designed in the Gothic Revival style that was prevailing in higher education architecture in that period in New Zealand – this style was also common in universities in Australia, Canada, and the United States and is often referred to as Collegiate Gothic [79].

The three buildings were selected because they share many common characteristics. The main current use in all case studies is offices for universities, with similar occupation patterns, allowing for a fair comparison of energy consumption in the three cases. Additional uses, such as lecture theatres in building B and laboratories in building C, occupy a minor portion of the buildings' floor areas. Window types are similar in all buildings, consisting of single-glazed sash windows with timber frames, with similar window module sizes. They also have similar window-to-wall-ratios, with an average of 20.9%. All buildings have similar wall thicknesses ranging from 510 to 540 mm, but wall build-up layers differ amongst the three buildings. Case studies A and C have compact building shapes, with simple rectangular building footprints and a surface area to volume ratio of 0.81 and 0.49 respectively. Case study B presents a more elongated and complex building form, with additional façade features, including bay windows; it still achieves a low S/V ratio of 0.65 due to being a multi-storey building. Fig. 1 shows selected views of the buildings, illustrating the different configurations of façades and the similarities in typical indoor spaces and window sizes. In building B, walls had already been retrofitted with an internal layer of sprayed concrete, and the photo on the right shows the increased depth of window reveals resulting from this upgrade.

Energy auditing and indoor environmental assessments were undertaken in each case study building guided by EN 16247–2 Energy *audits Part 2*: *Buildings* [80], since this standard is recommended by EN 16883 [81]. This assessment included the following investigations.

1 Analysis of power bills: collection and analysis of power consumption for two years in each building. Evaluation of total energy consumption per floor area and comparison between case studies, taking into consideration their local climatic conditions.

Table 1
Overview of selected case study buildings.

	Case Study A	Case Study B	Case Study C
Identification			
City	Auckland	Wellington	Dunedin
Climate zone (according to NZS 4218:2009)	 Zone 1	 Zone 2	 Zone 3
Latitude	37°	41°	46°
Heating Degree Hours	20 kKh/a	42 kKh/a	57 kKh/a
Seismic risk area (according to Building Act 2004)	Low Risk	High Risk	Low Risk
Year of construction	1904	1903–1904	1919–1920
Main architectural styles	Italianate, Arts & Crafts	Gothic Revival, Edwardian	Gothic Revival
Heritage NZ listing	Category 2	Category 1	Category 1
Local council heritage listing	Listed, Category B	Listed[1]	Listed[1], entire external building envelope protected
Seismic resistance capacity (before strengthening works)	30% NBS[2] (Earthquake-prone)	Earthquake-prone[3]	10–15% NBS[2] (Earthquake-prone)
Seismic strengthening status	Retrofitted in 2014–2016	Retrofitted in 1990–1993	To be retrofitted (currently at design stage)
Main seismic strengthening systems	Plywood diaphragms with tie rods	Sprayed concrete, steel portal frames	Post-tensioning systems
Treated floor area	273m^2	5078m^2	1,161m^2
Number of storeys	2	4	3
Current use	Office spaces	Office spaces and lecture theatres	Office spaces, lecture theatres, and laboratories
Window-to-wall ratio (WWR)	18.5%	19.1%	25.1%
Surface area to volume ratio (S/V)	0.81	0.65	0.49

Notes: [1] No specific categories for local Council heritage listing. [2]Percentage of New Building Standard. [3]The NBS rating is not shown because there were different regulations at the time this building was strengthened.

Fig. 1. External and internal photos of case study buildings A, B, and C.

2 Thermal imaging: obtained in wintertime, from 13th to August 30, 2019, to maximise temperature difference between interior and exterior conditions. Images were taken with an infrared-fusion camera with a thermal sensitivity of 0.8 °C at 30 °C target temp (80 mK) and temperature measurement range of −20 °C to +150 °C.
3 Visual inspections: undertaken in winter, to understand building use, features, construction, presence or absence of insulation, and to detect visible issues such as mould, air gaps, and deterioration of materials, among other issues.
4 Spot temperature measurements: taken in winter at the same date as thermal imaging, to assess indoor conditions for thermal comfort and differences between various rooms and locations.
5 Indoor Environmental Quality questionnaire for building occupants: based on the thermal environment satisfaction survey from ASHRAE 55 – *Thermal Environmental Conditions for Human Occupancy* [82]. The questionnaire was offered online to all building occupants via the University of Auckland's Qualtrics platform.

2.3. Hygrothermal simulation

To evaluate the hygrothermal performance of the proposed retrofit packages, simulation was performed for the interventions that presented the highest risks of interstitial condensation. Hygrothermal simulation of selected envelope assemblies was developed with WUFI® Pro software [83], that allowed a realistic calculation of the transient coupled one- and two-dimensional heat and moisture transport in walls and other multi-layer building components exposed to natural weather. WUFI® uses the latest findings regarding vapour diffusion and moisture transport in building materials, and the software has been validated by detailed comparison with measurements obtained in the laboratory and on IBP's outdoor testing field [83].

The most critical intervention identified in this study was the addition of internal wall insulation, even though it is assumed that the insulation will be installed following manufacturer's instructions as shown in Fig. 9. Different insulation materials were selected based on a literature review of the most suitable type of material for masonry construction, considering hygrothermal performance and compatibility with historic fabric [28,84–87]. The materials included: calcium silicate boards, perlite boards, infill cellulose, mineral wool, and wood fibre. High performance vapour check and airtightness membranes were included in tests with cellulose, mineral wool, and wood fibre. Wall insulation materials were modelled with a thickness of 80 mm in buildings A and B, and 100 mm in building C, which have proven sufficient to achieve the EnerPHit standard in these buildings, according to a sensitivity analysis.

Simulation was performed for the worst-case orientation scenarios: prevailing driving rain and lowest hours of solar exposure. Models were simulated for a period of 10 years to evaluate the long-term impacts and suitability of retrofit solutions [88]. The results from hygrothermal simulation in WUFI® were used to guide the selection of wall insulation materials to be utilised in the proposed retrofit scenarios developed through energy simulation. Additional 2D hygrothermal simulation of specific details, such as midfloor beams protruding through wall insulation, could provide additional guidance on hygrothermal risks, but were outside the scope of this study.

2.4. Development of retrofit scenarios through energy simulation

Following the energy audit and hygrothermal simulation, energy retrofit scenarios were proposed for each building to investigate the potential savings and benefits from improving the building envelope in conjunction with seismic upgrade works. ASHRAE's Energy Guideline for Historic Buildings [89] points out that an energy model can help project teams better understand a building's energy use and estimate savings from possible energy efficiency measures. For a historic building, an energy model can also take on the role of evaluating the performance of some of its character defining features and to quantify the trade-offs for energy efficiency and/or thermal comfort that come with preserving a given character defining feature [89]. According to EN 16883, special attention should be given to the collection of input data, since standard values usually provided for calculation models often do not take into account the specific conditions in historic buildings. To increase the confidence level of the calculated model, the use of a validated building calculation model is recommended [68]. Therefore, to create a baseline building model, detailed input was gathered from original plans and details, in-situ dimension measurements, and visual inspections.

Cumulative retrofit scenarios were developed, ranging from the least invasive to the most comprehensive upgrades, based on extant literature and best practices [28,90–92]. The method for proposing and assessing possible interventions was guided by EN 16883 and also by international charters for heritage conservation, considering the concepts of minimal intervention, compatibility, and reversibility, among others [15,93]. The final goal of the retrofit scenarios was to evaluate the possibility of achieving EnerPHit certification through the energy demand method in a sensible way that considers heritage conservation principles.

Energy simulation was performed with PHPP version 9.6, the Passive House Planning Package, developed by the Passive House Institute. PHPP is an integrated tool for stationary energy balance calculations, including all energy flows within the system boundary. The programme is based on European and international standards (including EN ISO 13790). Even though PHPP was originally developed for low energy and passive houses, it also provides reliable results for old or historic buildings. Accurate results can be expected for space heating and cooling, primary energy, and domestic hot water and electricity demands [28]. The PHPP is continuously validated and refined based on measurements and new research results. In 2019, PHPP version 9.6 was evaluated using the ANSI/ASHRAE Standard 140, a comparative testing method for building energy programmes [94].

In addition, selected junctions were modelled in the software THERM Version 7.7.10 [95] to obtain thermal bridging psi-values, which were then added to PHPP. THERM was developed by Lawrence Berkeley National Laboratory (LBNL) and allows two-dimensional conduction heat-transfer analysis based on the finite-element method [95]. Window upgrades were calculated in the software WINDOW Version 7.7.10, also developed by LBNL for calculations of total window thermal performance indices [96].

2.4.1. *Geometry simplification*

There are often challenges with the intrinsic limitations in simulation models when attempting to describe the actual geometric features and peculiarities of heritage buildings. A simplified geometry is often necessary to meet the requirements of building energy simulation tools, but inaccuracies due to oversimplification in some geometrical features must be avoided [97]. The selected buildings have many complex decorative façade elements, while the PHPP software relies on simplified geometries to allow for calculations. Therefore, building geometry had to be simplified to simple orthogonal shapes which still provided the same areas and properties as the real geometry. For example, arch windows had to be modelled as rectangular window shapes while keeping the total area of the simplified rectangle equal to the original curved shape. Also, the modelled geometry only includes the building thermal envelope and, where roof insulation was installed at the ceiling level, complex roof geometries did not need to be modelled as they were outside of the thermal envelope.

2.4.2. *Thermal envelope properties*

Existing literature acknowledges that in-situ measurements of U-values are often appropriate for accurate energy simulation of historic buildings, as the thermal properties of historic materials are highly variable [98,99]. Standard values from published sources of construction material properties may not accurately describe historic materials; however, these sources can serve as a useful starting point for models [89]. Since in-situ measurements were not possible in this study due to access and equipment limitations, U-values for existing construction components were calculated according to ISO 6946 [100]. PHPP was used for the calculation, as its spreadsheet for U-value calculation complies with ISO 6946. Tabulated values were used for both existing and proposed building materials.

This approach complies with the criteria for EnerPHit certification, which states that, if the heat transfer resistance of existing building components is taken into account for the improvement of the heat transfer coefficients of modernised building components, this must be demonstrated in accordance with the accepted technical standards. It is sufficient to adopt a conservative approximation of the thermal conductivity of the present building materials from suitable reference charts [69].

