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INTERACTIVE PARAMETRIC STRUCTURAL DESIGN AND OPTIMISATION TOOL FOR DESIGN OF FRP-REINFORCED MASS TIMBER BUILDINGS

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ABSTRACT: The inherent material properties of mass timber can restrict its serviceability performance, particularly for long-span floor system applications. Hybrid fiber-reinforced polymer (FRP)-timber composite systems have been proposed with enhanced static and dynamic serviceability behaviour, however the lack of a comprehensive structural design tool for such products has hindered their broader adoption. This paper introduces a parametric analysis tool designed to compare traditional mass timber with FRP-timber constructions. The tool evaluates span capacities for both pure mass timber and FRP-reinforced mass timber flexural elements in a typical post-and-beam building configuration. These span capacities are then integrated within a parametric computer-aided design (CAD) tool to enable interactive structural size optimisation for variable building grid size, height, number of stories, loading condition, and element spans. Since long-span timber elements are often constrained by serviceability requirements, CFRP reinforcements are assessed for their potential to increase stiffness and natural frequencies, and thus enable longer spans for the same element thickness; or reduced element thickness for the same span.

KEYWORDS: mass timber, parametric design, structural performance, CFRP, hybrid timber construction

1 – INTRODUCTION

In recent years, mass timber structures have gained prominence as a sustainable alternative to traditional building materials, aligning with global efforts to reduce carbon emissions [1]. However, the physical characteristics of timber, and CLT in particular, often limit its application in structures requiring longer spans or taller buildings [2-4]. This limitation necessitates increasing the cross-sections significantly to meet stiffness requirements and pass serviceability checks, which can strain timber supply chains and render timber-only solutions impractical for certain applications.

To overcome these challenges, the construction industry has increasingly turned to hybrid solutions, such as timber-concrete [5] and steel-timber composites [6]. Additionally, Fibre-Reinforced Polymers (FRP) have been explored, primarily for retrofitting but also for enhancing the strength and stiffness of new structures through combinations with timber [7-13]. Among these, Carbon Fiber-Reinforced Polymer (CFRP)-timber composites stand out for their ability to significantly increase natural frequencies and stiffness, key factors in serviceability design [8,9].

While considerable research has focused on FRP-glulam and FRP-CLT composites, the broader adoption of these materials has been disadvantaged by a lack of comprehensive design tools compared to other hybrid structures. Recognising the potential to maintain the lightness of timber while substantially improving its structural performance, this paper introduces a parametric design tool specifically developed for early-stage comparison of design alternatives. This tool aims to quantify the optimised use of wood fibres in hybrid constructions, potentially transforming the approach to sustainable building design. This paper presents the developed parametric tool and results comparing mass timber buildings with their CFRP-timber alternatives in terms of volume of timber used, reduction of depth of slabs and beams, and the increase of spans.

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2 –PARAMETRIC DESIGN TOOL

2.1 OVERVIEW

A parametric structural design tool was developed for a rectangular grid post-and-beam structure and implemented in Rhino/Grasshopper (GH). The tool is developed as an integrated computational design workflow for geometric modelling and structural design, allowing for real-time user customisation of geometric and design parameters for a mass timber (glulam columns and beams, CLT slabs) or FRP-timber structure (CFRP-reinforced CLT slab). As such, it is intended to support early-stage comparison of post-and-beam design alternatives, enabling architects and engineers to quantify the optimised use of wood fibres in hybrid timber construction.

A parametric structural design tool was developed in Rhino/Grasshopper (GH) to optimise rectangular grid post-and-beam structures. This tool integrates geometric modelling and structural design, allowing real-time user customisation of key design parameters for both mass timber (glulam columns and beams, CLT slabs) and hybrid FRP-timber structures (CFRP-reinforced CLT slabs). The tool supports early-stage design exploration, enabling architects and engineers to assess material efficiency and optimise wood fibre usage in hybrid timber construction.

The design tool is implemented as a Grasshopper script, as shown in Figure 1. Users can customise the building layout and loading conditions, after which the tool conducts automatic structural size optimisation using pre-design span tables. Once optimal member dimensions are determined, the tool generates a 3D model and calculates the volumes of timber and FRP required. The tool consists of three primary modules:

1. Geometry Module – Defines the number of bays, storeys, and overall structure size.
2. Design Variables – Determines the minimum cross-sections required to meet structural performance criteria.
3. Volume Calculation Module – Computes the total timber volume needed for the design.

