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Incorporating Sustainable Development Principles into Building Design

Jeung-Hwan Doh and Dane Miller

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Abstract

The main aim of this research is to utilise the focus of sustainable design to compare the material and subsequent environmental impacts of multi-storey structures situated in Australia. The structure types under investigation were characterised by post-tensioned and conventionally reinforced floor and roof flat plate slab systems. The foundation designs are undertaken for isolated spread footings on 32 structural model types with constant external dimensions which were composed of floor and roof slabs of varying concrete strength, span length and construction method, with all footing designs providing equivalent structural performance. The results from this study have reinforced the evidence that post-tensioned construction can have significant effects in reducing material requirements and provide increased structural and environmental efficiency. Through reducing the frame mass, the footing systems were able to be designed using significantly less embodied energy when compared to the reinforced concrete structures. It is also noted that further investigation in the foundational requirements of these models is warranted, with the need to investigate the use of mat foundations for cases where isolated spread footings have required more than 50% of the structural plan area and for the footings that have required excessively thick sections to resist large shearing actions for larger spanned cases at 10 and 13.33 m.

Keywords: embodied energy, sustainable development, sustainable design, global warming potential, post-tensioned structure, reinforced concrete structure, footing

1. Introduction

In recent times sustainable development and design has become an increasingly important issue to consider in our built environment [1–3]. The factors driving the adoption of sustainable development and design are numerous but perhaps the most significant is a growing concern about anthropogenic global warming caused through carbon emissions. The building

and construction industry is a significant contributor to carbon emissions through the consumption of large quantities of energy. The main aim of this research is to utilise the focus of sustainable design to compare the material and subsequent environmental impacts of multi-storey structures in Australia.

Globally, greenhouse gas emissions are rising exponentially with most of this rise occurring in the last 60 years. Australia is ranked in the top 10 greenhouse gas emitting countries in the world with 25 t CO_{2-e} per capita in 2012 [4]. Australia's greenhouse gas emissions peaked in 2009. It has since declined, however now is not the time for complacency [1].

The introduction of energy efficiency provisions in the National Construction Code (NCC) [5] has attempted to address global warming issues by prescribing the requirements for operational energy efficiency. Soon after these changes the Green Building Council of Australia introduced the Green Star rating system which defines optional requirements above the NCC for energy efficiency and sustainability. Green Star's rise in popularity is a clear indication that building owners, developers and occupiers are demanding sustainable and energy-efficient buildings. Aside from addressing sustainability and global warming issues, stakeholders recognise the benefits that green buildings offer with lower operational costs being a prominent motivator.

The incorporation of the requirements of the NCC [5] and Green Star into buildings inevitably lowers operational energy consumption during a structures' life cycle. This has resulted in a more significant portion of the life cycle energy being represented by the structure itself which is referred to as embodied energy. This is clearly a target area for further reducing the energy consumed by a building [3]. Currently, the NCC [6] does not identify embodied energy as an area to improve the energy performance of buildings. Furthermore, the prominent building rating systems place insufficient emphasis on embodied energy considerations.

Due to the lack of emphasis placed on embodied energy outcomes, structural engineers have a limited obligation to incorporate measures requiring reduce energy consumption into the structural design. Typically design is governed by the requirements of the architect and classical building design objectives such as economy, utility, durability and comfort. Engineers should strive to not only achieve these requirements but to incorporate sustainability into their designs by improving structural efficiency and specification of appropriate materials. The building materials industry has recognised the importance of sustainability with extensive research being conducted in this area. The cement and steel manufacturing industries in Australia have adopted the use of alternative fuels and renewable energy sources in an attempt to lower greenhouse gas emissions and operational costs. The steel industry has also adopted the use of alternative manufacturing methods to preserve natural resources and utilise waste products. Likewise, the cement manufacturing industry uses waste products as partial cement replacements, often from the steel manufacturing industry, to preserve natural resources and lower operational costs [7].

The environmental impacts of the built environment and the need to incorporate sustainable design quantifying the environmental impacts of structures are continually evolving areas of research. This field would benefit greatly from increased industry collaboration.

2. Construction building material

The rate of human population growth globally has been exponential, and continued growth is seemingly inevitable. Australia's population alone is expected to increase to approximately 35.5 million before 2060; this growth comes with increasing pressures for infrastructure, housing and other related services [8]. This trend is unfortunately not limited to Australia, many other developed countries have similar predictions of population growth for the next 50 years, and the developing countries are showing trends of much faster population growth rates. These trends in growth are driving a demand that has ultimately led to the built environment becoming the largest single cause of anthropogenic climate change [9]. Construction, operations and maintenance of buildings have an estimated accumulation of 50% of all energy usage and as such are causing more than 50% of all anthropogenic greenhouse gas (GHG) emissions [10]. In Australia, approximately 30 million tonnes of finished building products are produced each year, with over 56% of this mass being attributed to concrete and 6% to steel [11] as shown in **Figure 1**.

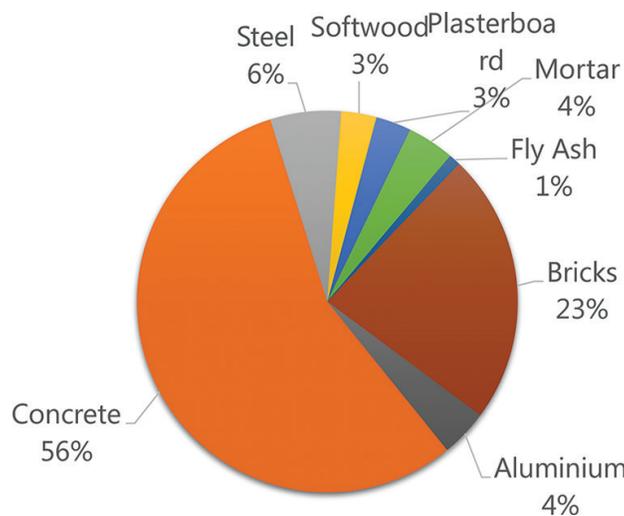


Figure 1. Finished building materials required in 2005, based on mass percentage. Image reproduced from the Australia Government [11].

