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STUDY ON EMBODIED CARBON FOOTPRINT OF MULTI-UNIT RESIDENTIAL BUILDINGS

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ABSTRACT: Numerous studies highlight the importance of reducing embodied carbon, which includes greenhouse gas (GHG) emissions from the production of building materials, as a critical strategy in combating climate change. Nonetheless, to evaluate the GHG emissions avoided using low carbon design strategies, such the integration of a wood structure, a reference scenario using a conventional structural system must be modelled. To reduce the costs, comparisons could be made using average GHG emission thresholds developed for different building types and structural materials. This study aims at calculating average carbon footprints, expressed in kg CO2-eq/m², for multi-residential mid-rise buildings, considering four different structural systems: reinforced concrete, light-gauge steel frame, light wood frame, and mass timber. Despite the diverse sizes of the buildings studied, the results indicate that the carbon footprint associated with structural materials is relatively consistent for buildings with the same type of structural system when measured per square meter of total floor area (m²).

KEYWORDS: embodied carbon, GHG emissions, structural material, timber, average carbon footprint.

1 – INTRODUCTION

The importance of reducing embodied carbon, which includes greenhouse gas (GHG) emissions from the production of building materials, is highlighted by numerous studies as a critical strategy in combating climate change [1, 2]. To guide the design team in selecting construction materials that minimize the building's overall carbon footprint, the carbon footprint for each considered scenario must be assessed and compared. Thus, to highlight the GHG emissions avoided by opting for a wood structure, a reference scenario using a conventional structural system must be modelled. Comparing two structural concepts can significantly increase the costs associated with evaluating these avoided GHG emissions at the predesign phase of a project. To limit these costs, comparisons could be made using average GHG emission thresholds developed for different building types and structural materials, rather than modelling a baseline for each project.

This project aims to document the carbon benefits of wood construction through comparative assessments of GHG emissions for a specific building typology. Specifically, the objective of this study is to calculate the average carbon footprint, expressed in kg CO2-eq/m² of total floor area, of multi-unit residential mid-rise buildings, constructed in Quebec in recent years considering four different structural systems.

2 – METHODOLOGY

2.1 AVERAGE CARBON FOOTPRINT ASSESSMENT

The average carbon footprint per square meter (m²) of floor area is calculated using the GESTIMAT tool, taking into account the GHG emissions related to the production of structural materials.

The study considers four different structural systems: reinforced concrete, light-gauge steel frame, light wood frame and mass timber. The sample include 19 five- and six-storey residential buildings built in Quebec in recent years.

Quantities of structural materials have been determined specifically for each building to allow a precise modelling of each project with the tool GESTIMAT (Version 2.0). The study follows the MRNF protocole developed in collaboration with Cecobois [3].

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2.1 QUANTIFICATION OF STRUCTURAL MATERIALS

Four (4) to five (5) mid-rise multi-residential projects built in the Quebec City and Montréal regions were identified for each structural system evaluated. A structural engineer quantified the structural materials for each project, using manufacturer's shop and structural drawings or information provided by structural calculation software or 3D modeling software.

The quantification of materials takes into account the elements of the main structure, including floor and roof structures, as well as the structure around openings. In addition, the structure of the exterior walls, inter-unit walls and corridor walls were included for all structural systems to ensure that the comparison is representative for light wood frame and light-gauge steel frame structures, where these walls are an integral part of the structure. Foundations were excluded from the GHG assessments since they depend more on the interior parking layout and soil quality than on the superstructure. However, the ground floor slab is included, since its configuration and reinforcement may be dependent on the structural system used for the superstructure.

These quantities of structural materials enabled precise modeling of each project in the GESTIMAT tool.

2.2 GESTIMAT/GHGMAT TOOL

GESTIMAT (GHGMAT in English) is a web-based tool developed by Cecobois for the Ministry of Natural Resources and Forest (MRNF) to conduct comparative GHG emissions assessments. It is a user-friendly, reliable, transparent and powerful tool based on life cycle assessment (LCA) [4, 5, 6].

