Life-Cycle Assessment for Structural Engineers

Megan Stringer, PE
Chair, SEAONC SDC
Holmes Culley
San Francisco, CA

Frances Yang, SE LEED AP BD+C
Chair, SEI Sustainability Committee
LCA Working Group
Arup
San Francisco, CA

Abstract

"Sustainable" and "green" have been the buzzwords around the architectural, engineering and construction (AEC) industry for many years. With clients demanding more from their buildings, green rating systems becoming increasingly popular, and green buildings codes being developed and adopted, the structural engineering community has a vital role to play in the sustainable design movement. It is widely recognized that human-caused greenhouse gas emissions are largely responsible for global warming, with carbon dioxide being the most abundant of the greenhouse gases. The United States is a top emitter of carbon dioxide, with over a third of the emissions coming from buildings. While currently most of this impact is from buildings' energy use during operations, this is coming down, and thus the environmental embodied energy impact of building materials is becoming increasingly significant.

Understanding the role structural engineers can play in reducing the embodied energy impact of buildings requires awareness of the environmental impacts of the building materials being specified and what measures are most effective in reducing them. Life-cycle assessment (LCA) can be a valuable tool for this. LCA is a way to quantify the environmental impacts and resource use, such as greenhouse gas emissions and energy consumption, of a product from all stages of its life. It allows for comparison of various building systems and offers a comprehensive way to evaluate and reduce the environmental impact of buildings. LCA is quickly becoming a fundamental part of the sustainable design movement and will have a vital role in the push towards a more sustainable built environment.

Introduction

LCA is rapidly becoming the primary method of measuring the sustainability of buildings as its offers a scientific approach to accounting for the impact buildings have on the environment. As sustainability becomes increasingly important, it is imperative for the structural engineering community to be engaged in the movement. This paper introduces the concepts of life-cycle assessment to structural engineers and is intended to set the foundation for two other papers on LCA; "Lessons Learned from Recent LCA Studies" and "SEAOC SDC LCA Case Studies – Comparing 8 Different Structural/Seismic Systems." This paper is a collaborative effort of the ASCE SEI's Sustainability Committee and the SEAONC Sustainable Design Committee.

Why the Structural Engineer?

The range is large for various reasons, but approximately 50% of the embodied energy of buildings is in the structure. (See following paper, "Lessons Learned from Recent LCA Case Studies" for more detail.) With this knowledge, it becomes evident that structural engineers have an important role to play. The senior vice president of LEED stated when likening LCA to energy modeling, "One of the things we want to try to do is initiate a discussion between the designer and the structural engineer in the same way that energy modeling initiated a discussion between the designer and the mechanical engineer.” (Melton, 2013) This statement implies that structural engineers can have a new service to offer, but only if they acquire the necessary skills and knowledge about LCA.

What is LCA?

Understanding the role structural engineers can play in reducing the embodied energy impact of buildings requires awareness of the environmental impacts of the building materials being specified and what measures are most effective in reducing them. The U.S. Environmental Protection Agency (EPA) defines LCA as a “technique to assess the environmental aspects and potential impacts associated with a product, process, or service, by compiling an inventory of relevant energy and material inputs and environmental releases, evaluating the potential environmental impacts associated with identified inputs and releases, and interpreting the results to help you make a more informed decision.” Looking at the impacts of the product, process, or service over its life cycle “…provides a comprehensive view of the environmental aspects of the product or process and a more accurate picture of the true environmental trade-offs in a product and process selection.” (EPA, 2006)

There are four main phases of an LCA:

1. Goal and scope - the context of the assessment is outlined. Proper definition of the parameters and boundaries of the LCA is essential for the meaningful interpretation of the results.

2. Life-cycle inventory analysis (LCIA) – the materials, energy, and environmental releases are identified. This is the primary data collection phase.

3. Life-cycle impact assessment – the potential effects from the inventory are assessed.

4. Interpretation – the results from the assessment are evaluated. Results are translated into “practical terms and that can be used to improve the sustainability of the building.” (Kestner et. al., 2010)

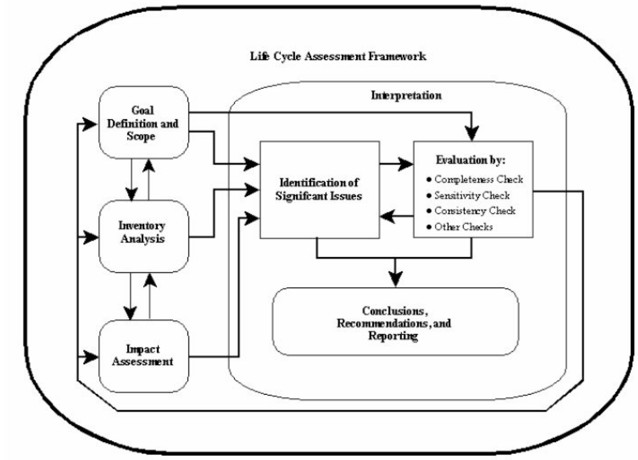


Exhibit 5-1. Relationship of Interpretation Steps with other Phases of LCA (Source: ISO, 1998b)

Figure 2 – LCA Components Flow Chart[1]

LCA was initially developed to evaluate and reduce the environment impacts of industrial processes and has since been applied to other industries and processes, including buildings. The life cycle of a building can be divided into four phases:

1. Initial construction – includes the environmental impacts from the construction of the building including resource extraction, production and manufacturing of the building materials, transportation of the materials to site, and construction.

2. Building operation – includes the energy and water consumed during the daily operation of the building, as well as the waste generated.

3. Reoccurring maintenance and renovation – includes impacts from materials and energy use required to maintain the building.

4. End of life – includes impacts related to demolition and disposal of the building.

[1] Source: International Standards Organization

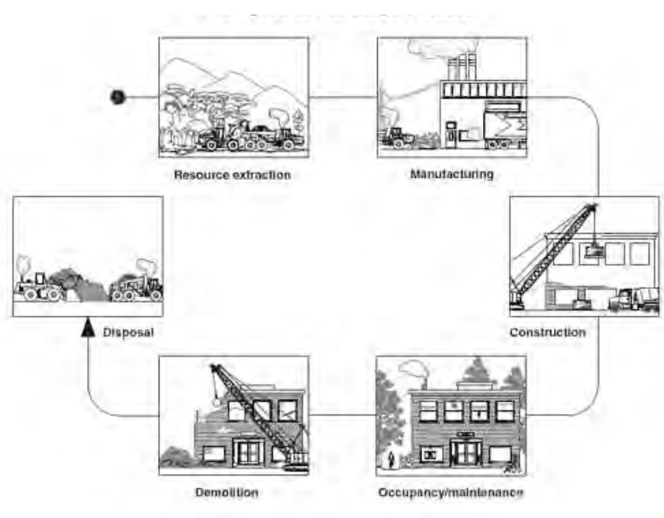


Figure 3 – LCA of a Building

A comprehensive and accurate calculation of a building's embodied energy requires looking at the impacts of a building over its life; from extraction of raw materials to end-of-life. This reflects cradle the cradle-to-grave concept. Areas or phases that are the most energy intensive can be determined and then improved upon. The LCA can show the relative impacts, for example, of using materials sourced from one location versus another, versus adding supplementary cementitious materials into a concrete mix. It allows one to identify and replace materials or processes that are very energy intensive with materials or processes that are less.

In addition to the environmental impacts of the structural materials, structural engineers need also to consider the "…effect of material choice on energy requirements for heating and cooling over the lifetime of the building…" [Levine et al]. Holistic design approaches must be taken. For example, a high performing building envelope could have a high embodied energy but the building's energy savings on heating and cooling demands could offset the envelope's embodied impact. As more projects take an integrated design approach, structural engineers can provide a more significant contribution to the sustainability of their buildings and will need to be aware of LCA principals to participate effectively in the integrated design process.

Metrics of an LCA

The most popular metrics of an LCA performed in the U.S. are the impact categories below, with description and units of measure as indicated. (Curran and Andersen, 2012)

1. Global Warming Potential (kg CO_2 equivalent) – increase in the temperature of the Earth's atmosphere and oceans.

2. Acidification (moles of H+ equivalent) – Increase in acidity of oceans, freshwater, and soil affecting aquatic life.

3. Eutrophication (kg N or PO_4 equivalent) – Excess nutrients in water bodies leading to oxygen depletion and algae growth which adversely affect aquatic life.

4. Stratospheric Ozone Depletion (kg CFC-11 equivalent) – reduction of the ozone layer, which protects against UV rays.

5. Photochemical Ozone Creation (kg NO_x or C_2H_6 equivalent) – air pollution creating the phenomenon of "smog," affecting human health.

6. Criteria Air Pollutants (ppm) – particulate matter in the air affecting respiratory health, such as inducing asthma.

7. Human Health (kg DCB eq) – substances identified as toxic to humans, sometimes classified into those related to cancer and non-cancer damage in humans.

8. Ecotoxicity (kg DCB eq) – indicator of toxic damage to non-human living organisms, i.e. toxic burden on an ecosystem, mostly from heavy metals, sometimes classified into fresh water aquatic, terrestrial, and marine ecotoxicity.

American designers should be aware that other impact categories and classification systems are more popular in other countries.

Benefits of LCA

Once the basic purpose and methodology of LCA is understood, it becomes evident how LCA can offer several benefits to sustainable design:

1. LCA moves beyond simplistic assumptions to determine better indicators of burdens on the environment.

2. It can account for impacts over the full life-cycle of a building. All too often, vendors focus on a narrow snapshot to claim sustainability credentials. LCA helps overcome "green washing" by providing a

more complete picture of environmental effects inherent in choosing certain structural materials.

3. LCA also allows one to evaluate performance across a variety of environmental and human health indicators. It is common to see manufacturers touting environmental merits based on a single characteristic (e.g. recycled content), but there are often trade-offs for materials between types of environmental impacts. LCA recognizes this and provides the most complete information through the inventory, and allows the user to make choices weighted by goals and priorities on a case-by-case basis. (Anderson et. al., 2012)

Tools for Structural Engineers to perform an LCA

Performing a whole building LCA is a complex undertaking as buildings are made up of a variety of raw materials and manufactured products, are designed by building professionals in multiple industries, and constructed with a variety of construction practices. The building's operational energy use also can vary greatly depending on climate, occupant behavior, and the MEP systems and their interaction with the structure. Despite all of these complexities LCA is still the only tool that offers an approximate measurement of environmental impacts and there are some tools that simplify the exercise.

The primary assessment tool for buildings in the U.S. is the freely downloadable, online software tool: Athena Impact Estimator. Two other similar tools are still available but no longer supported: a simplified version of the above, called the Athena EcoCalculator, and one developed more for contractors by the National Institute for Standards and Technology, the Building for Environmental and Economic Sustainability software (BEES).

These software packages have pre-defined building products and assemblies with their environmental impacts already derived. Thus, the user merely needs to select and add elements to represent the building as closely as possible. If one has a material take off, it is even more straightforward to have Athena Impact Estimator report impacts for unit material quantities using the Additional Bill of Materials function. Note, this method produces significantly different results compared to using the traditional "add elements" function, as is further described in the final paper of this set "SEAOC SDC LCA Case Studies."

More sophisticated software, geared for products, is available through Pre who produce- SimaPro and PE International who make GaBi. Furthermore, the principal source for inventory data in the U.S. is the National Renewable Energy Laboratory – U.S. Life-Cycle Inventory Database. However, non-LCA practitioners may find these formats difficult to work with for simple calculations. On the other hand, several tools seem to be emerging that can offer structural designers a fuller toolbox for performing an LCA, including ones that tie directly to building information models. Although Athena's Impact Estimator, GaBi and SimaPro are the only ones explicitly preapproved by the current whole building LCA credit of LEEDv4 (and the Pilot Credit 63), the language does keep the door open for new tools.

It is essential to remember that LCA is a methodology to determine the environmental impact of a product, process, or service. It is analogous to environmental accounting. Results are only as reliable as the data going into the accounting, and comparisons can only be made across studies following the same set of assumptions. This is why we often see a range in final impacts, and sometimes see conflicting conclusions, particularly regarding steel versus concrete. LCA is more useful for indicating what can be done within a given system to reduce impacts (e.g. reducing cement or using salvaged steel or timber).

Limitations

At the same time, users of LCA need to keep in mind its limitations. LCA excels at accounting for the input and output flows of a defined process or system, and then relating those to indicators of environmental and health burdens when those relationships are well known and well understood. Consequently, where risks are uncertain or the inventory does not include required data, the impacts carry equal uncertainty or can simply not be provided by LCA. For example, LCA is generally poor at quantifying the effects of building products in use because there is little data collected on emissions in use over the broad range of conditions. Buildings are not like consumer products (like water bottles and cell phones) where what they will contain, how they will be used, and how long till they get replaced, are relatively predictable. Nearly every building is unique and how it will function and change over its life is nearly unpredictable.

Similarly, effects such as land use impacts, biodiversity, and water shortage are not addressed as robust through LCA because of insufficient data, too much complexity, and/or lack of agreement on how to model for these. Even the human and environmental toxicity metrics are highly debated. Thus, schemes that directly address human health of product content, responsible land management, and responsible water management are some of the essential tools to fill the gaps of LCA. In summary, there are many complimentary tools in a complete sustainability toolkit, of which LCA is only one.

