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EMBODIED ENERGY ASSESSMENT OF THE STRUCTURAL SYSTEM IN CONCRETE BUILDINGS: A CASE STUDY ON 7 SOUTH EAST QUEENSLAND STRUCTURES

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ABSTRACT

The contribution of the building industry to a wide range of environmental impacts is extensive with the construction, operation and maintenance of buildings accounting for approximately 50% of all energy usage and anthropogenic greenhouse gas (GHG) emissions globally. Previous attempts to mitigate buildings environmental impacts have focused on the optimisation of operational energy requirements to improve life cycle energy consumption. Societies increased awareness of environmental issues, as well as improved technology; result in reductions of operational energy consumption. The outcome being increased embodied energy contributions to a structures life cycle. At present, no design standards include the assessment of structures embodied energy. This research was conducted to obtain an understanding of the embodied energy present in recently constructed concrete buildings in the South East Queensland region of Australia. In order to develop standards, current baselines values need to be generated to assess existing performance. The focus was quantifying and analysing the embodied energy of a number of existing concrete buildings of various heights and structural systems. The study was conducted on seven structures to investigate the suitability of this methodology in developing sound baseline values for the building design industry. The outcome of these buildings based on current green building ratings systems was also considered.

KEYWORDS

Sustainable development, concrete structures, structural design, embodied energy, green building rating system.

INTRODUCTION

The construction industry is responsible for a significant proportion of global energy consumption. It has been estimated that in the United States and in the European Union, the contribution of the construction sector to total energy consumption is approximately 40% (IPCC 2007, BEDB 2010).

Furthermore, it has been reported that in the United States alone, the construction industry produces 149 million tons of waste per annum (Winkler 2010), most of which is landfill (Frey 2007). The construction industry is responsible for a significant amount of waste produced: estimates range from 25% to 40% of total waste generated (Frey 2007).

Traditionally, the construction industry has been driven by economy. Negative impacts on the environment can be perceived a shortcoming of this one sided approach (Turner 2006). More recently, these shortcomings have been recognised, initiating a shift towards Sustainable Development (SD) (Persson, 2009, Miller and Doh 2014). The building development industry has responded to these challenges though the implementation of 'green' building rating systems. In these schemes, developers volunteer to subject their buildings to an assessment to determine their environmental credentials, quantifying a building's environmental performance.

In Australia, Green Star is considered the premier 'green' building rating tool. Green Star is based on LEED, the leading tool in the USA, and BREEAM, an UK based tool that is considered one of the world's pioneering systems (Fowler and Rauch 2006, Frey 2007). In the systems considered, developments are assessed based on the complete building life cycle (BLC): credits are earned for reductions in embodied energy (EE) and reductions in operational energy (OE).

This study presents an analysis of Green Star, BREEAM and LEED focussing on the proportion of marks earned for EE and OE. The results are compared with the significance of OE and EE in the BLC of a typical building based on life cycle analysis studies conducted previously. Structural building performance, in terms of EE, was then calculated for seven multi-residential buildings located in South East Queensland and Northern New South Wales. For comparison purposes, each building was subjected to a preliminary Green Star rating. This assessment focusses on credits earned through structural design only. The result of these ratings was compared to the environmental footprint determined previously. Results of the analysis are used to establish a benchmark in the rating of structural systems in terms of environmental performance.

EMBODIED ENERGY IN SUSTAINABLE DEVELOPMENT

Analysis of 'Green' Building Rating Tools

Three rating systems are considered in this study: Green Star, BREEAM and LEED.

The Green Building Council of Australia introduced Green Star in 2003 (GBCA 2014). Depending on building type, points can be earned in a number of categories: management, indoor environment quality, energy, transport, water, materials, land use & ecology and emissions. Based on the marks earned in the individual categories, and the weight assigned to the categories, a total score is assigned to a building. Points for innovation are assessed to achieve a final score. Environmental performance is presented in the form of a number of 'stars' ranging from 1 (10-19 points) to 6 (+75 points).

By analysing the detailed rating criteria, the allocation of marks, that could be influenced by a designing structural engineer, in all green building rating systems assessed was determined. For the Green Star assessment multiple building types were included: 'Education v1', 'Healthcare v1', 'Industrial v1', 'Multi Unit Residential v1' and 'Office v3' (GBCA 2014). It was estimated between 6% and 7% of marks are earned through structural design.