GESTIMAT enables the estimation and comparison of GHG emissions related to the production of materials (from the cradle to the factory gate or A1-A3, i.e., manufactured and ready for shipment) for various building structure and civil engineering scenarios. GHG emissions are quantified by multiplying material quantities by the GHG emission factors specific to each material.

These emission factors have been provided by specialised research centres: CIRAIG (International Reference Centre for Life Cycle Assessment and Sustainable Transition) and LIRIDE (Interdisciplinary Research Laboratory in Life Cycle Assessment and Circular Economy). The emissions factors have been specifically developed, using Ecoinvent database (including the Quebec Life Cycle Inventory Database) as well as product specifications, to represent the construction sector in Quebec and Canada.

3 – STRUCTURAL SYSTEMS STUDIED

The structural material GHG emissions assessments were performed on the 19 selected buildings, including 5 buildings with reinforced concrete structures, 5 buildings with light-gauge steel frame structures, 5 buildings with light wood frame structures, and 4 buildings with mass timber structures.

3.1 Reinforced Concrete Buildings

Five buildings with reinforced concrete structures were analyzed in this study. A reinforced concrete structure is composed mainly of columns with a regular pattern varying from 6.8 m x 5.3 m to 7.1 m x 5.5 m, floor and roof slabs, and reinforced concrete shearwalls (Figure 1).

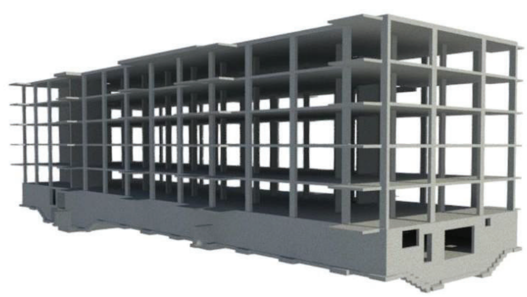

Figure 1. Typical reinforced concrete structure
Image credit: L2C Experts Conseil

Reinforced concrete balconies and steel canopies were taken into account in the analysis, as well as steel shear rails used to provide continuity to reinforced concrete floor slabs. In this type of structure, inter-unit walls, corridor walls and exterior façade walls are generally composed of light-gauge steel posts and rails.

In general, the reinforced concrete superstructure follows the same structural grid as the underground parking. Therefore, no additional reinforcement is required for the ground floor slab.

3.2 Light-Gauge Steel Frame Buildings

Five buildings with a light-gauge steel frame structure were analyzed in this study. Light-gauge steel-framed structures are composed of load-bearing interior and

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exterior walls of structural steel studs reinforced with steel channels, steel floor joists covered with a slab-on-deck and steel roof joists covered with a steel deck (Figure 2)

Figure 2. Typical light-gauge steel frame structure
Image credit: TMS Prefabricated Buildings

Shearwalls are made of reinforced concrete. Balconies are made of steel or reinforced concrete depending on the project. All inter-unit walls, corridor walls and exterior façade walls were included in this study.

The ground floor slab, made of reinforced concrete, is designed to transfer the vertical loads from the structural walls to the concrete column of the underground parking structure. Therefore, the ground floor slab requires additional reinforcement.

3.3 Light Wood Frame Buildings

Five buildings with a light wood frame structure were analyzed in this study. Light wood frame structures consist of load-bearing exterior and interior wood stud walls, occasional engineered wood beams, wood floor joists and light-frame wood roof trusses. The walls, floors and roof are covered with structural wood panels. A 38 mm (1.5 in) concrete topping is also added to the floors.

Steel or reinforced concrete balconies were also considered. All inter-unit walls, corridor walls and exterior façade walls were included in this study.

Figure 3. Light wood frame structure
Project: Le Prisme Logisco, Photo credit: Le natif

As for light-gauge steel frame, the ground floor slab requires additional reinforcement to enable the transfer of the vertical loads from the structural walls to the concrete columns of the underground parking structure.

3.4 Mass timber Buildings

Four buildings with mass timber structures were analyzed in this study. The mass timber structures evaluated in this project are composed mostly of glued laminated timber (Glulam) and cross-laminated timber (CLT) elements. Resistance to gravity loads is provided by Glulam beams and columns, supporting floor and roof CLT slabs. A 38 mm concrete topping is also added to the floors. Shearwalls are made of CLT.

