

The Use of Wood in Construction

A Triple Bottom Line Assessment of the use of
Laminated Wood in Construction Relative to
Reinforced Concrete

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Abstract:

There is a current trend of increasing structural wood use in the construction of medium scale commercial or institutional buildings. The driving force behind this trend is for sustainable development. As compared to concrete, wood is a construction material harvested from renewable resources, manufactured with relatively low energy input, and wood is almost 100% recyclable because it is biodegradable. These properties make wood a potentially better construction material than concrete in terms of sustainability.

This report presents a triple-bottom line assessment on the use of structural laminated wood. Due to the lack of accessibility to the design information of the building, the assessment is based on the case-studies of buildings with similar design requirements as the new SUB building. In addition to the case studies, anticipated concerns over the use of wood and concrete in the construction of the new SUB buildings are presented. Based on the findings, it is concluded that wood is overall a more sustainable choice. However, it is also discovered that recycling strategy can have a critical effect on the environmental impact of the use of wood, and should be carefully accounted for during the design process.

The report has three basic constituents: the environmental impact analysis, the economical impact analysis, and the social impact analysis. The analysis on the environmental impacts focuses on the comparison of the life-cycle carbon emissions associated with laminated wood and concrete. The economical impact analysis presents the overall cost advantage of wood over concrete. The social impact analysis addresses two health issues --- one physical and another mental---related to the use of wood in the construction of the new SUB building.

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1.0 Introduction ---background knowledge of the two materials in comparison:

The two structural materials being analyzed are laminated wood (also known as engineered wood) and steel-reinforced concrete.

1.1 Laminated wood:

Laminated wood is a composite material, consisting of wood and adhesives, and is available in several varieties; the most commonly used types of structural laminated wood are: laminated veneer lumber (LVL), parallel strand lumber (PSL), and glued-laminated timber (“glulam”). Another type of laminated wood, known as cross-laminated timber has recently been developed and is being introduced to the construction industry.

Glulam is composed of smaller individual pieces of standard dimension lumber, such as 2x4 or 2x6, arranged in the same axial direction and glued together with adhesives to form a single, larger beam.

LVL is made up of thin sheets of wood veneers and layers of adhesive to form a single piece of lumber, with the grains of the veneers arranged in the same direction.

PSL is made up of thin strands of wood, glued together into a continuous piece of lumber.

Cross-laminated timber is manufactured in a similar fashion to glulam, except that the smaller pieces of lumber are arranged in perpendicular layers to create large panels, as opposed to long beams.

1.2 Steel-reinforced concrete:

Concrete is a composite material, made up of coarse aggregate (such as crushed limestone or granite), fine aggregate (usually sand), a binding material (cement, or cement-like substances such as granulated furnace slag or fly ash), water, and additives.

As a structural material, concrete is strong in compression, but weak in tension. Thus, steel rods are used to reinforce concrete structures with the required tensile strength.

2.0 Environmental Impact:

2.1 Considerations for assessing carbon emissions

The nature of reinforced-concrete and wood are intrinsically different, which affects the comparison of embodied greenhouse gas emissions of a building over its life-cycle.

Wood is an organic material, and can be used as biomass and combusted to produce energy. The use of waste lumber for energy production are generally viewed as being carbon-neutral, if they are used to displace energy that would have been produced using conventional fossil fuels such as coal, natural gas, or heavy oil. Wood, when harvested and used in construction, acts as a carbon sink, effectively locking away carbon in a solid form. Also, reforesting land that has been logged allows for new trees to be grown, sequestering carbon in solid form. (Dodoo, Gustavsson, & Sathre, 2009)

Conversely, concrete and the steel used for reinforcement are inorganic materials, and thus cannot be used as biomass for energy production. Also, the production of cement, one of the components of concrete, generates greenhouse gases, not only from the fuel combusted to produce the required heat to react cements' constituent ingredients together, but also from the chemical reactions (known as “calcination”) that the ingredients undergo, which produces carbon dioxide as a product. However, a portion of the carbon dioxide produced from the calcination reaction during the manufacture of cement is slowly reabsorbed by concrete, as the cement component of concrete slowly reverts back into its constituent chemical compounds. This process is known as carbonation, and takes place over many decades. Theoretically, a maximum of 75% of the carbon dioxide produced from cement by calcination can be recovered through carbonation. (Dodoo, Gustavsson, & Sathre, 2009)

