Comparing the embodied energy of structural systems in buildings

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ABSTRACT: There are a number of factors that typically influence the selection of a structural system including code, cost, construction schedule and site constraints. As sustainability increasingly becomes an important goal during the design process, the role of structure in the overall sustainability of a building will need to be considered in terms of embodied energy, building longevity, reuse and deconstruction. The structure of a typical office building contributes roughly one-third to one-quarter of the total embodied energy and double the amount contributed by interior finishes. Consequently, the structure of a building should be a primary target for reducing the embodied energy of a building. While there has been much research on the embodied energy of structural materials, there has been less research into comparing the embodied energy of structural systems. Life-cycle analysis (LCA) tools exist to calculate the embodied energy of a proposed structural system during the early stages of the design process. However, the over simplified nature of these tools can provide misleading conclusions about which structural materials and systems will have the lowest environmental impact. To allow architects and engineers to consider issues of sustainability in the design and selection of a structural system, a transparent and easily understood metric for comparing the embodied energy of structural systems is required. In order to better understand the relationship between structural systems and embodied energy, this paper examines the embodied energy of materials used in typical steel and reinforced concrete structural systems by calculating the amount of material needed for different systems and the embodied energy of selected bay sizes. This method accounts for the varying size and amount of material needed for different spans and columns sizes. By using bay sizes, alternative structural systems are more easily compared to one another. Finally, a 4-story laboratory building, in design at the University of Oregon in Eugene, Oregon, was used as a case study to test the use of bay sizes as a comparative tool. Using schematic plans furnished by the architects to identify the bay sizes used in the building, a one-way concrete slab and beam or one-way joist slab proved to be the structural systems with the lowest embodied energy (both approximately 5,000 GJ).

1 INTRODUCTION

1.1 *Rationale*

There are a number of factors that typically influence the selection of a structural system including code, cost, construction schedule and site constraints. As sustainability increasingly becomes an important goal during the design process, the role of structure in the overall sustainability of a building will need to be considered in terms of embodied energy, building longevity, reuse and deconstruction. The structure of a typical office building contributes roughly one-quarter to one-third of the total embodied energy (Cole & Kernan 1996, Suzuki & Oka 1998). Although the occupation phase of a building's life cycle currently dominates energy use (Junilla et al. 2006, Scheuer et al. 2003). As operational energy use is minimized through high-performance design, construction and equipment, embodied energy will play a larger role in the overall energy consumption of a building (Thormark 2002). Consequently, the structural system should be a primary target for reducing the embodied energy of a building.

1.2 *Shortcomings of Existing LCA Tools for Schematic Design*

There has been much research on the embodied energy of building materials, including structural materials, as evidenced by the Inventory of Carbon and Energy (ICE) produced by the Sustainable Energy Research Team (SERT) at the University of Bath (Hammond & Jones, 2008), This inventory surveys peer-reviewed articles on the embodied energy of construction materials and reports the average values found from these sources. For the purposes of this paper, embodied energy is defined as the total primary energy consumed during resource extraction, transportation, manufacturing and fabrication of construction materials, known as "cradle-to-gate" or "cradle-to-site" as opposed to the "cradle-to-grave" method of calculating embodied energy that would also include primary energy expended on the maintenance and disposal of building materials (Hammond & Jones 2008). As construction and installation methods, building maintenance and demolition can vary greatly, this report focused on the more consistent and quantifiable components of the embodied energy of structural materials.

While the environmental impact of manufacturing a pound of concrete versus a pound of steel is well documented, there has been less research into comparing the embodied energy of structural systems. The environmental impact of a 4-story building with a structural steel frame versus a concrete frame is difficult to compare and generalize because buildings are complex entities with structural systems dependent on required spans, fire separations, site conditions, and numerous other criteria. Fully designing alternative structural systems in order to calculate quantities of materials and consequently the embodied energy of each is a tedious task. As there is little time during the early stages of architectural and engineering design for such time-consuming research, means of quickly evaluating the embodied energy of alternative structural systems are required.