Figure 4. Mass timber structure
Project: Arbora Montreal, Photo credit: Cecobois

Inter-unit walls, corridor walls and exterior façade walls that are not made of CLT are made of light-gauge steel studs and rails. Steel balconies were also included in the study.

Two of these buildings are 8-story buildings, including 7 residential floors made of mass timber, resting on a commercial reinforced concrete ground floor. For these buildings, only the structure of the 7 upper floors was considered, including the reinforced concrete slab underneath the mass timber structure was considered in the analysis.

4 – RESULTS AND DISCUSSIONS

The material quantification for each building's structure allowed for precise modeling in the GESTIMAT tool. The GHG emission results from GESTIMAT were analyzed for each structural system to calculate the average carbon footprint per square meter of floor area and assess variability. This enabled comparisons of the average carbon footprint per m² across the different structural systems. Since the configuration and the reinforcement of the ground floor slab is influenced by the transfer load patterns of the superstructure structural system, its specific impact is highlighted in the analysis of the results.

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4.1 Reinforced Concrete Buildings

For reinforced concrete buildings, Figure 5 shows the distribution of GHG emissions between the different construction systems, is given considering an average of the buildings studied. Reinforced concrete beams, columns and shearwalls account for 10% of GHG emissions, reinforced concrete floor and roof slabs account for the majority of GHG emissions: 11% for the ground level slab, 51% for above ground slabs, 16 % for the roof slab. Reinforced concrete balconies and steel stud walls are responsible for 5% and 7% of GHG emissions respectively.

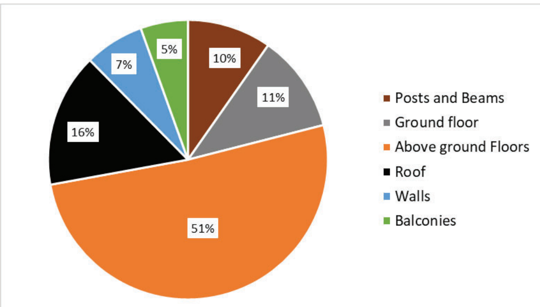

Figure 5. Distribution of GHG emissions for reinforced concrete buildings

4.2 Light-Gauge Steel Frame Buildings

For light-gauge steel frame buildings, Figure 6 shows the distribution of GHG emissions considering an average of the buildings studied. For this structural system, the majority of GHG emissions are associated with floors and walls: 17% for the reinforced concrete slab at ground level slab, 41% for the steel joist floors with slab-on-deck above ground floors, and 30 % for the steel stud walls and reinforced concrete shearwalls. The steel joist roofing with steel decking counts for 16 % of the GHG emissions and reinforced concrete balconies supported by steel members are responsible for 6 % of the total.

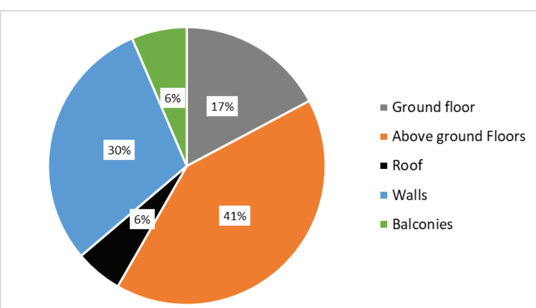

Figure 6. Distribution of GHG emissions for Light-Gauge Steel Frame Buildings

4.3 Light Wood Frame Buildings

For buildings with light wood framing, GHG emissions related to the production of structural materials are divided between the load-bearing and shearwall structure made of wood studs covered with OSB panels (13%), the wood floor joists covered with plywood and concrete covering (26%), the roof made of wood trusses covered with plywood (3%), and the prefabricated reinforced concrete balconies (11%). The reinforced concrete slab transferring the loads at ground level accounts for 45 % of the emissions, while the engineered wood reinforcing elements are responsible for only 2%. Figure 7 shows the distribution of emissions between the different construction systems, considering an average of the buildings studied.