The parametric tool selects the smallest feasible CLT panel cross-section under typical loading conditions. Based on the minimum panel type required to span 6000 mm using only timber CLT, corresponding to Figure 2 and Figure 3.

Pre-design span tables are based on XLAM Design Guidelines [9], assuming floor deflections are governed by vibration and serviceability limits. A parametric analysis was performed to determine similar span tables and the maximum span achievable for FRP-reinforced CLT cross-sections, considering stiffness, mass, and vibration performance. By integrating span tables into this visual parametric tool, the workflow provides a streamlined approach to optimising timber use while enhancing structural efficiency.

Recognising the potential to optimise timber use while enhancing structural performance, span tables were integrated within a visual parametric design tool developed using Rhino/Grasshopper.

3 – CASE STUDY: COMPARISON OF TIMBER USE AND SPAN CAPACITY

3.1 CASE STUDIES

The parametric tool was applied to two case studies, to explore how the incorporation of CFRP as reinforcement could improve the efficiency of timber structural members and how this can be translated into the application of CFRP reinforcement in mass timber buildings. The first case study explores how CFRP-reinforced CLT can be used to decrease the depth of slabs and beams. The second case study explores how CFRP-reinforced CLT can be used to increase the design span while maintaining slab depth.

An exemplar 10-storey post-and-beam building was used to analyse the impact of CFRP-reinforced CLT slabs. Figure 2 presents the 3D render generated by the Rhino/GH tool. The structural grid consists of posts spaced at 6000 mm x 7000 mm, with beams running over four continuous spans. CLT slabs span 6000 mm along the horizontal axis (left to right). Figure 3 illustrates the general plan, including layout and span orientations for the building.

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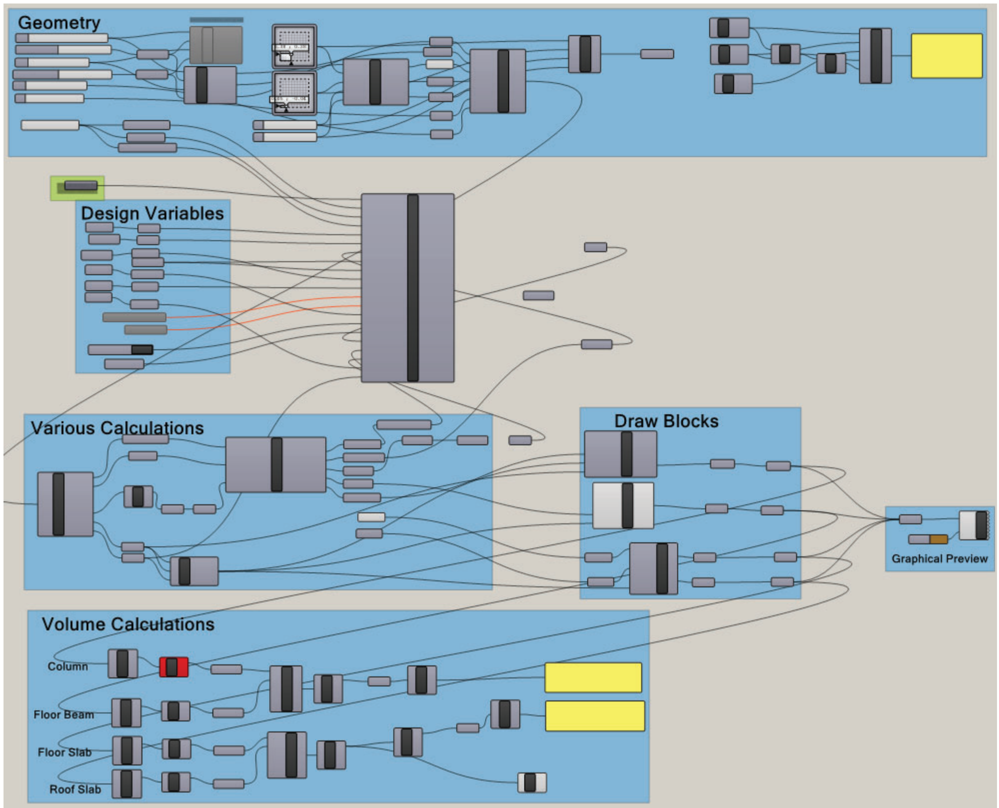

Figure 1. Schematic view of the GH script and different modules.

