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TIMBER VAULTS FOR ULTRA-LOW-CARBON BUILDING STRUCTURES

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ABSTRACT: This paper explores the benefits of using curvature and arching action in timber flooring systems to reduce the embodied carbon and aid in material efficiency. In this paper, the embodied carbon of the proposed timber barrel vault system with granular infill is compared with a more conventional cross laminated timber (CLT) floor. The proposed barrel vault system is constructed out of curved glue-laminated timber that spans between supporting beams. Steel ties are used to restrain the horizontal thrust forces generated by the vault. A two-dimensional parametric optimisation of the barrel vault floor system and the CLT floor in terms of minimising embodied carbon was undertaken using a script written in MATLAB, analysed using matrix stiffness methods and optimised using a genetic algorithm. The analysis was carried out on spans ranging between 4m and 12m with the optimal solution dependent on the interaction between the fabrication stresses, arch height, and rod diameter. The resulting design for 4m to 12m spanning office floors results in a 35% to 41% reduction in embodied carbon compared to an equivalent CLT system.

KEYWORDS: Timber vaults, optimisation, genetic algorithm, embodied carbon, fabrication stresses

1 INTRODUCTION

1.1 SUSTAINABLE MATERIAL EFFICIENCY

Building materials production emits around 10% of global energy-related CO_2 emissions, largely driven by cement and steel manufacturing [1]. To address this, the focus has shifted towards reducing embodied carbon in building materials. Embodied carbon factors are often linked to a unit volume or mass of material and therefore reducing the quantity of material results in concomitant reduction in the environmental impact of the building.

Floors typically account for 50% to 70% of a building structure's material consumption and weight [2]. Adding to this, floor area demand is predicted to increase by 75% between 2020 and 2050, with 80% expected to occur within developing countries [3]. Thus, material reduction in floors while maintaining safety is becoming even more critical to reducing overall embodied carbon in buildings.

Timber has recently re-emerged as an alternative for building structures with the introduction of mass timber products. Designers are increasingly turning to cross-laminated timber (CLT) panels as an environmentally friendly option for constructing buildings [4]. These panels, which are made from orthogonally bonded layers of sawn timber, have enabled faster construction through automated prefabrication, lower material uncertainty, and enabled longer spans made from timber. These benefits have consequently allowed CLT to be used in slab systems and walls. The simple and familiar geometries provided by CLT, and other mass timber products, have made it possible for the risk averse construction industry to adopt the material within their designs. Mass-timber buildings have also been shown to provide lower embodied carbon solutions when compared to steel and concrete [2]-[4] and, with the added advantage of biogenic carbon sequestration, this makes timber a viable solution to support a net-zero building industry.

However, CLT slabs are not optimal in their construction; the core material in a CLT slab does not contribute significantly to the member strength as it merely acts as a spacer between the extreme top and bottom fibres, which does most of the work [4]. Additionally, the cost of using timber in buildings is still seen as more expensive than designs utilising steel and concrete [2]. There are, therefore, numerous motivations for the efficient use of timber to ensure sustainability: to minimise fossil emissions during the construction stage, which are permanently released into the atmosphere; reduce cost; to ensure the sustainable use and distribution of a finite resource, which is under ever increasing demand.

New forests will be required for timber buildings to act as a carbon sink, which will threaten existing biodiversity and will increase competition for land. According to a comprehensive study by Mishra et al. [7] even if there is additional demand for timber in construction, the global

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plantation area would need to expand by 100% by 2100 compared to 2020 with this figure increasing to 200% if 90% of all new urban dwellers were to live in timber buildings. Therefore, to ensure a sustainable supply of timber in the future will require a material first approach whereby existing timber designs are optimised for material efficiency based on the actual stress distribution within the member [8]. The challenge is to create flooring systems and design methods that balance low embodied carbon solutions with safety standards, while meeting the performance expectations.

1.2 COMPRESSION VAULTS: STRUCTURAL TIMBER INSPIRED BY NATURE

Unlike concrete and steel structures, timber beams are often governed by serviceability limit states (deflection or vibration) as opposed to strength, since their low mass-to-stiffness ratio results in thick floors and high material consumption. As a result of this, the low span-to-depth ratios required to satisfy serviceability requirements make it difficult to justify using timber beams for long spans.

Trees have evolved to be strong under combined compression and bending forces to support their own weight all while resisting the prevailing winds. This can be taken advantage of by developing vaulted floor systems that act primarily in compression and bending, with the geometric stiffness of the vault compensating for the low timber stiffness. The additional stiffness benefits of using vaults have been demonstrated by Hawkins et al. [9] in previous work on concrete **floors**, where increased structural efficiency resulted in significant reductions in embodied carbon, particularly for longer spans.

Curved timber structures are fabricated by bending initially straight lamellas to the specified curvature, before bonding them with adhesive to lock-in the curvature and enable composite action. Advances in laminating techniques and adhesives have enabled the creation of highly complex geometries, such as the Urbach Tower at the Remstal Gartenschau in Germany [10] and the work by Robeller et.al [11] on curved-folded thin shell CLT structures. During fabrication, high initial stresses can develop in curved timber structures, leading to overstressing under service loads if the lamellas are too thick [12]. However, the viscoelastic behaviour of wood causes the initial bending stresses to decrease over time, a process known as stress relaxation. As shown by Lara-Bocanegra et Al. [12], the initial bending stresses can decrease by 45% to 66% after two years, with the reduction largely depending on the initial curvature of the beam, moisture content and temperature.