While numerous studies have calculated the embodied energy of theoretical office buildings (Cole & Kernan 1996, Scheuer et al, 2003), it is difficult to apply the results of these studies to the design of a new building due to the unique requirements of each building. Furthermore, when the size of the building and material used is held constant, the embodied energy of a structural system, normalized in terms of MJ/m^2, can still vary by up to 50% depending on the building (Suzuki & Oka 1998). Consequently, comparing case studies of entire buildings is not an accurate means of comparing alternatives for the design of a new building.

Commercially available life-cycle analysis (LCA) tools, such as the ATHENA EcoCalculator (AEC), exist to calculate the embodied energy of a proposed structural system during the early stages of the design process. (ATHENA™ is a registered trademark of the ATHENA Sustainable Materials Institute, Merrickville, Ontario, Canada.) In a review of fourteen models for the environmental assessment of buildings, Seo (2002) noted a number of shortcomings in existing tools including the need for a more comprehensive assessment model, the ability to readily compare alternatives, the time-consuming effort to input data specifically acquired for the assessments, and the need to be specially educated in the use of the tools due to their complexity. Furthermore, the over simplified nature of these LCA tools can provide misleading conclusions about which structural materials and systems will have the lowest environmental impact.

The AEC uses overall building square footage and a selection of predetermined structural assemblies to calculate the embodied energy of the structural system. However, regardless of the size or height of the building, the AEC always concluded that a steel structure had a lower embodied energy than a concrete structure during simulations conducted by the authors. This directly contradicts research to the contrary that shows a steel structure has a higher embodied energy than a comparable reinforced concrete system (Cole & Kernan 1996).

Furthermore, the simplified inputs used by the AEC ignore issues of floor-to-floor heights or span lengths that could change the amount of material required. Unfortunately, the proprietary nature of the data and calculations used by commercially available LCA software precludes a better understanding of how the structural systems are being compared. For example, the AEC includes the on-site construction of assemblies, maintenance and replacement cycles over an assumed building service life, and structural system demolition and transportation to landfill. However, as there is no connection between the durability of a structural material or system and the actual service life of a building (O'Connor 2004), the assumptions made about difficult to calculate quantities, such as building service life, could lead to the potentially false conclusion that a steel structural system is always better than a concrete one.

In order for architects and engineers to consider issues of sustainability in the design and selection of a structural system, a transparent and easily understood metric for comparing the embodied energy of structural systems is required.

2 EMBODIED ENERGY OF TYPICAL STRUCTURAL BAYS

2.1 *Decision Making During Schematic Design*

In order to better understand the relationship between structural systems and embodied energy, this paper examines the embodied energy of materials used in typical steel and reinforced concrete structural systems by calculating the amount of material needed and the embodied energy of selected bay sizes. This method accounts for the varying size and amount of material needed for different spans and columns sizes. By using bay sizes, alternative structural systems are more easily and quickly compared to one another.

2.2 *Typical Structural Bays*

Because concrete and steel systems are not identical in how they optimize member size and type for a given bay size and assembly (flat plate versus one-way beam system for example), a range of six "model bay" sizes were developed for each structural system based on the schematic drawings of a laboratory building in the schematic design phase (Table 1). As the data calculated will be applied to a laboratory building certain criteria, such as a floor-to-floor height of 4.25 m (14 ft), were used. The area of the bays increases in a linear function as roughly a multiple of the smallest bay size. The model bay contained a single column centered on the tributary area for the given bay size. The width and length of the bay for steel or concrete were adjusted so that the dimensions were appropriate for the materials. For steel, rectangular bays with length equal to 1.25 times the width met the approximate square footage of the "model bay," while concrete bays were square as is typical in normative practice to maximize the efficiency of each system.

Table 1. Typical structural bay sizes used in this study.