2.2 Life-cycle assessment of carbon emissions

Life-cycle assessments encompass the entire existence of a construction material, and examine the impacts involved in the following stages:

- harvesting of the material in its raw form from the environment

- transportation of the raw material to processing facilities
- processing of the raw material into a construction material
- transportation of the construction material to the construction site
- assembly processes involved in constructing a building
- demolition of the building at the end of its service life
- disposal of the waste material produced from demolition

2.3 Case studies comparing carbon emissions for life-cycle of wood-frame buildings and reinforced-concrete buildings

In one study, researchers in Sweden performed life-cycle assessments for a wood-framed structure and its reinforced-concrete equivalent (Dodoo, Gustavsson, & Sathre, 2009), and assumed that the following environmentally responsible practices were used for both structures:

- 15% of the cement required to produce the concrete is replaced with fly ash, which is a waste product generated from coal power plants, and is considered to not have any carbon emissions.
- 90% of the reinforcing steel is recovered from the demolished concrete building and recycled, displacing the need to harvest and process raw ore to manufacture new steel. The remaining 10% is lost during the demolition and recycling processes.
- 90% of the waste concrete is recovered from the demolished concrete building, crushed and recycled to produce coarse aggregate, displacing the need to harvest virgin aggregate. The remaining 10% is lost during the demolition and recycling processes.
- 90% of the wood from the wood-framed building is recovered and used for energy production. The remaining 10% is lost during demolition and releases methane into the atmosphere by decomposing.
- The forests that the wood is logged from are sustainably managed, and the logged land is reforested.

However, the wood-framed houses used for this study utilized dimensional lumber, instead of laminated lumber. Adjustments were made to the carbon emissions balance to reflect the

increased amounts of carbon emitted during manufacturing of laminated lumber, in comparison to dimensional lumber (See Appendix A). These adjustments are based on another study which compared the energy used to manufacture dimensional lumber and laminated wood (National Association of Forest Industries).

With the adjustments to the calculations to reflect the carbon impact of manufacturing laminated wood, the net embodied carbon impact of the laminated wood structure was found to be negative 7.29 tonnes, essentially preventing the release of 7.29 tonnes of carbon into the atmosphere. On the other hand, the reinforced-concrete structure was found by the study to have a positive net embodied carbon emission balance, emitting 36.6 tonnes of carbon into the atmosphere. Thus, the laminated wood building had a 43.9 tonne advantage over the reinforced-concrete structure in terms of embodied carbon emissions. (See Appendix A)

In a related study, other researchers assessed the embodied carbon emissions when 50% of the wood from the demolished wood-frame building was reused as construction material for a new building, and the remaining 50% was used as fuel for energy production. By reusing 50% of the wood from the demolished wood-frame building the researchers found that the overall life-cycle produced 9% less carbon than using 100% of the waste wood for energy production (Borjesson, & Gustavsson, 2000).

From these case studies, there is much evidence that constructing a building out of laminated wood emits much less carbon, in comparison to constructing a building out of reinforced-concrete, if environmentally sustainable strategies are used during disposal. As shown in the following section, environmentally sensible choices are important for the life-cycle of a building.

2.4 Significance of disposal methods on carbon emissions

Depending on the disposal method chosen, the life-cycle carbon emissions can vary significantly.

