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Mass timber carbon solutions – Reducing Life-Cycle Carbon Emissions with Mass Timber Construction

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Abstract: Mass timber construction is gaining momentum every year, driven by the urgency of reducing carbon emissions in the construction world. Some of its advantages are structural performance, ease of construction, and a variety of options to suit different applications. One of the biggest risks in timber buildings LCAs is confusion over biogenic carbon. LCAs and dynamic thermal simulations were used to compare alternative scenarios focusing on material substitutions: changing the materials of the structure, slabs, external walls and core to certain mass timber solutions can deliver significant embodied and operational carbon reductions. The results show how a careful mass timber design can lead to significant carbon savings.

Keywords: Mass timber, LCA, embodied carbon, carbon emissions, thermal mass

1. Introduction

This dissertation aims to get to an understanding of how employing mass timber (MT) construction techniques into a design affects the whole life cycle (WLC) CO_2 emissions of the building. A community building in London is going to be analysed as case study: firstly, its building elements will be examined and LCAs will be conducted, focused on the GWP linkable to MTC. In addition, operational energy is also taken into account: by performing dynamic thermal simulations, its heating and cooling loads (and the resulting carbon emissions) will be estimated. The chosen climate model is the RCP 8.5 for London in 2100, in order to test a future-proof scenario and at the same time accentuate the risks of overheating. Several scenarios selected to represent designs with different approaches to MTC are going to be proposed and compared with the base case using dedicated LCA and thermal simulations. By analysing the heating and cooling loads with different construction scenarios, the contribution of MTC to the building's operational energy can be identified.

Through a series of thermal simulations without the heating and cooling systems, the passive operational temperatures of the building can also be analysed to understand if some slab constructions can bring operational carbon savings as a thermal mass effect.

Finally, the data gathered from the literature review, LCA and simulations will be considered to propose a cumulative “environmental best case” scenario, combining different MTC techniques to achieve relevant carbon emission reductions.

2. Theoretical background

Comparing different MT types and products is an essential step for selecting the right EWP for each application: two of the main distinguishing factors are structural characteristics and environmental impact. The literature shows how materials such as glued laminated timber (glulam or GLT) and laminated veneer lumber (LVL) are particularly suitable for structural elements such as beams and columns because they are made up of layers of parallel strands of wood, all oriented in the same direction, which together give high strength in the grain direction. In cross-laminated timber (CLT), however, each layer is laid crosswise, perpendicular to the adjacent ones. This strategy gives CLT isotropy, which makes the material behave more uniformly, making it ideal for surfaces such as walls and slabs. While the structural data for these products is well known and reported, the carbon emission factor, known as the Global Warming Potential (GWP), of each EWP can be deduced through a Life Cycle Assessment (LCA) that a company can carry out for each product: the results of this assessment are then published in a standardised Environmental Product Declaration (EPD).

A number of EPDs have been selected for glulam, CLT and LVL in order to compare them and find average GWP values for each typology in the 2023 MT market. The calculated average GWP of CLT is of 121.75 $kgCO_{2e}/m^3$, while glulam and LVL have average values of 172.18 and 210.22 respectively. Nonetheless, it was found that the actual EC of each product can be much different than these numbers: e.g., 1/3 of the glulam products have a GWP lower than 65 $kgCO_{2e}/m^3$, while 1/10 is above 350 $kgCO_{2e}/m^3$, without an apparent difference in the final product. The same also happens in CLT (from 34 to 330 $kgCO_{2e}/m^3$) and LVL (91 to 361 $kgCO_{2e}/m^3$). Comparing LVL and glulam, though, requires a wider scope since the first is much stronger than the latter, allowing for smaller cross sections to be used (Pollmeier, 2023).

3. Overview of the case study building

A community building called "W3", currently being built in Kings Cross, London, was chosen as a case study for this thesis, in collaboration with Haptic Architects: the aim is to use it test the findings of the literature review and to better understand the impact of its components on the building's WLC CO_{2e} emissions. This is a 13.50 metres high building with three floors above the ground; the open, flexible internal spaces, together with a modular façade solution, ensure that the building can respond appropriately to the changing functions in the years to come. The core of the building, containing two staircases, a central lift and the machine rooms, is offset to the east side of the plan to free up the central space for the community functions. The substructure of the W site is a common system shared between the three buildings, comprehensive of foundations and a common basement. Since the scope of this study is to analyse what impact MT design choices can have on the life-cycle emissions of a building, only the part above the ceiling level of the basement was considered.

