CSCE Annual Conference
Growing with youth – Croître avec les jeunes

Laval (Greater Montreal)
June 12 - 15, 2019

SUSTAINABLE DESIGN OF REINFORCED CONCRETE FLAT-PLATE BUILDINGS BASED ON COST, EMBODIED ENERGY, AND CARBON FOOTPRINT

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Abstract: Energy is required in all phases of a building life cycle. Embodied energy and carbon emissions of a building are associated with production, transportation, disposal, and recycling of materials, and during their construction and demolition. A cost-optimized structural design of individual members is obtained by selecting the quantities of materials that satisfy a certain design-code at a minimum cost. For a reinforced concrete structural element, concrete and rebars are optimized for cost. A member thus proportioned for a minimum cost may not always result in lower embodied energy and carbon emission. A different design approach is needed to reduce the embodied energy and carbon to a lower level. In this study, the objective functions for cost, embodied energy, and CO_2 emission were defined and used in the structural design of a set of RC flat-plate residential buildings with 5-, 10-, and 15-storeys, located in Montreal, Canada. The trade-off between the cost and two other variables was studied. It has been found that some significant reduction in embodied energy and CO_2 emission is possible for a small increase of the cost for the 5-, 10-, and 15-storey variants. For an optimized solution, the maximum reinforcement ratio of columns has been found to increase with the building height. A slab thickness taken 24% smaller than the minimum thickness specified by CSA 23.3-14 has been found to be most effective in meeting the objective of cost optimization and embodied energy and CO_2 emission reduction.

1 INTRODUCTION

Buildings use about 30% of worldwide energy consumption and are responsible for 25-40% greenhouse gas emissions (IPCC 2007). The concept of sustainable development, which aims for the efficient use of renewable natural resources to produce energy with a reduced carbon imprint to meet the current needs without affecting the availability of the natural resources to meet the energy requirements for future, has emerged due to depletion of fossil fuel and increase of green-house gases (GHG) (WCED 1987, Ashley and Lemay 2008). Many researchers use different approaches to identify measurable factors for sustainable development (Lippiatt 1999, Ding 2008). Among these factors, emission of carbon dioxide (CO_2) and the embodied energy (EE), which accounts for the energy consumed in non-operating stages of a building, i.e., extraction of raw materials, production of building materials and their transportation, construction, demolition, deposal, and recycling, have been identified as most important. The building structural frames, usually constituting the largest mass of buildings, account for a major contributor to their embodied energy (Foraboschi et al. 2014, Cole 1997). According to some studies, embodied energy shares 5% to 40% of total life cycle energy of a building (Sartori and Hestnes 2007).

Since concrete is the most widely used material in construction worldwide, the total amount of embodied energy in reinforced concrete (RC) structures is very high. The global production of concrete increased from 40 million cubic meters in 1900 to 6.4 billion cubic meters in 1997 (CTBUH 2009). According to some comparative study by Chiniforush et al. (2018) on the buildings with RC, steel-timber composite, and steel-concrete composite structural frames, the RC building has the largest embodied energy. The CO_2 emission generated in the production of cement consists of 5% of the global CO_2 emissions due to global human activities (Worrell et al., 2001). It has been identified that concrete structures induce 73% of environmental impacts in construction industry (Thiel et al. 2013).

Since RC buildings are among the most common building type in the world and they account for a very high amount embodied energy and the carbon imprint, it is imperative that their structural design should consider not only the initial cost involvement, but also the minimization of embodied and carbon emission. The conventional design method aims for minimization of material cost, simultaneously meeting the structural strength and service requirement as specified in the code. For the design optimization, however, it is required to minimize the embodied energy and embodied CO_2 (EC). Various research works for the design of individual structural elements such as RC column, rectangular beam, and slab have been carried out for the minimization of these two environment related factors while keeping the associated increase in cost reasonably low, at least, if not fully optimized.

The embodied energy and CO_2 gas for RC column design with varying design parameters were investigated (Park et al. 2014, Yeo and Potra 2015). Optimization of a slab design for the embodied energy by modifying its design parameters was studied by Miller et al. 2015. A sustainable design method, which minimizes the embodied energy and CO_2 emission of an RC column, was proposed by Yoon et al. (2018). Yeo et al. (2011) proposed a sustainable design of a regular reinforced beam for a reduced embodied energy and carbon emission. Despite these developments, a combined optimization application in all structural elements is to be done on a prototype building for simultaneous minimization and / or optimization of cost, embodied energy, and embodied CO_2 on the entire structure. This research gap is the principle motivation for this current undertaking presented in this paper.