1.3 AIMS AND OBJECTIVES

Considering the need for lower embodied carbon structures, this project aims to create a low carbon flooring system using the compression and bending strength properties of timber in combination with the stiffness benefits of vaults. The research compares the embodied carbon of conventional CLT floors with a timber barrel vault design and hypothesises that timber vaults will have the similar efficiency savings as concrete vaults, but with the advantage of simpler design and fabrication and lower embodied carbon. To equilibrate the compression forces in the vault, steel rods acting in tension are provided. This paper describes the preliminary feasibility investigation of using timber vaults as potential embodied carbon saving when compared with cross laminated timber floors.

2 METHODOLOGY

2.1 BASIC PARAMETERS

Two floor systems were adopted during the study with spans ranging from 4m to 12m. The first type of floor investigated in the study was a single span CLT floor designed to Eurocode 5 [13] and shown in Figure 1. The resultant embodied carbon calculated from the CLT floor was then compared to the proposed curved timber floor systems. An optimisation exercise using a genetic algorithm was carried out for the barrel vault flooring system, shown in Figure 2, which comprises of a single spanning parabolic arch supported on two glulam beams with steel ties to counter lateral thrust. Granular fill of earth, gravel or rubble provides a level top surface and is hypothesised to improve vibration and acoustic performance. The material used for all the timber elements was C24, with the properties adopted from EN 338:2016 [14] for sawn timber and EN 14080:2013 [15] for glue-laminated timber.

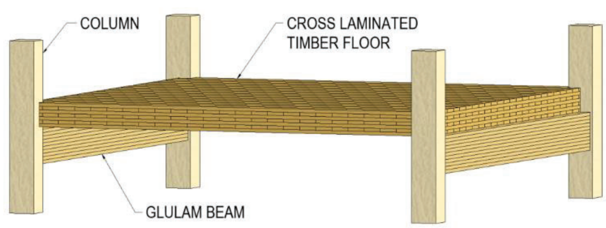

Figure 1: *Cross laminated timber floor*

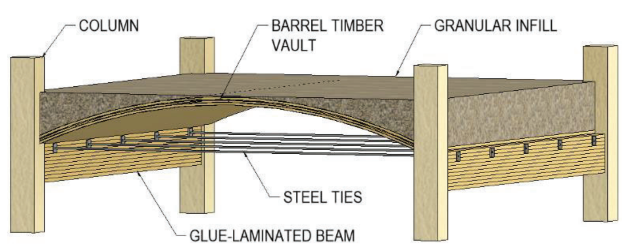

Figure 2: *Barrel vault timber floor*

2.2 DESIGN CRITERIA

Floor loadings were selected to represent a typical office design according to BS EN 1991-1-1 [16]. The design loadings included a live load of 3.5 kN/m^2 (2.5 kN/m^2 office loading and 1 kN/m^2 for movable partitions) and a superimposed dead load of 1 kN/m^2 with ULS partial load

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factors of 1.5 and 1.35 respectively. The self-weight of the beams, arch and infill were included as permanent dead load with a ULS load factor of 1.35.

Deflections were calculated under serviceability limit state (SLS) under both short term and long-term loading in accordance with BS EN 1995-1-1 [13]. A limiting instantaneous deflection (ω_{inst}) of Span/300 and long-term deflection (ω_{fin}) of Span/250 was adopted in the designs. A partial load factor of 1 was used for both imposed and dead loads. To account for creep and moisture effects on deflection, a creep factor (k_{def}) of 0.6 was used under service class 1.

Two load patterns were considered, as shown in Figure 3. The first comprises a uniformly distributed imposed load over the full width of the floor to determine the maximum compression in the vault. The second load pattern consists of only applying the imposed load over half the floor to determine the maximum bending moment. The granular infill material was applied proportionally to the height of the vault.

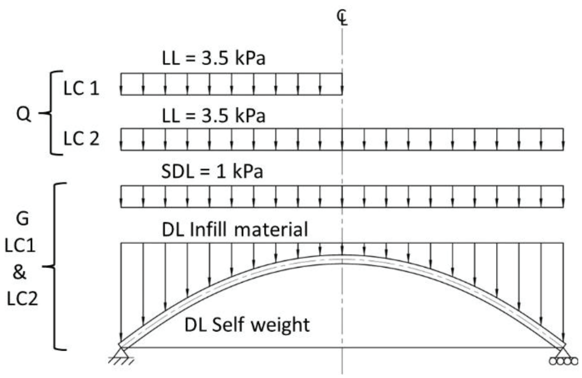

Figure 3: *Applied loading on the barrel-vault floor structure*

2.3 EMBODIED CARBON FACTORS

The focus of the study is limited to cradle-to-gate emissions (Modules A1-A3) and the embodied carbon and density values of the materials presented in **Table 1**. The carbon footprint of each floor design was calculated by summing the products of each material's quantity and its corresponding embodied carbon value.

