A PROJECT-BASED COMPARISON BETWEEN REINFORCED AND POST-TENSIONED STRUCTURES FROM A SUSTAINABILITY PERSPECTIVE


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Abstract

This paper presents a comparison between reinforced and post-tensioned concrete slab options with a focus on sustainability. The study is done on an actual project, Strata SE1, a high-rise building in London designed to promote sustainability with its efficient design and unique wind turbines. The paper gives a practical approach on the importance of structural design efficiency and how it translates to the sustainability triple bottom line concentrating on the design and construction stages. For each option, the environmental impact is measured through energy and carbon emission; the social impact is assessed using a ranking scheme; and the cost is given to evaluate the economic impact. The construction time and its impact on the environment are also discussed along with the measures that can speed up construction. The results show the post-tensioned solution with spans up to 9.5 meters allowed savings of 720 ton of CO_2 from slab material alone.

Keywords: Sustainability, Concrete Comparison, Post-Tensioning, Environmental Impact, Carbon Emission, Social Impact

1 Introduction

The design of structures has always carried challenges and designers constantly strive to present optimal solutions. While in the past the emphasis was on performance, time and cost, a new factor, sustainability, is now added to the decision-making process. As focus has been primarily on controlling energy consumption and social factors during the use phase of buildings, the need to address the early stages of the buildings life cycle, design and construction phases, and their impact on the environment and the community is becoming essential.

This study is an effort towards tackling these early stages by providing a comprehensive and practical assessment for evaluating structural efficiency with respect to material selection, quantity and construction time and how they translate into the environment and social well-being.

A comparison between post-tensioned and reinforced concrete options related to slab construction is presented with the aim of covering the sustainability triple bottom line: environment, social and economic. The comparison is carried out on Strata SE1 project located in center London and for which the concrete frame was completed in 2009. The building is a residential high-rise 147 meters in height with 41 post-tensioned flat slabs including 40 typical floors and a world’s first roof supporting wind turbines expected to provide a part of the building’s operational energy.

2 Structural Slab Design

It was decided from the start that in-situ concrete would work best. The building's curved slab edges can be formed easily and economically with concrete, and concrete provides acoustics and thermal advantages. Therefore, only structural options with in-situ concrete were considered for the comparative analysis:

- PT: flat slab post-tensioned concrete
- RC1: flat slab reinforced concrete
- RC2: slab with drop beams all in reinforced concrete

		Structure Type		
Structural Item	**Unit**	**PT**	**RC1**	**RC2**
Average Slab Area	m^2	630	630	630
Overall Area	m^2	25,202	25,202	25,202
Slab Thickness	mm	200	260	210[a]
Rebar Rate	kg/m^2	11.6	21.6	19.5
PT Strand Rate	kg/m^2	3.5	0	0
PT Ducts Rate (1.4 lm/m^2)	kg/m^2	0.6	0	0
PT Anchors (0.1 pc/m^2)	kg/m^2	0.4	0	0

Table 1: Slab Material Quantity

Using the same design assumptions, the options were designed to the British Standards to meet equivalent serviceability, ultimate state, and deflection limits (set to 10mm at all façade perimeters). The material[b] quantity rates per meter square of slab are shown in Table 1.

3 Construction Time Period

A fast construction schedule was required for this project as it was located in a busy area in London. It is therefore important to adopt a construction system that speeds up construction.
Structural Frame Design: The floor cycle estimates using the same criteria for PT, RC1 and RC2 are respectively 5, 6.5 and 8.5 days. This yields a total increase of 60 working days between PT and RC1; and 140 days between PT and RC2. Time saving on the PT option is due to less material and hence less installation time and labor, to stressing of the tendons and consequently early de-shoring. The actual floor-cycle achieved on the PT slab was 4.5 days on average.
Other Factors: Construction Management and Structural Detailing
Effective construction management makes a huge impact on work flow and deadlines. It is hard to quantify the related savings, but the project was completed 12 weeks ahead of estimated schedule. From a detailing perspective, small improvements from efficient detailing can add up. One special detailing of the PT layout for example is estimated to have saved the site about 1.5 weeks.

4 Environmental Impact

The environmental impact is assessed based on the unit rates of embodied energy and carbon listed in Table 2. They are taken from the ICE report (Hammond & Jones, 2008) which is based on LCI (Life Cycle Inventory) cradle-to-gate and 40% recycled content for steel.

Material Type	Embodied Energy (MJ/kg)	Embodied CO_2 ($kgCO_2/kg$)
Concrete C32/40 (1:1.5:3)	1.11	0.159
Rebar (Bar & rod)	24.6	1.71
PT Strand (Wire)	36	2.83
Duct (Galvanized Sheet)	39	2.82
Anchors (General Steel)	24.4	1.77

Table 2: Environmental Unit Rates

This reference was used due to its comprehensive database and application to the UK market. The LCI approach was deemed satisfactory given the scarcity and variability of data on LCA (Life Cycle Assessment) cradle-to-grave.

[a] The value is the equivalent slab thickness based on 180mm slab thickness and 600mm deep beams along the long spans and façade perimeter needed for deflection control.
[b] The slab area and material rates relate to the 40 typical stories. The PT roof is excluded from the analysis as its impact on the overall quantities is negligible and its design is very particular due to the supported wind turbines.