The possible disposal strategies for wood and their impacts on carbon emissions are as follows:

- demolition of the building generates waste wood, which is used as carbon-neutral biomass for energy production, displacing the use of fossil fuels for energy production.
- the building is carefully dismantled at the end of its service life. Useable lumber from the dismantled building is recovered and reused as construction material for a new building development, displacing the need for trees to be harvested and processed for new lumber.
- demolition of the building generates waste wood, which is disposed of in a landfill. The methane gas generated from the decomposing wood is captured and used as fuel for energy production, displacing the need for fossil fuels for energy production.
- demolition of the building generates waste wood, which is disposed of in a landfill. The methane gas produced from the decomposition of the wood is allowed to escape into the atmosphere, contributing to greenhouse gas emissions.

Options in the life-cycle process of reinforced concrete-framed buildings are also available for disposal, with two possibilities for the management of the generated waste:

- demolition of the building generates waste concrete, which is recycled by being crushed and used as coarse aggregate filling material for roads and drainage systems, displacing the need to mine and process fresh aggregates such as gravel
- demolition of the building generates waste concrete, which is crushed and discarded in a landfill

(Note: Carbonisation, the re-absorption of carbon dioxide by cement, takes place for both disposal options for concrete.)

Depending on the disposal method chosen, the greenhouse gas emissions for the wood-framed building can vary significantly, ranging from being a negative sum (the lumber prevents a net amount of greenhouse gases into the atmosphere over its life-cycle), to being a positive sum (the lumber releases a net amount of greenhouse gases into the atmosphere over its life-cycle).

For example, in a study done by Swedish researchers (Borjesson, & Gustavsson, 2000), when all of the wood from a demolished building was used as for energy production, the overall embodied carbon emissions for the building's life-cycle was -97 tonnes. This was because the wood was used to displace coal fuelled power plants, and using laminated wood for energy production is generally considered carbon-neutral. However, when the wood was discarded in a landfill and allowed to decompose and freely release methane into the atmosphere, the overall carbon emissions was +3 tonnes, due to methane being a greenhouse gas.

All of these options for the disposal of reinforced-concrete and wood will affect their life-cycle carbon emissions. If unsustainable choices are made, the environmental advantages of wood compared to concrete shown in the case studies can be over weighed by the negative impacts of these choices.

3.0 Economic Impact:

The economic impact of laminated wood beams and steel-reinforced concrete are considered as follows:

3.1 Laminated Wood Beams:

Materials

The key materials used in laminated wood beams are soft wood strips and glue. The cost of soft wood strips is relatively low. Wood is a bountiful resource in much of Canada but in particular in British Columbia. The fact that much of the wood required to produce Laminated Wood Beams for the new SUB can be harvested within the province will help to keep costs of transportation down but also allows LEED credits for the use of local materials. The manufacturing technology required for these beams is well established in the Pacific Northwest and Southern British Columbia and thus allows all of the beam production to be completed locally. This local production will allow for further cost reduction through minimization of transportation costs.

Construction

Laminated wood beams may be constructed using standard framing tools and do not require complicated forming equipment. Wood beams do not require any curing time on site as traditional concrete construction does. This lack of curing time may allow significant reductions in construction time. In the case of an eight storey building constructed in London England the construction time was reduced from 72 to 49 weeks by using laminated wood instead of concrete construction.(Ward, 2009) Laminated wood beams may be assembled by workers experienced in

wood frame residential construction. Construction with Laminated Wood Beams typically does not require on site cutting or trimming of beams and is more of an assembly process. This allows faster build times and less waiting on a construction site.

Demolition/Disposal

At the end of the usable life of the New Student Union Building the Laminated Wood Beams may still be structurally sound. In such a case they may be removed whole as the building is demolished. These beams may be used as beams in another project locally at UBC or within Vancouver. This use of existing wooden beams may be seen in the CK Choi building here at UBC. This presents a tremendous cost savings both for the new building and for the disposal of the demolished materials.

If at the end of the usable life of the New SUB the beams are found to not be structurally sound they may be reprocessed into another form of building material such as Parallam or Oriented Strand Board. This reprocessing likely would not occur on site but may allow the cost of removal and disposal to be significantly offset by the sale of the repurposed material.

