MARKET ACCESS

A Study Comparing the Global Warming Potential of Timber and Reinforced Concrete Construction in Office and Apartment Buildings

Project number: PNA308a-1213 February 2017

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

Forest & Wood Products Australia

A Study Comparing the Global Warming Potential of Timber and Reinforced Concrete Construction in Office and Apartment Buildings

Prepared for

Forest & Wood Products Australia

By

Associate Professor Grace Ding & Professor Perry Forsythe

Publication: A Study Comparing the Global Warming Potential of Timber and Reinforced Concrete Construction in Office and Apartment Buildings

Project No: PNA308a-1213

IMPORTANT NOTICE

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

ISBN: 978-1-925213-56-0

Researcher/s:
Associate Professor Grace Ding
Professor Perry Forsythe

University of Technology Sydney
Faculty of Design Architecture and Building
P.O. Box 123 Broadway, NSW, 2007, Australia»

Final report received by FWPA in October, 2016

Forest & Wood Products Australia Limited
Level 11, 10-16 Queen St, Melbourne, Victoria, 3000
T +61 3 9927 3200 F +61 3 9927 3288
E info@fwpa.com.au
W www.fwpa.com.au

Executive Summary

This research presents the results of a study of global warming potential (GWP) of the main structural elements for a hypothetical office building and apartment building, located in New South Wales, Australia. Both buildings were assessed for two different superstructures - a conventional cast-in-place reinforced concrete (RC) framed building and; an engineered timber (Timber) building. The emphasis was on comparing the superstructures of these two options whilst most other variables were constant under both options. The study forms part of a broader based research project (published separately) that compares the time and cost of these options.

The study looked at GWP from cradle to construction site gate.

This piece of work primarily shows the value proposition that a timber structure provides in reducing GWP. For instance, one key finding was that the GWP per Gross Floor Area (GFA) per square metre (m^2) for the office building would be 202 and 46 $kgCO_{2\text{-}e}/m^2$ respectively for the RC and timber design. Put another way the RC design would result in 4.4 times greater GWP than the timber building.

For the apartment building, the GWP per GFA (m^2) was 205 and 93 $kgCO_{2\text{-}e}/m^2$ respectively for the RC and timber design options, meaning the RC option would result in 2.1 times more GWP than the timber building.

The amount of GHG sequestered potentially in the timber was calculated at 2,500 and 1411 $tCO_{2\text{-}e}$ respectively for the office and apartment buildings.

The cradle-to-gate approach taken by this research, which excluded end-of-life GWP, meant that this was not taken into account in the above calculations. End-of-life of timber products are normally in three scenarios: reused/recycled for manufacturing into other wood products; incineration for energy recovery; and wood waste to landfill. For the timber products to be reused/recycled the carbon remains sequestered, whilst if timber products are incinerated or landfilled the sequestered carbon may be released back to the atmosphere. Since the study is based two hypothetical buildings it is difficult to ascertain the end-of-life treatment for the timber products. Therefore it was excluded from the study. If carbon sequestration is added, by virtue of confidence in reuse/recycling at end-of-life, then there would be significantly stronger outcomes for timber construction, which would add to the already favourable outcomes reflected in this study.

Table of Contents

Introduction

This report presents the results of a study of global warming potential (GWP) for two hypothetical buildings under two different design options located in NSW, Australia. The objective of the work was to quantify and compare the environmental impacts associated with typical mid-rise office and multi-storey apartment buildings under competing construction design options including:

- a conventional cast-in-place reinforced concrete framed building, including post-tensioning technology (RC)
- an engineered wood products design, including LVL and CLT timber products used in column, beam and panel formats (Timber).

Many aspects of the two types of building were similar having the same floor plate, Gross Floor Area (GFA), number of storeys, shape, structural loadings, fitout, finishes, facade, fire and sound resistance requirements, and building services requirements.

