Comparing the embodied energy of structural systems in parking garages

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ABSTRACT: The structure of a typical office building contributes roughly one-quarter to one-third of the total embodied energy. Although the occupation phase of a building's life cycle currently dominates energy use, 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. Consequently, the structural system should be a primary target for reducing the embodied energy of a building. Parking garages offer an ideal case study for comparing the embodied energy of a variety of structural systems. As above grade parking garages have little operational energy use outside of lighting and have few materials or systems beside the structure, the embodied energy of the structure comprises a majority of the environmental impacts during its life-cycle. By selecting existing parking garages built over the last 10 years of similar height and in the same seismic zone, the design loads, column lengths and structural layouts are similar. This consistency makes more accurate comparisons between structural systems possible. Using material take-offs of three existing parking structures with one-way spans, one pre-cast concrete, one post-tensioned concrete and one cellular steel, this study shows that there is little difference in the normalized embodied energy of structural systems used for parking garages if steel with high-recycled content is used. The most important step architects and engineers can take to reduce the embodied energy of a parking garage structure is to specify steel products with a high recycled content, specifically reinforcing bars and structural sections.

1 INTRODUCTION

1.1 *Rationale*

There are a number of primary factors that influence the selection of a structural system during the design process including building codes, cost, scale of the project, and bay sizes required by the program (Griffin et al. 2010a). Very little consideration is given to ways the structure could contribute to improving sustainable outcomes. This is in spite of the fact that the structure of a typical office building contributes roughly one-quarter of the total embodied energy (Cole & Kernan 1996, Suzuki & Oka 1998) and is, at the very least, the armature for all other building systems. Like building envelopes, mechanical systems and other aspects of a building, the structural system needs to be understood in terms of wide range of sustainability issues: embodied energy, operational energy, longevity and reuse. 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.

Parking garages offer an ideal case study for comparing the embodied energy of a variety of structural systems. As above grade parking garages have little operational energy use outside of lighting and have few materials or systems beside the structure, the embodied energy of the structural materials comprises a majority of the environmental impacts during its life cycle. As the urban population in the United States is estimated to increase by over twenty percent by 2030 (United Nations 2006), parking garages will contribute significantly the environmental impact of the built environment due to the high demand for automotive storage in both urban and suburban areas (Chester et al. 2010).

1.2 *Embodied energy and parking garages*

This paper uses embodied energy as a sustainability metric to compare structural systems as it can also serve as a good indicator of relative raw material depletion, greenhouse gas emissions, and general degradation of the natural environment when comparing alternatives (Ashley, 2009). 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" as opposed to the "cradle-to-grave" method of calculating embodied energy that would also include primary energy expended on the transportation, construction, maintenance and disposal of building materials. As transportation, construction methods, building maintenance, life-cycle, and demolition can vary greatly, this paper focuses on the more consistent and quantifiable components of the embodied energy of structural materials. Specifically, there is no connection to the service life of a building and the material used for its structure (O'Connor 2004). A comparison of North American and European office buildings indicated that the assumed service life of these buildings was not matching the actual service life (Junilla et al. 2006). A life cycle analysis (LCA) study of two theoretical, five-story office buildings, one with a steel frame and concrete slabs and the other with a cast-in-place concrete structural system, showed similar energy use during construction, operation and end-of-life (Guggemos and Horvath 2005). However, the energy used in these steel and concrete structures differed most significantly in the "cradle-to-gate" manufacture of the building materials.

Instead of office buildings typical of theoretical and case study based whole building LCA studies, this paper uses parking garages to avoid the variance found in and across office building studies. 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 with uniform grids to the design of a new building due to the unique requirements of each new site and program that making using a similar standardized grid impossible. Due to a wide range of assumptions, it is even difficult to compare one theoretical office building LCA study to another (Robertson, et al. 2012). 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/ft^2, can still vary by up to 50% depending on the building (Suzuki & Oka 1998). Consequently, using case studies of office buildings to compare alternative structural systems has limited accuracy. As parking garages have predictable loads, consistent floor-to-floor heights and accommodate exactly the same program, there should be fewer variables distorting comparisons between different structural systems. This paper uses real, built parking garages rather than a theoretical design to study the effects of irregularities that develop due to site constraints typical of urban infill projects. One major difference between parking garage structures and those used in office buildings is that garages typically use long one-way spans to create clearances for a driving lane and a row of parking on either side. Office buildings typically use two-way concrete systems or shorter span steel bays.

