LOW CARBON NOW
for Multi-Unit Residential Developments in Toronto

Building Smarter Structures: A Study in Low Embodied Carbon Structural Strategies

ENTUITIVE

Embodied Carbon of Baseline Building

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The structure of a typical residential tower can account for over 60% of the total embodied carbon of the building. Therefore, optimizing the structural layout to reduce quantities and minimize embodied emission is fundamental for our path towards Net Zero. The following study was developed to evaluate the embodied carbon of various structural systems and determine the optimal approach to a low-carbon pathway. A baseline building was developed, representing typical construction and design practices for a concrete residential tower in Toronto, in order to serve as a baseline for comparison.

Building Archetype

- 40-storey multi-unit residential building in Toronto
- 6 levels of podium
- 4 levels of below-grade parking
- 1800mm transfer slab at level 2
- Shear walls and columns vertical structure
- 200mm flat slabs
- Conventional concrete mix design
- Cantilever balconies

Foundation Design Assumptions

The below-grade structure was designed as a tanked foundation system to meet the City of Toronto Foundation Drainage Provisions. The following assumptions were made on the soil properties:

- Groundwater table is between P1 and P2 elevation.
- Bearing capacity of soil/rock: 1100 kPa ULS.
- No surcharge loading from adjacent buildings.

Embodied Carbon Impact of Balconies

The baseline structure was also designed without balconies to understand the embodied carbon emissions of the balconies.

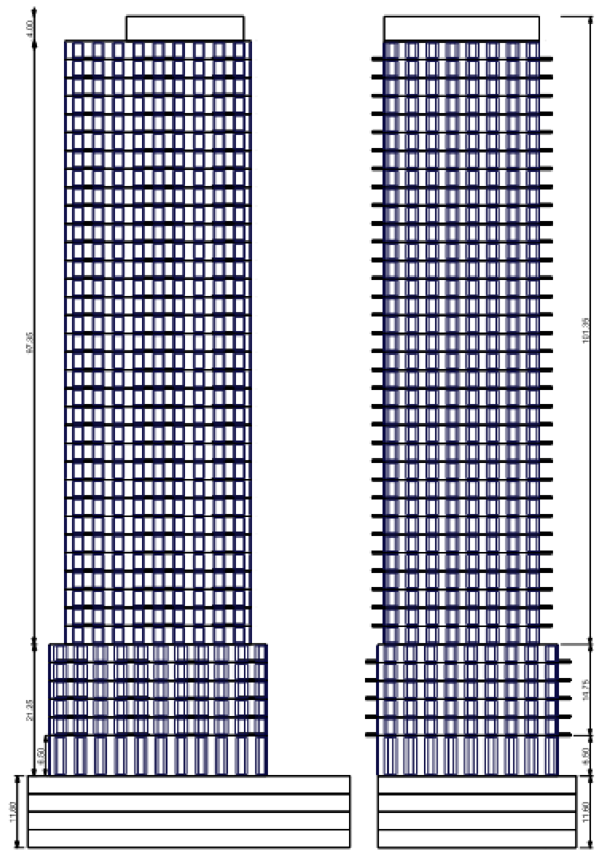
Results: Total GWP Intensity (A-C) of the building structure without balconies: 409 kg CO²e/m²

Conclusion: Balconies add roughly 3% embodied carbon to the structure.

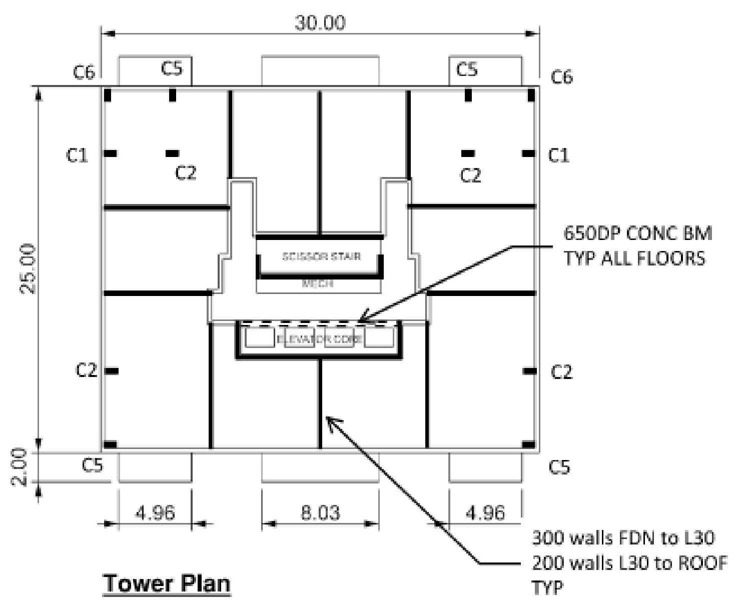
Note: the various structural studies presented in this document did not include balconies.

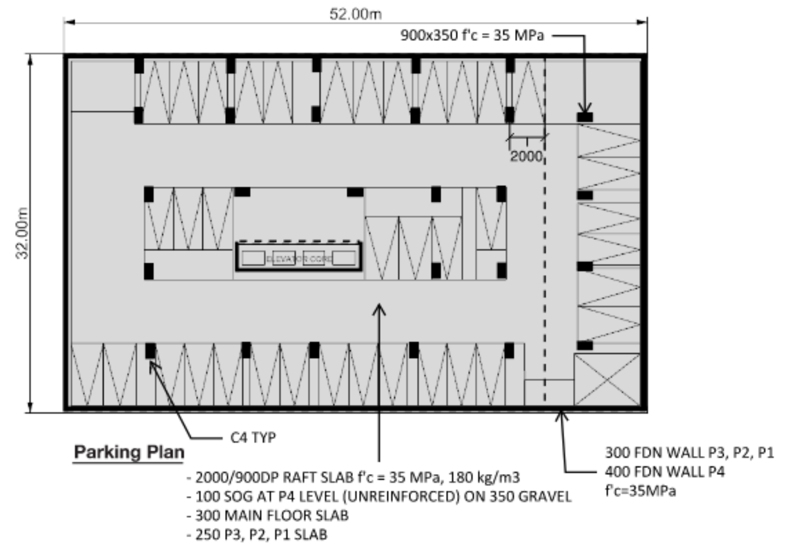
Embodied Carbon Results

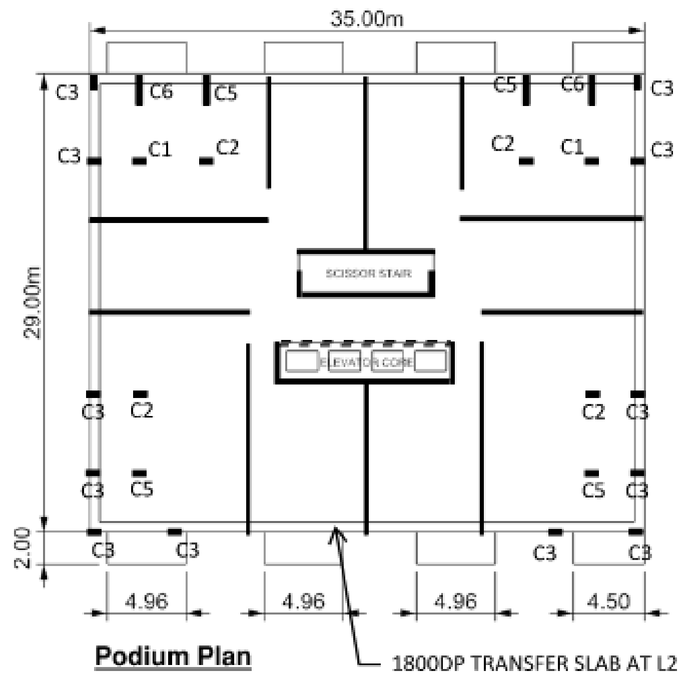
Life-Cycle Stage	GWP (tonnes CO_2e)	GWP Intensity (kg CO_2e/m^2)
A1-A3 – Construction Materials	9,890	352
A4 – Transportation to Site	203	7
A5 – Construction/Installation Process	1,293	46
C1 – Deconstruction/Demolition	95	3
C2 – Waste Transportation	221	8
C3 – Waste Processing	7	0
C4 – Waste Disposal	114	4
Total A-C	11,823	421


