The Role of the Structural Engineer in Sustainable Design

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When I suggest to architects that structural engineers have a role to play in sustainable design, they frequently respond with surprise. “What can you do, as a structural engineer, to improve the environmental performance of a building?,” they ask. Well, quite a lot, actually.

Structural engineers make many design choices with environmental ramifications, and are therefore a key team member in any construction project where the reduction of negative environmental impacts is a goal. Among the questions the structural engineer must address are:

- How are the structural materials manufactured?
- How will the structural components be assembled?
- How will the structural system affect the building’s energy use?
- Will the structural system be durable and adaptable?
- How will it be taken apart at the end of its life?
- Can the components be salvaged or recycled?

Questions like these must guide the engineer’s decisions throughout the project design. The engineering consultant must therefore have a good understanding of the principals of sustainable design, and know how his or her design affects the environmental performance of the building. There are many opportunities for the structural engineer to improve the building’s environmental performance that have little or no cost impact. The engineer should guide the architect toward design options that have the best environmental performance while remaining within the project’s budget.

1. WHAT IS SUSTAINABLE DESIGN AND WHY IS IT IMPORTANT?

In the broadest sense, “sustainable” development, as defined in the United Nations World Commission on the Environment and Development’s Brundtland Report (WCED, 1987), is “development that meets the needs of the present without compromising the ability of future generations to meet their own needs.” For the construction and operation of buildings, this boils down to

- minimizing the use of natural resources, especially non-renewable resources such as petroleum products; and
- maintaining a healthy environment both inside and outside the building.

The need for sustainable development has been well argued by others (Cortese, 1999; World Scientists’ Warning, 1992). World population has doubled over the past fifty years, and economic output has increased five-fold (U.S. Census Bureau, 2000). Both are expected to continue to increase. The supply of many of our natural resources is limited. It seems only prudent to find ways to grow that consume fewer resources.

Building construction consumes enormous quantities of resources. Construction and renovation activities presently account for 13% of the United States' economic output. Buildings account for 17% of the world's freshwater withdrawals, 25% of its wood harvest, and 40% of its material and energy use. 54% of the United States' energy consumption is directly or indirectly related to buildings and their construction (Augenbroe et al., 1998). Clearly, we in the building construction industry—architects, engineers, contractors—must do our part to reduce consumption.

2. ENVIRONMENTAL INDICATORS

Sustainable design measures are typically grouped into the following categories: site, energy and water use, material selection and use, indoor environmental quality, and waste. This paper will focus on those aspects of sustainable design that are most affected by the structural design of a building.

The structural engineer's most important task in sustainable design is to choose the right materials and put them together the right way. Sometimes the choice of materials is limited by the functional requirements of the building. The building geometry and loads may restrict the material choices. For instance, wood-framed construction is not appropriate for mid-rise and high-rise construction. In many cases, though, material choices may be made. In cases where the cost differential between the materials is small, or where an owner may be willing to pay a premium for a greener building, the engineer should select the material and the building system that does the least harm to the environment.

The engineer should consider the following factors when selecting materials:

- environmental impact of its production (embodied energy, pollution generation, etc.);
- durability;
- effect on indoor air quality; and
- disposal.

Considerations in the selection of the structural system are:

- efficient use of materials;
- adaptability for other uses; and
- effect on building energy consumption.

2.1 Life-Cycle Assessment

Life-cycle assessment (LCA) is the cradle-to-grave evaluation of a material or system. The broader the system that is studied, the more reliable the results will be. LCAs generally consider the following factors:

- embodied energy (the energy consumed, including transportation energy, during the life of the material or system; this typically includes fuels and electricity, while labor and renewable energy is typically excluded),

- toxicity during all stages of use,
- pollutants, including greenhouse gases,
- water consumption, and
- waste generation.

Factors such as recycled-material content may affect all of the above categories. For instance, compared to steel with a low recycled-material content, steel with a high recycled-material content has lower embodied energy, produces less pollution, uses less water in its production, and uses more materials that might otherwise enter the waste stream.

Standards for performing LCAs are still in flux. A number of organizations are doing work in this area, including the U.S. National Institute of Standards and Technology (NIST) and the Athena Sustainable Materials Institute (ASMI) in Canada. NIST is developing an LCA software tool called BEES (Building for Environmental and Economic Sustainability), and ASMI is developing a software tool called Athena. Both products, still in their infancy, permit a comparison of the environmental impacts that result from different building systems. It should soon be possible to perform relatively sophisticated analyses of design options that account for many building systems, geographic regions, and other factors.

Figures 1 through 4 show the relative embodied energies of six common structural materials: steel (rolled structural shapes), concrete, reinforced concrete, sawn lumber, glu-lam beams (GLBs), and laminated-veneer lumber (LVL). (Embodied energy figures are from Athena; average of Montreal and Toronto installed embodied energy.) These figures include the embodied energy to produce, transport, and install the materials; the end-of-life costs are not included. Figure 1 shows the embodied energy per pound, and Figure 2 shows the embodied energy per cubic foot for each material. Figures 3 and 4 show the embodied energy of the material relative to its compressive and tensile strength, respectively. Figures 3 and 4 give the best picture of the relative embodied energy of the materials, since it accounts for their differing strengths. However, it is not necessarily an accurate representation of the embodied energy of a constructed structural system because it does not account for the effect on other building systems, or even the effect on other structural systems, of the material use. For example, a steel-framed building is generally lighter than a concrete-framed building, which reduces foundation loads and therefore the quantity of concrete used in the foundation.

Steel has by far the highest embodied energy relative to compressive strength of any of these structural materials; its embodied energy is more than three times higher than the embodied energy of LVLs, which rank second. LVLs have about twice the embodied energy of GLBs, which is a useful comparison, since LVLs and GLBs generally are functionally interchangeable. When compressive strength is taken into account, sawn lumber and GLBs have similar embodied energy. Reinforced concrete has roughly twice the embodied energy of unreinforced concrete. When comparing the embodied energy of materials relative to tensile strength, steel's performance relative to concrete and wood improves markedly, due to the low tensile strength of concrete and wood relative to their compressive strength.

Similar comparisons could be made using other life-cycle measures, such as solid waste generation, air and water pollution, and greenhouse gas emissions. However, comparing building systems gives a better picture of environmental burdens than looking at materials in isolation. Later in this paper, the results of a couple of comparative life-cycle assessments for

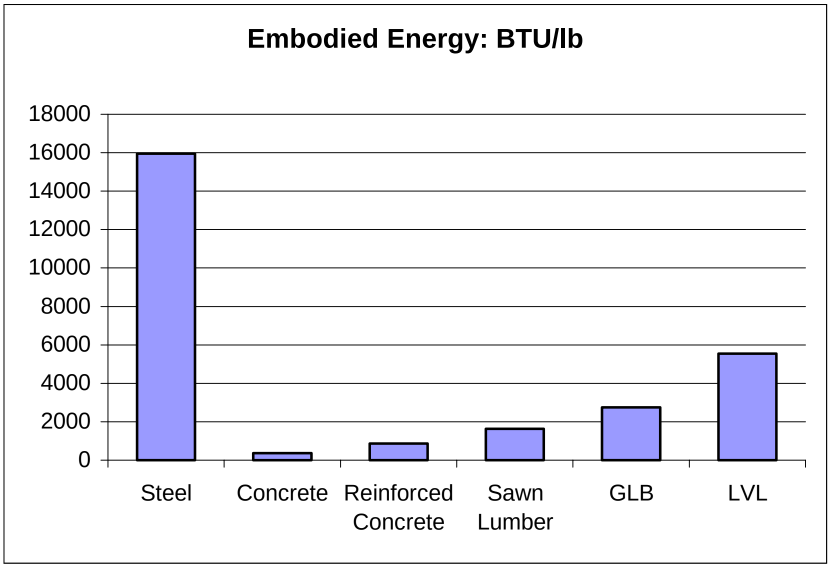

Figure 1: Embodied Energy per Pound (source: Athena)