Building Research Establishment's Environmental Assessment (BREEAM) was introduced in 1990 (BREEAM 2014). Like Green Star, points are awarded in a number of categories: management, health & wellbeing, energy, transport, water, material, waste, land use & ecology and pollution. The final score is presented in the form of a percentage. 30% constitutes a pass and a score above 85% is considered 'outstanding'.

The allocation of marks in BREEAM to structural engineering and EE reductions were determined using the methodology discussed. Under the current international edition of BREEAM, approximately 8%-11% of marks are attributed to structural design depending on building type.

In Leadership in Environmental and Energy Design (LEED), 110 points can be earned for all building types. Criteria depend on the building type and location (USGBC 2014). Buildings are rated: 'certified' (40-49 points), 'silver' (50-59 points), 'gold' (60-79 points) and 'platinum' (80+ points). Points are awarded for: sustainable sites, water efficiency, energy & atmosphere, materials & resources, indoor environmental quality and innovation & design process. The final score is determined by the sum of marks earned, innovation credit and 'regional priority credits'. These credits take the form of additional marks for existing rating criteria based on specific local needs. Depending on building type and specific edition of the LEED rating tool, approximately 5%-8% of credits are earned through structural engineering and EE reduction.

Embodied Energy in a Typical Building Life Cycle

Based on a review investigation conducted by Miller and Doh (2014), proportions of EE and OE in a typical BLC were compared from previously published studies. No clear relationship was found between the date of publication of the studies investigated and the proportion of EE as a part of total life cycle energy. It is not evident that the proportions of EE and OE have increased or decreased as a result in changes in industry practice. Similarly, no significant differences are present between buildings in Australia (21.8% EE on average) and studies globally (18.6% EE on average). Some differences in EE are observed when comparing different building types. On average, for the studies investigated, for residential buildings 25.9% of total energy is EE. For commercial and mixed use buildings, these percentages are 17.3% and 13.3% respectively. EE as a percentage of total BLC energy for the studies investigated was presented as adopted from Miller and Doh (2014), (Figure 1). For comparison, the proportion of marks allocated to structural design in Green Star, BREEAM and LEED are included based on the quantitative criteria assigning points from each system to structural design and EE reduction. At present it can be seen that green rating systems underestimate the EE contribution to a buildings life cycle in comparison to the studies presented (Figure 1).