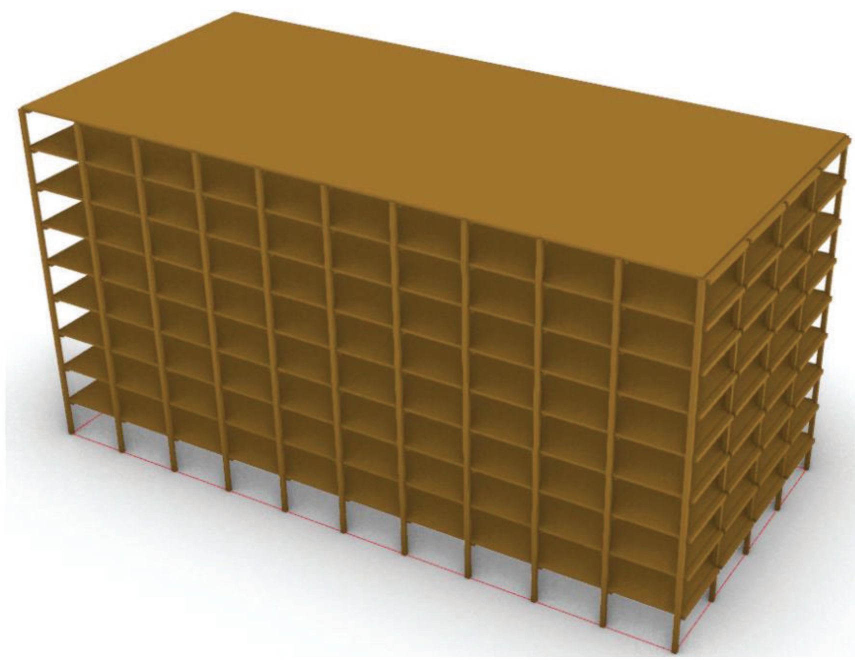

Figure 2. Interactive model based on GH script input for a reference mass timber building.

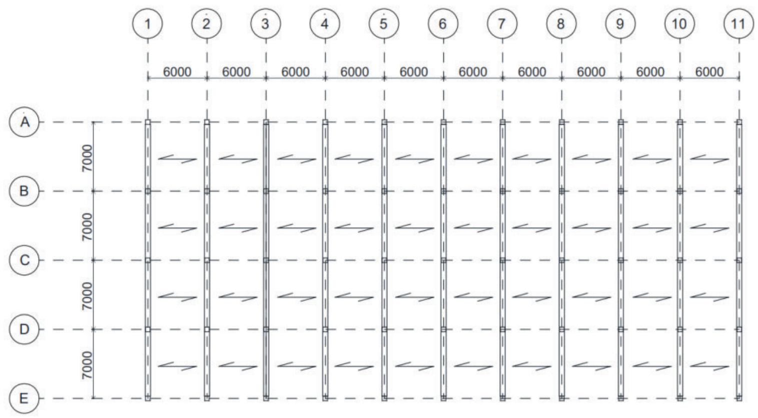

Figure 3. Grid, layout, and span orientation for case study 1.

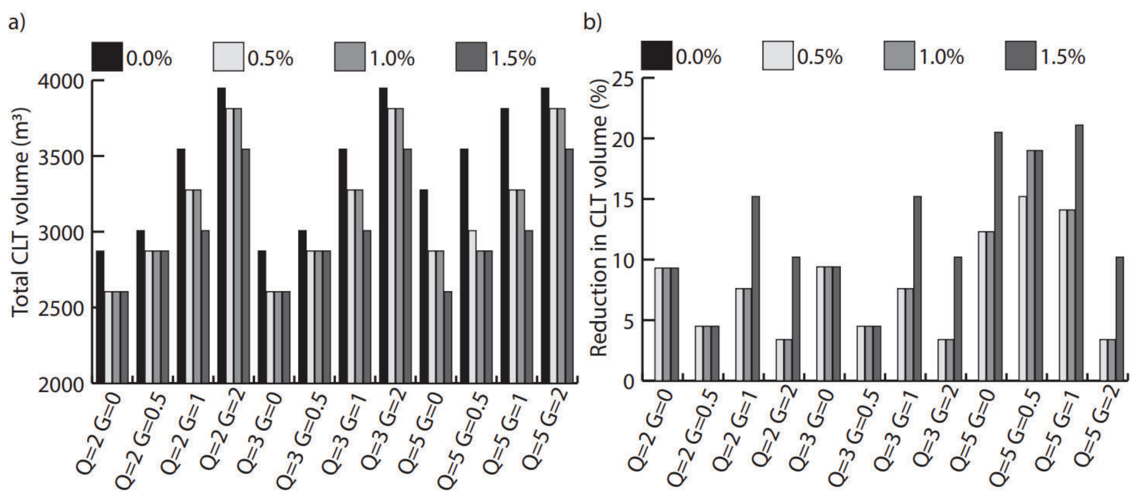

Figure 4. a) CLT volume in slabs for different load scenarios and reinforcement ratios, and b) volume of CLT reduction for different load scenarios and area reinforcement ratios.