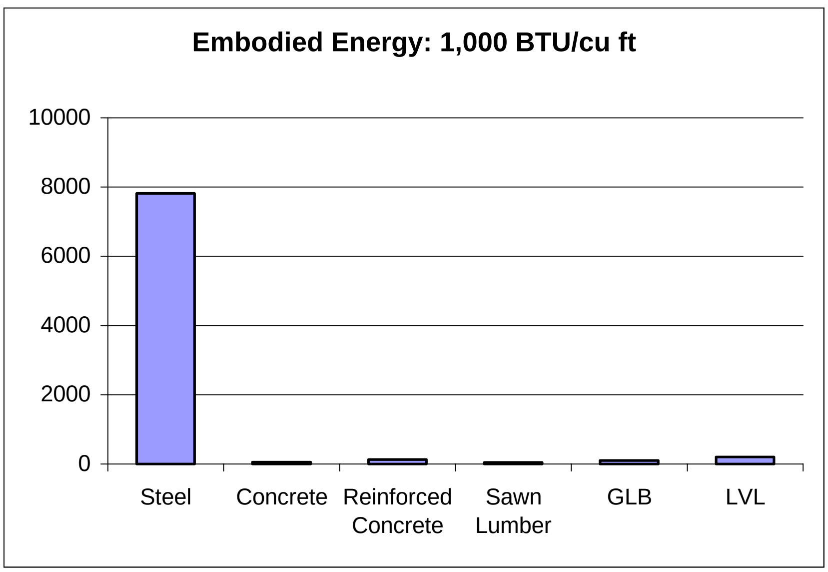

Figure 2: Embodied Energy per Cubic Foot (source: Athena)

building systems will be presented.

2.2 Robustness

"Robustness" is a measure of the durability and adaptability of a building system. Durability of the structural system is especially important since it is often the most difficult building system to repair or replace and is typically the most permanent building system. A green building should be built to last, using low maintenance materials. All the major structural materials can be

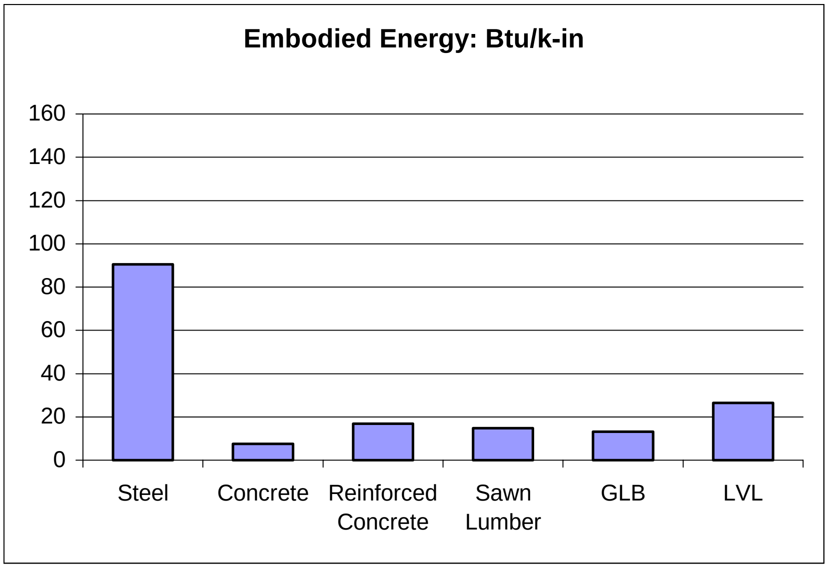

Figure 3: Embodied Energy Relative to Material Compressive Strength

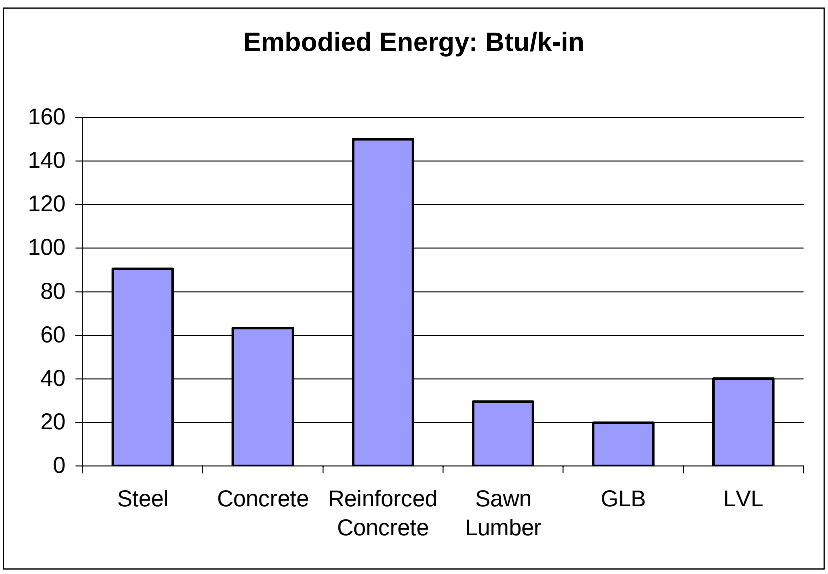

Figure 4: Embodied Energy Relative to Material Tensile Strength

durable if properly protected from damaging environmental factors. However, if this protection fails, as it often does over the life of a building, certain structural materials will fare better than others. For instance, concrete or masonry that is exposed to the weather will typically outlast untreated wood.

Adaptability is the ability of a building to adapt to change. Buildings almost inevitably change over their lifespans (see the excellent book by Stewart Brand: *How Buildings Learn*). The use may change: a warehouse might become an office building; a school may become a condominium. Additions may be made. The possibilities are endless. During the design phase, thought should be put into how to easily accommodate such future changes. For example, it may be better to use higher than code-required minimum live loads to allow the building to accommodate a change in use.

A special case of designing robust buildings occurs in high seismic and wind regions. Property losses due to earthquakes and hurricanes are frequently measured in the billions of dollars. From an environmental perspective, property losses are environmental losses, since these damaged or destroyed buildings are frequently replaced at great expense to the environment. Traditional seismic engineering philosophy is to allow structural materials to be overloaded, as long as they can deform and deflect without collapsing. Generally, though, these deformations are so extreme that the element is effectively destroyed and must be replaced. As a result, it is sometimes more economical to replace a building with heavy damage than to repair it. New seismic engineering technologies such as base isolation and energy dissipation permit a building to ride out an earthquake with little or no damage. Other technologies are being developed that concentrate damage in localized elements which can easily be swapped with new elements following a large earthquake. Similar concepts or other, as yet undeveloped, ideas may be appropriate for high wind regions.