2 SUSTAINBLE DESIGN OF RC FLAT PLATE BUILDINGS

2.1 Problem description

This paper presents a parametric design study for combined minimization and / or optimization of cost, embodied energy, and CO_2 emission of a set of RC residential buildings with flat plate floor system (selected for its increased popularity due to certain advantages) of 5-, 10-, and 15-storeys, located in Montreal, Canada. The building has a plan area of 960 m^2. The column vertical steel ratio and slab thickness were the parameters against which the design optimization was performed. The plan of the prototype buildings is shown in Figure 1. An RC shear wall core is located in the middle of the building. The thickness of the walls was kept the same for all variants with an equal number of storeys. For 5-, 10-, and 15-storey variants, column of 3, 6, and 9 different dimensions respectively were used. In the case of the 5-storey building, no cross-sectional reduction of columns and walls over height was made. The sectional reduction was done for column and wall at 5-storey interval over height for 10- and 15-storey variants. The design optimization of the shear walls is beyond the scope of the study.

2.2 Structural analysis and design

For load calculation and analysis, National Building Code of Canada, 2015 (NBCC 2015) was followed and the design of columns and slabs was performed according to the Canadian concrete structure design standard CSA 23.3-14. The design parameters which are kept constant for both columns and slabs are given in Table 1. A square cross-sectional geometry was selected for all columns. The area of steel reinforcement in a column section is determined by the design specification of CSA 23.3-14, using software ETABS 2016 and spColumn.

In addition to axial loads, mostly due to lateral loading, columns are subject to significant bending moments in both orthogonal directions. Among all load combinations as specified by the Code, those consisting of lateral loads such as earthquake and wind are usually the most critical for mid to high-rise buildings located in an area with high earthquake or wind-speed.

For a given cross section and reinforcement arrangement of a column, a design strength curve can be constructed for various pairs of axial force and bending moment. The ratio of moment-to-axial force gives the associated vertical load eccentricity. The same can be done for the bending moment acting in the other orthogonal direction. The two curves are commonly known as the bi-axial interaction diagram shown in Figure 2. If the points representing the combinations of axial force and biaxial moments lie within the envelope of the biaxial column interaction diagram, the design is considered structurally safe. For optimization, at least one point should lie on or very close to the design envelope. The software packages mentioned above were used for the optimization process.

The reference design of flat plate slabs was performed according to the relevant Canadian standard CSA 23.3-14. However, the slab thicknesses considered were 160-, 180-, 200-, and 210-mm. The minimum slab thickness according to the Code specified equation is found to be 209 mm, which is satisfied only by 210 mm thickness used. The Code, however, also allows a thinner slab, provided it satisfies the maximum allowable deflection limit l_n / 180, where l_n is nominal longer clear span in between columns. The deflection calculation must be done taking cracked sectional properties calculated according to the specified method in the Code. For a given slab thickness, the design is optimized by providing the minimum amount of steel required for design against bending moments and punching shears. The steel ratio must not fall below the absolute minimum steel ratio specified by the Code.

