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STRUCTURAL EFFICIENCY FROM A SUSTAINABILITY PERSPECTIVE

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A practical approach to evaluate structural efficiency is presented, taking into consideration various structural alternatives applied to a high-rise building located in central London, UK. The study focuses on the choice of the slab system between conventional reinforced and bonded post-tensioned concrete and tackles the sustainability triple bottom line: environmental, social, and economic. The environmental impact is assessed using European factors restricted to embodied energy and embodied carbon dioxide (CO_2); the social impact is assessed using a ranking scheme considering construction time, material usage, and indoor and outdoor factors. The results show that the post-tensioned concrete option contributed to the project's sustainability goals and led to considerable savings of approximately 25% on the overall slab's embodied energy and embodied carbon while presenting an economical solution and social benefits.

INTRODUCTION

Construction material, construction activity, and the operability of a building impact our quality of life in many ways. As population levels around the world continue to rise and more building structures are required, the construction impact is set to increase. To fully assess the effect of buildings on the environment, it is important to assess the impact of the construction phase in addition to the impact of the operational phase. There has been tremendous focus on the operational phase, given the fact that it accounts for approximately 90% of the environmental impact. However, as buildings become more environmentally efficient during the operation phase, the impact of the construction phase and, consequently, the structural efficiency, become essential.

This study aims to evaluate structural efficiency over the building's life cycle through a practical approach, covering the sustainability triple bottom line: environmental, social, and economic. The focus is on slab construction for bonded post-tensioned and conventional reinforced concrete slab options with an emphasis on the construction phase. The comparison is carried out on an actual project—Strata SE1—a high-rise building in London designed with stringent sustainability requirements. The evaluation of structural efficiency examines material selection, quantity, construction time, and architectural features and how they translate into the environment and social well-being.

PROJECT DESCRIPTION

The project is a multi-unit residential building (482 ft tall) with 41 post-tensioned flat slabs designed using European standards with a central core and only two internal columns. The building has several unique features, with offset columns and wind turbines housed at the top of the tower and resting on a post-tensioned transfer slab. It is the world's first building with wind turbines destined to supply a portion of the building's operational energy.

For the structural slab design, the following objectives were put in place:

- Structural performance: Frame a solution that simplifies forming, routing of mechanical services, and architectural layout flexibility; reach the thinnest achievable slab thickness for spans of 31 ft; and frame

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a solution that controls deflection and cracks to meet cladding requirements and tolerances. Deflection was set to 0.4 in. on all the façade elements and to *L* (span)/360 internally.
- Construction: Achieve a fast construction schedule and stay below budget.
- Sustainability: Optimize use of resources, minimize carbon footprint, and reduce social impact of the construction work.

STRUCTURAL SLAB OPTIONS

Given the slab layouts and the sustainability goals set for the project, it was decided from the start that an in-place concrete frame would work better than a steel frame. The main reasons behind this assessment were the curved slab edges, which could be formed easily and economically with concrete; advantages of concrete, such as acoustic isolation, resilience, and thermal mass properties (Schokker 2010); and lateral stability capacity. Therefore, only the following in-place concrete options were considered for the comparative analysis:
- PT: Flat-slab post-tensioned concrete with a bonded system (bonded post-tensioning is common in UK building construction);
- RC1: Flat-slab reinforced concrete; and
- RC2: Slab with drop beams all in reinforced concrete.

A detailed design for all three options was performed following the same assumptions to allow for a fair comparison. Given the project location, the structures were designed according to the British code to meet equivalent serviceability, ultimate state, and deflection limits. Table 1 shows the material quantity rates per square foot of slab. Non-prestressed reinforcement rates represent all conventional reinforcement needed, including detailing requirements, such as trim bars around openings and bars at slab edges. The overall slab area shown in the table is the exact value from the built project accounting for all recesses, openings, and so on.

The roof slab supporting the wind turbine is excluded from the aforementioned quantities. Its quantities do not affect the analysis, as the overall material quantities are driven by the typical 40 stories. The roof slab is very specific to the loads induced by the wind turbines. It involves concentrated wind loads and moments transferred by the turbines to the slab.

