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How sustainable are our typical structural shapes and materials?

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Abstract

Designing and building structures that minimize their impact on the environment is an important requirement facing today's architects, engineers, builders and the construction industry in general. Numerous factors can contribute to the impact of a structures on the environment. Many of these factors are a direct or indirect result of the structure's energy consumption. Although limiting energy consumption is not the only factor, it is currently viewed as one of the most important ones.

The outside shape of a building, how it is constructed, together with the main structural material(s) that are chosen, can have a significant impact on the amount of energy that is needed to build it, operate it and, eventually, demolish, recycle or dispose of what is left.

The paper discusses, mostly from the energy consumption point of view, some aspects of how structural shapes and materials can determine the environmental performance of a building. The aim of the paper is not to give an exact research-based account of specific shapes and materials from their environmental performance point of view, but rather to offer some selected comments and ideas on this subject mostly from a practicing engineer's perspective. The paper also presents some comments on how the environmental performance of a structure can be improved through the choice of certain shapes and materials.

Examples of the common construction systems used in Canada today are also explored from their environmental performance point of view to determine how they have evolved in this respect since early 1990.

Keywords: Embodied Energy, Operational Energy, Environmental Impact, Primary and Secondary Structures

1. Energy consumption of a structure over its lifespan

Minimizing the environmental impact of new and existing buildings is a challenge for everyone involved in today's building industry. Over their lifecycle buildings consume energy, directly or indirectly, in various forms. It includes energy required not only for operating of a building, but also all the energy associated with its production, preparation and handling of the construction materials, the actual erection of the structure, its maintenance, repairs and renovations, and finally with its demolition and recycling of the construction waste.

The energy required for the production of materials or building components is referred to as embodied energy and is usually given per unit weight of the particular material or building component. It can also be measured in the equivalency of carbon released per kilogram of the building product or material ($kgCO_2e/m^3$). By summing up the energy required for all the materials within the building structure together with the energy required for the erection of the building, we obtain the embodied energy of the whole building, meaning the energy required to "produce" the whole building. Starting with the embodied energy E_E which is required to "produce" it, the building then begins to consume operational energy O_{E}.. Over its lifecycle the building is likely to undergo some renovations, which will require energy (for partial demolitions, new building components, new finishes etc.) and thus will increase the embodied energy of the building. However, assuming that the renovation is carried out in an environmentally responsible manner, it is reasonable to expect that the operational energy consumption (per unit time period) after the renovation will be lower than prior to the renovation. At the end of the lifecycle the building again requires demolition energy D_E for its demolition and the disposal and recycling of the construction waste. Figure 1 schematically illustrates the energy consumption of a structure over its lifespan.

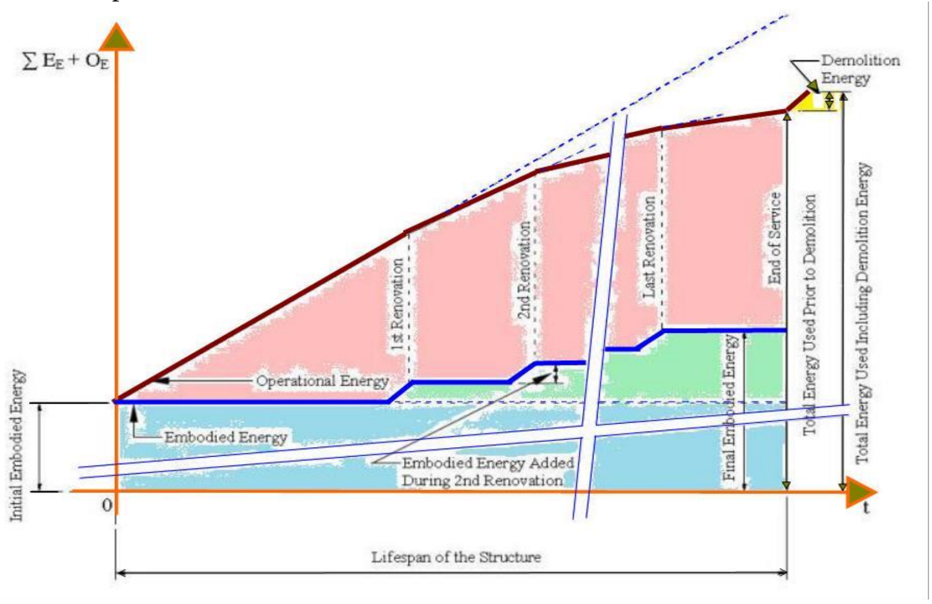

Figure 1: Energy consumption of a structure over its lifespan.
E_e = Embodied energy; O_e = Operational energy

