SUSTAINABLE DESIGN AND ENERGY CONSUMPTION ANALYSIS FOR STRUCTURAL COMPONENTS

Joseph M. Danatzko,[1] Halil Sezen,[2] and Qian Chen[3]

ABSTRACT
The engineering community has been striving to design more sustainable buildings in an attempt to reduce both environmental impact and energy use during all phases of design, construction and operation. Design professionals currently have very limited guidance or tools to incorporate life-cycle and sustainability concepts into their designs. After reviewing the capabilities and limitations of four current life cycle analysis (LCA) computer programs, this research has selected the Athena Impact Estimator v4.0 to perform parametric studies of structural members made up of different construction materials. The energy consumption values are calculated and compared for columns, beams, concrete suspended slabs, precast double-tee sections and various other floor types. While Athena did offer some insights based on its LCA results, this research has concluded that existing LCA and sustainability analysis programs have too few options to meet the current needs of design professionals. A more accurate, sophisticated whole-building LCA tool needs to be developed to assess sustainable properties of design alternatives and to produce the most sustainable structural systems.

KEYWORDS
life cycle analysis, construction materials, sustainability, structural members, energy consumption, buildings

INTRODUCTION
As financial limitations and civic requirements mount in modern society, engineers and architects are increasingly required to incorporate sustainability concepts into their design. In all areas of civil engineering, engineers are encouraged to ensure that projects have the maximum lifespan for their intended use and employ the least amount of natural recourses (e.g., raw materials, water, land and energy required for extraction, processing, transportation, installing, and/or disposal of such materials/products) while still meeting client, economic, societal demands and code requirements.

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Two fields of civil engineering that are constantly assessing their ability to achieve sustainable goals are the engineering design and construction industries. For both new and rehabilitation projects, the goal of these industries is to achieve lasting and environmentally sound solutions to the problems faced in modern culture. Achieving this goal requires the design and construction engineers to assess all the related aspects and processes involved in a project. These include, but are not limited to, the embodied energy in building materials, design alternative maintenance requirements, material durability, recycled material contents, project adherence to and applicability within sustainable rating systems, structural system design methodologies, relation of sustainability to construction type, economy and availability of sustainable construction materials, and life cycle analysis (LCA) (Hill and Bowen 1997; Desai 1998; Mundy and Livesey 2004; Ding 2007; Passer et al. 2007; Kibert 2008; USGBC 2009). These aspects can vary and be influenced by local conditions and the economy (Beheiry et al. 2006).

In recent years, various rating systems, e.g., the Leadership in Energy and Environmental Design (LEED) Green Building Rating System (USGBC 2009) and the Green Globes Building Assessment Protocol (GBI 2012), have been developed. These programs have provided guidelines to facilitate the design, construction, operation, and demolition/disposal of green buildings or other green structures. However, these consensus-based rating systems have limited ability to address the aforementioned complexity in achieving the sustainable goals of the industries using them. For example, the LEED rating system, most widely used in the U.S. and globally, grades various design and construction approaches on a credit-weighted point system based on environmental impact in 13 categories (USGBC 2009; 2012). While the program offers various means through which a sustainable design can be achieved, including the selection of building site, conservation of water and energy, recycling and reuse of building materials and structural members, etc., it is limited in how the overall design of new structural systems can improve projects' sustainability. This is due to the lack of points addressing the efficiency of structures (Teller and Bergman 2010). Additional considerations could be given to the efficiency of using construction materials in structural systems, energy consumption and environmental impact of structures, recyclability of structural materials/components when the proposed projects reach the end of their life spans, and other important sustainable properties of structural systems.

At present, structural engineers, one of the key players in the design phase of a project, have less influence on a project's approach to LEED certification. Their current roles are limited to: 1) evaluating and specifying sustainable building materials (e.g., accounting for recycled content in structural steel), 2) assessing structural sufficiency in building reuse, and 3) providing structural support for some green building elements such as glass façades, green roofs, and rainwater/grey water collection tanks (Kestner 2007; Teller and Bergman 2010). To proactively address these issues, the engineering community needs to assess existing rating systems for their applicability to sustainable structural design. They also need to go further to better define the sustainable properties of the structures. In addition, further research is needed to provide structural designers and constructors with more accurate and holistic methods for minimizing the environmental impact of structural system design and construction. Particularly, research on the effect of structural form, system and magnitude on building design relative to a structure's overall sustainable qualities can be helpful in addressing the means and methods pertinent to sustainable project development phases, which include planning, design, and implementation.

Some existing studies have explored the energy demand and environmental performance of different structural systems and materials, generating inconsistent results. For example, Hauke and Siebers (2011) calculated and compared the total primary energy demand and global warming potential (GWP) of two different structural systems, structural steel and reinforced concrete frames, for a single story building. Based on the fixed span, eaves height, and bay distance, steel was found to be more competitive than concrete in terms of material use and environmental impact. However, research conducted by Buckley et al. (2006), using the Athena LCA software tool to analyze a school building, found that the cast-in-place concrete system had less overall environmental impact than the structural steel system despite its greater resource use. Passer et al. (2007) also performed an LCA-based pre-feasibility study on three office buildings with load bearing systems made of reinforced concrete, steel, and timber. While steel- and timber constructions were found to be more efficient in material use, the performance of all three systems was similar in the life cycle impact assessment based on the generic data sets currently used for construction products.

These conflicting research results imply that sustainable structural design is a complex task. There is no simple solution to this problem, as that concrete structures are always more environmentally friendly than steel structures, or vice versa. Also, sustainable structural design based on a simple choice of concrete, steel, or other material (such as wood) is not optimal. This approach prevents more deliberate consideration focused on how to maximize the environmental performance of individual structural members. As suggested by Passer et al. (2007), civil engineers need to study issues related to structural design, service life of building products, and assessment tools more intensively. "Structural sustainability" should be added as a fourth dimension of sustainability besides environmental, social, and economical considerations.