The embodied carbon value for timber was sourced form an environmental product declaration (EPD 000124) [17] from a UK-based large timber merchant, which covers life cycle stages A1-A3, which includes tree felling, transport, processing, kiln drying, and finishing. The study assumed melamine-urea formaldehyde (MUF) resin, and its embodied carbon value was taken from Wilson [18] with a spread rate of 300 g/m^2 [19]. MUF resin was selected for the study based on consultations with glulam manufactures, as it is commonly used due to its cost-effectiveness and reliable performance [20], [21]. The embodied carbon value for the infill material was obtained from the Inventory of Carbon and Energy Circular Ecology [22].

Table 1: *Embodied carbon factors*

Material	Sawn timber (C24)	Adhesive (MUF)	Steel	Gravel infill
Density (kg/m^3)	420	-	7850	1835
Embodied carbon (kgCO$_2$e/kg)	115	1.775	1.55	0.00747

2.4 STRENGTH CAPACITY INCLUDING FABRICATION STRESSES

The design moment capacity, including fabrication stresses, shown in Figure 4, was calculated at each point along the length of the parabolic vault. The capacity was calculated at each point to avoid over conservatism, as the minimum fabrication stresses occur at the supports and the maximum occur at the centre of the vault. Equation 1 defines the height, u, of a parabolic vault with maximum height (h) and span (L). Utilising Equation 1 and its first and second derivatives, the curvature (K) and radius of curvature (R) at each point along the vault can be determined from Equation 2. Equation 3 determines the initial fabrication stresses at each point along the length of the beam using the Young's modulus of timber (E) and the moment of inertia of the lamella (I).

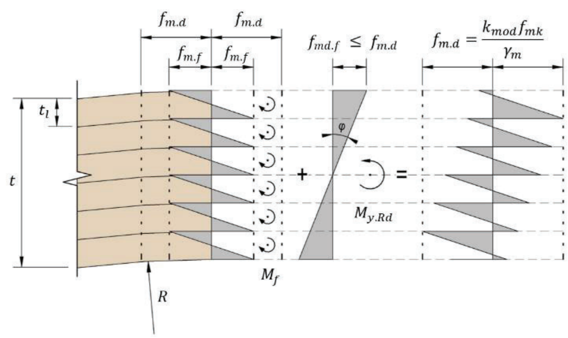

Figure 4: *Design load capacity in bending including fabrication and in-service stresses*

Stress relaxation was considered by reducing the initial fabrication stresses by 20%, which accounts for 1 week of relaxation, as adopted from Lara-Bocanegra [12]. The moment capacity of the section, Equation 4, was determined by limiting the maximum bending stress in the section to the design stress ($f_{md.f}$) as shown in **Figure 4**.

$$u = 4h\left(\frac{x}{L} - \left(\frac{x}{L}\right)^2\right) \tag{1}$$

$$K = \frac{1}{R} = \frac{|u''|}{[1 + (u')^2]^{\frac{3}{2}}} \tag{2}$$

$$f_{m.f} = \frac{KEI}{Z_l} \tag{3}$$

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The maximum additional stress capacity ($f_{md.f}$) was calculated by varying the curvature (φ) until the maximum design stress (f_{md}) within the timber was achieved. The maximum stress in the section occurs at the interface between the top and bottom lamellas and governs the moment capacity of the section. The utilisation of the section was calculated using Equation 5 using the calculated axial force ($N_{C.0.ED}$) and moment ($M_{0.ED}$) with the respective axial capacity ($N_{c.0.RD}$) and moment capacity ($M_{0.RD}$). The axial capacity incorporates the effect of buckling by including an instability factor (k_c).

$$M_{0.RD} = f_{md.f} Z_{xx} \quad (4)$$

$$\frac{N_{C.0.ED}}{k_c N_{c.0.RD}} + \frac{M_{0.ED}}{M_{0.RD}} \leq 1 \quad (5)$$

2.5 PARAMETRIC DESIGN OPTIMISATION OF THE BARREL VAULT

Optimisation studies date back over 50 years with genetic algorithms (GAs) being widely used and recognised in the optimisation of steel and concrete structures [23]. The optimisation study used in this paper comprises of a number of continuous and discrete variables, and the GA has proven to be a powerful tool when multiple interacting variables are used [24].

A two-dimensional parametric optimisation of the CLT floor and barrel vault in terms of embodied carbon was undertaken using a script written in MATLAB [25]. The vault design was optimised by considering the arch height, lamella thickness and steel rod diameter as continuous variables. The number of lamellas used in the parabolic arch and glulam beams was set as a discrete variable. The vault was discretised into a series of beams and nodes and analysed using matrix stiffness methods.

The genetic algorithm function in MATLAB [25] was used to find the optimal design as it is well-suited to handle both discrete and continuous variables by incorporating a penalty term into the objective function [26]. This penalty term transforms the constrained optimisation problem into an unconstrained one. During the optimisation process, the penalty function effectively penalises individuals in the population that violate the constraints more severely, guiding the search towards feasible solutions [27]. Figure 6 shows the optimisation process that was used for the vaults. The optimisation exercise evaluated a range of lamella thickness, steel rod diameters and arch heights for spans ranging from 4m to 12m.