Model bay	Area	Steel bay	Concrete bay
m x m	m^2	m x m	m x m
4.9 x 4.9	24	4.3 x 5.5	4.9 x 4.9
	37		6.1 x 6.1
6.7 x 6.7	45	5.5 x 8.2	
	53		7.3 x 7.3
6.1 x 11.6	71	7.2 x 9.8	8.5 x 8.5
8.5 x 11.0	94	8.5 x 11.0	9.7 x 9.7
11.0 x 11.0	121	9.2 x 13.1	11.0 x 11.0
12.2 x 12.2	149	11.1 x 13.4	12.2 x 12.2

Once the model bay sizes were established, the weight of construction materials for each bay size and assembly in steel and concrete were calculated. The calculations for both assemblies assumed a live load of 100 lb/ft^2 (4.88 kPa). Materials for both systems were restricted to structural members; no finishes or enclosures were considered. Due to the size of the data set, tables of steel and concrete weights for each bay size have been omitted from this paper.

The assembly of a typical steel bay consisted of a concrete topped metal deck, wide flange beams, wide flange girders and wide flange columns. Steel calculations used load factors of 1.2 times the dead load and 1.6 times the live load as well as an allowable stress of 0.9 times 50 ksi (345 MPa) steel. The maximum deflection was limited at the span length divided by 240. The minimum member sizes for each bay are summarized in Table 2. Bolts, plates and other connection materials were omitted from the calculations.

Table 2. Steel assemblies for various bay sizes.

Bay size m x m	Area m^2	Beam size	No. of beams	Girder Size	Column Size
4.3 x 5.5	24	W10x12	4	W12x26	W8x24
5.5 x 8.2	45	W10x17	5	W21x44	W8x31
7.2 x 9.8	71	W10x39	6	W27x84	W8x40
8.5 x 11.0	94	W12x40	7	W30x90	W10x45
9.2 x 13.1	121	W12x50	7	W30x132	W12x53
11.1 x 13.4	149	W14x68	7	W30x173	W12x53

Five different assemblies for concrete were considered, as the optimal bay size for each system is limited (Table 3). Concrete assemblies included two-way flat plate (TWFP), two-way flat plate with drops (TWFPD), one-way beam and slab (OWBS), one-way joist slab (OWJS) and waffle slab (WS). Concrete systems used a ratio of sand to cement to aggregate equal to 1: 2: 4, with a concrete strength of 4,000 psi (28 MPa). A density of 2,300 kg/m^3 is used for converting volume of concrete into weight. A recycled steel strength of 60 ksi (414 MPa) was assumed for any concrete reinforcement. The amount of concrete and reinforcing steel required for the various bay sizes of each assembly were calculated using design tables provided by the Concrete Steel Reinforcing Institute (CSRI 1997).

Table 3. Concrete assemblies and optimal range of bay areas for each.

Assembly type	Min. area m^2	Max. area m^2
Two-way flat plate	23	90
Two-way flat plate with drops	36	144
One-way beam and slab	36	174
One-way joist slab	36	144
Waffle slab	52	207

All of the total construction materials quantities for a given structural bay were checked against the commercially available Athena Impact Calculator (AIC) and found to be within 5% of the bill of materials generated by the software.

2.3 *Embodied Energy Calculations*

For each structural bay, the embodied energy was calculated based on the total amount of materials required for the loading conditions and material properties noted in Section 2.2. The embodied energy values for steel and concrete used in this paper were those selected by the ICE (Table 4) and use cradle-to-gate boundaries. As much of the steel manufactured in the US has high recycled content, the embodied energy value used is for steel with a recycled content of 42.7%. This a worldwide average and the value is often much higher in the US, potentially reducing the embodied energy of the steel structural bay. The value for sheet steel is used for steel decking, however, steel decking could also be made from galvanized or stainless steel both of which have higher embodied energy values than standard sheet steel. The ICE does not provide numbers for recycled steel sheet as it is not a typical production route, so the embodied energy for virgin material is used here.

Table 4. Selected embodied energies (EE) for structural materials from ICE (Hammond & Jones 2008).