This paper aims to provide some deep understanding on how the sustainability of different types of structural members and materials can be affected by design loads, column heights, beam lengths and other factors. It also evaluates four commonly used LCA computer programs. This research does not target the whole-building structural system analysis at the current stage. The findings are expected to offer valuable insights for structural engineers to optimize the overall sustainability of their design through wisely selecting structural members and construction materials. The findings are more applicable to high-rise, multi-story buildings, but may not be very useful for designing low-rise residential buildings due to the dominant use of timber instead of structural steel and concrete in these structures. The research will also be helpful in assisting the design of "mixed structures" that combine the use of steel, concrete, timber and other structural materials to better utilize their environmental characteristics under different design parameter values.

SUSTAINABILITY AND STRUCTURAL SYSTEMS

The choice of structural load carrying system for a given project significantly affects the sustainability of the project in terms of resource use, energy consumption, environmental impacts, etc. (Buckley et al. 2006; Passer et al. 2007; John et al. 2009; Hauke and Siebers 2011; Cho et al. 2012). This system includes floor slabs, beams, columns and/or structural walls. In general, timber-framed buildings have lower initial embodied energy and GWP compared to concrete- and steel-framed buildings (John et al. 2009). As a project's size increases, structural system complexity can also increase. This is mainly due to factors including, but not limited to, design load increase. As a result, tall buildings and larger projects often encounter limitations to achieve better sustainable design (Wood 2007; Deane 2008; Elnimeri and Gupta 2008; Moon 2008; Shi and Han 2009). For example, primary load bearing systems in these projects typically require materials with higher strength properties such as steel, cast-in-place concrete, and prestressed/precast concrete. These materials often have higher initial embodied energy and GWP than some other materials, such as timber (Roaf et al. 2005; John et al. 2009).

As mentioned above, the structural materials (primarily concrete, steel, and to some extent, timber) selected for a project can greatly affect the overall project sustainability. Besides initial embodied energy and GWP, these materials also vary in other sustainable qualities (e.g., pollution control and control/utilization of waste in the manufacturing process, recycling rates, locality, and energy consumption during the operations and maintenance phases). Their use in a structural load carrying system can have unique effects of project sustainability (Szekely 1996; Penttala 1997; Horvath and Hendrickson 1998; Fruehan et al. 2002; Buckley et al. 2006; Naik 2008; Hauke and Siebers 2011). Therefore, for each of these primary construction materials, their individual sustainable qualities, e.g., byproducts associated with their production, production energies required for member fabrication/construction and total embodied energy, should be considered. Issues surrounding their use and application as sustainable materials should also be taken into consideration. Conclusions based on a single indicator could be biased and inaccurate (John et al. 2009).

Engineers have various methods to design a structural element or system. From material choice to lateral force-resisting systems, a structural system and its layout become a combination of the architectural form and engineering properties (two aspects that can often be at odds with one another). It is assumed here that the goal of sustainable structural design is the production of a structural system that meets the needs of the owner and user while minimizing the environmental impact and conserving resources wherever possible. Danatzko and Sezen (2010; 2011) investigate and discuss five sustainable structural design methodologies: minimizing material use, minimizing material production energy, minimizing embodied energy, life-cycle analysis/inventory, and maximizing structural system reuse. The proposed design methodologies are evaluated to determine which, if any, can produce the most sustainable structural designs. It was determined that no single methodology can address all the issues surrounding sustainable structural design. Combinations of two or more methodologies may increase the ability of design professionals to produce more sustainable designs. However, the complexity of decision-making also increases.

This paper uses the fourth methodology (i.e., LCA) to perform parametric studies that generate some deep understanding on how the sustainability of individual structural members made of different materials is affected by changing design parameter values. The reason for this is that LCA overlaps with some other methods and also provides comparatively more comprehensive information for analysis and decision-making.

REVIEW OF LIFE CYCLE ANALYSIS AND COMPUTER PROGRAMS

Successful sustainable design, for any structure, relies on the ability of the designers to provide input for a client on design alternatives. Accurate design alternative predictions require various measures of energy and environmental impact analysis involving a wide range of issues. The issues include, but are not limited to, production and embodied energies associated with construction materials, as well as an analysis of the environmental impact materials can have over their lifetime. While the producers of façade and non-structural building construction materials present designers and engineers with the sustainable properties of their products, all construction materials involved, including structural materials, must be accounted for as well.

Life cycle analysis (LCA), also known as life cycle assessment, is a widely used method to evaluate a product's ecological impact over its entire life span (ASTM 2005). This is done so that the sustainability of the product can be better determined. LCA is a holistic and complex approach that consists of four phases: goal definition and scoping, inventory, impact assessment, and interpretation. For most materials/products used in construction, their life cycle stages include extraction of raw materials, processing and fabrication, transportation, installation, use and maintenance, and reuse/recycling/disposal. At each stage, use of resources as well as emissions into the air, water, and ground are evaluated based on international standards for LCA principles and methodologies, such as ISO 14040 and ISO 14044 (ISO 2006a; 2006b). LCA can provide more objective and complete measurement of the sustainability of construction materials/products to support sustainable design.

The accuracy and value of a project's total LCA highly depends on an accurate prediction of used energy and environmental impact. Since the sustainability of individual materials contributes to total project sustainability, an accurate prediction of the sustainable qualities of these materials is required during design alternative analysis. Specifically, the energy requirements for production, transportation and use, environmental impact, and end-of-life options of such materials must be clearly determined. Although it is relatively difficult to quantify material sustainable properties, progress has been made in recent years through the efforts and active involvement of construction materials industries and research institutions (e.g., VanGeem 2006).

