Improving Thermal Efficiency in Lightweight Construction:

Mass timber as thermal mass

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Since Australia’s acknowledgment of climate change and its need to reduce greenhouse gas emitting activities, the national construction regulations have been used as a tool to reduce greenhouse gas emissions which may result from heating and cooling buildings.

The enhancements from NO thermal performance regulation to the 5 Star minimum requirements could often be met by increasing levels of floor, wall and ceiling insulation and installing improved glazing.

However, the enhancements required to achieve 6 or more Stars, may best be achieved through the incorporation of carefully considered and placed thermal capacitance.

Traditionally, the materials selected to provide thermal capacitance include clay brick and concrete-based products. However, these are massive materials and have a relatively high embodied energy.
Background – Greenhouse Gas Emissions

Pre 2002 - No requirement for insulation or thermal performance

2002 - Draft energy efficiency regulations (Building Code of Australia)

2003 – 4 Stars (BCA)

2007 – 5 Stars (BCA)

2010 – 6 Stars (BCA)

2020 – 7 Stars ?? (originally 2015)

However in 2016, New South Wales has BASIX (approx 5.5 stars), the Northern Territory is 5 Stars, and South Australia and Queensland offer state based reductions in performance requirements.
Background – Previous Research

1990 - : Private practice (low to zero energy housing)

2004-2006: the ‘No Bills House’ project (a net zero house)

2006-2011: The Empirical Validation of AccuRate
           (comparing data from real buildings to results from Accurate)

2012: Unsuccessful ARC grant application
      (Tasmanian plantation timber as thermal mass)

2012: Energy Storage Network Conference
      (the capacity for built fabric to store energy)

2011 - : Simulated use of mass-timber as thermal mass
          (over 2000 simulations completed)
Over 2000 simulations have been completed which have compared the use of mass-timber and traditional thermal mass systems within many house designs. Simulations have included thermal mass in floors, lining of external walls, partition walls and ceilings.

The types of thermal mass that been simulated has included:

- Standard 90mm stud framing with plasterboard lining
- 90mm solid softwood and hardwood
- 110mm solid softwood and hardwood
- 90mm concrete block
- 110mm clay brick
- Concrete variations

BUT does reality verify the simulated data??
Background – Solid Wood Context

Australia has established just over 2 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 hardwood, and in Tasmania consist largely of Eucalyptus Nitens.

Due to international trends the expected markets for the output from these plantations is now in flux, which has significantly impacted demand of fibre for pulp.

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).
Background – Solid Wood Context

Much of this low-grade plantation material is unacceptable for appearance applications and fails to meet either standard and market requirements for strength and board distortion for structural applications.

The confluence of the volatility 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 Australian forest plantations.

Additionally, plantation forests contribute to meeting Australia’s greenhouse gas abatement and carbon sequestration targets. They currently offset approximately 4% of Australia’s annual greenhouse gas emissions and sequester about 22 million tons of carbon dioxide annually (DCEE 2012 National Greenhouse Gas Inventory).
Background – Solid Wood Context

In some of Australia’s largest sawmills up to 50% of the sawn production does not meet structural grade requirements and is categorized as ‘fall-down’ grade with limited and at times unviable market opportunities.

Most of this low-grade sawn wood is sold at a loss.

Tasmania has the largest hardwood saw log plantation estate in Australia most of which consists of shining gum (E. nitens).

Additionally, these plantations are yielding significant volumes of low-grade material.

These saw log plantations are expected to supply around 930,000 m³ of log each year in Tasmania from 2025 onwards.

However, it is estimated that 780,000 m³ of this resource is of low quality and will produce low grade timber.
Background – Solid Wood Context

Using ABARE 2012 forecasts for plantation softwood and hardwood log production and assuming a conservative 35% of sawn output is fall-down grade, then by 2015 there would have been an estimated 10 million cubic metres of low-grade material, with a negative financial value.

Significantly, it is predicted that 73% of Tasmania’s hardwood plantation forests will yield poor quality material unsuitable for traditional solid products (ABARE).