The optimisation exercise is split into two branches. The first branch entails using the defined geometry for a specific set of input parameters to calculate the volumes and mass of the of each of the floor materials. The resultant mass of material is then multiplied by an embodied carbon factor and summed together to obtain the overall embodied carbon of the system. The second branch of the analyses performs a structural analysis of the system with the applied loading.

The capacity of the section, utilising the input geometry, is calculated, and used to determine the utilisation factors for each of the ultimate and serviceability limit states. With the increase in curvature of the beam there is a concomitant increase in fabrication stresses and therefore, to mitigate these stresses, the lamellas thickness needs to reduce. However, the fabrication of glue-laminated vault requires material to be planed off each of the faces of the lamellas to achieve a smooth surface to ensure adequate bonding between the layers. Conversations with glulam manufactures indicate that approximately 5mm of timber is planed off the top and bottom of the lamellas and 10mm is planed off each side irrespective of lamella thickness as shown in Figure 5. The tighter the radius of the lamellas, the thinner the lamellas need to be, and more material wastage occurs due to planing. This wastage has been included in the optimisation exercise.

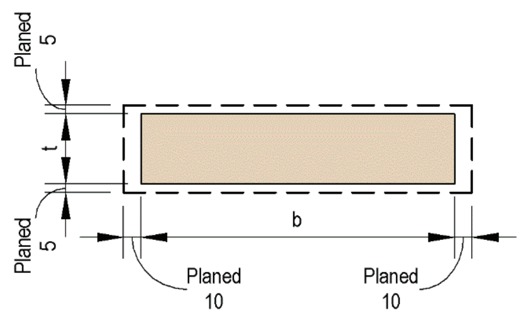

Figure 5: *Material wastage due to planing*

2.6 DESIGN OPTIMISATION OF THE CLT FLOOR

The cross laminated timber (CLT) floor system (Figure 1), was designed according to Eurocode 5 [13] and rests on two glulam beams. The equivalent stiffness was calculated using the gamma method to account for the orthogonal timber layers. The floor thickness was optimised by considering the lamellas thickness and number of lamellas.

The one-way spanning system was designed to meet both the ultimate limit states and serviceability limit states described in Section 2.1. Two CLT floor designs were considered; one that only met the deflection limits and another that satisfied both the deflection and vibration limits, to assess the impact of vibration in longer span designs. The vibration design of the CLT floor limited the natural frequency to 8Hz and satisfied the requirements of Eurocode 5 [13]. The embodied carbon calculation does not include fixings, columns, insulation, and other non-structural elements.