In addition, for database consistency, the wire and galvanized sheet rates used here for PT strands and duct are from virgin material as no other values are given in the ICE source. However, both can have up to 95% recycled content yielding conservative results on the PT option.
The cumulative environmental impact of the concrete stories is shown in Figure 1. The differences between RC1, RC2 with respect to PT are listed in Table 3 which shows that the environmental difference is significant especially between PT and RC1.
RC1 results in an increase of about 720 tons of CO_2 from the PT option, equivalent to 26% increase on the overall carbon emission of the structural frame. Similar increase is noted on the energy consumption. Between PT and RC2, the values are closer with RC2 having about 5% increase in energy and carbon; RC2 though requires elaborate formwork, more workmanship, and reduced layout flexibility due to the existence of drop beams.

Parameters	RC1 vs. PT	RC2 vs. PT
Embodied Energy (GJ)	6,394	1,613
	+ 25%	+ 6%
Embodied CO2 (ton)	722	132
	+ 26%	+ 5%

Table 3: Environmental Performance

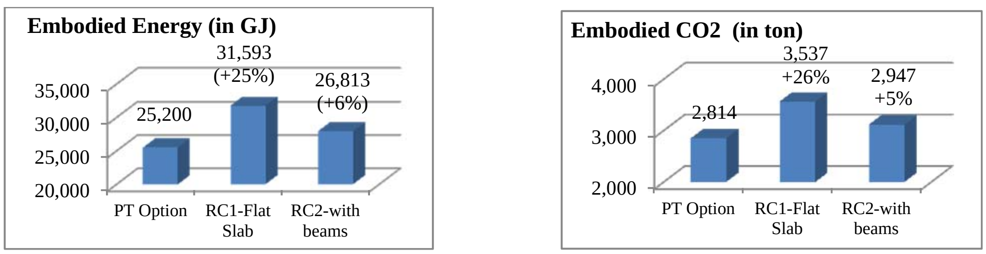

Figure 1: Embodied Energy and Carbon

The results can be extrapolated to determine the environmental LCA of the concrete slabs. It is expected that the transport, construction process and demolition phases to cover the gate-to-grave will add between 10% and 20% to the LCI results. As the three options involve cast-in-situ concrete, the same differences in percentages are hence projected for the slabs LCA.
It is also important to note that concrete alone accounts for 55% of the embodied energy of the slabs; and about 70% of total embodied carbon.

5 Social Impact Comparison

While individual social impacts are beyond this study, a ranking approach is used to assess the efficiency of the various options in reducing social discomfort as tabulated in Table 4.

	Social Factor	PT	RC1	RC2
During Construction	Reduced social nuisances	1	3	2
	Faster construction cycle	1	2	3
During Use Phase	Indoor living conditions	1	1	2
	Outdoor impact	1	2	3
Total Points (lower is better)		4	8	10

Table 4: Ranking of Structural Options on Social Factors

During construction, a wide array of social discomfort can occur. Designs requiring less of the same material lead to less disruption due to reduced pollution, trucking, traffic congestion, and waste.

In addition, a faster construction cycle can also reduce nuisances of construction sites. The PT option saved the community about 3 months of construction time and related disruptions.
During the use phase, well-being depends largely on the conditions of interior spaces: concrete has clear benefits in lighting, acoustical and thermal comfort (applicable to all three options); flat soffit improves on the architectural flexibility and contributes to the visual comfort; and designs with drop beams lower the flexibility of internal room layout and restrain the view.
On the outdoor, the slab thicknesses in Table 1 show that RC1 and RC2 would yield respectively an increase of 2.4m and 16m in overall building height leading to more shadowing effects, and cladding material. The additional building height would have similarly led to increased operational energy and carbon emissions increasing considerably the above environmental results.

For the overall social impact, the ranking placed the options in decreasing order according to their efficiency in each item. A weighted scoring scheme could be used by assigning importance factor to each item but for Strata project, the PT option ranked first in all categories. The evaluation was based on material quantities and type, construction time and architectural features.

6 Cost Impact

Direct cost estimate for the three options was carried out. Based on unit prices of the years 2008-2009, the PT, RC1 and RC2 yield respectively 74£/m^2, 77£/m^2 and 84£/m^2. The prices include all material and placement costs for concrete, rebar, PT strands, ducts, anchors and formwork.
Further indirect cost reductions on the PT came from the reduced columns and foundation material due to the lighter concrete weight; savings in cladding material from the lowered building height; and the fast construction schedule. When comparing cost impact, a holistic approach is needed to cover both direct and indirect cost.

7 Conclusion

Construction material, construction activity and the operability of a building impact in many ways our quality of life. Construction stakeholders work to find a balance between providing a sustainable environment while keeping living spaces and daily routines enjoyable as well as providing cost-effective secure structures. This study shows that the pursuit of a better environment need not arise at the expense of social well-being or additional cost or prolonged construction time.

Embodied energy and carbon were calculated, and a ranking scheme was considered for the social impact. The study for Strata SE1 building with 9.5m spans showed that the post-tensioned concrete option used less material, saved more than 6,400 GJ in embodied energy and 720 tons of carbon emission, achieved a fast construction cycle, kept all the benefits of concrete and provided the best social benefits during construction and during operability. These benefits did not impose additional cost and the project was constructed within budget.

If environmental and social impacts are considered at the pre-design stage when decisions on structural material and type are made, efficiency in structural design can intensively contribute to human well-being and a sustainable environment.

8 References

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