Given the above, the study mainly focused upon comparing the superstructure of the competing design options for both building types. For instance, the competing design options used the same construction methods for things like substructure (concrete), façade, building services and fitout – only the superstructures differed.

Life cycle assessment (LCA) was used as the method for determining the potential environmental impacts of the buildings in terms of GWP. The report is structured to include background information of the case study buildings, research method and analysis.

Methodology

Two key aspects define the overall research methodology: first, the means for the defining the case study buildings and second, the means for calculating the associated GWP for the competing construction methods. Each aspect is dealt with under separate subheadings below.

Case study buildings

It is important to note that design input information for the two case study buildings (including spatial definition, performance requirements, construction detailing and material specification for the competing construction design options), have been taken from two separately published FWPA reports titled*:*

- *Rethinking office construction - consider timber and;*
- *Rethinking apartment construction - consider timber*

The office building involved 7 floor levels in the superstructure, with a footprint area of 1,944 m² and a 9.0 x 9.0 m column grid. The apartment building involved 8 floor levels in the superstructure with a footprint area of 760 m² and using a column grid with infill walls for the reinforced concrete (RC) option, and cellular construction for the timber option.

Whilst both timber and concrete options aimed to represent reality in terms of both design and construction requirements, they should not be taken as representative for all new building situations, or all current building stock. After the structural and building enclosure designs were completed a bill of materials was calculated for both design options. This bill of materials was used to assess the environmental impact of each design option for the GWP.

Table 1 below summarises construction details for the timber and RC options of both the office and apartment buildings. The office timber building predominantly uses a laminated veneer lumber (LVL) structure for all floor, beam and column assemblies, with cross-laminated timber (CLT) used to a lesser extent for core shaft walls. No suspended ceiling construction was included as the HVAC services were designed to remain exposed to the underside of the timber floor panels. Fibre reinforced concrete was also used as part of the timber cassette flooring structure to improve acoustic performance for the timber design.

The timber apartment building predominantly uses CLT panels for all external and internal walls and floors. Even so, one of the floors (being the transfer slab on the first floor and columns below) was constructed using RC columns, beams and slabs.

In contrast, the RC structures for both the office and apartment buildings were conventional post tensioned, cast-in-place RC columns, beams and slabs.

For greater detail on these case studies, please refer to the previously mentioned publications.

Table 1 - Summary of construction details

Building elements	Construction details			
	Office		Apartment	
	Timber (No ceiling)	RC	Timber	RC
Columns (CL)	LVL	50 or 40 MPa RC	40 MPa RC (to transfer slab level only)	40 MPa RC
Superstructure floors and beams (UF)	LVL beams & panels prefabricated into floor cassettes & 20 MPa fibre reinforced concrete for sound insulation	40 MPa RC beams and slabs	40 MPa transfer slab; LVL beams & CLT floor panels elsewhere	40 MPa RC beams & slabs
Roof (RF)	LVL beams & floor cassettes	40 MPa RC beams and slabs	CLT panels to roof	40 MPa RC beams & slabs
External walls (EW)	CLT panels (to the lift/stair/ services core of the building)	40 MPa RC (to the lift/stair/ services core walls of the building)	CLT panels	40 MPa RC & Hebel blocks
Internal walls (NW)	CLT panels (to the lift/stair/ services core walls of the building)	40 MPa RC (to the lift/stair/ services core walls of the building)	CLT panels & timber stud frame	40 MPa RC & Hebel blocks and steel stud frame
Wall finishes (WF)	Exposed timber structure & factory applied sealer finish (to the lift/stair/ services core walls of the building)	Exposed concrete (to the lift/stair/ services core walls of the building)	Plasterboard or fibre cement board lining & insulation (for sound insulated bounding walls, core walls etc.)	Plasterboard or fibre cement board lining & insulation (for sound insulated bounding walls, core walls etc.)
Floor finishes (FF)	Exposed timber	Exposed concrete	Exposed timber & 20 MPa plain concrete for sound insulation	Exposed concrete
Ceiling finishes (CF)	Exposed timber structure & self-finish	Plasterboard suspended ceiling with metal grid	Plasterboard lining or plasterboard suspended ceiling	Plasterboard suspended ceiling with metal grid & insulation