2 METHODOLOGY

2.1 *Structure selection*

To ensure design consistency, the authors partnered with the largest structural engineering firm in Portland, Oregon and used their archive of structural drawings to find comparable case studies. A survey was undertaken of all parking garages the firm had completed in the last decade to ensure the same code requirements for seismic design. Ten parking garages using different structural systems were found to be of similar number of stories, design loads, column length, and structural layout. After excluding atypical layouts or mixed structural systems, three parking garages – one using precast concrete spans, one using cellular steel spans and one using post-tensioned concrete spans – were selected.

All three of these parking garages have one story partially below grade and were built on in-fill sites next to existing buildings and roads. Despite efforts to minimize differences between the three selected garages, some inconsistencies exist. The cellular steel and post-tensioned concrete garages are located six miles apart in Portland, Oregon with the precast concrete parking structure is located in Boise, Idaho. The overall parking area of the garages varies with two within 10% of each other and the third is almost three times larger. Two of the parking garages, the precast concrete and cellular steel, were built on previously existing surface parking lots for hospitals and the post-tensioned is for a transit center that includes bus parking on the ground floor. Consequently, the post-tensioned garage has a slightly taller first story and a thicker slab on grade to accommodate the buses. Finally, although all are within the same seismic zone, they vary slightly in soil conditions, as every construction site inevitably will have its own unique conditions. Table 1 summarizes the parameters of the parking garages used in this study. These differences could have an impact on the comparison of structural systems and will be taken into consideration when analyzing results.

Table 1. Parameters of parking garages used in this study

Primary Span	Stories	Area (ft^2)*	Typ. Span (ft)**	Typ. Story (ft)	Soil Bearing (lb/ft^2)***
Precast Concrete	3	132,000	56.0	11.0	4,500
Cellular Steel	4	143,000	58.5	11.0	5,000
Post-Tension Conc.	4	313,000	60.5	11.0	5,000

*multiply by 0.093 to convert to m^2

**multiply by 0.305 to convert to m

***multiply by 0.048 to convert to kPa

2.2 *Description of selected structural systems*

The three-story precast concrete parking garage consists of a slab on grade with two stories of precast double tees above. As the ground floor is partially below grade, two sides (west and south) of the garage are cast-in-place concrete walls supporting the double tees with cast-in-place columns and precast beams supporting the double tees everywhere else. There is a 3 inch (7.6 cm) concrete topping on the double tees. The lateral load resisting system is a series of cast-in-place concrete shear walls. The overall dimensions of the rectangular parking garage are 173 feet (52.7 m) by 274 feet (83.5 m). Currently only first two stories of the parking garage are constructed but the structural drawings include a future third story. This study includes the yet unbuilt third story as all of the vertical and lateral supports that have been designed and built are designed to carry the third story. Including the third story also increases the square footage and number of stories to make this garage more compatible with the other case studies.

The four-story cellular steel parking garage consists of a slab on grade and three stories of cellular steel beams with a galvanized steel deck and 3.5 inch (8.9 cm) topping. The ground floor has a cast-in-place concrete wall on one side as this floor is partially below grade. The remainder of the structure consists of steel wide-flange beams and steel columns. The lateral load resisting system consists of concentrically braced frames deployed in an I-shaped formation near the center of the structure. The overall dimensions of this rectangular parking garage with a kink in the middle are roughly 117 feet (35.7 m) at its widest and 358 feet (109 m) long.

The four-story post-tensioned concrete parking garage has a slab on grade that is double the thickness, 10 inches (25.4 cm), of the other two parking garages, as it must accommodate buses. The remaining floors consist of one-way, post-tensioned, cast-in-place beams and 5.5 inch (14.0 cm) one-way, post-tensioned slab. Like the all of the other garages, the ground floor is partially below grade and has a concrete wall on two sides. The rest of the gravity load system consists of cast-in-place columns. The lateral load resisting system consists of cast-in-place concrete shear walls in near the center of the garage and moment resisting concrete frames on the short ends.

The overall dimensions of this rectangular parking garage are 242 feet (73.8 m) by 343 feet (104.5 m).

