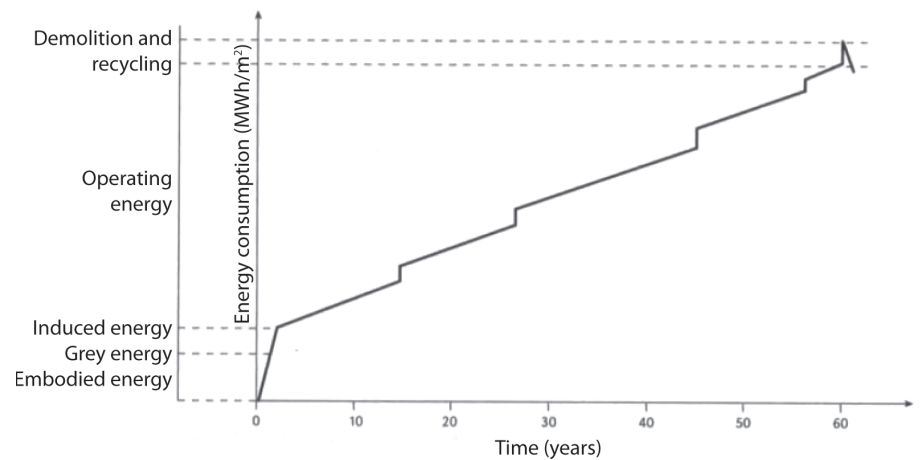


Sustainability of Structural Materials and Systems

Alexer Taganas

Instructor

Werner Lang



Sustainability of Structural Materials and Systems

Alexer Taganas

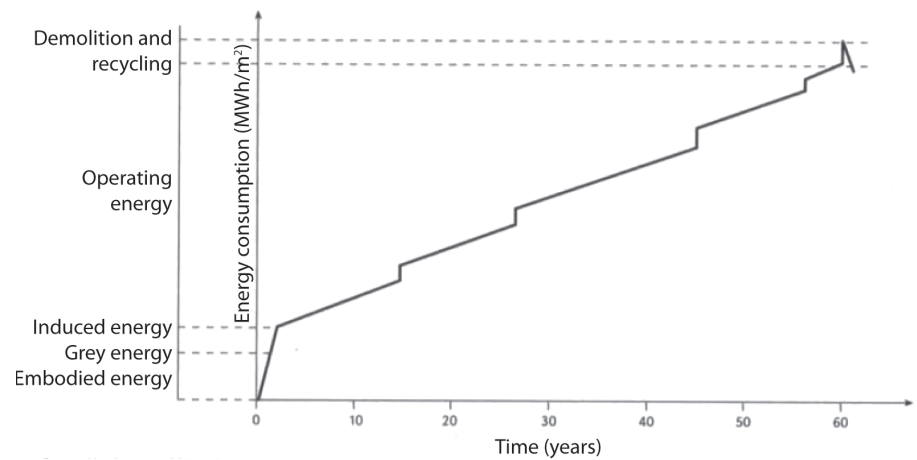


Fig. 01 Energy consumed in the life of a building

Introduction

In the course of a building's life span, the majority of energy consumption is during its operational phase. Lighting, heating and cooling the interior spaces of a building require huge sums of energy which are traditionally supplied through the burning of fossil fuels. Therefore, sustainable attributes of buildings have primarily focused on advances in envelope efficiencies and mechanical systems that minimize heating and cooling loads. Energy consumption, however, begins before the first user walks through the entry door. Notice must also be made to energies during the initial construction phase of a building since the rate of consumption at this time is paramount to those during operation (see Figure 01).

A significant portion of construction energy is embodied in the material of structural elements through avenues of extraction, processing ('embodied energy') and transport ('grey energy') of materials from source to the construction site where these elements are then assembled ('induced energy'). The construction industry accounts for nearly half of the world's

resource usage and up to 40% of its energy consumption.¹ In typical buildings, these elements represent roughly 20% of the total construction cost but nearly 80% of the building's mass. The structural design engineer, if aware of the embodied energy and other environmental impacts associated with different materials, is in a position to make a significant contribution to reducing the overall environmental impact of a building.