PROJECT CONSTRUCTION SCHEDULE

Constructing a high-rise on a very tight site in London, where the Strata project is located, comprises many challenges. One of the main focuses is to reduce disruptions to nearby communities and businesses and complete the construction work as fast as possible. It is therefore vital to adopt a construction system that speeds up the construction schedule.

Structural frame design

Estimates of the construction time of the three concrete options were computed. The estimates for each option were based on same concrete strength, loadings,

Table 1—Slab material quantity

		Structure type		
Structural item	Unit	PT	RC1	RC2
Average slab area	ft^2	6781	6781	6781
Overall area	ft^2	271,272	271,272	271,272
Slab thickness	in.	Approximately 8 (200 mm)	Approximately 10 (260 mm)	8.3*
Non-prestressed reinforcement rate	lb/ft^2	2.38	4.42	3.99
PT strand rate	lb/ft^2	0.72	0	0
PT ducts rate (0.43 ft/ft^2)	lb/ft^2	0.12	0	0
PT anchors (0.01 pc/ft^2)	lb/ft^2	0.08	0	0

*Value represents equivalent slab thickness. It is based on slab of 7.1 and 23.6 in. (180 and 600 mm) deep beams placed along long spans and perimeter to control deflection.

deflection control, and forming and labor resources. The floor cycles came out at 5, 6.5, and 8.5 days for the PT, RC1, and RC2 options, respectively. Consequently, for the 40 stories, RC1 yields a total increase of 60 working days with respect to the PT option and RC2 yields an increase of 140 working days with respect to PT. With additional forming and labor resources consisting of an entire slab forming set and back-propping, the floor cycle for the RC options can be improved; however, this additional forming adds—in addition to its cost—an environmental impact caused by the extra formwork material, its mobilization, and more waste. Time savings for the PT option is due to less material and hence less installation time and labor, stressing of the tendons and, consequently, faster deshoring. The actual floor cycle achieved for the PT slab was 4.5 days on average, yielding even greater time savings.

Construction management

On job sites, as trades are interlinked, efficient coordination and control of the work to minimize errors and enhance information-sharing significantly improve the construction workflow and deadlines. It is hard to quantify the related savings, but the project was completed 12 weeks ahead of the estimated schedule.

Structural detailing

While the choice of the structural frame has a major impact on the construction time period, small improvements from thorough detailing can also help in reducing the construction time. A simple example is the construction requirement for this project to avoid complicated, skewed blockouts at the PT anchor locations and the slabs' curved edges. Skewed blockouts require more labor and material and, most importantly, would lead to increased friction losses at the anchor and higher risk of damage to the post-tensioning tendons. With efficient detailing, these blockouts were avoided at no extra cost or resources. Every anchor would have necessitated approximately 2 additional minutes for installation or, alternatively, more labor cost. This seems negligible, but when counting 2000 anchors required for the project, this amounts to 67 hours; therefore, this saved the site approximately 1.5 weeks on the PT trade schedule.

MATERIAL AND ENVIRONMENTAL RATES

The overall material quantity for the 40 stories is listed in Table 2 along with the unit rates of embodied energy and embodied CO_2.

The environmental factors listed are taken from the *ICE* report (Hammond and Jones 2008), which is based on life-cycle inventory (LCI) cradle-to-gate and 40% recycled content for steel. This reference focuses on energy and carbon dioxide factors without representation of other greenhouse gases. It was used due to its comprehensive database on concrete slab material and application to the UK market. The LCI approach was deemed satisfactory given the scarcity and variability of data on life-cycle assessment (LCA) or cradle-to-grave; the use of the same material type in all options; and the abundance of cradle-to-gate values, which are documented by the material manufacturers (Sweet 2010). In addition, for database consistency, the wire and galvanized sheet rates used herein for PT strands and duct are from virgin material, as no other values are given in the *ICE* source. However, PT strand and ducts can have up to 95% recycled content. The results are, therefore, very conservative and the reality would yield higher savings in the PT option.

ENVIRONMENTAL IMPACT

The cumulative environmental impact of the concrete stories is shown in Fig. 1. The results point out that PT records the lowest embodied energy at 25,200 GJ and embodied CO_2 at 3101 tons. An estimated 6393 GJ in energy and 797 tons in CO_2 is added by using RC1 versus PT—an increase of approximately 25% in the overall embodied energy and CO_2. Between PT and RC2, the environmental differences are not as pronounced; PT saves approximately 5% in energy and CO_2. RC2, however, does not benefit from a simplified formwork that a flat slab presents. The existence of drop beams in RC2 requires elaborate formwork, more workmanship, changes to mechanical services distribution, and reduced layout flexibility.

