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PROJECT NUMBER: PNA289-1213a February 2016

Improving Thermal Efficiency in Lightweight Construction:

mass timber as thermal mass

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www.fwpa.com.au

FWPA Level 11, 10-16 Queen Street,
Melbourne VIC 3000, Australia
T +61 (0)3 9927 3200 F +61 (0)3 9927 3288
E info@fwpa.com.au W www.fwpa.com.au

Improving Thermal Efficiency in Lightweight Construction: mass timber as thermal mass

Prepared for

Forest & Wood Products Australia

by

Dr Mark Dewsbury

Publication: Improving Thermal Efficiency in Lightweight Construction: mass-timber as thermal mass

Project No: PNA289-1213a

This work is supported by funding provided to FWPA by the Department of Agriculture, Fisheries and Forestry (DAFF).

ISBN: New number 978-1-925213-40-9

Researchers:

This research was completed by the School of Architecture & Design, University of Tasmania. The research team was lead by Dr Mark Dewsbury, who was assisted by:

Dr Detlev Geard

Dr Tim Law

Miss Clare Dunlop

Mr Maxim Tooker

Mrs Stephanie Edwards

Executive Summary

This research task was established to obtain new data to inform opportunities to further improve the thermal efficiency of light-weight, timber framed, small to medium scaled buildings. The principle task of this project was to complete an empirical study assessing the measured thermal performance of mass-timber. This empirical study, within real buildings, could then be used to corroborate previous published building heating and cooling energy simulations, which had shown significant thermal performance benefit when mass-timber was substituted with standard framed systems, and concrete and clay brick thermal mass systems.

The mass-timber as thermal mass research tasks included the installation, detailed measurement and detailed simulation of two mass-timber systems within a very lightweight building (unenclosed perimeter, platform-floored with plywood cladding), namely a:

- Tasmanian plantation Eucalyptus vertically laminated 90mm partition wall, and
- European plantation cross-laminated timber system placed on the floor.

After the mass-timber systems were installed, environmental conditions were measured in great detail. The detailed measurement included an array of sensors in the subfloor zone, test building room zone, the roof space zone and a site weather station. The site weather station data were used in conjunction with other data from the Bureau of Meteorology to create a site-specific climate file for each experiment. The site data and built fabric data were used to complete experiment specific detailed building thermal performance simulations, which included modifications to conductivity values, infiltration rates and conditioned temperatures, to more correctly reflect the as-built nature of the buildings.

From the outset it must be acknowledged that both mass-timber research tasks documented thermal performance benefits caused by timber acting as thermal mass. This improvement came from three pathways.

- Firstly, the inclusion of mass-timber elements which provided new thermal mass within the built fabric of the test building
- Secondly, in the case of the mass-timber flooring task, additional insulation in the flooring system was added by the softwood panels
- Thirdly, the inclusion of the built fabric structural elements, (joists, studs, plates, roofing structure), appear to further reduce peak minimum and maximum internal zone temperatures.

Additionally, in both research tasks the inclusion of the built fabric timber elements often lessened the gap between simulated and measured thermal performance data, indicating a correlation between reality and the capacity of the house energy rating software to model indirect gain and losses from thermal mass.

Previous building simulation research showed significant thermal performance benefit when mass-timber elements were added to the built fabric (Dewsbury, Geard et al. 2012, Dewsbury 2013, Dewsbury, Tooker et al. 2013). However, this building simulation based research was questioned due to the current presumption that masonry elements provide the best thermal mass. In this research the measured thermal performance of the mass-timber partition walls and mass-timber flooring provided a strong similarity to the simulated thermal performance. The strong correlation between the empirical and simulated data supports the hypothesis that mass-timber does provide effective thermal mass within buildings. Within this context, this research has shown that carefully placed mass-timber elements within the built fabric of buildings will provide a pathway to lightweight, low carbon and high thermal performance timber buildings.

The principle purpose of increased stringency in several components of the national construction code is to reduce the carbon emissions from the operation of buildings. This research has shown that the measured and simulated energy needs energy needs to heat and cool a building have been reduced. The development of the regulations has also included an objective to reduce peak loads from the operation of heating and cooling in new buildings, which has a significant impact on Australian power generation and distribution. In these tasks both the inclusion of the mass-timber and the inclusion of the built fabric thermal mass had a significant impact on the reduction on the peak energy calculations. Finally, internationally, there is a desire to reduce the carbon economy. When mass-timber elements are compared to traditional concrete and clay brick thermal mass elements, the mass-timber has:

- A lower embodied energy,
- Includes significant carbon sequestration, and
- Can provide significantly lighter and structurally adaptable buildings, which leads to further reductions in the carbon associated with the construction and maintenance of buildings.

Figure 1: 90mm plantation Eucalyptus nitens partition wall within test building

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Introduction

Resulting from the global awareness of climate change and its relationship to human activity, the Australian government has initiated a range of measures to reduce greenhouse gas emissions since 1992 (Harrington and Foster 1999, COAG 2010). The measures include regulations to reduce the amount of energy that may be required to condition residential and commercial buildings (Drogemuller 1999, Tucker, Newton et al. 2002, ABCB 2003). In response to these legislative changes the Nationwide House Energy Rating Scheme (NatHERS) was established and in co-operation with state governments and industry, established 69 Australian climate specific thermal comfort bandwidths, zone specific internal energy loads and star-bands, (from 0 to 10), for Australian housing (Ballinger and Cassell 1995).

Based on the newly developed Star Rating based metric it was agreed that a minimum performance rating of 3.5 to 4 Stars would be adopted by all jurisdictions in 2003-2004 (ABCB 2003). The minimum thermal performance requirement was upgraded to 5 Stars in 2006 (ABCB 2005), and to 6 Stars in 2010 (ABCB 2010). The change from no or minimal built envelope thermal performance regulations in 2002 to the 6 Star requirement of 2010 has had a significant impact on material choices and construction methods in the cooler and hotter climates (Nolan and Dewsbury 2006). It is expected that by 2020 the regulations will include other aspects that effect building energy use, including domestic hot water services and lighting, and a further increase to the minimum Star Rating requirement (Pitt & Sherry 2010).

These regulatory developments are inherently linked to the thermal performance of lightweight buildings, which rely greatly on the quality of envelope design and construction. A high quality lightweight timber framed building is achieved through the appropriate use of insulation within the subfloor, external walls, internal walls, ceiling and roofing built fabric systems, between unconditioned and conditioned spaces, and through the careful installation of building membranes to control infiltration (Nolan and Dewsbury 2006, Department of Industry 2013). The insulation will significantly reduce the unwanted outward or inward heat flow to occupied and often conditioned spaces. After matters affecting the design of a high quality envelope are achieved, and subject to climate and access or exclusion of solar radiation, thermal mass can then be used to moderate temperature fluctuations within each room (Dewsbury and Nolan 2015, Slee and Hyde 2015).

However, as the Australian design and construction sector has continued to adopt the required level of thermal performance specified by the Building Code of Australia, there has been a significant reduction in the use of lightweight timber platform floored construction systems. This has generally resulted from industry-based recommendations to use more massive systems in preference to well designed and constructed mixed mass and lightweight systems, from general marketing literature and the energy rating industry. Within these sectors there has been a common recommendation to replace lightweight construction systems with more massive systems such as a concrete slab-on-ground floor (Iskra 2004, Sustainable Energy Authority 2004, Tony Isaacs Consulting Pty Ltd 2006, Floyd Energy 2014).