2.3 Efficient Use of Materials

Selection of materials is only one piece of the puzzle; it is also necessary to use the selected materials efficiently. For example, wood I-joists use wood much more efficiently than joists made of sawn lumber. I-joists concentrate the material where it is needed (at the flanges) and use stronger material at the flange than at the web. Another example: castellated steel beams are made by cutting the web of a standard rolled wide-flange beam along its length in a zigzag pattern, separating and offsetting the top and the bottom of the beam so that the “teeth” align, and welding the two pieces together. The end product is a deeper steel beam with large holes in the web. It has the same amount of material but is considerably stronger and stiffer than the original shape.

Frequently, shop fabrication is more efficient than field fabrication. There is less waste, and what waste occurs is more likely to be recycled. The Wood Truss Council of America (not an impartial entity) sponsored a study of two homes, one built using traditional “stick-built” construction, and one built using prefabricated wall panels and floor and roof trusses, and found that the job-site waste created by the stick-built house was four times higher (WTCA, 1996). Unfortunately, shop waste was not reported. There is also reportedly less waste when using precast concrete compared to cast-in-place concrete.

Another way to use structural materials efficiently is to mesh their structural function with other building functions. There are a number of examples in Europe where precast slab elements contain voids through which heating and cooling air is circulated, combining structural and mechanical functions (see for example www.termodeck.com). Another example of this practice is the elimination of finishes over structural materials. Structural concrete and masonry walls, for example, may be left exposed; if thoughtfully designed and carefully constructed, such elements can be highly attractive as well. Such design approaches require the close and early collaboration of team members, which is one of the reasons it is critical in a green building project to bring the team together early in the project.

3. STRUCTURAL MATERIALS

The major structural materials are concrete, masonry, steel, and wood. There are a number of other structural materials available, such as earth and straw, which hold great promise for the future of sustainable construction. These materials are not widely used at present, and it is not clear whether they will play a role in the construction of larger buildings. This paper will only examine more traditional and widely-used structural materials.

3.1 Reinforced Concrete

Concrete has the following positive attributes from an environmental standpoint:

- Most raw materials (primarily aggregate, water, and limestone) used in concrete production are abundant and locally available.
- The extraction of raw materials for concrete is less environmentally damaging than the extraction of raw materials for steel and wood construction.
- Concrete has low embodied energy; reinforced concrete has moderate embodied energy.
- Reinforced concrete is moderately recyclable. Crushed concrete may be used as aggregate in new concrete or as a base material. Reinforcement is generally separated and recycled (Figure 5).
- Concrete is highly durable (when properly designed and constructed to protect the reinforcement from corrosion) and requires little maintenance.
- Concrete has high thermal mass, which may be used to reduce heating and cooling demands.
- Concrete can serve as a finish material, reducing the materials used in the building.

On the other hand:

- Cement production creates a lot of carbon dioxide, which is a greenhouse gas. One ton of CO_2 is produced per ton of cement, and cement production accounts for 2% of the human-generated CO_2 production in the U.S.
- Cement production is energy intensive; U.S. cement production consumed about 0.4 quadrillion Btu of energy in 1994, roughly 0.5 percent of the total U.S. energy consumption (AIA, 1999; Energy Information Administration, 2000-1).
- Cast-in-place concrete elements are generally not salvageable for use elsewhere.

The following methods may be used to reduce concrete’s environmental demand:

- Replace cement with fly ash or ground granulated blast furnace slag (GGBFS). Both of these cement substitutes are waste products of other industrial processes, and their use can substantially reduce embodied energy and carbon dioxide emissions in a given quantity of concrete. These additives can also improve concrete’s strength and durability with little or no cost penalty. The primary drawback of flyash and GGBFS substitution is a somewhat slower strength gain, but the additional curing time can generally be accommodated easily, particularly for foundation elements, many of which are not fully loaded until well after they are cast. Flyash sometimes contains traces of arsenic and may be regulated as a hazardous material in some locales.

Figure 5: Concrete Reinforcement at Demolition Site Separated for Recycling

- Replace virgin aggregates with recycled concrete aggregate, glass, or other materials. Concrete made with recycled concrete aggregate may be weaker than concrete using stone aggregates. More cement may be required to compensate for this lesser strength, so the environmental tradeoffs of less concrete waste versus more cement must be considered. Care must be taken to ensure that replacement aggregates do not chemically react with other concrete constituents, which could cause premature failure of the concrete.

- Use non-toxic form release agents.

- Specify cement from more efficient producers. This may not be possible if a given producer uses both high- and low-efficiency manufacturing processes at the same location.

- Although it is not currently practiced, it may be feasible to design precast concrete structures such that standard components such as hollow-core planks and prestressed T-beams could be easily salvaged at the end of the structure's life for use elsewhere.

Cement is produced in several locations in and around New England. It therefore does not need to be transported long distances to the ready-mix plant. New England's only cement producer is in Maine. Other plants are located in eastern New York, northeastern Pennsylvania, and southern Quebec (Figure 6). (In our discussion of materials, we include material sources in the New England region, as this paper was originally directed towards a Boston audience. Locally-produced products use fewer transportation-related resources.)

3.2 Masonry

Masonry construction shares many of the benefits and drawbacks of concrete. Brick and stone are often used as veneers and seldom used as structural materials in new construction in New England, so this paper will restrict comments to concrete masonry (CMU) construction.

CMU is precast concrete. It therefore shares the attributes of reinforced concrete discussed in the previous section. Since CMU is plant-fabricated, waste is minimized. CMU can be left exposed as an interior or exterior finish material, and the surface of the blocks may be textured to improve their appearance. CMU is a durable, locally-made material, with fairly low embodied energy, which makes it highly suitable for sustainable construction. It can be recycled like concrete. It is potentially salvageable, although the labor costs associated with removing old mortar may be high. Grouted cells also make salvage difficult.

3.3 Steel

Structural steel is certainly the most "high-tech" material of the big four structural materials. Because of the complexity of the manufacturing process and the large investment required in production facilities, rolled structural steel shapes are manufactured in only a handful of locations in the United States (Figure 7).

Structural steel's positive attributes are:

- Structural steel rolled shapes are currently made almost entirely from recycled scrap steel (total recycled content is about 94%; post-consumer content is about 62%) (Steel Recycling Institute, 1999).

Figure 6: Cement Production in the New England Region

- Steel is easily deconstructed and recycled. One study showed that it is more economical to deconstruct bolted connections than welded connections (Trusty, 2001).

- Steel is salvageable. It is likely that structural steel frames will one day be disassembled, and the beams and columns returned to a steel fabricator for refabrication and reuse in new construction.

On the other hand:

- Steel has high embodied energy relative to other structural materials. Most steel production in the United States uses either electric arc furnaces (EAFs) or basic oxygen furnaces (BOFs). All structural rolled shapes used in the United States are currently produced in EAFs, which use less energy than BOFs. Nevertheless, an EAF when it is melting scrap may use as much electricity as a town with a population of 100,000 (Steel-UK). The U.S. steel industry has decreased its energy consumption by 45% since 1975. In 1991, steel production for the construction industry consumed about 0.2 quadrillion Btu of energy, roughly 0.3 percent of the total U.S. energy consumption for that year (AIA, 1999; Energy Information Administration, 2000-1).

- Steel production produces high greenhouse gas emissions. In 1994, U.S. steel production for the construction industry emitted about 5.9 million tonnes of CO_2, roughly 0.4 percent of the total U.S. carbon emissions for that year (LBL, 1999; Energy Information Administration, 2000-2). This figure assumes that steel production for the construction industry emits CO_2 at the same rate as the average for all steel production.