Research undertaken in Australia also shows that concrete and steel are two of the highest contributing materials to global warming impacts at 12 and 29% for concrete and steel, respectively (**Figure 2**). This evidence underlines the importance of our management of these key building resources. Consequently, reducing the use of these materials in structures will show significant reductions in environmental impacts generated from the construction sector.

Once again this trend extends beyond Australia, with figures from other developed regions having similar percentages of concrete and steel making up the majority of finished building products. The major contributor to carbon pollution and the obvious associated environmental impacts in both the United States and Europe can be attributed to construction activities. The United States construction industry is responsible for using 40% of the country's total energy use,

and 16% of the yearly water supply, additionally the industry consumes on an annual basis over 40% of the total mined raw stone, sand and gravel material and 25% of the logged raw timber [1].

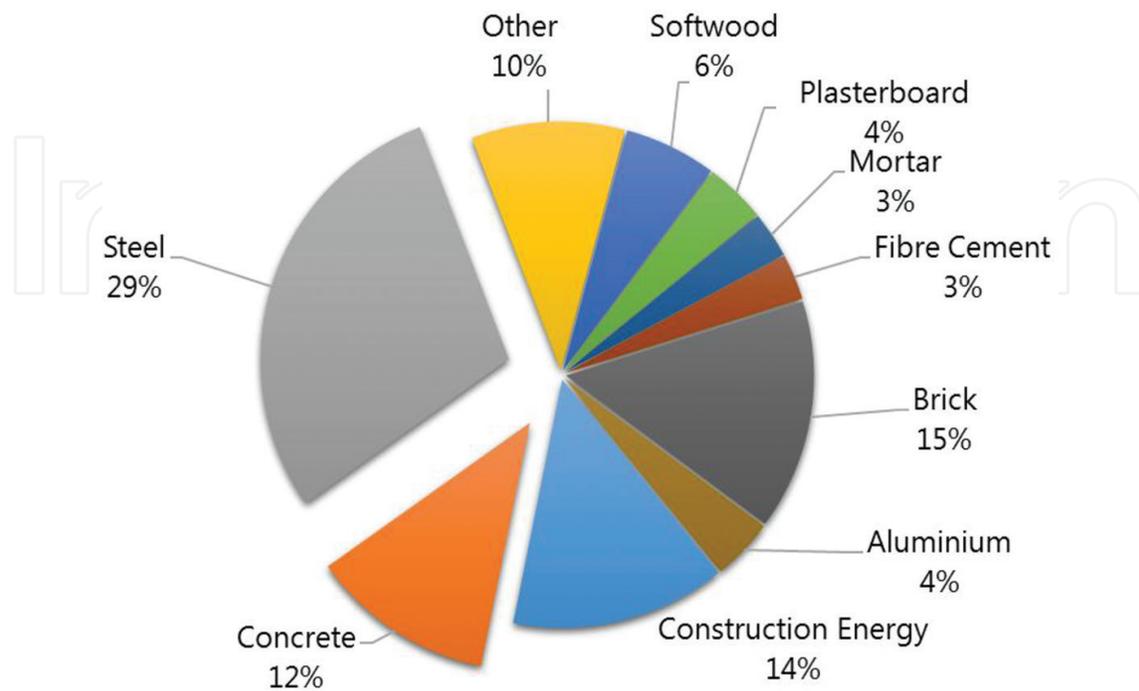


Figure 2. Global warming influence from construction materials in Australia [12, 13].

Countries participating in the Organisation for Economic Cooperative Development (OECD) demonstrated that 25–40% of the final energy consumption can be attributed to the building sector [14]. Having this knowledge enables a more complete understanding of the benefits and impacts that a sustainable construction (SC) approach will provide globally. As discussed the growing population, increasing demand for the built environment and its resources will continue to increase, therefore any improvements using more efficient approaches or technologies benefiting sustainability outcomes will be advantageous to the industry. When considering the magnitude of the global issues, even a small level of improved design efficiency could lead to significant reduction in negative environmental impacts. According to Hasegawa [14], by increasing the importance of improved efficiency in the structural design of buildings, two-thirds of the primary factors contributing to the poor environmental performance of building will be reduced, resulting in the minimisation of construction and demolition waste and in the reduction of CO₂ emissions.

3. Review of existing research

3.1. Post-tensioned and reinforced concrete suspended slab investigation

The use of post-tensioning systems on building construction is able to significantly reduce the concrete volume and steel mass required for a structure, resulting in substantial reductions in the structure's total weight [2]. As indicated in **Figures 3** and **4**, a reduction in concrete volume ranged between 5 and 23% as well as a reduction in steel mass ranging between 23 and 44%

is obtainable using post-tensioning methods as opposed to conventional reinforcing. The outcomes of the investigation indicated that not only are the post-tensioned office buildings more efficient in material usage, but more importantly in terms of an environmental impact assessment (EIA) through energy consumption and global warming potential.

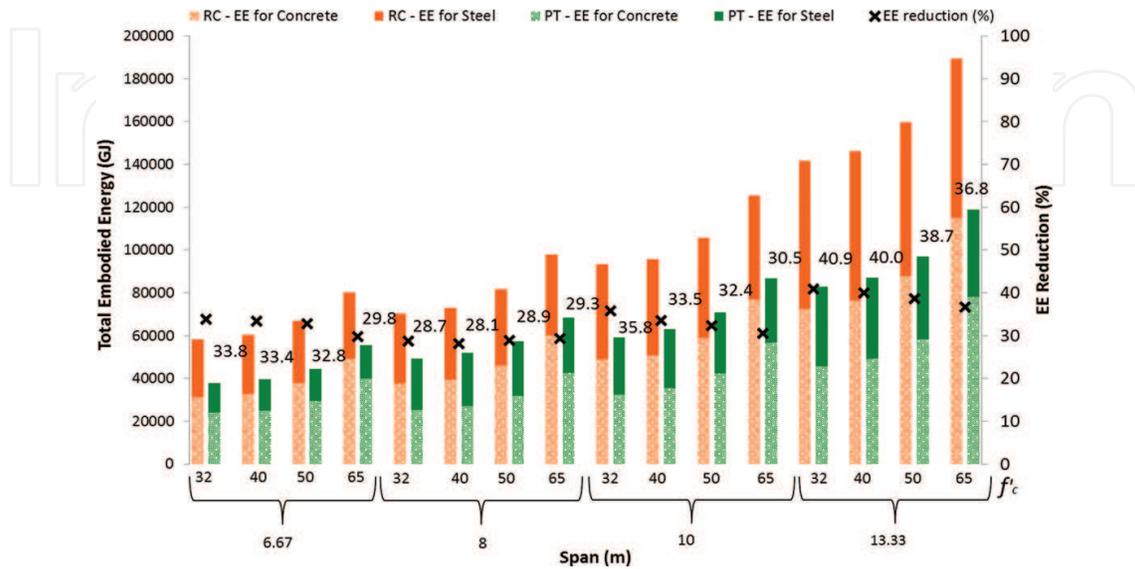


Figure 3. The required embodied energy values of various office structure types [2].