NS Elevations

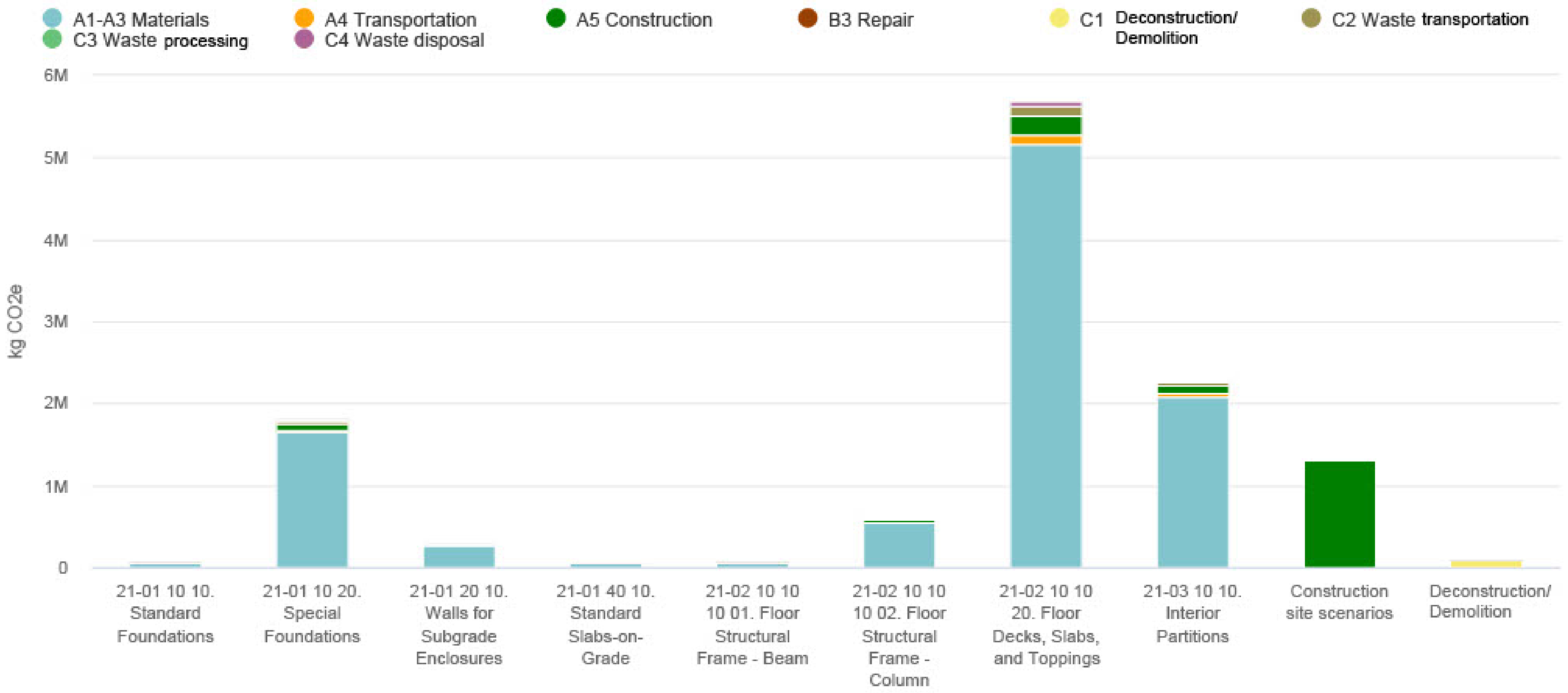
EW Elevations







Embodied Carbon Distribution per Structural Element



Slab Strategies for the Tower

Slabs typically account for about 40% of the total embodied carbon in the structure, serving as a carbon sink in the building. As such, reducing material quantities in the slabs will have the greatest impact on reducing emissions, but will also reduce the loads carried from the slabs down to the foundations. In this study we evaluated two slab construction strategies for the tower, an alternative to a conventional 200mm reinforced concrete slab, which reduced the slab thickness.

Construction Strategies for Slab Thickness - Tower

Slab System		Slab Thickness (mm)	Comments
Baseline	Reinforced Concrete Slab	200	Typical slab system in Toronto.
Achievable	Reinforced Concrete Slab - Backshoring Method	180	Reduction in slab thickness was achieved on the same grid layout with a reshoring procedure practiced in Western Canada where the cast slab is cured to 70% of the specified design strength or 25MPa minimum, upon which the formwork is sequentially removed and backshored immediately.
Design Limit	Post-Tensioned Slab	165	Slab thickness is fairly thin and can be impractical. Post-tensioned slabs are typically used to get longer spans for the same slab depth. A 165mm PT slab is doable but acoustic issues arise which need to be addressed.

Embodied Carbon Analysis

Tower layout and structural properties:

- Vertical Elements = Discrete Columns
- Grid = 6.5m x 6.5m
- Floor plate = 25m x 30m
- No. of Tower Stories = 33
- Slab f'c = 35 MPa
- Column & Core Wall f'c = 35-60 MPa
- LCA Scope: Modules A1-A5, C1-C4

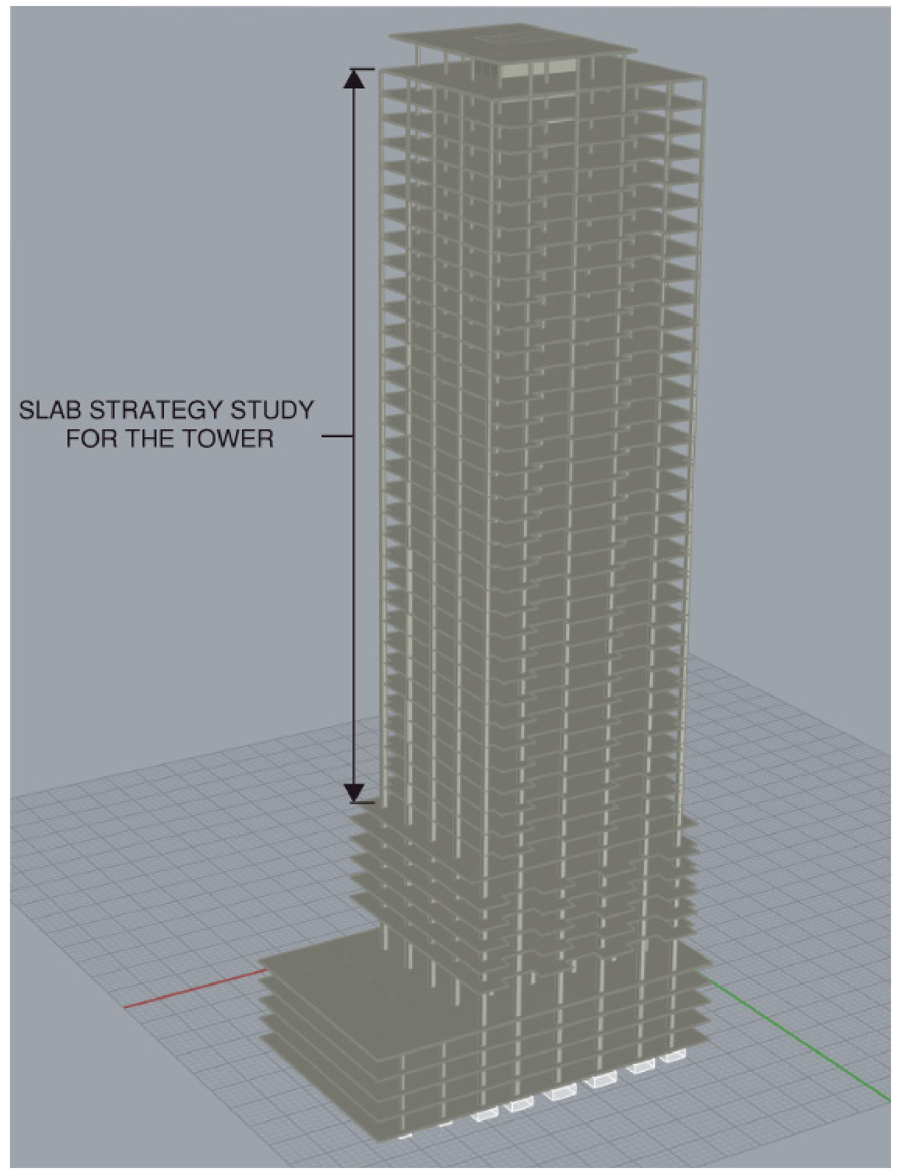


Fig. 2 Scope of Slab & Column Layout Strategy for EC Analysis

Embodied Carbon Results - Tower as a Whole

Slab System	GWP (tonnes CO_2e)	GWP Intensity (kg CO_2e/m^2)
Baseline – 200 RC Slab	4,968	221
Achievable – 180 RC Backshoring*	4,740	210 (-5%)
Design Limit – 165 PT Slab**	4,479	199 (-10%)

Embodied Carbon Results - Tower Slabs Only

Slab System	GWP (kg CO_2e)	GWP Intensity (kg CO_2e/m^2)
Baseline – 200 RC Slab	2,683	119
Achievable – 180 RC Backshoring*	2,457	109 (-8%)
Design Limit – 165 PT Slab**	2,201	98 (-18%)

**Acoustic elements for a 180mm slab would add about 115,914 kg CO_2e or 5.1 kg CO_2e/m^2.*
***Acoustic elements for a 165mm slab would add about 215,054 kg CO_2e or 9.5 kg CO_2e/m^2.*