- Although roughly 80% of the structural steel used in construction in the United States

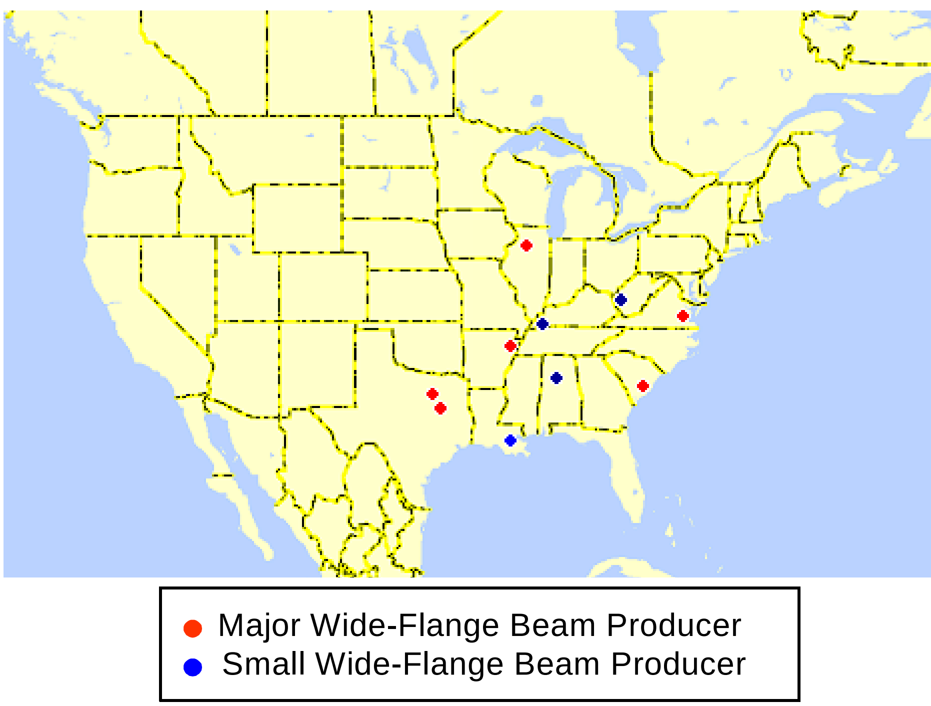

Figure 7: Wide-Flange Shape Production in the United States

comes from domestic producers, structural steel is not produced locally in many parts of the country. Major rolled shape production facilities are located in Texas, Arkansas, South Carolina, and Illinois. Chapparal Steel recently opened a steel plant in Virginia, which is the closest producer to New England.

- Structural steel frequently requires more fireproofing than other structural materials.
- Steel has poor durability in certain environments when it is not protected.

The following approaches may be taken to reduce the environmental demands of structural steel use:

- Use steel produced as close to the job site as possible.
- Use composite beam design, as it significantly reduces the total steel required for a given loading.
- Investigate the suitability of castellated beams.
- Use braced frames instead of moment-resisting frames in the lateral-load-resisting system, as they generally save on the overall steel tonnage.
- Use wide-flange sections instead of tube and pipe sections when there is no significant difference in weight, as wide-flange sections usually contain a higher percentage of recycled steel (in some applications, particularly compression, a lower-weight section may be possible if tubes are used instead of wide flanges).

3.4 Wood

Wood has the following positive traits:

- Wood has the least embodied energy of the major structural materials.
- Wood is the only renewable material of the major structural materials.
- Wood, especially timbers, is easily salvageable.
- Wood is biodegradable.
- Wood is a good thermal insulator relative to the other major structural materials.
- Wood is often available locally.

On the other hand:

- Destructive logging practices are common. Logging can cause significant soil erosion and pollutant runoff, habitat alteration and destruction, and harmful air emissions, while intact forests consume carbon dioxide and have other environmental benefits. In the United States, deforestation peaked at the turn of the 19th to 20th centuries; currently, tree growth nationwide exceeds harvest (AIA, 1999).

- Wood has poor durability in certain environments when not protected.

Engineered wood products are manufactured structural components made of wood and binders. Examples of engineered wood products are I-joists, glu-lam beams, laminated veneer lumber (LVL), plywood, and oriented-strand board (OSB). Engineered wood has the following environmental benefits:

- Engineered wood makes efficient use of materials. For instance, I-joists concentrate the material at the top and bottom of the member where it is most needed to resist bending. Engineered wood products have more uniform material properties than sawn lumber, so they have much higher strength. For example, the allowable bending stress of an LVL or glu-lam beam is approximately three times higher than the allowable bending stress of a Spruce-Pine-Fir (SPF) graded sawn timber.

- Smaller trees and scrap wood may be used in its production.

- Like sawn timber, engineered wood beams and posts are generally salvageable.

On the other hand:

- Engineered wood members have higher embodied energy than sawn lumber.

- Glues presently used to manufacture engineered wood are toxic. Softwood plywood and most structural members use phenol formaldehyde glues. These glues are made from crude oil and natural gas. Formaldehyde is a probable human carcinogen, and phenol can cause central nervous system toxicity and paralysis, so these chemical components must be used with care (AIA, 1999). Fortunately, when fully cured, the resulting product is non-toxic. An alternative glue called polymeric diphenyl methylene diisocyanate (PMDI), which is formaldehyde-free, is entering the market. PMDI is a waterproof polyurethane-type binder that is very toxic before it cures (EBN, Nov. 1999). The U.S. Department of Energy recently announced that it is funding research into bark-based adhesives, which would presumably be less toxic and not contain petroleum products.

- Engineered wood products are less likely to be locally grown and produced than sawn lumber.

One way to improve the sustainability of wood structural elements is to use wood that has been harvested from “certified” forests. Forest certification is a process that rates a forest using various environmental and social criteria. There are two principal rating systems currently used in the United States. One program is run by the Forest Stewardship Council (FSC), an international, non-governmental organization that accredits third-party certifiers and facilitates the development of forest management standards. The other program is called the Sustainable Forestry Initiative (SFI), and it is run by the American Forest & Paper Association (AFPA). The AFPA is the national trade association for the forest, paper, and wood products industries. All member companies are required to participate in the SFI. Although the SFI is a laudable program, most environmental advocates prefer the FSC program because it is more comprehensive than the SFI, its ratings are independent, and the certified forest products are physically stamped so that they may be easily identified. The FSC program is the only certification recognized by the Leadership Energy and Environmental Design (LEED) program, which is the leading green building rating system in the U.S. (LEED is discussed in detail in Section 5.)

Pressure-treated wood presents a number of environmental hazards. About 17% of all soft-wood consumed in the United States was pressure-treated in 1997 (EBN, Mar. 1997). The most popular chemical used to pressure-treat wood is chromated copper arsenate (CCA), which is toxic when ingested. Arsenic, an ingredient of CCA, is a known human carcinogen. Disposal of pressure-treated lumber is perhaps the greatest concern. It should not be burned and should only be disposed of in lined landfills to prevent its toxic ingredients from leaching into groundwater. The most attractive end-of-life option is to salvage pressure-treated wood and reuse it in new construction. Alternative copper-based treatments are on the market, such as ammoniacal copper quaternary compound (ACQ). ACQ is less toxic but is more expensive and may not be as effective. The designer must weigh these environmental drawbacks against pressure-treated wood's durability compared to most untreated woods; it may be that the environmental benefits accrued by a longer product life outweigh the drawbacks.