Extensive investigations were made to find reference material properties amongst New Zealand historic buildings, but very limited sources were available. Therefore, tabulated material properties from ISO 10456 [101] were adopted for U-value calculations, as these provide widely accepted international reference values. Since ISO 10456 does not include tabulated values for solid clay brick, other sources were consulted for brick thermal properties. These included NZS 4214:2006 [102], which shows conductivity values for brick ranging from 0.20 W/mK to 1.20 W/mK, EN 1745 [103], BRE 443:2006 [104], Fraunhofer's library of material properties contained in WUFI, the PHPP manual (2015), and an extensive study carried out in Italy by Dondi et al. [105], which tested 29 samples of clay brick from Italy and obtained a range of different values. A study commissioned by English Heritage highlighted that variation in brick texture, density, and structure influence dry thermal conductivity [98]. Considering all the different sources and the review of the literature, a thermal conductivity of 0.80 W/mK was adopted for solid clay brick masonry in the models. BRE 443:2006 [104] states that joints in masonry may be disregarded if the difference in thermal resistance between bridging material and the bridged material is less than 0.1 m^2K/W, a condition that applies to almost all brickwork and to most walls built with dense masonry units [106]. According to ISO 10456 [101], lime-sand mortar has a similar conductivity to bricks; thus, further calculations were not required to assess the effect of mortar on the thermal performance of brick masonry. A sensitivity analysis was conducted to test the different values presented in the literature and this demonstrated that the range in thermal conductivity of the evaluated bricks did not make a significant difference for the final results. The methodology for calculating the thermal properties of air layers inside double leaf masonry walls was based on values from BS EN ISO 6946:2017 [100]. The air layers inside double-leaf walls in the case study buildings were considered unventilated layers, according to the criteria in this standard. Construction details were drawn by the authors based on archival research of original drawings, as well as in-situ measurements and observations.

2.4.3. *Building occupancy*

The model assumed standard occupancy values for office/administration buildings, according to the default values provided in PHPP. It considered the building is occupied from 7am to 6pm, following an occupancy pattern based on DIN V 18-599-10:7–2005 [107]. The number of occupants was entered according to information provided by the building managers.

2.4.4. *Airtightness*

Due to access limitations and possible disruptions to building occupants, airtightness was not measured on site through a blower-door test, but was instead estimated according to available local literature. Air change rates were estimated according to previous measurements of New Zealand buildings from the Building Research Association of New Zealand (BRANZ) database of more than 100 residential building airtightness measurements [108], and were then used to develop a classification of house airtightness in four type categories, each characterised by a base level infiltration rate. According to this database, all pre-1960's houses with strip flooring and timber windows were considered in a category named "draughty", with an average of 20 ac/h. Considering the age of the case study buildings and their construction techniques, they all fit into the "draughty" category. A value of 20 ac/h was initially utilised in the PHPP models, but results for the baseline models were not consistent with measured energy consumption from the building. Further analysis identified that there are two main differences between the "draughty" buildings from the database and the case studies: i) the database consists mainly of timber framed wall construction, whereas the case studies have more airtight construction due to masonry walls; and ii) the case studies have more compact building shapes (S/V ratios below 0.81) than the database. Internationally, there are few examples of blower door test results for historic URM buildings, and a similar case study in Europe indicated results around 10 ac/h [28]. After a review of literature and sensitivity analysis was conducted, a value of 8 ac/h was adopted instead of 20 ac/h, which resulted in better correlation between power bills and modelled results. However, we highlight that this is a significant limitation in this study.

2.4.5. Climate data

Climate data for the three cities was available in PHPP. These climate files are based on hourly Typical Meteorological Year (TMY) weather data files produced by New Zealand's National Institute of Water and Atmospheric Research (NIWA) [109].

2.4.6. Model calibration

Best practice energy simulation of existing buildings suggests that baseline models should be calibrated to actual consumption to ensure that the model results are as accurate a reflection of the true performance of the building as possible. In historic buildings, model calibration is essential [89]. Therefore, calibration was undertaken by comparing measured energy consumption over the preceding 12 months provided by building administrators with the results from PHPP. TMY data was compared with weather files from the National Institute of Water and Atmospheric Research (NIWA) for the year of simulation [110]. Since no significant discrepancies were found, the default TMY was utilised in the energy models.

2.5. Assessment of retrofit impact on heritage

To evaluate the suitability of energy retrofit measures, a systematic assessment was made not only of technical and economic aspects, but also of how the interventions could affect the physical building and its heritage significance [68]. The assessment was based on the five-point scale and criteria proposed by EN 16883 [68] to which a new category "integration with seismic strengthening" was introduced to highlight the specific points considered in this study. Certain assessment categories proposed by EN 16883 (economic viability, capital costs, and returns) were excluded because they were outside the scope of this study.

3. Results and discussion

Selected results from the study are presented and discussed in the sections below, including the assessment of current performance, development and simulation of retrofit scenarios, and heritage impact assessment.

3.1. Energy audit and indoor environment assessment

Power consumption data for each building is shown in Fig. 2, presenting the total energy use per square metre of treated floor area for one year (August 2018–July 2019). In general, power consumption follows the climate conditions where the case studies are located, with the building in Dunedin (C) having the highest consumption per square metre and the one in Auckland (A) the lowest.

Fig. 2. Measured energy consumption obtained from power bills.

According to the University of Otago where building C is located, the energy consumption in this building is 40% higher than new buildings with a similar use in the same institution. This is related to inefficient heating systems, lighting, use of portable heaters by occupants (see discussion below), and inefficiency of the building envelope.

Infrared thermal imaging revealed several performance issues in the building envelope. Thermography was more effective in building C, as the climatic conditions and the heating schedule in the building allowed for a better visualisation due to the higher temperature difference between interior and exterior. The main issue was the lack of continuous insulation in ceiling spaces, as shown in Fig. 3 for case study C, which led to conducting a visual inspection of the roof space.

Visual inspection was documented with photographs of critical aspects found in the three buildings. The main findings were related to decay, lack of maintenance, modifications, and occupants' preferences. Following the identification of issues in ceiling insulation through thermography in case study C, an inspection of roof space revealed that insulation was only installed in half of the ceiling space: Fig. 4 (a) shows that the areas on the right-hand side remain uninsulated, causing significant heat losses. Also, air draughts through windows were common in all buildings due to lack of maintenance, as per Fig. 4 (b) showing how the original sash windows do not close properly and leave a visible gap at the bottom in building C.

To maintain building occupants' thermal comfort, many portable electric heaters were used in office spaces, which were brought from home by the occupants (Fig. 5). This practice, found in all case studies, clearly indicates that the fixed heating devices installed in the buildings are not enough to ensure comfortable conditions in winter.

Temperature measurements (Table 2) were taken in a selection of rooms, on the same winter day as thermal imaging was taken, to understand indoor conditions and variations inside the buildings, as well as to inform the calibration of energy models. The same equipment was utilised for measurements in all buildings.

The measurements revealed high variation between rooms as there were different heating systems and room layouts in the buildings. It is worth mentioning that in building C, wall radiators were not able to spread heating through rooms appropriately, resulting in variations of up to 3 °C even within the same room [111].

Following the previous assessments carried out on site, a one-off online questionnaire collected data on the overall occupants' perceptions regarding thermal comfort, acoustic quality, daylighting, indoor air quality, and energy use, among other aspects. Only the results on energy and thermal comfort are reported in this study, as these are the most relevant to the focus on thermal retrofit strategies. The response rates for questionnaires were 10.7% in case study A, 13.1% in case study B, and 32% in case study C. Fig. 6 shows the level of satisfaction with internal temperatures in summer and winter respectively.

Overall, there was dissatisfaction with indoor temperatures both in winter and in summer. In case study C, located in the coldest climate, 60% of respondents revealed dissatisfaction in winter. In summer, dissatisfaction was also high: 53% of participating building occupants were dissatisfied or very dissatisfied with indoor temperatures. In Case study A, located in the warmest of the three climate zones, the level of dissatisfaction was higher in winter than in summer. Auckland is usually known as a "mild climate", but the lack of insulation, the use of single glazing, and the orientation of the building contributed to cold indoor temperatures. Although case study B showed higher percentages of satisfaction and neutrality regarding indoor temperatures, the open-ended questions revealed many issues in the building, due to its construction techniques. Table 3 shows selected comments from open-ended questions related to indoor comfort in the three case studies.

The comments revealed that window ventilation is not enough to

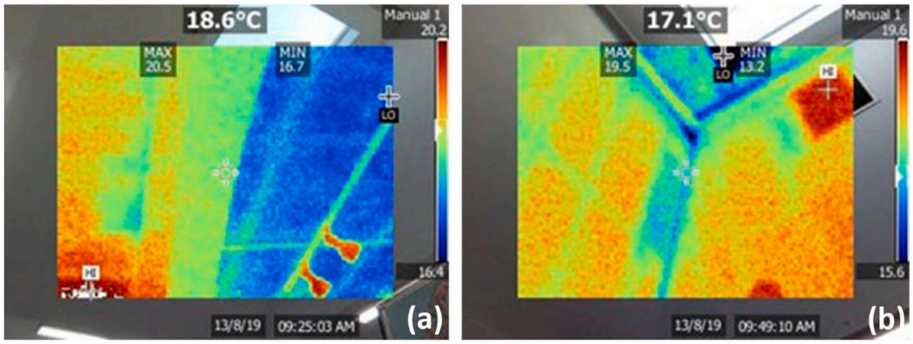

Fig. 3. Thermal imaging showing gaps in ceiling insulation in the attic space in case study C. Images taken with an infrared-fusion camera with a thermal sensitivity of 0.8 °C at 30 °C target temp (80 mK); date: 13th August 2019. Photo credit: Priscila Besen.

Fig. 4. Photos of case study C showing key issues. Photo credit: Priscila Besen.

Fig. 5. Use of personal portable heaters by building occupants in case studies C (a) and A (b). Photo credit: Priscila Besen.

Table 2
Spot indoor air temperature measurements in the three case studies in winter – Temperature range.

