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QUANTIFYING AND REDUCING EMBODIED CARBON IN THE ACOUSTIC DESIGN OF MASS TIMBER BUILDINGS

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ABSTRACT: An adoption of mass timber construction is the construction industry's best shot at reducing its significantly large contribution to global CO_2 emissions and to play its part in slowing down the climate crisis. Acoustic design in mass timber buildings typically relies on mass and facing materials in order to meet design criteria, and can account for a high proportion of the embodied carbon (CO_{2e}) per m² on a build. In order to fit with the ethos of mass timber construction; low embodied carbon, reusable, cradle to cradle materials must be adopted.

This paper presents the findings of a study into the relationship of acoustic performance and CO_{2e}, and proposes alternate approaches that reduce the CO_{2e}/m² of the acoustic design by up to 66% with little to no detriment to acoustic performance. Through single variable analysis in third party laboratory testing, and in situ testing, it has been found to be possible to utilise low CO_2e acoustic systems that reduce the CO_2e/m² in not only the acoustic design, but structural, M&E and architectural disciplines, too.

KEYWORDS: Acoustics, Mass Timber, CLT, Embodied Carbon

1. INTRODUCTION

Mass timber construction (predominantly Cross Laminated Timber [CLT] in Europe), is a method of utilizing sustainably FCS forestry commissioned timber to create building material that is used for structural support, roofs, floors and walls. It has garnered praise from most building design disciplines for its material properties – from structural loading capacity through to its biophilic appeal. Provided reforestation of these FSC supplies keeps up with demand, and in fact accelerates beyond it, the carbon sequestering capability of mass timber construction could lead to a significant reduction in the carbon emissions of the construction industry. To go theoretically further, if adopted on a global scale, mass timber could sequester more carbon than is omitted during the construction program.

Reforestation, increased biodiversity and an increased use of biomass fuels all are secondary beneficial factors to mass timber construction, too. However, the variability in moisture content, density, surface mass and timber species from manufacturer to manufacturer can create uncertainty in the acoustic and structural design of mass timber, leading to overspecification of floor and wall systems. Given these two disciplines have a historical tendency to utilise heavyweight isotropic mass in order to achieve relevant design criteria, the CO_{2e} of acoustic and structural design in mass timber buildings often account for an unnecessarily large proportion of the overall building design.

This paper sets out an observed correlation in acoustic performance and CO_2e/m² in mass timber construction and proposes alternative methods of construction and design approach that greatly reduces the CO_2e/m² of the acoustic design.

2. EMBODIED CARBON AS A METRIC OF SUSTAINABILITY

The lifecycle of a material can be allocated an embodied carbon figure given as CO_{2e}, which is obtained through a review of the CO_2 emissions generated from the entire lifespan of the material. This broadly covers raw material sourcing, manufacturing, transportation and longevity of the material (i.e. does it need replacement/maintenance throughout its life, and can it be demounted, recycled or reused at the end of life). As a result of this, a quantitative metric can and should be placed on any building material being used within a mass timber

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building – from the structural timber, right the way through to the light switches.

Manufacturers of building materials can opt into obtaining Life Cycle Assessments (LCA) in accordance with ISO 14040:2006 or EPD (Environmental Protection Declaration) in accordance with ISO 14025:2006 in order to provide evidence of the 'sustainability' of their products. However, these assessments are self declarations that are peer reviewed by regulatory bodies, but do not always address secondary ancillary materials required for those products to be used effectively – for example, floating floor isolators requiring heavy mass to obtain sufficient isolation efficiency or ceiling hangers requiring multiple layers of plasterboard. As a result, seemingly low CO_{2e} material products in isolation seem to fit the mass timber ethos, yet require high CO_{2e} materials such as multiple plasterboard linings and wet trades such as concrete and screed in order for them to meet required acoustic performance criteria.