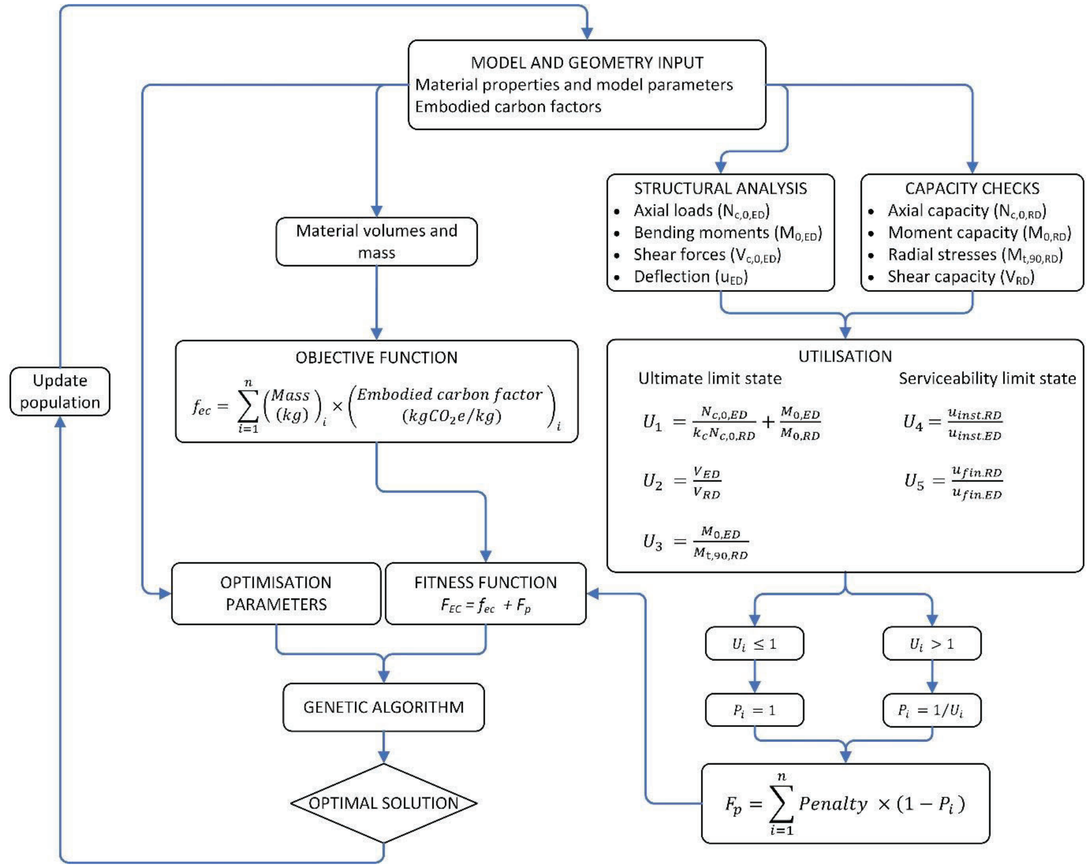

Figure 6: *Constrained optimisation process using Genetic Algorithms*

3 RESULTS AND DISCUSSION

The optimal embodied carbon solution for the vault system depends on the interplay between the arch height, rod diameter, number, and thickness of the lamellas. Figure 8 to Figure 10 shows the embodied carbon for an 8m span barrel vault compared to a CLT design, with and without vibration design. The optimal solution is indicated in the figures. The plots distinguish the embodied carbon contribution per square metre of the primary glulam beams, parabolic barrel vault, gravel infill and steel.

Embodied carbon with fixed arch height

The first investigation determined the impact of arch height on embodied carbon, with the results shown in Figure 8. The optimal arch height has a direct impact on the overall building height and solution feasibility. Using Section 2.5, the variables shown in Figure 8 were optimised for an 8m span and the lamella thickness of the primary glulam beams were fixed at 40mm to minimise material wastage. The CLT floor's embodied carbon, with and without vibration design, is also presented to show the magnitude of embodied carbon savings over the range of vault heights. The lowest carbon design occurs at a height of 0.6m (Span-to-height of 13). Near the optimal solution, there is minimal variation in embodied carbon. For instance, decreasing the arch height to 0.5m results in only a 2.45% increase in embodied carbon.

Embodied carbon savings decrease with increasing arch height, due to material wastage resulting from larger curvature causing higher fabrication stresses, which necessitates thinner lamellas.

For low arch heights, the steel rod diameter must increase significantly to control the horizontal thrust forces and ensure the design is compression governed over bending. Arch heights below 0.26m for the 8m span floor system produces higher embodied carbon than the CLT floor due to need for a large steel rod diameter required to restrain the horizontal thrust force produced by the shallow vault.

Embodied carbon fixed diameter of the steel rod

The second analysis examined the impact of rod diameter on embodied carbon, with the results presented in Figure 9. For an 8m span, when the steel rod diameter is less than 12mm, the system shifts from being compression governed to bending as the steel rod's utilisation is exceeded. At rod diameters exceeding 12mm, the steel rod has sufficient capacity to enable a compression governed vault system to form. Also, with rod diameters exceeding 12mm, the strength utilisation of the steel rod decreases and only the stiffness affects the optimal solution. This shift to a compression system results in a 150mm decrease in vault thickness, as shown in Figure 7(b), and a corresponding reduction in embodied carbon.

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Figure 7(a) shows that the optimal solution is achieved at the minimum diameter of the steel rod (greater than 12mm) that results in negligible fabrication stresses. Rod diameters between 12mm and 21mm require vault heights that result in high lamella curvatures, leading to residual fabrication stresses that reduce the bending capacity of the section.

For rod diameters greater than the optimal diameter of 21mm, the vault thickness remains relatively constant with only a minimal variation of 1.7 $kgCO_2e/m^2$ between a rod diameter of 21mm and 70mm. This indicates that increasing the rod diameter beyond 21mm has little effect on the embodied carbon of the vault, which is also seen in Figure 9.

Strength vs Deflection

During this analysis, the optimal solution produced by optimising for strength alone (Combined bending and compression with buckling), and deflection alone, is compared with the optimal solution found by considering both strength and deflection design requirements. The results are shown in Table 2.

Strength and deflection have competing objectives to minimise embodied carbon: strength aims for a solution with low arch height, and large number of lamellas to minimise fabrication stress, while deflection seeks a high arch height to maximise the beneficial properties of the geometric stiffness of the vault but still considers the weight of the fill material. The deflection only optimal solution considers both live load distributions (full live load and half the live load). Additionally, the deflection only solution also aims for a solution with the minimum number of lamellas that results in the lowest possible waste. Therefore, in this problem, the solution tends to the maximum lamella thickness.

To satisfy both strength and deflection requirements, the optimisation compromises between the two solutions. The height of the arch is predominately governed by deflection, while the number of lamellas is determined by the fabrication stresses. The increase in arch height from the strength optimal solution causes the lamella to become thinner resulting in additional material wastage. The optimal solution based solely on the deflection only criteria results in the lowest embodied carbon solution at the optimal rod diameter, due to there being no fabrication stress constraints. The quantity of embodied carbon is then followed by the strength only solution.

