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The contribution of column optimization on the embodied energy performance of concrete framed buildings

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Abstract: The incorporation of sustainability principles into the structural engineering design of buildings is increasingly important. Historically the focus of improvements to the environmental performance of structures has been operational energy considerations. Current research has highlighted the requirement for changing the approach by increasing the consideration of embodied energy in structures. This research was conducted to build on previous research by the authors in quantifying the contribution of column optimization to the embodied energy performance of concrete framed buildings. Ultimately, the authors intend to develop mechanisms through which sustainable design can be quantified, enabling alleviation prior to construction. Columns are a key structural element to consider as part of this development process. The outcomes of this assessment reinforced previous findings, observing that reduced structural weight as a result of other sustainable design measures carries manifold benefits include column design savings. Through the quantification of the embodied energy outcomes during this research phase, the columns were shown to contribute up to 19.71% of the total embodied energy of the structural system dependent upon construction technique used.

Keywords: embodied, concrete, environmental, column, slab, span, punching, steel

I. INTRODUCTION

Human activities discharging carbon dioxide due to the combustion of fossil fuels increases atmospheric greenhouse gases (GHG). This has resulted in higher global temperatures (approx. 0.6°C) during the past century [1]. Buildings are said to contribute up to 40% of global energy usage and one third of global GHG emissions [2]. Concrete is an extensively used construction resource on account of its wide range of architectural and engineering benefits. In 2007, it was revealed that current average concrete consumption is roughly one tonne per year for every living human being. It was identified as the second most utilized resource behind only water [3]. In Australia, approximately 30 million tonnes of raw building materials are produced annually, with over 56% of this quantity, by mass, attributed to concrete and an additional 6% being steel [4]. In addition, the study also showed that steel and concrete accounted for roughly 41% of the global warming impacts caused by the building sector in Australia [4]. Therefore, even small reductions of GHG per tonne of manufactured concrete can be comparable with creating significant global improvements [3].

Environmentally Sustainable Design (ESD) or “green design” is an attempt to use design principles and strategies with the purpose of reducing environmental impacts generated from construction and operation of buildings [5]. There rises the no longer acceptable fact that only architects are responsible for centralizing the pressing environmental needs; while structural engineers remain somewhat dormant [6]. Structural engineers have the ability and responsibility to interweave ESD with current design methodologies to expect an improvement in the structural effectiveness of a building. This is achieved through the improved efficiency of a structural system in parallel with maintaining equivalent structural performance [7].

By altering the design methodology to include the aspect of sustainability, significant resource savings, improved marketability of a structure and vast environmental benefits to every new structure may be provided. Previous research conducted by Miller et al. [7] was to quantify the environmental impact efficiencies, which could be acquired by using post-tensioned (PT) slabs over conventionally reinforced concrete (RC) slabs in a typical 11-storey office structure. The aim of this research was to build on previous outcomes in quantifying the contribution of column optimization to the embodied energy (EE) performance of concrete framed buildings.

II. METHODOLOGY

To attain this, a multi-stage research methodology based on quantitative analysis was adopted (Figure 1). This methodology was sub-divided into two major components: Structural Design and Environmental Assessment. Each component comprised of several distinct stages.

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During the Structural Design phase, the Design Definition involved defining the structural parameters and characteristics of the column system that was based upon the investigation of Miller et al. [7]. Manual Calculations were undertaken in accordance with Australian Standards, typically AS3600-2009 (Concrete Structure) [8] and AS1170-2002 (Design Loading Actions) [9].

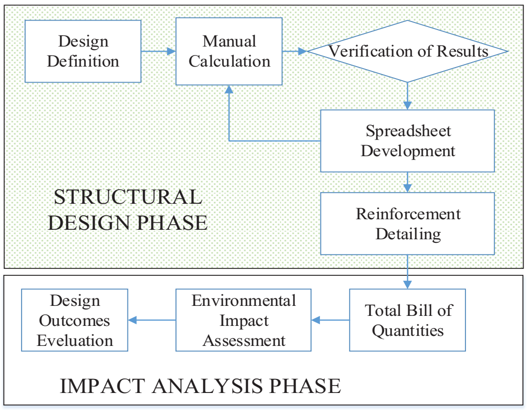

Figure 1. Methodology for Structural Design and Environmental Analysis

After verifying the obtained results, spreadsheets were developed to facilitate the design phase, applied for all structural models. The reinforcement detailing was implemented in accordance with the instructions set forth by Australian Standard and the Concrete Institute of Australia [8, 10] that allowed a total Bill of Quantities (BOQ) to be formulated for the Environmental Impact Assessment (EIA) phase. Using the BOQ, an EIA was conducted using data obtained from the extensive literature review by Miller et al. [7], to estimate the environmental impacts of each structure in terms of embodied energy as presented in Table 1. Based on the baseline assessment, the design outcomes were evaluated across both RC and PT structural frame models.