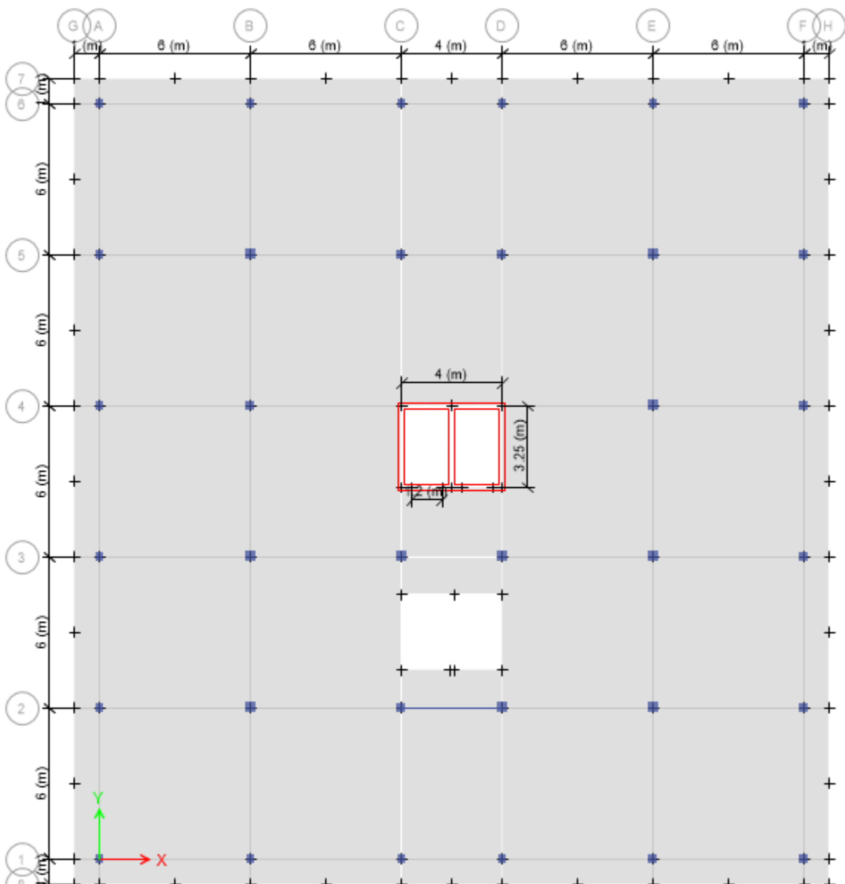


Figure 1: Prototype Framing Plan of flat plate floor supported by square columns

2.3 Objective Functions

Yeo and Gabbai (2011) have developed an objective function of the embodied energy for a single beam. Yoon et al. (2018) have defined the objective functions of cost and CO_2 emission for a column. The limitation of this approach is that member-wise design is difficult to be implemented accurately in practice because members are continuous and the detailing requires consideration of continuity. Also, optimization is simultaneously related among different structural elements such as slabs, beams, columns, and shear walls. Therefore, the current study aims for a wholistic optimization of the cost, embodied energy, and CO_2 emission of an RC building consisting columns and flat plate and, accordingly, the objectives functions for the entire slab-column structure have been developed, as shown in equations 1 through 3. These equations were developed for the total of all elements in consideration by modifying the equations for a single element given by Yeo and Gabbai (2011) and Yoon et al. (2018).

Table 1: Constant analysis and design parameters

RC design		Dynamic Earthquake Analysis	
Compressive strength of column concrete	35 MPa	Peak ground acceleration	0.377
Compressive strength of slab concrete	25 MPa	Spectral acceleration S_a (0.2)	0.594
Reinforcement yield strength	400 MPa	Spectral acceleration S_a (0.5)	0.310
Density of steel	7850 kg/m^3	Spectral acceleration S_a (1.0)	0.148
Density of steel	2400 kg/m^3	Spectral acceleration S_a (2.0)	0.068
Young's modulus of steel	2×10^5 MPa	Spectral acceleration S_a (5.0)	0.018
		Spectral acceleration S_a (10.0)	0.0061
Floor load		Site class	C
Live load	1.9 kPa	Importance factor, I_E	1.0
Partitioning + floor finish (dead load)	3.0 kPa	Damping ratio	0.05
		Ductility modifier, R_d	1.3
Wind analysis		Overstrength, R_o	1.3
Velocity pressure	0.42 kPa		
Gust effect factor, C_g	2.0		
Importance factor, I_W	1.0		
Terrain Type	Rough		

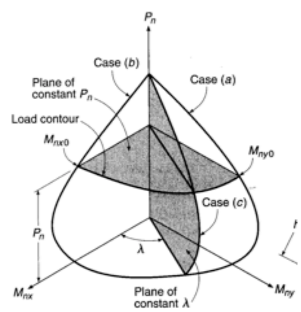


Figure 2: Column interaction diagram for bi-axial bending moments (Source: Nilson et al. 2010)

$$[1]\ \mathrm{a}\,(\mathrm{V},\mathrm{M_s}) = \mathrm{C^c}\left[\mathrm{M}_s\left(\frac{\mathrm{R}}{100}-\frac{1}{\rho_s}\right)+V\right]$$