Private companies and government entities have created tools, in the form of LCA computer programs (e.g., BEES, GaBi and SimaPro), to assist designers working in the different fields in predicting energy and environmental impacts of materials and products. These programs vary in capability and address different issues, such as focusing solely on energy use, environmental impact, and other sustainable properties emphasized by some green building rating systems. For example, the Athena EcoCalculator has been used by the Green Globes rating system to assess the sustainability of project material selected (Athena 2007). These existing LCA programs make calculations based on data from a variety of industries and attempt to unify the results between alternative designs.

Cooper and Fava (2006) conducted a survey among 65 LCA practitioners from North America, Europe, Brazil, China, and a few other countries. They found that 69% of them had experience with off-the-shelf LCA software. Of these, 58% used GaBi, 31% used SimaPro, and the remainder used TEAM, BEES, Umberto and other programs. Although the wide use of GaBi and SimaPro was noticed in the study, many practitioners specified that they just used these programs to assess individual building materials and products such as fly ash, carpets, light bulbs, and acoustical ceilings. Therefore, it is unclear whether these tools are good for conducting LCA on the building structures. This research searched the U.S. Department of Energy (USDOE) website for software tools used for whole-building analysis under the subject of "Sustainability/Green Buildings". The Athena Model and BEES were found to be the only two LCA tools developed in North America among the total nine LCA programs listed (USDOE 2011).

In this paper, four computer programs (GaBi v5, BEES v4.0, SimaPro v7.1, and Athena Impact Estimator v4.0) are evaluated for their applicability to the life cycle analysis of building design alternatives. These programs typically employ databases created from information provided by various sectors of the construction industry and construction materials producers. These programs rely on the reported energy values, environmental impact and other sustainable properties of construction materials and processes.

GaBi LCA Software (GaBi v5)

GaBi 5 LCA software is developed by PE International in Germany (PE International 2011). It performs parallel analysis of environmental problems in product life cycles according to ISO standards and the optimization of production sequences from an economic point of view. GaBi enables consideration of different cost factors associated with the processes and the products' life cycles. It also provides users with advanced wizards when they key in various cost types. GaBi also assesses the products' socio-economic performance, making it the only LCA software tool to incorporate the three dimensions of sustainability. The databases used in the program are the largest on the market, containing over 4,500 ready-to-use Life Cycle Inventory (LCI) profiles, based on the primary data from European-based industry sources. Free access to the U.S. LCI database is now available to users. However, this database, which was created by the U.S. National Renewable Energy Laboratory and its partners in 2003, is still limited and needs further development and expansion.

To address the growing need for whole-building life cycle analysis, PE International has recently developed a professional software solution: GaBi Build-it (PE International 2008). This program is based on a generic building model. After users enter the amount of building materials and the energy demand for the building, the program can calculate the building's environmental impact in line with ISO 14040/14044 and the requirements of the German Council for Sustainable Construction. With over 600 eco-profiles for various building materials and energy production, this software is able to compare different building alternatives within the planning stage. However, at present, the software is only available in the German language. In addition, the use of a generic building model may not accurately represent different types of buildings or some specific buildings.

Building for Environmental and Economic Sustainability (BEES v4.0)

The BEES Version 4.0 program was developed at the Building and Fire Research Laboratory of the National Institute of Standards and Technology (NIST) (Lippiatt 2007). It is an LCA tool that performs side-by-side comparison of a single construction material type involved in an individual project design. The program interface allows its user to set weighting ratios for various aspects of both environmental and economic impacts resulting from a product's use. These impacts can then be compared to those of another product in the same major group. An example of the program's material comparison options would include comparison of two concrete beams, made with 100% Portland cement mix and 15% fly-ash cement mix concrete, respectively, from either the same or different locations (input as distance from manufacturing plant to project site). The scores calculated for a product's environmental impact and economic performance over its life cycle are generated from a database contained within the program. The databases are periodically updated by NIST laboratories and contain data associated with raw materials, byproducts of production, wastes due to installation and maintenance, type of energy employed in production and land use associated with life cycle stages of a construction material.

The BEES v4.0 program allows users to compare construction materials by setting the weight of the importance of economic and environmental outputs to the overall project goals, e.g., 50/50 for equally important economic and environmental impacts. Also, the environmental impact of a product can be determined as a function of distance from the project site to emphasize the significance of using locally produced products (Lippiat and Boyles 2001). However, the BEES v4.0 outputs are computed from internal tables that are not available to the user. Also, economy of scale or construction advantages of different design alternatives cannot be compared because material quantities cannot be defined within the program. In addition, at the current stage, the databases used by BEES are still limited, with environmental and economic performance data for only 230 building products. Therefore, using BEES for whole-building LCA is not practical.

SimaPro Software

The SimaPro LCA program, developed by PRé Consultants (2009) in The Netherlands, offers its users an extensive database of predefined materials, and the ability to edit and compare these materials and products. The program also allows the user to perform environmental, energy and life cycle analyses using various analysis methods, including BEES and TRACI. SimaPro v7.1 falls short as it only allows for comparison of product alternatives and not design alternatives. The limited raw material inputs hinder the ability of a user to define new products, which leads to limitations in the results and the program's effectiveness to compare alternative project designs. Similar to the BEES v4.0 program, material quantities cannot be considered in SimaPro v7.1. Therefore, the environmental effectiveness and economic efficiency cannot be compared for different structural systems with varying construction materials.

Athena Impact Estimator for Buildings

The Athena Impact Estimator v4.0, developed by the Athena Sustainable Materials Institute (Athena 2008), includes environmental and energy analysis measures. It also allows for alternative design comparison by life cycle stage or embodied energy effect. The environmental impact and energy values are determined from an industry-generated database. The database includes both interior and exterior building components and covers some factors such as concrete strength and fly ash content. The analysis results can provide insight into energy expenditures and environmental impact during each stage of the building's life. Unlike BEES and SimaPro, the Athena Impact Estimator v4.0 considers material quantities in its analysis. The program also has a larger database and is able to simulate more than 1000 different assembly combinations. This allows it to model the structure and envelope systems for over 95% of building stock in North America. So far, it is the only software tool in North America that evaluates whole buildings and assemblies based on internationally recognized LCA methodology (Athena 2008).