4. Environmental analysis of the building elements and materials

The structural frame of W3 is mostly made of glulam columns and beams, made by the Austrian company Wiehag. This EWP has an upfront EC of 54 $kgCO_{2e}/m^3$, well below the average glulam upfront carbon of 172.18 $kgCO_{2e}/m^3$. 36 columns and 37 beams between the ground and first floor are made of steel due to a size constraint: some recessions in the plan at the ground floor cause a misalignment between some columns on the first floor and the ones at the ground floor. This creates horizontal loads that, in an all-glulam scenario, would have required large cross-section of the affected beams and columns, deemed too wide for the architectural design. Even though the steel components make up just 1.60 m^3, approximately 1% of the entire structure, their total EC amounts to 15 tCO_{2e}. Surprisingly, this is higher than the EC of the glulam part, which constitutes 99% of the structure, and stands at 11.8 tCO_{2e}. The significant disparity in carbon emissions can be attributed to the upfront carbon value (A1-A3) of steel, which is 6,100 $kgCO_{2e}/m^3$, surpassing the Wiehag value by over 100 times. Consequently, the combined EC of the entire frame reaches 26.8 tCO_{2e}.

The constructions of the floors and the roof are based on a 220 mm-thick CLT slab, made by the German company Derix. In both the internal slabs and the roof, the design involves the MT slab as the main structural element, while different layers are laid above it to improve the acoustic and fire performance, together with providing a stable and walkable finishing. On top of the 220 mm CLT slab, 270 mm are available for services and finishes, depending on the occupant's preference. The standard foreseen floor construction will consist, top to bottom, of a timber flooring, cement screed, plywood, fibre, a floating floor system and the aforementioned CLT. The Derix EWP is also a very carbon efficient one compared to the rest of the market. Moreover, the production centre of this EWP is located 520 km south-east from London, a relatively close location compared to other European MT manufacturers, making the transport emissions low as well. The total EC of the internal floors is 36.9 tCO_{2e}: the CLT slabs contribute with 17 tCO_{2e}, but the role of the plywood and fibre cement boards layers was found to be important as well, with respective GWPs of 6.7 and 12 tCO_{2e}, while wood flooring adds 1.2 tCO_{2e} to the total.

The main wall components are (outside to inside) a solid cladding with 150 and 160 mm decorative fins, a breather membrane, a sheathing layer of 15 mm OSB, 230 mm of mineral wool insulation, a second layer of OSB, a vapour retarder, a high thermal performance plasterboard and an expected finishing to be executed by the future tenants. On the west, south and a southern part of the east façade, the wall cassettes contain the aforementioned elements with radiata pine cladding and fins. On the north and the northern part of the east façade, aluminium was used for the cladding and fins, while a ventilated cavity and an additional plasterboard acting as a sound and fire barrier are added on the inside of the wall.

The foundations, basement and ground floor slab and core of W3, including its walls, slabs and stairs, are entirely made with reinforced concrete (RC): the first two are parts of a substructure shared with W1 and W2. The original design featured a CLT core, but a structural analysis showed how its offset position in the plan would have required extensive shear walls that would have occupied a larger part of the plan, thus reducing the area available for the community functions. Since using RC would have allowed a smaller core, this became the preferred choice. The same RC construction used in W3 as in the rest of the W site and built at the same time, which allowed for a smooth building program. The chosen concrete includes a portion of recycled aggregates, making it a less impactful material than the virgin one.

5. Proposed scenarios

The existing structure of W3, consisting of glulam and steel elements, can be compared with alternative scenarios where one or both of the materials are replaced with different EWPs.