If the used wood is not suitable to be reprocessed it may be gasified into Syngas to power an electric generating station locally at UBC or elsewhere within British Columbia. The spent wooden beams may also be chipped and burned for heating fuel. If a suitable non-toxic adhesive was used in the production of the Laminated Wood Beams the chipped beams may be used as landscape mulch around the UBC campus.

Ultimately all of these “disposal” methods prevent the spent building materials from being buried in a landfill and allowed to decompose to methane. They also present methods of cost savings on disposal or potential profit from the disposal of the demolished building.

3.2 Steel-reinforced Concrete:

Materials

The base materials for steel-reinforced concrete are steel, aggregate, and Portland cement. Where steel itself is a product of iron ore and carbon. Although steel and aggregate may be recycled a number of times they both start as mined materials. This mineral extraction is costly and energy intensive. Steel requires a good deal of processing to transform its mined ore into a usable material. Aggregate is produced by mechanically crushing rock or recycled concrete to create gravel. Portland Cement is produced through a very energy intensive process where its raw mined materials are heated to high temperature and carbon dioxide is released. Although the production of cement may be done locally the steel required to reinforce the structure must be transported a great distance to the construction site. Thus this construction method may not qualify for the local materials LEED credit.

Construction

The construction of a steel reinforced concrete building requires the assembly of a wooden or composite form to contain the liquid concrete while it cures. As the forms are assembled steel rebar is added to reinforce the concrete structure. Once the forms are completed concrete is pumped into the void and allowed to cure for a number of days. This forming process requires workers skilled at concrete work and may not be done by residential framers. If the construction takes place in the winter months heat may be necessary to allow the concrete to cure properly. This heat is typically added by way of propane burning heaters which heat the building to be cured.

Demolition/Disposal

Demolition of a concrete building requires more force than the demolition of a wood framed building. The concrete removed from the building may be crushed and used as aggregate for road construction or in the production of new concrete. This recycling is a large downgrade in quality from the initial to final product. Also the cost of transporting large volumes of concrete is high due to its high density. It is unlikely that costs could be recouped or offset by selling the old concrete after the demolition of the New SUB.

4.0 Social Impact - Wood Adhesives and Health Concerns

The main concern with wood adhesives is formaldehyde emission, for the dominant adhesives are formaldehyde-containing. Formaldehyde is identified as toxic, allergenic, and carcinogenic. Depending on the concentration and exposure time, formaldehyde concentration in air 0.1ppm can cause mild symptoms such as sensitization symptoms, to severe ones such as aggravated asthma.

4.1 In-service formaldehyde emission

The concern over formaldehyde emission from wood products is mainly associated with Urea-formaldehyde (UF) adhesives (TECO, 2010). UF adhesive is chemically unstable, especially against hydrolysis and produces a relatively high amount of free formaldehyde. UF is thus mainly found in interior and non-structural laminated-wood and furniture for which resistance to moisture is not required (TECO, 2010).

In structural wood such as Glulam, adhesives used are phenol-formaldehyde (PF) and sometimes polymeric methylene di-isocyanate (PMDI). PF and PMDI are designed for moisture and heat resistance, with PMDI more expensive than PF. PMDI is an alternative for PF for applications which require more strict moisture and heat resistance. Since PF is much more stable than UF, the formaldehyde emission level from Glulam is very low. As for PMDI, it is not a formaldehyde-based adhesive thus produces no formaldehyde emission. PMDI also has no other VOC emission problems. Because of the low emission levels, Glulam products have been exemplified by CARB (as recent as 2008), one of the world's most stringent formaldehyde emissions standards (APA, 2010). In addition, formaldehyde concentration declines over time (APA, 2010). Thus with proper ventilation, formaldehyde emission can be further reduced. Therefore, there is no concern with formaldehyde emission

from Glulam during its service time. In fact, the use of Glulam in the construction of the new SUB will meet the LEED Canada criteria for indoor air quality, which requires formaldehyde concentration below 0.027ppm and prohibits the use of UF.