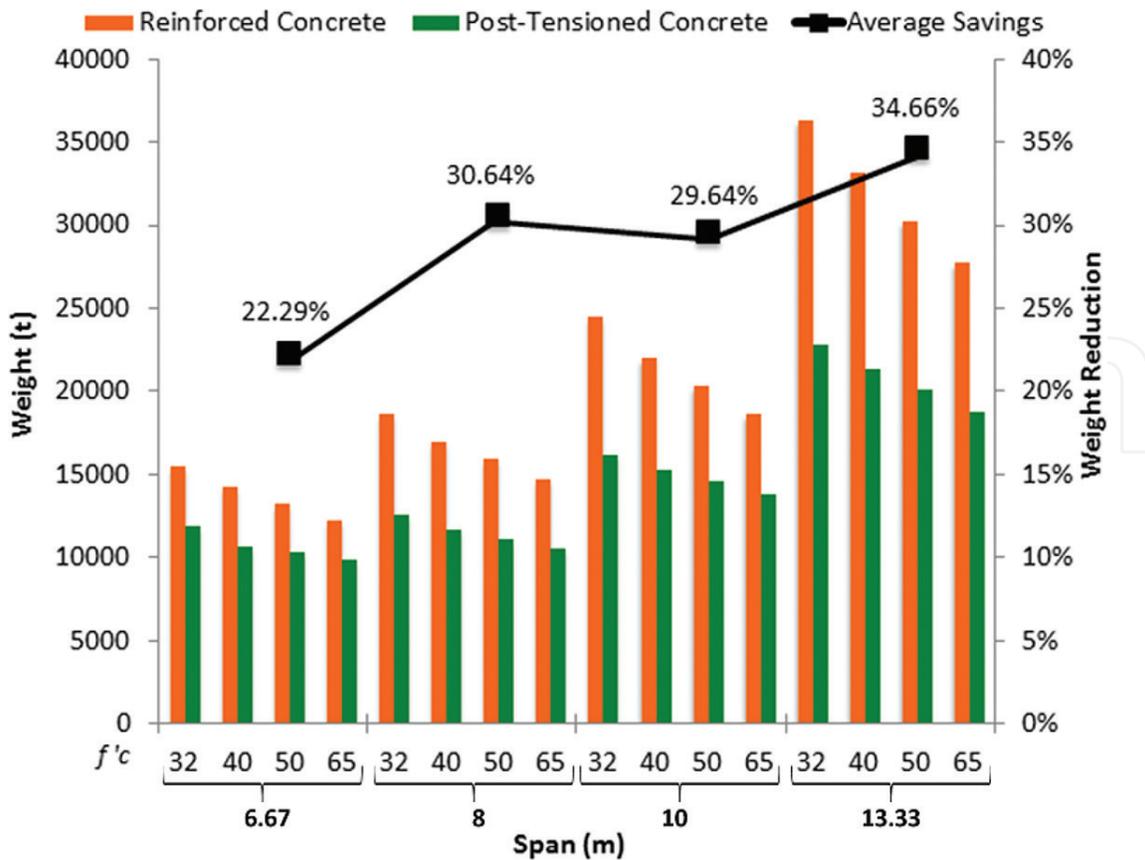


Figure 4. Variation in building weight by span length and concrete strength [2].

It was identified that the effectiveness of post-tensioning is greatest for spans exceeding 10 m, with the highest reduction in environmental impacts achieved being 41%. However, a minimum reduction in embodied energy (EE) and the global warming potential (GWP) of 28% was achieved for all structure types investigated [2].

Assessment of structural weight of slabs investigated was also undertaken. Results indicate structural weight savings for PT in comparison to RC construction. For the slab completing the required design task, achieving the least EE consumptions, average weight reductions between 22.3 and 34.7% were observed for PT buildings.

The disproportionate contribution of steel to EE of a structure compared to its contribution to structural weight was also investigated. Overall, the structure's weight accounted for between 40.8 and 59.6% of EE in previous study. These outcomes highlight the importance of steel usage optimisation for beneficial EE outcomes in concrete structural systems. Reduced structural frame weight can result in additional benefits to other structural components, including foundations, walls and columns that contribute to the structure's overall EE. Therefore, the overall reduction in EE of the entire structure through the use of PT and its overall effectiveness may be equal to or higher than those presented here. These additional considerations were outside the scope of this research but will be the focus of future investigations [2].

4. Environmental impact assessment (EIA) of footings

The main objectives of this study is to utilise the focus of sustainable design to compare the material and subsequent environmental impacts of footings for multi-storey structures situated in the South Eastern region of Queensland, Australia. The structure types under investigation were characterised by post-tensioned (PT) and conventionally reinforced (RC) floor and roof flat plate slab systems. The foundations footing designs were undertaken utilising isolated spread footings for the 32 structural model types. All the types had constant external dimensions which were composed of varying concrete strength, span length and construction method, with all footings designs providing equivalent structural performance. Following this, an environmental impact assessment (EIA) was undertaken, accounting for the embodied energy requirements for each varying structure type.