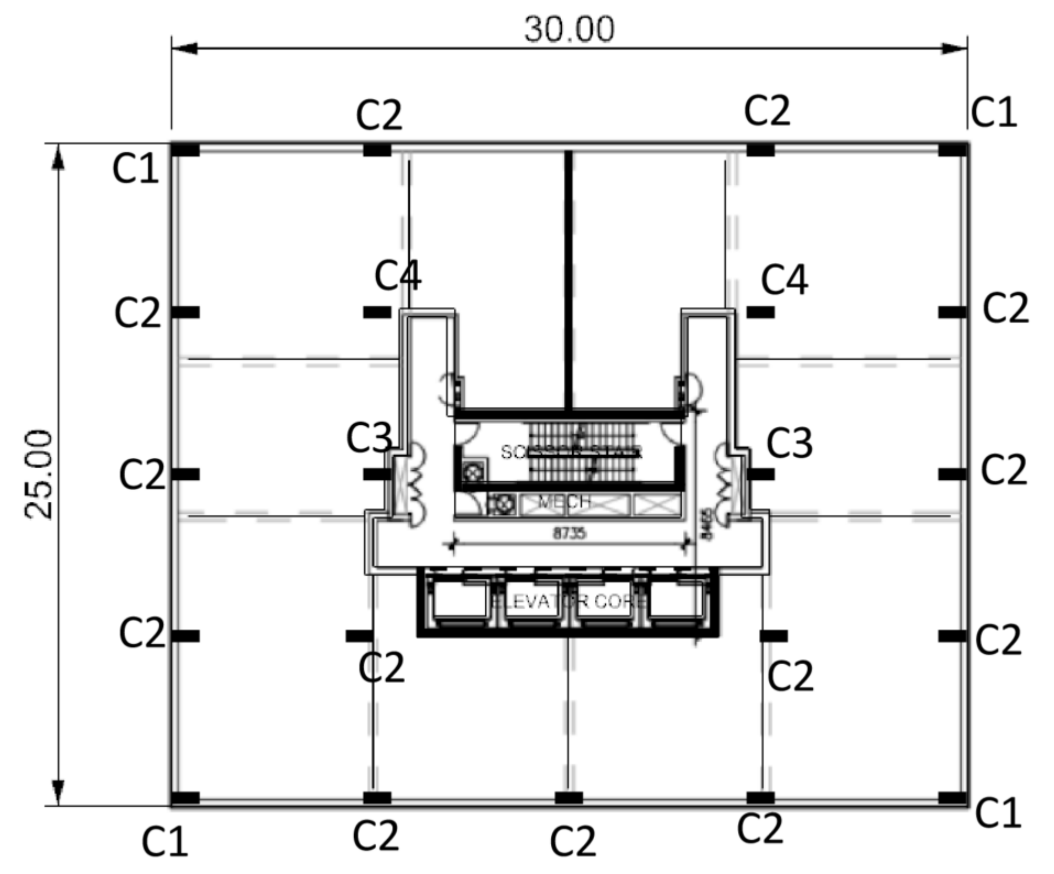


Fig. 1 Tower Grid Layout

Slab Study Takeaways

Reducing the slab thickness below 200mm introduces acoustic requirements. The added embodied carbon from the acoustic elements cuts the percent reduction of the thinner slabs by half.

Construction of typical reinforced concrete slabs in Western Canada typically practice reshoring method. Trades in the GTHA do not practice this method and we therefore need trades onboard very early in the project to achieve this.

Post-tensioned slabs are not standard construction in Ontario. Could be difficult to obtain trades and costly to execute.

Thin slabs (i.e, 165mm) can be impractical, such as introduce limitations on slab anchorage.

Column Layout Strategies for Tower

The column layout is mainly defined based on the architectural program. Typical residential buildings have a grid layout of 6.5m by 6.5m for a 200mm slab. The following study was conducted to evaluate the embodied carbon impact of two larger grid layouts in order to determine the optimal approach for the suite layout.

Embodied Carbon Analysis

Tower layout and structural properties:

- Vertical Elements = Discrete Columns
- Slab thickness = 200mm
- Floor plate = 25m x 30m
- No. of Tower Stories = 33
- Slab f'c = 35 MPa
- Column & Core Wall f'c = 35-60 MPa
- LCA Scope: Modules A1-A5, C1-C4

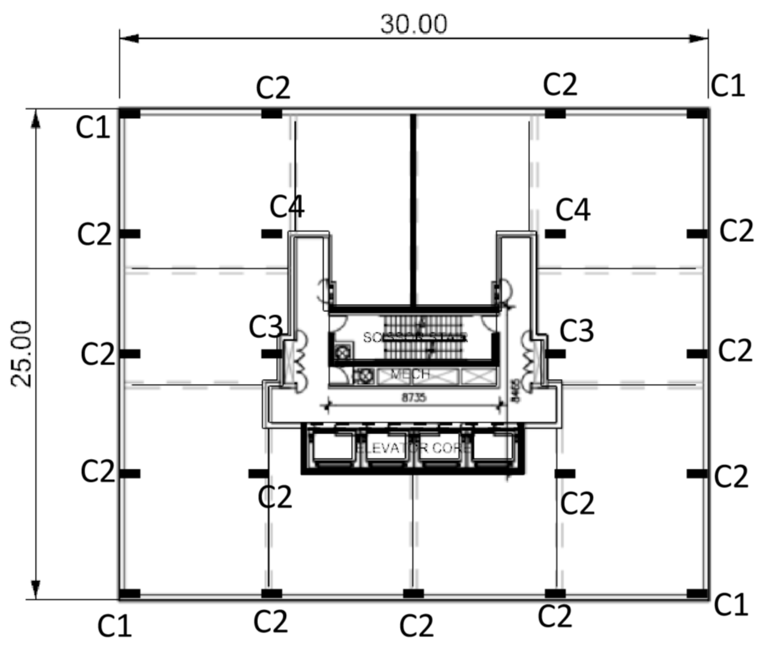


Fig. 3 Baseline Tower Grid Layout – 6.5m by 6.5m

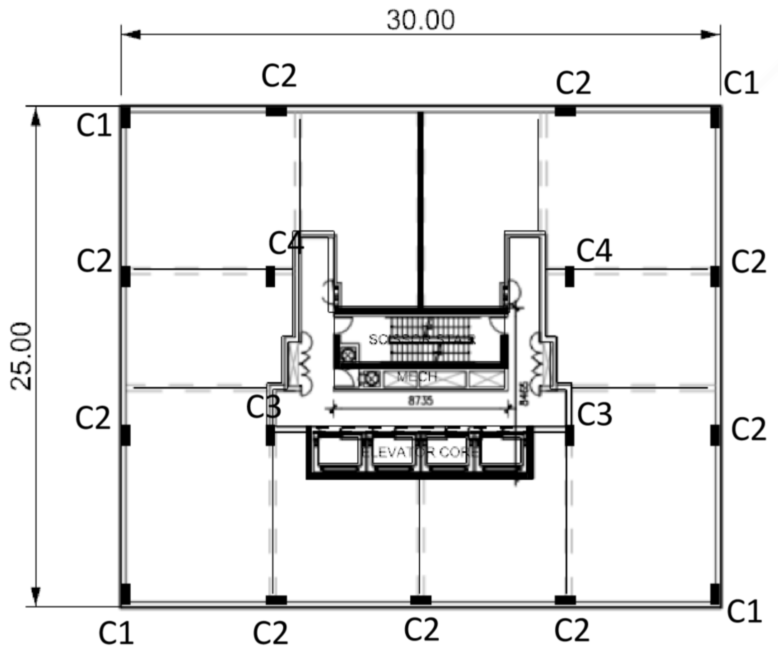


Fig. 4 Achievable Tower Grid Layout – 7.5m by 7.5m

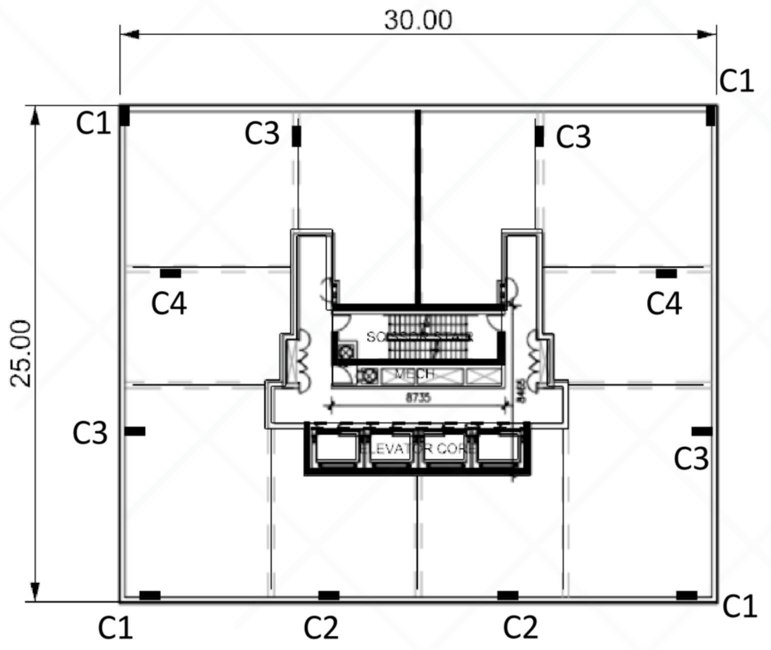


Fig. 5 Design Limit Tower Grid Layout – 8.5m by 8.5m

Design Strategies for Column Layout - Tower

Slab System		Grid Layout	Comments
Baseline	Reinforced Concrete Slab	6.5m x 6.5m	Typical slab and grid system in Toronto.
Achievable	Reinforced Concrete Slab - Backshoring Method	7.5m x 7.5m	Reduction in slab thickness was achieved on the same grid layout with a reshoring procedure practiced in Western Canada where the cast slab is cured to 70% of the specified design strength or 25MPa minimum, upon which the formwork is sequentially removed and backshored immediately.
Design Limit	Post-Tensioned Slab	8.5m x 8.5m	Post-tensioned slab construction is atypical for Toronto residential buildings.

Embodied Carbon Results - Tower as a Whole

Slab System	GWP (tonnes CO_2e)	GWP Intensity (kg CO_2e/m^2)
Baseline – 6.5x6.5m RC Slab	4,968	221
Achievable – 7.5x7.5m RC Backshoring	4,997	222 (+0.6%)
Design Limit – 8.5x8.5m PT Slab	4,870	216 (-2%)

Column Layout Study Takeaways

Achievable grid layout is limited to the architectural program, i.e., suite layouts, parking layouts, etc.