The results can be extrapolated to determine the LCA of the concrete slabs. The transport, construction process, and demolition phases to cover gate-to-grave are estimated to add between 10 and 20% to the LCI results (Kawai et al. 2005; Guggemos and Horvath 2005; Nielsen 2008). Due to lack of a coherent database, more research is needed to obtain reliable numbers.

It is important to note that per Table 3, concrete alone accounts for 56% on average of the embodied energy of the slabs and 72% of total embodied CO_2.

Moreover, as the three options involve cast-in-place concrete solid slabs and would benefit from the concrete's

Table 2—Material quantity and environmental unit rates

Material type	Overall material weight, U.S. ton			Embodied energy, MJ/lb	Embodied CO$_2$, lbCO$_2$/lb
	PT	RC1	RC2		
Concrete C32/40 (1:1.5:3)	13,886	18,052	14,581	0.50	0.159
Non-prestressed reinforcement (bar and rod)	322	601	543	11.2	1.71
PT strand (wire)	97	0	0	16.3	2.83
PT duct (galvanized sheet)	17	0	0	17.7	2.82
PT anchors (general steel)	12	0	0	11.1	1.77

Table 3—Contribution of material items in percentage

	Embodied energy, %			Embodied CO$_2$, %		
Material item	PT	RC1	RC2	PT	RC1	RC2
Concrete C32/40	56	58	55	71	74	71
Non-prestressed reinforcement (bar and rod)	29	42	45	18	26	29
PT strand (wire)	13	0	0	9	0	0
PT duct (galvanized sheet)	2	0	0	2	0	0
PT anchors (general steel)	1	0	0	1	0	0

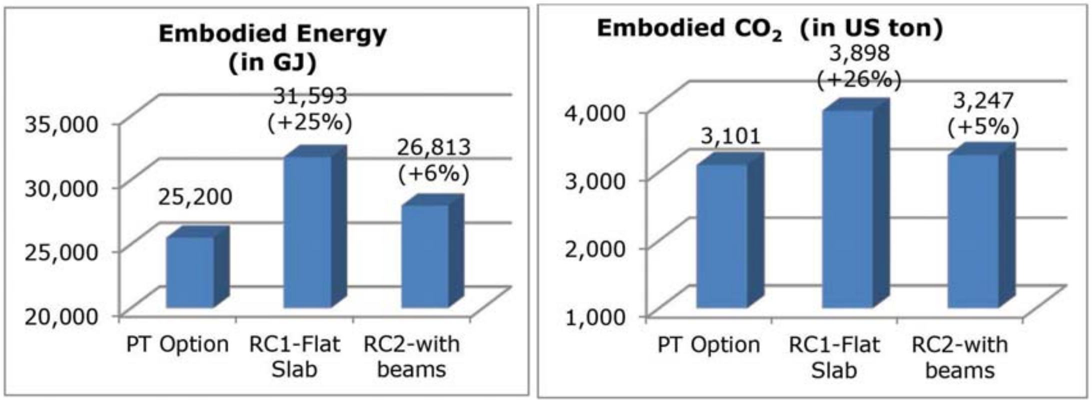

Fig. 1—Total embodied energy and carbon dioxide.

thermal mass properties, the environmental impact of the operational phase of the building is expected to be comparable for all the options. The savings in energy and carbon dioxide that resulted from the structural frame choice, therefore, would come at no extra burden to the overall building's LCA.

SOCIAL IMPACT

Human science is taking an increasing role in the built environment (Frank et al. 2003). Several studies discuss the social impact of construction and buildings on quality of life (Gangolells et al. 2009; Gilchrist and Allouche 2005). In this study, the social impact is assessed through a ranking scheme that gives a practical comparison of various structural slab options during construction and operability phases. The approach considers the effect of the construction time period, reduced nuisances reflected by material quantities and material type, and architectural features for indoor and outdoor impact, as shown in Table 4.

