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Improving the Environmental Compatibility of Three Common Structural Systems Used in Canada

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Abstract

Many factors contributing to the impact of new and existing structures on the environment are a direct or indirect result of the consumption of energy for building, operating, maintaining and disposing of these structures. The impact, however, is not limited to factors tied to energy consumption only, other factors, such as emissions, site impact, noise and light pollution etc., are also involved.

In the paper three structural systems widely used in Canada are briefly characterized. The three systems are:

> *System A:* Typically used for low-rise residential and commercial buildings one to two storeys high; main structural framing consists of wood or metal studs.
>
> *System B:* Usually employed for high-rise structures used as residential apartment or office buildings; main structural farming made from reinforced concrete.
>
> *System C:* Common structural system for single to two storey industrial, commercial and office structures; main load bearing system is constructed using structural steel framing.

Some possibilities of improving the environmental compatibility of these systems is discussed. The focus is on using advantages of the hexagonal shapes and patterns to achieve these improvements, mainly by better utilization of materials and more effective layout of the structures.

Keywords: Environmental compatibility, embodied energy, primary and secondary structure, hexagonal coverings.

1. Introduction

Canada's northern climate with its extreme seasonal variations in temperature creates a need for a large enough supply of inside spaces which can be conditioned to create a more hospitable environment than the one found outside. Buildings generally serve this purpose as they create an enclosed environment. Some studies show that Canadians spend about

90% of their time in buildings. During this time their productivity and quality of life are affected by this enclosed environment.

Buildings also represent a large component of the country's capital wealth. There are currently about 12.5 million residential homes and around 500,000 commercial and institutional buildings in Canada. Operating and maintaining these buildings as well as the production of new ones requires a significant amount of resources and energy. One estimate suggests that buildings in Canada account for:

1/3 of Canada's energy production

50% of the extracted natural resources in Canada

25% of landfill waste in Canada

10% of airborne particulates in Canada

35% of greenhouse gases.

The above numbers will be much higher if transportation and industrial energy related to the production and movement of building products is included (Lucuik [1]).

It is clear that the operation of existing buildings as well as the activities associated with building new ones and maintaining the existing ones have a major negative impact on the environment. Lessening this impact by improving the environmental performance of the new and existing buildings and ensuring that our construction related activities are carried out in a way that minimizes their environmental impact is an important task towards achieving environmental compatibility.

2. Description of the Three Systems

In the Canadian construction industry three types of structural systems appear to be dominant, although these systems do appear in different variations. Their description with general characteristics is presented in the following:

2.1. System A

This structural system is typically used for low-rise residential and commercial buildings one to two storeys high, both with and without a basement. The residential houses can be in the form of detached (a stand-alone structure), semi detached (two dwellings in one structure divided by a partition wall) or row houses (several dwellings beside each other divided by partition walls in one structure), all usually with a full or partial basement. The basement walls, carried by concrete strip footings, are typically made from plain concrete or concrete block masonry. The walls of the above ground structure consist of wood or cold formed steel profile ("metal stud") framing and concrete block masonry, finished on the inside with gypsum board and on the outside with clay brick veneer or steel, aluminum, wood or vinyl siding. The roof structure usually consists of asphalt shingles on oriented strand board or plywood, supported by wood or metal stud framing or by pre manufactured wood trusses.

2.2. System B

This system is usually employed for high-rise structures used as residential apartment or office buildings. The load bearing system is typically a reinforced concrete structure consisting of two way slabs with drop panels and capitols, possibly combined with one way slabs, supported by columns and walls. The buildings usually have one or more levels of parking below grade. The below grade structure is also of reinforced concrete using similar systems as the above grade one.

The enclosure of the buildings is generally a combination of masonry (concrete block or clay brick), curtain walls, architectural concrete pre-cast panels or various Exterior Insulation and Finish Systems EIFS.

2.3. System C

The third described system is a common structural system for single to two storey industrial, commercial and office structures, such as storage warehouses, manufacturing plants, low rise office buildings, large retail stores, industrial units, strip malls etc..