4.1. Methodology

The intention of this study is to utilise the process of structural design, to compare environmental impacts of mid-rise office structures in the South East Queensland region when PT and RC construction methods have been implemented. The results of this study shall further validate previous findings by Miller et al. [2], which have shown improvement of the environmental efficiency of office buildings where PT suspended floor and roof slabs have been used. Using embodied energy as an appropriate quantification tool for environmental performance, an evaluation of the structures foundation system shall be concluded. Specifically, the use of PT and RC raft footings for their respective PT and RC suspended floor system superstructures.

Previous research has been conducted that has investigated the potential reduction of environmental impacts. Previous research has investigated the potential reduction of the environmental

impacts of concrete framed buildings. In particular, detailed comparisons were performed of variations in environmental performance between PT and RC buildings [1, 2]. Authors undertook an investigation into the effects of varying span lengths between columns and also increased concrete characteristic strength parameters, resulting in 32 structural variations (i.e. 16 post-tensioned and 16 reinforced concrete structural models each composed of 4 variations in span length and concrete strength). The current study is intended to carry on from the previous work conducted in this field and apply the methods of assessment to the foundations of the structures to investigate associated manifold benefits.

This study shall utilise the same identical model characteristics for the design of a raft footing option. Three case studies shall be investigated: **Case A** consists of an RC raft with an RC structure; **Case B**, an RC raft with a PT structure; and **Case C**, a PT raft with a PT structure. In total, 48 model variations of concrete building systems were considered.

Ultimately, this study will help identify the material savings that can be gained in the foundation system of a multi-storey structure and what outcomes can be achieved in terms of structural design efficiency in concrete buildings.

In order to achieve this, a multi-stage research methodology was formulated. This methodology was categorised into two major components, structural design and environmental analysis. The structural design involved several distinct components including: (1) design definition: including the formulation for the design of the specific building to be analysed along with the identification of assumptions necessary to undertake the analysis; (2) manual calculations in accordance with the Australian Standard [15] to provide a detailed design of the structural element varied, that was used for inputs into the two-dimensional computer analysis program, RAPT; (3) the structural designs were finalised using the results obtained from the computer analysis and these were verified using comparison with hand calculations to ensure accuracy and suitability of the design; and (4) the structural requirements for each element were subsequently detailed allowing a bill of quantities (BOQ) to be generated and an environmental performance assessment undertaken. The methodology has been summarised in **Figure 5**.

Utilising the allowable bearing capacity and applied working loads ($1.0G + 1.0Q$) initial size estimates (length and width) were determined in accordance with the allowable bearing capacity and checked with the inclusion of the self-weight of the footing.

An initial trial depth was utilised to check for the effects of two-way punching shear, an inadequate design sections resulted in an increase in the footings thickness. Once all the critical design cases were satisfied, detailing of the steel reinforcement was conducted to check for development length at critical sections and minimum reinforcing specifications as specified by the Australian Standard.

4.2. Environmental impact analysis

Reducing the material requirements of a structure and its elements is only one of a wide range of measures that have the capacity to effectively reduce the environmental impacts of the construction industry. In order to keep this project in line with previous research, the same unit measures of embodied energy have been applied to the current study. For the footings constructed of 40 MPa concrete, the correlation of embodied energy is as follows: for every

cubic metre of concrete cast for the footings, 5670 MJ of energy is required [2]. For the embodied energy value of steel, 85.46 MJ is required per kg of installed reinforcement. These unit measures have then been applied to the material requirements, as determined from the bill of quantities, in order to determine environmental impacts of each footing system.

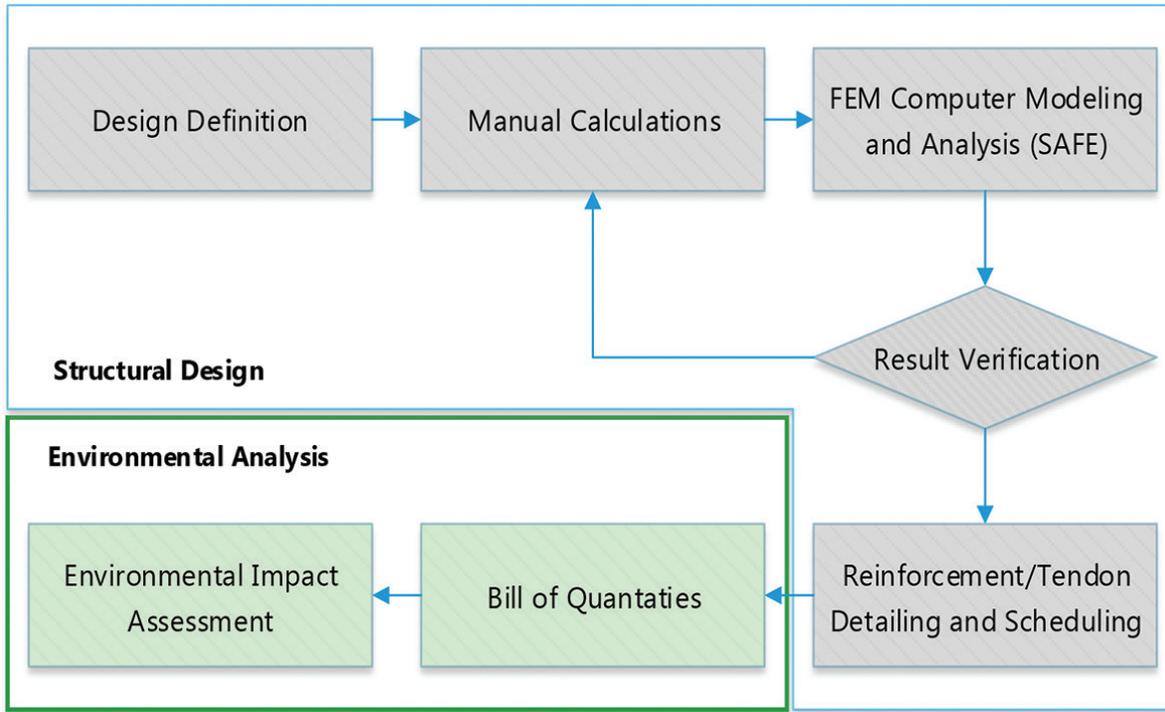


Figure 5. Methodology for structural design and environmental analysis.