There is minimal embodied carbon impact to adjusting the grid layout for this specific study.

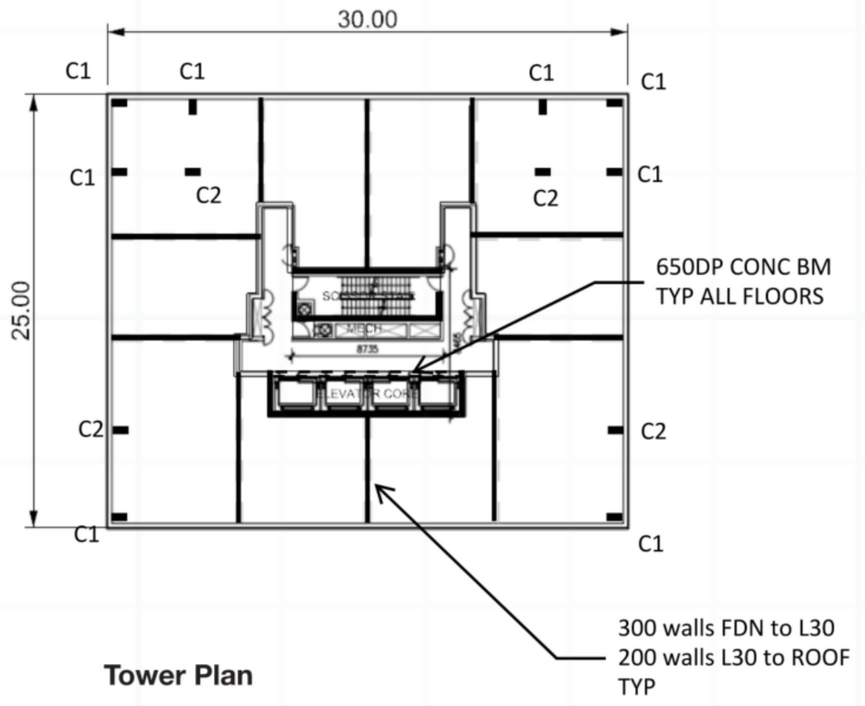
The Achievable slab system demonstrates a slight increase in embodied carbon due to the higher steel reinforcement density required in the slabs to accommodate the longer spans. The additional rebar adds more GWP than the savings achieved in the columns.

Lateral System
Strategies for Tower

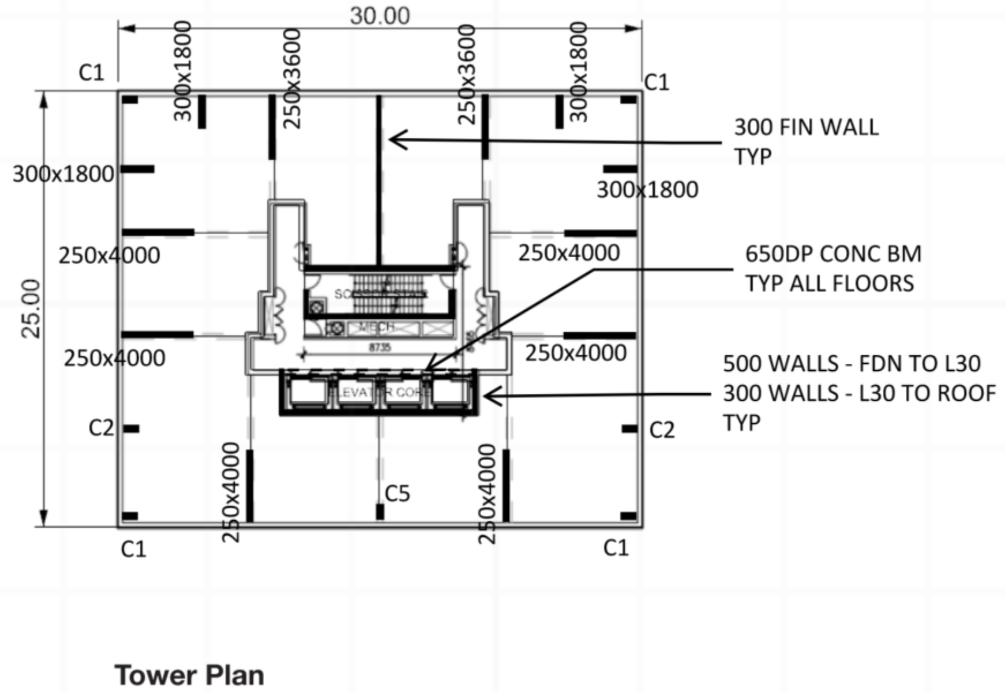
Structural walls are estimated to account for up to 25% of the total embodied carbon in the structure. Therefore, designing a lateral system that minimizes walls can have a considerable impact on the embodied emissions. Typical construction practice in a residential building in Toronto consists of walls between suites and a central core. In this study we evaluated the embodied carbon impact of two alternative approaches, which consisted of wallumns with a central core and fin wall, and columns with a central core and fin wall.