GWP Calculation Method

The report covers global warming potential (GWP) impacts, but the same principles can be used for any other environmental impacts. All greenhouse gas (GHG) emissions are quantified in tonnes of "CO_2 equivalent (CO_{2-e})" which is the standard unit for the GWP impact category in LCAs. GWP is an expression of the contribution of a product or service to potential warming of the atmosphere, possibly leading to climate change. The report uses the most recent figures for CO_2 equivalents for GHG emissions published by the Intergovernmental Panel on Climate Change (IPCC 2014). According to IPCC (2014), GWP is defined as a relative measure of how much heat a greenhouse gas traps in the atmosphere. It is used to compare the amount of heat trapped by a certain mass of the gas in question, to the amount of heat trapped by a similar mass of carbon dioxide at a specific time interval.

The boundary of the quantitative analysis was cradle-to-construction site gate. The components of GWP resulting from GHG emissions for all buildings are from processes for extracting and manufacturing the building materials, and the eventual delivering of the building materials up to the building site gate.

The study encompassed the superstructure support system and the building enclosure (where implicating timber and concrete on a comparative basis), but did not include finishes, services, fixtures and fittings within the building envelope. Any structure and materials outside the building envelope were not included in the study. The study also did not include GWP associated with actual construction and demolition processes as it is difficult to ascertain such issues from hypothetical case studies, without inadvertently introducing unnecessary subjectivity to the research findings. The study also did not include GWP concerning the lifetime operation of the buildings because this is usually dependent on user behaviour patterns which are again difficult to determine under hypothetical case study situations.

The cradle-to-gate LCA inventory data was taken directly from suppliers, literature, calculations and existing life cycle inventories. Life cycle inventory (LCI) data was also taken from an LCA software package (GaBi 4.3) based on European industry data but was adjusted to account for Australian conditions e.g. energy mix. The cradle-to-gate LCI of engineered wood products was generated by combining manufacturing LCI date with previously published dataset for upstream logging and adhesive resin manufacturing, as well as data for electricity generation, common thermal fuels, and ancillary materials use (Love 2010; Durlinger, Crossing & Wong 2013).

Results

General overview

Table 2 below presents the material requirement for the four case study buildings. The total volume of engineered wood products (LVL and CLT) used in the office timber option was 2,607 m^3 whilst the volume of RC used in the RC option was 4,315 m^3, demonstrating that much less timber material was used in the timber design for the superstructure in comparison to the RC option (approximately 40% less). On a related point, it is notable that timber has a much lower density than RC. For instance, timber is approximately 450 kg/m^3 for CLT and 600 kg/m^3 for LVL, whilst RC is approximately 2400 kg/m^3. Among other things, the timber option does not have to support as much material weight. With regard to the apartment building, the volume of the timber and RC options was 1,588 m^3 and 1,944 m^3 respectively.

It would seem that part of the reason for the smaller difference between timber and RC in the apartment building is because the timber option makes much greater use of solid, mass timber (via CLT) in the wall and floor plate construction, whilst the timber office building involves much less wall area and makes use of timber framed cassette floor panels (i.e. instead of solid mass timber).

Timber itself is 50% carbon (by dry weight) which is derived from carbon dioxide absorbed from the atmosphere during wood growth in the forest. The amount of stored GHG used in the timber design within the building structure and envelope for the office and apartment buildings respectively, is roughly equivalent to 2,500 and 1,411 tonnes of carbon dioxide equivalent.