While the low-grade timber is unmarketable under current building practice due to low strength and/or excess deformation, the research area I am pursuing explores whether this resource, when engineered into solid wood systems (i.e., CLT), can provide light weight, more sustainable and more thermally comfortable and efficient buildings.
Background – Solid Wood Context

The use of mass-timber products within the built fabric may provide improved thermal performance for a relatively small increase in embodied energy but also may significantly improve long-term carbon sequestration.

Additionally, traditional thermal mass materials normally require significant increases to structural systems and footings, further increasing built fabric embodied energy.

The structural properties of mass-timber systems like CLT provide significant opportunities for lower carbon, engineered light-weight buildings.
Background – What is Thermal Mass

Background – What is Thermal Mass

BUT it must be noted that in some climates thermal mass may not be beneficial.

# What can be Thermal Mass

<table>
<thead>
<tr>
<th>Material</th>
<th>Density Kg/m³</th>
<th>Specific Heat, J/(kg·K)</th>
<th>Thermal Capacitance kJ/m³.K (1m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Aluminium</td>
<td>2700</td>
<td>877</td>
<td>2367</td>
</tr>
<tr>
<td>Clay Brick Extruded</td>
<td>1700</td>
<td>800</td>
<td>1360</td>
</tr>
<tr>
<td>Concrete</td>
<td>2300</td>
<td>840</td>
<td>1932</td>
</tr>
<tr>
<td>Glass Wool Insulation</td>
<td>12</td>
<td>840</td>
<td>10</td>
</tr>
<tr>
<td>Paper Faced Plasterboard (6.8kg/m²)</td>
<td>680</td>
<td>1090</td>
<td>741</td>
</tr>
<tr>
<td>Softwood (Pine)</td>
<td>500</td>
<td>1630</td>
<td>815</td>
</tr>
<tr>
<td>Hardwood (Euc. Obliqua)</td>
<td>780</td>
<td>1630</td>
<td>1271</td>
</tr>
<tr>
<td>Steel (AISE-SAE 1020)</td>
<td>7860</td>
<td>490</td>
<td>3851</td>
</tr>
<tr>
<td>Water (at 25°C)</td>
<td>1000</td>
<td>4181</td>
<td>4181</td>
</tr>
<tr>
<td>CLT</td>
<td>470-590</td>
<td>1600-2100</td>
<td>3591</td>
</tr>
</tbody>
</table>
Is thermal mass linked to comfort

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Flow</td>
<td>20%</td>
</tr>
<tr>
<td>Air Temperature</td>
<td>20%</td>
</tr>
<tr>
<td>Mean Radiant Temperature</td>
<td>60%</td>
</tr>
</tbody>
</table>

The surface temperature of floors, walls and ceilings is critical in all climate types.

The longer the surface is within human comfort bandwidths, the lessor the desire to turn on the air-conditioner, heater, etc.

What was tested – mass-timber as partition walls

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

Figure 8: 90mm thick, vertically laminated E. Nitens panels installed as partition walls
What was tested – mass-timber as flooring

Figure 9: 180mm 5 ply softwood CLT panel

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

Test Buildings with detailed construction knowledge → Empirical data acquisition

Non-standard detailed building simulation

Comparison and analysis of empirical and simulated data

Figure 5: Empirical validation task framework
Where was the mass-timber tested?
What was measured