The main load bearing system is constructed using structural steel framing. The roof structure is supported on corrugated galvanized steel deck, which is fastened to open web steel joists (OWSJ - light steel trusses). The OWSJs are typically supported by steel beams (hot rolled profiles), often utilizing the Gerber beam system for better material efficiency, with drop-in beams between cantilevered ends of beams from neighboring spans. The beams, in turn, are supported by steel columns, typically hollow structural tubes or I beams, resting on rectangular reinforced concrete piers and footings. Suspended floors are of similar construction as the roof, but with a heavier steel deck, which usually has a concrete slab reinforced with a steel wire mesh on top of it. The ground floor is, in most cases, concrete slab-on-grade (plain concrete sometimes reinforced with a steel wire mesh, polypropylene or steel fibers or steel reinforcement).

Typical enclosures are pre-cast composite planks with foam insulation, curtain wall, metal stud framing and/or concrete block masonry with clay brick veneer or EIFS.

3. Environmental Compatibility of the Three Systems from the Energy Point of View

In Figure 1 the embodied energy and the operating energy requirements of typical examples of the three structural systems described previously are compared. The values in Figure 1 have been compiled from various sources and represent only a rough comparison of the embodied and operating energies of the discussed systems (Trusty and Meil [2], [3]), (Vegh and Straube [4]).

Figure 1: Comparison of the Embodied and Operating Energies for the Three Systems

Building Type	Description	Gross Floor Area [m²]	Embodied Energy – Structure only [GJ/m²]	Operating Energy – Per Annum [GJ/m²]
A) Residential - low rise [2)]	Wood framing with concrete basement, brick veneer	223	1.14	1)
	Steel stud framing with concrete basement, brick veneer	223	1.74	1)
B) Office - high rise [2)]	Reinforced concrete two way slab, columns, one basement level, 13 above grade floors; Envelope - 40% brick, 60% curtain wall	21740	1.53 (1.58[1])	0.69 (0.31[1])
C) Industrial - low rise [3)]	33 x 66 m (bays 11 x 11m) single storey, structural steel framing, RC footings 100mm slab-on-grade floor, enclosure – pre-cast composite plank	2178	2.16	1.0

Note : **1)** Initial embodied energy for current residential structures has been estimated to be equivalent to 9 – 18 years worth of operating energy for Vancouver, BC climate and 7 – 13 years of operating energy for Toronto, Ontario climate [2].

2) Trust, Meil – ATHENA Project [2], [3]

3) Vegh, Straube 2001 [4]

The embodied energy of the main structural frame itself is quite often not as significant as the operational energy, especially when considered over many years of lifespan of the structure. Also just comparing different structural materials that make up the main structural frame will likely not yield always yield an optimal solution. In terms of embodied energy of the structure studies have been carried out that suggest that the embodied energy of wood framed low-rise buildings is less than of a steel or concrete alternative. However, while one material may require less energy to produce than the other, it is important to consider other aspects and requirements for the building such as function, durability, resistance to certain environments, local source of a particular material, aesthetics, features of the site etc..

4. Improving the Environmental Compatibility of the Three Systems

When comparing the three systems with respect to their environmental compatibility one has to keep in mind all the many different aspects that may influence this. Among the most important ones are:

a. The embodied energy of the structure, which can be further divided into the embodied energy of the Primary Structure and the embodied energy of the Secondary Structure and of the finishes (embodied energy of the furnishings of the buildings is not included).
b. Operating energy of the structure.
c. Demolition energy.
d. Efficient use of water in the structure and on the building site.
e. Proper choice and management of the building site during construction, use and demolition.
f. Use of renewable and local resources.
g. Minimizing emissions into the atmosphere during construction, use and demolition.
h. Minimizing noise and light pollution.
i. Optimizing the indoor air quality, eliminating indoor pollutants, using materials with low VOCs.

The improvement of the environmental compatibility for newly designed structures is a process in which the above aspects are addressed and procedures are planned initially within the design phase. The planned procedures are then implemented during construction, use, renovations and possibly even during the final demolition and disposal of the structure. For existing structures, however, selected aspects from the ones noted above are often addressed separately. They should at some point be also considered within the context of the whole structure and its surroundings.