LCA in Building Codes and Rating Systems

As building codes and green building rating systems evolve, LCA is gaining in popularity as a sustainable design method. A few examples illustrate this trend (Anderson et. al., 2012):

- Upcoming LEED v4 (previously titled LEED 2012), whole building LCA is a Materials and Resources credit option, to be released in fall of this year, and currently available as Pilot Credit 63 to LEEDv3 projects.

- International Green Construction Code (IgCC) 2012 offers multiple project elective points if a whole building LCA is conducted;

- American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) 189.1 allows the use of LCA as a performance option for selecting a building's materials in lieu of prescriptive minimums for recycled, regional, and biobased materials

- Living Building Challenge 2.0 requires an embodied carbon calculation of the project within the Materials Petal

- International rating systems such as the UK's BREEAM, Germany's DGNB, and Hong Kong's BEAM Plus all contain tools to evaluate building material impacts using LCA

Clients are demanding more from their buildings. Green rating systems, such as LEED and Green Globes, have seen significant increases in buildings being certified not just because owners want the label but because going green makes economic sense. The rising cost of energy needed to run modern buildings can be a powerful motivator to adopt green building practices. Green building codes such as the IgCC and the California Green Building Code are being developed and adopted by jurisdictions. All of this means that incorporating green building practices into the AEC industry's everyday business should be embraced and will soon become necessary.

Conclusion

The transition from simple assumptions and prescriptive methods for environmental design to LCA, offers structural engineers several opportunities. LCA provides structural engineers with a scientific approach to accounting for the impact their buildings have on the environment. It allows for recognition of a wider set of design and specification choices, which shifts more weight of decisions from the contractor and architect to the structural engineer. With LCA, higher level design decisions (e.g. design for deconstruction, resilient structures, and utilization of thermal mass) can potentially be taken into account. Consequently, LCA is best utilized in the early phases of design to compare different structural schemes and can be incorporated into everyday structural design to minimize economic and environmental costs. Understanding the environmental tradeoffs of the different structural systems will allow for a comprehensive recommendation to clients and will aid in their decision making.

In recognition of this, LCA is becoming the primary method of measuring the sustainability of buildings as it offers a comprehensive way to evaluate and reduce their environmental impact. While the tools and use of LCA in practice is continuing to improve, structural engineers can better position themselves by engaging in these changes and embrace this opportunity to illustrate their contribution to sustainable design.

The industry has the duty to do its part in halting global warming. Structural engineers can play a major role in getting this accomplished. While it is normal that people resist change, sustainable design strategies are necessary and becoming the new normal. Encompassing a green philosophy should be strived for and put into practice everyday.

References

Athena Sustainable Materials Institute, ATHENA Impact Estimator™ v4.2 and ATHENA EcoCalculator™ v3.7 [Online] www.athenasmi.org.

Anderson, J. and Thornback, J. "A guide to understanding the embodied impacts of construction products," London, 2012.

Anderson, John E., Slivers, Adam and Yang, Frances. "Life-cycle assessment – Coming your way soon." Structural Engineer October 2012.

Curran, M. A. "Life cycle assessment: principles and practice," Cincinnati, Ohio, 2006.

Curran, M. A. and Notten, P. "Summary of Global Life Cycle Inventory Data Resources," 2006.

German Sustainable Building Council, "Neubau Büro- und Verwaltungsgebäude, Version 2012." [Online]. Available: http://www.dgnb.de/de/. [Accessed: 15-Jul-2013].

ISO, "ISO 14044 - Environmental management – Life cycle assessment – Requirements and guidelines," 2006.

Kestner, Dirk M., P.E., Jennifer Goupil, P.E., and Emily Lorenz, P.E., eds. *Sustainability Guidelines for the Structural Engineer*. Reston: American Society of Civil Engineers, 2010. Print.

Levine, Mark and Urge-Vorsatz, Diana. "Chapter 6: Residential and Commercial Buildings." IPCC Fourth Assessment Report: Climate Change 2007 (AR4). 2007.

"Life Cycle Assessment: Principles and Practice." May 2006 [Online] http://www.epa.gov/nrmrl/std/lca/lca.html

Melton, P. "Whole-Building Life-Cycle Assessment: Taking the Measure of a Green Building," *Environmental Building News*, May 2013. BuildingGreen, Vermont.

National Institute of Standards and Technology, "BEES: Building for Environmental and Economic Sustainability." [Online] http://www.nist.gov/el/economics/BEESSoftware.cfm.

PRE Product Ecology Consultants, "SimaPro LCA Software." [Online] http://www.pre-sustainability.com/simapro-lca-software.

"Structures and Carbon How Materials Affect the Climate." ASCE-SEI Sustainability Committee. Ed. Mark D. Webster, P.E. American Society of Civil Engineers, 2012. Web. 11 Dec. 2012.

United States Green Building Council, "Leadership in Energy and Environmental Design: New Construction and Major Renovations v2009." [Online] http://www.usgbc.org/leed/rating-systems/new-construction.

United States Green Building Council, "LEEDv4 for Buidling Design and Construction: Ballot Version." [Online] http://www.usgbc.org/leed/v4.

U.S. National Renewable Energy Labratories Life-Cycle Inventory Database [Online] http://www.nrel.gov/lci/.

Lessons Learned from Recent LCA Studies

Frances Yang, SE LEED AP BD+C
Chair, SEI Sustainability Committee
LCA Working Group
SEAOC Sustainable Design Committee

Abstract

How does embodied energy compare to operational energy? What percentage of a building's embodied carbon emissions come from structure? How about when compared to the full life-cycle, including refurbishments and demolition? These are just some of the questions to which life-cycle assessment case studies offer us answers. This presentation offers a focused synthesis of data coming from over two dozen past case studies, as performed by the ASCE/SEI Sustainability Committee's LCA Working Group. From the analysis, structural engineers can learn several lessons about how their decisions affect the environmental performance of buildings.

Acknowledgements

This paper describes the process and findings of a collaborative effort of several members of the SEI Sustainability Committee, primarily those within the LCA Working Group. This paper draws from a work product entitled "Top 10 Structural Sustainability FAQs Answered by LCA," which represents contributions from Adam Slivers, Dirk Kestner, John Anderson, Kathrina Simonen, Kelly Roberts, Lionel Lemay, Mark Webster, Martha VanGeem, Matthew Comber, Rebecca Jones, Stephen Buonopane, Terry McDonnell, and Tona Rodriguez-Nikl.

Introduction

The construction industry has been identified as a decisive sector in achieving a sustainable twenty-first century. (DOE FEMP, 2003; WBCSD 2010) In light of this, structural engineers, central actors and designers of the built environment, have increasingly come to accept their new role as stewards for the natural environment in addition to their traditional roles as designers. Beyond accepting their new role, however, structural engineers must still find sound scientific evidence to provide basis for their decisions, as they do with all engineering choices.

The use of life-cycle assessment (LCA) provides the foundation for quantitative verification of the environmental performance of products and processes, including built structures. Parties in both the buildings industry and research arena have used LCA to produce a prolific number of whole building case studies in recent years. In observing this, the LCA Working Group of the SEI Sustainability Committee looked to recent and reputable LCA case studies for their quantitative results to provide direction to common questions asked by our community.

This endeavor led the group to amass the first ever "Top 10" list of questions most commonly asked about LCA and how it pertains to structural engineering. The answers, authored by our member experts, come from a focused literature review of over two dozen different case studies based on life-cycle assessment, with current and geographically-specific applicability. The "Top 10" have been informally published in blog form to provide readers an avenue to continue the dialogue, as engagement of all parties in the supply-chain is essential to making our built environment more sustainable. Readers are encouraged to follow this link to participate: http://structureandsustainability.blogspot.com/2012/03/top-10-questions-ses-have-about.html.

In an effort to collaborate with the innovative LCA work of the SEAOC Sustainable Design Committees (SDC), this paper focuses now on two of the "top 10" questions. Question 3 (Q3) asks "How do operational impacts compare to embodied impact?" and question 4 (Q4) queries "How much of total embodied impact comes from structure?" These were specifically chosen for attention in this paper to provide greater context for the preliminary results of the SEAOC SDC case study work.

Q3: How do operational impacts compare to embodied impact?

http://structureandsustainability.blogspot.com/2013/05/q3-operational-vs-embodied-energy.html

The approximate average across several case studies (Perez, 2008; Ramesh, 2010; Junilla, 2006) is 20% of the total life-cycle energy, as often cited in the building practice. Figure 1 illustrates the typical trend of both embodied and operational energy over a typical 60 year building life to arrive at this final 20/80 proportion of embodied to operational.

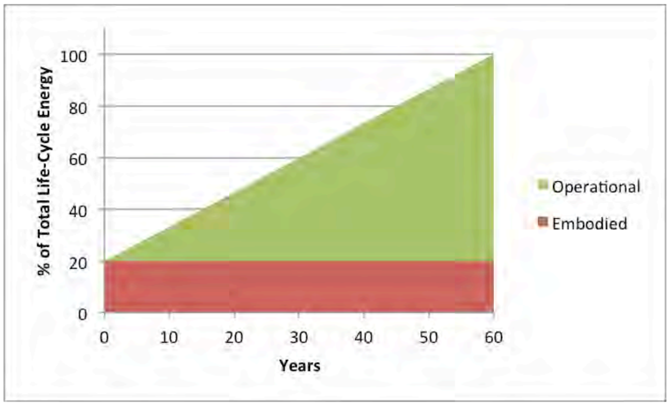


Figure 1: Contrast of typical embodied and operational energy trends.

However, the results amongst these studies actually ranged from 10% to 30%, and depended on what was included or excluded, the building life assumed, and the operational performance. Operational performance was most dictated by climate and occupant behavior, while intentional reductions in operational impacts were acknowledged for low-energy designs. (Perez, 2008; Ramesh, 2010; Junilla, 2006)

Another cited study performed a particularly rigorous analysis to test this proportion. Basbagill ran a conceptual building design through all possible permutations of preset values within 31 variables that defined shape, massing, materials, systems, and dimensions. Figure 2 shows a random sampling of 5000 of these scenarios, from which a mean ratio of embodied to total life-cycle impacts of 18.66% is extracted (Basbagill, 2013). The significance of Basbagill's study is that it reveals the large scatter that departs from the often cited 20/80 ratio. It reveals that design decisions can affect the operational and embodied outcomes significantly, such that a singular focus on the operational portion may be too narrow a view.

Furthermore, Q3 highlights three reasons that embodied impacts are increasingly important:

1. As operational energy reductions progress and building codes governing them are tightened, the proportion of environmental impacts arising from embodied energy will consequently increase.
2. With respect to climate change, the global environmental issue of utmost urgency, carbon emission reductions, need to occur now, which points to the GWP arising from industry, i.e., the embodied carbon.
3. The savings from operational energy reduction will not be realized until further in the future and can depend on realizing the building's full design life span, for which there is no guarantee.

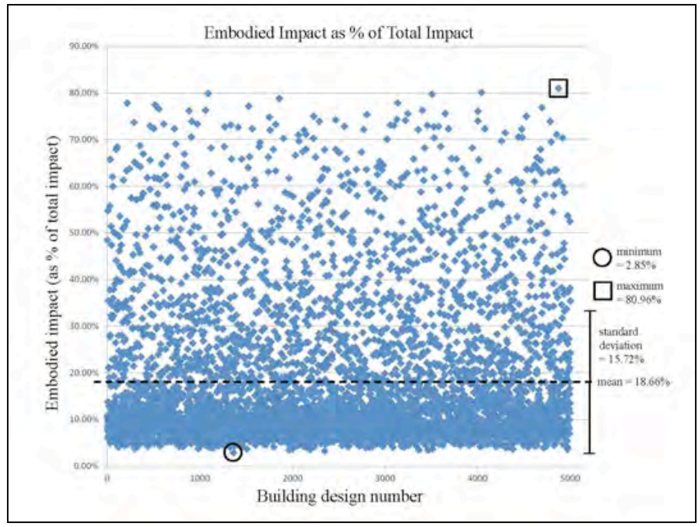


Figure 2: Results of Basbagill study comparing embodied within total.

In addition to the reasons to be increasingly concerned about embodied impacts, many ways are identified by which structural engineers can influence the operational energy performance of buildings. Examples include reduction of artificial lighting, air infiltration, and thermal breaks, improved insulation, energy storage for passive and active temperature regulation (thermal mass), and envelope performance (shading and glazing). Not all of these studies had quantified savings to report, but the highest savings identified was 20% for two very different buildings. Integral to the case study findings, Q3 points readers to design guidance on how to implement the named strategies, including the SEAONC SDC white paper of 2006 and the SEI book Sustainable Design Guidelines for the Structural Engineer.

Q4: How much of total embodied impacts come from structure?

http://structureandsustainability.blogspot.com/2013/05/q4-how-much-of-total-embodied-impact.html

Following on from Q3, Q4 looks more specifically at the structural portion of environmental impacts. The findings are divided into three categories: embodied energy (or carbon) up to construction, embodied energy (or carbon) over the building lifespan excluding repair and rebuild, and embodied energy (or carbon) over the building lifespan including repair and rebuild.