It is difficult to determine where the wood used for construction in New England originates. This author noted primarily Quebec suppliers in an informal survey of a local lumberyard in a Boston suburb. In 1999, Quebec was responsible for 66% of the 11 billion bd ft of lumber produced in the New England states and eastern Canadian provinces of Quebec, New Brunswick, and Nova Scotia (see Figure 8) (Quebec Lumber Manufacturers' Association, 2000; U.S. Census Bureau, 2000). Assuming a recovery ratio of 55% (i.e., the percentage of usable wood product obtained from the harvest), Quebec produced 6 billion bd ft of lumber, enough wood to build one-half million, 2,000 sq ft homes. In 1992, there were five OSB producers in the New England region (two in Maine and three in Canada), but no plywood producers.

Several ideas for reducing the environmental demands of wood construction are:

- Use wood harvested from certified forests.
- Use regionally grown and produced sawn lumber and engineered wood products.
- Use panelized or modular construction to reduce waste.

4. DECONSTRUCTION

Construction practice today is still mostly based on the concept of linear flow: raw materials are extracted from the earth and manufactured into useful products, these products are used, and at the end of their lives they are discarded and taken to landfills or incinerated. One consequence of linear flow is that construction and demolition waste accounts for 25% of land-fill waste in the United States (Augenbroe et al., 1998). Another concept called circular flow is now gaining support. In circular flow, after a material is used, it is separated from other materials, sorted, remanufactured if necessary, and reused. The idea is to eliminate the extraction of raw materials stage as well as the disposal stage, which can address a host of environmental problems.

Deconstruction is reverse construction. At the end of its life, a building may be dismantled into its constituent parts so that these parts can be sorted and reused. The building designers can make deconstruction easier by assembling the building in such a way that the different materials can be easily separated. For example, when designing for deconstruction, the use of composite materials such as structural insulated panels, where rigid insulation is bonded to OSB or plywood sheathing, should be discouraged unless they can be disassembled and reused elsewhere without separating the insulation from the sheathing.

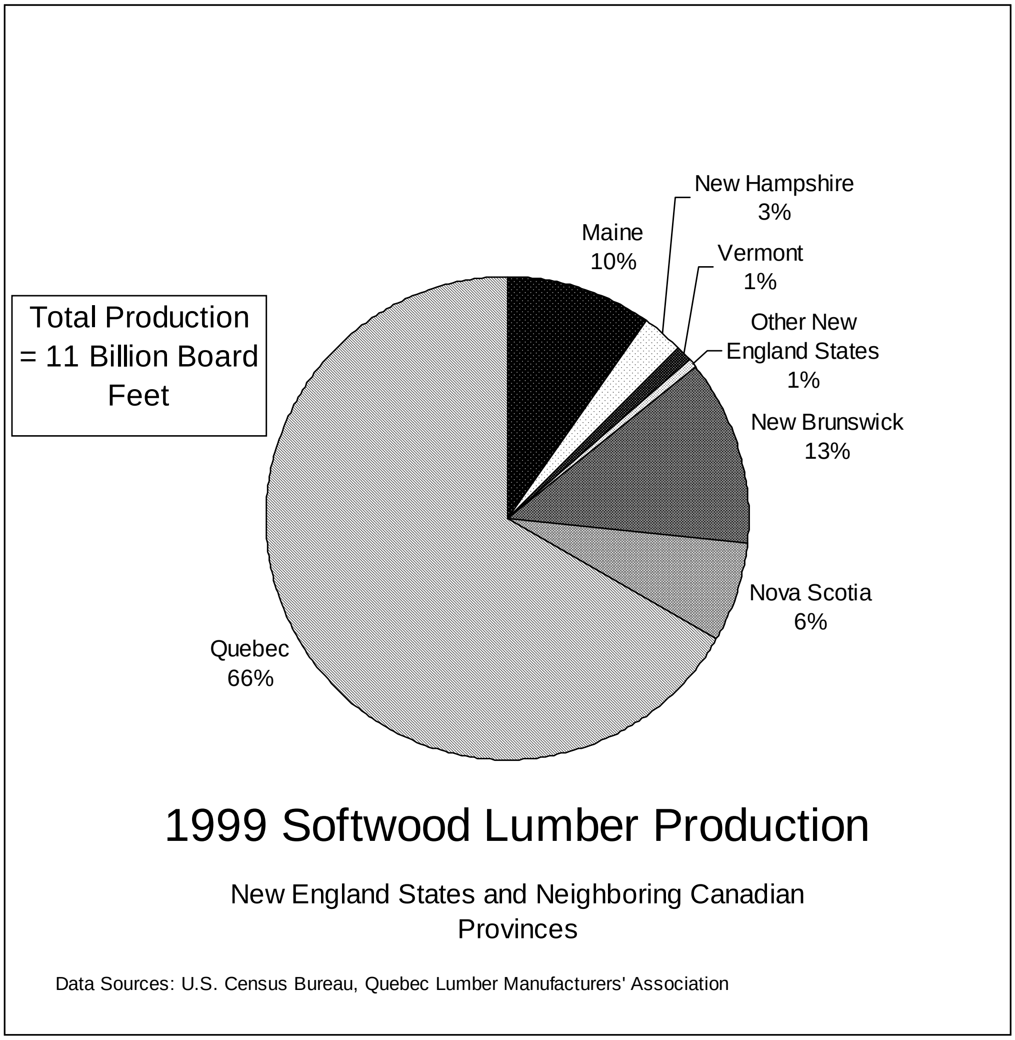

Figure 8: 1999 Softwood Lumber Production

A study by the University of Florida Center for Construction & Environment found that deconstructing six wood-framed houses was more economical than demolishing the houses using traditional methods (Guy, no date). Although deconstruction was more labor-intensive and time-consuming, the salvage value of the recovered materials and the reduction in disposal costs resulted in a net cost savings. This outcome is heavily dependent on labor costs, so results may be different in other markets.

5. DESIGNING WITH LEED™

The Leadership in Energy and Environmental Design (LEED) Green Building Rating System™, created by the United States Green Building Council (USGBC), is positioned to be the leader in green design standards for the United States. The USGBC is a coalition of "product manufacturers, environmental groups, building owners, building professionals, utilities, city governments, research institutions, professional societies, and universities" (quoted from www.usgbc.org). The group formed to develop consensus standards for reducing the environmental impacts of building construction.

LEED 2.0, the current version of the LEED standard, assigns points in various categories for green design features. The building receives a rating based on the total number of points earned. There are a total of sixty-nine points available. The lowest rating is Certified, for which at least twenty-six points are needed. From Certified, the ratings range up through Silver and Gold to Platinum, the highest rating, which is awarded if fifty-two or more points are earned. Certification is obtained by submitting supporting documentation to a USGBC certification committee. As shown in Figure 9, points are available in six categories.

LEED does *not* directly address design for robustness, deconstructibility, salvageability, or material life-cycle assessment measures such as embodied energy. However, Innovation and Design Process points might be obtainable for designs that consider these factors.

The structural engineer's domain is primarily the Materials and Resources category. Within this category there are seven sub-categories (Figure 10):

- Building Reuse: up to three points, depending on how much of an existing building on the site is reused.
- Construction Waste Management: up to two points for recycling/salvaging construction, demolition, and land-clearing waste.
- Resource Reuse: up to two points for using salvaged/refurbished materials.
- Recycled Content: up to two points for using recycled-content materials.