While different EC results are therefore expected by the alternatives, an impact on the energy demand for heating and cooling is not anticipated due to the fact that the beams and columns occupy a relatively low volume compared to other building elements such as the walls or the slabs. Moreover, the fact that the external fabric is made up of cassettes with insulation placed side by side on the outside of the frame leads to an expected absence of thermal bridges in the structural joints. Steel beams were considered first. Using the comparison table made by Pollmeier for BauBuche (Pollmeier, 2023), an equivalent volume of MT beams and pillars can be estimated: the 1.60 m^3 of steel could be substituted by 40 m^3 of glulam, 23.4 m^3 of softwood laminated veneer lumber (LVL) or 16 m^3 of hardwood LVL. The first scenario tested was a structural framework made entirely of Wiehag glulam: the amount of wood required to replace the steel columns and beams is about 25 times greater, while if we consider the rectangular area occupied by the beam, as if the cross-section were a rectangle, glulam would cause a 2.5 fold increase. A similar solution representing a compromise between an architectural desire for structural elements with a small cross-section and EC savings could be the replacement of steel parts with hardwood LVL. BauBuche by Pollmeier is the only hardwood found with enough structural and environmental data to elaborate a scenario. Following on this principle, a third solution would be to replace both the steel and the glulam elements with beech LVL, in order to seek a reduction in plan footprint of the entire frame.

One strategy that has been evaluated to improve the thermal mass performance of W3 while at the same time keeping a low upfront carbon is designing alternative slab constructions. Different scenarios and materials were considered for this possibility, using a simple CLT slab with a thin and lightweight flooring system (such as a suspended wooden floor system), or the same slab with an earthen floor or a layer of concrete above it. Lastly, a slab entirely made of concrete was tested as a way to compare these solution to a "business-as-usual" industry standard. It needs to be noted that although the specific weight of each solution was calculated, structural feasibility was not considered for this study: some solutions, being heavier than others, might require a stronger structural support, leading to an increase in material use and consequent EC. For this reason, the final consequences of this scenarios would require deeper and larger-scale structural analyses to be soundly designed.

The composite CLT and concrete solution was inspired by the SOM "Timber Tower" concept (SOM, 2013). In this research project, a 70 mm thick concrete layer was placed on top of the CLT slabs in order to improve the otherwise poor sound insulation performance of MTC (Vardaxis, Bard Hagberg and Dahlström, 2022). Earthen floors are made with a mixture of sand, clay soil and fibre. One or more of these elements are normally obtained on site or in the close proximities. The finishing sealing is usually made with linseed oil, tung oil, pine rosin, beeswax and dipentene, making the final surface durable and washable. The final colour is influenced both by the materials used and possible pigmentations that can be added during the process. Although an EPD of this kind of product was not found, clay and rammed earth (RE), being materials similar to earth flooring, were used as substitutes in the LCA and thermal simulations.

An alternative scenario for the construction of the external walls was considered. While the current case involves a cassette system fixed on the glulam structural frame, a possible alternative could be evaluating the possibility of a load-bearing CLT wall substituting the external glulam columns. This would bring relevant upfront carbon reductions due to the removal of the outer 20 glulam columns of each floor, corresponding to 29.57 $^{\mathrm{m}^3}$.

Moreover, the inner plasterboard can be discarded, since visual grade CLT can be used as a finishing material and a fire protection layer if adequately sized (Waugh Thistleton Architects, 2023). At the same time, the MT layer will bring a thermal insulation contribution to the wall construction, allowing a reduction of the thickness of the rock wool layer. With a 140 mm CLT layer and the mineral wool insulation thickness reduced from 200 to 155 mm, the U-value of the external wall (0.20 W/m^{2}K) was kept unchanged.

6. Results

The results of the environmental analyses of the aforementioned scenarios are now reported. The environmentally weakest point of the structure is the groups of steel elements: although the amount of material required to fulfil the same role is almost 15 times higher for LVL and 25 times higher for glulam, in both cases the actual EC of the structure is lower than that of the steel version. If the Wiehag glulam was used instead of steel, the resulting GWP would be 3.5 tCO_{2e}, that is 11.5 tCO_{2e} or 76% less than the GWP of the base case steel.