The aforementioned Athena EcoCalculator (Athena 2007) is a free software tool provided by the Athena Institute. This tool provides instant LCA results for hundreds of commonly used building structure and envelope assemblies. However, since the embedded results are based on detailed assessments previously conducted by Athena experts using the Athena Impact Estimator, the EcoCalculator's capacity may be limited.

The Athena Impact Estimator is limited by its focus on general architectural and quantity comparisons. It has difficulty in accurately comparing varying structural design layouts. Similar to the previous programs discussed, it relies heavily on industry-defined databases in which data sets are generic and may not always be accurate due to the lack of peer review and validation.

Comments on LCA Computer Programs

In general, the LCA programs reviewed above rely heavily on industry-defined databases for analysis. These databases can distort outputs in a manner not helpful for comparing design alternatives. For example, existing research found that LCA data varies in different countries or regions (e.g., Europe and New Zealand) due to different manufacturing practices and energy uses (Nebel et al. 2009). Therefore, data sources for the LCA program affect the accuracy of analysis results. Also, the reviewed programs lack the ability to fully define a project's building envelope and/or structural system. Each of the four programs only provides general comparisons for design alternatives. For example, material strength, durability or similar properties are not fully incorporated into program-defined sustainable properties. Using multiple programs may lead to more effective design results, but their shortcomings are often overlapping and may not provide all the necessary solutions for accurate design alternative comparisons at this point in time.

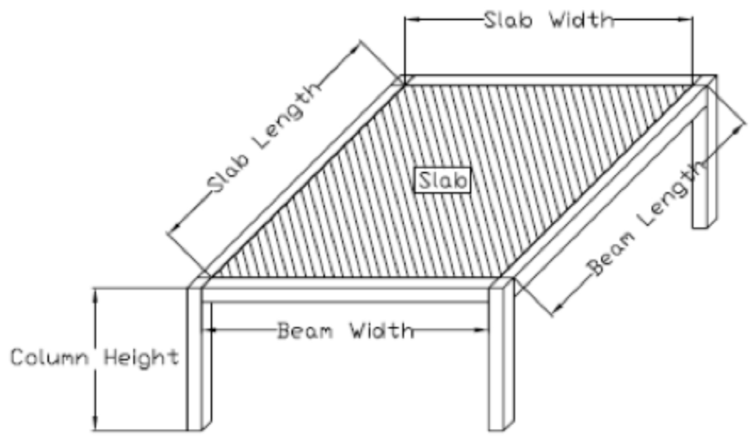
From the review of selected LCA computer programs and analysis of their pros and cons, this research concluded that the Athena Impact Estimator v4.0 would best serve in parametric studies to assess the relationship between selected structural members and their energy consumption/environmental impact. The program is a whole-building LCA tool that can also assist the design of a sustainable whole structural system. Its data is more complete and appropriately representative of U.S. manufacturing processes. The program will have broader applications in sustainable building design in the North American construction industry.

METHODOLOGY

This research adopts a parametric study approach to assessing the energy consumption and environmental impact of different structural components and materials with changing design parameter values. Specifically, energy demands for individual life cycle stages of a simple structure are calculated and compared for beams, columns and floor slabs considering steel, concrete, and wood materials. This research is an initial attempt to understand how the sustainability of selected types of structural members and materials can be affected by varied design parameter values. It is not intended to be inclusive of all different structural members. Also, walls and roof are typically not structural members, and therefore not included. In this research, the Athena Impact Estimator v4.0 is used for life cycle analysis. The life cycle stages include manufacturing, construction, operating and maintenance, end-of-life, and total lifespan. In addition to element types and materials, this research also investigated the effects of parameters such as magnitude of floor live load, concrete strength, concrete fly ash percentage, and variation in member lengths on energy consumption. Since the environmental impact is closely related to energy use, structural components and materials that are associated with lower energy consumption will also have a lower environmental impact.

The parametric study used a generic model, representing a one-story structure with one slab, four beams and four columns (Figure 1). For each analysis, the value of only one parameter (e.g., height, span, live load, or concrete strength) of the selected structural member was varied while the values of all other parameters of the model were kept constant. In all analyses, the project location was set to "USA" with a "commercial" building type and a 50-year life expectancy. Further details of the building model, detailed analysis and output information are provided in Danatzko (2010). This paper only presents some major findings.

FIGURE 1. Illustration of generic structure model in Athena Impact Estimator.



RESULTS AND DISCUSSIONS

Energy Consumption for Column Members

The required energy consumption was calculated using the Athena Impact Estimator v4.0 for wide flange (WF) steel and concrete columns. For the column energy predictions, slab and beam dimensions were held constant. Only the floor-to-floor height, column type and magnitude of live load were varied, one at a time. The concrete suspended slab was 20 ft square (gross area of 400 sq ft) with a concrete strength of 4000 psi. All beams were WF steel and 20 ft long.

The analyses were performed for floor live loads of 45, 75 and 100 psf. The column height varied from 10 to 15 ft. Figures 2 and 3 show the calculated energy uses for varying column heights and live loads for steel (WF) and concrete columns. As illustrated in Figure 2, the required energy linearly increases with increasing column height or the amount of materials

FIGURE 2. Column height versus total energy consumption for 75 psf live load.