4.1 Demolition and Reuse of Structural Members

In the authors own experience with demolitions, many structures are taken down long before the load bearing structural system is at or close to the end of its service life. It is also not unusual that structural members from these demolitions, that are still in good condition, are discarded rather that reused. Changing this practice would certainly help reduce the use of new materials and energy, as well as reduce construction waste. Following are some examples related to the three described systems with suggestions that could improve the environmental compatibility both for newly designed structures as well as for existing ones:

1. The main framing of the described system C typically consists of structural steel members. These members are usually connected using welded or bolted connections hence they can relatively easily disassembled, when the structure is being taken down. This, however, is often not the case. Although the steel is typically separated and partly or fully recycled, the individual steel members are cut or otherwise damaged during this process. A lot of energy is being used to remove and recycle the steel. It would seem that it would be easier to take more care in the removal process and reuse the members directly, where possible. The problem with the "direct reusing" of the steel is, however, not only in the dismantling process. From the designer's perspective it is much easier, and from a liability point of view safer, to use new products as their quality, size tolerances, strength, etc. are guaranteed by other parties. This implies that the reasons the used members are not being directly reused are, in the most part, not engineering reasons but liability (i.e. non engineering) problems. To circumvent this, new procedures for certification of used steel members together with updated Code provisions would have to be developed.
2. Similar issue as described above but for wood members potentially exists for the described System A. During demolition of these types of structures the wood framing is typically pulled down together with the rest of the structure and then buried in a landfill. Cost, time required for the demolition, condition of the demolished members and liability are the main reasons for the structural members not being reused. As noted above new procedures for certification of used structural parts together with updated Code provisions would have to be developed to help their reuse.
3. During partial demolition, which typically takes place when a structure is being renovated, portions of a structure that are to be replaced or modified are removed. It is often the case that during this process structural parts that are far from reaching the end of their service life are removed and discarded together with other deteriorated or damaged parts. This is true for all three of the described systems, but mostly for systems A and C. The reasons will vary from structure to structure, but quite often it is more practical to remove a whole section of a structure, in which the individual parts are connected together, rather than separating them. In certain cases it is not practically possible to separate individual members without damaging them. To address this problem we have to start with the design of the new structure. By separating the structure at the design stage into Primary and Secondary Structure, where the Secondary Structure is the part of the structure which will be renovated (replaced) during the service life of the structure, we can focus on making the Secondary Structure, or at least the sections that need to be replaced together, from components of similar life spans. In this way whole sections of a structure that will be replaced during a renovation

will have served, more or less, their useful service life. The concept of Primary and Secondary Structure is described in more detail in (Vegh *et. al.* [5]).

4.2 Reduction of Embodied Energy Using Hexagonal Disjoint Coverings

Hexagonal disjoint coverings can be successfully used in the design of structural systems that are environmentally compatible from the point of view of material and energy. This is described in more detail in (Vegh *et. al.* [5]), (Vegh L. and Vegh P. [6], [7]).

Consider an infinite slab-column system that can be used for single or multistory buildings. The columns supporting the slabs are located in the mid point of theoretical regular polygons. To satisfy the condition of disjoint covering of the infinite slab, three alternative numbers of sides are considered: n = 3, 4 and 6. The polygons are equal in area and in-plane shape.

