Multi-objective optimization of CLT-concrete composite floor using NSGA-II algorithm

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RESUME Cross-laminated timber (CLT) is an engineered wood product made of multiple glued layers in the form of a panel. Each CLT layer oriented perpendicular to the adjacent one. This type of structural element is particularly suitable for the application of a floor system. CLT-concrete composite (CCC) could be a solution for a long-span floor system of the mid-and high-rise building. This study focused on multi-objective optimization of the CCC floor using the genetic algorithm (NSGA-II). The three optimization objectives were to minimize total thickness, total weight, and total material cost taking into account structural, vibration comfort, and thermal constraints. Solutions are presented in the form of a Pareto front of 8 m and 10 m floor spans.

Keywords Multi-objective optimization, CLT-concrete composite, vibration comfort, NSGA-II

I. INTRODUCTION

The timber-concrete composite (TCC) concept was first adopted to build bridge structures in the 1940s and the renovation of old timber structures. Recently, this type of structure received much attention since it possesses many advantages in terms of the environment; mechanical resistance and rigidity; fire, seismic, acoustic, thermal performance; the capability of prefabrication; and rapid installation on-site (Frangi et al., 2010; Lukaszewska, 2009). Cross-laminated timber (CLT) is an engineered wood product made of multiple glued layers to form a panel. Each layer of the CLT is oriented perpendicular to the adjacent one (FIGURE 1). Since CLT is a relatively new engineered wood product, the idea came to form the CLT-concrete composite (CCC). They inherited the advantages of traditional TCC structures, i.e., wooden beam–concrete slab. Moreover, the gain in static height of CCC floors over TCC one would make CCC more appealing for mid-and high-rise buildings. CCC is suitable for long-span floor systems (more than 8 m), where the serviceability conditions usually control the design. In general, the CLT-concrete composite floor performance is enhanced compared to the bare CLT floor. This study aims to optimize CLT-concrete composite (CCC) floor design by minimizing total thickness, total weight, and cost of constituent materials (CLT, concrete, connector, fire protection) while keeping the design in the range of structural constraints.

II. CLT-CONCRETE COMPOSITE FLOOR

A. *Objectives of the optimization problem*

The optimization objectives are total weight, total thickness, and cost. The cost function comprised only the cost of constituent materials, such as CLT, concrete, connector, fire protection element. The floor thickness is the sum thickness of CLT, concrete, insulation layer, and fire protection gypsum board. The total weight is calculated as the weight of the floor per surface unit. These objectives are quite often conflicting since the more performant in terms of the vibration comfort leads to important weight and thickness of the floor. Using higher class material would reduce the weight and thickness and raise the total cost. The expressions for the cost function are the sum of material costs (Equation 1).

$$C = C_t + C_c + C_{cnt} + \boldsymbol{C_{gyps}} \tag{1}$$

TABLE 1. Price and density of floor components

Cost		Class	Price	Unit	Density	Unit
Timber	C_t	[E1; E2; E3]	[865; 821; 778]	CU/m3	[515; 500; 490]	kg/m3
Concrete	C_c	[C25]	[632]	CU/m3	[2250]	kg/m3
Connector	C_{cnt}	-	6	CU/cnt	-	-
Gypsum board	C_{gyps}	[12.7mm; 15.9mm; 25.4mm]	[9; 12; 15]	CU/m2	[0.72; 0.72; 0.72]	kg/m3

B. CLT-concrete floor design

The design was performed for the CCC 1m-strip with regards to the optimization variables (TABLE 2). Based on experimental results (Thai et al., 2020), we could dispose of a maximum of 3 rows of the notched connector in the 1m-width.

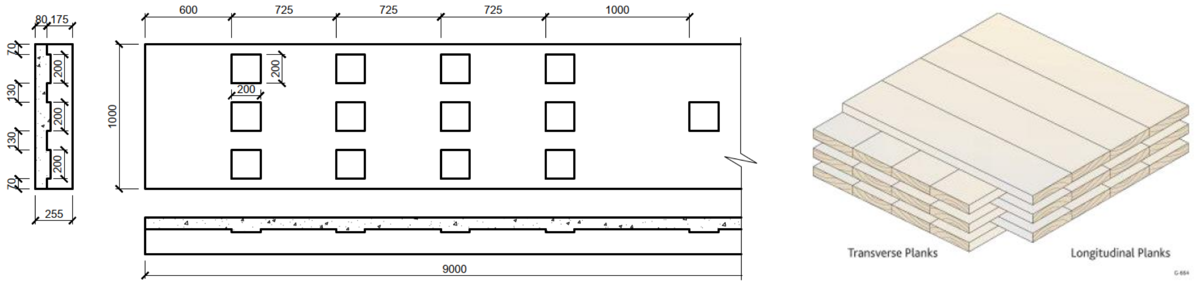

FIGURE 1. Connector layout of the CCC floor strip (Thai et al., 2021) and CLT panel configuration (Karacabeyli and Gagnon, 2019)