The general adoption of these principles appears to be caused by opinions that any thermal mass is good, regardless of quantity or solar access, and that it is too costly or the construction process is too difficult to construct well insulated and thermally efficient lightweight buildings. This Australian pattern appears to be at odds with international design and construction trends where there are an assortment of methods to provide high quality insulation and thermal mass within lightweight buildings (Nolan and Dewsbury 2007). Within this context, there is a significant need for appropriate and specific building science knowledge and education in the Australian building design, construction and thermal performance industries (Marceau 1999, Tucker, Newton et al. 2002, HIA 2004, Iskra 2004, Productivity Commission 2004, Henderson 2005, Murphy, Head et al. 2005, Energy Partners 2007, Williamson, Plaves et al. 2007, Dewsbury, Wallis et al. 2009, Wallis and Dewsbury 2009, Dewsbury 2011). Similarly, timber products and lightweight construction should be considered as complementary elements, which can provide high thermal performance buildings, and utilises an ongoing sustainability and readily available Australian timber resource.

Thermal capacitance is not often considered within the context of lightweight buildings as the traditional materials selected to provide thermal capacitance include clay brick, cement and concrete based products. These products do provide good thermal capacitance but they are massive and have a relatively high value for embodied energy. Their significant mass requires the structural systems of the building to be increased to carry additional load, thereby further increasing the quantity of building materials, their relative embodied energy and costs. Looking to the future, the use of these traditional massive materials may reduce heating and cooling energy but also significantly increase the embodied energy and decrease the carbon sequestration of a building's construction materials. Slee et al (2013) have explored the issue of too much thermal mass. Since 2004 Dewsbury has explored the use of different materials as thermal mass and the 'right-sizing' of thermal mass to reduce the heating and cooling energy needs for new and existing houses (Dewsbury 2009, Dewsbury 2011, Dewsbury 2012, Dewsbury 2012, Dewsbury, Fay et al. 2013, Dewsbury, Tooker et al. 2013). This research has included the construction of low to zero energy homes and the completion of many house energy rating simulations which have explored built fabric and its impact on simulated heating and cooling energy. Many of the recent thermal performance simulations were completed for houses located in Tasmania and Victoria, and compared the relative thermal performance of typical timber framed, 110mm clay brick, 90mm concrete block, 90mm mass-timber and 110mm mass-timber partition wall systems (Dewsbury 2012, Dewsbury and Fay 2013). In most cases, the mass-timber partition wall system scenarios provided the best simulated thermal performance result. However, this is not just an area of exploration in Australasia, internationally there has been a recent and significant increase in researchers and practitioners exploring how thermal mass might be retrofitted to existing buildings (Aanestad 2013, Gjerde 2013).

The thermal benefits from mass-timber construction include, but are not limited to, its thermal conductivity, thermal capacitance, infiltration reduction properties, vapour permeability and thermal lag properties. Of these five significant benefits, only three are well catered for in the current house energy rating and building simulation software. Internationally, the design and manufacture of mass-timber products for use in low and medium rise residential and commercial buildings has been shown to increase thermal performance, carbon storage and earthquake resistance (Lattke and Lehmann 2007, Muller 2010, Kotsopoulos, Farina et al. 2012, Kildsgaard, Jarnehammar et al. 2013).

Past empirical validation research within the Launceston test buildings has already verified construction practices and their impact on thermal performance (Dewsbury, Nolan et al. 2007, Dewsbury, Fay et al. 2008). However, these two facets of built fabric insulation and timber products as thermal capacitance were one of many spring-boards for this research task, which has focused on two tasks, namely:

- The measured thermal performance and effectiveness of mass-timber partition walls as thermal mass.
- The measured thermal performance and effectiveness of mass-timber partition walls as thermal mass.

This report covers a vast quantity of research, and an introduction to the research task reasoning, the nation-wide house energy rating scheme system, and the general methodology. Research results follow this section. Due to the complexity and quantity of data, task-specific appendices are included with this report, namely:

- Appendix 1: Mass-timber as partition walls for thermal mass
- Appendix 2: Mass-timber flooring for thermal mass

It had originally been intended that the project would include the measured thermal performance and effectiveness of mass-timber internal lining as thermal mass. However, due to financial constraints, this task was not completed. Nevertheless, the positive findings from the partition wall and floor tasks do assert the need for empirical data on mass-timber as wall lining.

The final sections to this report are Conclusions, Recommendations (which includes future research needs), Acknowledgements and Bibliography.

Mass-timber as thermal mass

In many climates, the correct placement of thermal mass within a building is critical for optimum thermal performance. However, the general principles behind the structural systems of lightweight timber buildings have normally excluded the use of thermal mass. In response to this dilemma, the building thermal performance simulation-based research completed by Dewsbury (2012, 2013, 2013, 2015) explored the use of mass-timber as thermal mass in new housing, or as a retrofit to existing housing. The earlier research, focussed principally on the use of mass-timber as partition walls. However the 2015 research also explored the thermal performance benefits when mass-timber systems were simulated as part of floor, external wall and ceiling systems. The data from the simulated use of timber as thermal mass found that in many situations the mass-timber provided a very similar or better thermal performance result than the traditional clay brick and concrete block solutions.

Internationally, a range of construction systems have been developed that are made from solid and mass-timber materials which have been used for flooring, internal walls, external walls and ceilings to significantly improve the insulation value, construction process, building structural engineering and cost effectiveness of lightweight construction (KLH Massivholz GmbH 2012). At times the mass-timber floor has been combined with a concrete screed coating to further improve the fire retardant properties and other regulatory requirements of multi-use and multi-storey buildings. Internationally, some of these systems have been in use for more than a decade, but they have had limited use within the Australian market. Rarely has the discussion on the benefits of mass-timber systems included a critical assessment of its effectiveness as thermal mass. However, all manufacturers have completed extensive testing, (within the ISO framework) to publish conductivity and thermal capacitance values for their mass-timber products (KLH (UK) 2014).

As mentioned in the introduction, researchers in New Zealand and Australia have completed desktop building simulation research, which has shown positive thermal performance results when mass-timber elements have been added to buildings as thermal mass (Dewsbury, Geard et al. 2012, Dewsbury, Tooker et al. 2013, Gjerde 2013, Dewsbury and Chandler 2015). To ascertain whether the desktop thermal simulation research findings are correct, mass-timber systems need to be empirically tested for thermal performance benefit within real buildings. For this initial Australian empirical thermal performance task mass-timber as partition walls and flooring, was tested within the very lightweight, unenclosed, platform-floored test building at the Launceston Campus University of Tasmania. Due to the newness of mass-timber elements within the Australian construction industry, this task provided the opportunity to display mass-timber made from Tasmanian hardwood plantation E. Nitens in a vertical lamination format in a partition wall, and imported softwood cross-laminated-timber (CLT) panels were used as mass-timber flooring. In both cases detailed measurements were taken and a detailed building thermal performance simulation was completed. The simulated and measured (empirical) data were compared. The methodology of the empirical validation process is discussed in more detail below in the methodology sections.

Nation-wide house energy rating scheme (NatHERS) & empirical validation

When climatically specific and well-placed quantities of insulation and thermal mass are used, the impact on energy use to condition a house can be reduced significantly (CSIRO 2009, Aelenei 2010, Slee and Hyde 2015). The first priority in many building designs is to use passive principles to establish a thermally comfortable internal environment. However, the internal room temperatures achieved through an unconditioned passive building operation may often be hotter or cooler than the occupant's expectation for human comfort, leading to the use of mechanical heating and cooling systems. Within the NatHERS house energy rating framework, when a conditioned and occupied room becomes thermally uncomfortable natural ventilation strategies are invoked (ABCB 2006). When passive ventilation does not provide an appropriate improvement, generic energy consuming mechanical heating and cooling systems are simulated. The NatHERS system applies nationally agreed thermal comfort temperature bandwidths for 69 climate typologies within Australia (Ballinger and Cassell 1995, Delsante 2005, Lee 2005, Marker 2005, ABCB 2006). A NatHERS simulation, for energy rating purposes, calculates the amount of energy in mega-joules that may be required to maintain human thermal comfort within each room of a house.