4.2 Formaldehyde emission in manufacturing

However, Glulam poses greater danger during the manufacturing process, because PF, UF, and PMDI are species formed from curing reactions which involve VOC's such as formaldehyde. It is also noticed that the occupational standards for formaldehyde emission is well above the standards for in-service emissions:

Table 1- Occupational Formaldehyde Exposure Limits (International Agency for Research on Cancer 2006)

Region	Concentration (ppm)	Type
Canada-Alberta	2.0	Ceiling (upper limit)
Canada-Ontario	0.3	Ceiling (upper limit)
Canada-Quebec	2.0	Ceiling (upper limit)

Notice also that the outlined limit is actually above the concentration which causes sensitizations. Thus wood adhesives still present a certain level of health hazard in the manufacturing process.

4.3 Formaldehyde emission in recycling

Laminated wood is generally recycled in three ways: 1) being chipped to make fiberboards or chipboards, 2) being incinerated as biofuel, or 3) being composted to be used as mulch. When Glulam beams are recycled to make fiberboards or chipboards, portions of the

wood with adhesives are removed to achieve proper adhesion. However, wood with adhesives only accounts for less than 3% of the total mass, thus it does not greatly influence the effectiveness of the recycling process. In terms of incineration, wood adhesives do not contribute to toxic combustion gas emission at all (dioxin levels in wood combustion,). Moreover, glulam has high combustion heat or effective calorific value, and is thus a comparable biofuel resource as natural and untreated wood. As for wood composting, the mulch made from laminated wood including glulam, OSB, and LVL are tested for contaminants that have been identified by the Environmental Protection Agency (EPA) as toxic, and no toxic contaminants are found (Marutzky, 2002). Therefore wood adhesives have no negative impacts in the recycling of laminated wood.

4.4 Feasibility of formaldehyde-free adhesives

It also came to our attention that most recent research indicates possibility of formaldehyde resin substitution, or partial substitution by natural resins including those developed from castor oil, tannin and soy product.

4.4.1 Castor oil-based polyurethane adhesive

A research conducted at Sao Carlos University investigated and demonstrated the feasibility of using a castor oil-based polyurethane as an alternative to formaldehyde-based adhesives in producing Glulam. The researchers assessed the mechanical performance of castor oil-based polyurethane in comparison with *Cascophen*, a liquid phenol-resorcinol-formaldehyde resin for the use in gluing structural wood members. Two species of wood, *Eucalyptus grandis* (leafy) and *Pinus caribea* var. *hondureniss* (conifer) are studied. Test results summarized as below:

Table 2 - Moment of rupture of beams (kN.m) (Azambuja, & Dias, 2006)

Beam	Adhesive	<i>Pinus caribea</i> var. <i>hondurensis</i>	<i>Eucalyptus grandis</i>
B-1	Cascophen	10.12	17.31
B-2	Castor oil	9.13	20.42
B-3	Castor oil	7.59	18.66
B-4	Cascophen	3.78	7.59
B-5	Castor oil	4.66	7.41
B-6	Castor oil	4.66	8.76

Table 3 - Summary of the efficiency values of the Eucalyptus grandis beams

	Beam 1	Beam 2	Beam 3	Beam 4	Beam 5	Beam 6
Adhesive	Cascophen	Castor oil	Castor oil	Cascophen	Castor oil	Castor oil
Effective EI (10 ³ kN.cm ²)	2532	3145	2449	805	879	929
Theoretical EI (10 ³ kN.cm ²)	2754	3206	2757	957	928	994
Efficiency (%)	91.9	98.1	88.8	84.1	94.8	93.4

Table 4 - Summary of the efficiency values of the Pinus Caribea beams

	Beam 1	Beam 2	Beam 3	Beam 4	Beam 5	Beam 6
Adhesive	Cascophen	Castor oil	Castor oil	Cascophen	Castor oil	Castor oil
Effective EI (10 ³ kN.cm ²)	1219	1250	1259	367	432	426
Theoretical EI (10 ³ kN.cm ²)	1229	1195	1208	379	407	401
Efficiency (%)	99.1	104.6	104.2	97.0	106.0	106.3

Test results indicate equal or better strength and rupture performance from castor-oil based polyurethane (Azambuja, & Dias, 2006). Since it is also proven non-aggressive to human and the environment, this castor oil-based adhesive is a valid alternative to formaldehyde adhesives that are commonly in use.