In order to enable future widespread application of the presented research outcomes, it is intended that the environmental impacts be measured, be in the form of a relative estimation, EE. The results provided show an indicative comparison of the environmental impacts with the reduction in structural frame mass, associated with utilising PT slabs over RC slab frame elements. More importantly, the carry-on effects transmitted to the foundation of the structure allow for more lightweight footing systems to be utilised. These outcomes are presented in **Figures 6–11** and distinguish the individual contribution associated with concrete, steel and overall EE as well as the percentage reduction gained from utilising a favourable PT system.

4.3. Assumption

To undertake the design and analysis of each footing, the following assumptions were applied throughout the study:

- The soil conditions, i.e. soil bearing capacity and other associated characteristics are considered uniform throughout the site;
- Groundwater conditions are negligible and have no effect in terms of generating hydrostatic pressures on the base of the footing system;

- Overturning moment conditions generated from horizontal loading such as wind loads are negligible on the design actions of the footing system and will not be considered;
- Property boundaries pose no restriction upon the footing dimensions;
- The weight of overburden soil pressure can be neglected as it is assumed this has been accounted for in the allowable soil bearing capacity, based on geotechnical advice; and
- Shear reinforcement (stirrups) will not be utilised to resist one- or two-way shearing actions as in practice it is not considered economical to do so.

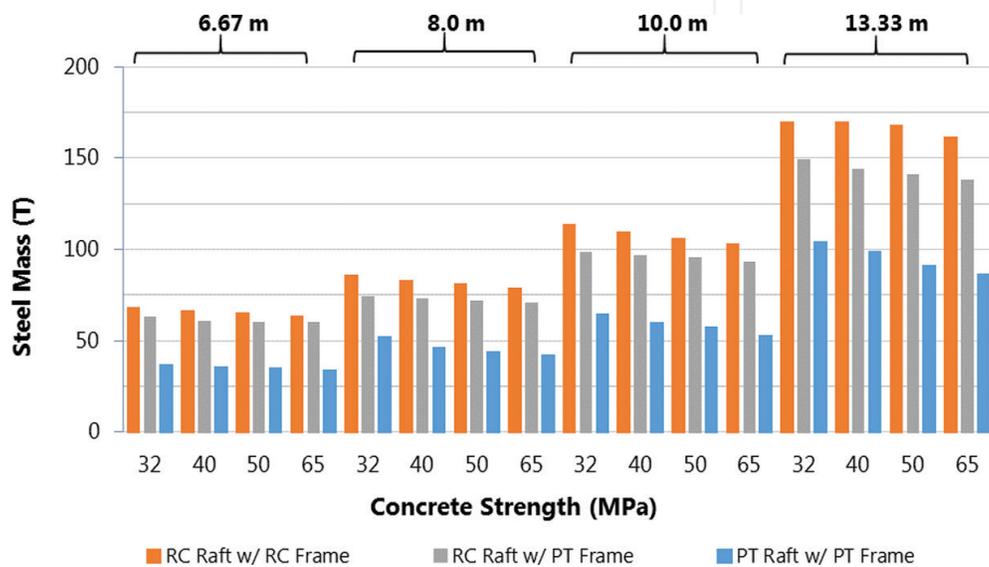


Figure 6. Comparison of concrete strength and span length with the steel mass required in each raft footing.

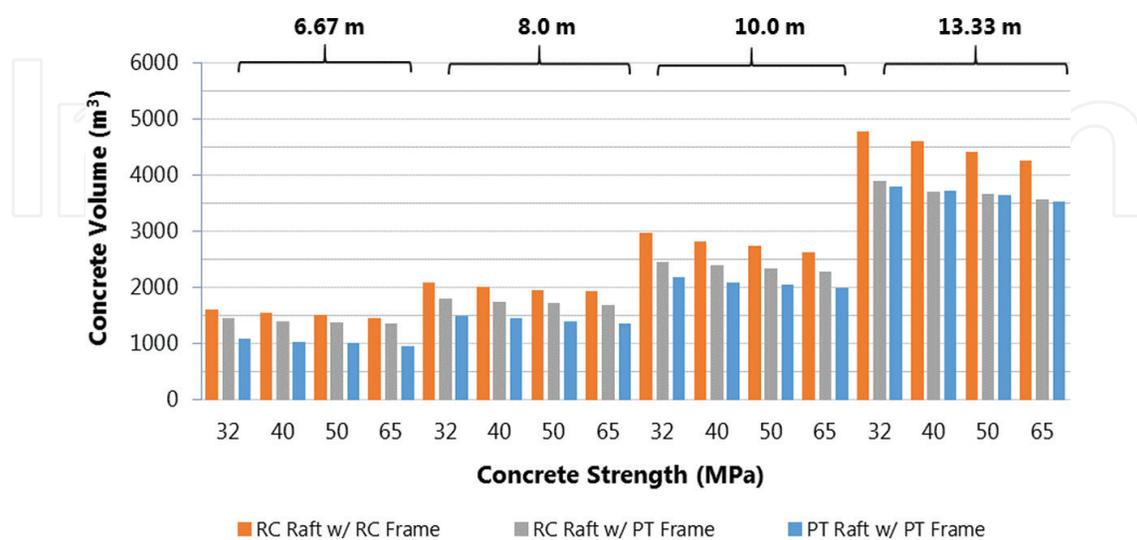


Figure 7. Comparison of concrete strength and span length with concrete volume in each raft footing.