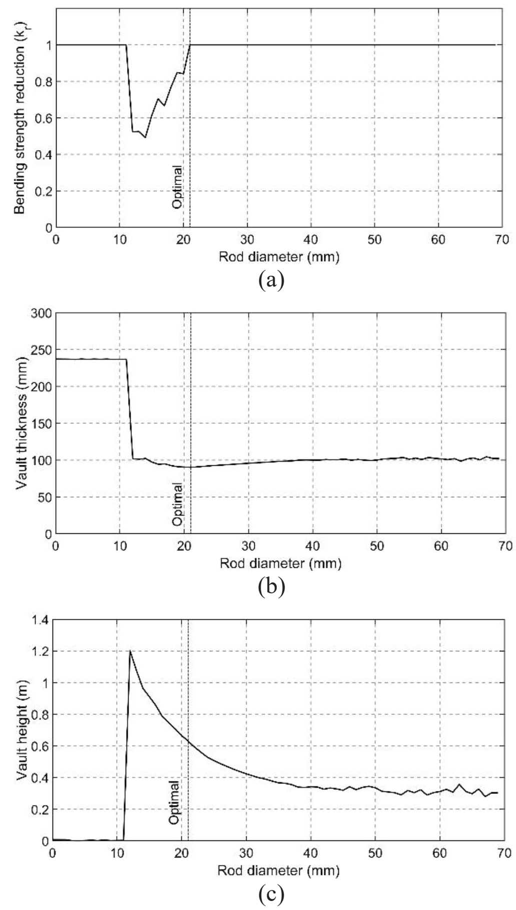

Figure 7: *Results for an 8m span parabolic vault showing, (a) The vault thickness with increasing rod diameter, (b) Vault height, (c) Bending strength reduction*

However, meeting both criteria results in a higher embodied carbon due to the increase in arch height from the strength only optimal solution and number of lamellas from the deflection only optimal solution.

Embodied carbon fixed lamella thickness

Figure 10 presents the results of the optimisation analysis by fixing the lamella thickness and limiting it to between 2mm and 40mm. The analysis indicated that the optimal number of lamellas is 3 with an optimal lamella thickness of 30mm for an 8m span.

Table 2: *Parabolic vault optimisation results for an 8m span barrel vault at the optimal rod diameter*

Optimisation constraint	**Arch height (m)**	**Lamellas (no.)**	**Lamella thickness (t) (mm)**	**Embodied carbon ($kgCO_2e/m^2$)**	**Utilisation**		
					Strength (incl. buckling)	Instantaneous deflection (ω_{inst})	Long term deflection (ω_{fin})
Strength	0.38	3	33	35.19	1	1.93	2.18
Strength + Deflection	0.56	3	30	36.84	1	0.9	1
Deflection	0.60	1	78	29.10	>> 1[(1)]	0.9	1

1) Fabrication stresses utilises most of the section's capacity

lamellas results in a sudden drop in the embodied carbon due to a reduction in fabrication material wastage. The choice of lamella thickness and number of lamellas is shown to not influence the embodied carbon in the primary beams.

Embodied carbon with increasing span

The analysis was repeated for spans between 4m and 12m with the results presented in Figure 11. Utilising the barrel vault floor system results in a reduction in embodied carbon between 35% and 41%, compared to the equivalent CLT floor when only considering strength design, buckling and deflection. However, at spans exceeding 5m, vibration governs the design of the CLT floor, and therefore it is likely that the barrel vaults will need to be checked and designed for vibration as well. It is worth noting that the diameter of the steel rod is determined by its stiffness rather than its strength. The strength utilisation of the steel rod in all the spans was around 50%, thus using higher strength steel is unnecessary.

Design considerations

The analysis showed that incorporating curvature in the floor design saves embodied carbon when compared to a traditional CLT floor design. However, there are several aspects that have not been considered that could make the floor system more inefficient, which include:

- Vibration. However, adding granular fill to the system is likely to enhance its damping properties and, when combined with the geometric stiffness of the vault, may prove more advantageous than a CLT floor system when vibration dominates the design at long spans.
- Fire design was not considered in the analysis and could result in additional embodied carbon in the design of the vault structure with the addition of a charring layer or other fire-resistant systems. This would also be necessary for the CLT system.
- The fabrication of curved timber members presents several challenges that may impact the feasibility of the floor solution. The production costs of curved timber members may be higher, as the process will be more labour intensive and require more resources compared to CLT floor fabrication. Additional design and fabrication of the connection between the steel rod and the timber beam is required, and the addition of fill entails an additional construction activity on site, which could increase construction time.
- Overall height of the optimal vaulted floor system is typically higher than the equivalent CLT floor and this may impose a constraint on the overall building design.
- Self-weight bending of the steel tie rod has not been considered which may lead to a reduction in geometric stiffness of the tie and therefore the floor as a whole.

However, several aspects which may improve efficiency have also not been considered in this preliminary investigation, including the following:

- Utilising double curvature in the form of groin vaults could eliminate the need for primary beams and provide a more efficient solution. This was demonstrated with concrete groin vaults in the research undertaken by Hawkins et al. [9].
- The addition of prestress. As shown in [28], the addition of prestress reduces the maximum vertical displacement.
- Optimising the form of the vault to reduce the bending moments caused by the gravel infill.