Table 1. Embodied Energy values to be utilized in the Environmental Impact Assessment

Construction Material	**Embodied Energy**
Concrete (32 MPa)	4880.4 MJ/m^3
Concrete (40 MPa)	5670 MJ/m^3
Concrete (50 MPa)	7182 MJ/m^3
Concrete (65 MPa)	10348.8 MJ/m^3
Steel Reinforcement	85.46 MJ/tonne
Galvanized Steel	38 MJ/tonne

2.1 Structural Parameters

The 11-storey office structure with car parking on the ground floor and ten floors of commercial space is indicative of typical current construction practices in the South East Queensland (SEQ) region of Australia. Concrete strength of 32 MPa was investigated in this study for both PT and RC options. Simple flat plate construction arranged in a square grid with varying number of spans was applied through the typical floors and roof. The structure's external dimensions were kept constant at 40.5 by 40.5 metres to allow for accurate comparison between the different span lengths. The span lengths investigated in this study included 6.67, 8, 10 and 13.33 metres which provides between 3 and 6 spans for the total building dimension.

2.2 Punching Shear in Flat Plate

As aforementioned, the typical office structure investigated involved flat plate construction. However, there commonly arises a critical analysis problem relating to punching shear around the slab-column connections. Particularly, for corner and edge columns, punching shear is found to be the focus of study due to the unbalance loading condition along with the unsymmetrical stress distribution in these locations [11]. Punching shear failure can be controlled by a combination of slab thickness variations, column dimension variations or a combination of these two. In this study, the slab thickness data designed as minimum slab thickness requirements extracted from previous research [7] as shown in Table 2. The thickness of these slabs remained constant so as to achieve minimum column sizes allowing the columns to be designed to resist punching shear failure in the absence of additional reinforcement. The strength of the slabs in punching shear was determined in compliance with Clause 9.2 (AS3600-2009) [8].

Table 2. Slab Thickness

Slab Span (m)	RC		PT	
	Floor (mm)	Roof (mm)	Floor (mm)	Roof (mm)
6.67	335	235	250	200
8	415	300	270	210
10	555	400	360	290
13.33	830	635	520	400

The minimum column sizes were obtained with respect to the exterior column of both RC and PT slabs with the varying span lengths described. Due to thinner thickness in the PT slabs, which made punching shear failure become more critical, the column sizes of columns in PT slabs were more significant in comparison with RC.

2.3 Structural Column Design

A load takedown was performed, which allowed dead and live loads to be transferred into the column elements that would ultimately be transmitted into the lower columns. These columns were designed to satisfy strength and serviceability requirements as stipulated in Section 10 of AS3600-2009 [8]. The final column sizes can be determined using an iterative design process. Biaxial bending and compression were checked to ensure compliance with the Standard. Sufficient reinforcement was provided; while simultaneously steel congestion must be avoided. The size and reinforcement detailing of the bottom column were maintained consistently and used for the entire structure. Table 3 presents the column size in details.

Table 3. Column size

Slab Span (m)	RC			PT		
	Punching shear (mm)	Final Exterior (mm)	Final Interior (mm)	Punching shear (mm)	Final Exterior (mm)	Final Interior (mm)
6.67	350	430	585	460	460	575
8	425	560	770	650	650	700
10	585	810	1100	800	800	940
13.33	840	1380	1960	1115	1115	1580

After design and verification, a BOQ was generated enabling the EIA comparisons to be completed.

III. RESULTS AND DISCUSSION

Material requirements as determined from the BOQ were applied to corresponding factors to quantify the environmental impacts using an EIA for materials in the column systems. In addition, the findings for concrete columns were combined together with previous research outcomes by Miller et al. [7] to calculate the material requirements for the whole building structure. Based on this, the proportion of EE that columns contribute to the entire structure was estimated.

3.1 Material Requirements and Embodied Energy in Columns

Through the implementation of PT methods as opposed to RC methods, the material requirements for column systems could be curtailed significantly. Using the BOQ generated for each structure, the achievable reduction in concrete volume and steel mass were represented (Figures 2 and 3) respectively.