4.4.2 Honeymoon fast-set adhesives for glulam and fingerjoints of higher natural materials content

Honeymoon adhesive is a patented wood adhesive developed in the 1970's, originally being a pure phenol-resorcinol-formaldehyde (PRF) adhesive. Due to the increasing interest for environmental friendly products, a new types of honeymoon adhesive, where up to 65% of the total adhesive resins is replace with natural materials such as tannin extract is being developed. Adhesion is achieved by two components of the adhesive, with component A being a PRF resin with varying tannin content and component B being pure tannin. Test results as the following:

Table 5 - Summary of tensile strength with respect to tannin content (Mansouri, Pizzi, & Fredon, 2009)

Component A	Component B	Strength (% Wood failure)		
		Dry (N)	24 h cold soaking (N)	6 h boiling (N)
100 PRF	100 Tannin	2,553 (0)	2,071 (35)	2,351 (51)
90 PRF + 10 Tannin	100 Tannin	3,244 (50)	2,066 (10)	2,105 (80)
80 PRF + 20 Tannin	100 Tannin	3,156 (15)	2,108 (10)	2,143 (65)
70 PRF + 30 Tannin	100 Tannin	2,734 (70)	2,468 (50)	2,571 (76)
50 PRF + 50 Tannin + 5% NH ₃	100 Tannin	2,613 (22)	1,764 (50)	1,707 (70)
40 PRF + 60 Tannin	100 Tannin	2,242 (0)	605 (0)	1,059 (3)
BS 1204-1 requirement		≥ 2,500	≥ 2,000	≥ 1,500

*The last line is the British standard for glulam testing.

Results from this table show that at 65% tannin content, the glulam still meets the standard (Mansouri, Pizzi, & Fredon, 2009). Thus this report provides a valid method for reducing formaldehyde in glulam adhesives.

4.4.3 Protein-based Adhesive

Protein-based Adhesives were originally used for wood adhesion before adhesives derived from petroleum, such as PF, emerged in 1970's, presenting superior bond durability and

cost advantage. Current research has been focused on developing new protein-based adhesives with comparable properties as PF, and three types of product are already under testing for commercialization (USB, 2008):

- 1) A soy/phenol-resorcinol-formaldehyde (PRF) system for use in Oriented strand board (OSB) and plywood
- 2) A soy meal/flour formaldehyde-free glue to replace UF adhesives
- 3) A foaming glue for plywood

4.4.4 Commercialization of natural adhesives

In terms of commercialization of natural wood adhesives, we only found a few products for interior applications (such as Soyad® from Pure-Bond), none for structural wood replacements. The situation is mainly due to the fact that the current structural wood adhesives, PF and PMDI, produce almost zero emission except for during the manufacturing process, thus generating little concern from the consumer and presenting insufficient motivation for the industry to replace these structural wood adhesives. However, in view of the environmental benefits from using natural adhesives derived from renewable resources, there is still the potential for natural resin in structural wood. Thus we can see that it is reasonable to expect more choices with adhesive use by the time the construction of the new SUB begins, and therefore making wood a even more sustainable construction material.

5.0 Conclusion and Recommendations:

Generally laminated wood has an advantage over concrete in terms of life-cycle embodied carbon emissions as well as life-cycle economic expenditure. Regarding social impacts of laminated wood, there is a health concern associated with formaldehyde emissions from wood adhesives. However, these risks involved are manageable and do not negate the overall sustainability of laminated wood.

Environmentally, laminated wood buildings produce fewer embodied carbon emissions, compared to their concrete equivalents. However, careful choices must be made to ensure that sustainable methods are used to manage the laminated wood building after it has reached the end of its service life. These sustainable methods include using the laminated wood waste for energy production to replace power generated by conventional fossil fuels, and recycling and reusing the laminated wood in the construction of a new building.