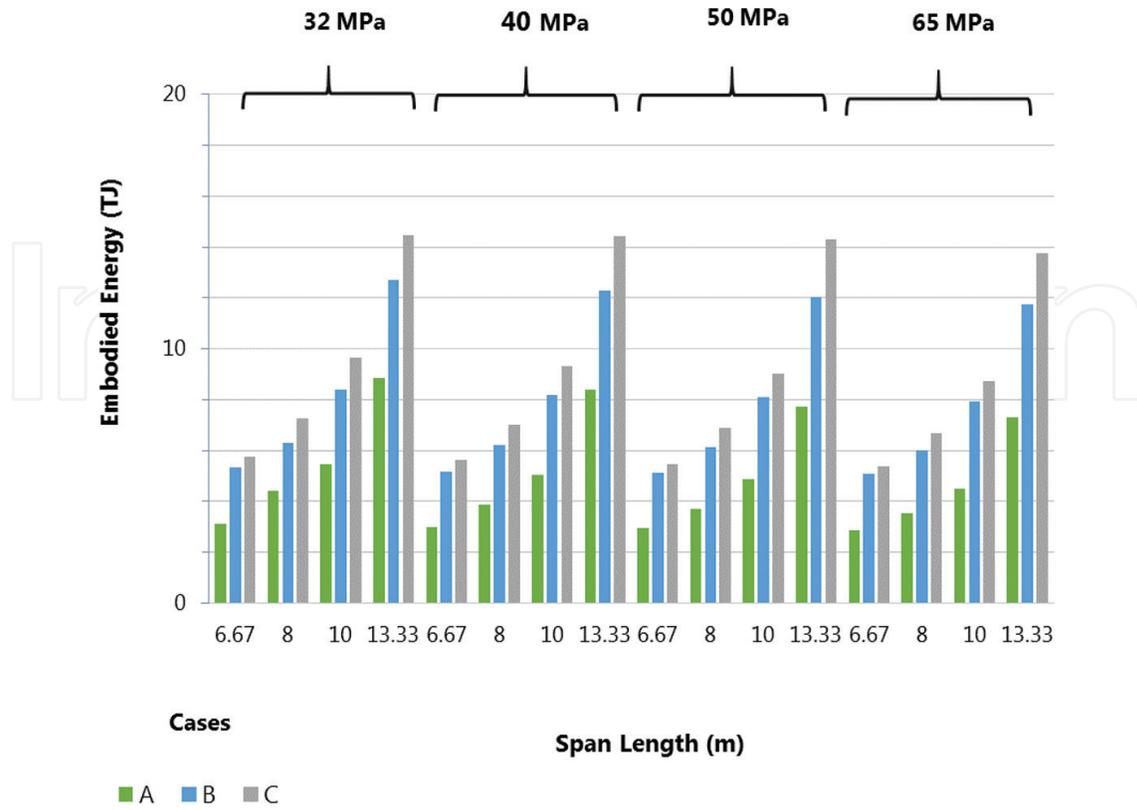


Figure 8. Overall trend comparison of embodied energy contributed by steel.

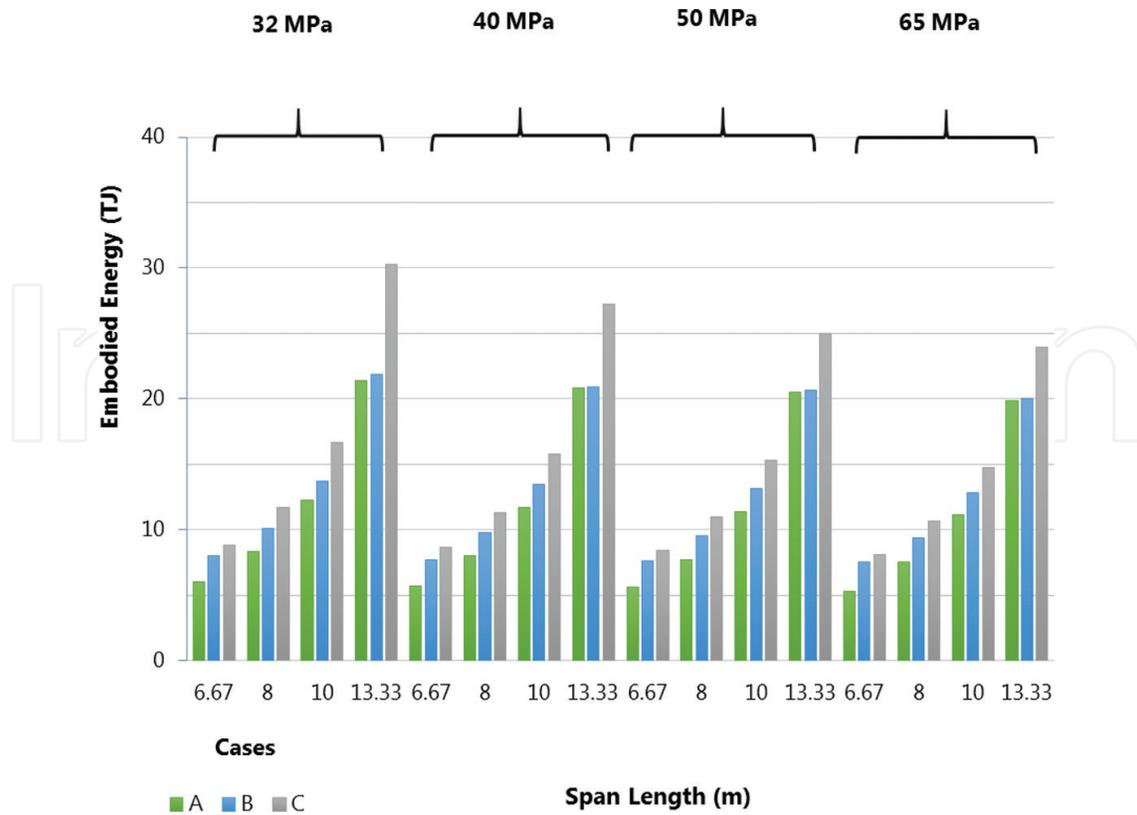


Figure 9. Overall trend comparison of embodied energy contributed by concrete.