	Case Study A	Case Study B	Case Study C
Maximum indoor air temperature measured	21.2 °C	22.1 °C	22.3 °C
Minimum indoor air temperature measured	16.8 °C	17.2 °C	16.5 °C
Date of measurements	27th August 2019	August 30, 2019	13th August 2019

provide acceptable indoor conditions in these buildings. There are rooms with small windows where ventilation is ineffective; in addition, window ventilation generates significant heat losses in winter. Occupants also reported that when it is raining or too windy, opening windows becomes impractical. Comments also highlighted significant issues about the lack of maintenance that means windows become stuck and cannot be opened for summer ventilation. Comments also highlighted discomfort related to seating next to single glazed windows, draughts from windows, and excessive solar heat gains, as the original windows have a high G-value.

The questionnaire demonstrated that the indoor conditions in these historic buildings affect the wellbeing of occupants and their productivity. For instance, an occupant in building C reported falling asleep in

Fig. 6. Level of satisfaction with indoor temperatures in the case studies in winter and summer.

the summer because the building gets too hot, while another said it is hard to work in winter because of the low temperatures. One of the responses above confirmed the practice of bringing personal heaters to offices to compensate for the insufficient heating provided in the building. The comments from building occupants reinforce the need for improving thermal comfort which would be a result of energy retrofitting URM buildings.

3.2. *Development of retrofit scenarios and simulation*

As discussed in the methodology, the study developed retrofit scenarios by 1) analysing the baseline model; 2) assessing hygrothermal risks through simulation; and then 3) developing energy simulation. The following sections discuss all these steps and the results obtained.

3.2.1. *Baseline analysis*

The PHPP baseline model allowed an analysis of the main sources of heat loss in a building in its current configuration. Fig. 7 shows the percentage of heat loss from each building element.

Ventilation, external walls, and fenestration were found to be the main sources of heat losses in the buildings, with some variations between the three buildings due to the building form and construction configurations. Ventilation is a high source of heat loss, due to the draughts in junctions, windows, and doors. Although contributing to solar heat gains, windows undergo high rates of heat losses due to single glazing and timber frames providing low levels of insulation. External walls are responsible for significant heat loss in the buildings because the brick masonry walls remain uninsulated. Roof and ceilings make a lower contribution to heat losses in these buildings because these are the only portions of the buildings that currently contain thermal insulation. This analysis informed the proposal of retrofit scenarios based on the current building components that need to be upgraded to reduce heat losses.

Calibration was developed by comparing the baseline model with measured energy consumption. The models revealed that, when considering a setpoint of 16.5 °C – which was found to be the minimum temperature through spot measurements (Table 2) – the simulated energy consumption values were in line with measured consumption on site. However, to achieve EnerPHit certification and ensure comfortable conditions for occupants, a setpoint of 20 °C was utilised in the models for assessing all retrofit scenarios.

3.2.2. *Proposed retrofit scenarios*

As described in the methodology, cumulative retrofit scenarios were developed according to the least invasive to the most invasive works. Although external insulation is a preferred solution from a technical perspective, in historic buildings the application of internal insulation offers a possibility to improve the historic buildings' energy performance without compromising the buildings' architectural appearance [112]. Given the historic significance of the external façades of the selected case studies and heritage protection restrictions, the proposed energy retrofit interventions were located internally. Fig. 8 illustrates

Table 3
Selected comments from open-ended questions.

	Case Study A	Case Study B	Case Study C
Comments about summer comfort and ventilation	"In summer it is necessary to have a fan, since the windows don't provide enough cooling air flow, even when wide open." "(…) unfortunately, some windows have been 'painted shut', or swell in the wet weather, and are hard to open."	"It gets very hot. We need to have the window open. In the top floor, the heat from the building rises up, and we seem to get the whole lot." "Last summer our office hit 32°, even though we had 3 fans going." "(…) opening the windows only does so much so we invested in our own personal fans (…)." "Very poor in summer, small windows give minimal air flow."	"I fall asleep because it is so hot." "In my opinion it is far too warm, this however might be due to the preferences of other office occupants." "It is OK if you can open the window, but often too windy or dusty to do this."
Comments about winter comfort and heating systems	"The lack of insulation makes it inefficient in terms of heating." "Wall-mounted heaters automatically shut off after certain hours. If you're working early/late, you need a plug-in heater to keep warm."	"It can get very cold – there are wall bar heaters but some days I've kept my coat on most of the day." "When the radiators haven't been on, the office is frigid. Mondays can be terrible, as it can take almost all day for the temperature to go up after being off over the weekend."	"It is so, so cold in winter, it is hard to work in this environment." "I am overall still happy to be working in my office, I just need to wear many layers of clothes." "(…) people bring in bar heaters, both officially and unofficially."

the proposed retrofit packages for the study.

Retrofit scenario 1 is the baseline, consisting of the original building before seismic strengthening or energy retrofit take place. Scenario 2 contains only the baseline building with seismic upgrades. This was modelled in accordance with drawings from engineers for these buildings, and was considered as a "fixed" factor not to be altered.

Retrofit scenario 3 includes roof and underfloor insulation, which are the most common type of energy upgrade and are generally considered a low-cost intervention with minimal visual impact [39]. The type of under floor insulation selected is Polyisocyanurate (PIR) boards, due to durability when used around crawl spaces and for moisture protection. Underfloor insulation installation must provide available access to crawl spaces or allow for the temporary removal of timber floors followed by reinstatement. Glass wool blankets are already used in the case study buildings for roof insulation, and one of the most common insulation materials in New Zealand [113]. To keep the same material and avoid changes that could result in compatibility issues, and to ensure ease of installation, glass wool insulation is added on top of the existing timber structure to reduce the effect of thermal bridging and increase the thermal resistance of roofs and ceilings. The thickness of insulation is determined according to sizes of cavities and sensitivity analysis through PHPP models to achieve EnerPHit requirements.

Retrofit scenario 4 includes window upgrades and airtightness. Secondary glazing is generally a less intrusive option than replacement of original windows. However, while this type of window upgrade is supported by the national heritage authority in New Zealand found in these buildings [36], there are few examples of this application in the country [39]. High performance windows with timber frames and Low-e Argon-filled double glazing are utilised in the retrofit scenarios and are installed internally while maintaining original windows on the exterior. The selected windows are Passive House certified, and have a slim frame profile, minimising the visual impact of this addition. The selected windows are openable to the interior to allow for natural ventilation in summer. The only exception to window upgrades are the stained glass windows in the Council Chamber room in case study B, which already has secondary glazing added to the exterior of the original windows for decay protection. No further window upgrades are proposed for these windows, as they have high historic and architectural value. Airtightness is enhanced by adding different materials in the inner layers of the building envelope, such as internal lime plaster in walls and plywood diaphragms (also part of seismic upgrades in case study A) with tapes to ensure airtight junctions in ceilings.

In retrofit scenario 5, a heat recovery ventilation system with efficiency rate above 80% is introduced to provide constant ventilation to the building, keep healthy indoor environments, and reduce the heating demand by heat recovery. The installation of such a system would rely on the careful design of ducting and the placement of the heat exchange unit in a way that does not impact the heritage fabric.

Retrofit scenario 6 is the most comprehensive and includes wall insulation. As all façades have heritage significance and protection, internal insulation is proposed (Fig. 9). Cavity insulation would only be possible in case study A, due to the suitable size of the air cavity. However, due to potential reversibility concerns, internal insulation applied to the inner face of walls is the preferred option. As wall

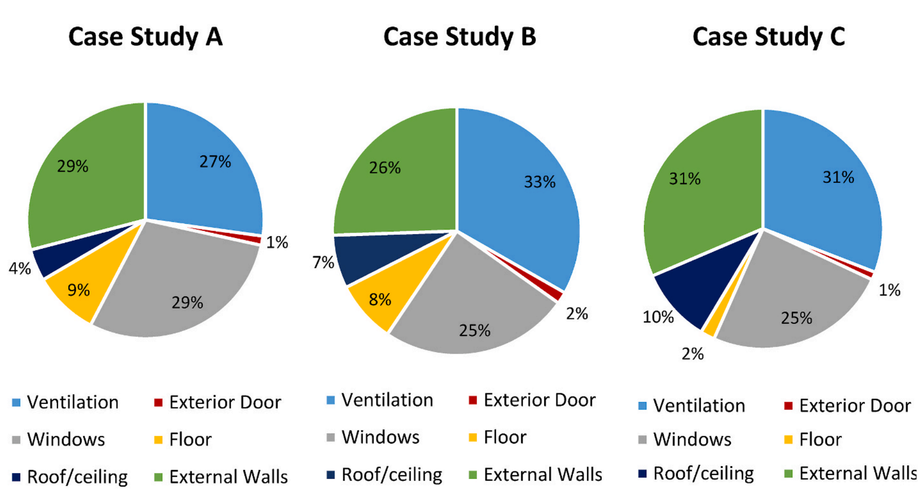

Fig. 7. Heat losses (%) in baseline models as calculated by PHPP.

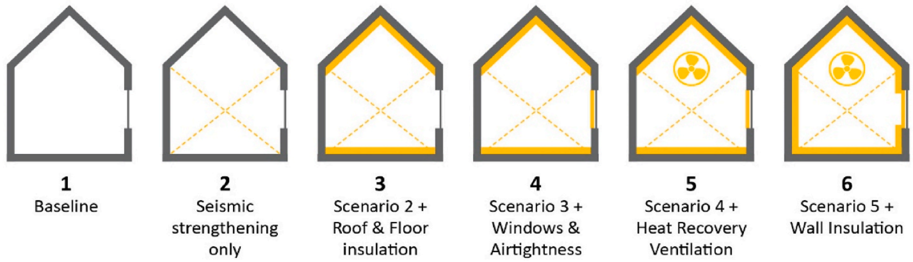

Fig. 8. Proposed cumulative retrofit scenarios.

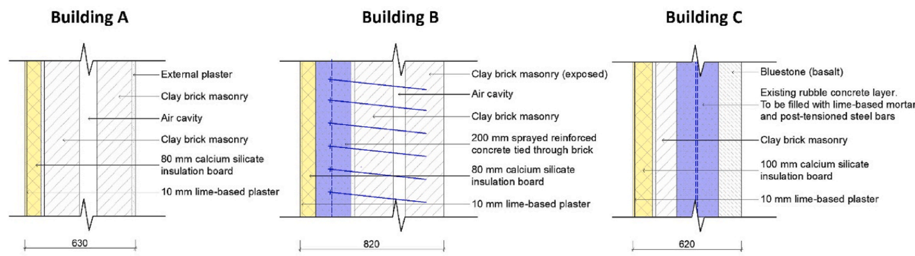

Fig. 9. Proposed retrofit details for wall constructions: energy-related interventions shown in yellow, seismic-related interventions shown in purple. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

insulation is one of the riskiest interventions for moisture management in building assemblies, a hygrothermal simulation was run and its results guided the selection of suitable materials.