Material	EE	Notes
	MJ/kg	
Engineering Steel	13.1	Recycled content
Concrete	0.95	1:2:4 - cement : sand : aggregate ratio with no fly ash substitution
Steel Rebar	8.8	Recycled content 42.7%
Steel Sheet	31.5	Virgin material

Comparing a single structural bay, steel bays of all dimensions have a higher embodied energy than equivalent sized bays for all of the concrete assemblies analyzed in this study (Table 5). The structural bay with the lowest embodied energy is dependent on the bay size with the waffle slab having the lowest for all 71 m^2 sized bays and one-way beam and slab for 149m^2. However, there is no difference in the embodied energy of 53 m^2 (7.3 m by 7.3 m) structural bay for two-way flat plate with drops, one-way beam and slab or one-way joist slab assemblies.

Table 5. Embodied energy (EE) of steel and concrete structural bays.

Area	Steel bay	Concr. bay	EE Steel	EE* TWFP	EE** TWFPD	EE*** OWBS	EE**** OWJS	EE***** WS
m^2	m x m	m x m	GJ	GJ	GJ	GJ	GJ	GJ
24	4.3 x 5.5	4.9 x 4.9	21	10				
37		6.1 x 6.1			19	21	20	
45	5.5 x 8.2	6.7 x 6.7	42	25				
53		7.3 x 7.3			32	32	32	31
71	7.2 x 9.8	8.5 x 8.5	89	67	52	47	48	43
94	8.5 x 11.0	9.7 x 9.7	118	86	80	63	71	69
121	9.2 x 13.1	11.0 x 11.0	163		115	85	98	90
149	11.1 x 13.4	12.2 x 12.2	228		159	112	128	129

*Two-way flat plate (TWFP) bay dimensions differ from those shown in the “Concr. bay” column, as rectangular bays are more efficient for longer span TWFP systems, but the area of the bay is consistent.
71 m^2 = 6.1 m x 11.6 m. 94 m^2 = 8.5 m x 11.0 m.
**Two-way flat plate with drops (TWFPD)
***One-way beam and slab (OWBS)
****One-way joist slab (OWJS)
*****Waffle slab or two-way joist slab (WS)

The embodied energies of the structural bays in Table 5 are corroborated by other studies. The theoretical 3-story office building used by Cole and Kernan (1996) was designed with structural bays of 56 m^2 (7.5 m by 7.5 m) and compared steel and concrete structural systems. While the exact structural assemblies are not detailed, the comparison can still be used to test the general validity of the values arrived for this research. The embodied energy of just the structural system (above grade horizontal and vertical components) for a single structural bay was 55 GJ for steel and 42 GJ for concrete. Extrapolating from Table 5, the equivalent steel structural bay in this study would have an embodied energy of 62 GJ, suggesting the material embodied energy values used in this study for steel may be high but within the 30% range for embodied energy data noted in the ICE. Potentially, the loading assumptions for this study (100 psf) are also greater than those used for the theoretical office building. While the 42 GJ is greater than the embodied energy of the 53 m^2 concrete structural bays calculated in this study, by extrapolating the two-way flat plate assembly data, a 56 m^2 structural bay would have an embodied energy of 43 GJ almost identical to the Cole and Kernan data.

2.4 *Comparisons to Existing LCA Tools*

In comparing the data in Table 5 to that generated using existing LCA tools, questions arise about the embodied energy values employed by these tools, in particular the AEC. The AEC uses an embodied energy of 1.8 MJ/m^2 for a steel assembly and 3.0 MJ/m^2 for concrete. These values are cradle-to-grave versus the cradle-to-gate figures used in this study and Cole and Kernan, and consequently it is expected that the embodied energy of structural bays using these values will be greater. For comparison, Cole and Kernan estimate the cradle-to-gate embodied energy for a steel assembly to be 0.98 MJ/m^2 and for a concrete assembly to be 0.74 MJ/m^2. Using a $71m^2$ structural bay for comparison, the AEC structural steel bay has an embodied energy of 127GJ and the AEC concrete bay has an embodied energy of 213GJ. Compared to the values in Table 5, this represents a 43% increase for steel and a 218-395% increase for concrete. It is clear there is a major difference in the embodied energy the AEC data assumes is added to a steel structure over a concrete structure after the building is erected or the data is otherwise flawed.