The IPCC 6th Assessment Report offers guidance on how to reduce CO_{2e} emissions in construction, which are broken into 3 leading changes that yield the largest net reduction emission reduction, as **Figure 1** illustrates. The size of the orange circle reflects the size of the contribution of net emission reduction, the intensity of the color within the circle reflects the cost implication of implementing it, assuming material cost, delivery and construction cost:

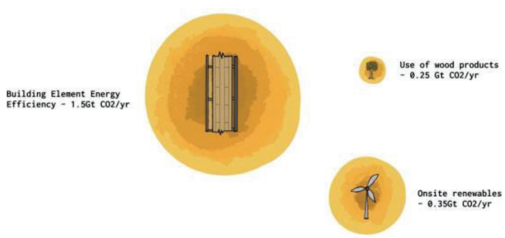

Figure 1: *Contribution to net emission reduction by 2030 (Gt CO_2/yr) – Construction* [(1)]

The IPCC report goes further, too. It suggests that not only changes to design criteria to aid emission reduction are considered, but also the role building materials play in the net emission reduction of CO_2 are too. **Figure 2** below reflects the data the IPCC report produces, in the same graphical format as Figure 1 follows:

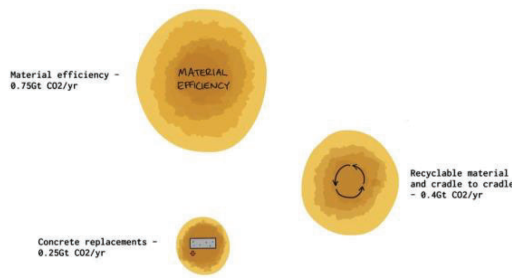

Figure 2: *Contribution to net emission reduction by 2030 (Gt CO_2/yr)- Industry* [(2)]

As can be seen from **Figure 2**, the efficiency of a building material (whether that be thermal, acoustic, lighting, M&E or other performance based metric) can have a large impact on net emission reduction. This can be interpreted as its ability to perform uniformly across time (low performance creep), as well as its ability to perform with as little secondary ancillary material support as possible, as discussed in the final paragraph of section 2.2**.** If this material was then to be recyclable at the end of its life (or even better demountable and reusable), the net emission reduction of the overall building is vastly improved. Lastly, the use of materials that replace concrete yields a smaller yet still significant impact on reducing emissions. In the context of building materials (i.e. facing layers, poured solutions and foundations), a reduction in the use of concrete still provides a significant chance to reduce net emissions and is largely interchangeable with materials with much lower CO_2 in most building types, but given the manufacturing, shipment and ultimate demolition of concrete accounts for 8% of global CO_2 emissions, a multi-disciplined approach to engineering out concrete where not required and favouring low CO_{2e} material is critical in slowing the climate crisis.

Finally, the benefits of switching to mass timber construction comes with many other quantitative benefits outside of CO_{2e}. Faster construction to meet demand of the housing crisis as urbanization increases worldwide, less site delivery movements, more dynamic thermal reaction, less on-site waste, and its biophilic appeal to name a few. **Figure 3** illustrates a comparison of two hypothetical 7 storey buildings, one constructed from 100% CLT, the other concrete frame and slab.

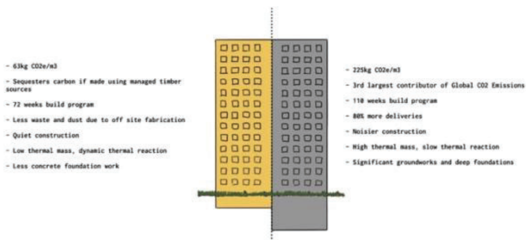

Figure 3: *Comparison of mass timber vs isotopic mass buildings.*

3. RELATIONSHIP OF EMBODIED CARBON AND ACOUSTIC PERFORMANCE

Correlating embodied carbon and acoustic performance is a difficult task to undertake due to the variables associated with design proposals, and the potential positive impacts that seemingly high CO_{2e} building materials may have on the performance of a building. A comparison with the analogy of a plastic wrapped cucumber creating unnecessary plastic waste can be drawn in construction – a plastic wrapped cucumber has a longer shelf life than an unwrapped cucumber, and is resistant to damage in transit. Therefore the plastic significantly reduces food waste - a major contributor of global CO_2 emissions. That said, alternatives to plastic wrap are now available that provide comparative, if not identical wrappage performance.