Table 4 shows the thermal transmittance of the main building envelope components for each retrofit scenario, calculated according to the methodology presented in section 2.4.2. As the current New Zealand Building Code does not specify thermal transmittance values for existing buildings, the new U-values were proposed according to the EnerPHit standard. Case study C was at the design stage for seismic strengthening at the time of the research. The proposed energy upgrades were based on the preferred strengthening strategy at the time, which included filling the existing wall cavity with lime-based mortar and post-tensioned steel

Table 4
Retrofit scenarios, including a summary of average U-values [W/(m^2K)] used for each component of the building fabric for the PHPP model.

	Retrofit Scenarios (cumulative)	Roof/Ceiling W/(m^2K)	Floor W/(m^2K)	Glazing U_g W/(m^2K)	Walls W/(m^2K)	Air tightness n_{50} (h^{-1})	Ventilation and effective heat recovery efficiency
BUILDING A – AUCKLAND							
1	Baseline	0.28	1.88	5.8	1.11	8	Windows only
2	Seismic strengthening only	0.26	1.88	5.8	1.11	7	Windows only
3	Scenario 2 + roof and underfloor insulation	0.17	0.31	5.8	1.11	7	Windows only
4	Scenario 3 + windows upgrade and airtightness	0.17	0.31	1.08	1.11	1	Windows only
5	Scenario 4 + heat recovery ventilation	0.17	0.31	1.08	1.11	1	Balanced ventilation system with heat recovery (eff. 81.7%)
6	Scenario 5 + wall insulation	0.17	0.31	1.08	0.37	1	Balanced ventilation system with heat recovery (eff. 81.7%)
BUILDING B – WELLINGTON							
1	Baseline	0.52	1.88	5.8	1.08	8	Windows and extractor fans
2	Seismic strengthening only	0.52	1.88	5.8	1.08	8	Windows and extractor fans
3	Scenario 2 + roof and underfloor insulation	0.21	0.19	5.8	0.98	8	Windows and extractor fans
4	Scenario 3 + windows upgrade and airtightness	0.21	0.19	1.08	0.98	1	Windows and extractor fans
5	Scenario 4 + heat recovery ventilation	0.21	0.19	1.08	0.98	1	Balanced ventilation system with heat recovery (eff. 83.8%)
6	Scenario 5 + wall insulation	0.21	0.19	1.08	0.35	1	Balanced ventilation system with heat recovery (eff. 83.8%)
BUILDING C – DUNEDIN							
1	Baseline	0.299	1.55	5.8	1.88	8	Windows and extractor fans
2	Seismic strengthening only	0.299	1.55	5.8	1.62	8	Windows and extractor fans
3	Scenario 2 + roof and underfloor insulation	0.15	0.16	5.8	1.62	1	Windows and extractor fans
4	Scenario 3 + windows upgrade and airtightness	0.15	0.16	1.08	1.62	1	Windows and extractor fans
5	Scenario 4 + heat recovery ventilation	0.15	0.16	1.08	1.62	1	Balanced ventilation system with heat recovery (eff 83.3%)
6	Scenario 5 + wall insulation	0.15	0.16	1.08	0.35	1	Balanced ventilation system with heat recovery (eff. 83.3%)

bars.

Values shown for building B do not apply to the Council Chamber room, as it needed to be carefully assessed for retrofit. This room is a triple-height space that is utilised for occasional events. There is significant original detailing in the timber, walls, and ceilings, and heritage significant stained glass windows, which are a memorial for staff and students who died in the world wars. These windows had already been upgraded with secondary glazing applied to the outside to provide protection from decay. The addition of secondary internal glazing and wall insulation would have a significant impact on this important space. The ceiling and floor of the room could possibly be insulated, if insulation could be added to existing cavities (this would be subject to confirmation through further investigations such as through the use of endoscope cameras). Therefore, given its heritage significance and its occasional occupancy pattern, no interventions are proposed for this room because any changes could have a significant visual impact. In addition, there are no significant requirements from occupants' comfort point of view since it is only used for occasional short meetings and gatherings. Fig. 10 shows the location of the Council Chamber room and the extent of the building that will be excluded from retrofit interventions, as well as an internal view of the configuration of the space and the stained-glass memorial windows.

3.2.3. Hygrothermal simulation results

As discussed in section 2.3, the potential materials identified for internal wall insulation are: 1) calcium silicate boards; 2) perlite boards; 3) infill cellulose; 4) mineral wool; and 5) wood fibre. These materials were assessed through hygrothermal simulation to identify the most suitable option to avoid interstitial condensation issues. The impact of the addition of wall insulation leads to different results in each building due to their different types of construction and the seismic strengthening technologies applied. Fig. 11 shows the total water content in the retrofitted wall assemblies obtained through WUFI simulation for a period of 10 years – a period recommended by best practices to provide a long-term evaluation of moisture transfer through the building assembly [88].

In buildings A and B, calcium silicate boards obtained the best results. Overall, it is predicted that total moisture content will achieve a balance and show stable values after the initial period with all the proposed material types, while mineral wool, cellulose insulation, and wood fibre are unlikely to present satisfactory results. Although vapour control membranes were integrated to the wall assemblies in the models to help obtain better results, issues are likely to remain.

Given the hygrothermal evaluation results, calcium silicate boards were chosen for internal wall insulation in all case studies. This material is commonly known as being a suitable type of capillary active insulation. Therefore, the proposed internal wall insulation consists of 80 mm rigid calcium silicate boards in case studies A and B, and 100 mm in case study C. Lime plaster will be applied as a finishing surface, which is airtight but vapour permeable, allowing possible moisture build-up from the wall to dry towards the interior environment. The insulation material can be attached to the existing masonry walls with a clay-based mortar, which can improve the potential for reversing this intervention, if required in the future.

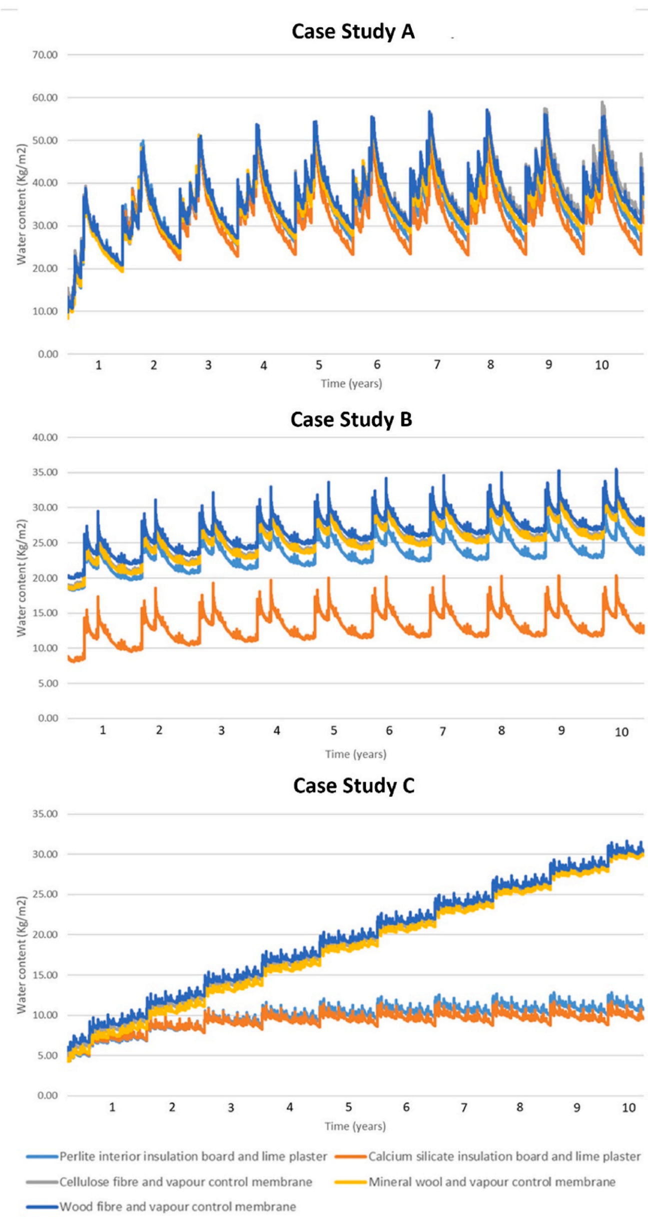

Fig. 11. Total water content in wall assembly over time for various internal insulation materials.

3.2.4. Energy simulation results

Fig. 12 shows the results from energy simulation, demonstrating the effect of the proposed retrofit scenarios on heating demand, while

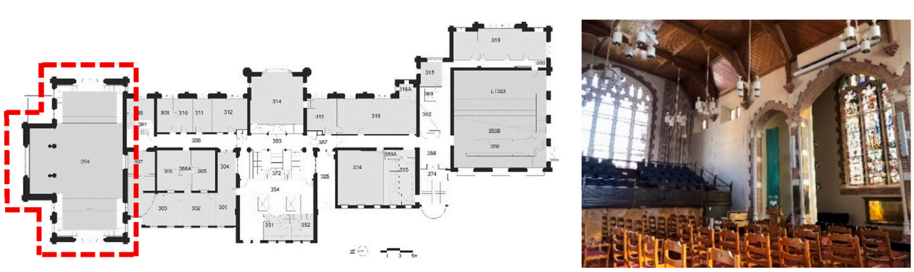

Fig. 10. Case study B: Floor plan and photo showing the Council Chambers room, which will be subject to minimal energy retrofit interventions due to its heritage significance.

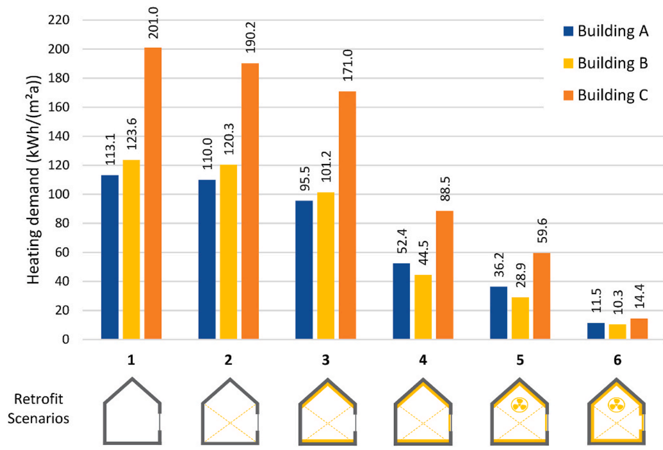

Fig. 12. Cumulative retrofit scenarios 1–6: heating demand results for case studies A (Auckland), B (Wellington), and C (Dunedin).