3 CASE STUDY

3.1 *Overview*

A 4-story laboratory building, that was in schematic design at the University of Oregon in Eugene, Oregon, was used as a case study to test the use of structural bays as a comparative tool for calculating embodied. Schematic plans furnished by the architects were used to identify the bay sizes used in the building. The numbers of bays of a given size in the building were totaled including all floors (Table 6). Using these figures and the data in Table 5, the total embodied energy for the building was calculated to compare the six assembly systems.

Table 6. Assessment of structural bays in the case study.

Bay size	Area	Bays	
m x m	m^2	No.	%
4.9 x 4.9	24	4	3
4.8 x 7.7	37	52	35
6.7 x 6.7	45		
6.5 x 8.5	55	44	29
6.5 x 10.9	71	44	29
9.7 x 9.7	94	6	4
11.0 x 11.0	121		
12.2 x 12.2	149		

3.2 *Embodied Energy of Alternative Structural Systems*

The assembly system with the lowest embodied energy for the case study building was either a concrete one-way beam and slab or one-way joist slab (Table 7). These two systems had the lowest embodied energies for structural bays in the 37 m^2 and 71 m^2 range that makes up 93% of the structural bays in the case study building. While the waffle slab does have structural bays with a lower embodied energy in the 71 m^2 range, the smallest bay size available for waffle slab construction is 55 m^2. Consequently, all of the smallest structural bays in the case study (37 m^2 and smaller) would be over designed in a waffle slab. Similarly, the two-way flat plate has structural bays with the lowest embodied energy for 45 m^2 and smaller, but as 65% of bays in the case study are larger, this assembly had the highest total embodied energy of the concrete systems. The steel assembly system had over double the embodied energy of all of the concrete systems with the exception of the two-way flat plate.

Table 7. The total embodied energy (EE) of alternative structural systems for the case study.

Assembly type	EE MJ
Steel	11,171
Two-way flat plate	6,467
Two-way flat plate with drops	5,208
One-way beam and slab	5,036
One-way joist slab	5,065
Waffle slab	5,391

4 CONCLUSIONS

Structural bay based embodied energy (SBBEE) calculations offer a fast, easy and relatively transparent way to compare the environmental impact of alternative structural systems. By accounting for the non-linear amounts of materials used by different assemblies for a given structural bay size, this method allows for more accurate assessment of embodied energy than traditional methods that use the same value of embodied energy per unit floor area regardless of the spans used. If a building was composed primarily of a single structural bay size, the data from Table 5 without any further calculations could be used to compare the embodied energy of alternative assemblies. This could prove invaluable for architects and engineers during the early phases of the design process where there is little time and too many alternatives to do a more thorough comparison of embodied energy alternatives.

For the four-story laboratory building used as a case study for this paper, the embodied energy of the two more commonly used assemblies – steel and two-way flat plate – proved to be the highest. All of the other concrete systems, especially the one-way beam and slab and one-way joist slab, offered significant reductions (17-55%) over the more commonly used systems.

There are still shortcomings to the SBBEE method that need to be addressed with future research. Foundations make up 10-15% of the embodied energy of structural systems (Cole and Kernan 1996) and should not be excluded from these calculations. As steel structures are lighter than concrete structures designed for similar spans, the embodied energy differential between steel and concrete assemblies would be reduced if foundations were accounted for. Despite greater transparency over the traditional bundled method of calculating the embodied energy of structural systems, the SBBEE method still requires a number of assumptions. Those assumptions include the materials used, their recycled content, floor-to-floor heights, and the loading conditions. The later two are often based on the program of the building. The comparison of alternatives is also limited to the assemblies chosen by the authors. This particular study excluded wood assemblies as building codes prevented their use in the case study building. If these issues could be addressed without increasing its complexity, the SBBEE method would be a powerful tool for comparing the environmental performance of structural systems early in the design process when its selection is typically made.

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