This section discusses environmental impacts and sustainable qualities of the three most prevalent materials in current construction – wood, concrete and steel – as well as benefits associated with their service as a building's structural system. Following this is a case study that compares the environmental impacts and benefits of two systems (pre-cast concrete frame and steel frame) using the Athena Institute's EcoCalculator for Assemblies.²

Wood

Of all building materials, wood is incomparable in regards to its

Material	Embodied energy (GJ/m ³)	Environmental impacts		
		GWP (kg/m ³)	AP (kg/m ³)	POCP (kg/m ³)
Aluminium	497	29 975.4	162	321.3
Bricks	5.4	342	3.6	30.6
Ceramic tiles	16	1142	8	102
Concrete	4.8	156	2.4	0.72
Glass	19.2	1365.6	96	4.8
Plaster board	4.5	238.5	2.7	1.8
Roof tiles	2.2	288.2	2.2	2.2
PVC	116	1932	17.9	0.69
Steel	200	17 840	80	6720
Wood	1.65	63.8	0.55	0.55

GWP, global warming potential; AP, acidification potential; POCP, photochemical ozone creation potential; PVC, polyvinyl chloride.

Fig. 02 Energy and environmental performance of timber compared with other common construction materials



Fig. 03 Timber frame construction

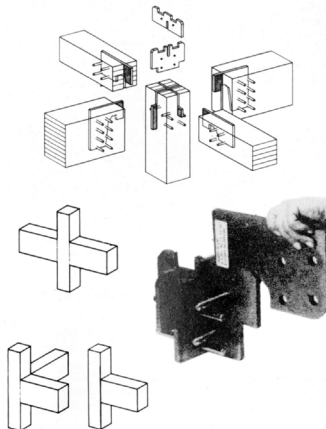


Fig. 04 Metal demountable timber joints



Fig. 05 Glulam construction

sustainability and environmental performance (see Figure 02). Wood is widely available and abundant; and through responsible forestry practices, a plentiful and ecologically responsible supply of wood can be maintained. Because very little embodied energy is required to process the raw material (a tree) into a usable product, wood is considered more sustainable than other common construction materials.

The versatility of wood is evident in its capacity to be used throughout the structure. Wood is most commonly used as structural frame-

work in single-family, aboveground residential construction. Economy has pervaded this industry and it is common practice to use smaller, high-strength wooden elements in abundant repetition (see Figure 03). To maintain structural integrity, strong fixings are employed throughout the frame, which make it difficult to recycle elements as reused structural stock.

A limitation of wooden members is that generally, smaller elements are readily more available than larger ones. However, a multitude of timber jointing techniques have been devel-

oped and perfected. Wooden members can be joined or spliced with timber plugs, bolts, nails or glues. Sophisticated joinery techniques have the capacity to allow a relatively easy sequence of disassembly of a timber structure at the end of its intended life (see Figure 04). While lamination has afforded the construction of larger structures using timber members (sometimes exceeding the strength capacity of steel members) it is important to realize that the process of lamination requires a greater amount of energy than pure timber construction. The increased energy demand and impregnated limitation

to recycling options of laminated timber may be compensated by its longer service life and the propagation of timber being used more widely in larger and taller structures (see Figure 05).

Concrete

The near worldwide abundance and availability of raw materials used to make concrete has made it the most important and widely used building material. The industrialized world currently produces and consumes 1.5 – 3.0 tons of concrete per capita per year. The primary constituent of concrete is Portland cement where by the year 2020, its worldwide consumption is expected to increase by 30%.³ Aggregates account for 70-75% of a concrete structure's volume while reinforcing steel is fundamental in typical concrete construction.