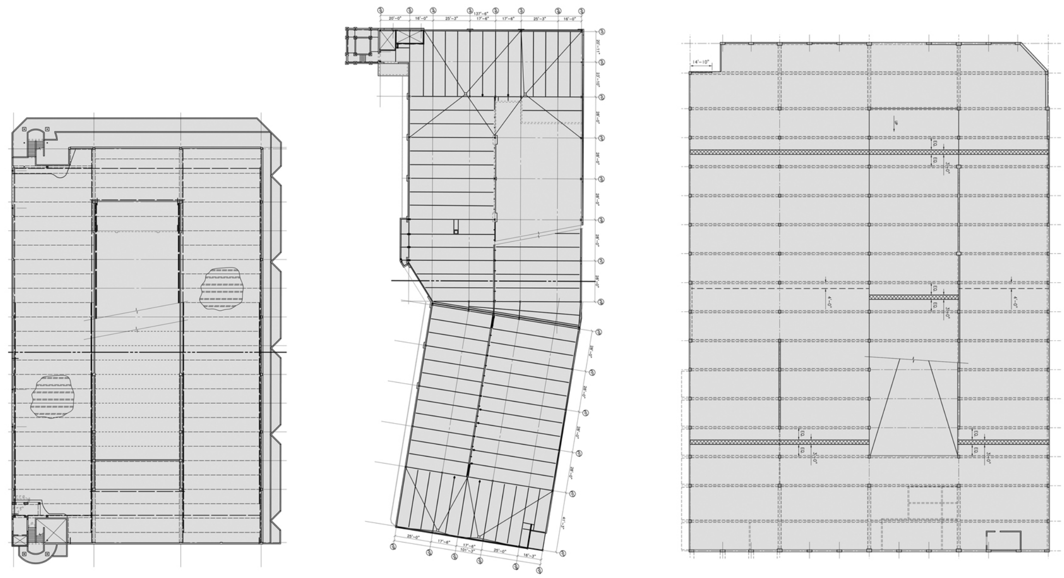

Figure 1. Plans at the same scale of the three case study parking garages (left to right): precast concrete, cellular steel and post-tensioned concrete.

2.3 *Data collection*

A complete digital and physical copy of the structural drawing set for each garage served as the primary source of information along with aerial photographs and visits to the two sites in Portland. Take-off calculations were done for each of the three garages to calculate the amount and types of steel and concrete used. At least three of the authors reviewed each of the spreadsheets to ensure accuracy and consistency in how materials were calculated and categorized. Due to the amount of the data collected, these detailed calculations have been omitted from this paper.

Throughout the data collection process all values and quantities reflected the specifications stated within the provided drawings. Consequently, all calculations are based on the assumption that during the construction process specifications were met precisely. In reality, the actual dimensions and strengths could differ from design drawings. For example, the assumption is made in this study that all materials do not exceed the stated minimum strength when it is a requirement that would likely be exceeded in practice. To account for splicing and other overlapping that is required when using steel reinforcing bars, an additional 20% of the total weight of these bars is included. Where measurements proved difficult rules of thumb were used, such as adding 2% of the linear length of a draped tendon to account for its slight curvature and extra length. Wherever possible, exact measurements were taken from the drawings to account for all of the structural materials in each parking garage. These materials were totaled by breaking down the types of structural materials used for each garage, such as different strengths of concrete, reinforcing bar, structural steel sections, etc. Each of these material totals was multiplied by the embodied energy for both virgin materials as well as the most likely case for the maximum use of cement substitutes and recycled content to calculate both a worst and best case scenario for the embodied energy of each parking garage. Material totals and embodied energy totals were normalized by the parking area of each garage in order to compare the systems used in the case studies to one another.

2.4 *Embodied energy of structural materials*

As justified in Section 1.2, this study uses cradle-to-gate embodied energy values from the ICE database (Hammond and Jones, 2008). The values used for concrete materials can be found in Table 2 and those for steel materials can be found in Table 3. These values are extrapolated from worldwide averages in the ICE database, which focuses on the implications for the United

Kingdom. Consequently, these values are not reflective of the specific conditions and primary energy sources used in the Pacific Northwest of the United States but are the most credible, peer reviewed embodied energy values in the authors' opinion.

Table 2. "Cradle-to-gate" embodied energy (MJ/lb)* of structural concrete with various portland cement replacement rates with fly ash. Data extrapolated from ICE (Hammond and Jones 2008).

PSI**	0% Fly Ash	25% Fly Ash	50% Fly Ash
4,000	0.413	0.360	0.307
4,500	0.434	0.382	0.330
5,000	0.445	0.403	0.381
6,000	0.505	0.443	0.381

* multiply by 2.02 to get MJ/kg

**multiply by 0.0069 to get MPa

Table 3. "Cradle-to-gate" embodied energy (MJ/lb)* of virgin and 93% recycled structural steel products. Data extrapolated from ICE (Hammond and Jones 2008).

Material	Virgin	93% Recycled Content
Structural Sections	17.3	5.4
Decking (Cold Formed Galvanized)	18.1	5.7
Reinforcing Bar	13.5	4.7
PT Tendons	16.1	5.1

* multiply by 2.02 to get MJ/kg

The comparison between the use of virgin materials and materials with a high cement replacement, in this case with fly ash, and recycled content highlights the impact that the use of recycled material can have on the embodied energy of a structure. For this study we assumed that structural concrete in foundations and slabs on grade could have a maximum cement replacement of 50% and other structural concrete would have a maximum replacement of 25%. This study uses a recycled content of 93 percent, which is typical in the steel mills found in the United States.