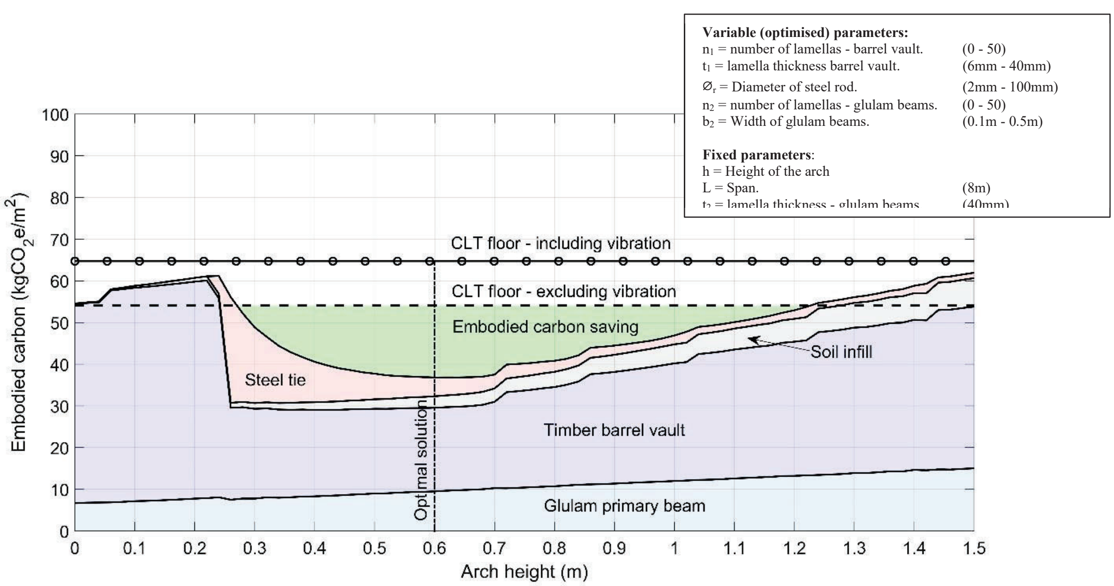

Figure 8: *Embodied carbon optimisation of the barrel vault by fixing the arch height for an 8m span floor*

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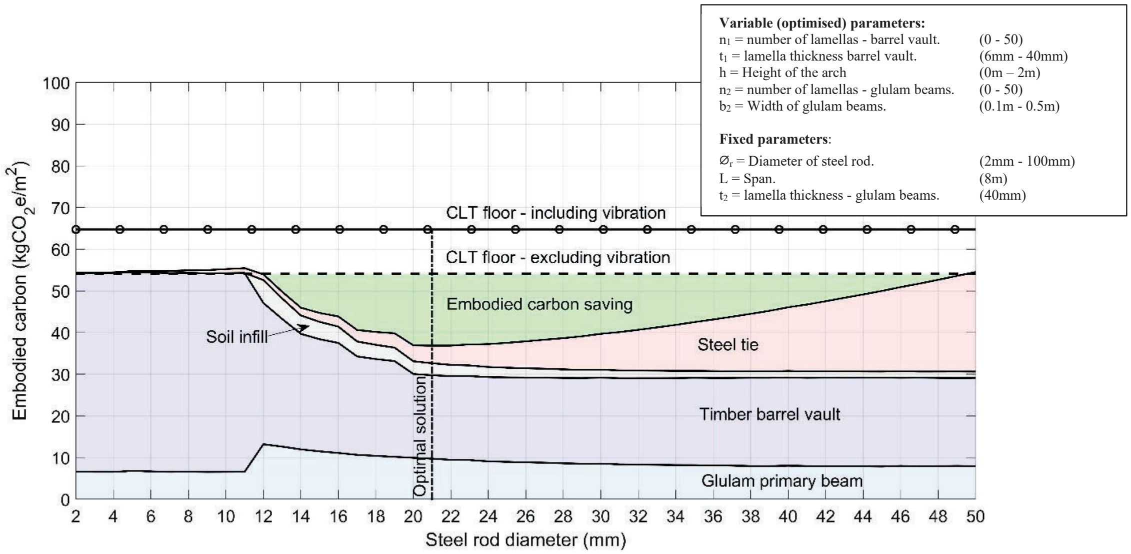

Figure 9: *Embodied carbon optimisation of the barrel vault by fixing the diameter of the steel rods for an 8m span floor*