In contrast, a total of 516 and 147 tonnes of reinforcement were used in the RC option design respectively for office and apartment buildings. In addition, the RC option design required 10,356 and 4,666 tonnes of concrete respectively for office and apartment buildings. Both concrete and steel reinforcement have high embodied energy intensity as the manufacturing processes of these materials require a great deal of fossil fuel energy, and consequently emit large amounts of fossil carbon dioxide (Reddy & Jagadish 2003; Hammond & Jones 2008).

Other significant materials used for the RC construction include 22 mm plywood for formwork and plasterboard as lining materials for walls and ceilings in the RC option. For the timber option, plasterboard and fibre cement board were used as lining materials to the interior and bulk insulation and unreinforced concrete were required for both sound and heat resistance in both building types. Even so, no wall and ceiling lining were required for the timber office building (as it was left exposed).

Table 2 - Summary of material quantities

Materials	**Unit**	**Quantity**			
		Office		**Apartment**	
		Timber	**RC**	**Timber**	**RC**
LVL	m^3	2,033		8	
CLT	m^3	574		1,580	
Softwood	m^2			34	
Concrete - 20 MPa	m^3	461		186	
Concrete - 40 MPa	m^3		4,286	438	1,944
Concrete - 50 MPa	m^3		29		
Reinforcing bars	kg		516,003	24,972	146,702
Formwork	m^2		22,401	979	10,041
Hebel blocks	m^2				3,465
Plasterboard	m^2		11,086	36,923	18,090
Fibre cement board	m^2			1,220	610
Steel studs	m			1430	14,107
Insulation	m^2	9,235		7,001	7,012

Tables 3 and 4 below present the impacts of GWP for the office and apartment buildings by elements, for both the timber and RC design options. In both building types, the timber building has substantially lower in GWP impacts than the RC design option.

Office Building Analysis

In Table 3, the GWP per GFA (m^2) for the office building was 46 and 202 $kgCO_{2-e}/m^2$ respectively for the timber and RC design. The RC design results in 4.4 times greater GWP than the timber building.

In both construction options, the floors in the superstructure (including beams and suspended slabs) have the highest GWP because beams and suspended slabs are the main structural component for the building. These floors constitute approximately 81% and 68% of the total GWP respectively for timber and RC design options. Even so, the timber option results in much lower GWP than the RC option, being only 38 $kgCO_{2-e}/m^2$ of GFA which was approximately 4 times less than the concrete superstructure floors and beams.