The true benefits provided by appropriate levels of thermal mass and tight well-insulated buildings can only become obvious when the energy required to maintain acceptable levels of thermal comfort is reduced. A significant by-product of this research is the acquisition of high quality data sets which can be used to inform the ongoing improvement and calibration of the CSIRO developed CHENATH building simulation software, which is the principle tool behind the Australian AccuRate, BERS and FirstRate house energy rating tools. Two key components of the NatHERS scheme are within the scope of this research, namely:

- The capacity for the software to adequately calculate the environmental temperature within a lightweight residential type of building
- The capacity for the software to adequately calculate the heating and/or cooling energy required to maintain thermal comfort.

Previous research has established that the occupancy and conditioning patterns adopted by the NatHERS do resemble modern households (Ambrose, James et al. 2013).

Additionally, recent empirical validation research has documented that the AccuRate and CHENATH softwares do consider built fabric and climatic variables quite well, but differences between measured and simulated results indicated the need for continuous built fabric, thermal mass and heating/cooling energy calculation algorithm improvement (Delsante 2006, Dewsbury, Soriano et al. 2009, Dewsbury 2011, Dewsbury, Soriano et al. 2011, Geard 2011, Dewsbury and Fay 2013, Dewsbury, Geard et al. 2014, Dewsbury 2015). One of the many recommendations from these previous research tasks was the matter of built fabric thermal mass, as its non-inclusion in the thermal calculation model may have been one of the possible causes of observed differences between measured and simulated temperatures. This is an important issue for the timber industry, as softwood and hardwood framing systems may provide significant thermal mass benefits within lightweight buildings, especially when the framing is partially or fully separated from the external environment and thermally connected to the internal environment. Within this context this research explored the effect of including the built fabric thermal mass within the detailed building simulations.

The resultant heating and cooling energy calculation provides the numeric input for a NatHERS star rating. For this to occur, the software must firstly calculate the temperature within each room of a house relative to the external environment. When the simulated room temperature is not within the accepted climate based thermal comfort bandwidth, the software invokes cooling and/or heating operation. The annual amount of heating and cooling energy calculated by the software establishes the star rating for the building (ABCB 2006).

To validate the effectiveness and correctness of building simulation software the results from detailed building simulations must be compared to measurements from a real building. This empirical validation methodology is internationally accepted as a requirement for all building simulation software tools. The empirical validation methodology is discussed below in the methodology sections.

The simplest method for comparing measured and simulated data is attained from the unconditioned mode of building operation, where the only energy inputs within the test building are the internal loads from the data logging equipment and, subject to internal and external temperatures, the flow of energy into or out of the test building (Dewsbury, Soriano et al. 2011, Dewsbury 2015). The more complex empirical validation of the heating and cooling energy calculations requires the building to be operated in heated and cooled modes. To date there has been no Australian empirical validation research, which has compared the energy use of a thermally controlled and conditioned test building to the energy calculation from a detailed simulation from the AccuRate Nationwide House Energy Rating Scheme approved house energy rating software. The inclusion of the heating and cooling component within this research allows for software developers to be made aware of differences between simulated and measured data sets for the ongoing improvement and calibration of the CSIRO developed building simulation tools.

Finally, although not a part of this research task, most accredited NatHERS software programs now include an embodied energy and carbon sequestration calculation module. These have been developed and implemented to allow for the accounting of built fabric carbon sequestration and embodied energy. The use of mass-timber for thermal mass, when compared with other traditional forms of thermal mass, may reduce the embodied energy and increase the carbon sequestration of the built fabric providing further incentives to use modern wood products in lightweight and thermally comfortable buildings.

The solid wood context

In Australian there is a significant and established private and public investment of just over two million hectares of hardwood and softwood plantation forests to help meet future solid timber, reconstituted wood and pulp product needs. About half of Australia’s plantations are softwood, mainly radiata pine, largely managed for sawlog production. In contrast, more than 75% of hardwood plantations are managed for fibre production. Only around 7% of the hardwood plantation estate was established for hardwood sawlog production, with only a small proportion being managed to maximize sawlog quality (ABARES 2012).

Due to international trends, the expected markets for the output from these plantations is now in flux, which has significantly impacted demand for pulp fibre. Additionally, the logs from Australia’s plantation estates are yielding significant quantities of low-grade material that is unacceptable for Australia’s dominant solid timber construction systems (sawn boards for appearance, and structural uses). Much of this low-grade plantation material is unacceptable for appearance applications, and fails to meet either standard and market requirements for strength or board distortion for structural applications. Internationally, the confluence of the collapse of the pulp wood market and the increasing quantities of low-grade solid wood has generated significant interest in the design of new mass-timber materials, enabling higher utilisation rates from plantation forests.

Increasing quantities of low-grade material are being produced from Australia's softwood and hardwood plantation forests. In some of Australia's largest softwood sawmills up to 50% of the sawn production does not meet structural grade requirements and is categorised as 'fall-down' grade, with limited, and at times unviable, market opportunities. Most of this low-grade sawn wood is sold at a loss (Stringer, 2012). Additionally, Australia's hardwood plantations are yielding significant volumes of low-grade material. Tasmania has the largest hardwood sawlog plantation estate in Australia, most of which is shining gum (E.nitens). These sawlog plantations are expected to supply around 150,000 m^3 of high quality sawlog each year in Tasmania from 2025 onwards. However, the remaining sawlog supply, around 780,000 m^3 a year, has been found to be of much lower quality. Previous research has demonstrated the low recovery rate for appearance and marketable structural grade sawn timber and veneer from plantation hardwoods (Innes and Greaves 2007, Farrell and Blum 2012). This has resulted in the exploration of various composite and solid wood products, with limited success.

The national plantation log harvest in 2009-2010 was 18.6 million cubic metres with an approximate value of $1.4 billion. This is forecast to increase to an annual average of 29 million cubic metres a year by 2015. By 2025, plantation hardwood sawlog supply is expected to increase to 1.3 million cubic metres a year. Using ABARE forecasts for plantation softwood and hardwood log production, and assuming a conservative 35% of sawn output is fall-down grade, then by 2015 an estimated 10 million cubic metres of low-grade material, with a negative financial value, will be produced each year. Significantly, it is predicted that 73% of Tasmania's hardwood plantation forests will yield poor quality material unsuitable for traditional solid products (ABARES 2012)

While the low-grade timber has limited marketability under current building practice, due to low strength and/or excessive deformation, mass-timber products may be able to use this low-grade plantation timber. Mass-timber elements are large timber panels assembled from sawn board held together with glue, mechanical fasteners or both in combination (). Significantly different from glued, peeled veneer and stick constructed glue laminated products, mass-timber products have the potential to act as a structural system and surface material simultaneously (Figure 3). Subject to the system design approach taken, mass-timber products can support multi-directional and multi-planar loads, yielding a product that is significantly more versatile than traditional timber stick, block masonry and concrete slab construction systems (Figure 4). Additionally, this dimensionally accurate and lightweight material lends itself to the use of digital prefabrication systems, which internationally, have been shown to provide more thermally efficient and economical housing.