The production of cement and the decarbonation of limestone into clinker is the most energy intensive factor in the manufacture of concrete. Thus, these processes are by far the largest contributors of a concrete product's CO₂ emission during its life cycle (see Figure 06). The process requires heating limestone and other raw materials to 1400 – 1450°C, primarily utilizing fossil fuels. Great advances have been made in the past several decades that have significantly reduced energy consumption by the cement industry. In 2006, alternative or waste fuels provided 9% of a cement plant's energy needs.⁴ A widely used method to reduce energy demand has been to substitute traditional clinkers with slag, fly ash and other by-products of industry, either in the cement or concrete manufacturing process. In

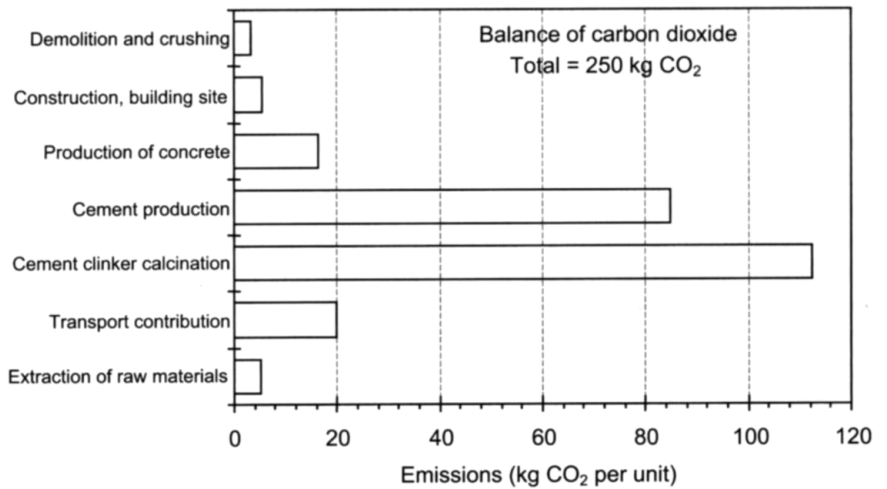


Fig. 06 CO₂ emissions from various phases in the life cycle of a concrete product

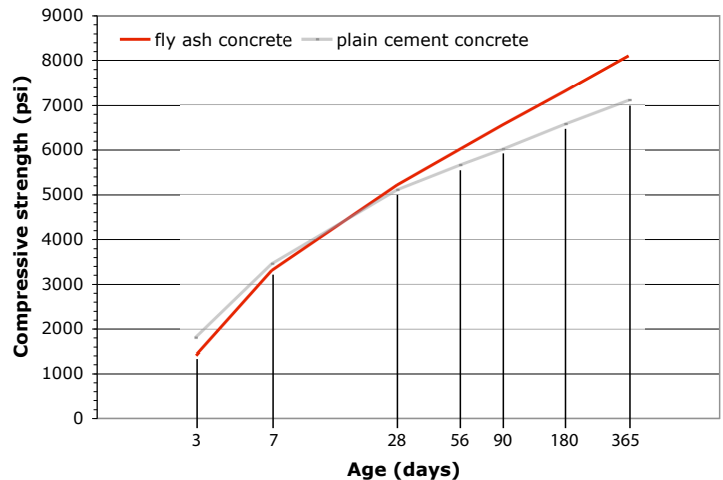


Fig. 07 Concrete performance increase using fly ash.

2007, cement production accounted for over 25% of total US industrial CO₂ emissions.⁵

The manufacture of concrete has and will continue to progress towards environmental soundness. However, for concrete structures to be considered sustainable, they should be designed and produced according to its specific use, i.e. expected lifetime, appropriate load cases, maintenance strategy, heating requirements, etc., utilizing inherent environmentally

beneficial characteristics of concrete in building design.

The strength of concrete is attributed to its exceptional capacity to resist compressive stresses. Conventional concrete has strengths of 7,000 psi or less while concrete that is considered high-strength is capable of compressive loads between 7,000 and 14,500 psi.⁶ Studies have found that the substitution of fly ash (a by-product of coal-fired electric generating plants) in up to 50% of pure cement

in a concrete mix will improve the technical performance of concrete. Besides improved workability and decreased permeability, the long-term strength of fly ash concrete is increased when compared to pure Portland cement concrete⁷ (see Figure 07). The use of fly ash and other clinker substitutes can decrease material flow and transportation energy into a construction site. Further, the concrete frame's design strength can be less due to the decreased weight of a concrete building.