For a typical building with a lifespan of several decades the operational energy component $\sum O_E$ of the overall energy consumption is usually substantially larger than the embodied and demolition energy component ($\sum E_E + \sum D_E$). This is because the operational energy component adds up over the many years of the structure's lifespan, while the embodied and the demolition component stays more or less constant with the exception of the changes to it that occur during renovations. If, however, the building's lifespan is somehow shortened the embodied and the demolition component becomes much more significant as it is not spread out over as many years (P.Vegh [1]).

2. Structural shapes and materials

2.1. Choice of structural shapes and its impact

Many structural shapes that are used today have been around since before the time when we became aware of the significant negative impact that buildings and the construction industry in general have on our environment. The common shapes are generally those that can be easily defined with Euclidian geometry and the Cartesian coordinate system for ease of structural analysis, design and construction, among other things. As the analysis, together with the building production and structural part fabrication methods, evolved, it became possible to design and construct non-standard shapes, components with various curvatures etc. Figure 2 shows a building with typical "rectangular prism shape" (left photo) and the use of curved and irregular façade shapes (middle and right photo) on two other buildings.

In the initial stages of designing a building one of the first things that are typically defined (besides its required purpose and function) are its overall outside shape and the material(s) for the main load bearing structure. The choice of both may often be limited by numerous parameters, such as the purpose and function for which the building is being designed, the size and shape of the parcel of land on which it is being built, the availability of materials, budget, etc. The shape is important in many ways, as it defines the building footprint, its inside volume, it forms the basis of its aesthetic appearance, the shape has a major impact on the lateral stiffness of the structure, etc. The final choice of the shape and materials can affect the energy consumption of structural components as well as of the building as-a-whole.

Figure 2: Building shapes (office building – left photo, condominiums – middle and right photo), Greater Toronto Area – Canada

Unfortunately, when the overall shape is chosen, it is often without enough consideration being given to the resulting environmental performance of the building. Available space and shape of the parcel of land on which the structure is to be built, required purpose and function of the building and aesthetics often dominate, if not being the only factors, leading to the initial shape choice. For buildings today, various levels of effort go into making their performance as energy efficient as possible, mostly through improving and optimizing the performance of their building envelope and of their mechanical systems. These efforts, however, may be at times limited by the already chosen shape(s).

The choice of the building shape may influence numerous aspects of the building's performance over its lifespan. This is true not only for the outside overall shape (the shape of the building envelope), but also for the shapes of individual parts and components of the structure.

2.2. Inspiration by nature

The inspiration for the choice of a shape can come from a variety of sources. One area that can be looked to for efficient optimized shapes are natural structures. By observing nature and its formations, both in the living and the non-living worlds, it is possible to find a vast number of various shapes, patterns, etc., which have certain optimized characteristics, that may be suitable for use in engineering structures.

All of nature's shapes and patterns appear to have a specific function and be efficient for this function. They are typically optimized for the conditions under which they are meant to perform, therefore, their use in engineering may bring several advantages. For example, numerous natural shapes are formed to use mainly tension or compression members for transferring loads in their load paths. For shapes loaded predominantly by gravity induced loading, large bending stresses are not too common.

Nature optimizes its shapes and structures also when it comes to the amount of material that is used for specific parts and components. Many natural shapes and patterns are governed by the "principle of minimum of potential energy" which ultimately leads to minimizing material use (more in L.Vegh, P. Vegh et.al. [2]).

2.3. Some parameters influenced by shape choice

Some more notable parameters which may be influenced by a particular choice of shape are outlined and briefly discussed below. It should be noted that designing a shape while trying to satisfy multiple parameters is not a simple task and may often require multiparametric optimization with competing requirements.