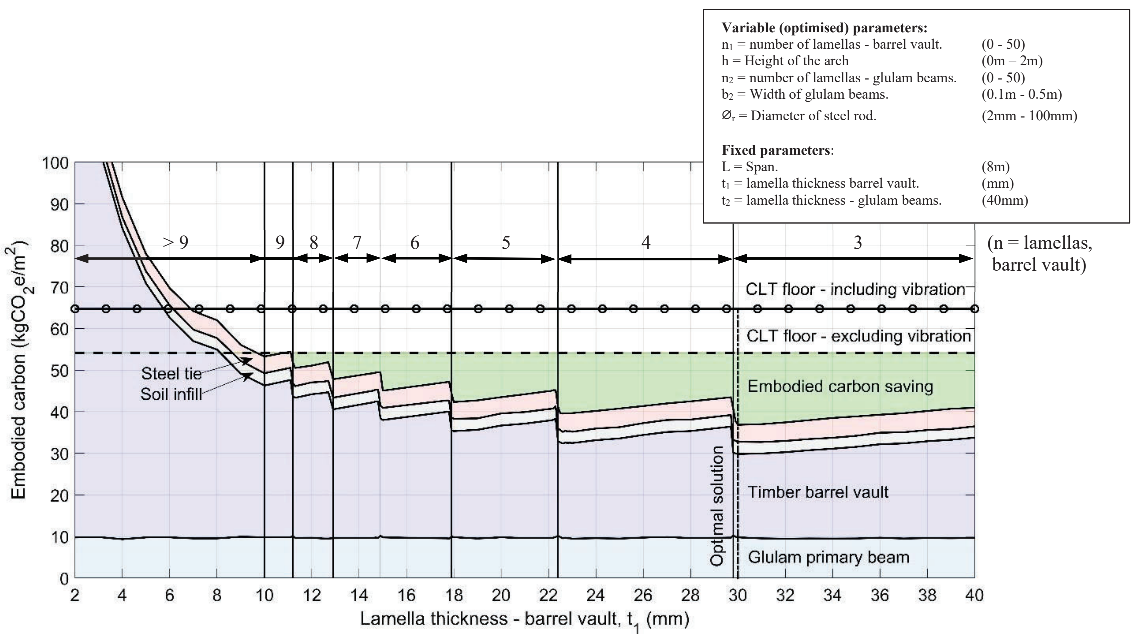

Figure 10: *Embodied carbon optimisation of the barrel vault by fixing the barrel vault lamella thickness*

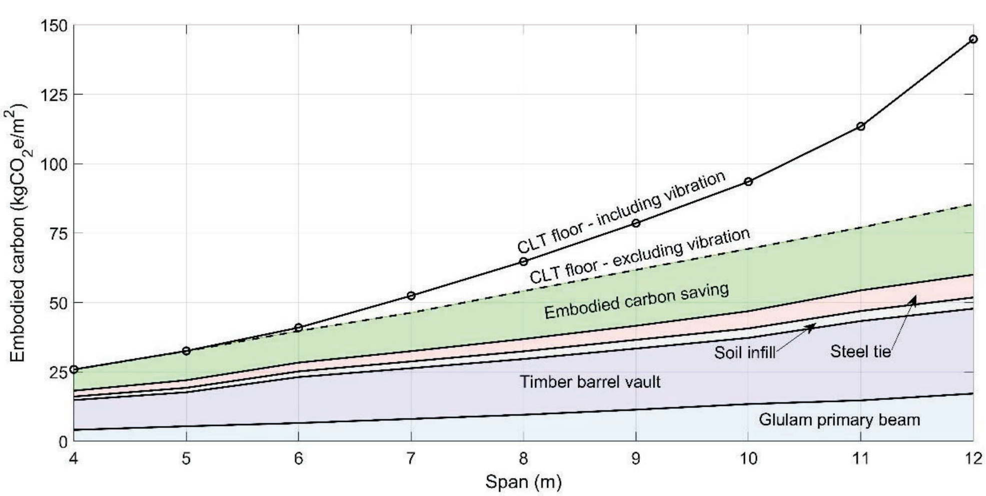

Figure 11: *Embodied carbon optimisation with increasing span*

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4 CONCLUSIONS

This paper investigates the potential of using timber barrel vaults as a low carbon alternative to CLT floors, by shifting the primary load resistance from bending to compression. A curved timber barrel vault system with granular infill is proposed, using glued, curved lamellas spanning between straight glulam beams, which span between columns. The horizontal forces generated by the vault is restrained by steel ties. An optimisation exercise using a genetic algorithm with a penalty function was performed, using both discrete and continuous parameters, to evaluate the performance of the system. Finally, the proposed system was compared to a CLT floor for a typical office design with spans between 4 to 12m. The key conclusions of the investigation are as follows:

- Compared with an equivalent CLT floor, the proposed barrel vault system provides a significant embodied carbon saving of between 35% and 41% across the analysed spans.
- The optimal design of the proposed timber vault solution is achieved when both strength and deflection utilisations are equal to one, which occurs at an optimal span-to-height ratio between 13 – 14.
- The arch height is predominantly governed by the deflection criteria with the number of lamellas determined by the fabrication stress.
- The optimal solution is dependent on the balance between the arch height, rod diameter and fabrication stresses. The optimal solution occurs at a maximum arch height that results in no stress reduction due to fabrication stresses, which is balanced by a steel rod with sufficient stiffness.
- The restraint by the tie at the optimal solution is dependent primarily on the stiffness of the material.

This paper shows that introducing curvature into timber floors provides a feasible and efficient solution to lowering embodied carbon. The process followed during the research shows a method that structural engineers can implement to optimise the reduction of their embodied carbon in buildings.

5 FUTURE WORK

To potentially achieve greater savings, the glulam primary beams can be removed by replacing the barrel vault with a doubly curved groin vault system, especially for longer spans. The next step is to analyse groin vaults and optimise their design by including vibration, acoustic performance, and fire design. This includes the form of the vault, the ease of fabrication, connection details, and coordination with building services to develop a cost-efficient solution. The study will also investigate the type and quantity of infill material that is needed to meet vibration and acoustic requirements while reducing the dead load. Furthermore, the potential of vaulted floor systems will be explored by comparing them with other efficient timber flooring systems that are currently on the market.

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