Concrete construction, particularly insulating concrete forms (ICF) is gaining demand in the abovegrade, single-family residential market, boasting increased durability during calamitous weather conditions as well as energy savings associated with its high thermal mass. The thermal capacity of concrete ranks among the highest in building materials (see Figure 08). ICF construction in homes has been known to decrease energy costs from 30-90% (depending on the climate, orientation, concrete surface exposure, ventilation system, etc.) when compared to typical wood-frame homes.⁸ More sophisticated systems exploit concrete's thermal properties by actively storing heating and cooling energy through a distribution network of pipes imbedded throughout the concrete structure, reducing indoor thermal energy requirements to an ultimate minimum (see Figure 09).

Steel

Recycled since the Pre-Industrial age, metals may be the earliest building material that has made recycling an integral part of its industry. Steel and aluminum are the most

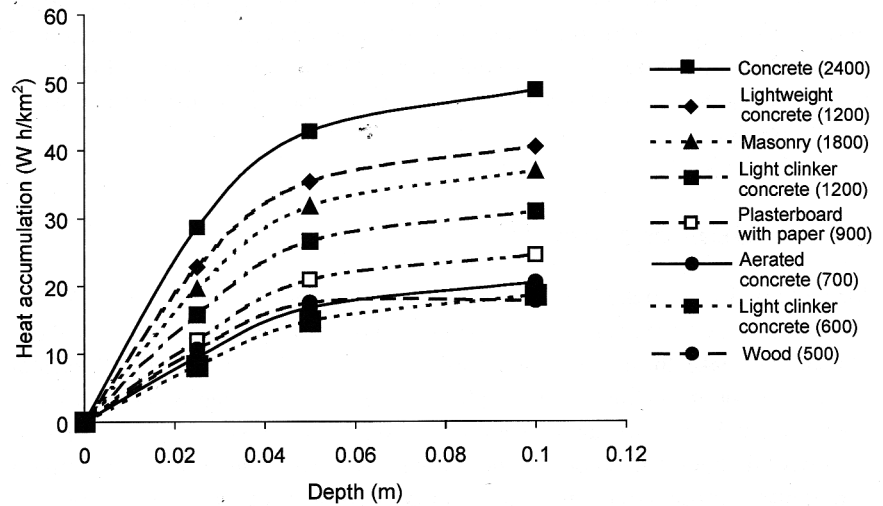


Fig. 08 Heat accumulation as a function of the depth of the materials. In key, material density shown in parentheses (in kg/m³)



Fig. 09 Radiant floor piping installation

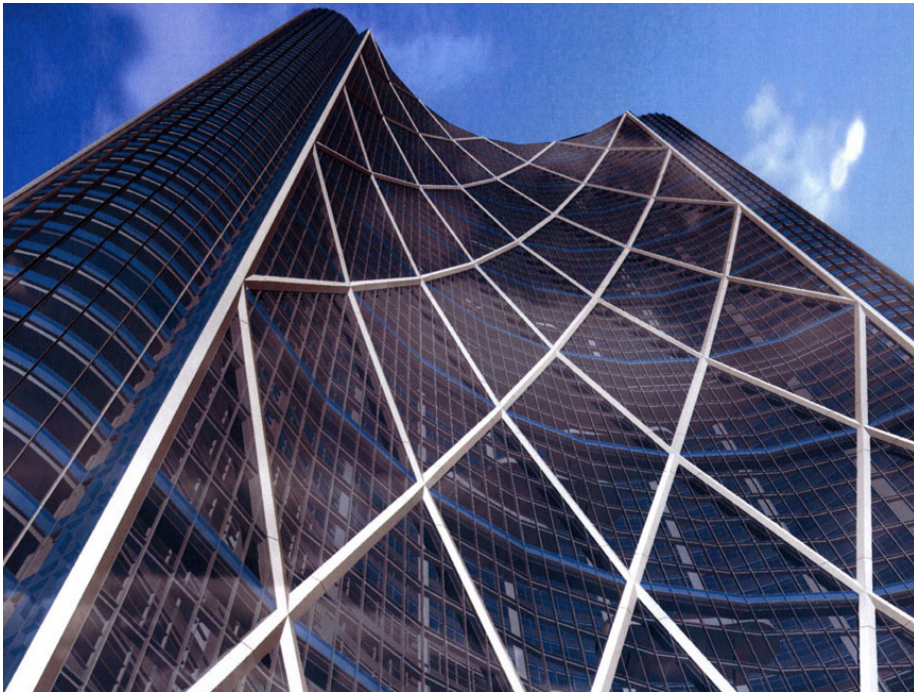
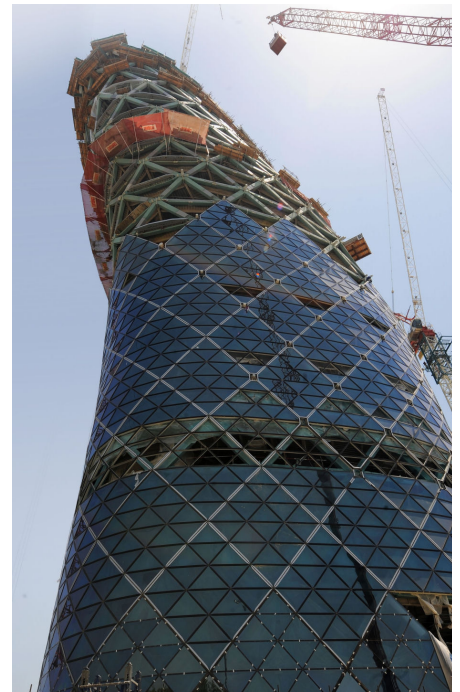