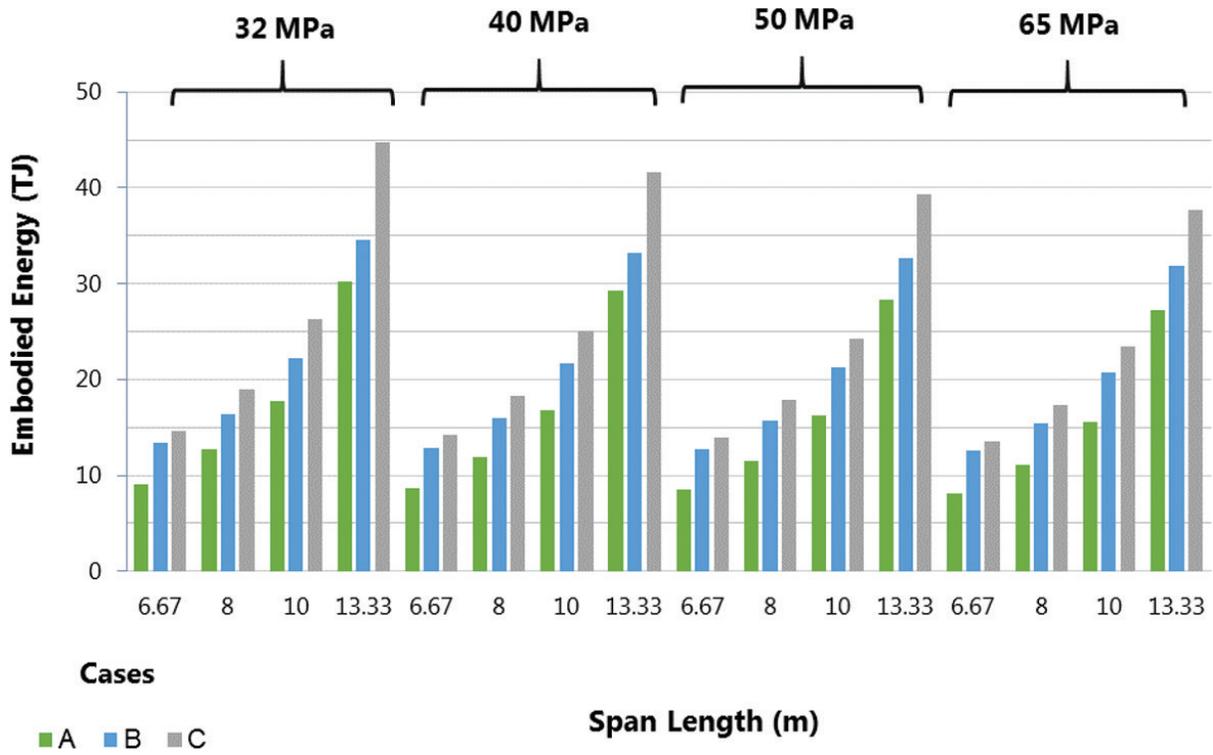


Figure 10. Overall comparison of embodied energy trend.

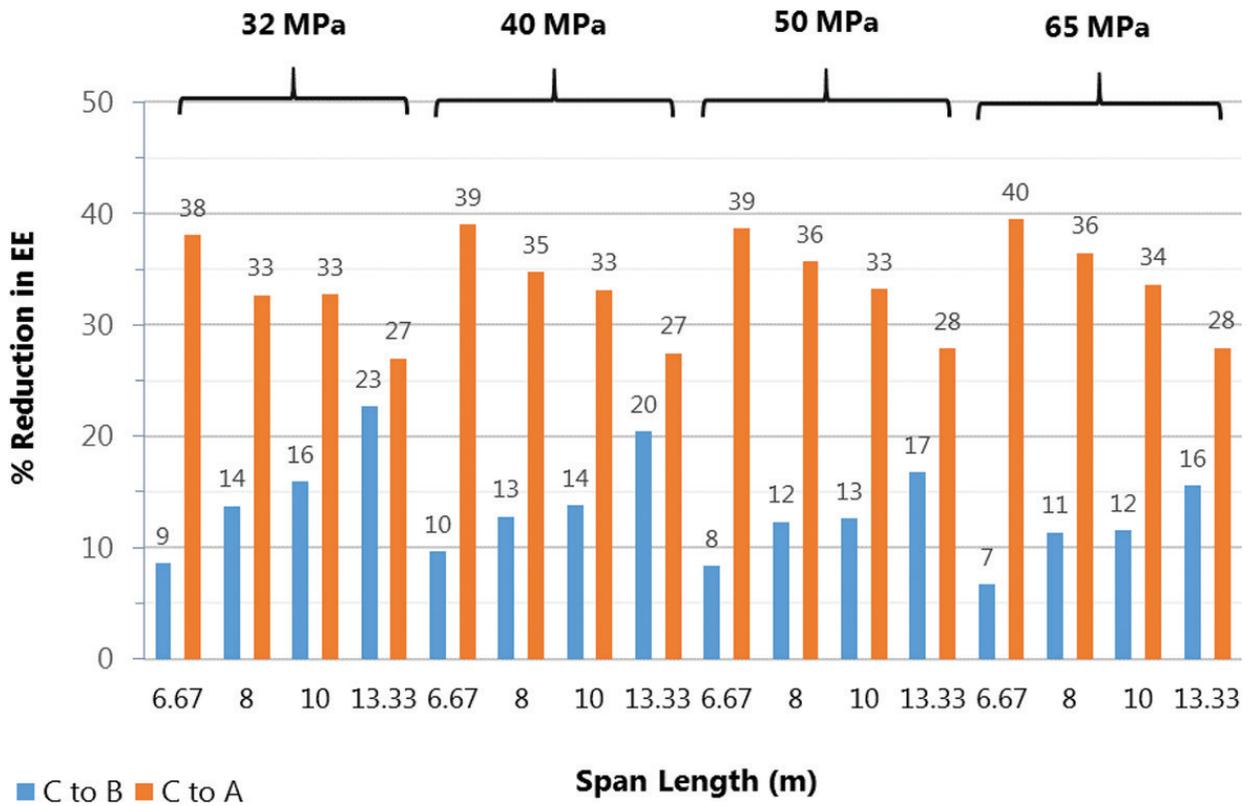


Figure 11. Percentage reduction of overall embodied energy between Cases C to B and C to A.

5. Results and discussion

As mentioned, the comparison of EE for each raft footing has been classified based on three cases based on the reinforcement/construction method utilised for the floor slabs and raft footing.

Case A: post-tension raft with post-tensioned structure

Considers a full PT system of floor slabs and raft footing solution. This case shall focus on examining the full effects of implementing a PT system for a foundation, specifically the benefits of utilising a PT raft.

Case B: reinforced concrete raft with post-tensioned structure

Focuses on a hybrid system of PT floor slabs and a RC raft footing system. This case shall specifically evaluate the efficiencies of reducing the structural frame mass by utilising PT in the floor slab system.