In the case of mass timber, commonly adopted concrete and screed pours onto the structural mass timber floors, or multiple layers of dense plasterboard wall linings is the plastic. Although these options all provide high thermal mass, good acoustic performance and predictable structural behavior, we must explore low CO_{2e} alternatives to meet comparable or identical performance. **Figures 4** presents an approximate correlation in airborne or impact acoustic performance and embodied carbon of concrete/screeded floor systems that can and are used in mass timber buildings. The estimated CO_{2e} of each system (not including the mass timber) has been obtained through 3rd party LCA.

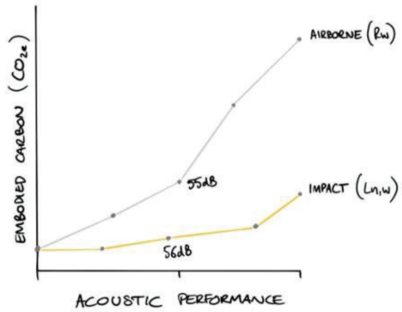

Figure 4: *Correlation of CO2e and acoustic performance in concrete/screeded acoustic floors in mass timber construction.*

Figure 4 provides not only an insight into the relationship between embodied carbon and acoustic performance in the context of floor systems, but also more broadly, the relationship between embodied carbon and general mass loading in mass timber construction. The implications of which have a significant impact on not only structural layouts, but also structural types that having varying CO_{2e} associated with them. **Figure 5** investigates the structural design implications of utilizing high dead loads to obtain high acoustic performance, and the effect on the CO_{2e} associated with that structural type.

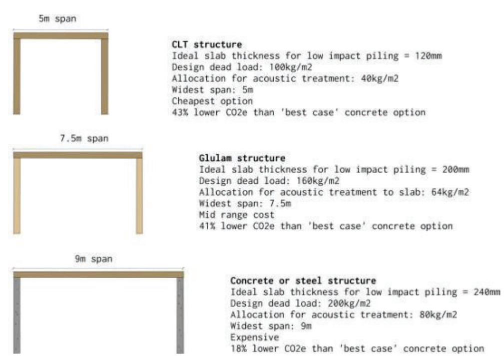

Figure 5: *Structural layout and design dead loads and CO_{2e}*

Figures 4 & 5 demonstrate that the reliance on heavy weight mass to achieve relevant acoustic performance criteria will tend to require heavier duty structural requirements, and subsequently result in higher CO_{2e} of the overall project. Increasing mass timber slab thickness to negate the requirement for heavy weight mass loading yields poor improvements in airborne performance relative to the uptake in cost. The mass law region of mass timber is narrower than

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isotopic materials, typically between 125Hz - 2000Hz in mass timber, compared with 63Hz to 2500Hz in isotopic material such as concrete. As a result, doubling the mass of a CLT floor or wall will not provide a 6dB increase in airborne performance. This can be demonstrated through Stora Enso's mass law formula for CLT floor panels as seen below as **Equation 1**, of which estimations compares favorably with almost all laboratory testing of bare CLT panels undertaken to date.

$$Rw = 12.2LOG * (m'CLT) + 15 \qquad (1)$$

where: m,CLT = surface mass of CLT in kg/m^2

Equation 1: *Stora Enso estimation of Rw performance of CLT floor*

4. DESIGN PRINCIPLES TO MAINTAIN ACOUSTIC PERFORMANCE AND REDUCE EMBODIED CARBON

A review of fundamentals of sound insulation design holds the key into looking at reducing embodied carbon in mass timber design. In order to obtain low resonance in a floating floor, and consequently providing good transmission loss values at low frequency on mass timber slabs, mass loading needs to be considered in conjunction with a selected resilient layer, the material properties of which are relative to one another depending on the dynamic stiffness of the resilient layer type, and the density of the mass layer. Resilient materials that have a linear load vs Fn relationship will naturally require more mass per m^2 in order to obtain low Fn, elastomeric materials less so. But both materials requiring mass in order to achieve a Fn that is sufficiently far 'left 'on an airborne sound insulation test, nonetheless. Conversely, ceiling or floor voids provide a much efficient method of lower the Fn of a separating element whilst keeping CO2e low. Airgaps does not cost the earth. The resonance of a floating floor or the resonance of an air stiffness can be calculated as shown below in **Figure 6**.