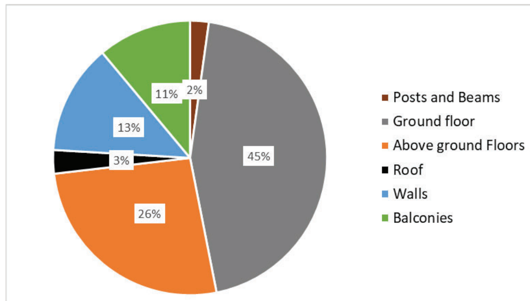

Figure 7. Distribution of GHG emissions for Light Wood Frame Buildings

4.4 Mass timber Buildings

For buildings with a mass timber structure, GHG emissions related to the production of structural materials are divided between the Glulam beam and column system (14%), the reinforced concrete slab under the mass timber structure (22 %), the CLT floors with concrete topping (31%), the CLT roof (2%), the walls (23%), including the CLT shearwalls, the steel stud wall and firewalls when needed, and the steel balconies (8%).

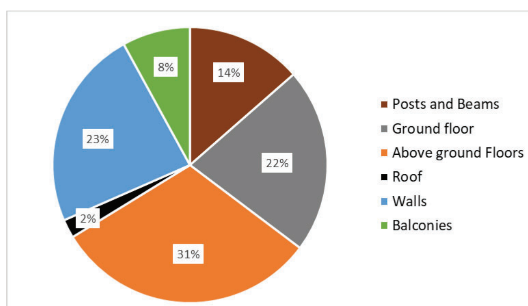

Figure 8. Distribution of GHG emissions for Mass timber Buildings

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4.5 Comparative Results

Comparing the average carbon footprint of different structural systems shows that wood structural systems reduce the carbon footprint of multi-unit residential building superstructures by over 60% (Figures 9). Furthermore, the low variability within a single structural system has little influence on the comparison between structural systems.

The influence of the added GHG emissions due to the ground floor reinforced concrete slab has been highlighted in Figure 10, as light frame super structure systems need to transfer vertical loads from the structural walls to the concrete columns of the parking garage beneath.

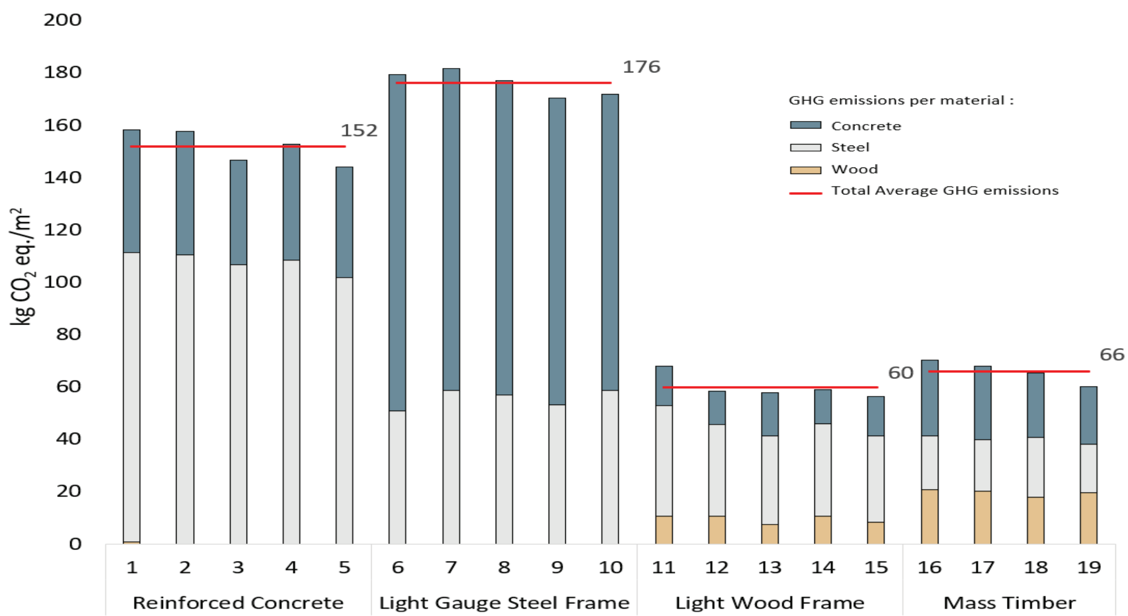

Figure 9. GHG emissions per m^2 of floor divided by material for all analysed buildings