Lateral System Options - Tower

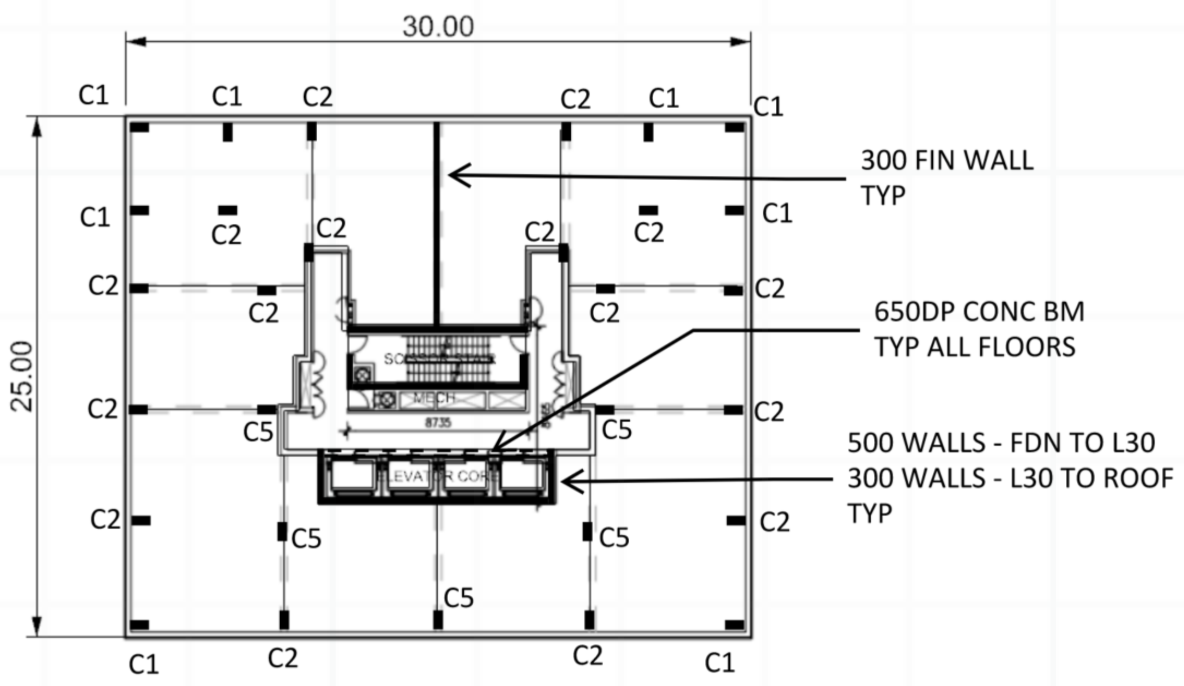
Option 1: Shear Walls between Suites



Option 2: Wallumns



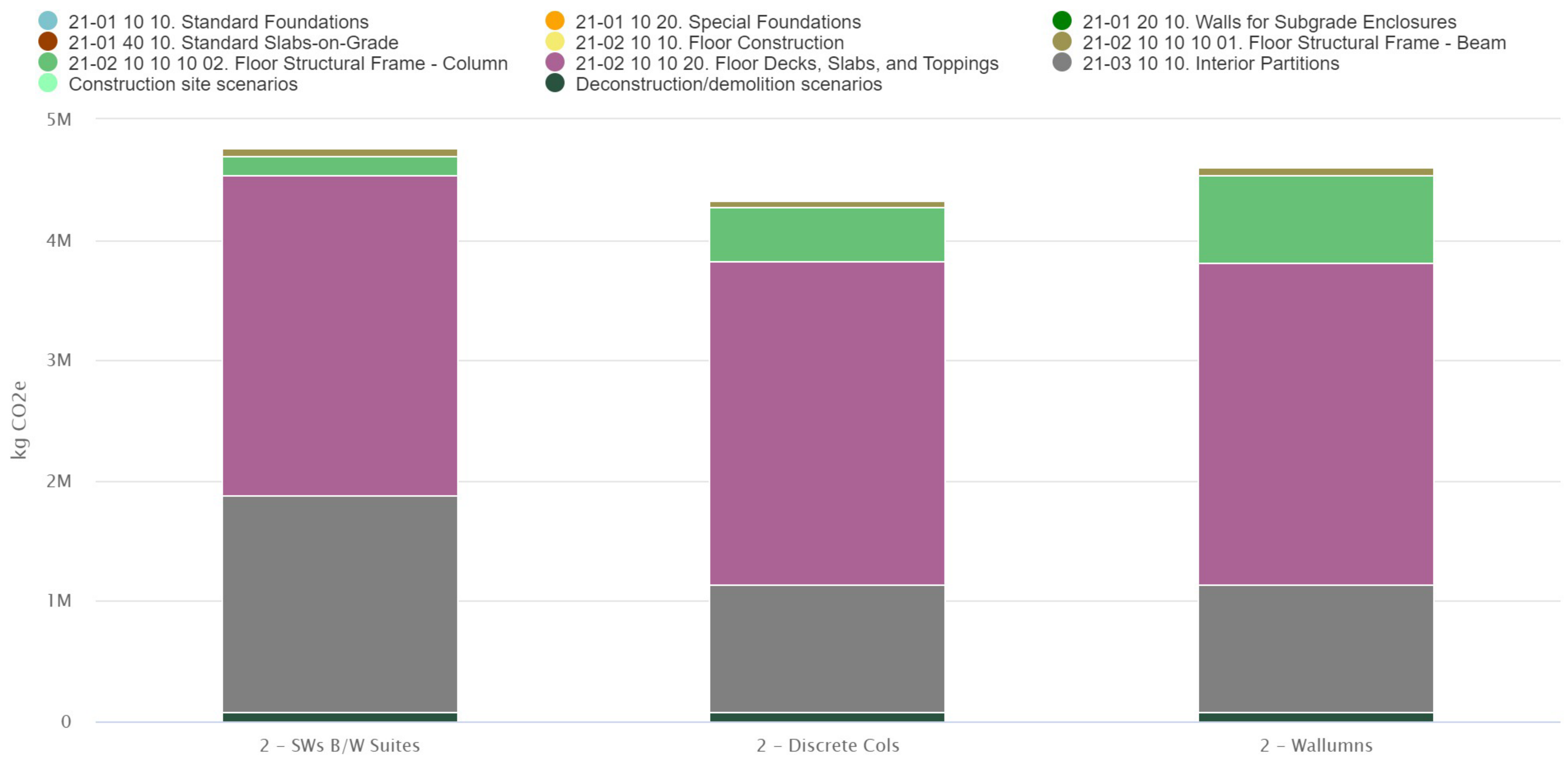
Option 3: Discrete Columns



Embodied Carbon Results - Tower as a Whole

Lateral System	GWP Structure (tonnes CO_2e)	GWP Intensity Structure (kg CO_2e/m^2)	GWP Intensity Demising Walls (kg CO_2e/m^2)	GWP Intensity Demising Walls & Structure (kg CO_2e/m^2)
1. Shear Walls between Suites	5,439	241	-	241
2. Wallumns	5,281	234 (-2.9%)	+2.0	237 (-2.1%)
3. Discrete Columns	5,014	223 (-7.8%)	+3.9	227 (-6.2%)

Embodied Carbon of Tower Structure per Lateral System



Lateral System Study Takeaways

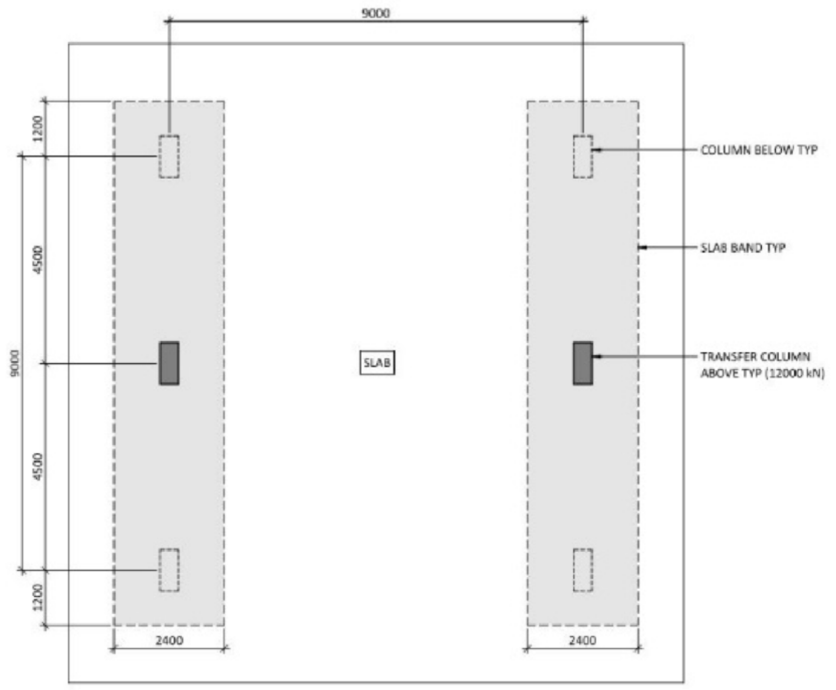
Architectural demising walls are required between suites in lieu of shear walls. The addition of demising walls introduces a slight increase in embodied carbon to the building.

Transfer Options for the Podium

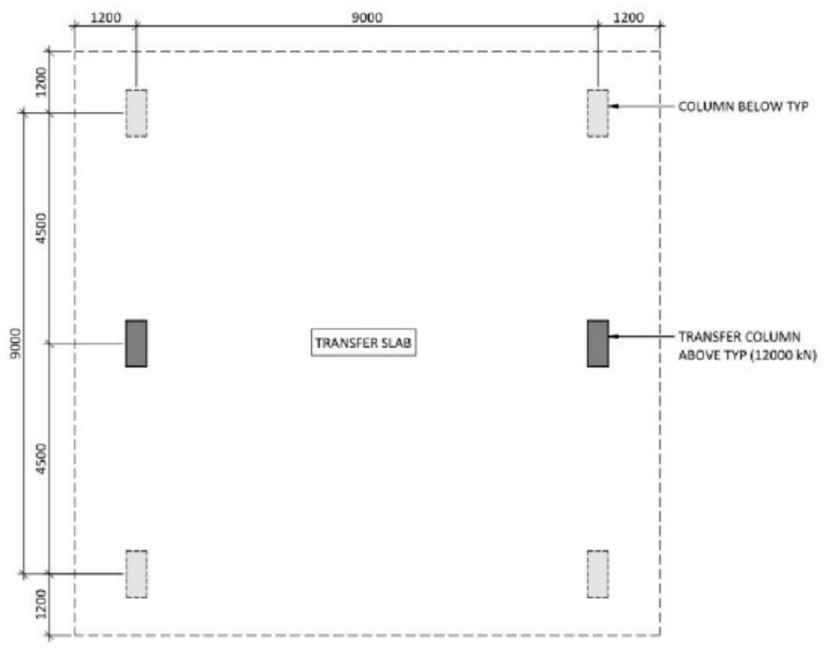
Transfer systems are both costly and carbon-heavy due to the large volume of reinforced concrete required to transition the loads between floors. The optimal solution is to avoid or limit transfers altogether, ideally by having the vertical elements extend from top to bottom without interruption. However, residential buildings in Toronto typically have at least one transfer floor which is often in the form of a transfer slab.

The following study evaluated the embodied carbon impact of various transfer systems on a 9m by 9m grid. These transfer systems were designed for a previous study for a 20-storey residential tower and therefore the focus should be on the percent difference in embodied carbon, rather than on the absolute intensity, as a 40-storey tower will have larger loads, and hence a greater embodied carbon intensity (kgCO²e/m²).