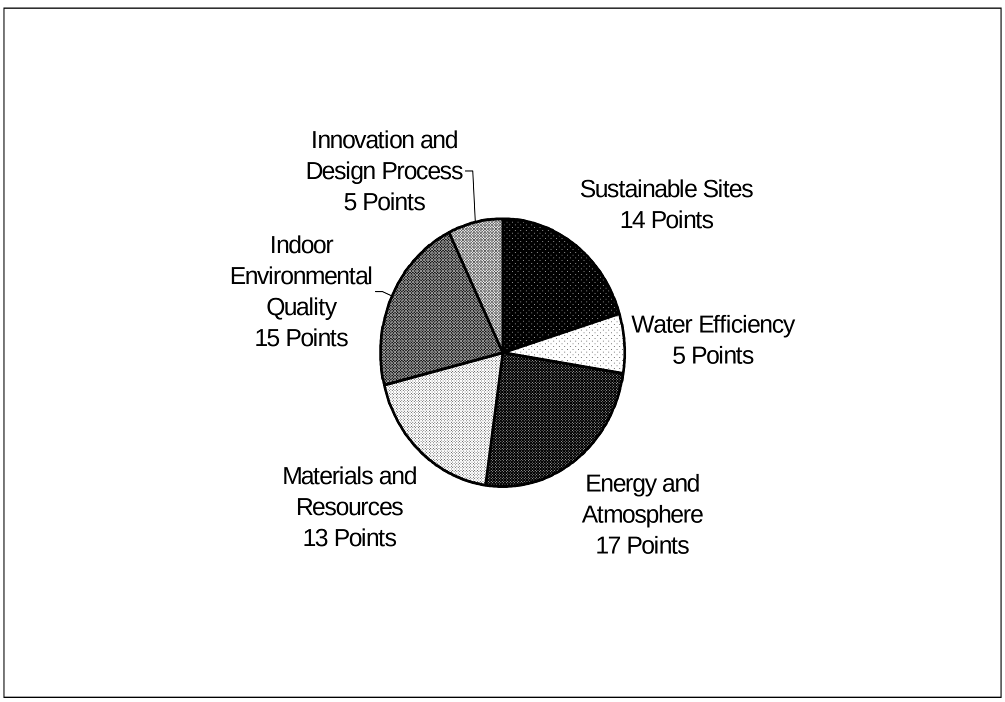

Figure 9: LEED Categories

- Local/Regional Materials: up to two points for using “regionally” manufactured and extracted materials; “regionally” is generously defined as within a 500-mile radius of the construction site.

- Rapidly Renewable Materials: one point for using rapidly renewable materials, which are defined as materials having a growth cycle of ten years or less.

- Certified Wood: one point for using wood from certified forests.

LEED points apply to a building as a whole; therefore the design team must decide which points they will go for at the beginning of the project, and all team members must then work together towards that goal. For example, if the structural engineer focuses on using regionally-produced structural materials, while the architect concentrates on using architectural products with high-recycled material content, there’s a chance that neither LEED goal will be met.

LEED places greater weight on recycled and regionally-produced materials than on embodied energy and pollution indices, which are not explicitly addressed. Thus, when comparing a steel structural system to a wood-framed structural system, the steel system may earn Recycled Content points and, if fabricated regionally, Local/Regional Material points. The wood structure, with much lower embodied energy and less pollution generation, may earn no points, unless it uses certified or regionally-grown wood.

The rapidly renewable materials credit is designed to apply to wood products made using fast-growing species such as poplar, which may be harvested when it is as little as ten years old and used for engineered wood products such as oriented-strand board. As LEED gains sup-

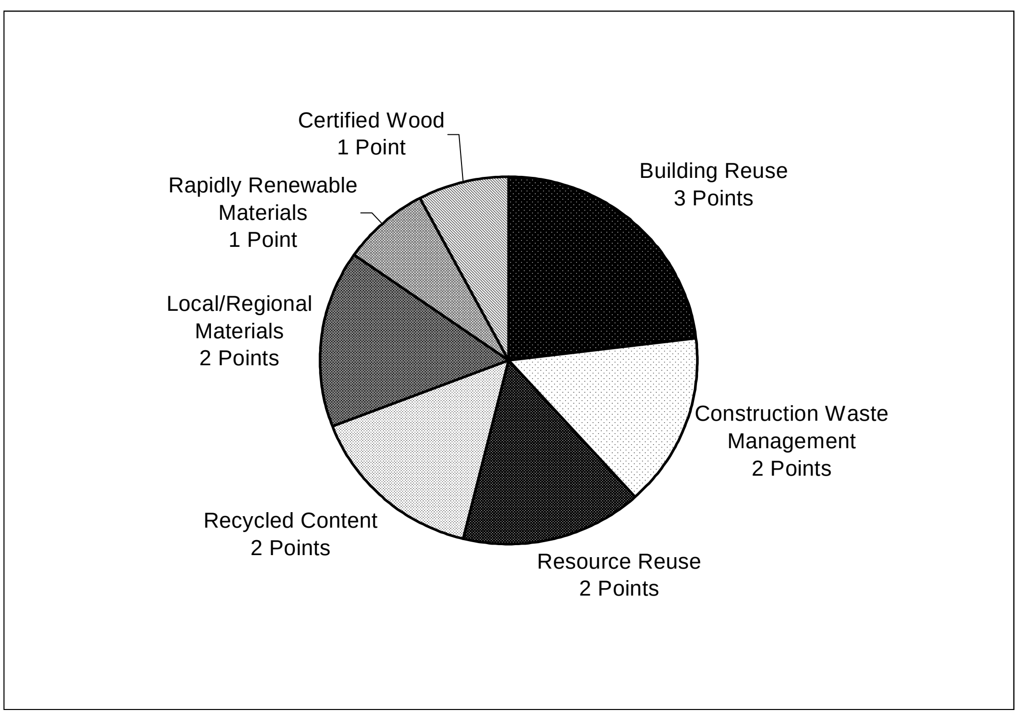

Figure 10: LEED Materials and Resources Credits

port, we may find that it gains enough market influence to encourage the manufacture of more products using these species.

Certain material choices may provide points in more than one category. For instance, using materials in new construction that are salvaged from a building demolished on the site could contribute to both Construction Waste Management points and Resource Reuse points.

The cited problems notwithstanding, LEED is a practical, useful building assessment tool that, on the whole, provides a good relative measure of how green a building is. It is a work in progress, and we can expect some of the problems to be rectified in future generations of LEED.

6. SAMPLE LCA STUDIES

A number of life-cycle assessment studies have been performed comparing alternate structural systems. These studies do not consider the effect of the choice of the structural system on non-structural systems. For instance, fireproofing and finish requirements may vary with the choice of structural systems. Nevertheless, the studies provide a taste of what to expect as LCA models become more sophisticated.

Figure 11 shows a comparison by Environmental Building News, using a beta version of the Athena software, of three alternative floor framing systems for a 10,700-sq-ft office space with 23- to 30-ft spans (EBN, Nov. 1999). Figure 12 shows the results of a University of British Columbia study, using an early version of the Athena software, of three alternative designs for a 4,600-sq-m (about 50,000-sq-ft), three-story office building with one level of underground parking (Athena, undated). This study included an examination of the energy required to demolish the building as well, considering either recycling or reusing the building structural components (Figure 13) (Athena, undated). As a final example, Buchanan and Honey performed embodied energy and CO_2 emission LCAs of three alternate building designs (Figure 14) (Buchanan and Honey, 1994). The authors assume that the non-structural environmental demands are the same for the alternate designs, which, as discussed above, is not necessarily the case.