Table 3 - Summary of GWP per m^2 of GFA by building elements for office building

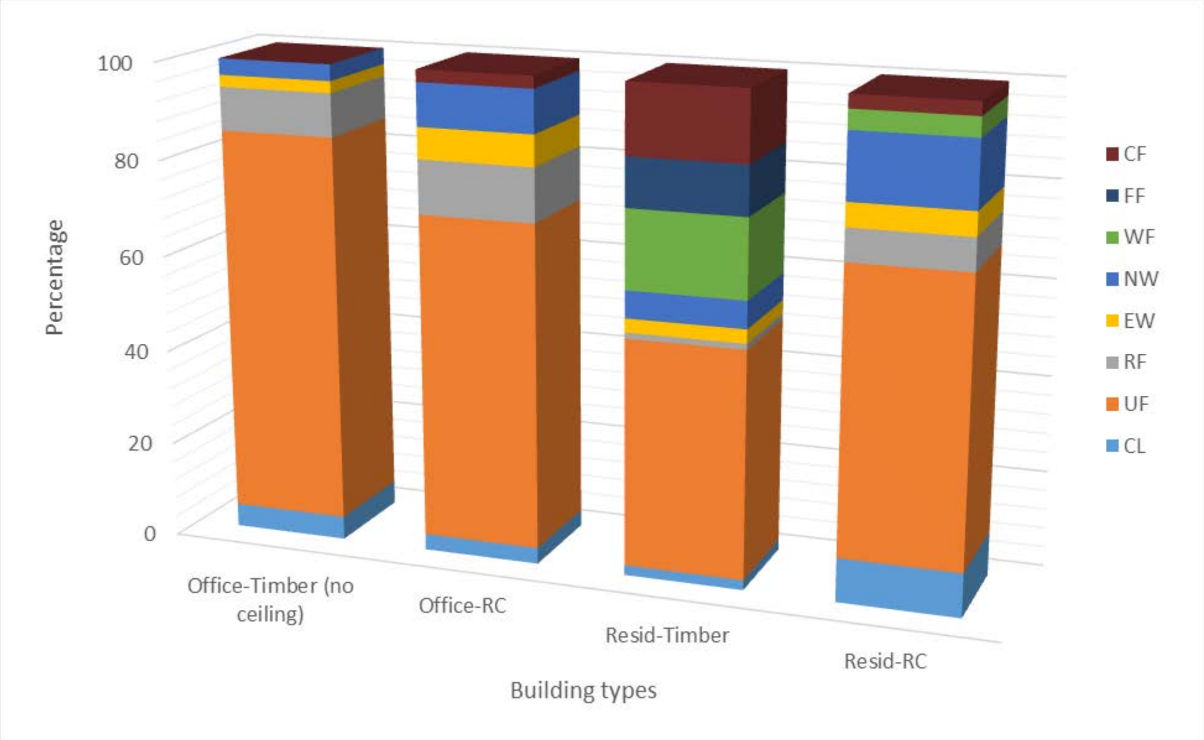
Elements	**Office building ($kgCO_{2-e}/m^2$)**			
	Timber	**% Total**	**RC**	**% Total**
CL	2.22	4.81	6.75	3.34
UF	37.09	80.40	136.18	67.48
RF	4.14	8.97	22.60	11.20
EW	1.13	2.45	13.13	6.51
NW	1.55	3.37	18.05	8.94
WF	-	-	-	-
FF	-	-	-	-
CF	-	-	5.09	2.52
Total	**46**	**100**	**202**	**100**

Note:
CL - Columns; RF - Roofs; NW - Internal walls; FF - Floor finishes
UF - Superstructure floors & beams; EW - External walls; WF - Wall finishes; CF - Ceiling finishes

Table 3 and Figure 1 show the percentage distribution of GWP by building elements for each design option for both office and apartment buildings. For the office building, the structural components represented 100% and 98% of the total GWP respectively for the timber and RC options. The GWP of the interior components of wall, floor and ceiling finishes are relatively insignificant in the RC option and the timber option can principally be finished as is. That is it can be decorated rather than lined with plasterboard.

Figure 2 below presents the GWP per GFA by building elements. In the Figure, the timber office building outperformed the RC design in all the structural elements. Of the elements shown, the superstructure elements of floors and beams averaged 68-81% and were by the far the largest source of emissions in terms of GWP.