Economically, the overall cost of using Laminated Wood Beams is likely to be less, compared to using conventional steel reinforced concrete construction. Studies indicate that cost savings of 10-15% are possible when using laminated wood instead of concrete. The exact amount of savings may vary depending on the actual floor plan chosen and the overall design of the building. In general, buildings constructed using laminated wood tend to be more economical than using concrete.

Finally, the perceived health concern over formaldehyde emission, a social issue of the use of laminated wood, is not sufficiently justified. It is because the wood adhesives used in structural wood produce formaldehyde emissions well below internationally recognized safe limits. In addition, the risks involved with high formaldehyde concentration during the manufacturing process are controllable. Moreover, the outlook of natural resin substitutes in place of synthetic resins currently in use is promising, providing a means for further reducing the health risks.

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Appendix A - :

Adjustments to calculations used in Dodoo, Gustavsson, & Sathre, 2009 to approximate laminated wood

Table 2 (taken from Dodoo, Gustavsson, & Sathre, 2009)

Description	Carbon balance (tonnes)		
	Concrete frame	Wood frame	Net difference
Construction phase (Year 0)			
Fossil fuel used for material production		77	54*
Cement calcination reaction	23.3	4.4	18.9
Fossil fuel used for biomass recovery		0.5	0.9
Substitution of fossil fuel by biomass residues	-19.9	-37.7	17.8
Carbon stock change-forest harvesting	93.1	144.3	-51.2
Carbon stored in wooden building material	-28.2	-40.3	12.1
Total from construction	145.8	125.6	20.2
Service life (Years 1-100)			
Cement carbonation reaction	-5.4	-0.6	-4.8
Carbon stock change-forest regrowth	-93.1	-144.3	51.2
Total from service life	-98.5	-144.9	46.4
Post-use phase (after year 100)			
fossil fuel used for material recovery			
-concrete	6.1	1	5.1
-wood	0.7	0.9	-0.2
Substitution of fossil fuel by demolition wood	-25.5	-36.4	10.9
Substitution of ore-based steel	-15.5	-9.6	-5.9
Cement carbonation reaction	-4.7	-1	-3.7
carbon released from wooden building material	28.2	40.3	-12.1
Total from post-use	-10.7	-4.8	-5.9
Total over complete life-cycle	36.6	-24.1	60.7

*This table assumes values for dimensional lumber.

.According to file from www.nafi.com.au/files/library/CSIROLCA.doc (National Association of Forest Industries)

laminated wood is 1.32 times more energy intensive to produce

By adjusting this number according (54 tonnes *1.32 = 71.12), the carbon impact of laminated wood is found to be as follows:

Carbon balance
(tonnes)

Description	Concrete frame	Wood frame	Net difference
Construction phase (Year 0)			
Fossil fuel used for material production		77	71.1
Cement calcination reaction	23.3	4.4	18.9
Fossil fuel used for biomass recovery	0.5	0.9	-0.4
Substitution of fossil fuel by biomass residues	-19.9	-37.7	17.8
Carbon stock change-forest harvesting	93.1	144.3	-51.2
Carbon stored in wooden building material	-28.2	-40.3	12.1
Total from construction	145.8	142.7	3.1
Service life (Years 1-100)			
Cement carbonation reaction	-5.4	-0.6	-4.8
Carbon stock change-forest regrowth	-93.1	-144.3	51.2
Total from service life	-98.5	-144.9	46.4
Post-use phase (after year 100)			
fossil fuel used for material recovery			
-concrete	6.1	1	5.1
-wood	0.7	0.9	-0.2
Substitution of fossil fuel by demolition wood	-25.5	-36.4	10.9
Substitution of ore-based steel	-15.5	-9.6	-5.9
Cement carbonation reaction	-4.7	-1	-3.7
carbon released from wooden building material	28.2	40.3	-12.1
Total from post-use	-10.7	-4.8	-5.9
Total over complete life-cycle (approximate)	36.6	-7.29	43.89
(for <u>laminated</u> wood)			