7. CONCLUSION

We have much to learn in the practice of sustainable design. This paper has introduced a framework of concepts that may be used to evaluate the sustainability of a building's structural system. As the tools and ideas are developed further, these concepts will be refined, and the environmental implications of alternative structural design choices will become clearer. Even with the limited knowledge we have to date, it is possible to draw a number of useful conclusions regarding sustainable structural design:

- The choice and use of structural materials have many environmental impacts. Structural materials can account for more than 50% of a building's embodied energy and construction-related carbon emissions (see Figure 14), so much may be gained by considering environmental implications in the structural design.

- There is no "ideal" structural material; each has its pros and cons. Nevertheless, LCA studies show that certain structural systems impose greater strains on the environment than others.

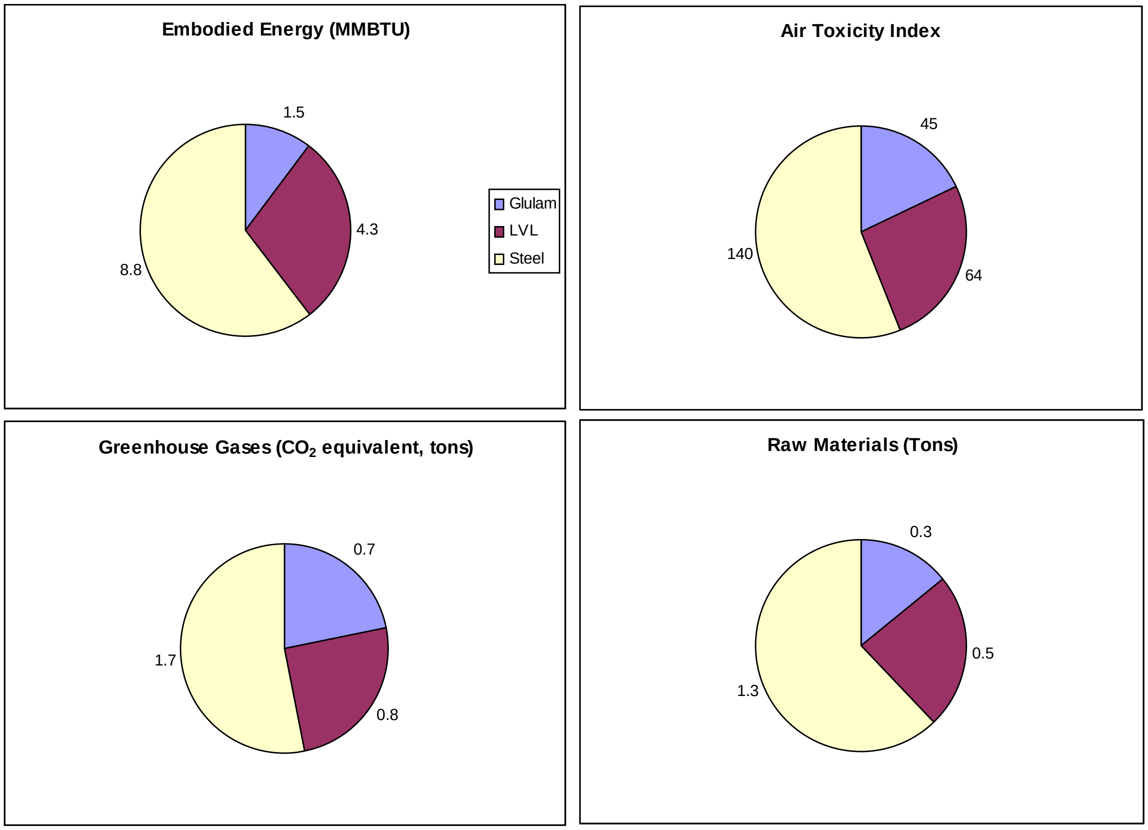

Figure 11: Athena Analysis Comparing Three Alternative Floor Framing Systems for a 10,700-sq-ft Office Space (source: Environmental Building News)

- Structural systems must be durable and adaptable.
- Structural designers should consider salvageability and recyclability at the end of the building's life.
- The structural engineer must work with the project team, particularly the architect and mechanical engineer, to improve the environmental performance of the structural system and the building as a whole. Collaboration should begin as early as possible in the project design.

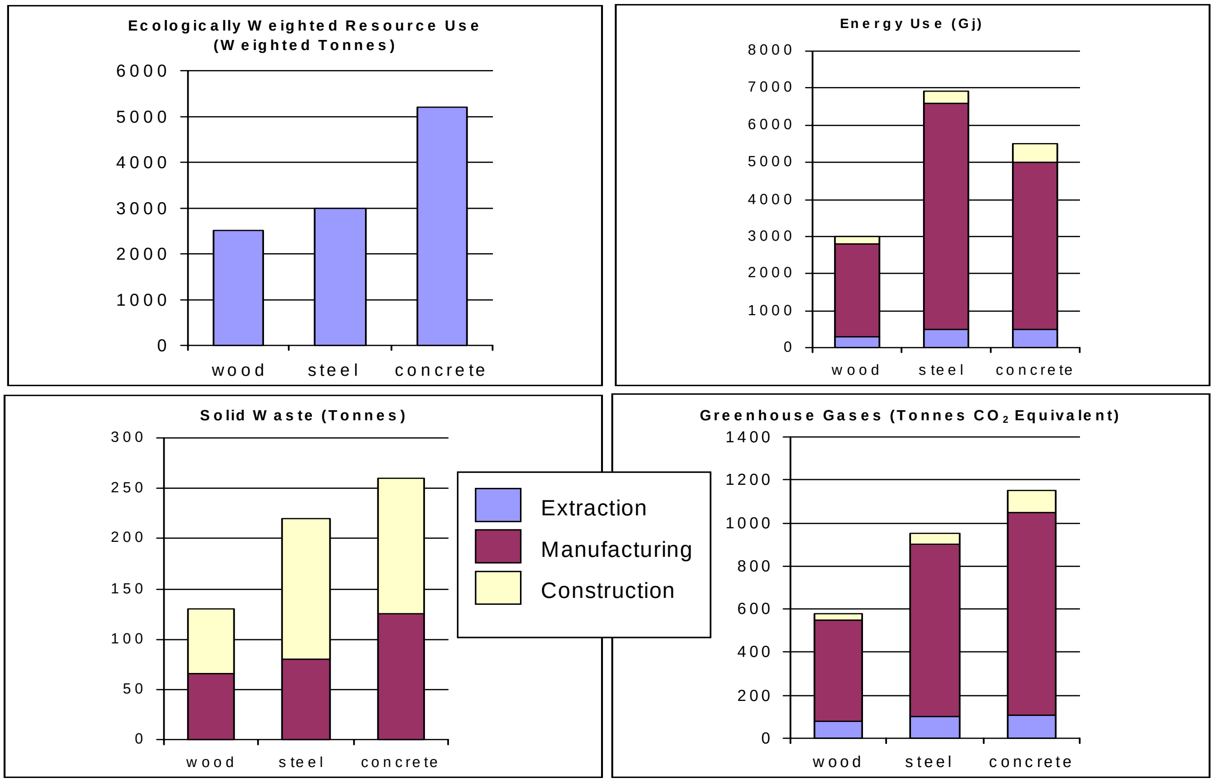

Figure 12: Athena Analysis Comparing Three Alternative Structural Systems for a 4,600-sq-m, Three-Story Office Building (source: Athena Project)