Figure 2: Photograph of CLT panel (Courtesy of Tilling)

Figure 3: CLT panel wall in multi-storey construction (www.karakusevic-carson.com/2012/bridport-house-hackney)

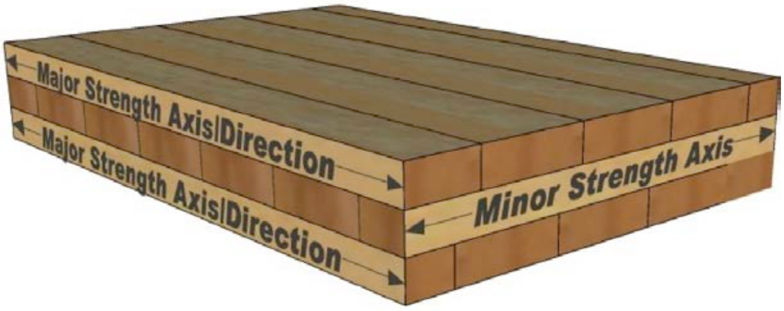

Figure 4: Diagram of cross-laminated timber panel (www.crosslamsolutions.com)

Methodology

To empirically validate the thermal performance of built fabric systems requires the careful combination of test buildings, detailed building environmental measurement, non-standard detailed building thermal simulations and the comparison of measured and simulated data, as shown in Figure 5 (Lomas, Eppel et al. 1994, Strachan 2008, Dewsbury 2011). The comparison between measured and simulated data sets allow for the identification of building simulation input variables that may need to be modified and/or algorithms that require improvement. This research task required the detailed measurement, the detailed thermal simulation and the analysis of the measured and simulated data sets of the two mass-timber built fabric systems as described below. The common elements of the methodology are discussed within this section. Task specific elements are discussed within the Appendix for each task.

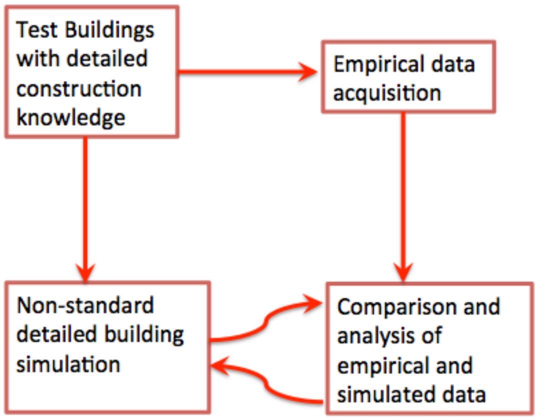

Figure 5: Empirical validation task framework

Built Fabric Methodology

Three purpose built thermal performance test buildings were established on the Launceston Campus University of Tasmania, in 2006 (Dewsbury, Fay et al. 2007, Dewsbury, Nolan et al. 2007, Dewsbury, Soriano et al. 2009, Dewsbury, Soriano et al. 2009, Dewsbury 2011, Dewsbury, Soriano et al. 2011, Dewsbury and Fay 2013). They were purpose-built for material thermal performance analysis and empirical validation research tasks for industry and government collaborators. The three test buildings comprise an unenclosed-perimeter platform-floored, enclosed-perimeter platform-floored and concrete slab-on-ground floored construction systems. For this task, Test Building 1, the unenclosed-perimeter platform-floored test building, as shown in Figure 6, was used.

Figure 6: Unenclosed-perimeter platform-floored test building

Task 1: Mass-timber partition walls as thermal mass

To ascertain if the positive thermal performance benefits from the previous simulation based mass-timber as thermal mass research is reflected in reality, the use of mass-timber for thermal mass required empirical validation. In line with the earlier desktop research, the first mass-timber system to be validated was the use of mass-timber as partition walls. Due to the limited availability of imported product and a desire from the research team to explore benefits from Australian plantation timbers, this task utilised Tasmanian plantation Eucalyptus Nitens. The method of constructing the mass-timber partition wall required:

- The sourcing of kiln dried, 90mm x 35mm E. Nitens plantation grown timber,
- The vertical nail lamination of the boards (as shown in Figure 7), and
- The joining and erection of panels within the test building room to mimic a partition wall (as shown in).

A more detailed account of this task is discussed in Appendix 1.

Figure 7: Nail lamination of E. Nitens 90x35 boards

Figure 8: 90mm thick, vertically laminated E. Nitens panels installed as partition walls

Task 2: Mass-timber flooring as thermal mass

As this task was to be completed after Task 1, a significant lead-time was established, which allowed for a deeper exploration of mass-timber systems that may be available in Australia. Tilling, who were a project collaborator, at this time was exploring a business model, which included the import of European made cross-laminated-timber (CLT) panels. To help promote product awareness, Tilling provided three softwood CLT panels for the mass-timber as flooring task. The methodology followed for this built fabric comprised:

- The mass-timber product was selected by the project steering committee,
- A manufacturer provided a softwood cross laminated timber (CLT) product accessible to the Australian construction industry,
- UTAS staff received the product in Launceston, and
- UTAS staff co-ordinated the installation of the panels, which were laid on top of the existing particleboard floor of the unenclosed-perimeter, platform-floored test building (as shown in Figure 9 and Figure 10).

A more detailed account of this task is discussed in Appendix 2.

Figure 9: 180mm 5 ply softwood CLT panel

Figure 10: Three softwood CLT panels installed inside test building on top of existing particleboard floor

Data acquisition methodology

For appropriate environmental measurement and data collection to occur, an extensive array of sensors was placed within the test building and on the timber elements. Additionally, a site weather station was used to obtain appropriate data for the simulation software climate file. This type of framework would enable a suitable measurement and data acquisition process to support the detailed thermal performance simulation and the comparison of measured and simulated data sets. This framework was developed by Dewsbury at the Launceston test buildings in 2006 (Dewsbury 2011, Dewsbury 2015).

The generic thermal measurement profile within the test building, for this task, is shown in Table 1. The measurements taken from the 600mm, 1200mm, 1200mm globe and 1800mm were averaged to provide an average room temperature. A site weather station collected data for air temperature, relative humidity, wind speed, wind direction and global solar irradiation, which were used in conjunction with other data from the Bureau of Meteorology to create experiment-specific climate input files. Additionally, high quality energy use metering was collected by one of the research collaborators, Aurora Energy, for comparison to simulated energy use.

The installation of all sensors required an initial calibration followed by intermediate calibration during the completion of the two research tasks. All temperature sensors were individually checked for calibration at zero degrees Celsius, room temperature and a temperature close to boiling point, as shown in and Figure 12. Any temperature sensor that did not provide a result within 0.2ºC was removed. However most temperature sensors were within 0.1ºC of the calibration temperature. The solar radiation, relative humidity and wind speed sensors were compared to output data from similar, pre-calibrated, sensors. The wind direction sensor output was compared to synchronous compass bearings taken beside the wind vane.

Table 1: Test building thermal measurement profile

Description	Function
1000mm below ground level temperature	Background & supporting data
Ground surface temperature	Background & supporting data
Mid-subfloor zone temperature	Thermal performance and validation data
Outside subfloor insulation surface temperature	Background & supporting data
Inside subfloor insulation surface temperature	Background & supporting data
Outside platform-floor surface temperature	Background & supporting data
Inside platform-floor surface temperature	Background & supporting data
600mm test building room temperature x 3	Thermal performance and validation data
1200mm test building room temperature x 3	Thermal performance and validation data
1200mm globe temperature x 3	Thermal performance and validation data
1800mm test building room temperature 3	Thermal performance and validation data
Inside ceiling surface temperature	Background & supporting data
Outside ceiling surface temperature	Background & supporting data
Outside ceiling insulation temperature	Background & supporting data
Mid-roof space air temperature	Thermal performance and validation data
Inside sarking surface temperature	Background & supporting data
Outside sarking surface temperature	Background & supporting data
Inside sheet-metal roof surface temperature	Background & supporting data
Outside sheet-metal roof surface temperature	Background & supporting data

With the exception of the energy use data, which was collected cumulatively every fifteen minutes, all other data was collected at ten minute intervals. All data, once cleaned, was averaged to hourly data for comparative analysis with the detailed simulation output temperature files (Lomas 1991). Other data that was collected, but is not included in this report, included a range of heat flow (flux) measurements, direct vertical north solar irradiation and diffuse solar irradiation. This data requires significant analysis and will be presented in future publications.