If BauBuche beech LVL was chosen instead, the EC of it would be around 4.5 tCO_{2e}, with a reduction from the base case of 10.5 tCO_{2e}. Using BauBuche for the entire frame, instead, brings to an increase in WLC CO_{2e} emissions: instead of the current 11.8 tCO_{2e} of the GLT structure, the EC would rise to 14.5 tCO_{2e}. A sensible reduction in size of the columns and beam would therefore cost 2.7 tCO_{2e}. So, a good compromise can be to keep the Wiehag glulam beams and columns as they are but use beech LVL as substitution for the steel parts, obtaining small cross-sections with one added ton of embodied CO_{2e} as a trade-off compared to the all-glulam solution. The final EC of such frame would be 16.3 tCO_{2e}, 40% less than the base case, with a saving of 10.5 tCO_{2e}.

Regarding the new walls, the solution of reducing the mineral wool layer and removing the plasterboard, the finishing and the outer glulam columns in favour of a CLT layer would bring an estimated EC saving of 12.63 tCO_{2e}, while not having an impact on operational energy due to the U-value being unchanged. However, the augmented thickness of the external walls causes a reduction of surface area of 2.46 m^2 per floor, or 7.39 m^2 in total.

Considering how this solution can be generally applied to different projects, a specific value of $kgCO_{2e}/m^2$ was estimated. The removal of a part of mineral wool insulation, an OSB sheet and the plasterboard brings a reduction of 22.7 $kgCO_{2e}/m^2$, while the addition of the CLT layer adds 12 $kgCO_{2e}/m^2$. Therefore, the total saving is of 10.7 $kgCO_{2e}$ per each m^2 of wall, without considering the narrowing of the frame elements consequent to the CLT structural contribution.

The slab scenarios were subsequently tested. The simpler CLT slab one just includes a wood flooring, essential for practical use but not relevant to the thermal analysis: this solution proved to cause higher thermal energy demand in all seasons than the built one, but halving its EC (from 36.90 to 18.20 tCO2e), causing a WLC emissions saving of 15.06 tCO_{2e}. Adding earth onto the CLT slab increments the heating demand but lowers the cooling more of a higher amount, bringing reductions in both operational and EC, of around and 4.41 tCO2e per year and 16 tCO_{2e}, respectively, with a total of 18.66 less tCO_{2e} WLC emissions. The "SOM-type" CLT+concrete scenario still brought a slight EC reduction due to the narrow thickness of the concrete layer and a reduction in the cooling load, but an almost equal increase in heating load as well, with a WLC reduction of 7.83 tCO_{2e}. Lastly, the full concrete slab tested as a comparison was the scenario that caused the most extreme heating load increase (+88.31 kgCO2e/year) and cooling load decrease (-180.28 $kgCO_{2e}$/year) due to its high thermal mass, but as expected, it also had the highest EC, resulting in the smaller WLC emissions reduction, at just 6.10 tCO_{2e}.

By combining the best performing scenarios (an all-glulam structure, the CLT+RE slabs, together with the walls and core proposals), the final carbon emissions reduction from the base case is of 62.90 tCO_{2e}, or 4.70 $kgCO_{2e}/m^2$.

7. Conclusions

As seen in the analysis, building with MT can lead to CO_{2e} emissions reductions throughout all the WLC stages. Variables that make a real difference in the environmental performance of the building include the specific choice of EWPs, where to use them, how the building and its structure are designed, and how to couple it with other materials to improve its weaknesses.

Therefore, designers should take a good amount of care in such choices if a high sustainability level is desired. Literature shows that glulam and LVL are more indicated for structural frame elements, both from an embodied carbon and a structural point of view – although it is essential to conduct precise analyses of the possible EWPs in order to understand which one would bring the biggest CO_2 reduction. For surface elements, CLT is demonstrated to be a very carbon-efficient and structurally sound material with great versatility.

The results show how replacing steel and concrete with mass timber elements results in a significant reduction in EC. Adding earthen flooring to CLT slabs proves to be a successful strategy, improving the thermal mass performance with a low carbon profile. Regarding the external walls, replacing the outer columns and the inner layers of a typical lightweight wall construction (plasterboard and part of the insulation) with a load bearing CLT layer can give significant EC reductions, around 10.5 $kgCO_{2e}/m^2$, while maintaining the same U-value. All in all, the carbon emission reduction opportunities with MTC are mostly located in the EC sector more than in the operational carbon one.

8. References

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