$$[2]\ \mathrm{b}\,(\mathrm{V},\mathrm{M_s}) = \mathrm{M_s}\mathrm{E_e^s}+\left(\mathrm{V}-\frac{\mathrm{M_s}}{\rho_s}\right)\mathrm{E_e^c}$$

$$[3]\ \mathrm{c}\,(\mathrm{V},\mathrm{M_s}) = \mathrm{M_s}\mathrm{E_c^s}+\left(\mathrm{V}-\frac{\mathrm{M_s}}{\rho_s}\right)\mathrm{E_c^c}$$

where, $\mathrm{a}\,(\mathrm{V},\mathrm{M_s})$, $\mathrm{b}\,(\mathrm{V},\mathrm{M_s})$, and $\mathrm{c}\,(\mathrm{V},\mathrm{M_s})$ are the objective functions for cost, embodied energy, and CO_2 emission. V and $\mathrm{M_s}$ are total gross concrete volume in m^3 and steel mass in kg respectively of all elements in consideration. The values of V and M_s for columns were obtained from a coded Excel file by importing data from the column design summary table generated by ETABS. The values of V and M_s for flat plates were obtained as material takeoff from the design outputs of spSlab. C_C denotes the cost of 1 m^3 concrete, and R is the cost ratio between 100 kg steel and 1 m^3 concrete. The coefficient E_e^c is the embodied energy (MJ) per 1 m^3 of concrete and E_e^s is the embodied energy (MJ) per 1 kg of the steel. The coefficient E_c^s is the embodied CO_2 emissions (kg CO_2) per 1 kg of steel and E_c^c denotes the CO_2 emissions (kg CO_2) per 1 m^3 of concrete.

The cost ratio, R, is used because of the closeness of prices between 1 m^3 of concrete and 100 kg steel(Yeo and Gabbai 2011). Yet the costs of concrete and steel may vary for different countries or their regions. Their costs, especially of steel, may fluctuate significantly over time. Therefore, for research purpose, instead of taking a value for a specific time and region, a general value was taken. According to some literature, the value of R falls between 0.80 and 1.1 (Zaforteza et al. 2009, Sahab et al. 2005, Guerra et al. 2011). The concrete costs for CSA specified 35 MPa and 25 MPa concretes were taken as CAD 220 and 200 per m^3(CBM-GCPL 2018). Accordingly, for convenience, the value of R is taken as 0.95. The embodied energy and CO_2 emission coefficients were taken from the table given by Hammond and Jones (2008). The embodied energy coefficients were taken as 1.39- and 1.11-MJ/ kg for 35 MPa column concrete (assumed as high strength concrete) and 25 MPa slab concrete respectively, which were then converted to 3336- and 2664-MJ/ m^3 respectively as values of E_e^c to be used in Equation 2. The value of embodied energy coefficient for recycled steel bars, E_e^s, was taken as 8.8 MJ /kg. The CO_2 emission coefficients were taken as 0.239- and 0.159-kg-CO_2/ kg for the 35 MPa and 25 MPa concrete respectively, which were then converted to 502- and 382 kg-CO_2/ m^3, respectively as the values of E_c^c to be used in Equation 3. The value of E_c^s to be used in Equation 3 was taken as 0.42 kg-CO_2/ kg for recycled steel bars.

2.4 Optimization method

In the optimization process for columns, the maximum of vertical steel ratio was varied between 2% to 5% stepwise by gradually reducing the column sizes in different input files. Due to high bending moments induced by lateral loading associated with large gravity forces, the bottom-most columns usually require the heaviest design. Therefore, most of the ground floor columns were designed for selected maximum steel ratio. In this study, no reduction in column sizes was done for the 5-storey variant. Accordingly, with constant section sizes and decreasing gravity and lateral loadings, the reinforcement requirements, hence the calculated steel ratios, were found to decrease with height for most columns. An overdesigned column converges towards its optimization point if a reduction is made for either on the cross-section area (with an increased steel ratio) or steel area (with a decreased steel ratio). The opposite is applicable for an under-designed column. Despite the higher embodied energy and carbon emission per 1 kg of steel than those of concrete, due to its much higher material strength, the use of higher steel ratio, in general, reduces the embodied energy and CO_2 emission of the structural element in consideration. Conversely, except for a very low steel ratio, the cost for a structural element increases with a design proportioning with a higher steel ratio. In the case of slab, for a given thickness, the reduction in steel amount always reduces its cost and associated embodied energy and CO_2 emission. The slab thickness, however, itself is a factor for an optimization. Hence, four different slab thicknesses were taken.