The first category of results draws from three different LCA studies on embodied energy or embodied carbon. The proportion of structural embodied energy/carbon to total energy/carbon ranges from 30-70%. One study (Kaethner & Burridge, 2012) compared embodied carbon across three different occupancy types of office, school, and hospital, considering 6 to 8 different concrete and steel structural systems for each.

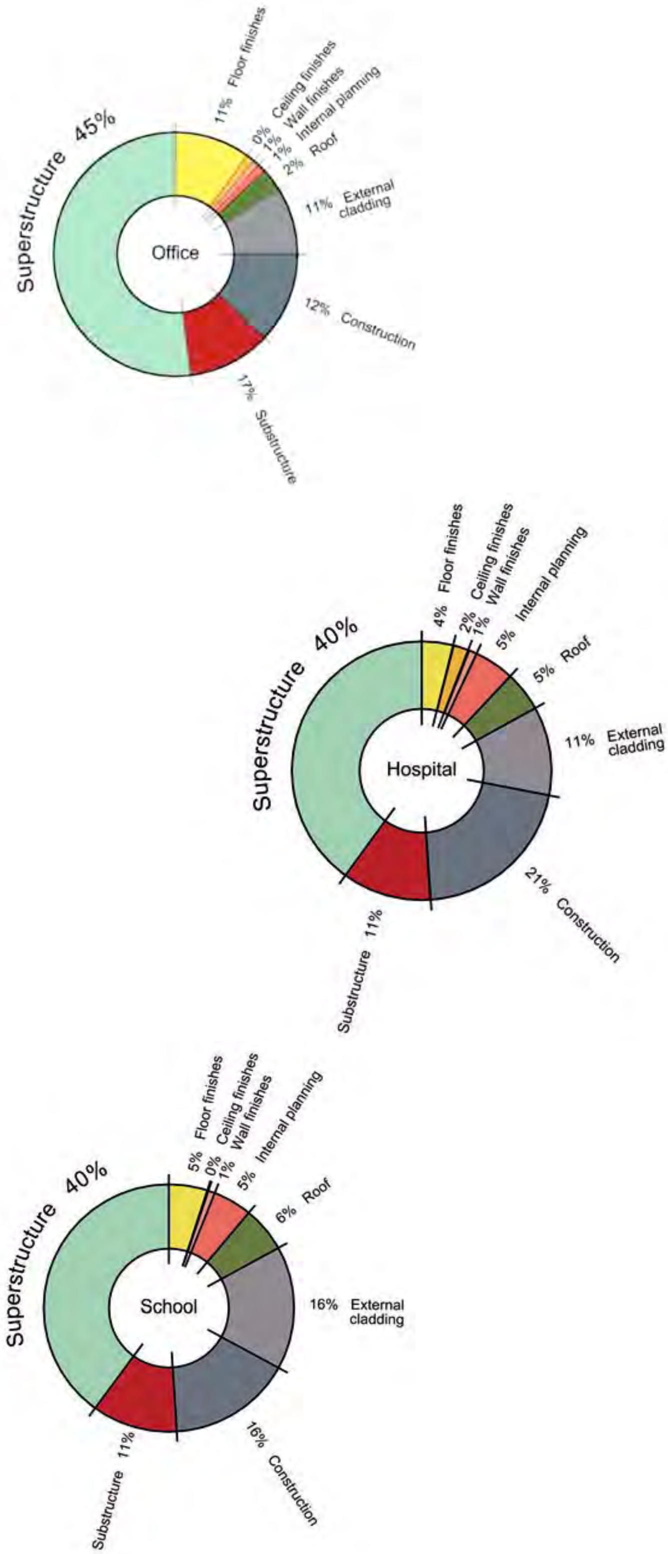


Figure 3: Breakdown of embodied carbon showing typical percentage from different element groups for three different building types. (Kaethner & Burridge, 2012)

It found the proportion of structure (including superstructure and foundation) to be approximately 50-60%. Breakdowns of these percentages into different element categories are displayed in Figure 3.

"Substructure" refers to foundation, "internal planning" refers to partitions, and "construction" includes on-site material wastage, construction activity, and gate-to-site transport. The "0%" label for ceiling finishes indicates it typically amounted to less than 1%. Elements excluded were MEP ducts, pipes, wiring, and equipment, furniture, fittings and fixtures, and replacements, maintenance, and end-of-life of the included items.

Looking at other studies for adding impacts due to operations, routine maintenance, replacements, and end-of-life, the structural proportion reduces to 6-57%, where the low end was an office building in Chicago and the high end was a warehouse.

The last category considers the probability of need to repair and/or rebuild after a catastrophic event such as an earthquake. This scenario led to a unique study that showed approximately 30% increase in embodied carbon when considering additional damage due to a likely seismic event. The study furthermore found a 77% savings of this embodied carbon by using a protective seismic system like base isolation, a topic which is addressed in further detail in a separate question, Q9.

Conclusions

The LCA working group of the SEI Sustainability Committee conducted a comprehensive review and synthesis of various reputable LCA case studies. This critical review challenged the assumption that the structural portion of building impacts is small by proportion. The findings divulge that this is in fact an over simplification of actual results.

In Q3, the often cited estimate that embodied to operational of 20/80 was found subject to much fluctuation due primarily to what was included or excluded, as well as climate, building type, occupancy, lifespan, and measures taken to improve operational performance, such as optimizing shape, massing, materials, systems, and dimensions.

In Q4, more case studies show that the proportion attributable to structure also ranges widely. Structure can be only 5% over the life-cycle in a traditional calculation, but as a portion of the embodied only, it accounts for about half (excluding

MEP and TI), and if one considers retrofit, repair and rebuild, it amounts to more.

Within Q4, the paper by Comber (2012) offers a model for considering the trade-off between impacts that may be incurred upfront in employing more robust seismic systems, with the probable savings that they offer later. Otherwise, within the literature review, the contributors did not find sufficient studies to compare the array of seismic systems in terms of embodied impacts and their effect on the embodied impact of the non-structural portion of buildings. Thus, the ongoing work of the SEAOC SDC fills a definite gap in the body of LCA case studies. The findings will surely offer more lessons for structural engineers.

References

Basbagill, J., Lepech, M. (2013). "Characterizing Life Cycle Impacts of Conceptual Building Designs". Energy and Buildings (in preparation)

Comber, Poland, & Sinclair (2012) "Environmental Impact Seismic Assessment: Application of Performance-Based Earthquake Engineering Methodologies to Optimize Environmental Performance", *Structures Congress 2012 Proceedings*, ASCE.

Kaethner. S. C. and Burridge, J. A., "Embodied CO2 of Structural Frames," *The Structural Engineer*. May 2012.

Kang, Grace and Alan Kren, (2006). "Structural Engineering Strategies Towards Sustainable Design," SEAOC Proceedings 2006. Pp.473-490.

Kestner, Dirk, Jennifer Goupil, and Emily Lorenz, (2010). Sustainability Guidelines for the Structural Engineer, Sponsored by Sustainability Committee of the Structural Engineering Institute of ASCE, Reston, VA: ASCE, 978-0-7844-1119-3.

Ochsendorf, J., et al., (2011). Methods, Impacts, and Opportunities in the Concrete Building Life Cycle, Massachusetts Institute of Technology Concrete Sustainability Hub, Cambridge, MA.

Perez Fernandez, Nicolas, (2008). "The influence of construction materials on life-cycle energy use and carbon dioxide emissions of medium size commercial buildings," School of Architecture, Victoria University of Wellington, July.

Ramesh, T., Prakasha, R., Shuklab, K. K. (2010) "Life cycle energy analysis of buildings: An overview," *Energy and Buildings*, 42, p.1592–1600

US Department of Energy Federal Energy Management Program (FEMP), "The Business Case for Sustainable Design in Federal Facilities". August 2003.

Webster et al. (2012) Structure and Carbon: *How Materials Affect the Climate* written by the Carbon Working Group of the Structural Engineering Institute's Sustainability Committee, ASCE.

World Business Council for Sustainable Development, *Vision 2050: The new agenda for business,* ISBN: 978-3-940388-56-8, Switzerland. February 2010.

SEAOC LCA Study
Comparing Environmental Impacts of Structural Systems

Anthony B. Court, SE;
Lisa Podesto, SE, LEED AP;
Patti Harburg-Petrich, SE, LEED AP

Sustainable Design Committees
of SEAOSD, SEAOCC, SEAOSC

Abstract

Decisions on structural systems and materials in everyday building design practice are rarely influenced by the sustainable design considerations. Green building rating systems have not traditionally offered specific methods for structural engineers to contribute to environmental footprint reduction through structural system and component selections. However, the life cycle assessment (LCA) approach recently incorporated into both CAL Green and LEED rating system offers a systematic procedure to inform structural engineers and their industry partners on the relative environmental impacts of different structural systems.

The Sustainable Design Committees of the four regional SEAOC member organizations and the statewide SEAOC Sustainable Design Committee are collaborating on a case study project investigating how an LCA analysis can be used to quantify the relative environmental impacts of different structural/seismic systems. The first phase studies a prototype 5-story office building in Los Angeles to compare the life cycle impacts of eight different structural/seismic systems including steel, concrete, masonry, timber and hybrid solutions. The LCA tool used in this study is the Athena Impact Estimator. This paper outlines the goals and scope of the study and presents the initial findings. It also discusses the use of the Athena tool and areas for future study.

Background

Structural engineers have had limited ways to contribute to the sustainable design process as prescribed by the USGBC LEED (USGBC, 2012) green building rating system and current practice. The structural options have often been limited to specifying the use of flyash as a cement substitute, specifying minimum recycled content of steel, or specifying the use of FSC certified lumber. The green building rating systems have been based more on prescriptive guidelines than on science or engineering. At the same time, life cycle assessment (LCA) has emerged for application to products and more recently buildings, offering a science based approach to measuring and reducing environmental impacts of products and systems, including structural systems. Energy modeling has long been integrated into the design process to reduce the operational impacts of buildings. Structural engineers now have an opportunity to integrate LCA modeling into the structural design process to reduce the structural contribution to the environmental footprint.

The Green Globes rating system and recently the USGBC LEED system have adopted credits for using whole building LCA to reduce impacts. As explained by Scott Horst, senior vice president for LEED, "One of the things we want to try to do is to initiate a discussion between the designer and the structural engineer in the same way that that energy modeling inititated a discussion between the designer and the mechanical engineer" (Melton, 2013). The structural engineer can now be brought into the sustainable design process.

This SEAOC LCA case study is the first of its kind to focus on and precisely account for the structural/seismic systems and to compare between different seismic systems in a systematic way based on assessing alternative structures for functionally identical buildings (i.e. equivalent functional units). This study demonstrates the use of the LCA as a tool to measure and reduce the environmental impacts of the structural/seismic system and illustrates the potential for structural engineers to make a significant contributrion to the sustainable design process.

Intent

The SEAOC Sustainable Design Committee intends this LCA study to be the first phase of a multi-phased investigation into the relative environmental impacts of different structural systems in the broader context of synergistic integrated design of whole buildings through their full building life cycles including response to earthquakes. This initial phase compares different vertical and lateral structural systems for a prototype office building to assess their relative environmental impacts. This phase focuses on the structural systems in isolation and does not address the non-structural impacts, operational impacts, or seismic performance. It is intended to compare structural impacts for functionally equivalent alternative designs for the defined prototype office building.

The investigation is intended to provide insight into both the relative impacts of the different systems and into the process of using life cycle assessment as part of structural material selection and design, as well as into the use of the Athena Impact Estimator as a readily available accessment tool. It utilizes the ATHENA Impact Estimator (Athena, 2012), selected as the most practical available tool for use by structural engineers without special LCA expertise to evaluate structural alternatives in a whole building context. The LCA process, the Impact Estimator and other LCA tools are discussed in greater detail in "LCA for Structural Engineers" (Stringer, Yang, 2013) found elsewhere in these SEAOC 2013 Convention Proceedings, and in the final sections of this report.

The study is intended to be relevant and useful to practicing engineers and researchers, particularly as LCA becomes more widely adopted and integral to sustainable design practice and green building rating systems such as LEED and CAL Green.

While this first phase focuses on structural systems, LCA must consider structure in the context of the whole building and full life cycle including the operational phase to be an effective tool for sustainable design. The structure often contributes only a small part of the overall embodied impact of buildings, and the embodied impact is often relatively small compared to the operational impact over the life time of a building. The structure can also affect the non-structural and operational impacts. For example, if the structure is integrated into the design as an aesthetic and as exposed finish, then it can reduce the use of non-structural finish materials and associated impacts. If the structure is integrated to provide effective thermal mass, it can also reduce the operational HVAC demands and associated impacts.

Historically structure has contributed only about 30% to 50% of the embodied life cycle impacts and embodied impacts have amounted to only on in the range of 5% to 15% of total impacts, with operational impacts contributing the balance. Thus, structure has typically contributed only in the range of 3% to 5% of the total life cycle impact of buildings. As we now move toward more energy efficient designs, the operational impacts are declining. As we move further toward synergistic integrated design and net-zero buildings as targeted by Architecture 2030 (Architecture 2030, 2011), operational impacts can be reduced to zero and structural impacts can amount to 50% and more of the total life cycle impact. This trend, as illustrated in Figure 1, demonstrates the growing significance of structure to the sustainable design equation and the importance of being able to compare structural systems using LCA to help further reduce the overall environmental footprint.