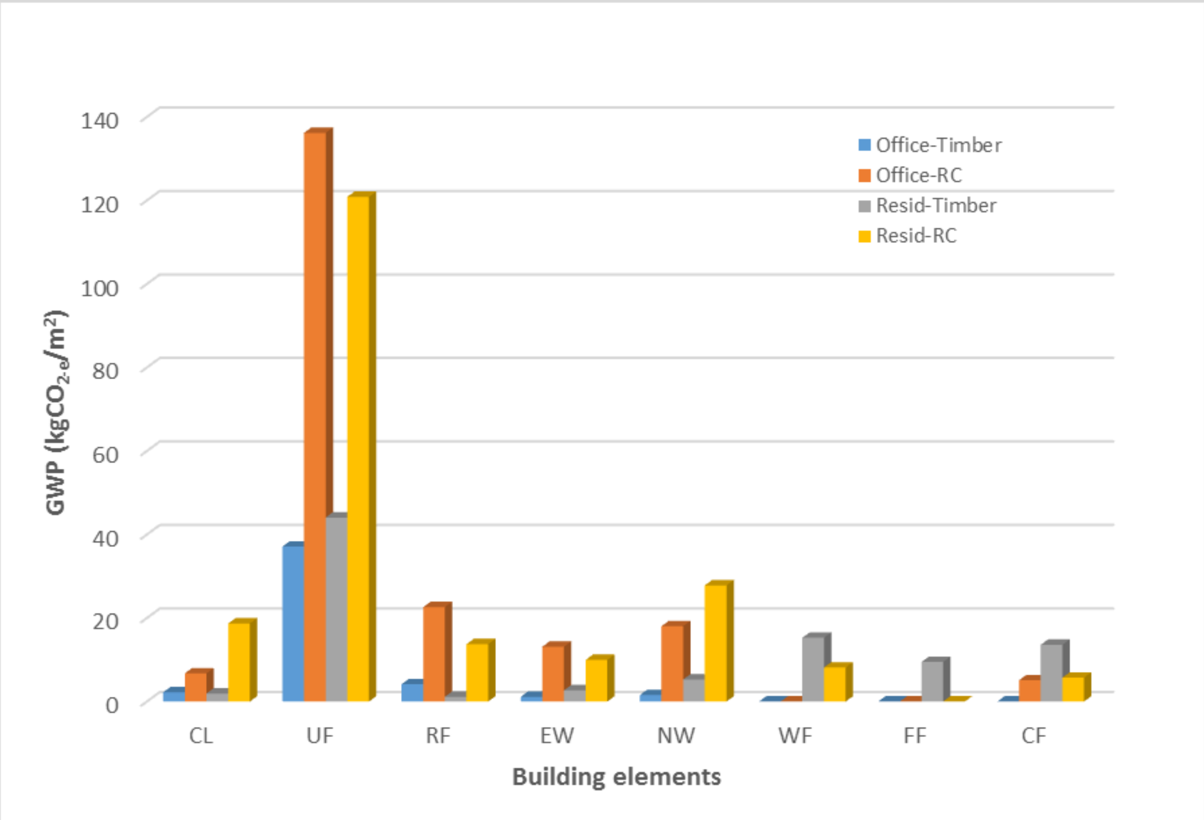
Figure 1 - Percentage of GWP by building types



Note:

CL - Columns	RF - Roofs	NW - Internal walls	FF - Floor finishes
UF - Superstructure floors & beams	EW - External walls	WF - Wall finishes	CF - Ceiling finishes

Figure 2 - GWP per GFA by building elements



Note:

CL - Columns	RF - Roofs	NW - Internal walls	FF - Floor finishes
UF - Superstructure floors & beams	EW - External walls	WF - Wall finishes	CF - Ceiling finishes

Apartment Building Analysis

In Table 4 the GWP per m^2 of GFA for the apartment building was 93 and 205 $kgCO_{2-e}/m^2$ respectively for the timber and RC design options. The RC option resulted in 2.1 times more GWP than the timber building. The gap between the RC and timber design options was narrower in the apartment building as the columns and ground floor transfer slab in the timber design used a RC structure. The GPW of this RC transfer slab in the timber option was 37 kg CO_{2-e}/m^2, contributing to 44% of the total GWP per GFA. In a similar situation, the GWP was predominately contained in the superstructure floors and beams (about 50%) but the timber design option demonstrated much lesser GWP than the RC design. The timber design was approximately 77 $kgCO_{2-e}/m^2$ less than the RC option.

Table 4 - Summary of GWP per m^2 of GFA by building elements for apartment building

Elements	Apartment building ($kgCO_{2-e}/m^2$)			
	Timber	**% Total**	**RC**	**% Total**
CL	1.93	2.07	18.68	9.11
UF	44.07	47.17	120.86	58.97
RF	1.13	1.21	13.74	6.70
EW	2.68	2.87	9.98	4.87
NW	5.28	5.65	27.82	13.58
WF	15.28	16.35	8.16	3.98
FF	9.48	10.14	-	-
CF	13.56	14.54	5.70	2.79
Total	**93**	**100**	**205**	**100**