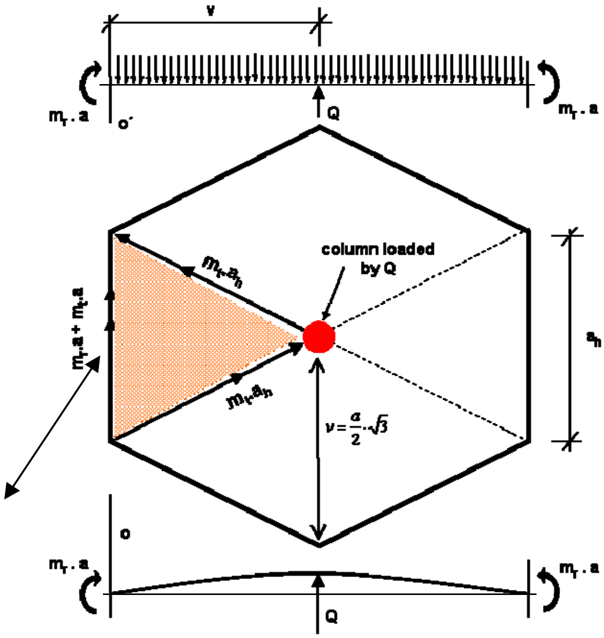

Figure 2: Hexagonal section of the slab-column system shown in Figure 3

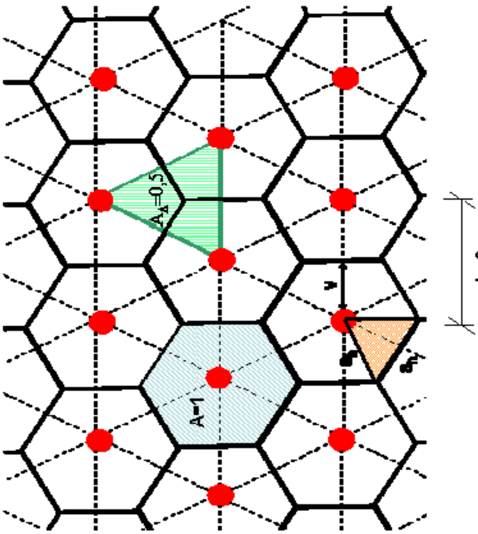

Figure 3: A slab-column system with theoretical hexagonal patterns. $\mathbf{l_h}$ is the column span; **A** is the area of the hexagon; **Q** is the load carried by each column; $\mathbf{Q_{limit}}$ is the ultimate load carrying capacity of each column; $\mathbf{m_r}$ is the radial ultimate moment; $\mathbf{m_t}$ is the transversal ultimate moment.

The slab is uniformly loaded and the column spans (l) are constant for each "*n*". The enclosed area of all the polygons is equal to unity (*A* = 1).The analysis of the three alternatives, is based on the yield-line theory. Figure 3 represents the optimized system with columns located in the mid-point of the theoretical hexagonal polygons (*n*=6).

The moment equilibrium condition to axis o – o´:

$$\left(\frac{Q}{6}\cdot v - \frac{Q}{6}\frac{v}{3}\right) = \frac{Q}{18}\cdot a_h \cdot \sqrt{3} = (m_r + m_t)\cdot a_h$$

$$Q_{limit} = (m_r + m_t)\frac{18}{\sqrt{3}} = (m_r + m_t)\cdot 10{,}3923 \tag{1}$$

$$Perimeter = 6 \cdot a_h$$

A comparison of the results of the analysis for the three alternative *n*: (n = 3, 4 and 6) is in Figure 4. The analysis clearly demonstrates that the hexagonal system results in minimum material consumption and maximum column span.

Figure 4: Comparison of the three alternatives.

Structural system	**triangular**	**square**	**hexagonal**
Perimeter	4.5588 (+ 14%)	4.0 (±0%)	3.7224 (- 7%)
A	1	1	1
Span l	0.8774	1.0	1.0746
Span %	- 12.3%	± 0%	+ 7.5%
Number of columns	same	same	same
Covering	disjoint	disjoint	disjoint
Wall system length	+ 14%	± 0%	- 7%
Boundary	straight	straight	zig-zag
Load bearing capacity limit of columns	15.5574 (- 29.58%)	12.0 (± 0%)	10.3923 (+ 13.33%)

The above results can be used to optimize material consumption for the primary load bearing structure for the above described System B.

5. Concluding Remarks

There are many different aspects that may influence the environmental compatibility of the described three structural systems. By focusing on some of them a few suggestions have been presented that may enhance the system's environmental compatibility.

One possibility is through the development of new Code provisions and new procedures for certification of used structural members, together with improvement of the demolition process of existing structures, both during the selective demolition when renovating and also during the final demolition stage.

Another possibility that is described is by utilizing the advantages of hexagonal coverings for the layout of the columns in the slab-column systems that are part of the described system B. This arrangement will result in material and energy savings.

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