2.3.1. Stiffness, rigidity and material consumption

If the chosen shape (of the whole building or of a partial components) is stiff against the effects of certain loads, the structure is better at resisting these loads thanks to the shape and not just through the strength of the materials used. This way the shape may be optimized for certain governing load directions and effects. This leads to a more economical structure from a material use point of view.

2.3.2. Shape optimization and protection against the outside elements

The outside shape of a building is formed by the building envelope which provides the protection of the inhabitants inside the building from the outside environment. Although the "efficiency" of this separation is mostly influenced by the materials used and by the quality and precision of their assembly, the shape can also have its role. The overall shape as well as shapes of certain parts of the structure can be designed and optimized for a specific function. These may include, for example, efficient transfer of particular loads, minimizing the effects of wind load, accelerated shedding of water and snow, collecting maximum amount of water or sunlight, providing protection from certain elements and their effects (rain, snow, wind, sun etc.) and shading parts of the façade and the surrounding area of the building, etc. The shape can also be made partially adaptable to selected effects through the use of sensors connected to movable parts, which can react (change shape) to selected conditions.

2.3.3. Using the shape for generating alternative energy

The building shape can also be used for generating alternative energy from the effects of the outside elements, such as solar, wind and temperature, by combining suitable sensors, solar panels, small wind turbines etc., with the building shape, that would be optimized for this purpose. The shape can be made partially adaptable to the selected effects as already mentioned in *2.3.2.* above.

2.3.4. Enhancing the sustainability of future renovations

The environmental performance of a structure can be improved if its lifespan is extended beyond the normal duration. The consequence of this is that material, energy and potentially construction waste are being saved because no old structure needs to be demolished and no new structure needs to be created. Even if the "replacement of the structure" is delayed, it means that the embodied energy of the original structure is spread out over more time resulting in its "per year embodied energy consumption" being lower. This is of course true for any part of the structure.

The idea is to implement the principle of Primary (P) and Secondary (S) structure (more in P.Vegh [1]). By "primary structure" we understand the basic fundamental system of parts, which form the main load bearing system, that typically does not change over the lifetime of the structure. "Secondary structure" (e.g. non load bearing partitions, parts of the building envelope, finishes etc.), on the other hand, may be rehabilitated and changed several times over the lifetime of the structure. The main idea is that certain parts, that are at the end of their lifespan, can be replaced, without damaging adjacent parts that can still last longer. If the shape and the way it is assembled allow for this, the effectiveness of future renovations will be enhanced.

During a renovation, the minimum of (S) should be replaced while at the same time achieving the greatest possible increase in energy efficiency for the operation of the building. The overall goal should be that the operational energy of the updated structure will be lower than before the renovations and rehabilitations and that any increase in embodied energy as a result of a renovation or rehabilitation will be, as a minimum, balanced by the savings in operational energy achieved before the next renovation or rehabilitation is required.

2.4. Structural materials

Shapes and materials exist together as one creates the other and, like shapes, most materials used in today's construction have been around for a long time. Since the construction industry became aware of its environmental impact, it has started to categorize materials based on their embodied energy and embodied carbon as well as based on other properties that may have an impact on the environment.

Although minimizing the use of high embodied energy (or carbon) materials leads to more sustainable structures, one very important factor, as we already mentioned in *2.3.4.*, is that a construction material needs to be durable so that structural parts made from this material, last as long as possible. Materials will not typically degrade or deteriorate on their own. This happens when we place them without adequate protection in an environment or conditions in which they deteriorate and ultimately fail. It can be said that most common structural materials can be reasonably considered "sustainable," if they are used in environments or conditions that are not detrimental to them so they can last long enough.

A choice of a shape will to some degree dictate which material can be used. With the above in mind, it is advisable to consider the material we want to use when selecting the shape itself. It is not only the optimum amount of material to be used but also things such as the optimum type of material, resistance of the material to expected conditions, its internal structure, properties etc., that may be important. Again, the ultimate goal is to achieve proper durability of the structure.