Note:
CL - Columns; RF - Roofs; NW - Internal walls; FF - Floor finishes
UF - Superstructure floors & beams; EW - External walls; WF - Wall finishes; CF - Ceiling finishes

From Figure 1 above, the percentage distribution of GWP by building elements for the structural components of the apartment building were 59 and 94% respectively of the total GWP in the timber and RC options. As was the case with the office building, the impacts of interior components were relatively insignificant. Similar to the office building, Figure 2 above shows that the timber option for the apartment building outperformed the RC design in all the structural elements except for the interior components of wall and ceiling finishes as more sound and heat insulation materials were required for the timber option.

Conclusions

A significant part of the value proposition offered by timber concerns its worth as an environmentally sustainable construction material. For instance, as the environmental impact of buildings gain more attention in both national and international policy agendas, the design and construction of green buildings will gradually approach main stream practice in the construction industry. As the operational energy and associated emissions of buildings are reduced through efficiency measures and renewable energy generation, the importance of embodied carbon emissions and life cycle environmental impacts associated with GHG emissions from building materials will become more significant. Here, timber buildings perform very well compared to other main flow construction methods used in office and apartment buildings.

This project performed a comparative LCA comparison between the use of a conventional reinforced concrete design (RC) and an engineered wood products (timber) design in the construction of a mid-rise office building and a multi-storey apartment building, in New

South Wales, Australia. The boundary for the study was confined to cradle-to-gate parameters and therefore construction processes, operating and final disposal stages were not included in the study. The results indicated that it is environmentally advantageous to construct the superstructure using engineered timber products such as LVL and CLT, rather than a cast-in-place RC structure. The results show that engineered timber products are not only structurally capable of supporting the building, but also result in emitting significantly less fossil fuel derived carbon dioxide to the atmosphere. When considering the GWP, the timber design outperformed the RC design in all structural elements. The results reveal that the timber design was much lighter in weight than the RC building. A key finding was that the GWP per GFA (m^2) for the office building was 46 and 202 $kgCO_{2\text{-}e}/m^2$ respectively for the timber and RC design, meaning the RC design result in 4.4 times greater GWP than the timber building. For the apartment building, the GWP per GFA (m^2) was 93 and 205 $kgCO_{2\text{-}e}/m^2$ respectively for the timber and RC design options, meaning the RC option resulted in 2.1 times more GWP than the timber building.

The amount of GHG sequestered in the timber was approximately 2,500 and 1,411 tonnes carbon dioxide equivalent respectively for the office and apartment buildings. Whilst this is significant and creates a potential advantage of timber over other materials, the ability to utilise carbon sequestration characteristics was limited in this study as the inclusion of it depends on the end-of-life assumptions for the building – primarily, how much timber will be reused and recycled and what are the associated energy and carbon emissions implications of this. As this study focuses on a cradle-to-gate approach, assumptions about re-use and recycling have not been taken into account.

However, even if a cradle-to-grave approach was used, then a limiting factor would be the low assumptions in the guiding literature (e.g. the Intergovernmental Panel on Climate Change; Ximenes 2012; Durlinger, Crossin & Wong 2013) concerning timber re-use and recycling at end-of-life. Because of recycling and recycling are highly unknown and uncertain, this effectively limits the ability to realise the above carbon sequestration in cradle-to-grave calculations. Since the study is based two hypothetical buildings it is difficult to ascertain the end-of-life treatment for the timber products. If carbon sequestration is added, by virtue of confidence in recycling/reuse at end-of-life, then there would be significantly stronger outcomes for timber construction, which would add to the already favourable outcomes reflected in this study. A future line of research could therefore focus on systematic ways of developing confidence that timber will be saved from disposal at landfill and instead reused or recycling, which would change existing end-of-life assumptions in LCA calculations. By implication, carbon sequestration could be more readily included in LCA studies. This should be quite achievable for the likes of CLT where using large, solid, prefabricated assemblies means that such panels should be easy to dismantle at demolition stage, and then taken away for recutting and reuse on other projects.