Figure 11: Thermoline calibration equipment for heated temperature sensor calibration

Figure 12: An ice filled thermos for cooled temperature sensor calibration

To gain adequate information on thermal performance and relative energy use, the test building operation for each built fabric task included four operational modes, namely:

- unoccupied and unconditioned (commonly known as 'free running' or 'free floating')
- unoccupied and continually heated (to a pre-set temperature)
- unoccupied and intermittently heated (to mimic a NatHERS room operation)
- unoccupied and continually cooled (to a pre-set and agreed temperature).

The temperatures measured, and the heating or cooling energy consumed, to maintain pre-set temperatures was compared to the outputs from the non-standard detailed simulation from the AccuRate house energy rating software.

Detailed thermal performance simulation methodology

To enable a more correct analysis of simulated and measured thermal performance data required the completion of non-standard house energy rating simulations. A standard thermal simulation and energy calculation for house energy rating includes a range of accepted default values for built fabric, infiltration, internal heat loads, thermostat set points and climate input data. All of these can vary significantly from the as constructed built fabric and the climatic conditions during the research task (Clarke, Strachan et al. 1994, Girault 1994, Lomas, Eppel et al. 1994, Strachan 2000, Dewsbury 2011). To enable a rigorous comparison of the measured and simulated data set results, changes were made to some front-end input and back-end scratch file inputs for each simulation, as shown in Table 2. Temperature thermostat set points for simulating the heated and cooled modes of operation were only established once the test building room data had been acquired and cleaned.

The initial research proposal only included the use of a modified conductivity value for the floor, walls and ceiling to account for the reduction in insulation caused by the framing factor (Syed and Kosny 2006, Kosny, Yarbrough et al. 2007, Dewsbury, Wallis et al. 2009). However, during the early stages of the research some collaborators requested that two simulation types be completed. The first simulation type was to include the modified conductivity values as described above. The second was to model each floor, wall and ceiling element as components, which allowed for the built fabric (timber framing) to be accounted for as thermal mass and insulation. For example, a wall might be modelled as:

- 10 m^2 plasterboard, insulation, cavity, cladding, and
- 1 m^2 plasterboard, 90mm softwood, cavity, cladding.

Table 2: Modified inputs for detailed simulation

Description	Reason	Experiment Type
Modified floor, wall and ceiling U-values	To account for the reduction in insulation resulting from timber framing	All simulations
Modified infiltration values	To use measured infiltration values rather than the default values	All simulations
Modified internal load values	To use measured internal energy load values rather than the default values	All simulations
Modified heating set points	To reflect the thermal condition of the experiment	Zero for free running and cooled modes of operation. Measured value for heated modes of operation.
Modified cooling set points	To reflect the thermal condition of the experiment	Zero for free running and heated modes of operation. Measured value for cooled modes of operation.
Natural ventilation	To account for non-ventilated operation	Hours of operation and thermostat set points set to zero.

The inclusion of the two simulation methods did provide different results, but also more than doubled the research task workloads by establishing eight simulation types for each built fabric type, namely:

- unconditioned with modified U-value (no-mass)
- unconditioned with modified built fabric thermal mass (with-mass)
- continuously heated with modified U-value (no-mass)
- continuously heated with modified built fabric thermal mass (with-mass)
- intermittently heated with modified U-value (no-mass)
- intermittently heated with modified built fabric thermal mass (with-mass)
- continuously cooled with modified U-value (no-mass)
- continuously cooled with modified built fabric thermal mass (with-mass)

The completion of the detailed simulation tasks provided simulation data sets, which were compared to the measured data sets for comparison and validation. The data sets included simulated hourly temperatures and energy for the subfloor zone, test building room and the roof space zone.

Data comparison methodology

The building software simulation tools have been developed to provide guidance on methods to provide better thermally performing and low energy buildings to building designers, regulators, individuals and organisations. The comparison of the simulated and measured data sets provide the critical findings for this research, i.e., is the software is producing a similar result to what has been measured. In this task the measured data was averaged into hourly values and the output data from the simulations was in an hourly format. To enable a quick and visually apparent comparison, the time series graphing function within Excel was used. An example of a time series graph is shown below in Figure 13. Each graph shows the average measured zone temperature, the with structural mass simulation data, the no structural mass simulation data and the site air temperatures for the duration of the task. This form of analysis allows for the quick identification of differences between the simulated and measured data. Additionally, this method is used to visualise the differences between the maximum and minimum simulated and measured data sets. This is a different approach from much of the northern hemisphere research where there is a strong focus on the average values and climates often require significant and year round heating. However, in Australia the average temperature may often be within human comfort bandwidths and the heating and or cooling may be used on a daily basis at times of minimum and maximum room temperature. Within this context, an awareness of differences that occur at these daily extremes is paramount for designing better Australian homes.

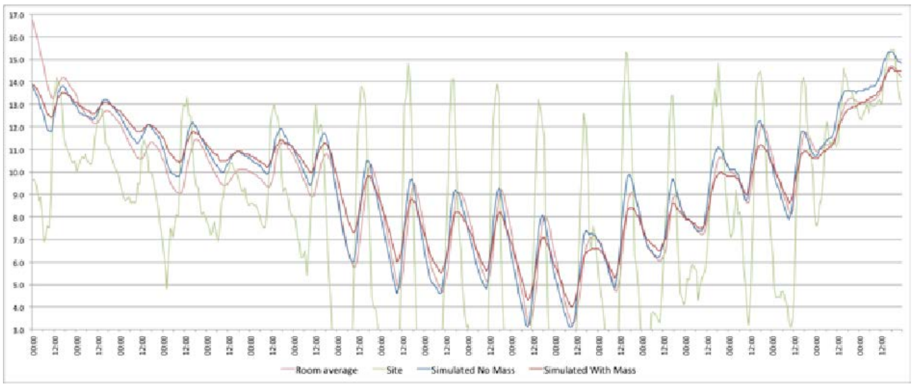

Figure 13: Example of time series analysis graph

Additionally, the residual values (measured data minus simulated data) were analysed graphically in a time series graph, as shown in Figure 14. This form of analysis high-lighted what often appeared to be daily patterns in the differences between simulated and measured data, which often occurred at times of daily minimum or maximum site temperature. A positive residual value = and under calculation of zone temperature. A negative residual value = an over calculation of zone temperature.

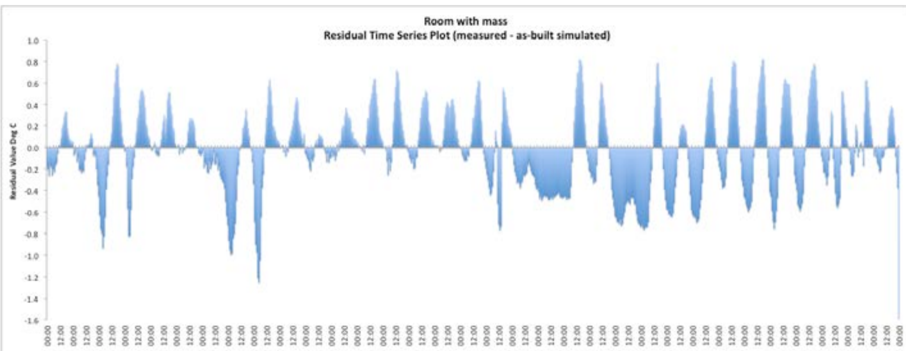

Figure 14: Example of residual time series analysis graph

These forms of graphical analysis provide an immediate visual representation of the data and form the basis for representing the data and results. However, to provide a deeper analysis of the data will require the use of statistical methods (del Mar Izquierdo 1995, Ghiaus 2003, Dewsbury 2015), which will be completed and published in future documents.

Methodology summary

The discussion above provides a detailed summary of the steps taken to establish built fabrics, acquire measured thermal performance data and the detailed building simulation process and the method used to compare the measured ands simulated data-sets. The next section presents task-specific experiences and findings from the research tasks.