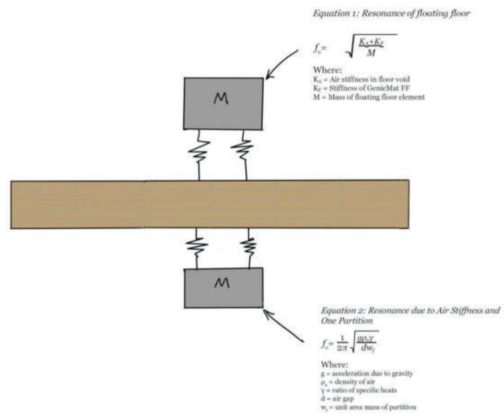

Figure 6: *Resonance calculations of separating elements of a slab.*

Figures 7 & 8 overleaf demonstrate this in effect. A relatively lightweight screed performs similarly to a dry laid, fully demountable boarded system on the same resilient layer, despite drastically different loadings – 82kg/m^2 for the screed, 30kg/m^2 for the dry laid board. It may be theorized that the resonance weakness in sound insulation still lies with the CLT, as the resonance of the floating floor isn't low enough to take this out. An inefficient use of a high CO_{2e} material. If we apply the same thinking to a ceiling void utilizing resilient clips and a sufficiently sized ceiling void (~150mm and above) and a single layer of 15mm plasterboard at 12.8kg/m^2, a much better airborne performance is achieved than the screed, whilst using ~85% less CO_{2e}/m^2.

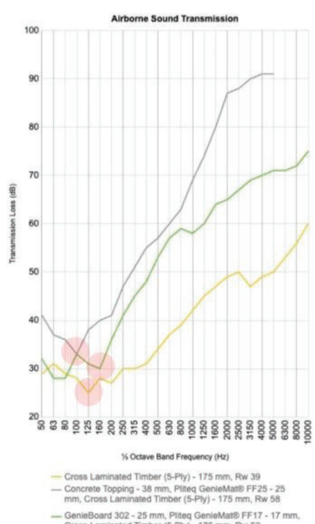

Figure 7: *Airborne and impact performance of differing mass layers on the same resilient layer, on CLT slab*

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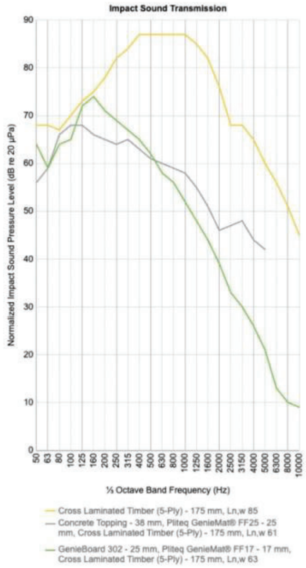

Figure 8: *Airborne and impact performance of differing ceiling void sizes on bare CLT slab*

5. VERIFYING HYPOTHESIS

Building mass timber buildings without using any form of concrete or screed still has many risks outside of acoustics. Insurance for the building is still a significant hurdle for developers as fire regulations are yet to recognize the extensive research into exposed mass timber fire performance. As a result, full encapsulation of the structure with minimum A2:Sfl1 rated material is required in order to obtain insurance for buildings over 7 storeys – materials that are commonly gypsum based. However, this balance of fire performance and the use of high-density material can still work hand in hand with the acoustic design, and obtain high quality acoustic performance. It is possible that we may be at a stage of overdesign of mass timber buildings to compensate for the high fire and acoustic criteria, reflective of current regulatory requirements. A case study of a care home is taken as an example of this. **Figure 9** below illustrates an acoustic system that was devised to provide encapsulation of the structure (direct fix plasterboard) to the soffit, and full class A2:Sfl1 encapsulation of the floors and walls, between each unit. 120 airborne and impact site tests were undertaken on separating floors and walls upon completion to check for compliance with $D_{nT,w} + C_{tr} \geq 45$dB and $L'_{Tn,w} \leq 62$dB. The average of these site tests are provided, with a data spread of +/- 6dB for airborne performance (largely driven by penetration details or pattressing requirements, and +/- 3dB for impact performance. It is unclear what variables affected the impact performance data spread, but it is theorized that CLT slab spans and room orientations were a contributing factor.