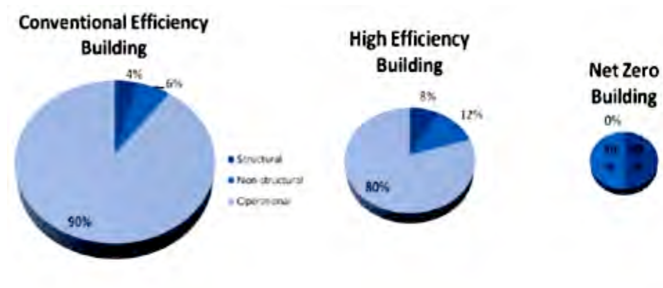


Figure 1: Significance of structure grows as overall footprint shrinks.

The SEAOC Sustainable Design Committee intends to design this LCA study so that future phases can investigate the relative impacts of non-structural systems and building operations and can account for potential reduction in those impacts achieveable through use of structure in synergistic integrated design. Future phases can also include collaboration with universities or LCA professionals to investigate the use of LCA tools such as GABI (PE International, 2012) or SimaPro (PRe, 2011) to provide comparative insight into the use of the different LCA tools.

Ultimately, of great interest to us as structural engineers in California will be consideration of the seismic performance and the environmental impacts of that performance. Buildings might be heavily damaged or destroyed by an earthquake or they might survive it with very little damage or disruption of services. These different performance levels will have very different environmental consequences. The Applied Technology Council is in the process of developing ATC-58 and ATC-86 which will ultimately provide tools for predicting seismic performance and environmental consequences using a life cycle assessment approach. Recent phases of these projects are reported in FEMA P-58 (FEMA 2012). When fully implemented, the FEMA P-58 methodology promises to provide a tool that future phases of this SEAOC LCA study can use to assess the seismic performance and associated environmental impacts of different seismic systems.

SEAOC intends as part of this study to document the schematic designs for each of the structural framing systems considered and to post those designs to the SEAOC SDC website for use in future phases of this study and for review and use by others interested in performing additional or comparative studies.

Finally, SEAOC intends to continue publishing and presenting reports after each phase of this ongoing LCA study for the benefit of the membership and the wider structural engineering and sustainable design community.

Scope

This initial phase of study focuses on assessing relative impacts of comparative structural systems for a prototype 5-story office building in Los Angeles. It utilizes preliminary schematic level structural designs generated by the regional SEAOC Sustainable Design Committees for the different structural/seismic systems as a basis for the assessments. The preliminary designs include primary vertical and lateral framing members and systems, with allowances for applicable connection systems. The designs include foundations and slabs-on-grade. Concrete and masonry structural sections include preliminary reinforcing designs or quantity estimates. The different structural systems are described in greater detail in later sections of this report.

For intitial consideration of non-structural systems, each building can be assumed to include a generic curtain wall system, single ply or equivalent roofing system, and drywall covered core walls and ceilings. The study is in the process of quantifying and assessing these architectural core-and-shell systems using the Athena Impact Estimator for comparison to the structural systems.

This preliminary non-structural assessment study will not include floor or ceiling finishes in the office spaces, partition systems, core service systems such as restroom fixtures or elevators, M-E-P systems, fireproofing or other non-structural systems.

The study includes development of bills of materials (BOMs) for each of the structural systems. These BOMs are further discussed in the Case Study Comparison section later in this report.

The study utilizes the Athena Impact Estimator to conduct LCAs based on the structural BOMs developed.

Comparisons between the BOMs and the environmental impacts of the different structural/seismic systems, use of the Athena program, and areas for future study are discussed in the final sections of this report.

Prototype Building Description & Assumptions

This phase of the study focuses on a prototype 5-story office building as illustrated in Figures 2 and 3.

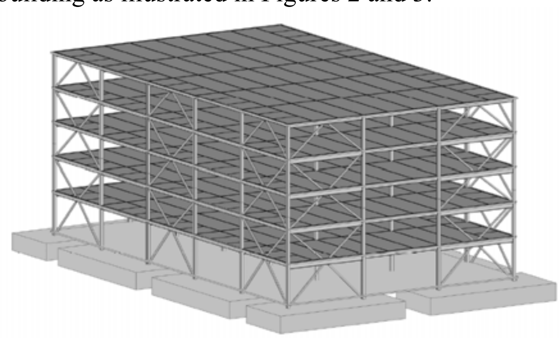


Figure 2: Prototype 5-story office building configuration (shown here with a generic bracing system).

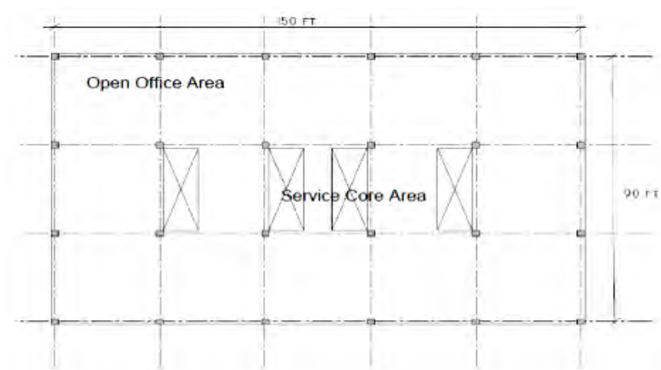


Figure 3: Typical Office Floor Plan.

The building data includes:

- Occupancy: office
- Location: Los Angeles
  - Latitude: +34.05224 degrees
  - Longitude: -118.24366 degrees
- Number of stories: 5
- Story Heights:
  - Level 1: 14' floor to floor
  - Level 2-5: 12' floor to floor
  - Overall height: 62'
- Plan Dimensions: 150' x 90'
- Column bays: 30 feet oc each direction
- Core size: 30' x 90'
- Core functions: stairs, elevators, restroom space, vertical shaft space, maintenance and storage room space.
- Office Space: 30 foot band around perimeter, no TIs.
- Curtain wall: aluminum and glass perimeter system
- Roofing: single ply system
- Core finishes: gypsum board walls and ceiling

The case study involves 8 different structural/seismic systems including two concrete systems, two masonry systems, two steel systems and two timber systems, as described in subsequent sections.

Each of the framing schemes is intended to provide a functionally equivalent facility, of the same size and dimensions, same column layout, same core area layout, same perimeter curtainwall and equivalent floor quality in terms of accoustic performance and "solidness". This last requirement is presumed satisfied by providing 1.5" concrete topping on the wood floor systems to approximate the feel of the concrete or composite deck floors for the other framing systems.

All buildings include a 5" concrete slab-on-grade and convential spread footings, sized for the respective structural system loads.

Design Criteria and Loading Assumptions

The structural systems are designed based on the 2012 IBC and the seismic hazard level associated with the site longitude and latitude. Structural loading considerations include:

Gravity Loads:
- Office live loads 50psf
- Partition loads 15 psf vertical
  10 psf lateral
- Roof live loads 20 psf
- Dead loads Structural weight plus allowance for ceilings, flooring and M-E-P systems.

Seismic Loads:
- 2012 IBC seismic demands based on site location
- Site Class D

Foundations:
- Soil bearing 3,000 psf (allowable)
- Sliding friction 0.3 (allowable)
- Passive pressure 300 pcf (allowable)

These foundation bearing capacities are considered to be relatively conservative for a typical 5-story office building where footings often extend to more capable bearing strata. This is a variable that can be adjusted in future phases of the study. These relatively low bearing values result in relatively large footings with relatively significant environmental impacts compared to the rest of the structure, particularly in comparison to the lower impact timber buildings.

Athena Impact Estimator

The Athena Impact Estimator (IE) is a life cycle assessment tool developed specifically for application to buildings and intended to measure the full life cycle environmental impacts from cradle-to-grave. It is available from the Athena Sustainable Materials Institute free of charge.

It is intended for use by "design teams to explore the environmental footprint of different material choices and core-and-shell system options". It follows the ISO 14040 series (ISO, 2006a)(ISO, 2006b) standard LCA procedures and provides a user friendly tool for performing the very complex task of assessing environmental impacts. It provides cradle-to-grave inventory profiles for whole buildings to account for all the energy and material flows from nature and the emissions back to air, land and water.

It provides a conceptual design tool for developing a comparative bills of materials based on the building size and configuration or it permits direct user input of a detailed bill of materials. It then calculates environmental impacts based on its internal life cycle inventory (LCI) databases and reports impact measures in terms of:
- global warming potential
- acidification potential
- smog potential
- ozone depletion potential
- eutrophication potential
- fossil fuel consumption.
- human health respiratory effects potential

For this study, we elected to compile bills of materials for each case study building and to directly input those BOMs using the "extra basic materials" feature of the Athena IE program. We used Version 4.02 which includes regionally customized LCI data for the Los Angeles area. For this phase, we did not include operational energy in our assessments. We entered data for each of our 8 cases study buildings and then used Athena IE to perform impact comparisons between the buildings.

CS-1: Concrete Special Moment Frame

The concrete special moment frame design includes four 2-bay moment frames aligned around the perimeter of the building. Typical floor and roof slabs were designed as 8" post-tensioned flat slabs. Columns were designed as uniform 24" square columns at all floors to simplify the forming and punching shear issues. Footings are square spread footings designed based on the 3,000 psf allowable soil bearing and design dead and live loads. The perimeter moment frames are supported on continuous grade beams. Typical framing plans and foundation plans are shown in Figures 4 and 5.

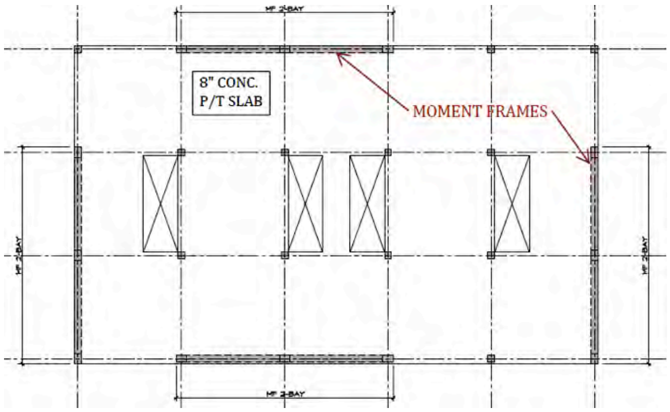


Figure 4: Concrete SMF - 8" PT slab plan.

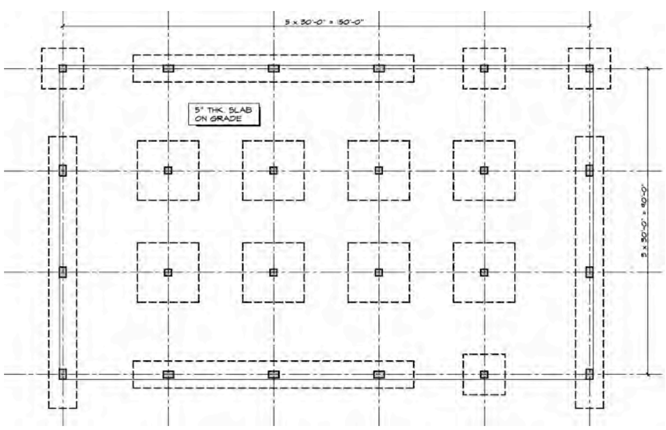
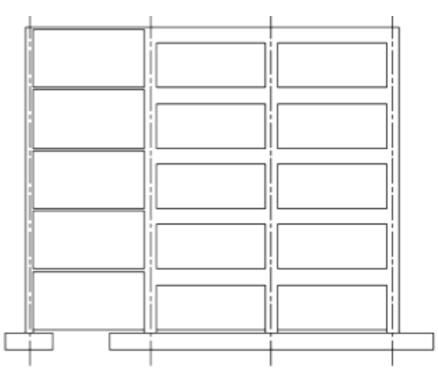


Figure 5: Concrete SMF - Foundation Plan.

The moment frames were analyzed and designed using ETABS to verify the beam and column sizes and seismic drift limits. Reinforcing was spot checked and proportioned based on experience and proprietary design charts. Reinforcing ratios range from 250 to 750 pounds per cubic yard. The typical moment frame elevation is shown in Figure 6.



MF Columns: 24"x36"
MF Beams: 24"x48"

Figure 6: Concrete SMF - Frame Elevation.

The post-tensioned floor slabs were designed based on experience and proprietary design charts. Post-tensioning and plain reinforcing ratios were determined to be approximately 145 pcy. Footings were designed based on computer analysis to determine size, thickness and reinforcement. Slab-on-grade was assumed to be 5" thick with 6x6 W2.9xW2.9 WWF.

Concrete compressive strength 4,000 psi was used for all concrete except the concrete slab on grade, which was based on 3000 psi. Flyash was assumed to be used at a rate of 25% of the total cementitious content.