3 RESULTS AND DISCUSSION

1. As 160-, 180-, and 200-mm slab-thicknesses are less than the minimum thickness calculated from the Code equation, their validity according to the Code was checked against maximum allowable deflection, which was found to be below the deflection limit for all thicknesses.

2. Drop panels are needed at all corner to provide enough two-way shear-resistance. Also, stud shear reinforcement is required for all other columns for the same reason.

3. For a same number of storeys, the building with 160 mm slabs experiences least gravity loads and earthquake load-effects on columns, resulting in the most economic design as well as the least embodied energy and CO_2 emission for columns. From Figure 3, for the slab design, the 180 mm variant has the most economical solution, while the 160 mm slab has least embodied energy and CO_2 emission and the 210 mm slab thickness has the highest embodied energy and CO_2 emission, as seen in the Figure 3 below. The cost difference is small between 160- and 200-mm slab. The

heavier reinforcement in the former and bulkier concrete in the latter have affected their respective cost.

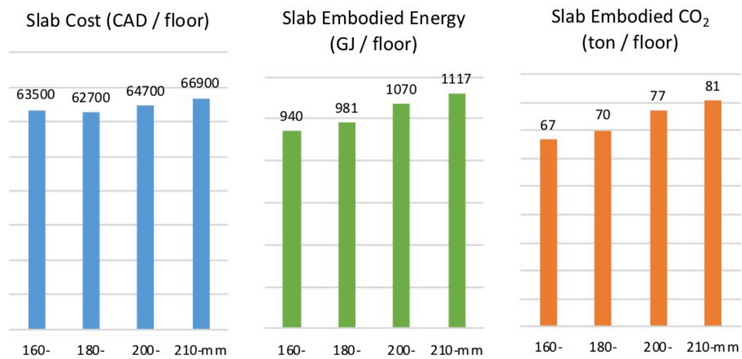


Figure 3: Cost, embodied energy, and embodied CO_2 of a single floor for different slab thicknesses

4. Since same slab thickness was maintained in all floors, the values of the three dependent variables, i.e., cost, embodied energy, and CO_2 emission, associated with floor slabs are linearly proportional to number of storeys. The non-linear variation in the three dependent variables for a building structure is likely to be induced by column design. Though the columns of the building with 160 mm slab have the least values for these dependent variables, however, due to larger quantities of concrete and steel associated with slabs than those of columns, the economy in the building structure is dependent mostly on the slab cost.

5. There is a fairly good correlation between average and maximum column steel ratio, as seen in Figure 4 below for different slab thicknesses. Such relationship may not be so distinct if design of the entire structure is not refined well enough.

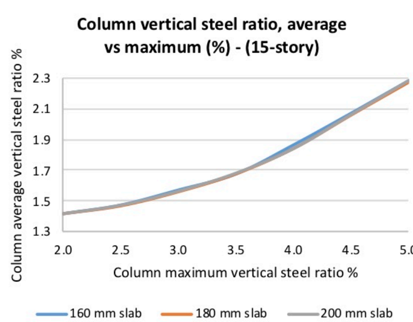
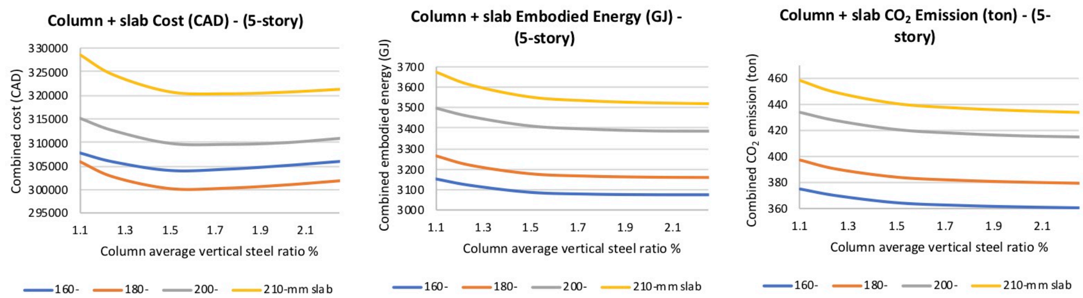