Fig. 10 Diagrid structures



widely used metals in construction, and trumping other building materials in terms of embodied energy (see Figure 02). Since they are alloyed from various raw materials, their processing requires substantial amounts of energy, mainly derived from fossil fuels. Like its contemporaries, the steel industry has made significant advances in its production practices, reduced its energy consumption by 33% since 1990⁹ – accounting for nearly 5% of the total U.S. manufacturing energy consumption.¹⁰ In 2007, steel and iron production accounted for nearly 45% of total US industrial CO₂ emissions.¹¹ Current trends advise that the demand for steel is anticipated to increase with the rapid growth of developing economies of countries aspiring to be considered on the same personal, corporate and municipal wealth of Western countries.

Steel is known for its superior capacity to resist tensile loads. This characteristically suits it as a primary structural material in tall and slender buildings that are subject to irregular lateral loads. Conventional steel frame construction is not too dissimilar from traditional post-beam methods as seen in timber frame construction, with the caveat that lateral resistance is usually administered to a concrete shear wall system or diagonally braced frames. Though shear walls and diagonal bracing elements are strategically placed throughout the structure, they can present limitations to valuable open plan floor plates. Recently, there has been garnering interest in the Diagrid system where the diagonal lateral bracing and vertical load bearing elements are one and the same. The system has been advertised as saving up to 20% of required steel when compared to a more traditional steel

frame system (i.e. less steel can do more) and its implementation can add to the iconography of tall structures¹² (see Figure 10). The necessary experience and skilled labor to construct Diagrids are still rare in the US. A pressing issue remains where the system reduction in material savings can be overshadowed by transportation costs and emissions to factories overseas who are capable of manufacturing the system's complicated and bespoke details.

Like timber, steel is produced in regular shapes and sizes that are optimized for typical applications. Structural properties have been standardized and its catalog is well known to the construction and design industry. Steel members can be connected mechanically using bolts and other connections, or chemically fused by welding. Mechanical connections have a distinct advantage

in regards to reuse and recycling by allowing for a strategic disassembly of the structure. However, reuse of structural elements is rare, owing to the lack of study and precedent that are necessary to give confidence in reusing steel in structural applications. In the mean time, the industry has offered advances in maintaining a steel product's longevity – namely, its resistance to corrosion. Protection from corrosion mainly relies on coating systems, e.g. zinc galvanization, fusion-bonded epoxy and paints.¹³ The ecological impacts of these treatments must also undergo further evaluation. The adoption of stainless steel and aluminum alloys in regular construction practice could prolong service life as well as minimize maintenance, which ultimately promotes steel's sustainability.