3 RESULTS

3.1 *Structural material quantities*

After spending a significant amount of time accounting for every structural component in each of the three case studies, the total amount of concrete and steel for each garage was normalized by the parking area of each structure (Figure 2). The precast concrete structure had the greatest amount of concrete per unit area and the cellular steel structure had the greatest amount of steel per unit area. The post-tensioned concrete garage came in the middle in terms of amount of concrete and has roughly half of the steel found in the cellular steel garage.

The amount of concrete in the precast garage is likely higher than it would normally be as it had the most cast-in-place concrete in the wall category, almost 14 pounds per square foot parking area, due to the depth of the first story below grade compared to the other two garages. The precast garage also had more concrete associated with the footings than the other two case studies. This is likely due to both the higher weight of the precast structure and the slightly weaker soil bearing pressure of this location. The amount of steel in the post-tensioned garage is greater than the precast structure due to the increased quantities of bar reinforcing in the post-tensioned slabs as well as its deeper and more reinforced slab on grade designed for bus parking.

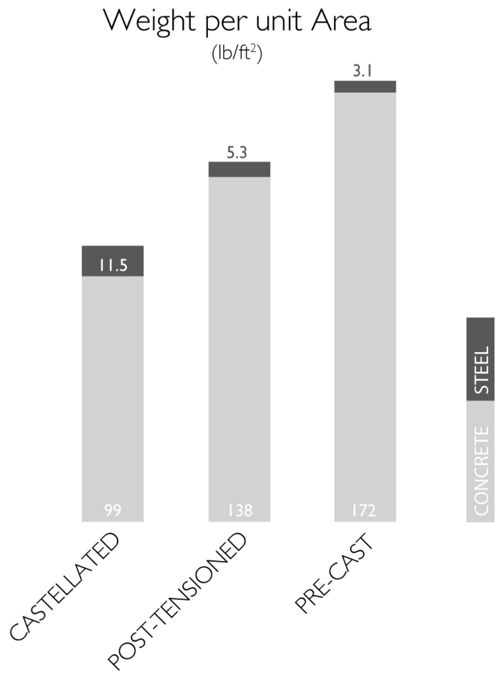

Figure 2. Structural material quantities per square foot of floor area. Multiply lb/ft^2 by 4.88 to get kg/m^2.

3.2 *Embodied energy of structural systems*

The total embodied energy for each parking garage was calculated based on the totals of each strength of concrete and type of steel used, once using values for virgin materials and once using values for the highest conceivable replacement of cement and recycled content in steel as discussed in Section 2.4 (Table 4). These two scenarios can create a range of embodied energy values that can be used to understand the trade-offs between using virgin and recycled materials. The greatest difference in embodied energy between the two material scenarios occurred in the cellular steel case study where there was a reduction of 59% using high volume fly ash concrete and high recycled content steel.

Table 4. Total "cradle-to-gate" embodied energy of each case study.

Primary Span	Area (ft^2)	Virgin (TJ)	Cement Replacement (TJ) and Recycled Content	Reduction in Embodied Energy
Precast Concrete	132,000	16.0	10.5	34%
Cellular Steel	143,000	30.8	12.7	59%
Post-Tension Conc.	313,000	42.3	24.7	42%

While the post-tensioned concrete structure had the highest embodied energy overall, it is three times larger in terms of parking area than the other two case studies. To compare the relative sustainability of each structural system, the embodied energy was normalized by the parking area of each garage (Table 5 and Figure 3). When comparing the structural systems using virgin materials, cellular steel is almost twice the embodied energy of either the two concrete structures. The zero-percent recycled content steel accounts for 82% of the embodied energy in the cellular steel garage. The precast concrete and post-tensioned concrete structures are within ten percent of each other as the pre-cast structure uses less steel but more concrete and the post-tensioned structure uses less concrete but more steel. All three of the structural systems have roughly the same embodied energy, within 11% of one another, when using materials with high-recycled content and replacement of portland cement.