Fig. 13 illustrates the frequency of overheating. The frequency of overheating was calculated in PHPP and represents the number of hours in a year where the indoor temperature exceeds 25 °C, considering that these buildings would not utilise active cooling. The resulting overheating percentage is the number of hours above 25 °C divided by the total number of hours of occupancy. All results were obtained from PHPP models, which included input from thermal bridging calculations developed in the software THERM.

Case study A is located in a low-risk seismic zone and the structural upgrades completed previously were minimal and limited to the mid-floor and ceiling. The plywood diaphragms that were added for seismic strengthening can be used for airtightness in the proposed energy upgrade. Thus, the air changes per hour were estimated to decrease from 8 ACH in scenario 1 to 7 ACH in scenario 2. However, to ensure airtight construction, all its junctions must be carefully taped. Plywood diaphragms also contribute to a small reduction in heating demand because they help lower the U-value of ceiling constructions. This shows that in some cases, seismic retrofit works can also help improve energy performance.

In all case studies, wall insulation has the greatest impact on heating demand, reducing it by over a third when compared to the previous retrofit scenario (number 5). Airtightness and window upgrading will make the second most significant reduction to heating demand, generating a reduction of over half of the previous retrofit scenario when considering a value of 1 ACH for the retrofitted building. In all three case studies, it would only be possible to achieve the required EnerPHit target

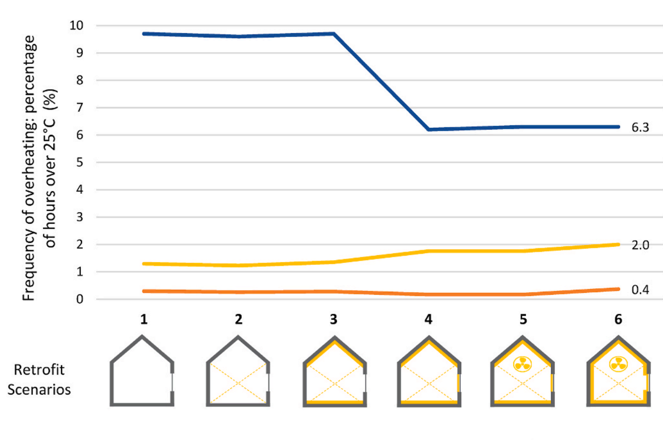

Fig. 13. Cumulative retrofit scenarios 1–6: frequency of overheating (%) results for case studies A, B, and C.

of 15 kWh/(m^2a) in retrofit scenario 6, which is the most comprehensive package as it includes wall insulation in addition to all the measures from previous scenarios. Overheating is below the limit of 10% required by the EnerPHit standard in all scenarios and is significantly lowered by window upgrades in case study A, as secondary glazing reduces the G-value of windows and related solar heat gains.

As discussed in section 3.2.4, although no energy retrofit interventions are proposed for the Council Chamber room in case study B, it was modelled in PHPP as-built and the building would still achieve the required heating demand for certification, since the improvements to the all other rooms compensate for this uninsulated area. However, the windows and walls in this room would not comply with EnerPHit's hygienic criteria and minimum thermal criteria for each component. An exemption for this type of situation is possible through the EnerPHit criteria for the component method, according to which "heat transfer coefficients of the exterior envelope building components may be exceeded if absolutely necessary, if required by the historical building preservation authorities" [69]. As this is a room with high heritage significance and a clear separation from the building, it is arguable that a better option could be to exclude it from the thermal envelope and ensure the walls and doors in contact with the other parts of the building are insulated and airtight. This type of flexibility is needed in order to carefully utilise the EnerPHit standard when dealing with historic structures.

Another important point about case study B is that the sprayed concrete system used for seismic strengthening in the inner layer of walls has already increased wall thickness and window reveal depth significantly, thus affecting daylighting in the rooms (Fig. 1). So, although wall insulation would provide a significant reduction in heating demand, the suitability of internal wall insulation for this building is questioned and is discussed further in section 3.3.

In case study C, the structural systems proposed by engineers included post-tensioning with steel rods within the wall (in the lime-reinforced cavity) or externally. Both systems were tested in PHPP and did not generate a significant difference in heating demand results. However, from an energy performance perspective, the option using external structural elements would be more reliable and less likely to cause future moisture-related issues. In this case, steel elements would be separated from the thermal envelope, with less interference on the wall assembly.

All buildings would be able to achieve the EnerPHit standard if the most comprehensive retrofit scenario (number 6) was implemented together with seismic strengthening. The reduction in heating demand by applying retrofit scenario 6 when compared to the baseline scenario could be up to 92% in building C, 91.6% in building B, and 89.9% in building A. However, section 3.3 provides further discussions on the potential risks and benefits for the most critical interventions.

3.3. Assessment of impact on heritage conservation

According to EN 16883 [68], a systematic assessment of a building should be made not only of technical aspects but also of how the interventions affect the building physically and its heritage significance. The method proposed by the standard is based on a tabular risk-benefit scheme to identify the best measures and eliminate inappropriate interventions. The assessment should encompass the categories presented in the standard, which include technical compatibility, the heritage significance of the building and its settings, energy, indoor environmental quality, aspects of use, economic viability, and impact on the outdoor environment. The last two categories are not included in this study as they were outside its scope. However, as the focus of the research is on the relationship between energy and seismic upgrades, a new category is proposed – the integration of retrofit solutions with seismic strengthening. Fig. 14 shows the five-point scale utilised in the assessment as proposed by EN 16883 [68], ranging from high risks to high benefits.

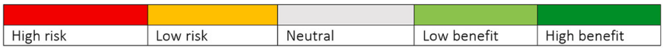

Fig. 14. Assessment scale according to EN 16883 (2017).

Appendix 1 elaborates further on the assessment for each retrofit scenario in each case study building. Retrofit scenario 1 is not included as it represents the baseline without any interventions proposed and therefore does not have any impact on the heritage value. Also, retrofit scenario 2 depends on the seismic strengthening strategy defined outside the scope of this research. It is assessed based on standard EN 16883, but not discussed.

According to the main international charters for the preservation and restoration of buildings and monuments [93], any intervention on a historic building, even of a structural nature, must be potentially reversible. If new structures are to be integrated within the existing building, in the specific case of load-bearing structures, the use of dry-assembled technologies is recommended, taking advantage of connections that allow the disassembling of the new structures at any time [114]. The potential reversibility of certain energy upgrades, such as roof insulation utilising glasswool blankets, is more achievable than others, such as wall insulation. The reversibility of calcium silicate boards utilised as wall insulation depends on how they are attached to the wall. In this study, although clay-based mortars are utilised as the attachment to the existing walls, it can still not be guaranteed that the potential reversibility would be damage-free.

Based on the assessment, in case study A, wall insulation is identified as the intervention that presents the highest risks, while roof and floor insulation, followed by window upgrades, present most benefits and lower risks. Because most seismic strengthening works were previously carried out in the roof and floors, insulation to those areas would have the most successful integration with structural upgrades. These areas of the building are already subject to interventions for seismic retrofit, therefore roof and floor insulation could be easily installed on site.

In case study B, due to the seismic strengthening with sprayed concrete, the addition of wall insulation internally would have a negatively high visual impact. The 200 mm concrete layer already installed has a significant visual impact, especially in window reveals. Thus, adding an additional layer of wall insulation would present many negative aspects, according to the assessment. Other interventions, such as secondary glazing and ventilation systems, would be very beneficial in this building, considering the comments from occupants about inadequate ventilation, overheating, and airtightness.

In case study C, the proposed strengthening system would have a low visual impact since new structural elements would be implemented inside the wall cavity. Therefore, the addition of wall insulation would also have a relatively low visual impact, as it only represents an increase of 100 mm to wall thickness. Window upgrades represent a strategy with the most potential benefits and lower risks in this case study, with high improvements to energy performance and occupant comfort and lower impacts on heritage fabric.

4. Conclusions

The case studies analysed in this research showed possible ways to implement deep energy retrofit in conjunction with seismic strengthening. The energy audit revealed several issues, with building C currently using 40% more energy than similar buildings on the same campus. A questionnaire given to building occupants revealed dissatisfaction with several factors, including insufficient heating, lack of insulation, draughts from windows, and inadequate indoor temperatures. In total, 60% of occupants were dissatisfied or very dissatisfied with temperatures in winter in building C, 38% in building A, and 14% in building B. In summer, dissatisfaction rates were 53% in building C, 27% in building B. and 33% in building A.

Retrofit scenarios proposed according to the EnerPHit standard showed that a reduction of heating demand of up to 92% in building C, 91.6% in building B, and 89.9% in building A could be achieved with the most comprehensive retrofit package, scenario 6, when compared to the baseline. Scenario 6 is the only retrofit package to achieve the EnerPHit standard and represents the most comprehensive scenario through its inclusion of roof, floor, and wall insulation, as well as upgraded windows through secondary glazing, airtightness, and heat recovery ventilation. Scenario 5, a relatively less invasive package that includes the beforementioned upgrades except for wall insulation, is also capable of achieving significant savings in heating demand.

Internal wall insulation was utilised in all retrofit simulations due to the significance of historic façades. Amongst materials selected, perlite boards and calcium silicate boards achieved good results in hygrothermal performance, due to their capillary-active properties. The assessment of retrofit impact on heritage fabric, according to EN 16883 [68], showed that the intervention with the most benefits is the upgrade of windows with secondary glazing, while the intervention with the highest risks is internal wall insulation.

The study showed that seismic strengthening systems can be compatible with energy retrofit options or present adverse effects, depending on the structure proposed. Sprayed concrete, for instance, can significantly increase wall thickness and hinder the possibility of adding additional insulation layers. This example shows how the retrofit of URM buildings needs to be carefully considered with a holistic approach as addressing only a single demand, such as structural upgrading, might lead to problems related to another discipline. Other seismic strengthening systems, such as plywood diaphragms introduced to ceilings and floors, can help improve airtightness and energy performance. The investigations reinforce the idea that integrated retrofit solutions need to be designed on a case-by-case basis, considering the particularities of each historic building.