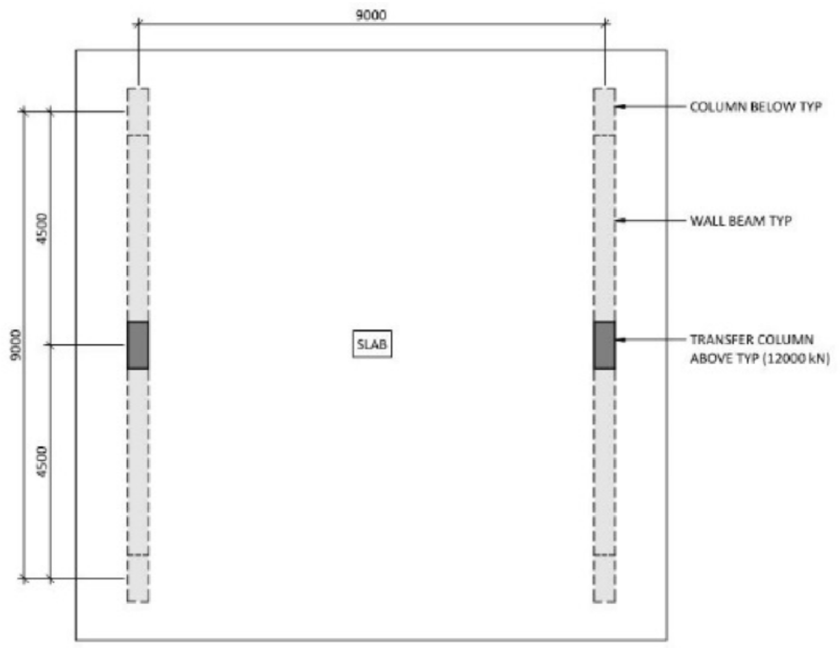
Orthogonal Transfer



ORTHOGONAL SLAB BAND TRANSFER SYSTEM
NTS

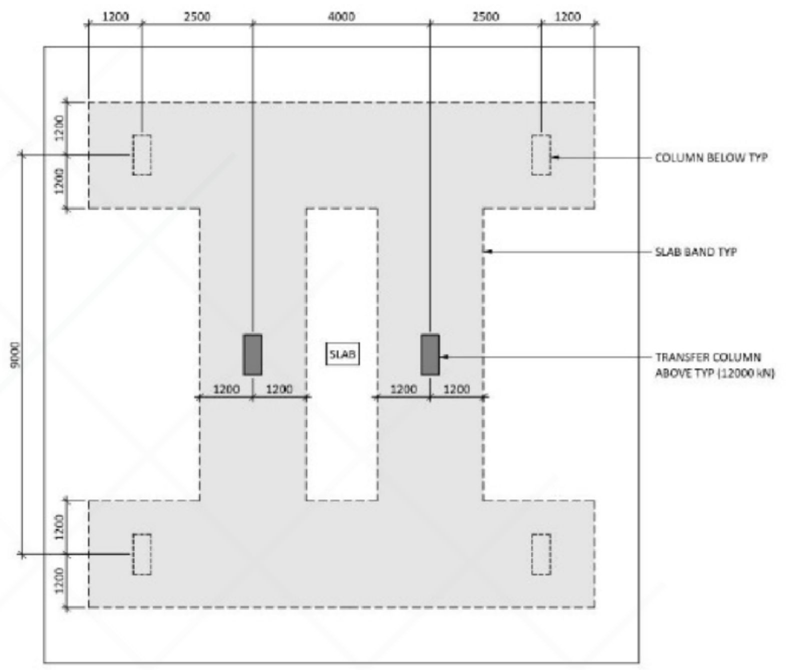


ORTHOGONAL TRANSFER SLAB SYSTEM
NTS

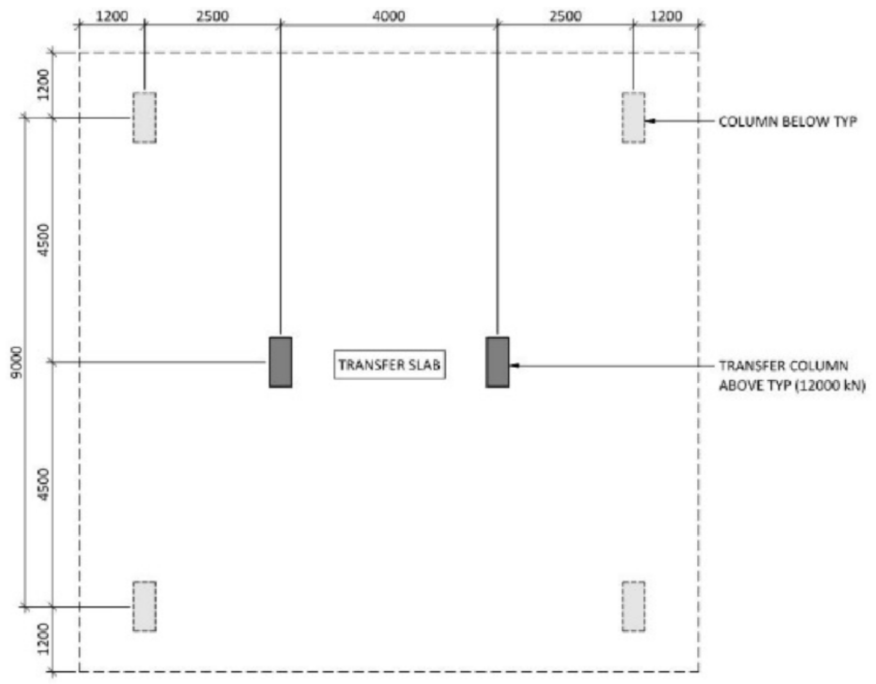


ORTHOGONAL WALL BEAM TRANSFER SYSTEM
NTS

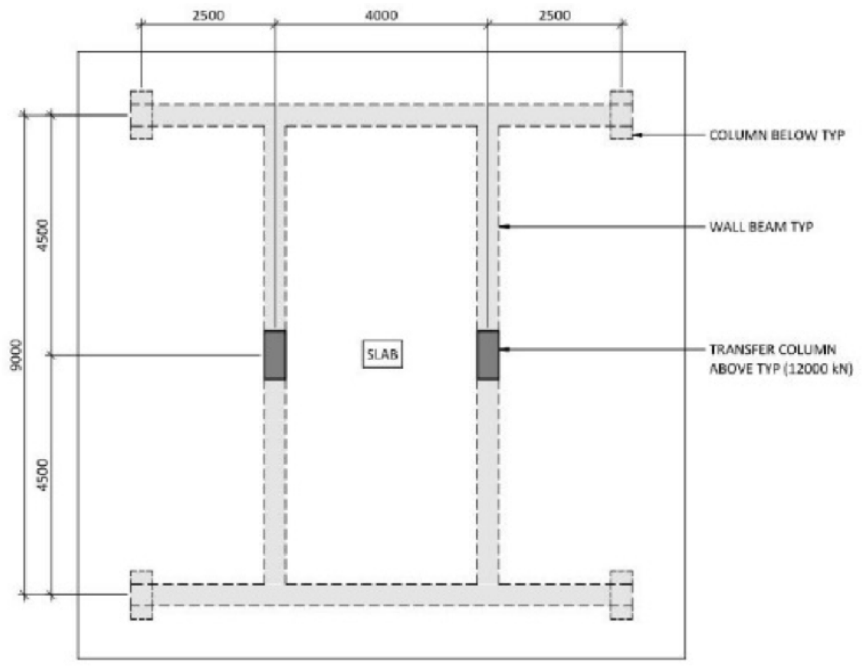
Non-Orthogonal Transfer Layout



NON-ORTHOGONAL SLAB BAND TRANSFER SYSTEM
NTS



NON-ORTHOGONAL TRANSFER SLAB SYSTEM
NTS



NON-ORTHOGONAL WALL BEAM TRANSFER SYSTEM
NTS

Structural Properties

Transfer System Parameters	
Bay Size	9m x 9m
Floor Plate	11.4m x 11.4m
Typical Slab Thickness	300mm
Transfer Slab Thickness	1200mm*
Slab & Transfers f'c	35 MPa
Transfer Load	12,000 kN (typical for 25 to 30-storey residential tower)

**Original study was conducted for a 20-storey residential tower. The transfer slab for a 40-storey tower would be about 1800mm deep.*

Embodied Carbon Results

Transfer Layout	A1-A3 GWP	Total A-C* GWP	
	(kg CO$_2$e/m^2)	(kg CO$_2$e/m^2)	% Difference
Orthogonal Slab Band	494	583	+62%
Orthogonal Transfer Slab	706	811	+126%
Orthogonal Wall Beam	295	359	Lowest EC
Non-Orthogonal Slab Band	734	844	+135%
Non-Orthogonal Transfer Slab	719	826	+130%
Non-Orthogonal Wall Beam	444	524	+46%

**Includes the following life-cycle stages: A1-A3, A4, A5, C1-C4.*

Transfer Study Takeaways

The viable transfer system is highly dependent on the grid layout.

Wall beams prevent access to areas, introducing architectural limitations. Additionally, non-orthogonal wall beam systems are impractical as they create inaccessible areas.

Greatest impact on reducing embodied carbon with transfer systems is achieved by limiting transfers to a single floor & minimizing the number of transfers.

Below-Grade Parking Options

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Below-grade parking structures add a significant amount of embodied carbon to the building due to the volume of concrete required to construct them. Typical residential towers in Toronto have four levels of parking, which was estimated to account for a quarter (28%) of the total embodied carbon of the baseline building structure in this research program. Therefore, the following study evaluates the embodied carbon impact of reducing the number of parking levels and the contribution these alternative options have on the building as a whole.

Embodied Carbon Results - Whole Building

Underground Parking System		Total A-C GWP			
		GWP (tonnes CO_2e)	GWP Intensity (kg CO_2e/m^2)	% Difference from Option 1	% of Below-Grade Structure Contribution
Option 1	4 Levels Below-Grade	11,477	409	-	28%
Option 2	3 Levels Below-Grade	11,010	392	-4%	25%
Option 3	2 Levels Below-Grade	10,611	378	-8%	22%
Option 4	1 Level Below-Grade	9,288	331	-12%	11%
Option 5	No Below-Grade Parking	9,246	329	-13%	10%

Foundation Design Assumptions

The below-grade structure was designed as a tanked foundation system to meet the City of Toronto Foundation Drainage Provisions. The following assumptions were made on the soil properties:

- Groundwater table is between P1 and P2 elevation.
- For no parking, structural tanking is not required as it is above the groundwater table.
- Bearing capacity of soil/rock: 1100 kPa ULS.
- Soil/rock bearing is valid for foundation depths associated with 1 level of underground parking.
- Assumed that bottom of footings for the no below-grade parking option is about 4.4m below ground floor.
- No surcharge loading from adjacent buildings.