For a theoretical three-story office building with a 24.6 ft by 24.6 ft (7.5 m by 7.5 m) structural grid, Cole and Kernan (1996) estimate the cradle-to-gate embodied energy for a steel structure to be 91 MJ/ft^2 (0.98 GJ/m^2) and for a concrete structure to be 69 MJ/ft^2 (0.74 GJ/m^2). While the exact structural assemblies are not detailed, a comparison can still be used to test the general validity of the values arrived from this research and their applicability to other building types. The high-recycled content steel embodied energy values in this study are within 3% of the Cole and Kernan data despite the use of longer spans in the parking garage, 60.5 feet (18.4 m) versus 24.6 feet (7.5 m) in the theoretical office building. This could be accounted for in the use of efficient cellular spans in the parking garage over conventional wide-flange beams. However, the high cement replacement concrete values for this study are 10-15% higher than the Cole and Kernan data. The normalized embodied energy values for the virgin concrete parking garage structures are approximately twice the value of those theoretical office building. This is likely due to the long one-way spans versus the shorter spanning, two-way system that could be used in an office building. Consequently, it is difficult to apply the results of this study directly to structural systems used in other building typologies, such as office buildings.

Table 5. Normalized "cradle-to-gate" embodied energy of each case study.

Primary Span	Virgin (MJ/ft^2)*	Cement Replacement (MJ/ft^2) and Recycled Content
Precast Concrete	121	80
Cellular Steel	215	88
Post-Tension Conc.	135	79

* multiply by 10.8 to get MJ/m^2

In comparison, the Athena Eco-Calculator (AEC) uses cradle-to-grave embodied energy values that include extraction, processing, transportation, construction, and disposal of each material for a low rise office building with a 60-year lifetime. The AEC uses a normalized embodied energy value of 155 MJ/ft^2 (1.67 GJ/m^2) for building with a conventional steel structure with steel joists and cast-in-place concrete foundation. A concrete column and beam structure with double tee spans, a concrete topping and cast-in-place concrete foundation has an embodied energy of 218 MJ/ft^2 (2.35 GJ/m^2). While the cradle-to-grave embodied energy value seems reasonable if the steel contains a high-recycled content, the AEC values for concrete contain assumptions that almost double the cradle-to-gate embodied energy calculated in this study. 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 as the building is erected and afterwards or the data is otherwise flawed (Griffin et al. 2010b).

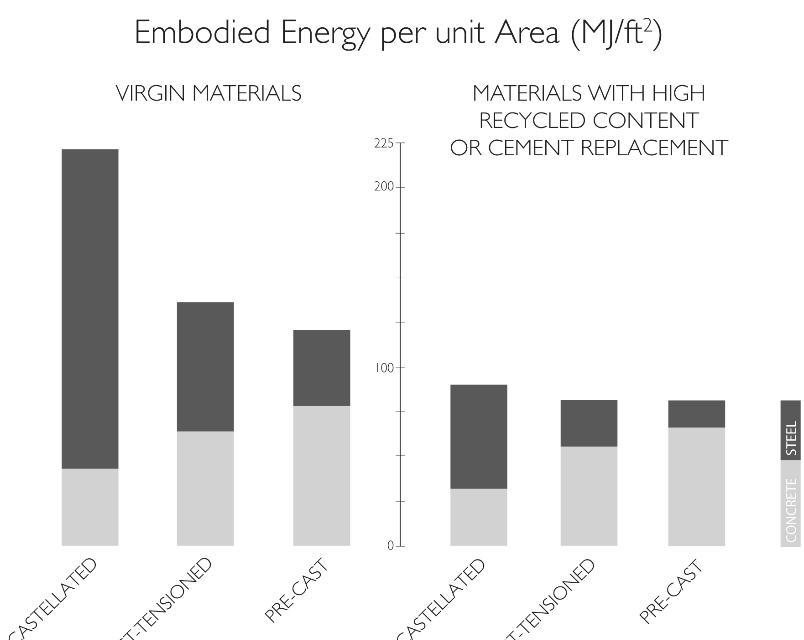

Figure 3. Cradle-to-gate embodied energy per square foot of floor area for each case study. Multiply by 10.8 to get MJ/m^2.

4 CONCLUSIONS

This study shows that there is little difference in the embodied energy of structural systems used for parking garages if steel with high-recycled content is used. In practice, it is far more likely to use high-recycled content steel than concrete with 50% replacement of portland cement with fly ash. This would negate the slight advantage the precast and post-tensioned concrete structural systems have. The most important step architects and engineers can take to reduce the embodied energy of a parking garage structures is to specify steel products with a high recycled content, specifically reinforcing bars and structural sections.

The authors propose a longitudinal study of the embodied energy of parking garages to verify the results of this sample and the development of tools for architects and engineers to more rapidly assess the environmental impact of these one-way structural systems. As the density of cities increases and new transportation infrastructure is built, parking garages will continue to provide opportunities to reduce the environmental impact of the built environment as well as insight into how structural systems in buildings of all types can be improved.

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