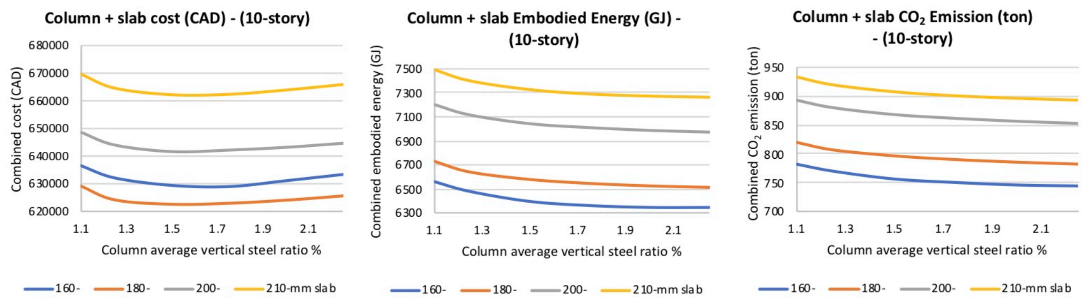
Figure 4: Average vs maximum column steel ratio for different slab thicknesses for 15-storey building

6. As it is seen in Figure 3, 180 mm slab is the least costly, the combined cost also is minimum for the building with 180 mm slabs, as apparent in the Figure 5, but for the 15-storey building, cost difference between buildings with160- and 180-mm slabs is small.

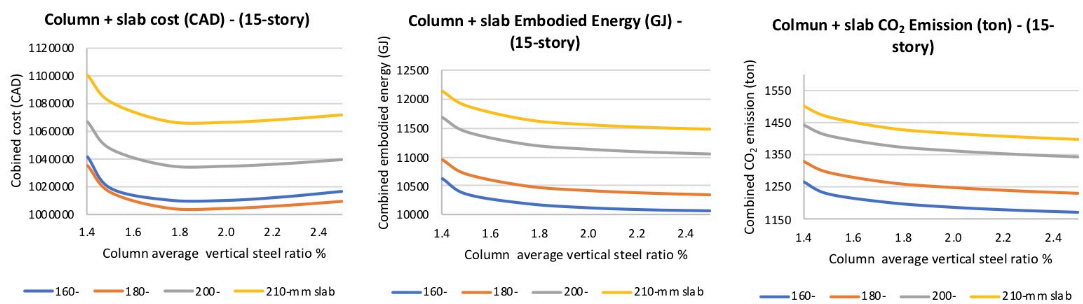
7. As can be seen from Figure 5, the building with 160 mm slabs has the least embodied energy and carbon emission for all numbers of storeys. Both embodied energy and CO_2 emission decrease with a decreasing rate against average column steel ratio. The building with 210 mm thickness has the most unfavorable values for three variables in all cases. A thicker slab requires lower amount of steel to resist bending moments. Sometimes, amount of steel for strength requirement is found to be much lower than the minimum steel ratio specified by the Code, hence the design is governed by the specified minimum steel ratio, resulting in greater amount of both concrete and steel than it is required for a more economical solution.



(a) 5-storey buildings



(b) 10-storey buildings



(c) 15-storey buildings

Figure 5: Structural cost, embodied energy, and CO_2 emission for different heights and slab thicknesses

8. The most favorable average column steel ratio seems to depend on the building height and varies between 1.5% to 2.0 % with values for a tall building towards the higher end of the range. Due to a correlation between maximum and average steel ratio, accordingly the maximum steel ratio for an optimum design of columns increases with building height.

9. The cost, embodied energy, and CO_2 emission per m^2 of floor increase with building height as seen in Figure 6 below. Similar trends were also found in the study by Chiniforush et al. (2018). Since slab thickness is constant for a given building, the variation of these quantities per m^2 is incurred by the change in the material quantity of columns, which increases non-linearly on building height. Column design varies along the height due to change in both vertical and lateral loads. The effect is most prominent in tall buildings due to increase in both lateral load intensity and total lateral load with building height. The bending moments in columns increase at an increasing rate as the building height increases.