Case C: reinforced concrete raft with reinforced concrete structure

Focuses on a fully conventional system of both RC slabs and raft footing options. This case shall be the baseline for comparison of the efficiencies of PT alternatives, Cases A and B.

5.1. Effects of increased concrete strength and span distance

One of the main purposes of this study was to investigate the controlling effects of utilising increased concrete strengths for the suspended slabs of a structure, as well as increasing the span length. **Figures 6** and **7** present the results for both of these cases for the resultant quantities of steel and concrete individually.

5.2. Steel and concrete contribution to EE

The outcomes from the environmental impact assessment have been presented in **Figures 8–11**. The contribution to EE from steel is depicted in **Figure 8**. An increased span length shows a direct correlation to higher levels of EE. Case C continues to have the highest rates of EE, followed by Case B. Case A however appears to have a significantly lower EE level compared to both Case B and Case C. As the concrete strength increases no obvious change in trend appears for the EE levels in identical span lengths in any of the cases.

Figure 9 depicts the EE contributed by concrete with similar trends to **Figure 8**, with a direct correlation between span length and increasing embodied energy. Case C continues to have the highest rates of EE in all levels of span length, and Case B shows a significant reduction for the 13.33 m span length. For example, in 32 MPa concrete strength, Case B shows a 27% EE reduction compared to Case C. Case A continually shows the lowest EE levels in all span lengths. There is a noticeable decline in EE overall (in all cases and span lengths) as concrete strength increases.

Figure 10 shows the overall comparison of EE, which combines the outcomes from both **Figures 8** and **9**. This indicates that increased span length shows a direct correlation to higher levels of embodied energy. Also highlighting that Case C continues to have the highest rates of EE in all span lengths, followed by B and then A. **Figure 10** also shows a slight decline in EE overall (in all cases and span lengths) as concrete strength increases.

Figure 11 shows the percentage of reduction in overall EE between Cases A, B and C. The obvious trend is that the EE reduction percentage is significantly larger between C and A, than it is between C and B. For example, with a concrete strength of 50 MPa and a span length of 6.67 m, C to A has a 31% higher reduction in EE than the corresponding C to B comparison. The greatest savings for C to A can continually be seen in the smaller span lengths, with savings decreasing as the span length increases.

A clear trend was observed in **Figure 9**, comparing reductions from Cases C to B and from C to A. For C to B, as span length increases, the overall reduction percentage increases; however, this is opposite to the reduction trend in C to A, which decreases in EE reduction as span increases. The explanation for this is that Case A utilises a PT raft solution and that at smaller spans the use of PT contributes to a significant reduction in concrete volume and ultimately a higher EE reduction percentage; however, as span increases and the amount of columns decreases, the effectiveness of PT to add additional support to punching shear is reduced. The reasoning behind this is that, only a finite quantity of tendons can contribute to the resistance of two-way shear around the critical shear perimeter, this is due to the impracticality of fitting tendons so close to one another. Therefore, it is more favourable to have a larger number of columns to distribute the tendons between in order to increase punching shear resistance under each column.

Overall, this study has focused on quantifying the material saving and the associated EE through the utilisation of PT, it can be seen for Cases A and B, where PT has been utilised, that significant savings can be achieved. This was observed through both a hybrid PT option or a combined raft and floor slab system. The savings typically range between 7 and 40% at 6.67 m spans and 65 MPa concrete strength.

When considering the most efficient structure type in terms of EE and materials savings, it can be clearly recognised that a full PT raft and floor slab combination with 6.67 m span is the most effective.

6. Conclusion

As global population growth continues to increase into the future at an ever increasing rate, the impacts and draining effect on natural resources and the environment will continue. This work presents a strong discussion, which shows that a level of inefficiency currently exists in structural engineering design and environmental performance and that this should be rectified. As engineers, we can begin by bringing concepts of sustainable design into everyday practice. This investigation has delivered a comprehensive overview of the current state of knowledge in relation to the concrete design and construction industry, with the possible benefits achievable by improving its efficiency.

It was highlighted that structural engineers and other engineers alike, play a restricted role in the integration of sustainable alternatives to any given project, as they are at the mercy of the client and architects' demands. This shows that greater focus needs to be placed on the integration of sustainable design solutions into structural designs through aiming to improve the structural effectiveness of a building. This is achieved through improved efficiency of a structural system while offering adequate structural performance.

It has been shown in this investigation that through reducing material requirements in the frame of a structure, subsequent flow-on effects can be achieved in the foundation system when raft footings are utilised. Through reducing the mass of the frame, a direct correlation can be seen in the reduction of the applied loads needing to be supported by the underlying foundational system. For this investigation, the use of raft footings has been effectively designed and detailed for the 48 office structure configurations considered. These configurations were separated into three distinct cases. Case A consisted of an RC raft with an RC structure, Case B, an RC raft with a PT structure and Case C, a PT raft with a PT structure, all together totalling 48 model variations.

Clear findings have been presented showing significant material efficiencies achievable in the Case A footing system characterised by a PT raft/frame combination, followed by a Case B, a hybrid RC raft/PT frame option. Overall, the PT footing system outperformed the RC footing systems in all cases in terms of material reductions of steel and concrete and the EIA criteria for embodied energy. For the PT raft coupled with a PT slab system a significant saving ranging between 27 and 40% was achieved. This was predicted due to a distinct variation in column loadings generated by variations in slab element types and characteristics and due to the advantages offered from the contribution of pre-stressing methods. In terms of the effects of increased concrete strength and span length, results suggested that for material requirements, the PT raft/PT frame option outperformed all other cases and was more effective at taking advantage of the higher strength concrete. Overall, however, as the span increased, the overall requirements of the footing increased linearly; also, as the concrete strength increased, the material and EE requirements decreased linearly, with the highest saving found in the PT raft/PT slab option. When comparing the results for embodied energy to previous studies, it showed that spread footings for shorter spans resulted in less embodied energy than the PT raft solution. This however was shown to be negated, due to the considerations of constructability when spread footings acquire greater than 50% of the structural area.

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