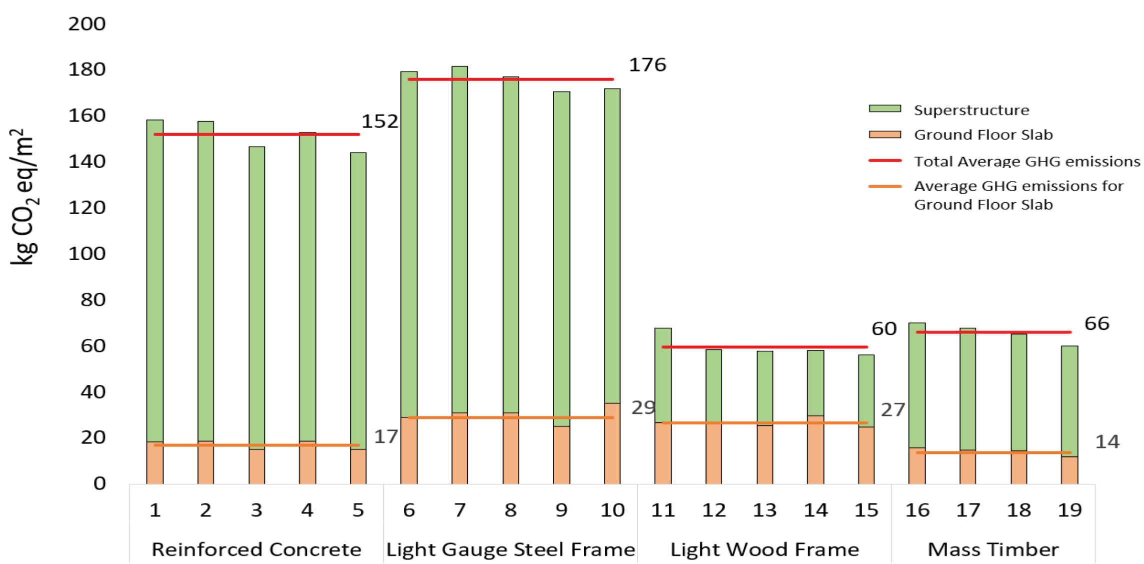

Figure 10. GHG emissions per m^2 of floor for all analysed buildings (highlighting the ground floor concrete slab)

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4 – CONCLUSION

This project aimed to document the carbon benefits of wood construction by comparing GHG emissions across different building types.

The study focused on mid-rise multi-unit residential buildings (5 to 6 stories) in Quebec, analyzing their average carbon footprint in kg CO2-eq/m² of floor area. Four structural systems were considered: reinforced concrete, light-gauge steel frame, light wood frame, and mass timber. A total of 19 buildings were evaluated, including five from each of the first three categories and four mass timber structures.

Structural engineers assessed the quantities of materials used in each project based on shop drawings, structural plans, or 3D models. This data enabled precise GHG emissions modeling with the GESTIMAT tool. The resulting emissions (A1-A3) were then analyzed to determine the average carbon footprint per m² for each structural system, as well as the variability within each type.

The average carbon footprints calculated for the superstructure were as follows: 152 ±5 kg CO2-eq/m² for reinforced concrete, 176 ±7.5 kg CO2-eq/m² for light-gauge steel frame, 60 ±2 kg CO2-eq/m² for light wood frame, and 66 ±3 kg CO2-eq/m² for mass timber. Results showed low variability (less than 10%) across each structural system.

The comparison of average carbon footprints indicated that wood structural systems reduce the carbon footprint from structural material production by over 60% for multi-unit residential buildings. Additionally, the low variability within each system had minimal impact on the comparisons. Even though the ground floor reinforced concrete slab caused additional GHG emissions which varies from one superstructure system to the other, its influence on the overall GHG reduction attained by the use of wood structure in relatively small. The study concluded that factors like climatic loads, soil quality, and architectural design had little effect on the average carbon footprint for each building type.

5 – ACKNOWLEDGEMENT

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