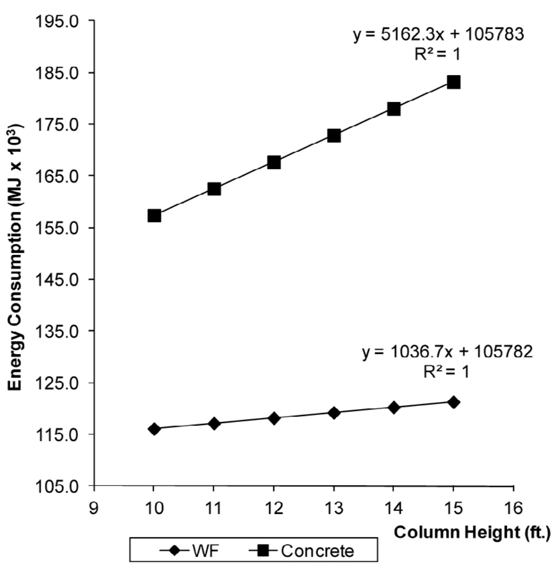
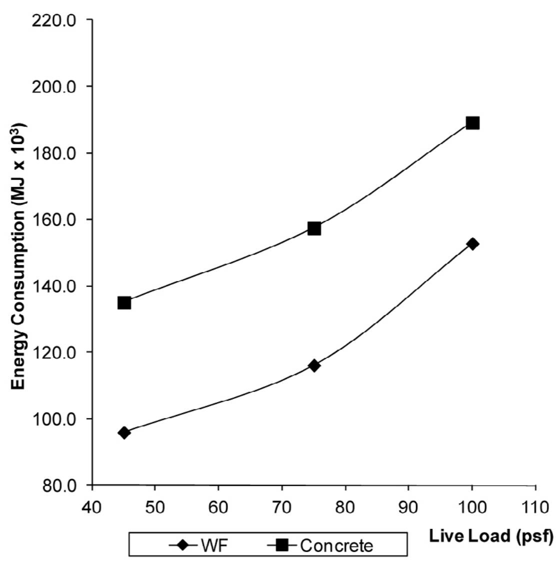


FIGURE 3. Live load versus total energy consumption for columns (column height of 10 ft).



used in the column for live load of 75 psf. The linear equations shown in the figure indicate that the total energy required for the construction and operation of the structure without columns (i.e., x = 0) is approximately 105,800 MJ, almost the same for both materials. The energy consumption increase rates (slopes of lines) are 5162 and 1037 MJ for concrete and steel, respectively. The results suggest that, according to the Athena Impact Estimator databases, the amount of energy required to produce a concrete column is approximately five times more than that of a steel column. Also, when column height increases, the energy consumption of concrete columns rises more sharply than that of steel columns. Figure 3 shows a very similar trend for uniform floor live loads of 45, 75 and 100 psf when column height is 10 ft. The energy consumption required for concrete is always larger than that for steel. Energy consumption increases as live load on columns increases, however, at similar increasing rates.

Energy Consumption for Beams

Energy consumption values were calculated for varying beam lengths and floor live loads. The concrete suspended floor slab was 20 ft square, the floor-to-floor height of the steel columns was 12 ft, and strength of the concrete was 4000 psi in all analyses.

Figure 4 shows the calculated energy consumption for beams with lengths varying from 15 to 40 ft. It should be noted that in the analysis only the beam length was increased in the longitudinal direction as shown in Figure 1. The beam and slab width was kept constant at 20 ft in the transverse direction. Figure 4 shows that the energy requirements for steel (WF) beams are consistently larger than those for concrete beams. While the energy requirements are markedly high for longer steel beams, the energy consumption for concrete beams increases slowly the longer the beam gets. Figure 5 shows that much less energy is required to produce a 15 ft long concrete beam than a steel beam for the three floor live load cases considered in the analyses. With increasing loads, energy requirements for steel increase more sharply than for concrete.

FIGURE 4. Beam length versus total energy consumption for 75 psf live load.

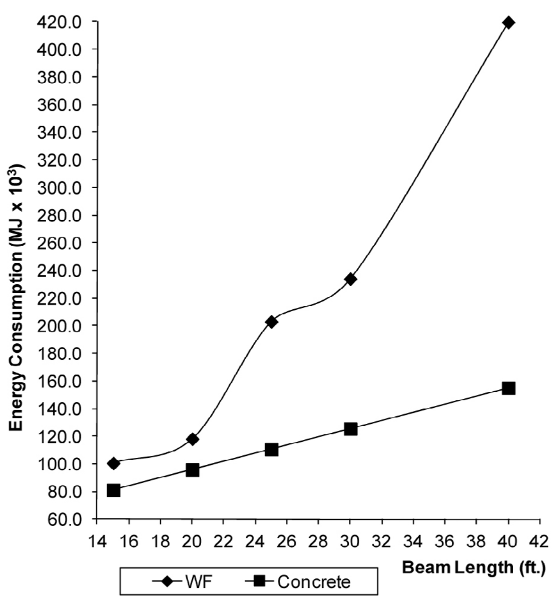
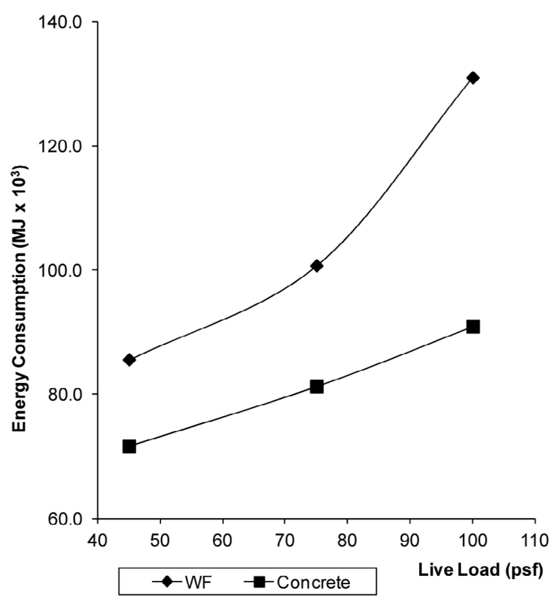


FIGURE 5. Live load versus total energy consumption for a 15 ft long beam.