Formwork for the slabs was assumed to be ¾" plywood with 2x4 at 16" on center strong backs spanning between a reusable aluminum shoring system. The plywood and strongbacks were assumed to be reused 5 times so a total of 13,500 square feet of floor forming was assumed for the entire building. The aluminum shoring system was assumed to be reused many times and was not accounted for in the LCA bill of materials. Column formwork was assumed to be ¾" plywood with 2-2x4 strongbacks at 16" on center, reused 5 times.

Since the design is preliminary and based on experience and proprietary design charts, it is intended to be slightly conservative. We expect that a savings in reinforcement allowances of 10% to 20% could be achieved in a final design. The 25% flyash replacement is considered to be higher than is typically used in practice but is considered an appropriate allowance given that the structure is intended to meet sustainable design objectives.

The summary bill of materials for the structural system is tabulated in the Case Study Comparison section of this report.

CS-2: Concrete Shear Wall

The concrete shear wall building design includes three C-shaped shear walls at the core of the building. Typical floors and roof slabs were designed as 8" post-tensioned flat slabs. Columns were designed as uniform 24" square columns at all floors to simplify the forming and punching shear issues. Typical column footings are square spread footings designed based on the 3,000 psf allowable soil bearing and the design dead and live loads. The C-shaped shear walls are supported on 3 foot thick mat footings. Typical framing plans and foundation plans are shown in Figures 7 and 8.

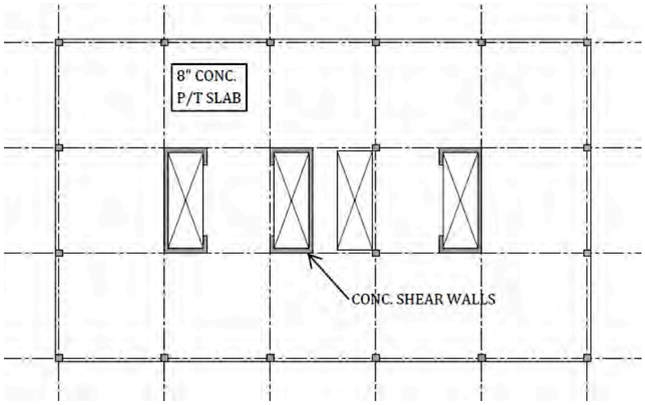


Figure 7: Concrete SW – Framing Plan.

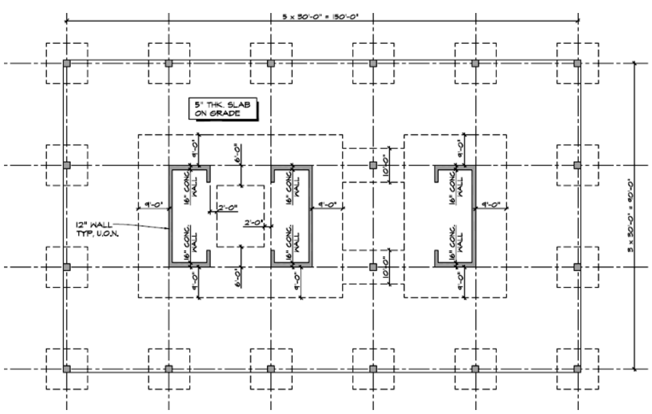


Figure 8: Concrete SW - Foundation Plan.

The shear walls were designed using an ETABS analysis to verify the thickness, drift and period of vibration. Reinforcing was spot checked and proportioned based on experience and proprietary design charts. Reinforcing ratios range from 150 to 200 pounds per cubic yard. Wall configuation is constant throughout the height of the building. The wall thickness steps down from 12" and 16" at the lower 3 floors to 8" and 12" at the upper two floors.

The post-tensioned floor slabs were designed based on experience and proprietary design charts. Post-tensioning and plain reinforcing ratios were determined to be approximately 145 pcy. Footings were designed based on computer analysis to determine size, thickness and reinforcement. Slab-on-grade were assumed to be 5" thick with 6x6 W2.9xW2.9 WWF.

Concrete compressive strength 4,000 psi was used for all concrete except the concrete slab on grade, which was based on 3000 psi. Flyash was assumed to be used at a rate of 25% of the total cementitious content.

Formwork for the slabs was assumed to be ¾" plywood with 2x4 at 16" on center strong backs spanning between a reusable aluminum shoring system. The plywood and strongbacks were assumed to be reused 5 times so a total of 13,500 square feet of floor forming was assumed for the entire building. The aluminum shoring system was assumed to be reused many times and was not accounted for in the LCA bill of materials. Column formwork was assumed to be ¾" plywood with 2-2x4 strongbacks at 16" on center, reused 5 times.

Since the design is preliminary and based on experience and proprietary design charts, it is intended to be slightly conservative. We expect that a savings in reinforcement allowances of 10% to 20% could be achieved in a final design. The 25% flyash replacement is considered to be higher than is typically used in practice but is considered an appropriate allowance given that the structure is intended to meet sustainable design objectives.

The summary bill of materials for the structural system is tabulated in the Case Study Comparison section of this report.

CS-3: Masonry Wall & Concrete Floor System

The masonry shear wall and concrete floor building design includes masonry core shear walls and 8" post-tensioned flat slabs at the roof and floors. As in the concrete buildings, columns were designed as uniform 24" square columns at all floors to simplify the forming and punching shear issues. Typical column footings are square spread footings designed based on the 3,000 psf allowable soil bearing and the design dead and live loads. The core shear walls are supported on 3 foot thick mat/spread footings. Typical framing plans and foundation plans are shown in Figures 9 and 10.

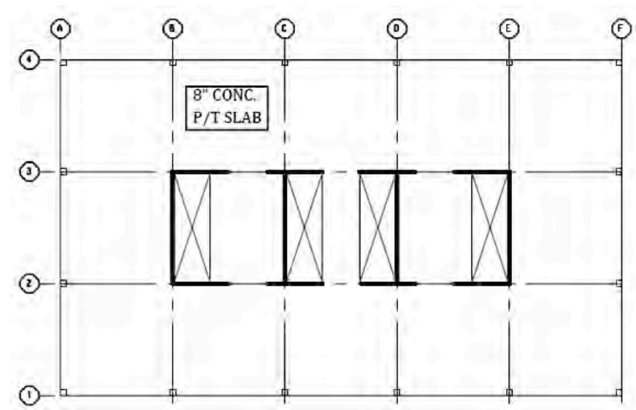
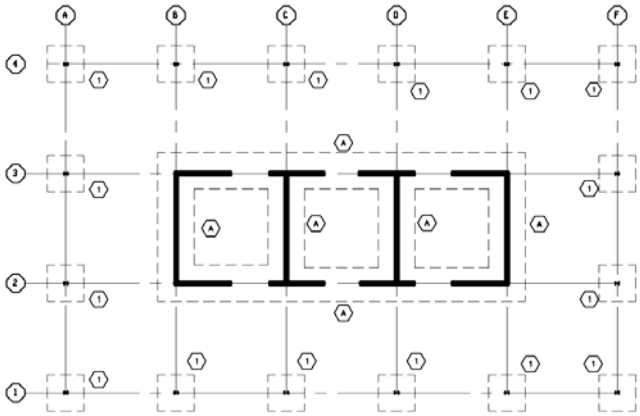


Figure 9: Masonry & Concrete - Framing Plan



Column Footings: 11'-6" sq x 2' thick
Corner Footings 8' sq x 2' thick
Wall footings: 10' wide x 3' thick

Figure 10: Masonry & Concrete - Foundation Plan

The shear walls were designed using an ETABS analysis to verify the thickness, drift, and period of vibration. Reinforcing was derived from the ETABS design module. Reinforcing ratios range from .003 to .005 each way. Wall configuation is constant throughout the height of the building. The wall thickness steps down from 12" at the lower 3 floors to 8" at the upper two floors.

The post-tensioned floor slabs were based on the concrete design schemes, using the same thickness and reinforcing ratios. Footings were designed based on computer analysis to determine size, thickness and reinforcement. Slab-on-grade were assumed to be 5" thick with 6x6 W2.9xW2.9 WWF.

Masonry compressive strength of 3,000 psi was used at the lower 2 levels and 1500 psi at the upper 3 levels. The grout was modeled as 3000 psi concrete with flyash used at a 25% cement replacement rate.

Concrete compressive strength of 4,000 psi was used for all concrete except the concrete slab on grade, which was based on 3000 psi. Flyash was assumed to be used at a rate of 25% of the total cementitious content.

As with the concrete buildings, formwork for the slabs was assumed to be ¾" plywood with 2x4 at 16" on center strong backs spaning between a reusable aluminum shoring system. The plywood and strongbacks were assumed to be reused 5 times so a total of 13,500 square feet of forming was assumed for the entire building. The aluminum shoring system was assumed to be reused many times and was not accounted for in the LCA bill of materials. Column formwork was assumed to be ¾" plywood with 2-2x4 strongbacks at 16" on center, reused 5 times.

As with the concrete buildings, the concrete design is intended to be slightly conservative. We expect that a savings in reinforcement allowances of 10% to 20% could be achieved in a final design. The 25% flyash replacement is considered to be higher than is typically used in practice but is considered an appropriate allowance given that the structure is intend to meet sustainable design objectives.

The summary bill of materials for the structural system is tabulated in the Case Study Comparison section of this report.

CS-4: Masonry Wall & Steel Floor System

The masonry shear wall and steel floor building includes masonry core shear walls and steel and 6.25 inch composite metal deck floor and roof system similar to the steel building options. The columns are all wide flange sections. Typical column footings are square spread footings designed based on the 3000 psf allowable soil bearing and design dead and live loads. The core shear walls are supported on 3 foot thick mat/spread footings. Typical framing plans and foundation plans are shown in Figures 11 and 12.

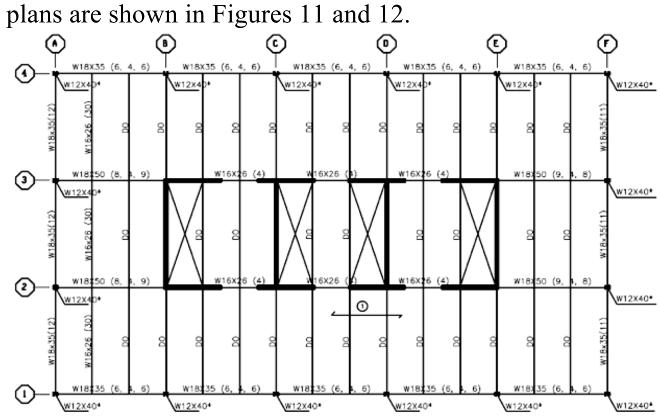
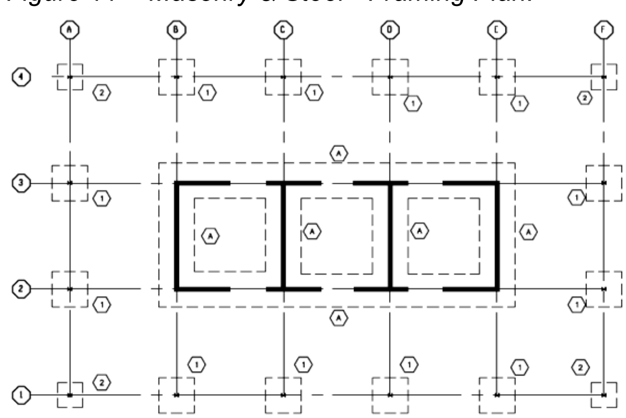


Figure 11 – Masonry & Steel - Framing Plan.



Typ. Col. Footings: 10' sq x 2' thick
Corner Footings 7' sq x 2' thick
Wall footings: 10' wide x 3' thick

Figure 12: Masonry & Steel - Foundation Plan.

The shear walls were designed using an ETABS analysis to verify the thickness, drift, and period of vibration. Reinforcing was derived from the ETABS design module. Reinforcing ratios are range from .0025 to .004 in each direction. Wall configuation is constant throughout the height of the building. The wall thickness steps down from 12” at the lower 3 floors to 8” at the upper two floors.

Footings were designed based on computer analysis to determine size, thickness and reinforcemetn. Slab-on-grade were assumed to be 5” thick with 6x6 W2.9xW2.9 WWF.

Masonry compressive strength of 3000 psi was used at the lower 2 levels and 1500 psi at the upper 3 levels. The grout was modeled as 3000 psi concrete with flyash used at a 25% cement replacement rate.

Concrete compressive strength of 4,000 psi was used for all concrete except the concrete slab-on-grade, which was based on 3000 psi. Flyash was assumed to be used at a rate of 25% of the total cementitious content.

The 25% flyash replacement is considered to be higher than is typically used in practice but is considered an appropriate allowance given that the structure is intended to meet sustainable design objectives.

The summary bill of materials for the structural system is tabulated in the Case Study Comparison section of this report.

CS-5 Steel Special Moment Frame

The steel special moment frame design was developed to include four 3-bay moment frames aligned around the perimeter of the building. Typical floors and roof systems were designed as 6.25” composite decks over wide flange composite steel beams and girders. Columns were designed as wide flange sections stepped down in size at the third floor. Footings are square spread footings designed based on the 3000 psf allowable soil bearing and design dead and live loads. The perimeter moment frame columns are rigidly linked at the foundation to a wide flange beam embedded in a continous concrete encasementment and supported on spread footings at each column. Typical framing plans and foundation plans are shown in Figures 13 and 14.