Results and Discussion

The results and discussion for this research come from eight different experiments. Each experiment ran for a minimum of twenty days. Each experiment acquired seven data sets which included measured temperatures, measured energy use, site weather data, BOM weather data, simulated temperatures and simulated energy use. The total research task has acquired 56 data sets. The data from each experiment was combined within Excel spread-sheets, to allow for graphical and analytical comparisons. The task-specific appendices include the graphical analysis of measured and simulated data for each experiment, within each task. The following section summarises some of the key findings.

General non task specific results

This research has found several matters that are common across most of the experiments within each of the two tasks. These are presented below in dot point form.

1. There were often significant differences between the measured and simulated temperatures from the unenclosed-perimeter platform-floored subfloor zone, as shown in Figure 15.

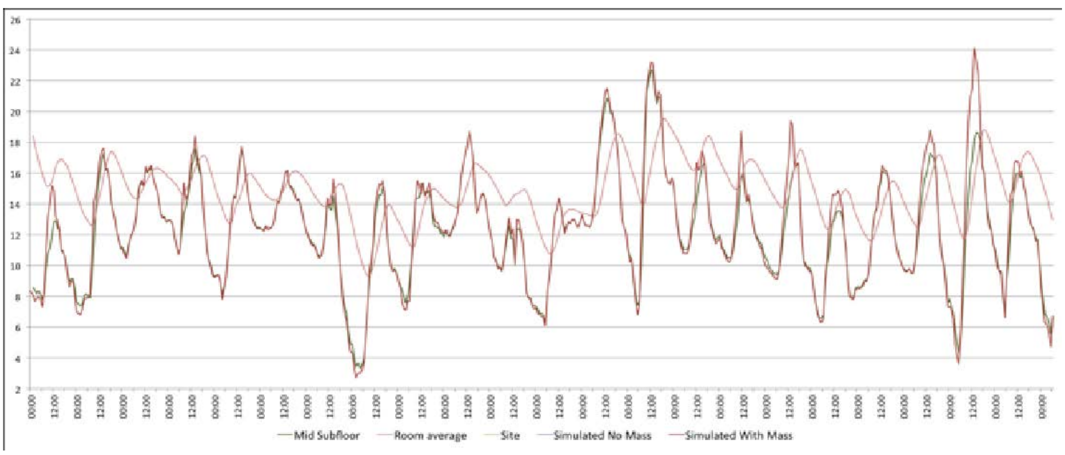

Figure 15: Unconditioned subfloor measured and simulated temperatures for mass-timber flooring as thermal mass

The variation between the measured and simulated subfloor zone temperatures, from the eight experiments, is shown below in Table 3. This significant variation was due to the current assumption within the NatHERS protocol that the temperature of an unenclosed-perimeter platform-floored building's subfloor zone is the same as the site air temperature. However, this research and previous research (Dewsbury 2011) demonstrates that this assumption is incorrect. Subject to the energy levels within the building and the floor built fabric system, (structure, lining and insulation), the energy flows between the room and the subfloor may be significantly different. In the context of cool site temperature leading to the operation of heating, a significantly warmer subfloor zone would lead to a lessor amount of energy loss from the heated room to the subfloor, leading to a warmer room or a lessor amount of energy use.

Table 3: Variation between measured and simulated subfloor zone temperatures

No-mass Simulation		With-mass Simulation	
Minimum	- 9.1 to – 1.5	Minimum	- 9.1 to – 1.6
Maximum	+ 1.1 to + 4.9	Maximum	+ 1.1 to + 4.9
Average	- 0.3 to - 0.6	Average	- 0.3 to - 0.6

There were often significant differences between the measured and simulated temperatures of the roof space zone, as shown in Figure 16. The greatest differences were observable between the maximum measured and simulated temperatures. The significance of the differences between simulated and measured maximum and measured temperatures is shown in

2. Table 4, where variations of up to -17.3°C (over calculation) for minimum zone temperature and +11.3°C (under calculation) for maximum zone temperature. An analysis of residual values and global solar radiation indicates that some of these variations may be due to radiant heat flow calculations. In a similar pattern to the subfloor scenario discussed above, the significant differences in roof space energy would effect the energy flow calculations between the roof space and the test cell room.

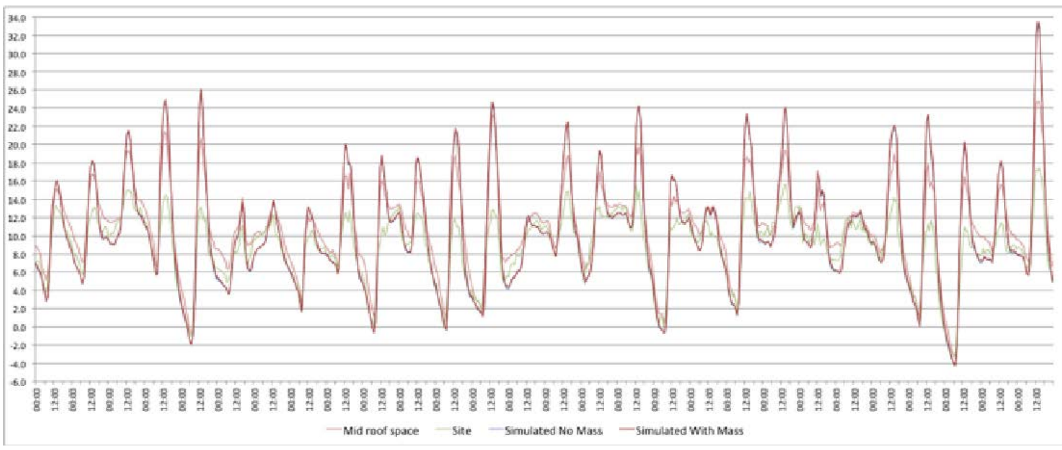

Figure 16: Intermittently heated task roof space zone measured and simulated no-mass and with-mass temperatures for mass-timber partition walls

Table 4: Variation between measured and simulated roof space zone temperatures

No-mass Simulation		With-mass Simulation	
Minimum	- 17.3 to – 1.5	Minimum	- 13.3 to – 1.6
Maximum	+ 3.9 to + 11.3	Maximum	+ 3.2 to + 11.3
Average	- 0.2 to + 1.7	Average	- 0.2 to + 1.8

The detailed simulations established a ‘raw’ energy use to condition the test building room, as shown in Figure 17. The green line represents the raw simulation result, whilst the orange line shows the measured energy use. As the software uses a simplify energy calculation, significant differences were expected. To account for the coefficient-of-performance (COP), of the reverse-cycle air-conditioner, the raw energy calculation was divided by 4.86, and is shown by the red line. This action provided a simulated energy use that was considerably less than the measured energy use. However, several researchers have found significantly higher energy consumption by air-conditioning systems, as installed in real buildings, and have called into question the standard method of testing for COP certification (Dunn 2005, Butler, Curtis et al. 2013, Mavuri 2014). To better estimate the as-built operational COP of the installed split-system reverse-cycle air-conditioner, the measured energy and output performance were analysed resulting in an operational COP closer to 2.4, rather than the laboratory certified 4.86. Considering there was approximately 400mm distance between the external inverter and the internal fan system, this significant difference in COP is of concern.