3.2 CASE STUDY 1 RESULTS: SAME COLUMN GRID DECREASED DEPTH

In the first scenario, the parametric tool was used to evaluate the effect of adding CFRP reinforcement to CLT slabs. The objective was to determine how much the depths of these elements could be decreased while maintaining the same grid spacing as in the timber-only alternative, which allows for smaller volumes of timber.

Figure 4 a) shows the total volume of CLT used in the building when using CLT-only or FRP-reinforced CLT with three area reinforcement ratios (0.5%, 1.0%, and 1.5%). Figure 4 b) shows the percent reduction for each area reinforcement ratio. The reduction in cross section due to the addition of CFRP reinforcement is significant, with reductions in timber volume of up to 21% for higher loads (Q=5 kPa, G=1 kPa). Table 1 shows the change in cross-section to maintain the 6m span, for different load scenarios and area reinforcement ratios, which translates into the volume reductions observed in Figure 4.

The effect of CFRP varies with the loads and the amount of reinforcement in a non-linear way, with reduction in CLT volume ranging from as little as 3.4% to 21.1%. Interestingly, for the example of [Q=2,G=0], a substantial volume reduction (9.3%) is seen with 0.5% reinforcement, and no further improvement can be achieved with the higher studied reinforcement ratios, making the initial reinforcement substantial and the differential effect of higher reinforcement ratios less meaningful.

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Table 1. Panel thickness at constant span (6000mm), for different area reinforcement ratios and load scenarios. Note: Superimposed Dead Load (SDL,G) denotes the extra dead load on top of self weight.

	Q=2kPa				Q=3kPa				Q=5kPa			
Reinforcement	SDL (kPa)				SDL (kPa)				SDL (kPa)			
	0	0.5	1.0	1.5	0	0.5	1.0	1.5	0	0.5	1.0	1.5
0.0%	CL5/190	CL5/200	CL7/240	CL7/270	CL5/190	CL5/200	CL7/240	CL7/270	CL5/220	CL7/240	CL7/260	CL7/270
0.5%	CL5/170	CL5/190	CL5/220	CL7/260	CL5/170	CL5/190	CL5/220	CL7/260	CL5/190	CL5/200	CL5/220	CL7/260
1.0%	CL5/170	CL5/190	CL5/220	CL7/260	CL5/170	CL5/190	CL5/220	CL7/260	CL5/190	CL5/190	CL5/220	CL7/260
1.5%	CL5/170	CL5/190	CL5/200	CL7/240	CL5/170	CL5/190	CL5/200	CL7/240	CL5/190	CL5/190	CL5/200	CL7/240

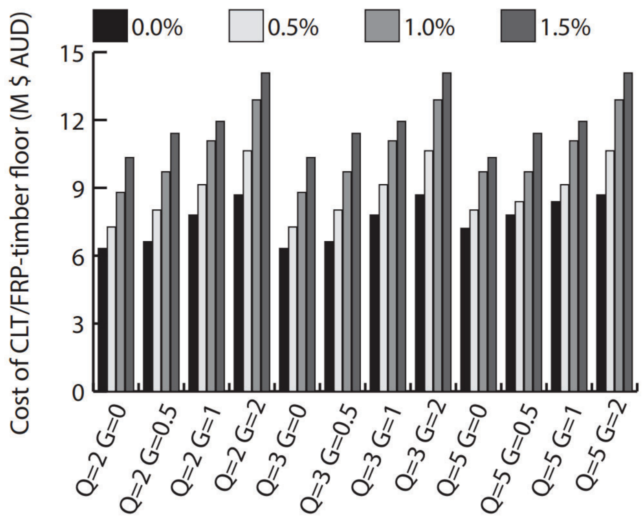

Figure 5. Cost comparison of CLT volume cost compared to FRP-timber alternatives for the volume reduction scenario (Case 1).