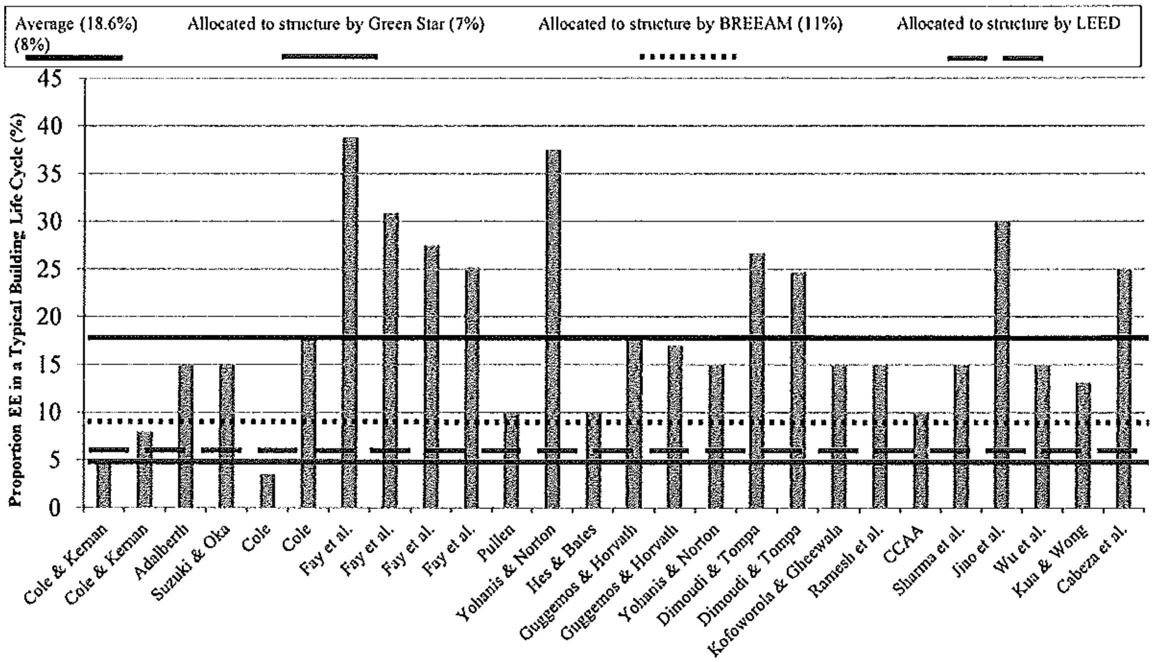

Figure 1. Embodied energy as a part of total life cycle energy as determined though comparing BLC studies and as considered by Green Star, BREEAM and LEED (Adopted from Miller and Doh 2014)

With the advent of clean energy sources popularity, OE requirements over the service life of a building will decrease. A recent study stated showed that construction techniques will not be required to change drastically to meet the challenge of carbon-neutral buildings (Zuo et al. 2013). With the industry moving towards the adaptation of Zero Energy Buildings (ZEB) (Zahedi 2010, Marszal and Heiselberg 2011, Zuo et al. 2012), the importance of reducing EE in sustainable development will increase. If the EE of a structure is maintained and the OE decreases, the EE compared to OE must proportionally increase. The outcome therefore follows that there will exist higher needs for improved EE efficiencies in structural design. Through the analysis of a typical bill of material quantities for high-rise structures (Chau et al, 2012), it was determined that approximately 90% EE of a building is part of the structural core. It is evident that the rating systems considered in this study underestimate the importance of the structural design process in terms of achieving SD objectives and ZEB's will only further emphasise this divide.

CASE STUDY OF RESIDENTIAL BUILDINGS IN SOUTH-EAST QUEENSLAND

Embodied Energy

Seven apartment buildings located in SEQ and Northern NSW were investigated. Each structure has a concrete frame using a combination of traditional reinforced concrete (RC) and post tension reinforcement (PT). The height of the buildings considered ranged from 4 to 35 stories (including basements). A bill of quantities (BOQ) for structural materials was produced from each building using constructing drawings supplied by the consulting engineer. Identification of these structures was not permitted for publication. The non-structural elements were omitted from the analysis and alternatively, this contribution was estimated using typical material quantities of non-structural elements per unit floor space from Chau et al. (2012). Using typical unit EE values per m^2 of floor space (Crawford 2011, Chau et al. 2012, Miller and Doh 2014), the embodied energy for the individual buildings were determined.

A number of assumptions were made during the analysis. It was assumed that the glass in the façade is 4mm thick and has a density of $2500kgm^{-2}$. To compare efficiency of the buildings, the EE per unit floor space was determined. Results of the analysis are presented (Table 1). For comparison, indices were assigned to each building. Baseline index 100 is arbitrarily assigned to building 7.

Green Star Rating

All buildings analysed were subjected to a mock Green Star rating based on the structural engineering influences assessment discussed. None of the buildings considered went through the official rating process. Details regarding building services, project management and other areas of rating were not documented with the degree of detail required for a comprehensive analysis. Assumptions were made when necessary. Assumptions required to assign points to all remaining marking categories would be ambiguous. Conclusions based on structural design scores provided greater benefit than conclusions based on a full rating. After analysis it was found that based on the assessment developed for structural engineering, all buildings in the case study achieve equal Green Star scores for credits related to structural design, being 1/10.45 marks (Table 1), with EE outcomes not resulting in variations of these outcomes. The Green Star scores achieved (Table 1) were based on assessment of the authors under a fixed criteria prepared prior to evaluation.