Construction phase

During the construction work, a wide array of social discomfort can occur (Gauzin-Muller 2002), such as air pollution, dirt and dust, noise, vibration, traffic, parking problems, and disruption to nearby businesses. These can be directly related to material quantity, type, and construction time:

- Using less of the same material leads to less disruption, reduced pollution, trucking, traffic congestion, deliveries, and waste. Because all options use concrete and reinforcement, based on the material quantities of Table 4, the options rank: 1) PT; 2) RC2; and 3) RC1.
- A faster construction cycle yields less disruption and helps alleviate the negative nuisances of construction sites. The options rank: 1) PT; 2) RC1; and 3) RC2 in terms of time savings. The PT option saved the community approximately 3 months of construction time and all related disruptions.

Operational phase

During the operational phase, improving indoor living conditions has a direct impact on economic and social benefits from increased productivity to better health. The average person spends 87% of their time indoors (Kleipis et al. 2001); thus, their well-being depends largely on the conditions of the interior spaces in terms of lighting, air quality, acoustics, sight openness (visual), and thermal comfort.

- Concrete has clear benefits for the aforementioned factors (applicable to all three options).
- Architecturally, a flexible and open indoor layout that a flat-slab system provides would contribute to better visual and living comfort. While both PT and RC1 options are based on flat slabs, RC2 includes drop beams. Such beams would lower the layout flexibility and restrain the view.
- Outdoors, efficient structures that reduce unnecessary building height stemming from pure floor thickness also help the environment with a lesser shadowing effect, less cladding material, and all its repercussions in energy consumption. The slab thicknesses in Table 1 show that RC1 and RC2 would have yielded increases of 7.9 and 52.5 ft in overall building height, respectively. A smaller building would also consume less energy in terms of its heating, cooling, and overall operation.

For the overall social impact, a weighted scoring scheme could be used by assigning an importance factor to each item. For Strata, the PT option ranks first in all categories, as summarized in Table 5.

ECONOMIC IMPACT

As with any project, cost-effectiveness plays an important role in deciding on an optimal solution. When comparing overall cost impact, however, a holistic approach is needed to cover both direct and indirect cost.

Direct cost estimates for the three options were done according to UK unit prices from 2008 to 2009. The prices for PT, RC1, and RC2 yield 6.9£/ft^2, 7.2£/ft^2, and 7.8£/ft^2, respectively, which include material and placement costs for concrete, non-prestressed reinforcement, PT strands, ducts, anchors, and formwork.

Further savings for the PT option came from indirect cost, such as 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.

CONCLUSIONS

The concept of sustainability is at the forefront of many aspects of our daily lives, and the area of construction is no exception. The United Nations World Commission on Environment and Development (Brundtland 1987) defines sustainability as “meeting the needs of the present without compromising the ability of future generations to meet their own needs.”

This study shows that building sustainable structures can be achieved without compromising social well-being, structural performance, or cost. The comparison between PT and RC structures indicates that structural efficiency

Table 4—Slab parameters

Material item*	Unit	PT	RC1	RC2
Material weight	U.S. ton	14,334	18,652	15,124
Increase in material weight	U.S. ton	—	4318	790
Main material type	—	Concrete	Concrete	Concrete
Increase in construction time	Days	—	60	140
Increase in building height	Foot	—	7.9	52.5
Structural slab configuration	—	Flat	Flat	Drop beams

*Increases shown in RC1 and RC2 columns are with respect to PT option.

Table 5—Ranking of concrete options on social impact

	Social factor	PT	RC1	RC2
Construction phase	Reduced negative social impacts	1	3	2
	Faster construction cycle	1	2	3
Operational phase	Indoor impact	1	1	2
	Outdoor impact	1	2	3
Total points (lower is better)		4	8	10

contributes to a building's overall sustainability assessment. For the Strata project, the use of PT slabs saved approximately 25% in embodied energy (6400 GJ) and embodied carbon (797 tons of CO_2) and yet it is the most economical solution. The results are based on structural efficiency alone and through an LCI of the slabs. On the social impact, the proposed ranking scheme shows that PT also has the best score for indoor living, outdoor living, and reduced construction disruption. This demonstrates that when structural efficiency is assessed at the design stage, it can result in considerable sustainability benefits. When deciding which structure type and material to use on a given building, the earlier sustainability factors are integrated into the decision-making process, the greater the possibilities of reaching sustainable solutions.

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