Energy Consumption for Different Floor Systems

Concrete Suspended Slab System

The required energy consumption was calculated for concrete suspended slab systems with varying slab sizes. In the analyses, all beams were WF steel and 20 ft long. All WF steel columns were 12 ft tall. While holding all other parameters constant during analyses, the length of the slab (Figure 1) was increased under varying floor live loads.

A 20 ft by 20 ft concrete suspended slab was analyzed using 3000, 4000 and 9000 psi concrete and uniform live loads of 45, 75 and 100 psf. The analysis results are displayed in Figures 6 and 7. In both figures, the energy consumption of the slab rises as concrete strength increases. Specifically, a steep rise of energy consumption can be seen when concrete strength changes from 3000 psi to 4000 psi. However, the energy consumption increases slowly when concrete strength changes from 4000 psi to 9000 psi. It was found that the slab's energy requirements for live loads of 45 and 75 psf were similar for three different concrete strengths. However, the energy consumption increases when the live load changes from 75 psf to 100 psf.

Based on different fly ash ratios in concrete (provided by the LCA program), the analyses were repeated for various gross floor areas and floor live loads. Although it can be seen in Figure 8 that the energy consumption decreases as fly-ash percentage increases, the decrease is usually small regardless of the floor area and floor live load used. In addition, as shown in Figure 9, energy consumption decreases by a small amount for all fly ash percentages when the live load is increased from 45 psf to 75 psf. By contrast, the slab's energy consumption for all fly ash percentages increases when live load is increased from 75 psf to 100 psf.

Precast Double Tee Floor System

A structure with a 400 sq ft gross slab area, four 20 ft long concrete beams and four 12 ft long concrete columns, was used to investigate the energy consumption required for a precast double-tee floor system. The structure models with and without concrete topping were analyzed

FIGURE 6. Concrete suspended slab concrete strength vs. total energy consumption.

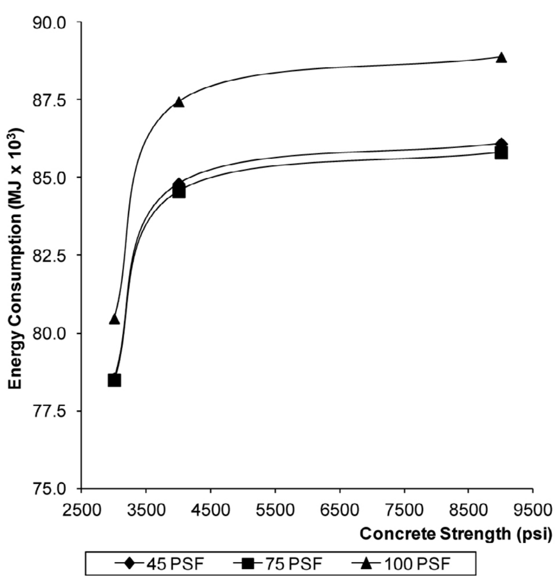


FIGURE 7. Live load vs. total energy consumption for concrete suspended slab at concrete strengths of 3000, 4000 and 9000 psi.

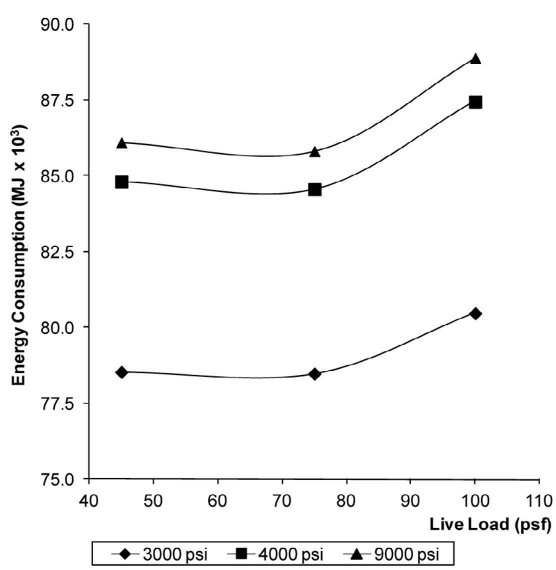


FIGURE 8. Gross floor area vs. energy consumption for different fly ash percentages (75 psf).

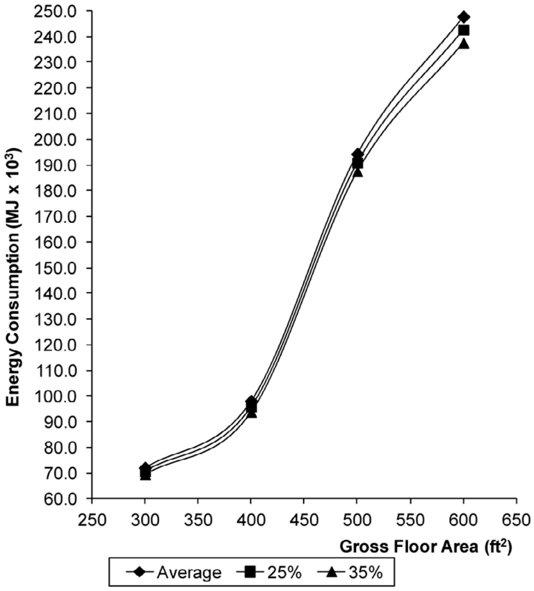
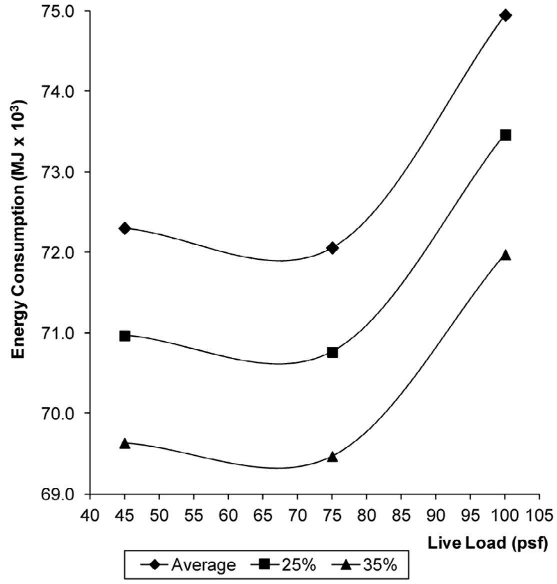