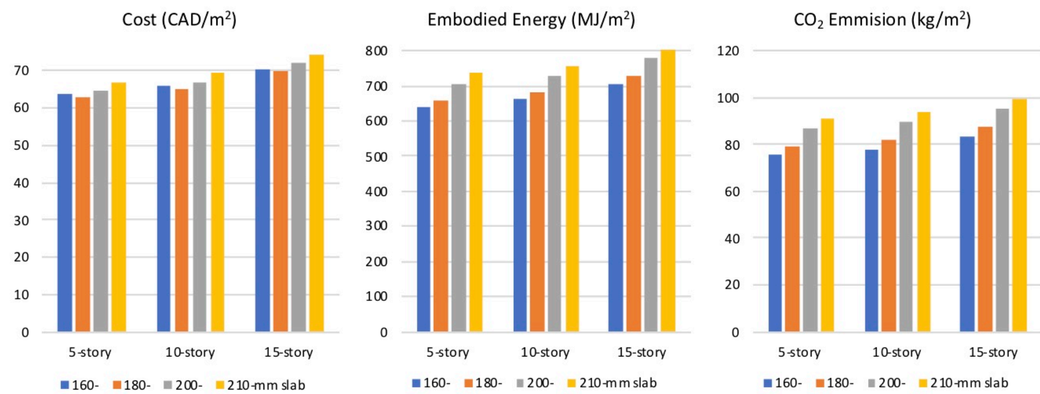


Figure 6: Cost, embodied energy, and CO_2 emission per m^2 for different heights and slab thickness

10. The saving per m^2 of floor area in adopting-slab thickness of 160-, 180-, and 200-mm against 210 mm for cost, embodied energy, and CO_2 emission is shown in Figure 7. The cost saving is the highest for 180 mm slab-thickness. The difference in savings due to 160- and 180-mm slab-thickness is minimum for 15-storey building. Conversely, the savings in embodied energy and CO_2 emission is highest for 160 mm slab-thickness. The savings per m^2 due to 160 mm slab thickness are on average approximately CAD 3.6, 98 MJ and 15.7 kg-CO_2 for cost, embodied energy, and CO_2 emission respectively.

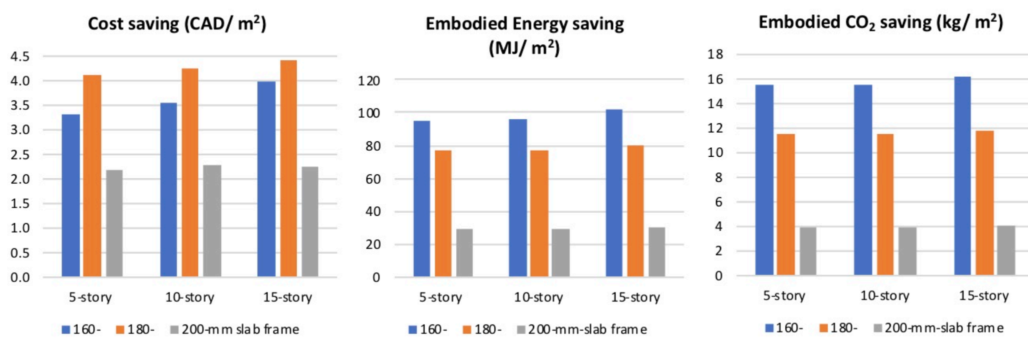


Figure 7: Saving per m^2 in cost, embodied energy, and CO_2 emission on 160-, 180- & 200-mm slab-thickness against 210 mm for different number of storeys

11. Table 2 summarizes the percentage saving in cost, embodied energy, and CO_2 emission for adopting 160-, 180-, and 200-mm slab-thickness against 210-mm. It also includes proposed carbon tax of CAD 20 per ton-CO_2 to be effective from January 1, 2019 in the calculation of the cost saving (Carbon tax plan 2018). From the table, the most favorable maximum column steel ratio for cost optimization is higher for taller buildings. For a 5-storey building, this ratio is approximately 3% on average, while for a 15-storey building, it is 4.4% on average.