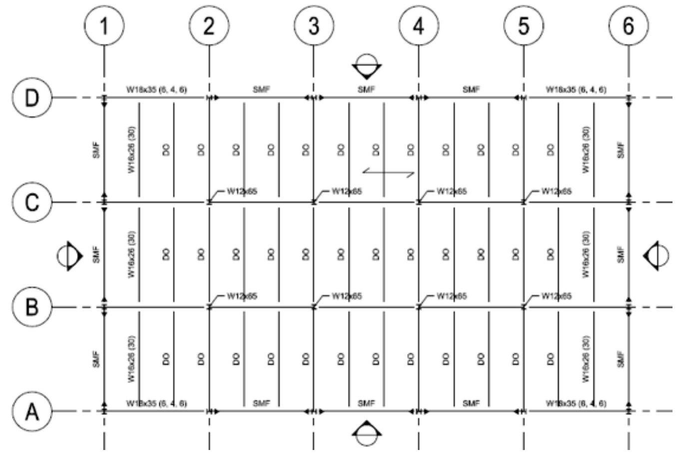


Figure 13: Steel SMF – Framing Plan.

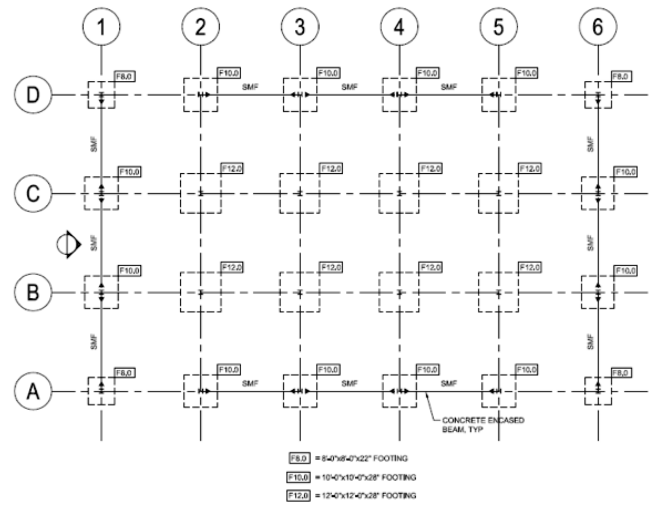


Figure 14: Steel SMF – Foundation Plan.

The moment frames were designed using an ETABS analysis to verify the beam and column sizes and seismic drift limits. Connections were detailed with stiffner plates and doubler plates per AISC258-10 requirements. Connection plate weight was accounted for the the bill of materials. The typical moment frame configuration is shown in Figure 18.

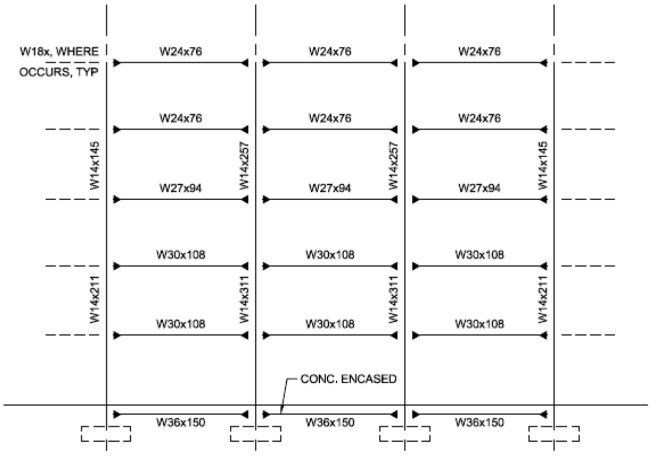


Figure 15 – Steel SMF Configuation.

Composite floor beams and girders were sized based on LRFD design requirements. Composite decking was verified based on typical deck manufacturer's span tables. Deck reinforcement was assumed to be 6x6 W2.9xW2.9 WWF.

Footings were designed based on computer analysis to specify size, thickness and reinforcement. Slab-on-grade were assumed to be 5" thick with 6x6 W2.9xW2.9 WWF.

Concrete compressive strength 4,000 psi was used for all concrete except the concrete slab on grade, which was based on 3,000 psi. Flyash was assumed to be used at a rate of 25% of the total cementitious content.

The 25% flyash replacement is considered to be higher than is typically used in practice but is considered an appropriate allowance given that the structure is intended to meet sustainable design objectives.

The summary bill of materials for the structural system is tabulated in the Case Study Comparison section of this report.

CS-6 Steel Buckling Restrained Braced Frame

The steel buckling restrained braced frame design includes two single-bay braced frames aligned at each perimeter side of the building. Typical floors and roof systems were designed as 6.25" composite decks over wide flange composite steel beams and girders. Columns were designed as wide flange sections stepped down in size at the third floor. Footings are square spread footings designed based on the 3000 psf allowable soil bearing and the design dead and live loads. The perimeter braced frames are supported on grade beams. Typical framing plans and foundation plans are shown in Figures 16 and 17.

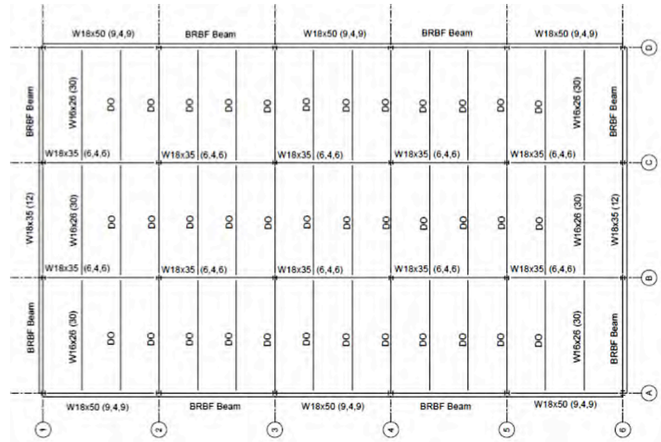


Figure 16: Steel BRBF – Framing Plan.

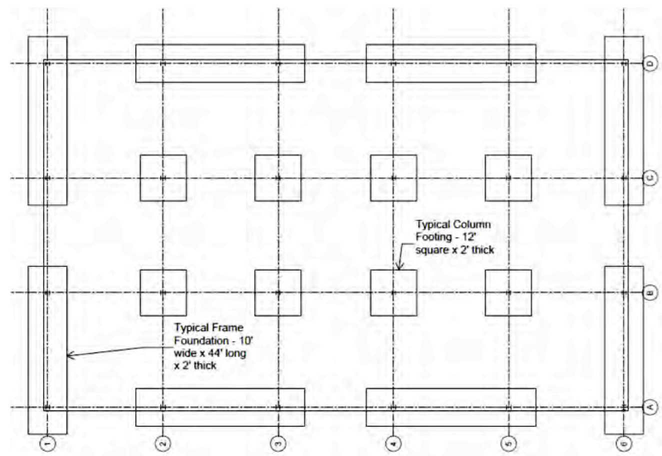


Figure 17: Steel BRBF – Foundation Plan.

The braced frames were designed using an ETABS analysis to verify the brace forces and AISC requirements to size the braces and casings. A typical BRBF configuration is shown in Figure 18 .

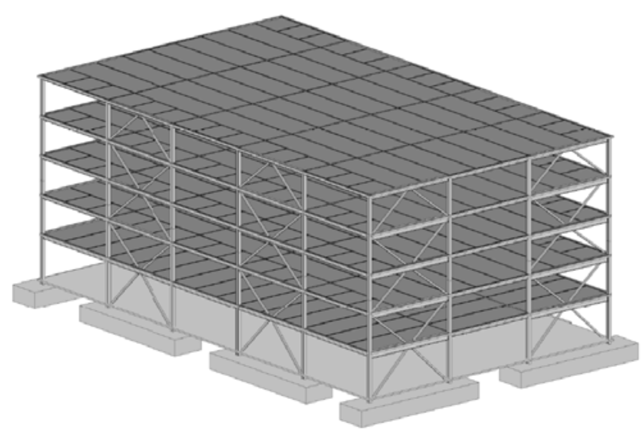


Figure 18 – Steel BRBF Configuration.

Composite floor beams and girders were siezed based on LRFD design requirements. Composite decking was verified based on typical deck manufacturer's span tables. Deck reinforcement was assumed to be 6x6 W2.9xW2.9 WWF.

Grade beams were designed for overturning, soil bearing, and and internal shear and flexure. Footings were designed based on computer analysis to specify size, thickness and reinforcement. Slab-on-grade were assumed to be 5" thick with 6x6 W2.9xW2.9 WWF.

Steel wide flange designs were based on 50 ksi steel. BRBF braces were designed based on 36 ksi steel. Concrete compressive strength of 4000 psi was used for all concrete except the concrete slab on grade, which was based on 3,000 psi. Flyash was assumed to be used at a rate of 25% of the total cementitious content.

The 25% flyash replacement is considered to be higher than is typically used in practice but is considered an appropriate allowance given that the structure is intended to meet sustainable design objectives.

The summary bill of materials for the structural system is tabulated in the Case Study Comparison section of this report.

CS-7 Wood Framed – Light Timber with BRBF (Preliminary)

The preliminary light framed timber building design includes I-joist floor and roof systems, GLB beams and girders, steel columns and steel BRBF lateral bracing systems. The BRBFs were located around the perimeter of the building with one frame on each side. All columns are HSS sections. Typical column footings are square spread footings designed based on the 3,000 psf allowable soil bearing and design dead and live loads. The perimeter BRBFs are supported on continous grade beams around the perimeter. Typical framing plans and foundation plans are shown in Figures 19 and 20.

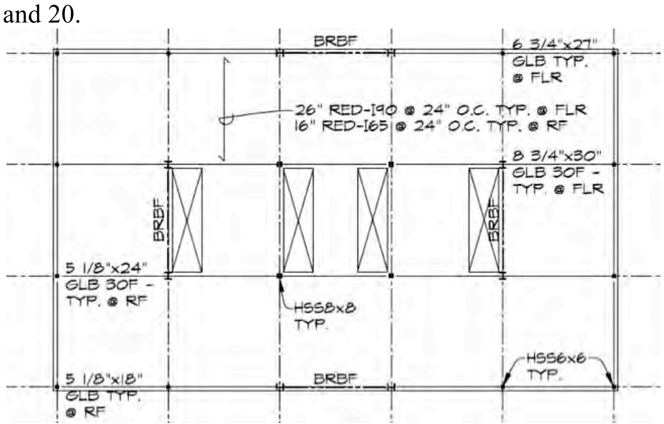


Figure 19 – Light Timber Framing Plan.

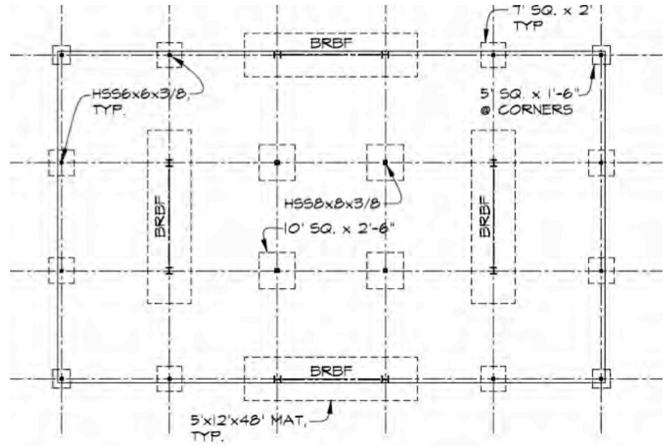


Figure 20 – Light Timber Foundation Plan

The braced frames were designed using an ETABS analysis to verify the brace forces and AISC requirements to size the braces and casings. A typical BRBF elevation is shown in Figure 21.

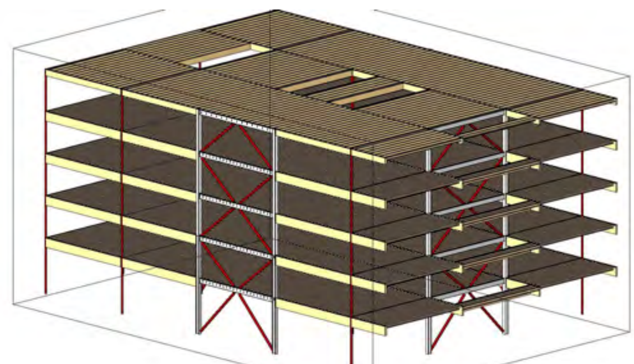


Figure 21 – Light Timber BRBF Configuration

Horizontal diaphragms were provided by ¾" plywood at the floors with 1.5" of concrete topping, and ½" plywood at the roof. The floor topping is non-structural but was provided to improve sound proofing and to provide office floor "quality".

Floors were framed with I-joists, selected to provide normal office quality in terms of floor vibration characteristics. Joists were supported on glued laminted beams. Joist hangers, beam hangers, and plywood nailing were accounted for in the bill of materials take offs.

Grade beams were designed for overturning, soil bearing, and and internal shear and flexure. Footings were designed based on computer analysis to specify size, thickness and reinforcement. Slab-on-grade were assumed to be 5" thick with 6x6 W2.9xW2.9 WWF.