Overall, the study demonstrates that it is possible and advisable to improve the building envelope in URM construction concurrently with seismic strengthening and achieve significant energy savings by developing tailored solutions for each case. The EnerPHit standard can be a useful reference for the development of energy retrofit works, especially if applied in conjunction with the methodology proposed by EN 16883. In the case of heritage buildings, there are potential problems with the application of fixed energy performance targets, and the focus should instead be on performance improvement compatible with the safeguarding of heritage values. The exemptions already available in the EnerPHit standard are crucial for the case of historic buildings and could be further expanded to allow the complete exclusion of selected building areas where no interventions are recommended.

This methodology for the development and assessment of retrofit scenarios can be replicated to other URM buildings in New Zealand and other countries with masonry building stocks subject to similar demands in terms of seismic risks, indoor environmental quality, and energy efficiency. The application of this method can be limited by cost considerations, approvals from heritage authorities, further in-situ testing such as blower door test and measurement of U-values, as well as further investigations on the constructability of the proposed upgrades, all factors that were outside the scope of this study and require further research. There is a need for further development of materials and integrated systems that can deliver both thermal insulation and structural strengthening at the same time, as well as retrofit constructions with lower embodied carbon and reduced environmental impacts. The study highlights the need to evolve from reactive to proactive retrofit approaches, moving from addressing urgent issues to creating pathways towards positive energy buildings. Overall, the research confirms that current seismic upgrade projects can be an opportunity to integrate energy improvements in historic URM buildings through sensible interventions in the heritage fabric, to ensure that these buildings can continue to serve a useful purpose in a post-carbon future.

CRediT authorship contribution statement

P. Besen: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **P. Boarin:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

Acknowledgements

The researchers are very grateful for all the assistance provided by all three universities that collaborated in this project by giving access and information about the case study buildings. We also thank all the building occupants who participated in questionnaires, as well as facilities managers, architects, and engineers who provided drawings and information about the case study buildings. We express our deepest gratitude to Dr. Kara Rosemeier and Prof. Errol Haarhoff for their advice on the research. This research was supported by a University of Auckland Doctoral scholarship awarded to Priscila Besen.

Appendix A. Assessment of impacts based on EN16883:2017

		Case Study A					Case Study B					Case Study C				
		Retrofit Scenarios					Retrofit Scenarios					Retrofit Scenarios				
Assessment categories	Assessment criteria	2	3	4	5	6	2	3	4	5	6	2	3	4	5	6
Technical compatibility	Hygrothermal risks															
	Structural risks															
	Corrosion risks															
	Salt reaction risks															
	Biological risks															
	Reversibility															
Heritage significance of the building and its settings	Risk of material impact															
	Risk of visual impact															
	Risk of spatial impact															
Energy	Energy performance and operational energy demand															
Indoor environmental quality	Indoor environmental conditions suitable for building fabric preservation															
	Indoor environmental conditions suitable for achieving good occupant comfort levels															
Aspects of use	Influence on the use and the users of the building															
	Ability of building users to manage and operate control systems															
Integration of retrofit solutions with seismic strengthening[1]	Compatibility with proposed seismic strengthening systems	2					2					2				
	Access allowed by seismic strengthening (i.e. elements were already affected by seismic interventions)	2					2					2				

[1]Proposed new category of assessment specific to buildings subject to combined energy and seismic retrofit. [2]Not applicable, as retrofit scenario 2 is seismic strengthening only.

References

[1] J. Hosagrahar, J. Soule, L.F. Girard, A. Potts, Cultural Heritage, the UN Sustainable Development Goals, and the New Urban Agenda, 2016. http://www.usicomos.org/wp-content/uploads/2016/05/Final-Concept-Note.pdf. (Accessed 30 April 2018).

[2] United Nations, Transforming Our World: the 2030, Agenda for Sustainable Development, 2015.

[3] S. Labadi, F. Giliberto, I. Rosetti, L. Shetabi, E. Yildirim, Heritage and sustainable development goals: policy guidance for heritage and development actors, paris. https://openarchive.icomos.org/id/eprint/2453/7/ICOMOS_SDGPG_2022.pdf, 2021. March 17, 2023.

[4] Preservation Green Lab, National trust for historic preservation, the greenest building: quantifying the environmental value of building reuse. https://savingplaces.org/, 2012. (Accessed 9 September 2022).

[5] H. Baker, A. Moncaster, H. Remøy, S. Wilkinson, Retention not demolition: how heritage thinking can inform carbon reduction, J. Architect. Conserv. 27 (2021) 176–194, https://doi.org/10.1080/13556207.2021.1948239.

[6] A. Power, Does demolition or refurbishment of old and inefficient homes help to increase our environmental, social and economic viability? Energy Pol. 36 (2008) 4487–4501, https://doi.org/10.1016/j.enpol.2008.09.022.

[7] G. Ding, X. Ying, Embodied and operating energy assessment of existing buildings – demolish or rebuild, Energy 182 (2019), https://doi.org/10.1016/j.energy.2019.06.056.

[8] V. Hasik, E. Escott, R. Bates, S. Carlisle, B. Faircloth, M.M. Bilec, Comparative whole-building life cycle assessment of renovation and new construction, Build. Environ. 161 (2019), 106218, https://doi.org/10.1016/J.BUILDENV.2019.106218.

[9] ICOMOS Climate Change and Cultural Heritage Working Group, The future of our pasts: engaging cultural heritage in climate action, Paris, https://indd.adobe.com/view/a9a551e3-3b23-4127-99fd-a7a80d91a29e, 2019.

[10] G. Carbonara, Energy efficiency as a protection tool, Energy Build. 95 (2015) 9–12, https://doi.org/10.1016/j.enbuild.2014.12.052.

[11] A.L. Webb, Energy retrofits in historic and traditional buildings: a review of problems and methods, Renew. Sustain. Energy Rev. 77 (2017) 748–759, https://doi.org/10.1016/j.rser.2017.01.145.

[12] M. Cassar, Climate change and the historic environment, London, UK, www.ucl.ac.uk/sustainableheritage/climatechange/, 2005. (Accessed 9 December 2019).

[13] D. McDermott, D. Binan, D. Bumbaru, G. Jungeblodt, I. Odiaua, J. Soule, N. Kuban, C. Murray, E. Avrami, H. Wilson, R. Jackson for Australia Nsces, M. Turner, P. Motta, S. Burke, T. Colletta, ICOMOS action plan: cultural heritage and localizing the UN sustainable development goals (SDGs). http://www.icomos.org/en/what-we-do/involvement-in-international-conventions/un-sustainable-development-goals-2, 2017. (Accessed 10 December 2019).

[14] O. Prizeman, Sustainable Building Conservation: Theory and Practice of Responsive Design in the Heritage Environment, RIBA Publishing, Newcastle upon Tyne, 2015.

[15] ICOMOS New Zealand, ICOMOS New Zealand Charter for the Conservation of Places of Cultural Heritage Value, 2010.

[16] D. Brown, Maori architecture: from fale to wharenui and beyond, Raupo, Auckland, New Zealand, 2009.

[17] R. Wolfe, New Zealand's Lost Heritage, New Holland Publishers, Auckland, New Zealand, 2013.

[18] Heritage New Zealand Pouhere Taonga, Lost heritage, heritage New Zealand Pouhere Taonga. https://www.heritage.org.nz/places/lost-heritage, 2023. (Accessed 25 May 2023).

[19] Ministry of Business Innovation & Employment, Building (Earthquake-Prone Buildings) Amendment Act, New Zealand Government, Wellington, New Zealand, 2016.

[20] I.E. Aigwi, O. Filippova, J. Ingham, R. Phipps, Unintended consequences of the earthquake-prone building legislation: an evaluation of two city centre regeneration strategies in New Zealand's provincial areas, Int. J. Disaster Risk Reduc. 49 (2020), https://doi.org/10.1016/j.ijdrr.2020.101644.

[21] Ministry of Business Innovation and Employment, EPB methodology: the methodology to identify earthquake-prone buildings, Wellington, https://www.building.govt.nz/assets/Uploads/building-code-compliance/b-stability/b1-structure/epb-methodology.pdf, 2017. (Accessed 26 May 2023).

[22] A.P. Russell, J.M. Ingham, Prevalence of New Zealand's unreinforced masonry buildings, Bull. N. Z. Soc. Earthq. Eng. 43 (2010) 182–202.

[23] Royal Comission, The performance of unreinforced masonry buildings in the 2010/2011 canterbury earthquake swarm. http://canterbury.royalcommission.govt.nz/vwluResources/ENG.ACA.0001G_Section_7_Performance_of_Unreinforced_Masonry_Buildings_in_the_2010_and_2011_Canterbury_Earthquake_Swarm.pdf/$file/ENG.ACA.0001G_Section_7_Performance_of_Unreinforced_Masonry_Buildings_, 2011. (Accessed 26 March 2019).

[24] I. Senaldi, G. Magenes, J.M. Ingham, Damage assessment of unreinforced stone masonry buildings after the 2010-2011 canterbury earthquakes, Int. J. Architect. Herit. 9 (2015) 605–627, https://doi.org/10.1080/15583058.2013.840688.

[25] D. Dizhur, Structural Performance: a Visual Record of Strengthened Vintage Masonry Buildings after the Christchurch Earthquakes to Inform a Safer Future, Dmytro Dizhur, Auckland, 2021.

[26] N. Ismail, K. McGrannachan, Lessons from canterbury characteristics of the buildings, BRANZ Build 134 (2013). https://www.buildmagazine.org.nz/index.php/articles/show/dunedins-earthquake-prone-buildings. June 2, 2023.

[27] S. Roaf, D. Crichton, F. Nicol, Adapting Buildings and Cities for Climate Change: a 21st Century Survival Guide, Elsevier: Architectural Press, Oxford, UK, 2009.

[28] A. Troi, Z. Bastian, Energy Efficiency Solutions for Historic Buildings. A Handbook, Birkhäuser Verlag GmbH, Basel, 2015.

[29] D. Camuffo, Microclimate for Cultural Heritage: Conservation, Restoration, and Maintenance of Indoor and Outdoor Monuments, second ed., second ed., Elsevier, 2014 https://doi.org/10.1016/C2013-0-00676-7.