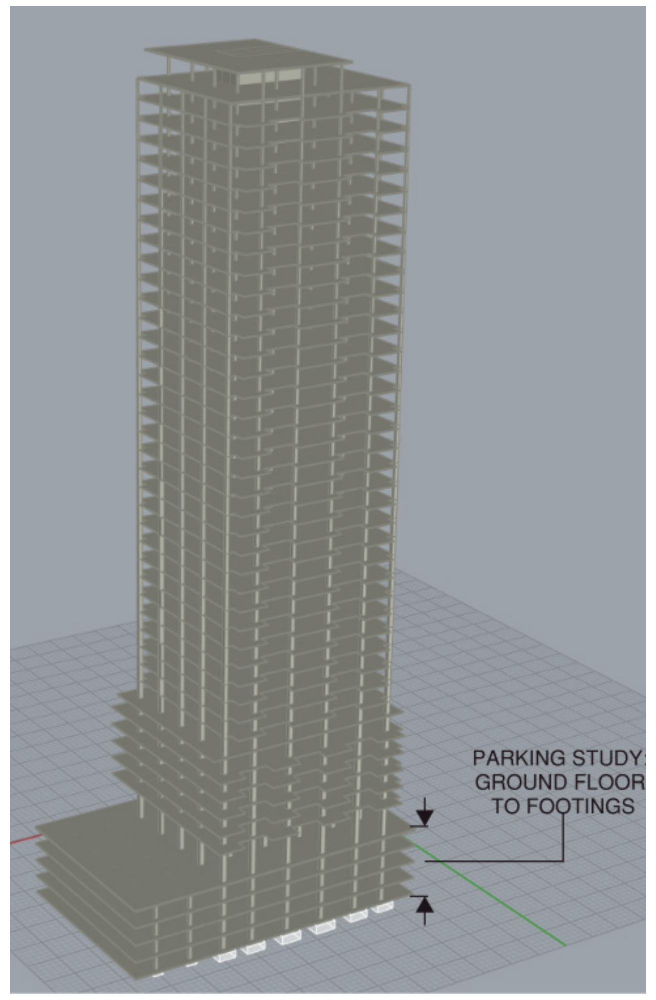
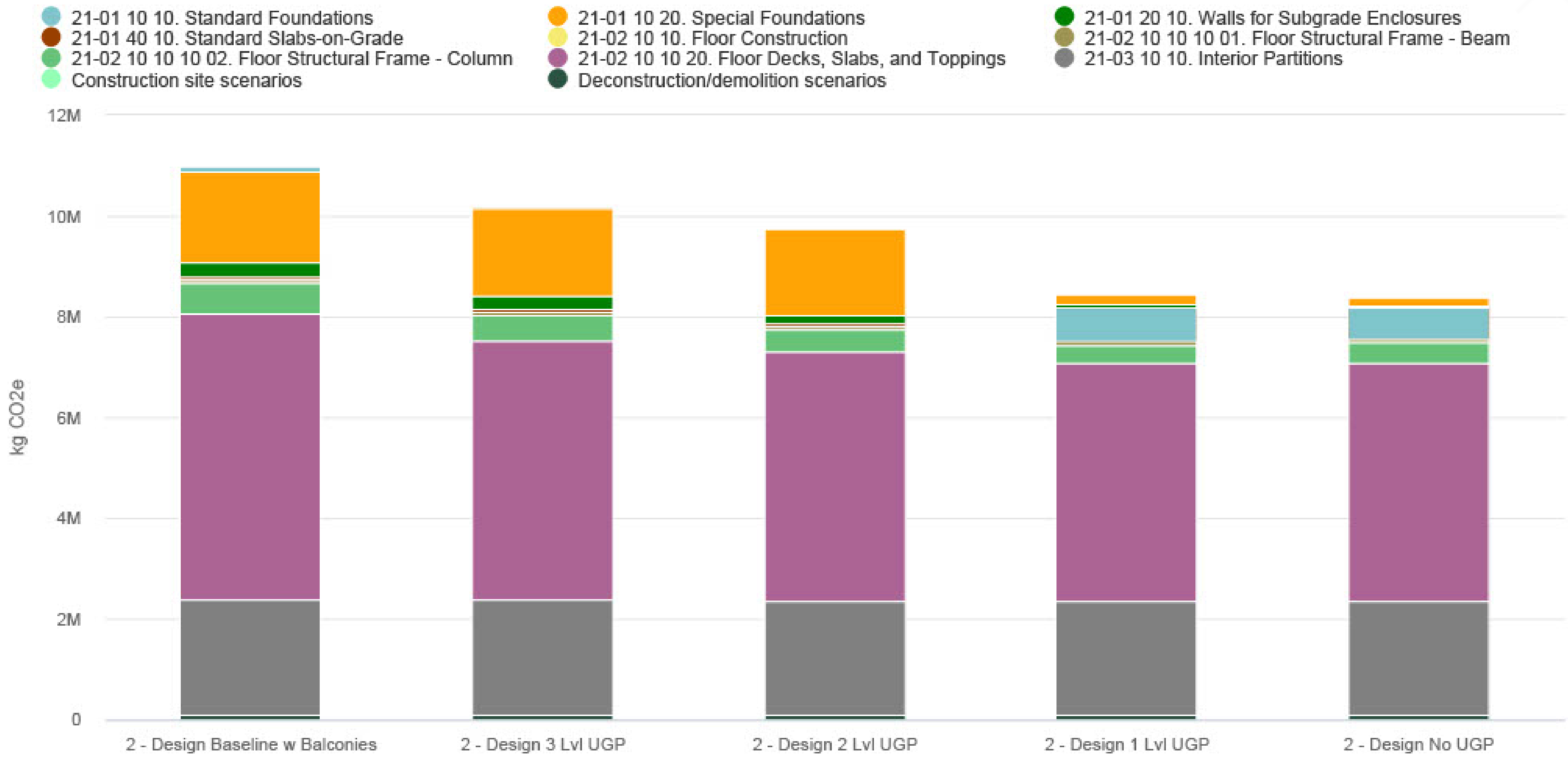


Fig. 6 Scope of BG Parking Study for EC Analysis

Embodied Carbon of Whole Structure per Below-Grade Structure



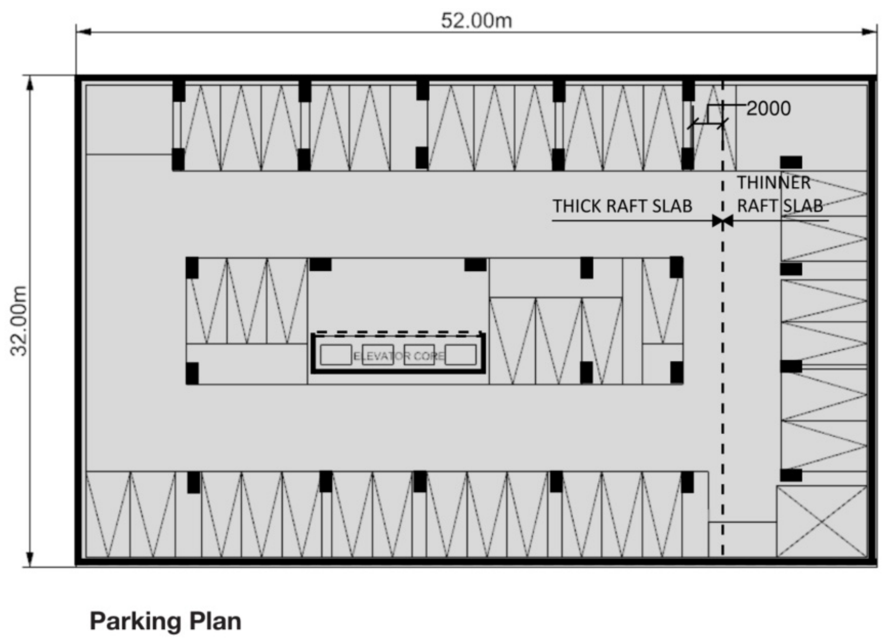


Fig. 7 Options 1-3 Foundation System (Tanked Raft Slab)

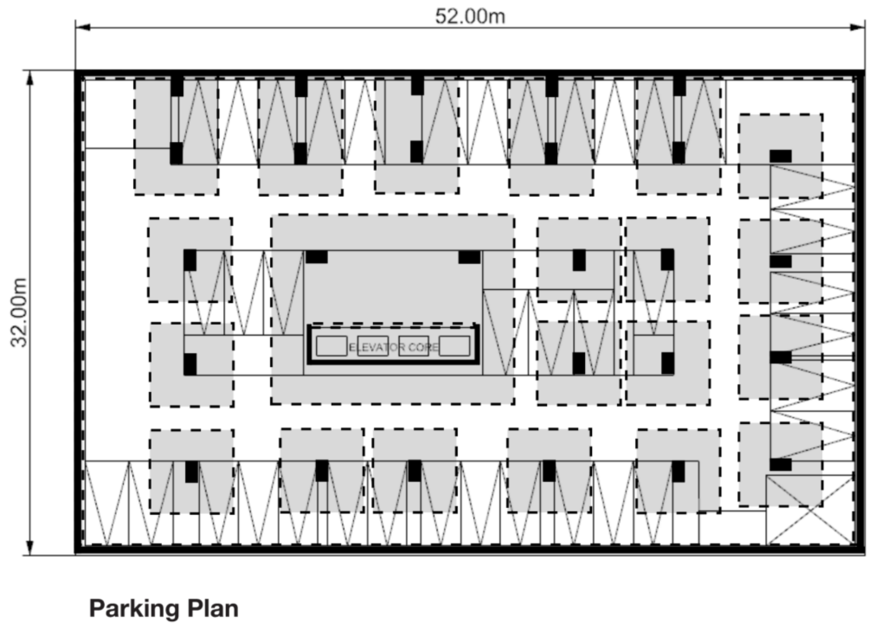


Fig. 8 Options 4-5 Foundation System (Pad Footings)