The results also indicate that the interior components of wall, floor and ceiling finishes are relatively insignificant in both design options for the office and apartment buildings. Structural components usually require zero to minimal maintenance during lifetime operation of the building, however interior elements will require substantially more frequent refurbishment and maintenance during the building operating stage. Of note, the scope of the study does not take into account such issues because they fall beyond the scope of the superstructure comparison between timber and RC options under consideration in the study. Even so, it is relevant to point out that these internal finishes may further impact significantly on life cycle GWP calculations. Timber and engineered timber products can also play an important role in interior elements which, in the same way as the structural elements, can help to substantially offset the impact of GWP emission during the lifetime of the building.

References

Alcorn A (2008). Global Sustainability and the New Zealand House. PhD Thesis, Victoria University of Wellington, Wellington

Athena Sustainable Materials Institute (2013). A cradle-to-gate life cycle assessment of Canadian laminated veneer lumber (LVL) manufacture, FP Innovations, Ottawa, Canada

Athena Sustainable Materials Institute (2013). A life cycle assessment of cross-laminated timber produced in Canada, FP Innovations, Ottawa, Canada

AUS LCI (2015). The Australian Life Cycle Inventory Database Initiative. http://www.auslci.com.au

Buchanan, A.H., John, S. & Love, S. (2012), LCA and carbon footprint of multi-storey timber building compared with steel and concrete buildings, World Conference on Timber Engineering (WCTE), 16-19 July, Auckland, NZ

Chen, J.Y. (2012), Comparison of environmental performance of a five-storey building built in cross-laminated timber and concrete, University of British Columbia: Vancouver, BC, Canada, August

Durlinger, B., Crossin, E. & Wong, J. (2013), Life cycle assessment of a cross laminated timber building, Forest & Wood Products Australia, February, Sydney

GaBi 4.3 Professional Life Cycle Software. www.gabi-software.com

Gan, K.S. & Massijaya, M.Y. (2014), Life cycle assessment for environmental product declaration of tropical plywood production in Malaysia and Indonesia, International Tropical Timber Organization, March

Gustavsson, L.; Joelsson, A.; Sathre, R. Life cycle primary energy use and carbon emission of an eight-storey wood-framed apartment building. Energy Build. 2010, 42, 230–242

Hammond, G.P. & Jones, C.I. (2008), Embodied energy and carbon in construction materials, proceedings of the Institution of Civil Engineers – Energy, 161 (2), pp. 87-98

IPCC (2014) Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R. & White, L.L. (eds.), Cambridge University Press, Cambridge, United Kingdom & New York, NY, USA, 1132 pp.

Lippiatt, B.C. BEES 4.0: Building for Environmental and Economic Sustainability, Technical Manual and User Guide; National Institute of Standards and Technology: Gaithersburg, MD, USA, 2007

Love, S. (2010) Carbon Footprint of New Zealand Laminated Veneer Lumber. Scion Research. Wellington

Nebel, B., Wittstock, B. and Alcorn, A. (2009) Life Cycle Assessment: Adopting and adapting overseas LCA data and methodologies for building materials in New Zealand. Report for the Ministry of Agriculture and Forestry, New Zealand. Wellington, Scion.

Reddy, B.V. & Jagadish, K.S. (2003), Embodied energy of common and alternative building materials and technologies, Energy and Buildings, Vol. 35 (2), pp. 129-137

Robertson, A.B., Lam F.C.F Y Cole, R.J. (2012), A comparative cradle-to-gate life cycle assessment of mid-rise office building construction alternatives: Laminated timber or reinforced concrete, Buildings, Vol 2, pp. 245-270

Takano, A., Winter, S. & Hughes, M. (2014), Comparison of life cycle assessment databases for building assessment, SB14, 28-30 October, Barcelona