FIGURE 9. Live load versus energy consumption for different fly ash percentages.



using various span lengths and live loads. Figure 10 shows that the total energy consumption increases with increasing span length and live load, and when concrete topping is included. As expected, the energy consumption increases as the slab size and live load increase.

Other Floor Systems

The energy consumption requirements for eight different floor types were calculated and compared. These eight floor types were: concrete suspended slab, precast double tee (topping excluded), precast double tee (topping included), light-frame wood truss system, wood I-joist, steel joist system, open web steel joist (topping excluded), and open web steel joist (topping included). All models included four 12 ft concrete columns and four 20 ft concrete beams on the perimeter of the model, as shown in Figure 1. The values for span and bay width were set at 20 ft, concrete strength was 4000 psi, uniform live load was set at 75 psf, and the number of bays was set at 1, where applicable, for the various floor types. All other inputs associated with the various floor types were maintained as equal as possible within the Athena Impact Estimator v4.0 program limits. For the light-frame wood truss system, the decking type was set to plywood and decking thickness was set at 1/2 in. For wood joist floors, decking thickness was set at 1/2 in., flange size was set at 1.5 × 1.5 in., decking type and web type were set to plywood, and flange type was set to MSR. For steel joist floors, decking thickness was set at 1/2 in., steel gauge was set at 16, joist type was set to 1 5/8 × 8 in., and joist spacing was set at 16.

Figure 11 shows the total energy consumption calculated for eight floor types. While the energy consumption for the light-frame wood truss system was the lowest, the energy consumption for a wood I-joist floor was higher than the energy required for a concrete suspended slab, open web steel joist (topping excluded), or open web steel joist (topping included), respectively. Energy consumption for a precast double tee floor (with topping excluded) was less than a steel joist floor but more than a wood I-joist floor. Energy consumption for a precast double tee floor (with topping included) was the highest of all floor types investigated.

FIGURE 10. Slab span versus total energy consumption.

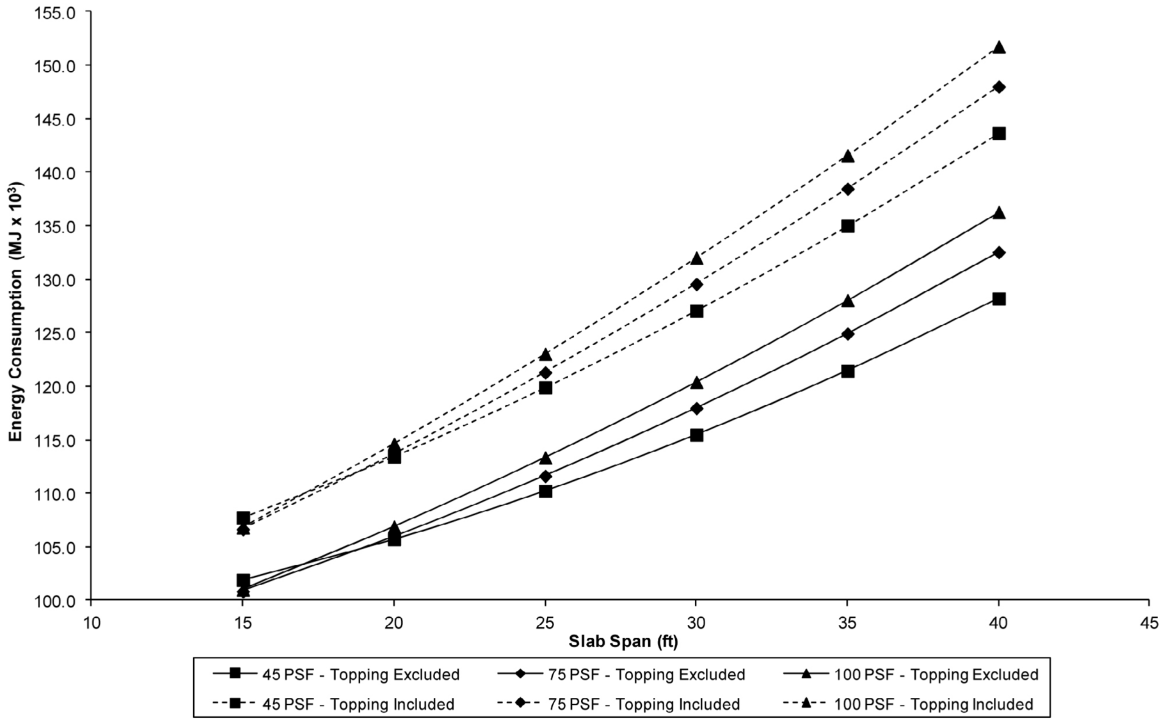
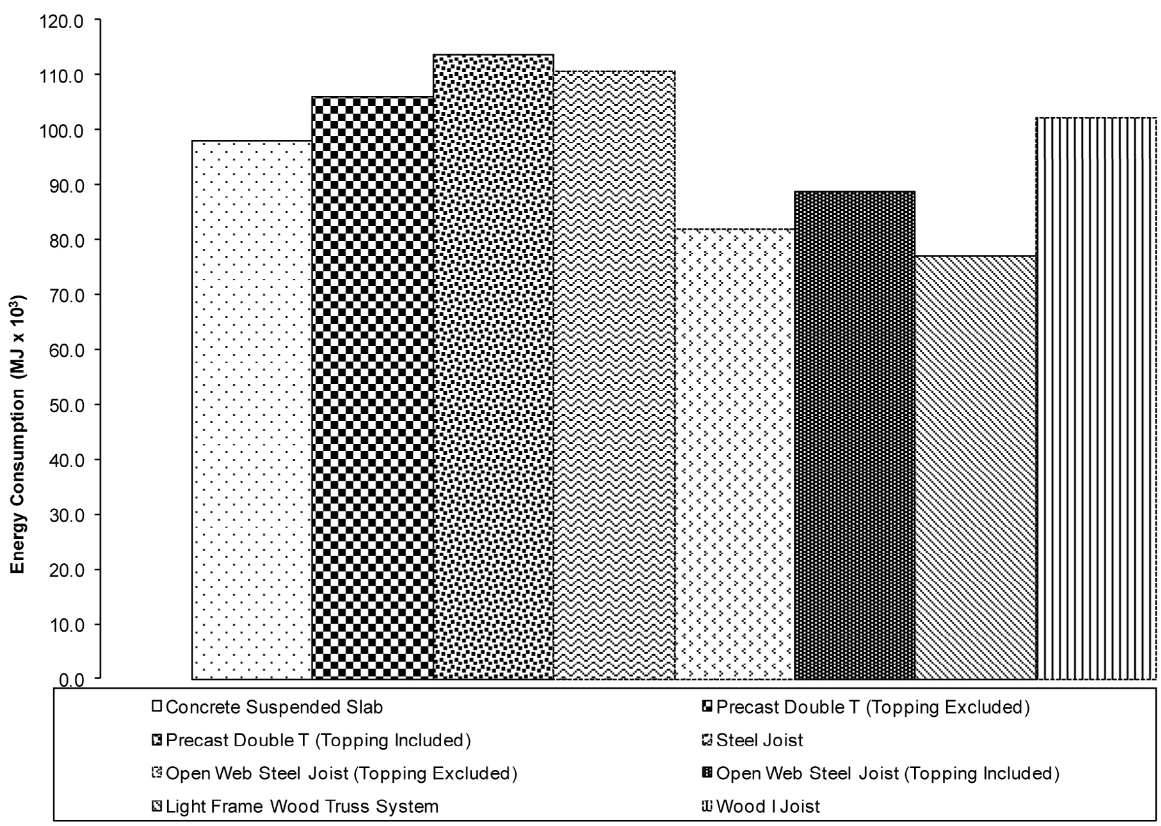