Table 1. Environmental footprint in terms of EE of seven residential buildings in SEQ

Structure	f'c Slabs (MPa)	Structural details*	Total EE (GJ)	Unit EE (GJ/m^2)	Index	Green Star score
Building 1	32, 40	2b 20f using RC and PT	208345.9	7.84	115.8	1/10.45
Building 2	32, 40	2b 33f, using PT	252400.1	7.92	117.0	1/10.45
Building 3	25, 32, 40	1b 4f using RC and PT	84673.5	6.78	100.17	1/10.45
Building 4	40	1b 26f using PT	129698.8	8.97	132.6	1/10.45
Building 5	32, 40	2b 15f using PT	185979.2	8.17	120.6	1/10.45
Building 6	32, 40	6f using RC and PT	29732.6	7.50	110.9	1/10.45
Building 7	25, 32, 40	1b 3f using RC and PT	76622.844	6.77	100	1/10.45
Average			**138207.6**	**7.71**	**113.9**	**1/10.45**

*f: number of floors, b: number of basements, RC: traditionally reinforced concrete, PT: post tension reinforced concrete

Discussion

It is evident that (structural) design methods impact the EE of a building significantly. Differences up to 30% of the case study buildings were observed. It can be concluded that reductions in EE as a result of (structural) design do not necessarily translate into increased Green Star scores. Figure 2 shows the relationship between building height (measured in number of stories) and EE per unit area (measured in GJm^{-2}). In LEED, buildings with an increased height to footprint ratio are awarded a number of credits for efficient use of space. It is evident from the trend line that a slight increase in EE per m^2 of floor space is present with increased building height. A trade-off between use of space and EE reduction must be made. Future research is required to appropriately quantify this correlation.

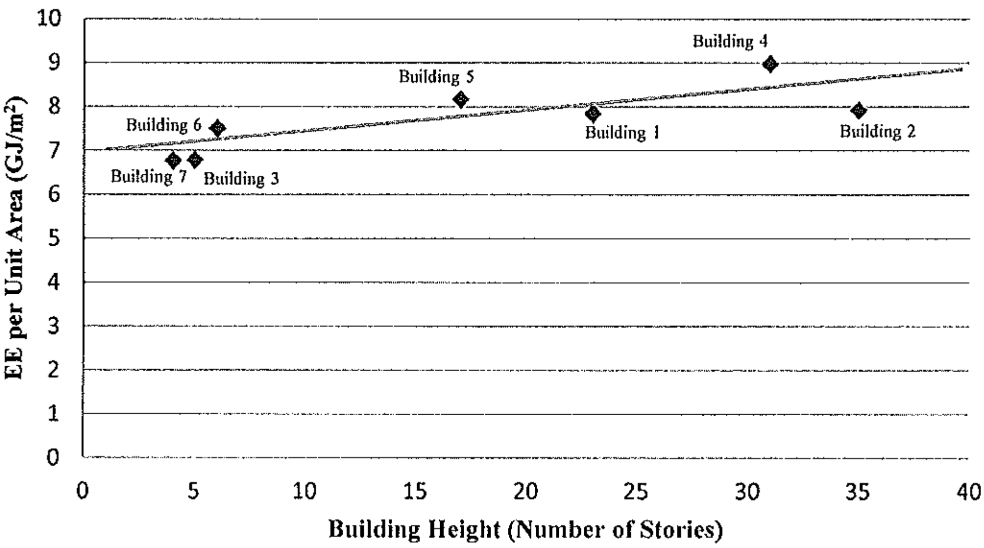

Figure 2. Development of EE with Increased Building height

CONCLUSIONS

Differences in design were present between the buildings considered. The main similarity from a structural aspect was the use of concrete as the main framing material. Each residential building used PT reinforcement to some degree. It is evident that no correlation exists between EE per unit floor space and Green Star score assigned to the structural system. It was established that EE of a structure was not represented with appropriate weight in 'green' building rating schemes based on a detailed previous study and investigation of the rating systems discussed. Under the current rating systems, efficiencies in EE through structural engineering may go unrewarded. In the case of the residential buildings considered, differences up to 33% in EE (Building 7: 6.768GJm^{-2} versus Building 4: 8.972 GJm^{-2}) are observed without changes in Green Star marks for the structural system.

This study addresses the need for a standard to quantify building performance in term of reducing EE of the structural system. It is noted that 'green' building rating tools effectively assess energy consumption during the in-service life of a building. Based on the preliminary Green Star rating, it was evident that complimentary performance criteria are required to assess the environmental footprint of a building in terms of EE. By completing a larger number of case studies, baseline EE values would establish to serve as a benchmark.

Based on the seven case studies completed, it can be concluded that these baseline values need to consider buildings with an increased height to footprint ratio. These tend to exhibit increased EE per unit floor space. A trade-off is usually required between efficient use of space and structural design efficiency.

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