<table>
<thead>
<tr>
<th>Description</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000mm below ground level temperature</td>
<td>Background &amp; supporting data</td>
</tr>
<tr>
<td>Ground surface temperature</td>
<td>Background &amp; supporting data</td>
</tr>
<tr>
<td>Mid-subfloor zone temperature</td>
<td>Thermal performance and validation data</td>
</tr>
<tr>
<td>Outside subfloor insulation surface temperature</td>
<td>Background &amp; supporting data</td>
</tr>
<tr>
<td>Inside subfloor insulation surface temperature</td>
<td></td>
</tr>
<tr>
<td>Outside platform-floor surface temperature</td>
<td></td>
</tr>
<tr>
<td>Inside platform-floor surface temperature</td>
<td></td>
</tr>
<tr>
<td>600mm test building room temperature x 3</td>
<td></td>
</tr>
<tr>
<td>1200mm test building room temperature x 3</td>
<td></td>
</tr>
<tr>
<td>1200mm globe temperature x 3</td>
<td></td>
</tr>
<tr>
<td>1800mm test building room temperature 3</td>
<td></td>
</tr>
<tr>
<td>Inside ceiling surface temperature</td>
<td></td>
</tr>
<tr>
<td>Outside ceiling surface temperature</td>
<td></td>
</tr>
<tr>
<td>Outside ceiling insulation temperature</td>
<td></td>
</tr>
<tr>
<td>Mid-roof space air temperature</td>
<td></td>
</tr>
<tr>
<td>Inside sarking surface temperature</td>
<td></td>
</tr>
<tr>
<td>Outside sarking surface temperature</td>
<td></td>
</tr>
<tr>
<td>Inside sheet-metal roof surface temperature</td>
<td></td>
</tr>
<tr>
<td>Outside sheet-metal roof surface temperature</td>
<td></td>
</tr>
</tbody>
</table>

Plus a calibrated site weather station
How was the building simulated

At the request of industry and government project collaborators, two simulation methods were developed, which allowed for the inclusion of the built fabric thermal mass. The final 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)
## Table 2: Modified inputs for detailed simulation

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

We have a lot of data that requires further analysis - Like this subfloor

*Figure 6: Unconditioned and unoccupied measured subfloor temperatures for mass-timber partition walls*
Results & Discussion

- Significant over calculation of maximum subfloor temperatures
- Under calculation of minimum subfloor temperatures

Figure 7: Unconditioned and unoccupied subfloor measured and simulated temperatures for mass-timber partition walls
Results & Discussion

- Significant over calculation of maximum roof space temperatures
- Under calculation of minimum roof space temperatures

Figure 53: Intermittently heated roof space zone measured and simulated no-mass and with-mass temperatures for mass-timber partition walls
Results & Discussion

• A generally good ‘fit’ between measured and no-mass simulated data
• This similarity between measured and simulated data provides empirically validation
Results & Discussion

- COP = 4.86
- Installed / As-built – 2.1
- There is a lot of international discussion re differences between laboratory testing and installed performance
- More research required

*Figure 35: Measured and simulated with-mass energy use for test cell room during the continuously heated mode of operation*
Results & Discussion

- Wall surface temperatures are warmer than the air temperature
- The wall is storing energy
- The wall is giving energy to the cooler air

*Figure 42: North face surface temperatures of eastern mass-timber partition wall during continuously heated mode of operation*
Results & Discussion

Temperature falling
- Wall losing energy earlier
- Lines apart

Temperature rising
- Wall absorbing energy
- Lines very close

Figure 46: Flux measurements from the eastern mass-timber partition wall during continuously heated mode of operation
Conclusion

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.

1. 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, mass timber and climatic inputs but requires ongoing improvement and calibration.
Conclusion

2. In most tasks there were significant differences between the measured and simulated data sets of the subfloor 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 spaces 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, impacting on calculated energy use.
Conclusion

3. 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.

4. 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. This methodology and its impact requires further analysis.
Conclusion

5. 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.

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.
Conclusion

6. 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 within small to medium buildings, which validates the previous desktop-based building simulation research.

The additional data, which included the surface temperatures and surface flux measurements provide additional supporting documentation of the thermal capacitor and thermal insulation properties of the mass-timber elements.
Recommendations – 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 analysis is required 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 when installed as internal lining, or as a ceiling, or as a combined floor/external wall lining/partition wall/ceiling system. This focused research must occur to provide an informed marketing advantage over traditional concrete and clay brick massive elements.
• The construction of 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. The 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.
Recommendations – Heating & 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.
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Questions