Connectors were assumed to have ductile rupture; horizontal slip was up to 10 mm for the critical connector at two ends. Normal concrete was chosen for the design—the choice for concrete-related variable limited in six classes: from C20 to C45. The concrete layer thickness continuously varied from 60 mm to 180 mm, with 5 mm step. CLT from the local manufacturer was chosen for the design. The CLT class varied from E1 to E3 with defined characteristics (elastic modulus, the strength of laminations, density, cost). CLT thickness varied from 89 mm to 244 mm, depending on the layup configuration (8-level variable). The bending stiffness would depend on the CLT layup and the disposition of connectors. The strength and stiffness contribution of the transversal laminations was omitted. The floor lower surface could opt for the protection of a fire-rated Type X gypsum board. There were four options at the disposal for the optimization. The thickness of insulation layer h_i between the CLT and the concrete could enhance the effective bending stiffness while increasing the total thickness.

C. Design variables

The decision variables are divided into five groups of variables: geometry, concrete, CLT, connector, and fire condition. Other design parameters are fixed and are involved in the optimization process. They are floor span L in mm and fire resistance rating in minutes t_fi. Fire resistance variables are characterized by the fire exposure rating time as short (30 minutes), medium (60 minutes), long (90 minutes), and extended (120 minutes). In this study, we opted for the extended exposure duration (120 minutes) for the residential floor.

TABLE 2. Optimization variables

Group	Name		Unit	Range
Geometry	Insulation thickness	h_i	mm	[0; 5;10; 15 mm]
Concrete	Modulus	E_c	MPa	[C20; C25; C30; C35; C45]
	Compression strength	f_c	MPa	[C20; C25; C30; C35; C45]
	Density	γ_c	kg/m³	[C20; C25; C30; C35; C45]
	Thickness	h_c	mm	[60-180, 5 mm]
CLT	Modulus	E_t	MPa	[E1; E2; E3]
	Bending strength	f_t_b	MPa	[E1; E2; E3]
	Tension strength	f_t_t	MPa	[E1; E2; E3]
	Shear strength	f_t_s	MPa	[E1; E2; E3]
	Density	γ_t	kg/m³	[E1; E2; E3]
	Thickness	h_t	mm	[89;105;143;175;197;213;244S;244L]

Connector	Rows	***n***	row	[1-2-3]
	Connector per row	***m***	col	[6; 8; 10; 12; 14]
Fire	Gypsum board time	***t_g***	minutes	[0; 15; 30; 60]
	Thickness gypsum	***h_g***	mm	[0; 12.7; 15.9; 25.4]

D. Design constraints

The structural, vibration comfort, and thermal constraints would validate each design found by the genetic algorithm. The constraints adopted were presented as following and calculated according to Timber design standard CSA-O86:2014 (updated 2017) and Concrete design standard CSA-A23:2014.

- Serviceability limit state (SLS)
    - Deflection (Standard term and long-term)
    - Vibration conditions (Standard term)
- Ultimate limit state (ULS)
    - Bending moment resistance (Standard-term, Long-term, and Short-term)
    - Connector shear resistance (Standard-term, Long-term, and Short-term)
    - Shear resistance (Standard-term, Long-term, and Short-term)

The constraints of SLS and ULS adopted the Gamma method (EN 1995-1-1, 2002) to calculate the effective bending stiffness. For SLS constraints, the deflection of a simple beam under distributed standard-term and the long-term load was calculated. The vibration performance of the CCC floor should comply the empirical limit proposed in the Canada TCC design guide (Cuerrier-Auclair, 2020). The ULS constraints are bending moment resistance, shear resistance of the composite section, and shear resistance of critical connectors (Cuerrier-Auclair, 2020).

III. NON-DOMINATED SORTING GENETIC ALGORITHM – II (NSGA-II)

In general, a multi-objective problem consisted of: minimize/maximize M objectives: $f_m(\mathbb{x}), m = 1,2,..,M$, with solution vector of n decision variables: $\mathbb{x} = (x_1, x_2, ..x_n)$, subjected to two types of constraints: J inequalities $g_j(\mathbb{x}) \geq 0, j = 1,2,..,J;$ K equalities $h_k(\mathbb{x}) = 0, k = 1,2,..,K;$ n boundaries $x_i^{(Lower)} \leq x_i \leq x_i^{(Upper)}, i = 1,2,..,n$. There is no global and unique dominant solution in a multi-objective optimization problem but a set of non-dominated solutions. The solution $x^{(1)}$ $dominated$ $x^{(2)}$ $\left(x^{(1)} \preccurlyeq x^{(2)}\right)$ when $x^{(1)}$ is not worse than $x^{(2)}$ in all objectives and $x^{(1)}$ is better than $x^{(2)}$ in at least one objective. The set of non-dominated solutions is called the Pareto front of the problem. In this study, Non-dominated Sorting Genetic Algorithm-II (NSGA-II) was used because of its simple implementation and low computational complexity. Genetic algorithm is a metaheuristic mimicry the process of natural selection by using the operator such as mutation, crossover, selection. (Mitchell, 1996). The implementation of NSGA-II was carried out by using package jMetalPy (Benítez-Hidalgo et al., 2019). The population of parents and offspring were both 300 individuals, the number of iterations was 200.