Concrete compressive strength of 3,000 psi was used for all concrete. Flyash was assumed to be used at a rate of 25% of the total cementitious content. The 25% flyash replacement is considered to be higher than is typically used in practice but is considered an appropriate allowance given that the structure is intended to meet sustainable design objectives.

The summary bill of materials for the structural system is tabulated in the Case Study Comparison section of this report.

CS-8 Wood Framed – Heavy Timber with Plywood Shear Walls (Preliminary)

The preliminary heavy timber building design utilized cross laminated timber (CLT) floor and roof systems, with GLB beams and girders, GLB columns and plywood shear walls at the core area. Typical column footings are square spread footings designed based on the 3,000 psf allowable soil bearing and the design dead and live loads. The light frame core shear/bearing walls are supported on a continous mat/grade beam. Typical framing plans and foundation plans are shown in Figures 22 and 23.

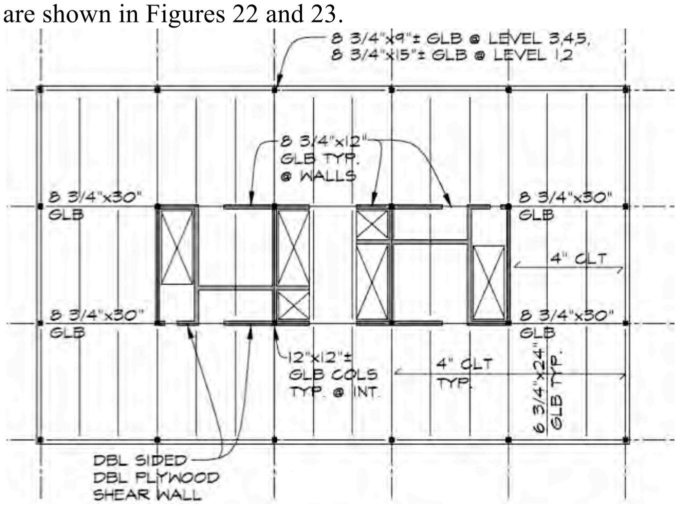


Figure 22: Heavy Timber CLT-GLB Floor Framing.

The light frame plywood shear walls were designed as double sided double walls around the core area. These double walls provide a slight framing challenge that can be easily resolved by framing one wall as a tiltup wall, and by adding the outer layers of sheathing after the double walls are erected. The double walls provide additional bearing capacity at the core bearing walls. GLBs run continously over the shear walls to facilitate drag and shear transfer connections. The total shear wall lengths are reduced at the upper floors based on the reduced shear demand. Shear wall overturning forces were checked and found to be resolved by gravity loads or addition of continuous steel rods where necessary.

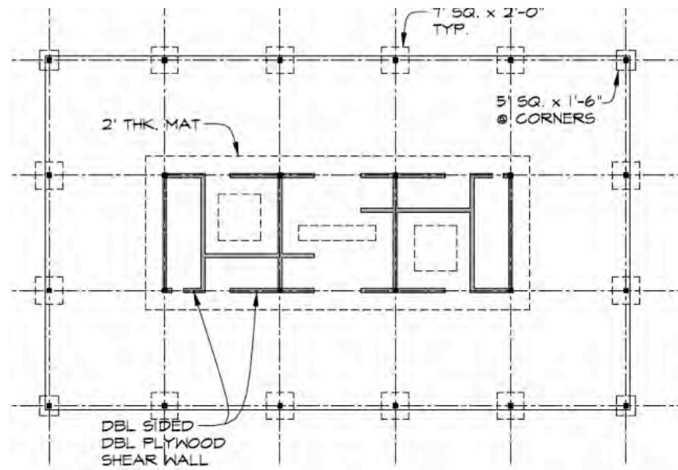


Figure 23: Heavy Timber CLT-GLB Foundation Plan.

Horizontal diaphragms were provided by the 4" thick solid wood CLT systems. 1.5" of concrete topping was added at the floors to provide better accoustic performance.

Floor and roof loads were supported with the 4" CLT system spanning between GLB beams and girders. Columns were sized as GLB sections. Steel hardware quantities, including column caps, beam and girder hangers, and CLT anchor pins, were estimated and accounted for in the bill of materials take off.

Mat/grade beams were designed for overturning, soil bearing, and internal shear and flexure. Spread footings were designed based on computer analysis to determine size, thickness and reinforcement. Slab-on-grade were assumed to be 5" thick with 6x6 W2.9xW2.9 WWF.

Concrete compressive strength of 3,000 psi was used for all concrete. Flyash was assumed to be used at a rate of 25% of the total cementitious content. The 25% flyash replacement is considered to be higher than is typically used in practice but is considered an appropriate allowance given that the structure is intend to meet sustainable design objectives.

The summary bill of materials for the structural system is tabulated in the Case Study Comparison section of this report.

Preliminary Case Study Comparisons:

The bills of materials for each of the structural/seismic framing systems were compiled individually in a format compatible with input to the Athena Impact Estimator. The BOMs were then summarized for comparison and materials were grouped into foundation, seismic increment to foundation, superstructure, and seismic increment to superstructure. This breakdown permits separate analysis of the structural weight and impacts associated with these material groups. The BOMs include allowances for connections based on preliminary material takeoffs and estimates, and for concrete forming based on reuse of wood forms five times for floors, columns and walls. These BOMs are summarized in Table 1.

The individual BOMs were then input into Athena IE using the "Extra Basic Materials" input feature and comparative impacts were assessed. The preliminary results are illustrated in the figures 24 through 30. These figures plot the total life cycle impacts associated with the structural systems for each case study building, assuming a 60 year building life. The impacts plotted include the seven measures reported by Athena including global warming potential, acidification potential, human health respiratory effects potential, smog potential, ozone depletion potential, eutrophication potential, and fossil fuel consumption.

These preliminary comparative plots indicate the relative impacts of each case study building. The units of measure are standard LCA units as used by Athena IE. The precise magnitudes are not significant, considering that LCA is an approximate science and that other buildings will have different configurations, BOMs and sets of impact measures. The relative impacts and the impact intensities, i.e., impact per unit or per square foot, are of greater usefulness. Impact intensities are tabulated in Figure 31.

The relative impacts of the different structural types are evident from the preliminary comparative impact plots. It can be seen that the timber buildings generally have significantly less impact than the steel buildings and the steel buildings generally have less impact than the concrete and masonry buildings. This relationship changes with some measures such as eutrophication in the case of the heavy timber buildings. The spike in eutrophication potential impact for the heavy timber building appears to be attributable to the glue resins used in the CLT and GLB systems, however this result will require verification through further investigation.

These prelimiary relative impact plots also allow us to compare different structural/seismic systems within the same material family. For example, the steel BRBF system typically has less impact than the steel special moment frame system, due to the lesser quantity of materials required. On the other hand, the concrete special moment frame generally has less impact than the concrete shear wall building, again due to the lesser quantities of material required. The masonry structures are fairly similar to each other in impact, with the masonry-concrete option having slightly higher impacts due to the greater concrete contribution and the greater weight of structure. The timber options are also generally similar to each other, with the light framed hybrid structure having slightly less impact, particularly with regard to euthrophication potential.

ISO guidelines for LCAs discourage the use of composite impact scores for evaluating different systems. The more typical basis for comparison is to evaluate single impacts of interest such as global warming potential, measured by the release of CO_2 equivalent units. Nonetheless, composite scores can be of interest, and for this study we ranked the different buildings by their relative ranking for each metric and then compiled Figure 32 to provide a visual representation of the relative combined impacts of the structural systems. By this combined ranking, you can see that the timber buildings perform the best, followed by steel, then masonry and concrete.

However, it should be noted that these comparisons consider the structural systems in isolation. If the structural systems are considered in the context of an integrated design, the conclusions may change dramatically. The concrete and masonry buildings may benefit from structure acting as finish, significantly reducing the need for redundant architectural finishes. The concrete and masonry may provide significant thermal mass benefits, thus reducing the life cycle operational energy demands. The thin profile of the concrete structure may be utilized to maximize natural daylighting, again reducing the operational energy demands. The steel structures may require extensive application of fireproofing, adding to their initial embodied impacts and disposal impacts.

Another area of analysis considered in this study is the relation between structural mass and environmental impact. Considering the foundation, superstructure, and seismic increments to structure tabulated in the BOMs, we preliminarily analyzed the relationship between the mass and the impacts. The results of that analysis are illustrated in Figure 33. This figure supports a preliminary conclusion that there can be a significant positive correlation. Heavier structures tend to have higher impacts. Certainly, there is an obvious truth that the use of more material results in greater impacts. These relationships guide us to some simple principles of sustainable design. If we design lighter more efficient structures, without significantly compromising the durability and disaster resilience of structures, we achieve more sustainable lower impact designs.

Use of Athena Impact Estimator

In this study, we found Athena IE to be generally a very easy to use and powerful tool for comparative life cycle assessments. Using the “extra basic materials” input feature provided a simple way to input our structural material quantities. The Athena IE material categories and units were generally easy to match to our structural material takeoffs. Output BOMs were easy to verify with our input BOMs, noting that the Athena makes percentage allowances for material waste, resulting in slightly larger output quantities than input quantities.

On the other hand, we found that Athena’s internal structural modeler which permits a user to define the building geometry and structural system types and then internally calculates the structural sizes and generates bills of materials was not easy to use effectively. In fact we had little success with this feature. Athena generated material quantities differed from our calculated quantities by factors of several times in some cases. A previous study of a four story structure in Chicago by Halcrow Yolles (Stek, et al, 2011) had more success using the internal structural modeler but still reported significant discrepancies ranging from several percent to several hundred percent between the Athena generated BOM quantities and the manually generated quantities.

A drawback of using the “extra basic materials” input feature is that it does not permit categorization of the materials into different components, such as, foundations, superstructure, floor slabs, or seismic systems. We used separate input file runs to separate materials into categories, which proved to be a cumbersome process. This task would be greatly facilitated if Athena adds this “component category” option to the “exta basic materials” input feature.

We did not find any other suitable LCA tool to perform a similar whole building assessment. We investigated using the B-Path program developed at Lawrence Berkeley Laboratories and found that it is a promising start, but for our purposes is incomplete and unsupported. Other sophisticated LCA tools such as GaBi and SimaPro are certainly capable of providing assessments but require greater expertise and licencing agreements for use.

Summary and Next Steps

We found that this preliminary first phase of study provides very useful insights into the application of LCA to buildings and structural/seismic systems in particular and into the relative impacts of different structural systems for functionally equivalent office building designs. However, the limited scope of the study to date leaves unanswered the question of placing the structural systems into the context of an integrated sustainable building design.

In future phases of this study, we intend to include the non-structural systems and to evaluate the operational impacts to better compare the whole building, considering the synergistic benefits of structure in integrated designs. We are also considering collaboration with the University of Washington to extend the study by using their Gabi LCA tool results to compare to our Athena LCA results. In the future, we plan also to apply the FEMA P-58 methodology to investigate seismic performance and the environmental impacts of seismic damage associated with the different structural/seismic system designs.

Finally, we caution that this report and the prelimiary first phase of study continue to undergo internal SEAOC SDC review. We caution against drawing definitive conclusions at this point as we continue to refine our preliminary assessments. We plan to update this report and post it to our SEAOC SDC website once our final review is complete.

SEAOC LCA Case Studies - Comparative Summaries 8/11/2013

Bill of Materials Summaries:

Study No.		1	2	3	4	5	6	7	8
Structural System	(units)	Concrete SMF	Concrete Shearwall	Masonry & Conc	Masonry & Stl	Steel SMF	Steel BRBF	Timber (light)	Timber GLB-CLT
Fdns		723.1	912.1	669.7	640.3	535.8	568.5	706.6	569.0
conc s.o.g.	cy	208.3	208.3	208.3	208.3	208.3	208.3	208.3	208.3
rebar - WWF	ton	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7
conc	cy	350.3	350.3	350.3	220.8	220.8	220.8	123.2	123.2
rebar	ton	7.8	7.8	7.8	5.74	5.74	5.74	2.77	2.77
Seismic foundation increment(added contribution of seismic system):									
conc	cy	164.5	353.48	111.1	211.7	106.7	139	375.1	237.5
rebar	ton	26.0	46.20	26.7	26.5	4.0	23	27.1	13.69
Gravity Systems									
steel	ton				160.4	183.4	183.4		
steel - HSS	ton							20.9	
mtl deck - 20ga	ton				74.25	74.25	74.25		
conc	cy	1890.67	1890.67	1816.00	989.6	989.6	989.6	250.00	250.00
rebar	ton	149.5	149.50	140.17	37.13	37.13	37.13	10.63	10.63
3/4" ply-forming	msf	17.99	17.99	15.29					
2x lumber	mbf	11.80	11.80	10.04				14.04	14.53
GLB	cuft							5181	11686
LVL	cuft							2288	
CLT (small frmg)	cuft								22500
OSB 7/16	msf							57.21	
plywd (3/4)/(3/8)	msf							108	
plywd (1/2)/(3/8)	msf							18	
galv sht stl	ton							1.88	
hardware	ton								10.32
Nails & bolts	ton							2.18	1.13
Seismic framing increment (added contribution of seismic system):									
Steel	ton					122.1	27.6	63.5	
Steel - HSS	ton						5.1	8.7	
conc	cy	352.30	378.9				6.1	8.6	
rebar	ton	65.94	75.8						
8" masonry	units			7344	7344				
12" masonry	units			11934	11934				
grout	cy			352.6	352.6				
rebar	ton			24.0	24.0				
wood studs	mbf							14.04	14.53
plywood 1/2"	msf								21.85
Fdn Wt	kips	2943	3727	2731	2612	2160	2317	2872	2303
Struct Wt	kips	6882	6955	7828	5549	3802	3626	1657	1964
Total Wt	kips	9825	10682	10559	8161	5963	5943	4529	4266

Notes:

1. Slab-on-grade based on 5" average with WWF. Concrete over metal deck assumes WWF.
2. Masonry options need review. Currently showing equal shear walls for buildings of different weight.