[30] A. Martínez-Molina, P. Boarin, I. Tort-Ausina, J.-L. Vivancos, Post-occupancy evaluation of a historic primary school in Spain: comparing PMV, TSV and PD for teachers' and pupils' thermal comfort, Build. Environ. 117 (2017) 248–259, https://doi.org/10.1016/j.buildenv.2017.03.010.

[31] A. Martínez-Molina, P. Boarin, I. Tort-Ausina, J.-L. Vivancos, Assessing visitors' thermal comfort in historic museum buildings: results from a Post-Occupancy Evaluation on a case study, Build. Environ. (2018) 291–302, https://doi.org/10.1016/j.buildenv.2018.02.003.

[32] M.J. Varas-Muriel, R. Fort, Microclimatic monitoring in an historic church fitted with modern heating: implications for the preventive conservation of its cultural heritage, Build. Environ. 145 (2018) 290–307, https://doi.org/10.1016/J.BUILDENV.2018.08.060.

[33] D. Bienvenido-Huertas, M. León-Muñoz, J.J. Martín-del-Río, C. Rubio-Bellido, Analysis of climate change impact on the preservation of heritage elements in historic buildings with a deficient indoor microclimate in warm regions, Build. Environ. 200 (2021), 107959, https://doi.org/10.1016/J.BUILDENV.2021.107959.

[34] G. Litti, S. Khoshdel, A. Audenaert, J. Braet, Hygrothermal performance evaluation of traditional brick masonry in historic buildings, Energy Build. 105 (2015) 393–411, https://doi.org/10.1016/j.enbuild.2015.07.049.

[35] P. De Berardinis, M. Rotilio, C. Marchionni, A. Friedman, Improving the energy-efficiency of historic masonry buildings. A case study: a minor centre in the Abruzzo region, Italy, Energy Build. 80 (2014) 415–423, https://doi.org/10.1016/j.enbuild.2014.05.047.

[36] R. McClean, Sustainable Management of Historic Heritage. Guide No. 6 Building Act 2004, 2007.

[37] H.M. Cho, S. Yang, S. Wi, S.J. Chang, S. Kim, Hygrothermal and energy retrofit planning of masonry façade historic building used as museum and office: a cultural properties case study, Energy 201 (2020), https://doi.org/10.1016/j.energy.2020.117607.

[38] Historic England, Energy efficiency and historic buildings: how to improve energy efficiency. https://doi.org/10.1108/ss.2011.11029caa.019, 2018.

[39] P. Besen, P. Boarin, E. Haarhoff, Energy and seismic retrofit of historic buildings in New Zealand: reflections on current policies and practice, Hist. Environ.: Policy and Practice 11 (2020) 91–117, https://doi.org/10.1080/17567505.2020.1715597.

[40] P. Besen, P. Boarin, Energy retrofit of historic buildings in Aotearoa New Zealand: current practice, challenges and opportunities, in: A. Ghaffarianhoseini, A. Ghaffarianhoseini, N. Nasmith (Eds.), Imaginable Futures: Design Thinking, and the Scientific Method, 54th International Conference of the Architectural Science Association 2020, Auckland University of Technology, Auckland, New Zealand, 2020, pp. 471–480.

[41] New Zealand Government, Residential Tenancies (Healthy Homes Standards) Regulations 2019, New Zealand Government, Wellington, New Zealand, New Zealand, 2019.

[42] L. Amitrano, N. Isaacs, K. Saville-Smith, M. Donn, M. Camilleri, A. Pollard, M. Babylon, R. Bishop, J. Roberti, L. Burrough, P. Au, L. Bint, J. Jowett, A. Hills, S. Cory, BEES Part 1: Final Report Building Energy End-Use Study SR 297/1, Judgeford, 2014.

[43] P. La Greca, G. Margani, Seismic and energy renovation measures for sustainable cities: a critical analysis of the Italian scenario, Sustainability (2018) 10, https://doi.org/10.3390/su10010254.

[44] G.M. Calvi, L. Sousa, C. Ruggeri, Energy efficiency and seismic resilience: a common approach, in: P. Gardoni, J.M. LaFave (Eds.), Multi-Hazard Approaches to Civil Infrastructure Engineering, Springer International Publishing, 2016, pp. 165–208, https://doi.org/10.1007/978-3-319-29713-2.

[45] V. Belpoliti, P. Boarin, M. Calzolari, P. Davoli, La riqualificazione energetico-ambientale del tessuto storico. Un borgo eco-sensibile per tradurre il sisma in opportunità, in: S.R. Ermolli, V. D'Ambrosio (Eds.), The Building Retrofit Challenge - Programazzione, Progettazione e Gestione Degli Interventi in Europa, Alinea Editrice, 2012, pp. 49–56. Firenze, Italy.

[46] P. Boarin, P. Davoli, Preliminary audit and performance improvement in retrofitting historic cultural heritage. Case studies of villages hit by earthquake in the Apennines, in: AiCARR (Ed.), 49° Convegno Internazionale AiCARR - Edifici Di Valore Storico: Progettare La Riqualificazione. Una Panoramica, Dalle Prestazioni Energetiche Alla Qualità Dell'aria Interna/49° AiCARR International Conference - Historical and Existing Buildings: Designi, AiCARR, Roma, 2014, pp. 759–773.

[47] F. Mistretta, F. Stochino, M. Sassu, Structural and thermal retrofitting of masonry walls: an integrated cost-analysis approach for the Italian context, Build. Environ. 155 (2019) 127–136, https://doi.org/10.1016/J.BUILDENV.2019.03.033.

[48] V. Pertile, L. De Stefani, R. Scotta, Development and characterization of a system for the seismic and energy retrofit of existing buildings, Procedia Struct. Integr. 11 (2018) 347–354, https://doi.org/10.1016/J.PROSTR.2018.11.045.

[49] S. Caprili, F. Del Carlo, G. Salvadori, An enhanced system for the combined seismic and energy retrofit of masonry buildings, Procedia Struct. Integr. 44 (2023) 1030–1037, https://doi.org/10.1016/J.PROSTR.2023.01.133.

[50] V. Pertile, A. Stella, L. De Stefani, R. Scotta, Seismic and energy integrated retrofitting of existing buildings with an innovative ICF-based system: design principles and case studies, Sustainability 13 (2021) 9363, https://doi.org/10.3390/SU13169363, 13 (2021) 9363.

[51] M.R. Valluzzi, E. Saler, A. Vignato, M. Salvalaggio, G. Croatto, G. Dorigatti, U. Turrini, Nested buildings: an innovative strategy for the integrated seismic and energy retrofit of existing masonry buildings with CLT panels, Sustainability 13 (2021) 1188, https://doi.org/10.3390/SU13031188, 13 (2021) 1188.

[52] A. Borri, M. Corradi, R. Sisti, C. Buratti, E. Belloni, E. Moretti, Masonry wall panels retrofitted with thermal-insulating GFRP-reinforced jacketing, Materials and Structures/Materiaux et Constructions 49 (2016) 3957–3968, https://doi.org/10.1617/S11527-015-0766-4/FIGURES/9.

[53] F. Longo, A. Cascardi, P. Lassandro, M.A. Aiello, Thermal and seismic capacity improvements for masonry building heritage: a unified retrofitting system, Sustainability 13 (2021) 1111, https://doi.org/10.3390/SU13031111, 13 (2021) 1111.

[54] S. Bertagni, P. Boarin, M. Zuppiroli, The dialogue between structural interventions and sustainability criteria in rating systems for cultural heritage: the experience of GBC historic building, International Journal of Architectural Heritage Conservation, Analysis, and Restoration (2018) 1–23, https://doi.org/10.1080/15583058.2018.1511001.

[55] C. Menna, L. Felicioni, P. Negro, A. Lupíšek, E. Romano, A. Prota, P. Hájek, Review of methods for the combined assessment of seismic resilience and energy efficiency towards sustainable retrofitting of existing European buildings, Sustain. Cities Soc. 77 (2022), 103556, https://doi.org/10.1016/J.SCS.2021.103556.

[56] X. Zhou, D. Derome, J. Carmeliet, Analysis of moisture risk in internally insulated masonry walls, Build. Environ. 212 (2022), 108734, https://doi.org/10.1016/J.BUILDENV.2021.108734.

[57] M. Harrestrup, S. Svendsen, Internal insulation applied in heritage multi-storey buildings with wooden beams embedded in solid masonry brick façades, Build. Environ. 99 (2016) 59–72, https://doi.org/10.1016/j.buildenv.2016.01.019.

[58] E. Vereecken, L. Van Gelder, H. Janssen, S. Roels, Interior insulation for wall retrofitting - a probabilistic analysis of energy savings and hygrothermal risks, Energy Build. 89 (2015) 231–244, https://doi.org/10.1016/j.enbuild.2014.12.031.

[59] D. Bottino-Leone, M. Larcher, D. Herrera-Avellanosa, F. Haas, A. Troi, Evaluation of natural-based internal insulation systems in historic buildings through a holistic approach, Energy 181 (2019) 521–531, https://doi.org/10.1016/J.ENERGY.2019.05.139.

[60] P. Besen, P. Boarin, The future of historic buildings: retrofitting to improve the thermal performance of New Zealand architectural heritage, in: G. Passerini, N. Marchettini (Eds.), Sustainable Development and Planning 2018, WIT Press, Siena, Italy, 2018, pp. 15–28, https://doi.org/10.2495/SDP180021.

[61] R. Paschoalin, N. Isaacs, Applying international guidelines on historic building's retrofit in New Zealand: a critical context view, Heritage 4 (2021) 3697–3711, https://doi.org/10.3390/heritage4040203.