IV. RESULT AND DISCUSSIONS

In the first solution set, the floor span was 8 m, and the exposure fire time was 2 hours. FIGURE 2 presents the front Pareto of the solutions (red points). These solutions are "equivalent."

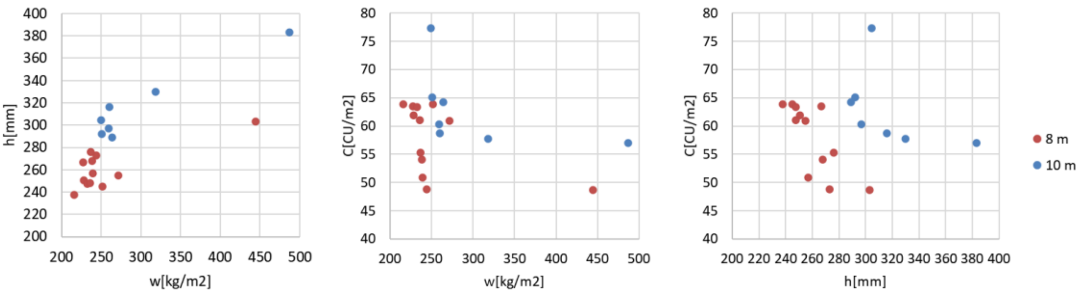

FIGURE 2. Front Pareto of the solutions for 8 m span floor 10 m span floor

The constraints of long-term deflection, vibration, and the short-term bending moment resistance constraints are the most restrictive since they are engaged by their high ratio (load per resistance). The obtained solutions tend to increase the concrete class rather than the concrete thickness. The thickest concrete layer was registered as 160 mm. Two distinct groups could be observed based on the CLT thickness (FIGURE 3). The solutions using a thinner CLT panel (175 mm and 143 mm) had limited serviceability performance and high cost. The other with 7-ply CLT panels (from 213 mm to 197 mm) had the most economical competitive solutions. This led to some drawbacks in terms of total weight and total thickness. However, these solutions had high serviceability performance (vibration, deflection).

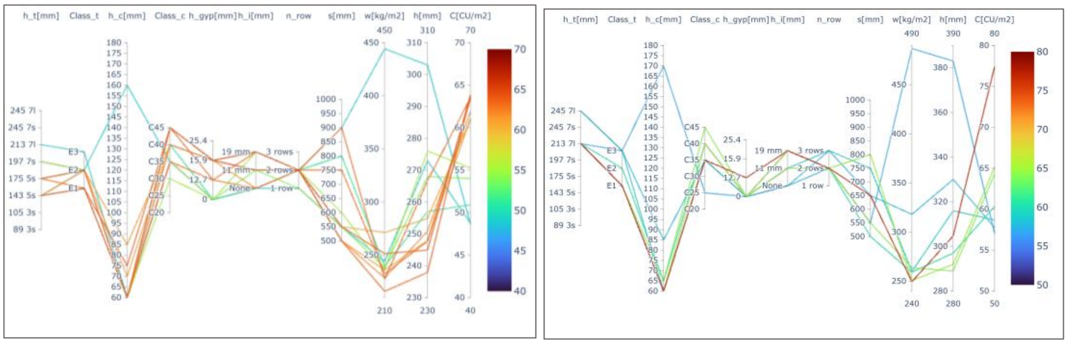

FIGURE 3. Parallel coordinate plot of the solutions for 8 m span floor 10 m span floor (color scale is for the cost)

In the second solution set, the floor span was 10 m at the fire exposure time of 2 hours (FIGURE 2 and FIGURE 3). Seven possible solutions were found. Since the span was significant, the found solutions go with the strongest CLT panels possible (213 mm and 245 mm). One could observe that the gypsum board was used in one solution. This is because the 7-ply CLT panel could withstand the extended fire exposure time.

V. CONCLUSION AND PERSPECTIVE

An optimization multi-objective based on the structural and economic requirements was carried out for CCC floor systems. The optimized solutions could be a starting point for engineers to work and developed their refined designs. The next step would be integrating the geometry impact on the individual connector performance (stiffness and strength) and the CLT panel structural integrity (bending stiffness reduced due to notch). A more sophisticated cost expression that comprises the execution phase will be added to the future optimization. A study parametric of different span length and imposed load and a decision-making method based on the multi-criteria method are in progress.

ACKNOWLEDGMENTS

The authors are grateful to Natural Sciences and Engineering Research Council (NSERC) of Canada for the financial support through its IRC and CRD programs (IRCPJ 461745-18 and RDCPJ 524504-18), the Region Nouvelle Aquitaine for the financial support (ref. 2017-1R10223), and the industrial partners of the NSERC industrial chair on eco-responsible wood construction (CIRCERB).

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