12. From Table 2, in the case of the 5-storey building, saving of 5.0%, 12.4%, and 16.1% for cost, embodied energy, and CO_2 emission respectively, can be achieved by using 160 mm slab-thickness instead of 210 mm. The corresponding savings for 180 mm slab-thickness are 6.2%, 9.8%, and 11.7% respectively. The average savings on 160 mm slab-thickness are 5.0%, 12.5%, and 16.3% for cost, embodied energy, and CO_2 emission respectively. The corresponding average values for 180 mm slab-thickness are 6.0%, 9.9%, and 11.9% respectively.

13. On average, sacrificing a saving of just 1.0% in cost, gains in savings of 2.6% and 4.4% in embodied energy and CO_2 emission respectively can be achieved if 160 mm slab-thickness is used instead of 180 mm, making the former thickness a better alternative on an overall optimization for all three variables.

Table 2: The percentage saving for the buildings with 160-, 180-, and 200-mm slabs with respect to one with 210-mm slabs and corresponding maximum column steel ratio

160-, 180- & 200-mm slab frame			% save against 210 mm slab frame			
No. of storey	slab thickness (mm)	Max. column Steel %	Cost	Cost C-tax included	Embodied energy	CO_2 emission
5	160	2.7	5.02	5.32	12.4	16.1
	180	2.7	6.17	6.31	9.8	11.7
	200	3.5	3.22	3.23	3.6	3.8
10	160	4.1	4.82	5.13	12.6	16.5
	180	4.1	5.85	6.02	10.1	12.2
	200	3.6	3.02	3.05	3.8	4.1
15	160	4.4	5.30	5.59	12.6	16.3
	180	4.4	5.85	6.01	9.9	11.9
	200	4.4	2.93	2.96	3.66	4.03

4 CONCLUSION

As a part of the optimization process, the objective functions for cost, embodied energy, and CO_2 emission were developed. Using these functions, the favorable overall and maximum column steel ratios were identified for the objective variables. An optimum slab thickness for different number of storeys was obtained. Unlike conventional design, in which structural elements are proportioned for cost minimization, this study performed an optimization also on two other variables, embodied energy and CO_2 emission, for an entire building structure excluding the shear walls. The steel ratio of ground floor was varied in a step-by-step-progressive process changing the maximum steel ratio from about 2% to 5%. Four different flat-plate slab thicknesses of 160-, 180-, 200-, and 210-mm (with first three below code specified thickness) were chosen. The condition to use these thicknesses was met by checking the maximum deflection, which was found below the allowable limit specified by the Code. Stud shear reinforcement for punching shear is to be provided for shear strength deficiency due to thickness reduction. Also, drop panels are needed at the corner columns.

For a 15-storey residential building with a plan-area of 960 m^2 in the Montreal city, the saving in the cost, embodied energy, and CO_2 emission of CAD 58000, 1470 GJ (Giga-Joule), and 235 ton-CO_2 respectively, can be achieved by adopting 160 mm flat-plate thickness instead of the Code-specified minimum plate thickness of 210 mm. The columns and slabs of both buildings are assumed to be optimized for the given slab thickness. Taking the average household electric consumption in Canada in 2014, which was 7th highest in the world (WEC 2016), the saving of 1470 GJ in embodied energy is equal to the energy consumption of 36 households in one year.

A slab thickness below code specified minimum should be encouraged for design optimization, provided it passes the allowable deflection limit specified by the Code. Moreover, since a thinner slab section requires heavier reinforcement, a careful consideration should be given on the steel congestion. Too closely spaced rebars increase labor cost and may affect the quality of concrete casting. In order to converge towards the optimum solution with a wholistic consideration of cost, embodied energy, and CO_2 emission, from the design analysis, a maximum steel ratio for ground floor columns is advised approximately as 3% for buildings with number of storeys up to 5, correspondingly 4.5% for buildings with number of storeys 15 or higher, and an intermediate maximum steel ratio for buildings with intermediate number of storeys.

The findings of the study should not be conceived as general because scenario may significantly vary depending on location, framing system, shear walls, material costs, building occupation-types, etc.

A further study on a moment resisting building frame is recommended. The inclusion of shear walls in optimization is recommended. Floor system consisting prestressed hollow core slabs can be studied for optimization technique. Such floors will allow storage of heat and night cooling in buildings and contribute to saving in operational energy in addition to reducing the volume of concrete used.

Acknowledgement

The support of the IC-IMPTCS Research Network is gratefully acknowledged.

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