FIGURE 11. Total energy consumption by floor type (concrete hollow core floor excluded).



Through the above discussions, it can be seen that sustainable structural design is an inherently complex process. As mentioned earlier, it is not a simply choice of concrete over steel or vice versa. The energy consumption/environmental impact of individual structural members can vary slightly or largely with changing design parameter values. Based on the generic models and design conditions used in this research, for some structural components (e.g., column), steel constantly has better environmental performance than concrete. However, it is the opposite for some other structural components such as beams, for which using concrete always consumes less energy. For the selected floor types, the results are mixed among steel, concrete, and wood. This research held some parameters constant while changing values of other parameter(s) for analysis. The real-world cases would be even more complicated since multiple parameters' values could vary in alternative designs. Further research in this area would be needed.

LIMITATIONS

Since little research has been done to investigate the sustainability of structural elements and systems, this research is limited by: 1) lack of previous research on quantification of sustainability for structural design alternatives, 2) lack and difficulty in developing equations and methods without heavily relying on industry-provided energy values and tables, 3) limited data on total production inputs and energy requirements for construction materials, and 4) limited number and accuracy of tools and computer programs to assess sustainability of design alternatives.

CONCLUDING REMARKS

This research paper pointed out the need for further investigation of the sustainability of structural components and systems to further minimize the energy consumption and environmental impact of sustainable buildings. It was found that the LEED 2009 ratings system, currently the most popular, does not reward projects for sustainable design of their structural systems in the same manner it does for other aspects of design (it does, however, give points to projects that maintain structural components for building reuse). The rating system also does not offer insights into how the structural frame system can be designed more efficiently to improve a project's overall sustainability. A review of current LCA computer tools showed that current LCA or design alternative comparison programs do not meet the needs of engineers to evaluate and optimize structural sustainability. The Athena Impact Estimator program is the only whole-building LCA tool in North America that can calculate energy consumption requirements for structural systems and building envelopes. Also, accurate prediction of the sustainability of design alternatives relies heavily on the accuracy of the data provided by the industry.

This paper used the Athena Impact Estimator v4.0 to investigate the energy consumption and environmental impact associated with different structural components and materials based on a simple generic structural model. The following conclusions were reached: 1) the amount of energy required to produce a concrete column is much higher than that needed for a steel column based on varied column heights and floor live loads, indicating that steel columns are more sustainable; 2) the energy requirements for steel (WF) beams are consistently larger than those for concrete beams with varying lengths and floor live loads, indicating that concrete is more sustainable material than steel if used in producing building beams; and 3) small variations exist in energy requirements for eight different floor slab systems selected by this research, but no single construction material (i.e., concrete, steel, and wood) is most sustainable for all design types.

This research contributed to a deeper understanding of the sustainability of individual structural components and materials under varied values of design parameters. The research findings suggested that sustainable structural design is a complex decision-making process. Deliberate considerations are required in the selection of structural forms, components, and materials based on the given design conditions. An integrated whole-building structural design and LCA tool needs to be developed, which should go beyond simply comparing different design alternatives and move toward intelligently offering insights and providing instant feedback throughout the design process. This will help ensure that the most sustainable structural design option can be determined.

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