With the use of PT slab construction, the concrete volume required for the columns of a structure experienced a dramatic reduction. The curtailment in concrete volume increased when the span length was increased, ranging from approximately 2.59% for a 6.67 metre span up to 34.98% for a 13.33 metre span. The steel mass required for the column structures was considerably reduced, to an even greater extent than what was experienced in the curtailment of concrete volume. However, the obtained results indicate that the reductions did not increase with increased span. The 8 metre span achieved the largest material reduction when the PT construction was used. It was evident from Figure 4 that for the entire structure, PT was able to dramatically reduce the weight of the structural frame through the reduction of material requirements. A reduction in weight shall result in significant reductions in material requirements of other structural elements such as foundations, concurrently contributing to the structure's overall EE consumption. However, this cannot be quantified as this was considered outside the scope of this study. In general, the results indicate that the usage of PT slabs, especially with large spans, was very effective in minimizing the material requirements for the framed buildings, with 10 metre and 13.33 metre spans experiencing reductions in weight of 27.36% and 34.19% respectively.

Reductions in environmental impacts associated with reduced material requirements achieved through the implementation of efficient structural design using PT construction methods were observed. Figure 5 displays at least more than 25 % reduction in EE was achievable in all structures and the highest reduction in EE of around 40.93% occurring in the 8 metre span. In addition, there was a noticeable pattern observed in the percentage reduction (Figure 5 compared with Figure 3). It can be seen from Figure 5, the EE utilization of column design was mostly attributed to steel. Hence the more reduction in usage of steel achieved, resulted in decreased EE consumption. The minimization of steel use and wastage during the construction phase cannot be overstated.

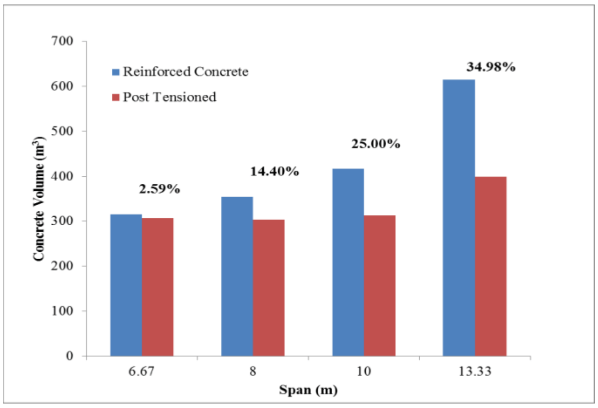

Figure 2. Concrete volumes of columns of Reinforced and Post Tensioned Concrete buildings

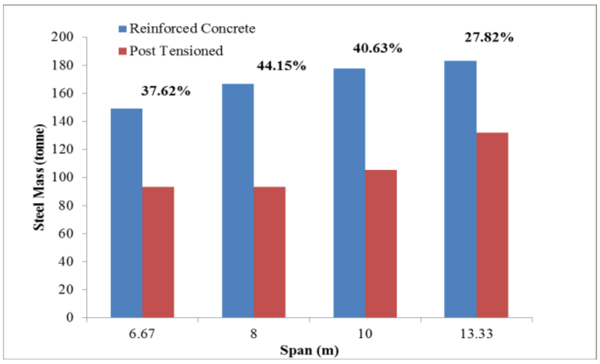

Figure 3. Steel mass of columns of Reinforced and Post Tensioned Concrete buildings