2.4.1. Desirable properties for future structural materials

Looking into the future for possible new materials, there are some properties that would certainly be useful to have for new structures. Research has been done on "intelligent materials" that are able to detect and communicate their deterioration and flaws or can even perform self-healing of certain damages on their own etc. One interesting property which is observed on living structures is their ability to "self-dimension" themselves in the process of their growth (growth of bones, tree limbs, etc.). During this process material is added where it is needed (areas of high stress) and, at the same time, taken away from where it is not required (areas of low or no stress). This ability would be very useful, provided it can be successfully replicated for engineering structures.

2.5. Minimizing energy through structural durability and reuse.

The lifecycle of a structure typically ends with a demolition, together with disposal and recycling of the construction waste. In the author's own experience with demolitions, many structures are demolished 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.

Developing shapes that can be easily reused, can be easily adapted for new functions or are easy to disassemble with minimal energy and material waste, could help the above problem. Structures could then be reused and refurbished with new "secondary parts", or, at worst, the demolition would become a simple disassembly with minimal waste, where the disassembled parts could be reused elsewhere.

A renovation or rehabilitation typically extends the lifecycle of an existing structure. With the use of modern materials and technologies it is possible to produce new structural components with reduced embodied energy. We can assume, that the trend of producing more energy efficient structural parts, both in terms of their embodied energy as well as in terms of their performance, will continue in the future. That means that more efficient structural components and materials should be available for future renovations and rehabilitations which could further enhance the environmental performance of structures provided that their lifespan is extended for long enough.

3. Common structural systems used in Canada today

In the Canadian construction industry three types of structural systems appear to be dominant. They do, however, appear in different variations. All of them predominantly make use of common "rectangular" structural shapes and materials that have been around for a long time, although some innovations, both in shape and in materials, are being tried. The description of the systems with general characteristics and with a focus on their environmental performance is presented in the following (more in P. Vegh [3], P. Vegh [4]).

3.1. System A – low rise wood or metal stud framing structure

This structural system is typically used for low-rise residential and commercial buildings one to two storeys high, both with and without a basement or an underground garage in case of row housing. 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 wall framing of the above ground structure consists of wood or cold formed steel profile ("metal stud") framing, sometimes referred to as "stick 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. Figure 3 shows typical wood construction of row housing as well as some wall framing.

Figure 3: System A - typical row housing structure constructed using wood framing with an underground reinforced concrete basement/garage.

3.2. System B – high rise reinforced concrete frame structure

This system is usually employed for high-rise structures used as residential multi-unit apartment buildings, office buildings and for commercial use. 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. Foundations are dependent on soil conditions with spread footings, caissons and raft slab foundations being quite common.

Figure 4: Two typical high-rise multi-unit residential buildings constructed using structural system B. Façades are a combination of Window Wall with precast concrete panels.

The enclosure of the buildings is generally a combination of masonry (concrete block or clay brick), curtain wall and window wall mostly with spandrel panels, various combinations of special glazing systems and structural glass facades, architectural concrete pre-cast panels, stone cladding panels or various Exterior Insulation and Finish Systems (EIFS).

3.3. System C – low rise structural steel framing structure

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-profiles, resting on rectangular or circular reinforced concrete piers and footings. Suspended floors are of similar construction as the roof, but with a heavier steel deck, which usually forms a composite structure with 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). In most cases these structures do not have a basement.

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.

Figure 5: Typical building structure being constructed using System C and a finished building.

3.4. Some comments on the environmental performance of systems A, B and C.

For all three systems 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 always yield an optimal solution. In terms of embodied energy of the structure, for example, 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.

In the following a discussion of some typical construction and design practices, use and the resulting environmental performance of the three descried systems is presented. Mainly the positive developments since the 1990s, if any, are considered.

3.4.1 System A

The main load bearing structure of this system and especially its basic features have not changed much since the 1990s. The shape of the structures is mostly determined by lot shape and size and by function requirements. The main change would be the increase in the use of recycled and scrap wood products as well as cold formed steel studs and some composite material products. The bigger change, which is not in the main structural system but contributes more to better environmental performance, is in the use of better secondary structural as well as non-structural components and finishes. Features such as better insulation of the buildings, better protection from water and other elements, more durable and environment resistant materials, more efficient mechanical and electrical systems, a selection of water and power saving features, finishes with less VOCs, etc. can be named among others. To a certain degree better attention to detail and increased scrutiny of the overall construction process is resulting in the production of better and more efficient buildings using this type of system.