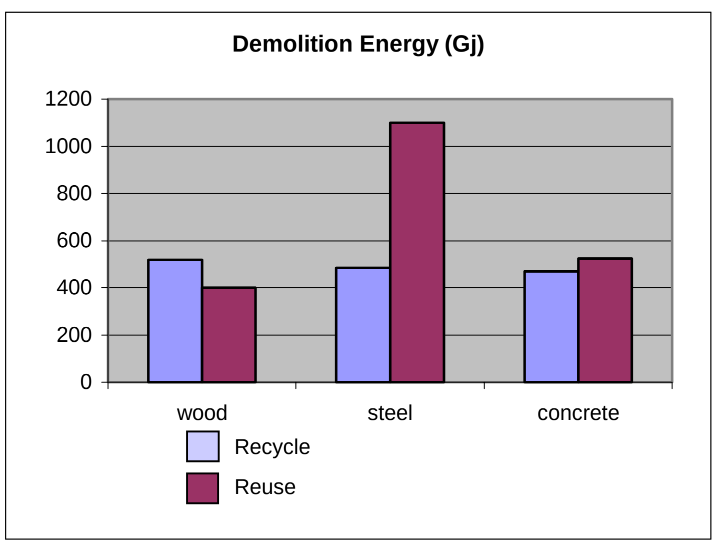

Figure 13: Athena Analysis Comparing Demolition Energy for the Building in Figure 12 (source: Athena Project)

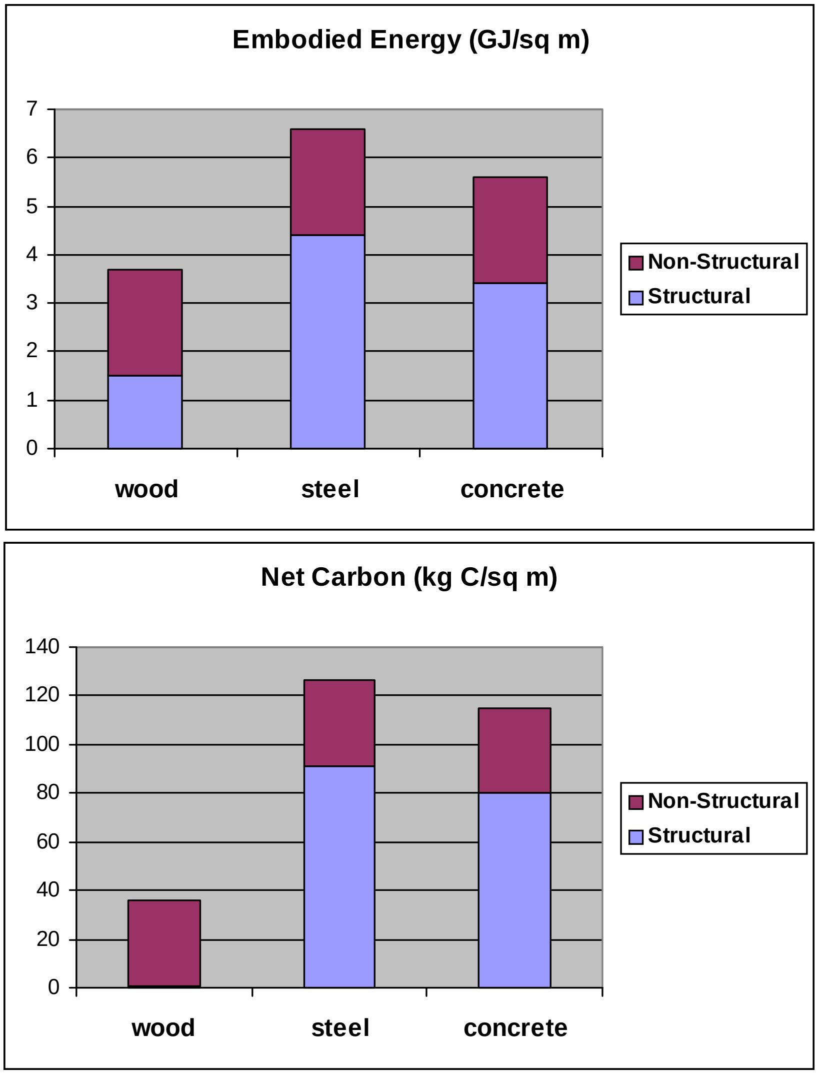

Figure 14: Buchanan & Honey Analysis Comparing Three Alternative Structural Systems (Source: David Walter)

References

1. American Institute of Architects (AIA) (1999). *Environmental Resource Guide*, John Wiley & Sons, 1999.

2. Athena Sustainable Materials Institute, www.athenasmi.ca/at-work/lca/structur.htm (no longer available at this address).

3. Augenbroe, Godfried and Pearce, Annie (1998). *Sustainable Construction in the United States of America*, Georgia Institute of Technology, College of Architecture, Construction Research Center, June 1998.

4. Brand, Stewart (1995). *How Buildings Learn*, Penguin Books, 1995.

5. Buchanan, Andrew H., and Honey, Brian G. (1994). "Energy and Carbon Dioxide Implica-

tions of Building Construction," *Energy and Buildings* 20(3) (as referenced in Walter 1999).

6. Cortese, Anthony D. (1999). "The Role of Engineers in Creating an Environmentally Sustainable Future," *Civil Engineering Practice*, Vol. 14, No. 1, Spring/Summer 1999.

7. Energy Information Administration (2000-1). *Annual Energy Review 1999*, U.S. Department of Energy, July 2000 (www.eia.doe.gov/aer).

8. Energy Information Administration (2000-2). *Emissions of Greenhouse Gases in the United States 1999*, U.S. Department of Energy, October 2000 (www.eia.doe.gov/oiaf/1605/ggrpt/index.html).

9. *Environmental Building News* (1997). "Disposal: The Achilles' Heel of CCA-Treated Wood," Vol. 6, No. 3, March 1997.

10. *Environmental Building News* (1999). "Structural Engineered Wood: Is It Green?," Vol. 8, No. 11, November 1999.

11. Guy, Bradley (no date). *Alachua County: Building Deconstruction Project*, University of Florida Center for Construction & Environment, no date, www.bcn.ufl.edu/sustainable.

12. Quebec Lumber Manufacturers' Association (2000). *The Quebec Lumber Industry: A Statistical Report, 1999 Edition*, April 2000.

13. Steel Recycling Institute (1999). "Steel Construction: Building for the Future," 1999, Steel Recycling Institute website, www.recycle-steel.org/construction/main.html.

14. Steel-UK website, http://www.steel.org.uk/makstlc.html.

15. Trusty, Wayne (2001). Conversation with the author, 17 January 2001.

16. United States Census Bureau (2000). U.S. Census website, www.census.gov/ipc/www/img/worldpop.gif.

17. United States Census Bureau (2000). *Lumber Production and Mill Stocks, 1999*, July 2000.

18. U.S. Green Building Council (2000). *LEED Green Building Rating System™ Version 2.0*, March 2000.

19. Walter, David (1999). *Environmental Consequences of Steel and Reinforced Concrete*, paper for CE 466, University of Illinois Urbana-Champaign, Fall 1999.

20. Wood Truss Council of America (WTCA), "What We Learned by Framing the American Dream," WTCA website, www.woodtruss.com/wtca/images/publication_images/fad.pdf.

21. World Commission on Environment and Development (WCED) (1987). *Our Common Future*, Oxford University Press, Oxford, 1987.

22. World Scientists' Warning to Humanity (1992). Union of Concerned Scientists website, www.ucsusa.org/resources/warning.htm.