Below-Grade Structure Study Takeaways

The embodied carbon contribution of below-grade structure to the whole building structure for tanked foundations: 22-28%

The embodied carbon contribution of below-grade structure to the whole building structure for non-tanked foundations: 10-11%

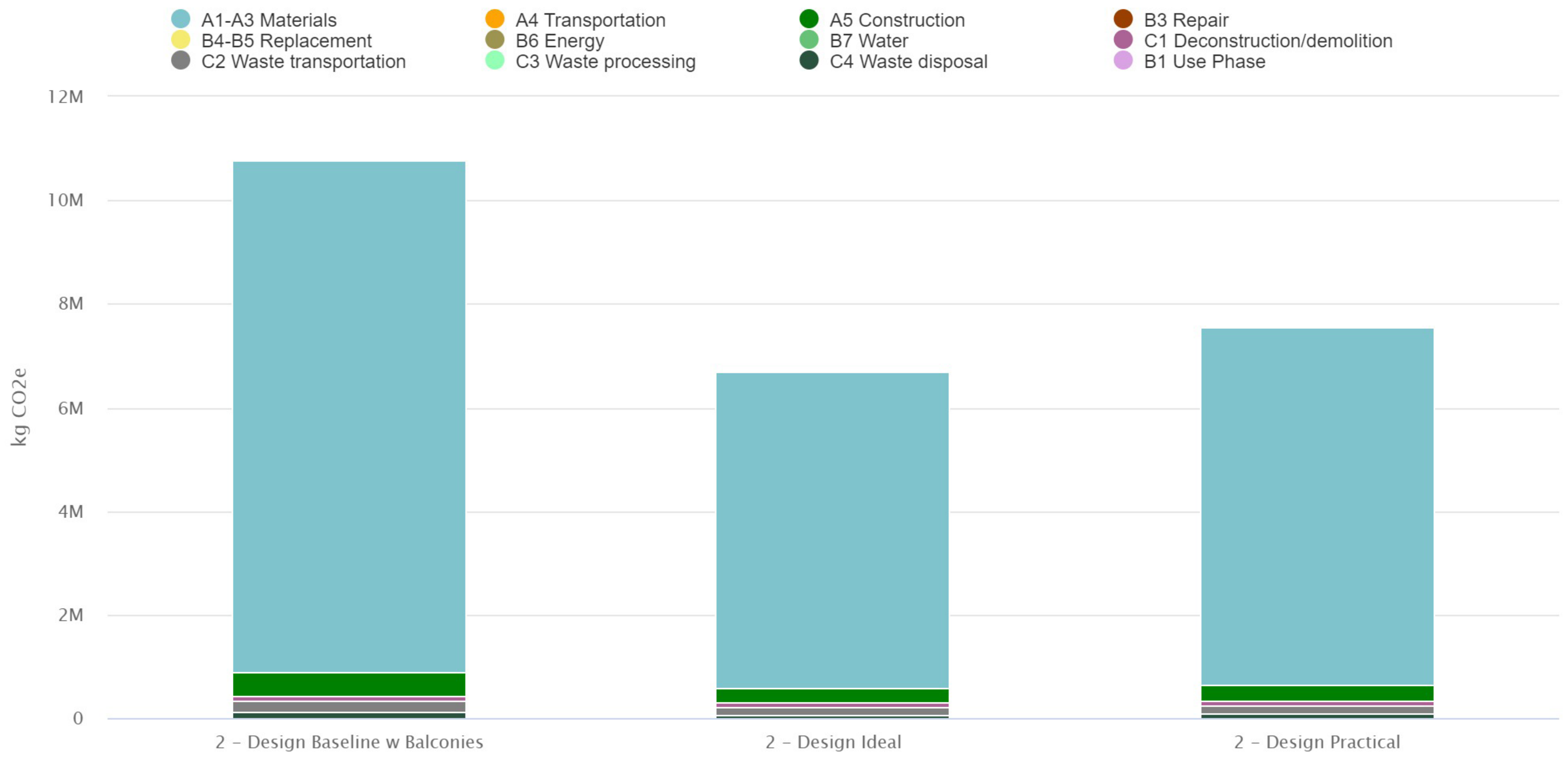
Low-Carbon Pathways

Low-Carbon Pathways

The results of the various structural studies were used to determine low-carbon pathways for the full building structure. Two pathways were selected:

Pathway	Structural Systems	Comments
Ideal	• 165mm PT slab with 4" insulation and 2 layers of GWB for acoustic requirements • No balconies • Discrete columns with architectural demising walls at a 6.5m x 6.5m grid, a central core and fin wall. • Transfers at Level 2 only made up of transfer beams and a transfer slab for the scissor stair. • One below-grade level.	This option is not considered realistic due to the acoustic requirements of the thin slab. One below-grade parking level was selected since no below-grade structure was deemed unrealistic for a building of this typology.
Practical	• 200mm RC slab • No balconies • Discrete columns with architectural demising walls at a 6.5m x 6.5m grid, a central core and fin wall. • Transfers at Level 2 only made up of transfer beams and a transfer slab for the scissor stair. • One below-grade level.	Although a PT slab system would achieve a larger grid layout, resulting in 2% embodied carbon savings, it is not standard construction in Ontario. Therefore, due to the minimal carbon reductions and added construction complexity, a standard reinforced concrete slab was selected.

Embodied Carbon of Whole Structure per Pathway



Embodied Carbon Results

Building System	GWP (tonnes CO_2e)	GWP Intensity (kg CO_2e/m^2)
Baseline (with balconies)	11,823	421
Ideal Pathway	7,659	273 (-35%)
Practical Pathway	8,545	304 (-28%)

Low Carbon Design Pathway Takeaways

Good, Better, & Best embodied carbon targets were set to align with IStructE's SCORS C, B, & A ratings for LCA modules A1-A5.

- Good "C" rating = 200-250 kg CO2e/m2.
- Better "B" rating = 150-200 kg CO2e/m2.
- Best "A" rating = 100-150 kg CO2e/m2.

The estimated GWP of all three designs for A1-A5 emissions is as follows:

- 406 kgCO2e/m2 for the Baseline,
- 262 kgCO2e/m2 for the Ideal Pathway
- 293 kgCO2e/m2 for the Realistic Pathway.

All of the designs exceeded the "C" rating (>250 kgCO2e/m2).

Low-Carbon Material Pathways

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Low-Carbon Material Pathways

The embodied carbon of the structure can be further reduced by selecting low-carbon materials. Several low-carbon iterations (LCI) were applied to the Ideal Pathway with the results summarized below. The description for the LCI's defines the changes from the baseline, all other conditions are the same.

Case	Description	GWP Intensity ($kg\ CO_2e/m^2$)	Difference from Baseline
Ideal Pathway (Baseline)	Industry average concrete mixes consisting of General Use Portland Cement (GU) and 10% supplementary cementitious materials (SCM) content. Industry average reinforcing bars.	273	-
LCI-01	Concrete mixes with GU cement and 35-50% slag cement.	235	-14%
LCI-02	Concrete mixes with General Use Portland Limestone (GUL) cement and 35-50% slag cement.	222	-18%
LCI-03	Lafarge's ECOPact Entry Level low-carbon concrete.	215	-21%
LCI-04	Lafarge's ECOPact Prime low-carbon concrete.	186	-32%
LCI-05	Lower-carbon rebar: Gerdau's rebar produced at the Whitby, ON plant.	266	-2%
Max LCI	LCI-04 and LCI-05	181	-34%

Note:

- *The LCIs are limited based on available lifecycle inventory data. For instance, another LCI would be a standard concrete mix with GUL cement. However, the EPD used for the analysis did not include this datapoint so it was not analyzed. Studies show that concrete with GUL cement has about 10% less embodied carbon than with GU cement.*
- *The data used to model Lafarge's ECOPact products (LCI-03 and LCI-04) was based on GWP values from Lafarge's plants in the Greater Toronto Area, one of which is the Innocon Mavis Plant. Where information was lacking for specific concrete strengths, assumptions were made to estimate the GWP value.*
- *All GWP values in the analysis represent current conditions and should be updated as more relevant data becomes available.*

Low-Carbon Material Takeaways

High SCM & low-carbon concrete products have performance implications, which could affect the construction schedule.

Low-Carbon Material Pathways

EN

Low-Carbon Material Pathways

The embodied carbon of the structure can be further reduced by selecting low-carbon materials. Several low-carbon iterations (LCI) were applied to the Practical Pathway with the results summarized below. The description for the LCI's defines the changes from the baseline, all other conditions are the same.

Case	Description	GWP Intensity (kg CO_2e/m^2)	Difference from Baseline
Practical Pathway (Baseline)	Industry average concrete mixes consisting of General Use Portland Cement (GU) and 10% supplementary cementitious materials (SCM) content. Industry average reinforcing bars.	304	-
LCI-01	Concrete mixes with GU cement and 35-50% slag cement.	262	-14%
LCI-02	Concrete mixes with General Use Portland Limestone (GUL) cement and 35-50% slag cement.	249	-18%
LCI-03	Lafarge's ECOPact Entry Level low-carbon concrete.	240	-21%
LCI-04	Lafarge's ECOPact Prime low-carbon concrete.	209	-31%
LCI-05	Lower-carbon rebar: Gerdau's rebar produced at the Whitby, ON plant.	296	-3%
Max LCI	LCI-04 and LCI-05	200	-34%

Note:

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