[62] C.R. Lloyd, M.F. Callau, T. Bishop, I.J. Smith, The efficacy of an energy efficient upgrade program in New Zealand, Energy Build. 40 (2008) 1228–1239, https://doi.org/10.1016/j.enbuild.2007.11.006.
[63] R. Gronert, Sustainable Thermal Retrofit of the New Zealand 1930's – 1950's Labour Party State House, Master Thesis, The University of Auckland, 2011.
[64] R. Gronert, Sustainable Thermal Retrofit of the New Zealand 1930's – 1950's Labour Party State House, The University of Auckland, 2011.
[65] P. Leardini, M. Manfredini, M. Callau, Energy upgrade to Passive House standard for historic public housing in New Zealand, Energy Build. 95 (2015) 211–218, https://doi.org/10.1016/j.enbuild.2015.03.031.
[66] W. Craft, L. Ding, D. Prasad, L. Partridge, D. Else, Development of a regenerative design model for building retrofits, in: Procedia Eng, Elsevier Ltd, 2017, pp. 658–668, https://doi.org/10.1016/j.proeng.2017.04.225.
[67] L. Given, The SAGE Encyclopedia of Qualitative Research Methods, SAGE Publications, Inc., Thousand Oaks, USA, 2008, https://doi.org/10.4135/9781412963909.
[68] European Committee for Standardisation, EN 16883:2017 Conservation of Cultural Heritage — Guidelines for Improving the Energy Performance of Historic Buildings, 2017.
[69] Passive House Institute, Criteria for the Passive House, EnerPHit and PHI Low Energy Building Standard, 2016.
[70] F. Rodrigues, M. Parada, R. Vicente, R. Oliveira, A. Alves, High energy efficiency retrofits in Portugal, Energy Proc. 83 (2015) 187–196, https://doi.org/10.1016/j.egypro.2015.12.209.
[71] F. Moran, T. Blight, S. Natarajan, A. Shea, The use of Passive House Planning Package to reduce energy use and CO2 emissions in historic dwellings, Energy Build. 75 (2014) 216–227, https://doi.org/10.1016/j.enbuild.2013.12.043.
[72] C. Jimenez-Bescos, R. Prewett, Monitoring IAQ and thermal comfort in a conservation area low energy retrofit, Energy Proc. 147 (2018) 195–201, https://doi.org/10.1016/j.egypro.2018.07.055.
[73] Passive House Institute, Criteria for buildings: passive house – EnerPHit – PHI low energy building version 10c. www.passivehouse.com, 2023.
[74] P. Besen, P. Boarin, The future of historic buildings: retrofitting to improve the thermal performance of New Zealand architectural heritage, in: G. Passerini, N. Marchettini (Eds.), Sustainable Development and Planning 2018, WIT Press, Siena, Italy, 2018, pp. 15–28, https://doi.org/10.2495/SDP180021.
[75] Standards New Zealand, NZS 4218: 2009 Thermal Insulation – Housing and Small Buildings, NZS, Wellington, 2009.
[76] Ministry of Business Innovation and Employment, H1 energy efficiency acceptable solution H1/AS1, New Zealand, https://www.building.govt.nz/building-code-compliance/h-energy-efficiency/h1-energy-efficiency/, 2022. (Accessed 28 May 2023).
[77] University of Otago, Seismic strengthening policy, policies and regulations. https://www.otago.ac.nz/administration/policies/otago038620.html, 2016. (Accessed 1 August 2020).
[78] New Zealand Government, Resource Management Act 1991, 1991. Wellington.
[79] J.M. Ziolkowski, The Juggler of Notre Dame and the Medievalizing of Modernity - Volume 3: the American Middle Ages, Open Book Publishers, 2018.
[80] European Committee for Standardization, EN 16247-2:2014 Energy Audits Part 2, Buildings, 2014.
[81] European Committee for Standardisation, EN 16883:2017 Conservation of cultural heritage — guidelines for improving the energy performance of historic buildings. https://shop.bsigroup.com/ProductDetail/?pid=000000000030322690, 2017.
[82] ASHRAE, ANSI/ASHRAE Standard 55-2013 Thermal Environmental Conditions for Human Occupancy, Atlanta, USA, 2013 https://doi.org/1041-2336.
[83] Fraunhofer Institute for Building Physics IBP, What Is WUFI®? WUFI, 2020. https://wufi.de/en/software/what-is-wufi/. (Accessed 20 May 2020).
[84] E. Vereecken, S. Roels, Capillary active interior insulation systems for wall retrofitting: a more nuanced story, Int. J. Architect. Herit. 10 (2016) 558–569, https://doi.org/10.1080/15583058.2015.1009575.
[85] E. Vereecken, L. Van Gelder, H. Janssen, S. Roels, Interior insulation for wall retrofitting - a probabilistic analysis of energy savings and hygrothermal risks, Energy Build. 89 (2015) 231–244, https://doi.org/10.1016/j.enbuild.2014.12.031.
[86] P. Steskens, X. Loncour, S. Roels, E. Vereecken, Interior Insulation of masonry walls – assessment and design, in: 2nd Int. Congress on Interior Insulation, 2013, pp. 62–69. Dresden, Germany.
[87] J. Zhao, J. Grunewald, U. Ruisinger, S. Feng, Evaluation of capillary-active mineral insulation systems for interior retrofit solution, Build. Environ. 115 (2017) 215–227, https://doi.org/10.1016/J.BUILDENV.2017.01.004.
[88] ASHRAE, ANSI/ASHRAE Standard 160-2016, Criteria for Moisture-Control Design Analysis in Buildings, Atlanta, USA, 2016.
[89] ASHRAE, ASHRAE Guideline 34-2019, Energy Guideline for Historic Buildings, Atlanta, GA, USA, 2019.
[90] V. Belpoliti, G. Bizzarri, P. Boarin, M. Calzolari, P. Davoli, A parametric method to assess the energy performance of historical urban settlements. Evaluation of the current energy performance and simulation of retrofit strategies for an Italian case study, J. Cult. Herit. 30 (2018) 155–167, https://doi.org/10.1016/J.CULHER.2017.08.009.
[91] P. De Berardinis, M. Rotilio, C. Marchionni, A. Friedman, Improving the energy-efficiency of historic masonry buildings. A case study: a minor centre in the Abruzzo region, Italy, Energy Build. 80 (2014) 415–423, https://doi.org/10.1016/j.enbuild.2014.05.047.
[92] K. Fabbri, L. Tronchin, V. Tarabusi, Energy retrofit and economic evaluation priorities applied at an Italian case study, Energy Proc. 45 (2014) 379–384, https://doi.org/10.1016/j.egypro.2014.01.041.
[93] ICOMOS, The Venice Charter 1964, 1964 https://doi.org/1964.
[94] Passive House Institute, Passive house planning package (PHPP). https://passivehouse.com/04_phpp/04_phpp.htm, 2019. (Accessed 20 May 2020).
[95] Lawrence Berkeley National Laboratory, THERM, LBNL - software. https://windows.lbl.gov/software/therm, 2020. (Accessed 26 July 2020).
[96] Lawrence Berkeley National Laboratory, WINDOW, LBNL - Software, 2020. https://windows.lbl.gov/software/window. (Accessed 26 July 2020).
[97] G.G. Akkurt, N. Aste, J. Borderon, A. Buda, M. Calzolari, D. Chung, V. Costanzo, C. Del Pero, G. Evola, H.E. Huerto-Cardenas, F. Leonforte, A. Lo Faro, E. Lucchi, L. Marletta, F. Nocera, V. Pracchi, C. Turhan, Dynamic thermal and hygrometric simulation of historical buildings: critical factors and possible solutions, Renew. Sustain. Energy Rev. 118 (2020), 109509, https://doi.org/10.1016/j.rser.2019.109509.
[98] S. Rhee-Duverne, P. Baker, Research into the Thermal Performance of Traditional Brick Walls, 2013. London, UK.
[99] C. Rye, C. Scott, The SPAB U-Value Report, 2012. London, UK.
[100] Iso, BS EN ISO 6946:2017 Building Components and Building Elements - Thermal Resistance and Thermal Transmittance - Calculation Methods, 2017.
[101] Iso, BS EN ISO 10456: 2007 Building materials and products: hygrothermal properties. Tabulated design values and procedures for determining declared and design thermal values. https://doi.org/10.1017/CBO9781107415324.004, 2007.
[102] Standards New Zealand, NZS 4214: 2006 - Methods of Determining the Total Thermal Resistance of Parts of Buildings, 2006. Wellington, New Zealand.
[103] European Committee for Standardization, BS EN 1745:2012 Masonry and Masonry Products-Methods for Determining Thermal Properties, 2012.
[104] B. Anderson, BRE 443:2006 Conventions for U-value calculations, Watford, UK, https://www.bre.co.uk/filelibrary/pdf/rpts/BR_443_(2006_Edition).pdf, 2006.
[105] M. Dondi, F. Mazzanti, P. Principi, M. Raimondo, G. Zanarini, Thermal conductivity of clay bricks, Journal of Materials in Civil Engineering, American Society of Civil Engineers (2004) 8–14, https://doi.org/10.1061/(ASCE)0899-1561(2004)16:3(287).
[106] B. Anderson, BRE 443:2006 Conventions for U-Value Calculations, 2006. Watford, UK.
[107] Deutsches Institut für Normung, DIN V 18-599-10:7-2005: Energy Efficiency of Buildings - Calculation of the Net, Final and Primary Energy Demand for Heating, Cooling, Ventilation, Domestic Hot Water and Lighting, 2005. Germany.
[108] M. Bassett, Naturally ventilated houses in New Zealand – simplified air infiltration prediction, in: CIB World Building Congress 2001, 2001. Wellington, New Zealand.
[109] J.E. Quinn, Affordable certified climate files - process used in New Zealand, in: South Pacific Passive House Conference 2015, Passive House Institute New Zealand, Auckland, New Zealand, 2015.
[110] National Institute of Water and Atmospheric Research (NIWA), Obtaining Climate Data from NIWA, NIWA, 2019. https://niwa.co.nz/climate/our-services/obtaining-climate-data-from-niwa. (Accessed 1 July 2020).
[111] World Health Organisation, Health Impact of Low Indoor Temperatures, Report on a WHO meeting., Copenhagen, Denmark, 1987.
[112] E.J. de P. Hansen, K.B. Wittchen, Energy savings due to internal façade insulation in historic buildings, in: T. Brostrom, L. Nilsen (Eds.), EEHB2018 3rd International Conference on Energy Efficiency in Historic Buildings, Visby, Sweden, 2018, pp. 22–31.
[113] BRANZ, Building research association of New Zealand, insulation: LEVEL - the authority on sustainable building. https://www.level.org.nz/fileadmin/downloads/Materials/LevelMInsul.pdf, 2020. (Accessed 25 May 2023).
[114] S. Bertagni, P. Boarin, M. Zuppiroli, The dialogue between structural interventions and sustainability criteria in rating systems for cultural heritage: the experience of GBC historic building, International Journal of Architectural Heritage Conservation, Analysis, and Restoration (2018) 1–23, https://doi.org/10.1080/15583058.2018.1511001.