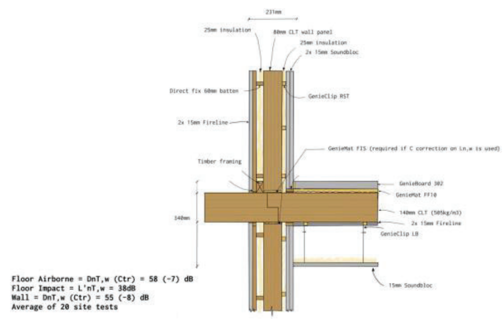

Figure 9: *Full encapsulation CLT detail for residential care home.*

It's estimated that the overdesign of this system led to an 'overspending' of approximately 5.6kg/m^2 of CO_{2e} or, accumulatively, 67.2tons of CO_{2e} across the whole development. If we adopt mass timber for even 20% of the current housing stock requirements, this will lead to an unnecessary 'spend' of approximately 8000 tons of CO_2 per year, at the current housing stock demand construction rate. The residential sector is arguably CLT smallest market currently in the UK, with offices making up most of the demand.

A similar case study was conducted on an office development where 1200m^2 of screed was to be poured on a 140mm CLT slab, with a 5mm virgin polyurethane foam resilient layer separating the two. This system was high in CO_{2e} (approximately 59kg/m^2), non-recyclable and likely to creep in impact performance across the lifespan of the building given the compressibility of the resilient material. An exercise was conducted to review the use of dry laid, demountable and recyclable material in lieu of the poured solution and it was deemed a cost saving system when factoring in the 12 week program saving it provided. **Figure 10** below illustrates the system that was installed.

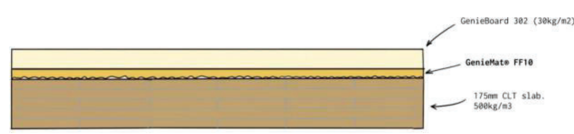

Figure 10: *Dry laid office floor system on CLT to meet BCO Shell and Core (DnT,w 45dB).*

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This system provided the structural requisite 0.4kN/m^2 dead load damping to meet minimum floor response factor requirements in conjunction with an installed raised access floor, and achieved an in situ performance of $D_{nT,w}$ 45dB and $L'_{nT,w}$ 50dB before the RAF was installed. The LCA estimated CO_{2e} saving across 1,200m^2 was approximately 34kg/m^2, or 40 tons of CO_{2e} across the development. If this approach would be adopted at current office development construction/refurbishment rates it will save up to 4800 tons of CO_{2e} per year. Providing service/conduit routing within this floor system to negate the requirement for the RAF would provide further significant CO_{2e} savings.

6. CONCLUSIONS

The design of mass timber buildings needs a considerate approach to utilize low embodied carbon materials to achieve relevant criteria for reasons twofold:

- To achieve the 'as little as possible' ethos when considering material use, wastage, cradle to grave material lifecycles in order to reduce embodied carbon in mass timber construction to as low levels as possible.
- To provide high quality mass timber buildings that perform as good or better than currently adopted high CO_{2e} construction (concrete, steel etc) that can be constructed fast, efficiently and to required specification - leading to the furthering of confidence, enthusiasm and trust in mass timber construction and all related engineering disciplines.

Mass Timber construction needs to be considered as a option for most construction projects where viable for the purposes of slowing down the climate crisis, and coordinated engineering approach between all disciplines (but most importantly fire, acoustic and structural) from an as early stage as possible, to ensure the viability of the design from a cost, buildability and cradle to cradle material perspective is ensured. Through third party data and assembly specific testing, this can be done and the elimination of high embodied carbon acoustic materials can be achieved.

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