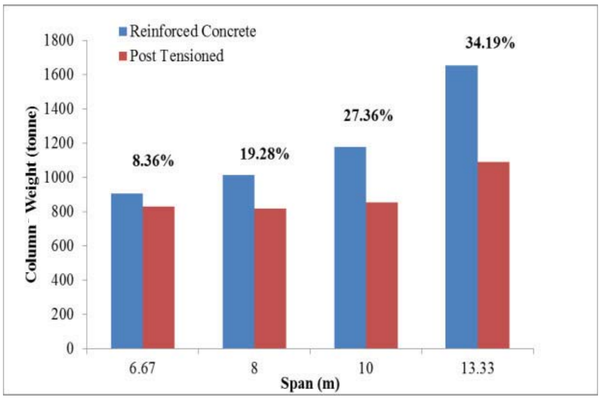

Figure 4. Weight of columns of Reinforced and Post Tensioned Concrete building

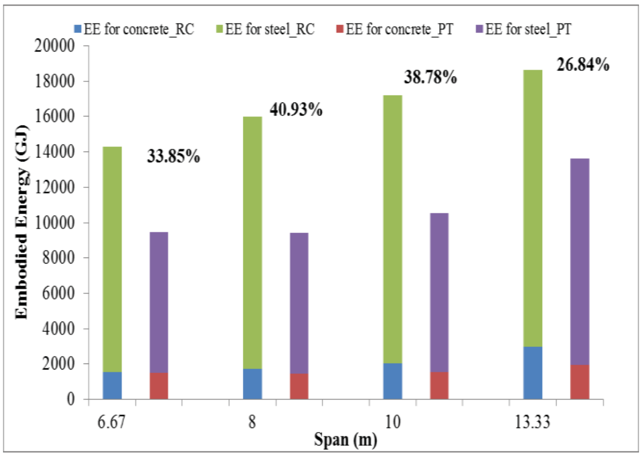

Figure 5. Embodied Energy value of columns of Reinforced and Post Tensioned Concrete buildings

3.2 Embodied Energy in Whole Building Structure

Figure 6 displays the contribution of EE from steel mass in contrast to concrete volume of constructing the slabs and columns.

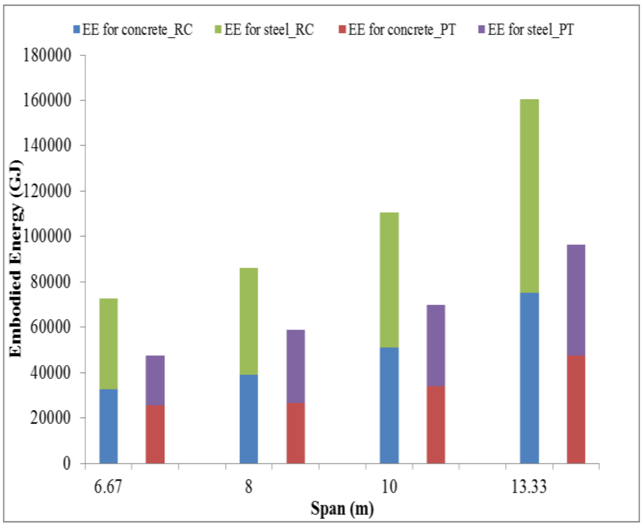

Figure 6. Overall embodied energy of the entire buildings

RC methods for spans 10 and 13.33 metres roughly consumed between 100,000 GJ and 150,000 GJ of EE through the material usage. In comparison, PT methods show EE consumption of approximately 70,000 GJ and 100,000GJ. These outcomes were almost two thirds in comparison with RC. For all analyzed structures, the concrete accounted for between 45% and 54 % of the overall EE. Although the usage of steel only comprised between 2.14% and 2.97% of the framed structure's weight, it had a considerable impact the structure's EE, which made up the remaining 46 % to 55% of the total. As referred to below (Figure 7), the columns contributed up to 19.71% of the total EE of the structural system. The contribution of columns to the entire structure was somewhat similar, particularly RC in a range of 11.62% to 19.71% and PT in a range of 13.99% to 19.70%. It was also recognized that the increasing span length might be a cause for less contribution of EE of columns to the entire structure.

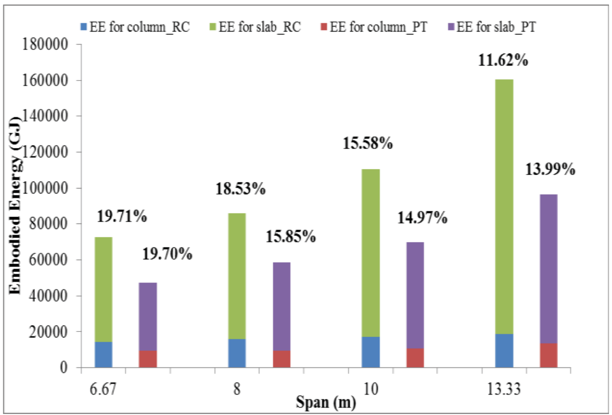

Figure 7. Contribution of embodied energy of column systems to the entire structure

IV.CONCLUSION

This investigation has showed that reduction in material requirements in the frame of structures and subsequent flow-on effects could be attainable in the column systems for that of PT floor and roof flat plate slab structures over the RC alternative. In most cases, the column in PT structures performed better than in RC ones in terms of material savings of steel and concrete along with EIA criteria for EE. It was found that span length greatly impacted on the achievable reductions in material savings and EE. Furthermore, due to span length, the contribution of column systems to the entire structure regarding EE was also influenced.

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