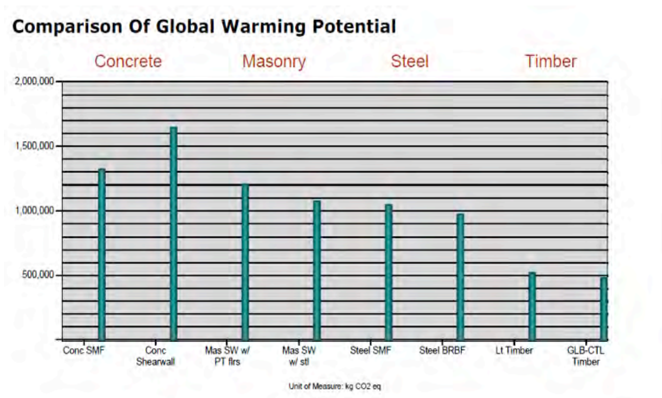


Figure 24: Global Warming Potential

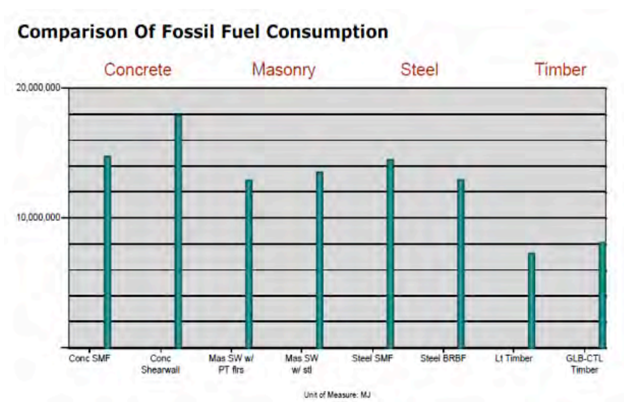


Figure 25: Fossil Fuel Consumption

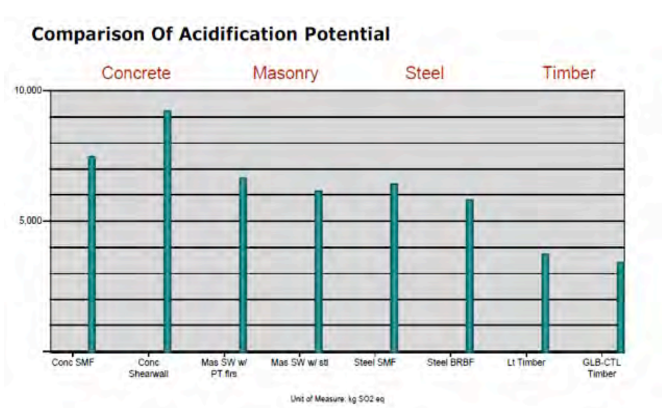


Figure 26: Acidification Potential.

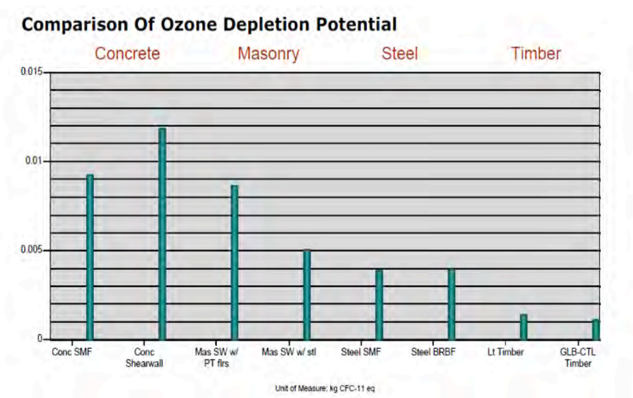


Figure 27: Ozone Depletion Potential

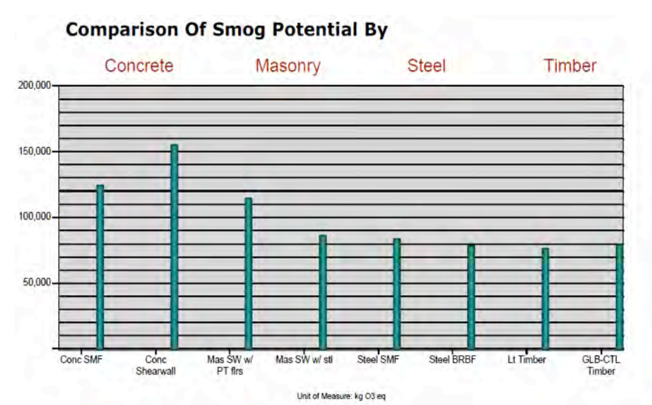


Figure 28: Smog Potential

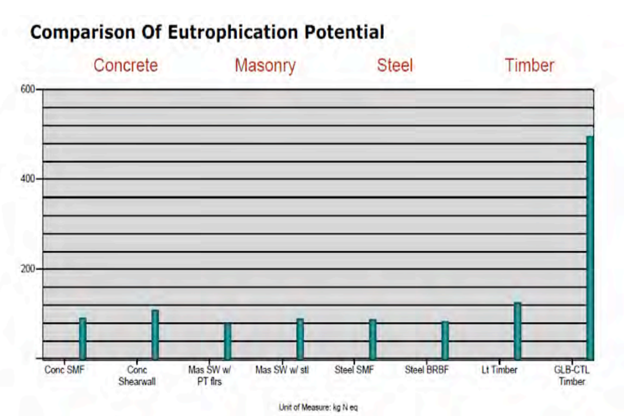


Figure 29: Eutrophication Potential

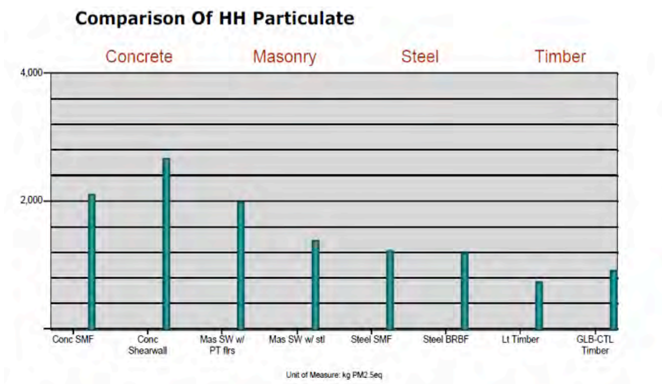


Figure 30: Human Health Criteria

Impact Intensities for Structural Systems - Preliminary 8/1/2013

System	GWP	Fossil Fuel Consumption	Acidification Potential	Ozone Depletion Potential	Smog Potential	Eutrophication Potential	Human Health Criteria
	(kg CO2e) (psf)	(MJ) (psf)	(moles H+ eq) (psf)	(kg CFC-11 eq) (per million sf)	kg O3 eq) (psf)	(kg N eq) (psf)	(kg PM10 eq) (psf)
Stl SMF	16.3	228.1	4.37	0.0356	0.622	0.00133	0.0319
Stl BRBF	14.5	204.4	4.00	0.0444	0.652	0.00133	0.0341
Conc SMF	19.3	216.3	5.04	0.1333	1.141	0.00133	0.0578
Conc SW	21.0	240.0	5.56	0.1393	1.215	0.00156	0.0615
Mas-Conc	19.6	226.7	5.11	0.1007	0.978	0.00148	0.0526
Mas-Stl	20.4	220.7	5.26	0.1422	1.185	0.00133	0.0622
Lt. Timber	4.9	72.6	2.30	0.0163	0.919	0.00104	0.0193
Hvy Timber	7.4	121.5	2.00	0.0163	0.578	0.00756	0.0267

Figure 31: Impact Intensities per Sq Ft

Unofficial Composite Impact Rankings

(Note: Composite ratings are discouraged by ISO Standards)

	GWP	Fossil Fuel Use	Ozone Depletion	Smog	Acidifi-cation	Eutrophi-cation	Human Health Critiria	Average Ranking	Overall Ranking
Conc SMF	7	7	7	7	7	5	7	6.7	7
Conc SW	8	8	8	8	8	6	8	7.7	8
Mas/Conc	6	3	6	6	6	1	6	4.9	6
Mas/Stl	5	5	5	5	4	4	5	4.7	5
Stl SMF	4	6	3	4	5	3	4	4.1	4
Stl BRBF	3	4	4	2	3	2	3	3.0	3
Lt. Timber	2	1	2	1	2	7	1	2.3	1
GLB-CLT	1	2	1	3	1	8	2	2.6	2

Note: This study considers structure only not total integrated design.

Figure 32: Composite Rankings

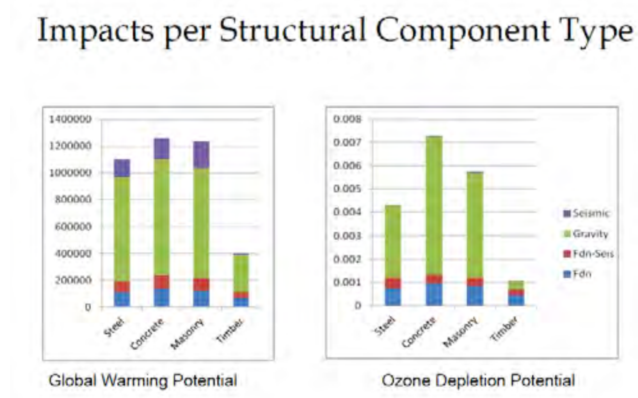
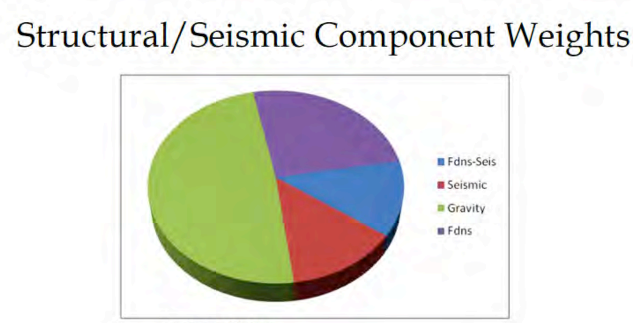


Figure 33: Component Impacts



Component Weights:

Gravity = 49%	Gravity + Fdns = 74%
Seismic = 13%	Seis + Fdn-seis = 26%
Foundations = 25%	
Fdn-Seis = 13%	
Total 100%	Total 100%

Figure 34: Component Weights

References

Athena, 2012, *Athena Impact Estimator for Buildings*, Athena Sustainable Materials Institute, last accessed on August 11, 2013, http://www.athenasmi.org/our-software-data/impact-estimator/.

Architecture 2030, 2011, *The 2030 Challenge*, last accessed on August 11, 2013, http://architecture2030.org/2030_challenge.

FEMA, 2012, *Seismic Performance Assessment of Buildings, Volume 1 – Methodology*, FEMA P-58-1, prepared by the Applied Technology Council for the Federal Emergency Management Agency, Washington, D.C.

ISO, 2006a, *Life Cycle Assessment-Principles and Framework*, ISO 14040:2006, International Organization for Standardization, Geneva, Switzerland.

ISO, 2006b, *Environmental Management – Life Cycle Assessment – Requirements and Guidelines*, ISO 14044:2006, International Organization for Standardization, Geneva, Switzerland.

Melton, P., *Whole Building Life Cycle Assessment: Taking the Measure of a Green Building*, Environmental Building News, May, 2013.

PE International, 2012, *GaBi 5 Software*, distributed by PE International, last accessed on August 11, 2013, http://www.gabi-software.com/.

PRé Sustainability, 2011, *SimaPro 7.3 Software*, distributed by Pré Sustainability, last accessed on August 12, 2013, http://www.pre-sustainability.com/simapro-lca-software.

Stek, E., DeLong, D., McDonnell, T., and Rodriguez, J. (2011) *Life Cycle Assessment Using ATHENA Impact Estimator for Buildings: A Case Study*. Structures Congress 2011: pp. 483-494.

Stringer, M., Yang, F., 2013, "LCA for Structural Engineers", *SEAOC 2013 Convention Proceedings*, Structural Engineers Association of Califonia, Sacramento, CA.

USGBC, 2012, *Leadership in Energy and Environmental Design (LEED) Draft Version 4*, United States Green Building Council, Washington D.C.