Although efficient in terms of area reinforcement, the current high cost of CFRP can make it prohibitively expensive. Considering an average cost of CLT of 2200 AUD/m^3 [14] and CFRP of 118000 AUD/m^3 [15]. Figure 5 shows that the high cost of CFRP significantly increases the cost of floor elements up to 72% in the highest reinforcement ratios. Studying the use of cheaper fibres could lead to more cost-effective solutions than the use of CFRP.

3.3 CASE STUDY 2 RESULTS: SAME DEPTH AND INCREASED COLUMN GRID

The second scenario examined the potential for increasing the spans of FRP-reinforced CLT slabs while maintaining the same cross-sectional dimensions of equivalent pure CLT elements. By adding CFRP reinforcement, the spans of the structural elements could be extended, allowing for more open and flexible floor plans without increasing the depth of the members. This application of CFRP-reinforced CLT composites could significantly enhance the design possibilities for mass timber buildings, particularly in commercial and institutional projects where open spaces are desirable.

Figure **6** a) shows the maximum span length used in the building, starting with the shallowest possible CLT and 6000mm spans. The span increases for three area reinforcement ratios (0.5%, 1.0%, and 1.5% area reinforcement ratio). Figure **6** b) shows the increase for each reinforcement ratio. The increased spans due to the addition of CFRP reinforcement is quantified in longer spans of up to 18% for higher loads (Q=5 kPa, G=0 kPa).

The effect of increasing CFRP reinforcement, is interestingly non-linear, and is more pronounced when the design loads are higher. Although spans can increase significantly, for some load scenarios the effect is as little as 3% span increase (200mm). In contrast to Case 1, where in some cases the increase in reinforcement ratios did not cause a differential reduction in timber volume, in case 2, the addition of CFRP reinforcement, for the ratios studied, presented an increase in span capacity proportional to the reinforcement ratios.

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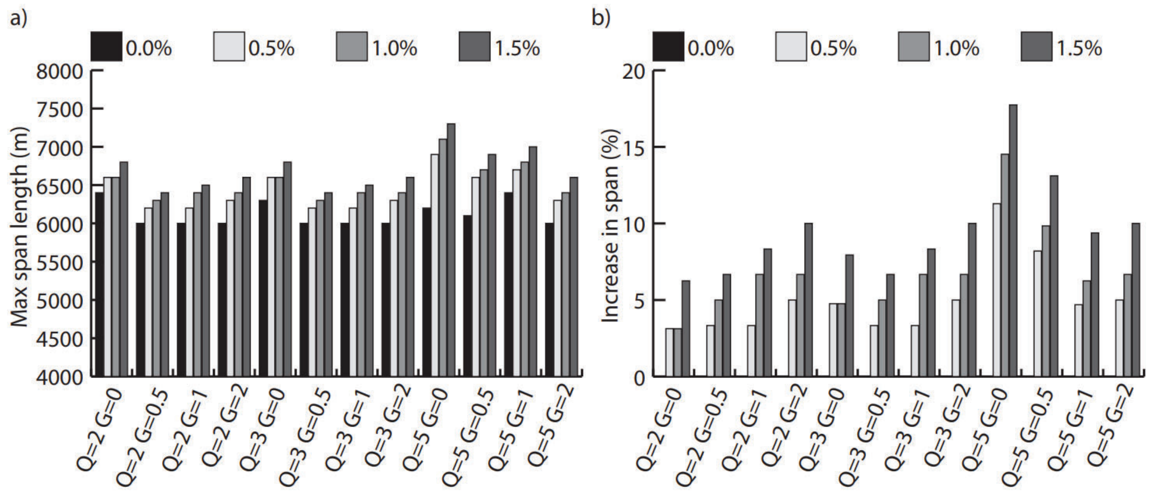

Figure 6. Maximum span of slabs for different load scenarios and reinforcement ratios, and b) span increase for different load scenarios and reinforcement ratios.

4 – CONCLUSIONS

This paper presents a parametric tool implementation using Rhino/Grasshopper to provide preliminary design dimensions of hybrid FRP-CLT floors in mass timber buildings. The main conclusions can be summarised as follows:

- The integration of CFRP into CLT panels and glulam beams has demonstrated significant improvements in serviceability performance, particularly in terms of deflections and vibration control.
- The increased stiffness and natural frequencies observed in FRP-reinforced CLT composites allows for longer spans or shallower composite members, making them suitable for a wider range of structural applications.
- The development of user-friendly tools and techniques allows for rapid, preliminary estimation of dimensional and cost comparison of mass timber and FRP-timber buildings.

5 – DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work the authors used ChatGPT 4 in order to improve the language and readability of the manuscript. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

6 – REFERENCES

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