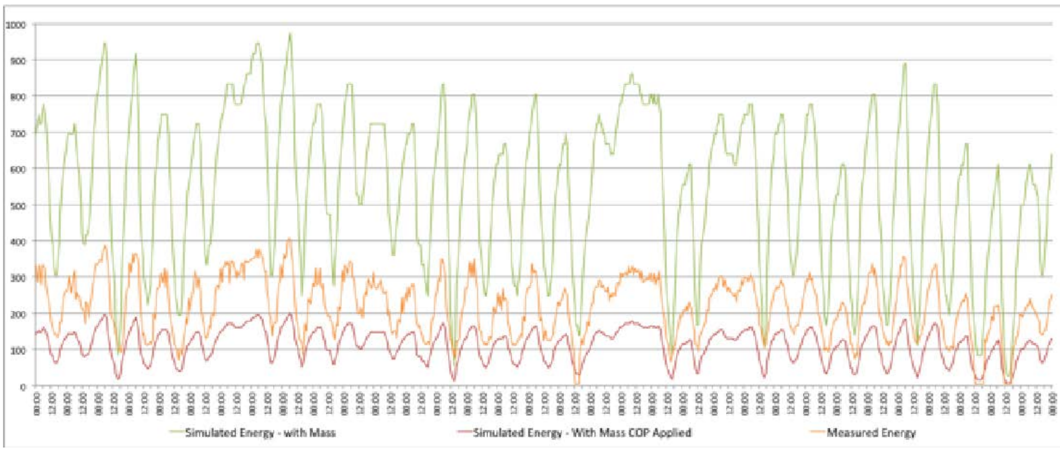

Figure 17: Measured and simulated with-mass energy use for test cell room during the continuously heated mode of operation

There is a need for simulation tools to allow for the input of heating and cooling equipment, which accounts for plant and equipment efficiency. However, this research has shown a significant difference between the laboratory test result and the measured installed energy use. This difference requires further investigation as the operational efficiency of the air-conditioner, the thermal resistance of the built fabric, or the thermal capacitance of the built fabric may all be contributing to the significant differences.

3. One of the key aspects of the implementation of thermal performance regulations is the capacity to reduce peak energy demands. This research has established three key aspects, namely:
- the correlation between the simulated and measured test cell room results show that the software is considering the thermal mass effect of the mass timber elements. This provides empirical data to support the previous simulation based thermal performance research, which showed lower energy needs, (or higher star rating results), when mass-timber improved buildings were compared to normal low mass buildings and traditional concrete or clay brick thermal mass buildings.
- By further including the built fabric thermal mass, peak energy demand can be further reduced, as shown below in Figure 18.
- The significant difference between measured use and simulated raw energy demonstrated that energy efficient appliances would play a significant role in the reduction of peak energy demand for heating and cooling Australian homes.

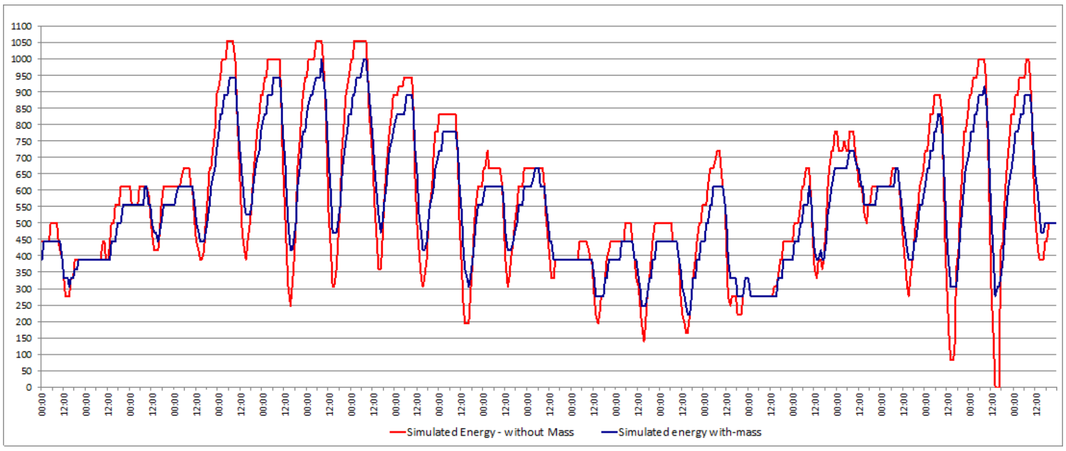

Figure 18: Simulated heating energy use for no-mass and with-mass built fabric variations

4. The reverse-cycle air-conditioner was selected based on its efficiency and its capacity to provide cool air, to allow a comparison of measured and simulated energy use for cooling. However during this research it was established that the on-board computer that forms a part of the equipment's efficiency and compliance, would not allow the room to be cooled to less than 18°C. Attempts were made to over-ride this control mechanism but they were unsuccessful. This doomed some of the continuously cooled tasks, leading to some limited success. Future research must consider the timing of experiments relative to site climate, to enable the completion of an effective and productive cooled operation experiment.

5. This research collected surface temperature data from the mass-timber partition walls and mass-timber flooring, which showed a consistently higher temperature than the room air temperature, indicating that the mass was storing energy for the air. This data requires deeper analysis to establish patterns of energy storage that are occurring.

6. This research collected surface flux measurements, which revealed the absorption and release of energy by the mass-timber walls and mass-timber flooring, which confirms the mass-timber is acting as a thermal capacitor. This data requires deeper analysis to

establish the rate of energy absorption and release relative to the mass and air temperatures.

To provide a better and more detailed report on the results from each task, they are listed below in dot point form. In all cases there is further information within the appendix for each task.

Task specific mass-timber as partition walls as thermal mass results

In this research task, a 90mm thick mass-timber partition was constructed from E. nitens plantation timber and installed within the very lightweight, unenclosed-perimeter platform-floored test building, as shown in Figure 7 and Figure 8. Extensive environmental and energy measurements were taken to provide a measured data set. The building was operated, unoccupied, in unconditioned, continuously heated, intermittently heated and continuously cooled modes of operation. The continuously cooled mode did not work as expected but has still provided valuable data for comparison. Detailed, as-built, no-mass and with-mass simulations were completed to provide a simulated data set. The analyses in this report have compared the measured and simulated thermal performance and the relative energy use to condition the test building room in its four modes of operation.

Initial analysis has revealed several findings, namely:

- As mentioned above, there were significant differences between the subfloor measured and simulated temperatures.
- As mentioned above, there were significant differences between the roof space measured and simulated temperatures.
- There were regular, and at times, significant differences between the test building room's measured and simulated temperatures. Often the average difference was quite small, but differences between the simulated and measured maximum and minimum temperatures were from -1.5^{o}C to +3.2^{o}C, which may have a significant impact on cooling and heating energy calculations.
- The inclusion of the built fabric thermal mass had a variable impact on the test building room simulations. Subject to operational mode and climatic conditions, the closeness of fit was generally better from the no-mass simulation type. However, this does require further analysis.
- The detailed analysis, as presented in Appendix 1, shows a reasonable correlation between simulated and measured temperatures, which confirms the thermal performance characteristic that mass-timber partition walls can provide effective thermal mass.
- Generally, as much as there were differences observed between the measured and simulated temperatures, the software did respond to hourly changes in environmental inputs.
- As mentioned above, the simulated raw energy use data was significantly different from the measured reverse-cycle air-conditioner energy use during heated modes of operation. This aspect of the software requires further empirical validation and calibration.

For further task specific information refer to Appendix 1.

Task specific mass-timber flooring as thermal mass results

In this research task, three cross-laminated timber panels made from European softwood species were provided by Tilling. The three panels were laid on top of the existing 19mm particleboard floor within the lightweight, plywood clad, unenclosed-perimeter platform-floored test building. Extensive environmental and energy measurements were taken to provide a measured data set. The building was operated, unoccupied, and unconditioned, continuously heated, intermittently heated and continuously cooled modes of operation. The continuously cooled mode only collected thirteen days of relevant data due to a power fluctuation that caused the reverse-cycle air-conditioner to turn off. Detailed, as-built, no-mass and with-mass simulations were completed to provide a simulated data set. The analyses in this report have compared the measured and simulated thermal performance and relative energy use to condition the test building room in its four modes of operation.