Case Study: Integrated Learning Center at Beamish-Munro Hall¹⁴

Architect: Bregman + Hamann
Architects

Structural: Halsall Associates Limited
Completed: September, 2004

The Integrated Learning Center at Queens University in Kingston, Canada is a 3-story, 2300m² (footprint) facility. The structure was design to seamlessly incorporate sustainable design concepts, and live building features (building components used for demonstration purposes from which students can learn about engineering). The goal is to have the building itself employed as a tool to educate engineering students. As part of the sustainable design process, life cycle analysis (LCA) of a cast-in-place concrete and structural steel system were compared.

In order to maximize the benefits of “live building” concepts, the design team planned to incorporate both cast-in-place concrete framing in some areas of the building, and structural steel supporting composite deck in others. Other structural systems, such as precast concrete and wood framing systems, were not used in any significant way because they were deemed not appropriate for the function of the facility.

The LCA software utilized by the design team was the Athena Institute's EcoCalculator for Assemblies. The software was used to model both the concrete system and the structural steel system for the building. It was determined that the system with the least environmental impact would be used in the larger main building, and the other system would be used in the smaller administration wing. Through this exercise, both the “live building” and sustainability requirements could be met.

The results of the life cycle analysis of the above structures indicate that the concrete structure has significantly lower energy consumption, air

and water toxicity and global warming potential. Solid waste emissions for both systems are roughly equal. Resource use for the concrete system is more than double that of the structural steel system (see Figure 12). Based on this data, it was the structural engineer's opinion that the concrete system has less environmental impact than the structural steel system. Therefore, the majority of the building was constructed using the concrete system.

The structural team also performed a second set of analysis for a single story structure, which seems intuitively well suited to steel framing. In this second set of analysis steel framing had less environmental impact than concrete in all categories.

Conclusions

As made evident by the study performed by the structural engineers of the ILC, the environmental impacts of a building structure can vary depending on the type of system selected. It must also be noted that the