3.4.2 System B

The basis of this system has also not changed much since the 1990s, however, there are some newer features which make it better in certain aspects as far as environmental performance is concerned. For new buildings - new software, better computing power, innovative optimization techniques, new manufacturing and fabrication machines as well as new procedures and installation techniques have made it possible to efficiently manufacture and assemble structural and façade components that make up more efficient shapes on the actual buildings. Although the shapes are driven more by aesthetics and function requirements, some enclosure shapes may undergo optimization for a variety of conditions. High rise buildings utilize curtain wall and window wall extensively for their facades, both of which have been undergoing improvements which has made their performance in energy efficiency, water tightness as well as longevity significantly better.

Use of high strength concrete and higher strength reinforcing and structural steel result in a reduced material mass and consequently into a reduction of dead load. A variety of other construction and finishing materials have also been modified and developed to be more efficient. All these factors have a positive effect on the environmental performance of this type of building structure.

Repair of high-rise buildings, especially if it has to be carried out from the outside, is difficult, costly and often can be very energy intensive. Over the last one to two decades use of materials and structural components with better durability as well as increased scrutiny and proof testing during installation, especially in the case of building enclosures, have resulted into a better final product which should require less frequent repairs in the future, saving material resources and energy. As such, this contributes to the enhancement of the environmental performance of these structures.

Based on the above, it can be said that the high-rise buildings being built or repaired using the described system today are in numerous aspects more environmentally efficient than they were in the 1990s.

3.4.3 System C

This system is typically used for utility and production type buildings, it is quite basic and the cost of construction, operation and maintenance is paramount. The main structural system has therefore been optimized quite extensively in the past in terms of material consumption and it has not changed much since the 1990s. Shapes of buildings using this system are predominantly driven by function.

It is quite easily constructed and deconstructed which enhances possibilities for recycling of the structural steel which typically forms the majority of the above ground structural frame. It is the recycling of steel which has been getting more common during demolitions of these types of buildings. From the point of view of generating construction waste during demolition, this system typically performs the best out of the three systems as a lot of the structure is actually recycled. The use of higher strength structural steel is also helping decrease the material mass and, consequently, the self-weight of these structures.

More efficient mechanical and electrical systems have been helping in the reduction of the operating energy of these buildings. Further, these types of buildings are typically covered by large flat roofs which are increasingly being used for the installation of solar panels. The resulting generated power is either used for the building itself or is being fed back into the power grid. This again helps in reducing the overall energy consumption of the buildings.

The above-described features are helping enhance the environmental performance of the structures that are built using this system today, as compared to the ones built in the 1990s or before.

4. Concluding remarks

There are many different aspects that may influence the environmental performance of structural systems and buildings in general. In the paper some comments on today's shapes and materials were presented together with a few ideas that may, if implemented, help improve the environmental performance of structures. The ideas are related to optimizing structural shapes so that they are used not only for the aesthetical appearance of the buildings, but can also play an active role in conserving energy etc. Considering and optimizing the shape and materials to be used for a structure early in the design stage can have a positive impact on the resulting structure in terms of its environmental efficiency.

In general, making structures and materials last longer, without premature failures and demolitions and refurbishing and reusing existing structures and extending their service life is one of the best ways to conserve their embodied energy by using it over an extended period of time.

Three structural systems that are commonly being used in today's Canadian construction industry and that mostly use common materials and typical "rectangular" shapes were described and some comments were presented on how their environmental performance has changed since the 1990s.

Although the main structures of these systems have not changed much since the 1990s, the environmental performance of structures using these systems has improved to some degree for all three systems. This improvement has been driven, among other, mostly by more efficient mechanical and electrical systems, by better performing building envelopes, by new techniques and materials with enhanced properties, and also, by increased scrutiny, review and testing during manufacturing and installation of various structural parts and components.

Further implementation of at least some of the ideas presented in Sections 1. and 2. of this paper could likely improve their environmental performance even further.

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