Initial analysis has revealed several findings, namely:

- As mentioned above, there were significant differences between the subfloor measured and simulated temperatures.
- As mentioned above, there were significant differences between the roof space measured and simulated temperatures.
- There were regular, and at times, significant differences between the test building room measured and simulated temperatures. During the unconditioned mode of operation the average difference was +0.2ºC, but the differences between minimum and maximum temperatures were more significant with a range of -3.2ºC to +3.4ºC. Generally, the measured room temperature was warmer than the simulated no-mass and with-mass data. This could be caused by the mass-timber providing greater thermal capacitance and/or insulation, or other external influences from the built fabric, subfloor zone or the roof space zone could be providing more energy than assumed. This requires further investigation and analysis.
- The inclusion of the built fabric mass had a variable impact on the test building room simulations. Subject to operational mode and climatic conditions, the closeness of fit was generally better from the no-mass simulation type. However, this does require further analysis.
- The analysis, as presented in Appendix 2, shows a reasonable correlation between simulated and measured temperatures, which supports the thermal performance characteristic that mass-timber flooring can provide effective thermal mass and additional insulation.
- Generally, as much as there were differences observed between the measured and simulated temperatures, the software did respond to hourly changes in environmental inputs.
- As mentioned above, the simulated raw energy use data was significantly different from the measured reverse-cycle air-conditioner energy use during heated modes of operation. This aspect of the software requires further empirical validation and calibration.

For further task specific information refer to Appendix 2.

Conclusion & Recommendations

This research undertook an empirical thermal performance assessment of two built fabric systems in conditioned and unconditioned modes of operation. Each of the built fabric systems was modelled within a building energy simulation program and used to complete as-built, experiment specific, detailed thermal performance simulations. From the data discussed above, and within Appendix 1 and Appendix 2 there were many findings.

Firstly, the general patterns of the measured and simulated data sets for the subfloor, room and roof space zones were similar, which indicates that the CHENATH software is considering many built fabric and climatic inputs but requires ongoing improvement and calibration.

In the unconditioned tasks there were significant differences between the measured and simulated data sets of the subfloor, room and roof-space zones. The differences often occur at minimum and maximum temperatures, which would also correspond with times when heating or cooling operation would be called upon to maintain thermal comfort. If the roof space were consistently warmer, then more energy would be flowing into the room, similarly if the subfloor zone were warmer, but cooler than the room; there would be a lesser flow of energy to the subfloor. Furthermore, the heating and cooling energy calculations may be significantly affected if the test building room is storing more energy or has a slower loss of energy. All these instances would impact on the energy within the test building room and corresponding heating and cooling energy to maintain human comfort. However, some of the differences appear to be linked to climatic variables, and this requires further investigation.

The Australian building simulation methodology adopts the site air temperature as the subfloor zone temperature within an unenclosed-perimeter platform-floored building. Past research has questioned this approach (Dewsbury, Soriano et al. 2009, Dewsbury 2011). This research has also identified significant differences between the measured subfloor zone temperature of the 6m x 6m building and the site air temperature. One could presume that the differences would be greater for a larger building. This aspect requires software improvement and calibration.

This research developed two simulation types, no-mass modified U-value and with-mass built fabric thermal mass. This research did show that this variation in the simulation input often produced significantly different results for the test building room and roof space, with a much less apparent effect on the subfloor temperatures. However, the two simulation types provided varying qualities of better fit between the simulated and measured data sets. This requires further analysis to establish probable benefits from, or problems with, the inclusion of the built fabric thermal mass, and to ongoing software development and algorithmic improvement.

The analysis of the measured and simulated energy use raised more questions than answers. As a reverse-cycle air-conditioner was used to provide heating and cooling it was expected that there would be significant differences between the measured and simulated data sets. However, it was expected that when a COP multiplier was used the differences between the measured and simulated data sets would reduce. However, the application of the COP multiplier allowed the measured energy use to be greater than the simulated energy use. This is a complex issue and requires further investigation, as the built fabric or the true efficiency of an installed reverse-cycle air-conditioner could be the cause the differences. One of the challenges that may face the deeper analysis of the reverse-cycle air-conditioner coefficient-of-performance is the current approved laboratory based testing method. The differences between a laboratory and the variability of a site environment and installation practise may be providing systemic losses that reduce the COP. This does require further investigation. Furthermore, one of the key aspects of thermal performance legislation is to reduce both general and peak energy demands. The use of reverse-cycle air-conditioners in this task showed a significantly lower measured peak energy demand when compared to the raw simulated energy needs, indicating that high efficiency appliances need to be included within the regulatory mix for heating and cooling of buildings.

The two tasks, mass-timber as partition walls and mass-timber as flooring, both produced results which confirmed the ability for mass-timber to act as a thermal capacitor, an additional insulator, reduce general heating and cooling energy loads and reduce peak heating and cooling energy loads. This confirms the potential for mass-timber elements to improve the thermal performance with small to medium buildings, which was established in the previous desktop-based building simulation research. This potential is corroborated by the reasonable correlation between the measured and simulated data sets, which provides initial empirical validation. The additional data, which included the surface temperatures and surface flux measurements provide additional supporting documentation of the thermal capacitor and thermal insulation properties. However, as discussed in the introduction, further research needs to occur to ensure that the right climate specific amount of mass-timber, as thermal capacitance, is designed into new and retrofitted to existing buildings.

Additionally, when used as a component of the external structure mass-timber elements provide additional thermal resistance and reduce the opportunities for unwanted infiltration and exfiltration. The thermal resistance benefits were validated within the mass-timber flooring as thermal mass task. However the benefits that may be achieved from infiltration and exfiltration reduction have not been tested yet.

This research task has raised many questions but some key areas of future research have been identified, namely:

Mass-timber

- This task collected data on mass-timber surface temperatures and flux. This data needs to be further analysed as it included Tasmanian plantation hardwood and European softwood mass-timber materials. The data requires further analysis to establish the rate of energy absorption and release subject to the test cell room temperature.
- This task has not had the capacity to explore the thermal performance benefits that may be achieved from mass-timber as insulation and thermal mass as in internal lining, or as a ceiling, or as a combined floor, external wall lining, partition wall and ceiling system. This focused research must occur to provide an informed marketing advantage over traditional concrete and clay brick massive elements.
- The opportunity to construct a small building with mass-timber elements as floor, lining and ceiling needs to occur to test and validate the infiltration and exfiltration benefits that may occur from this comprehensive building system.
- Further research needs to occur to support the development of Australian low-grade plantation wood use as locally made mass-timber materials.

CHENATH & AccuRate calibration

- A newer version of AccuRate with algorithmic improvements within the CHENATH program has recently been released. These simulations described above should be completed a second time to establish if the CHENATH improvements have reduced the differences between measured and simulated data sets.

- The tasks completed within this research need to be continued, so as to test other built fabric systems and the accuracy with which Australian thermal performance tools simulate temperatures and energy used to maintain human comfort.

Heating and Cooling Energy

- The reverse-cycle air-conditioner measured and simulated raw and COP applied energy uses are significantly different. This requires further investigation to ascertain if it is a built fabric or appliance-based issue.
- The test buildings have fan heaters installed. Now that the data acquisition process and test building room control has been demonstrated, it would be beneficial to collect a comparison energy use data set from less efficient heating sources.
- Similarly, other forms of heating and cooling could be tested.

Finally, this research task collected a large amount of data that needs further analysis and publishing within research and industry based publications to ensure the continuing increase in building science knowledge in Australia and internationally. This data and its analysis are needed by software developers to ensure thermal simulation algorithms and concepts are continuously improved.

Appendices

Supporting documents to this research report are included as appendices. Each appendix focuses on a particular research task, namely:

- Appendix 1: Mass-timber partition walls as thermal mass
- Appendix 2: Mass-timber flooring as thermal mass

Acknowledgements

This research was made possible by the significant technical and financial support provided by:

Forest & Wood Products Australia

The University of Tasmania

CSIRO

Department of Industry

CSR Bradfords

Aurora Energy

Tilling

Carawah

Daikin

Jessups Solar Squad

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