Fig. 11 Integrated Learning Center at BeamishMunro Hall

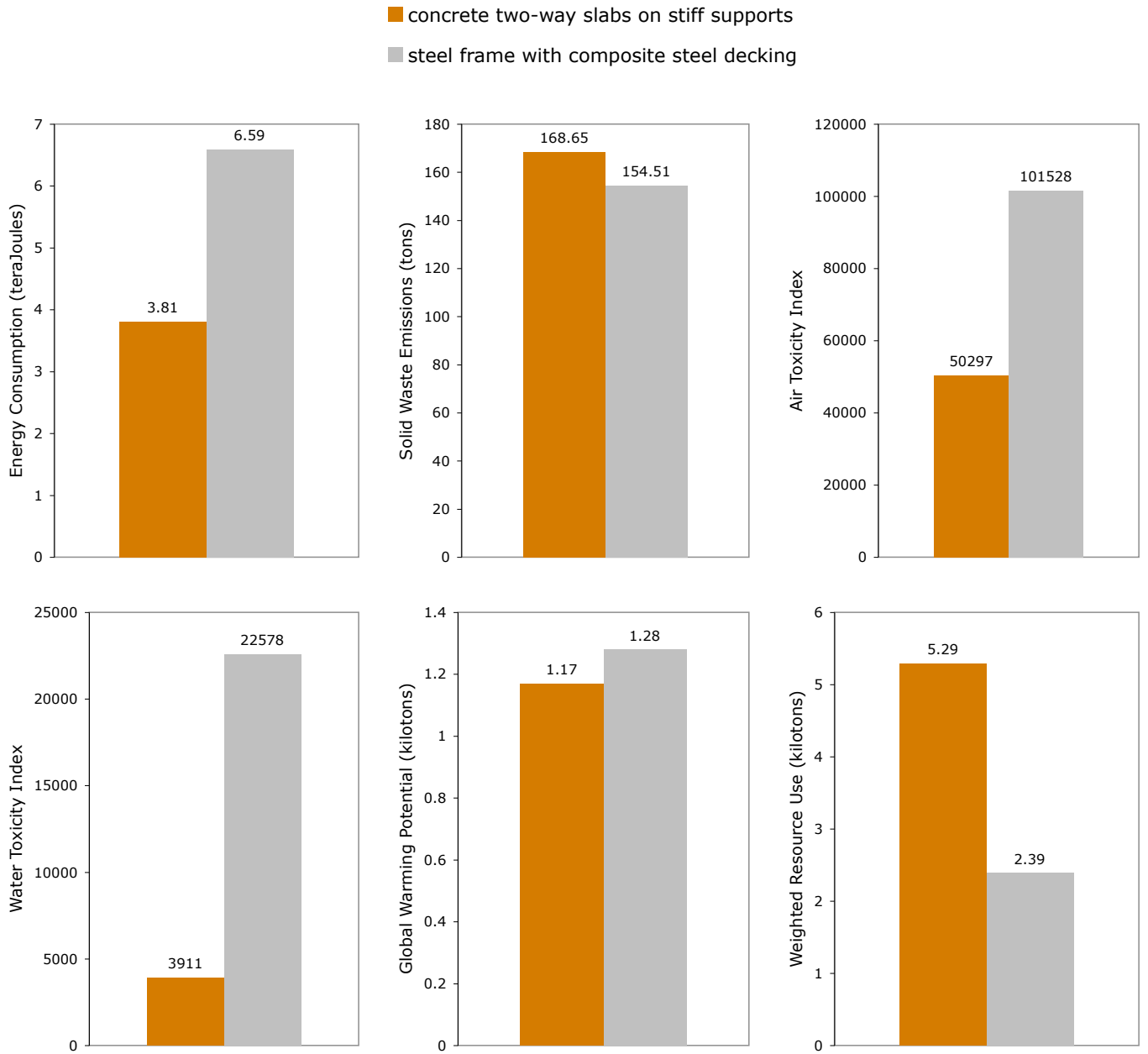


Fig. 12 Environmental impacts of structural steel vs. cast-in-place concrete at Queen's University - Integrated Learning Center

Athena software does not include the impact of disposal at the end of the building's service life in its life cycle analysis. Further investigations must be made regarding life cycle analysis methods and sources of referenced information.

As solutions for reducing a building's operational energy consumption become standard practice, the focus on environmentally beneficial standards will be adjusted toward structures and the production of their construction materials. The timber, concrete and steel industries continue to hedge supply as well as environmental demands of their products. Structural engineers should advance the search for lighter, stronger and more materially efficient structural systems by exploring new assemblies and structural hybridization through specific load design. The potential for reuse of structural elements must be further studied, which calls on designers to be more proactive in code revisions and fearless confidence in material strengths. Further, it must be recognized that a structural element's role can go beyond resisting forces and serving as framework for envelope and mechanical systems. A comprehensive knowledge in the mechanical as well as thermal capacities of materials (both widely used in construction today as well as emerging materials of future structures) will be necessary to provide safe, socially responsible and environmentally sound buildings.

Notes

1. Price Waterhouse Coopers, Engineering and construction industry sector, <http://www.pwc.com/gx/en/engineering-construction/index.jhtml> (accessed 14 August, 2009)
2. The Athena Institute EcoCalculator, avail-

able online at <http://www.athenasmi.org/tools/ecoCalculator/>

3. Khatib, Jamal M., Sustainability of construction materials, CRC Press LLC, Boca Raton, FL, 2009. p. 120-121.
4. Report on Sustainable Manufacturing, by the Portland Cement Association, 2008, online at http://www.cement.org/smreport08/images/shared_images/SustainReport08.pdf
5. US Greenhouse Gas Inventory Report, 2009, Industrial Processes, Environmental Protection Agency, online at <http://www.epa.gov/climatechange/emissions/downloads09/IndustrialProcesses.pdf>
6. Portland Cement Association, Cement and Concrete Basics, Frequently Asked Questions, http://www.cement.org/basics/concretebasics_faqs.asp (accessed 09 August, 2009).
7. Khatib, Jamal M., Sustainability of construction materials, CRC Press LLC, Boca Raton, FL, 2009. p. 127.
8. Concrete Homes - ICF Energy Efficiency, ICF Energy Savings, http://www.concrete-home.com/energy_savings.php (accessed 08 August 2009) and Khatib, Jamal M., Sustainability of construction materials, CRC Press LLC, Boca Raton, FL, 2009. p. 137.
9. The North American Steel Industry, Sustainable Steel: Energy Reduction, <http://www.sustainable-steel.org/energy.html> (accessed 08 August 2009).
10. Energy Consumption by Manufacturers, 2006, Energy Information Administration, online at http://www.eia.doe.gov/emeu/mecs/mecs2006/pdf/Table1_1.pdf
11. US Greenhouse Gas Inventory Report, 2009, Industrial Processes, Environmental Protection Agency, online at <http://www.epa.gov/climatechange/emissions/downloads09/IndustrialProcesses.pdf>
12. Charnish, Barry and Terry McDonnell, "The Bow": Unique Diagrid Structural System for a Sustainable Tall Building, Council on Tall Buildings and Urban Habitat, 2008, http://www.ctbuh.org/Portals/0/Repository/T9_CharnishMcDonnell.42bca656-37de-4f32-bb02-7717251e8a76.pdf (accessed 09 August 2009).
13. Khatib, Jamal M., Sustainability of construction materials, CRC Press LLC, Boca Raton, FL, 2009. p. 167.

14. Portions of this case study are derived from the report on the Integrated Learning Center's embedded energy impact. Considering Sustainability in the Selection of Structural Systems, by Halsall Associates Limited, 2003, online at <http://livebuilding.queensu.ca/files/Considering%20Sustainability.pdf>

Figures

Figure 01: From Chapter 4 in Environmental Design of Urban Buildings, Edited by Mat Santamouris, Earth Scan, Sterling, VA, 2006. p. 64.

Figure 02: From Chapter 2 in Sustainability of construction materials, Edited by Jamal M. Khatib, CRC Press LLC, Boca Raton, FL, 2009. p. 40.

Figure 03: Timber frame construction, <http://www.woodbusinessportal.com/upload/products/683.1.JPG> (accessed 15 August 2009).

Figure 04: From Chapter 13 in Ecology of Building Materials, by Bjorn Berge. Architectural Press, Woburn, MA, 2000. p. 227.

Figure 05: Glulam structure of the Cathedral of Christ the Light in Oakland, CA., http://www.flickr.com/photos/andrew_sherman/495655350/

Figure 06: From Chapter 5 in Sustainability of construction materials, Edited by Jamal M. Khatib, CRC Press LLC, Boca Raton, FL, 2009. p. 123.

Figure 07: Headwaters Resources, Fly Ash Performance, <http://www.flyash.com/performance.asp> (accessed 08 August 2009).

Figure 08: From Chapter 5 in Sustainability of construction materials, Edited by Jamal M. Khatib, CRC Press LLC, Boca Raton, FL, 2009. p. 136.

Figure 09: Radiant floor piping prior to concrete pour. <http://www.gotsun.com/radiant/slabprep/largsl1.jpg>

Figure 10: "The Bow"/EnCana Building, Calgary, CAN, <http://www.sotawall.com/portfolio/Canada/TheBow-c528/03%20-%20The%20Bow%20-%20Rendering.jpg> and Capital Gate Tower, Abu Dhabi, <http://www.51abcd.com/forum/UploadFile/2009-5/20095306123570740.jpg>

Figure 11: Beamish-Munro Hall at Queen's

University, Kingston, CAN, <http://www.buildinggreen.com/articleimages/1403/learningcenter.jpg>

Figure 12: From Halsall's report on the Integrated Learning Center's embedded energy impact.

References

Athena Institute: <http://www.athenasmi.org/>

Energy Information Administration: <http://www.eia.doe.gov/>

North American Steel Industry: <http://www.sustainable-steel.org/index.html>

Portland Cement Association, Sustainable Development: <http://www.cement.org/SD/index.asp>

U.S. Department of Agriculture, Forest Economics and Policy, <http://www.srs.fs.usda.gov/econ/default.htm>

U.S. Environmental Protection Agency: <http://www.epa.gov/>

