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Design and Embodied Carbon Optimisation of a Composite Floor System with Thin Concrete Shells on a Beam Grid

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Abstract

Thin shell floors can reduce concrete consumption compared to conventional reinforced concrete flat slabs. Prefabrication of shell structures for longer spans may require segmentation, and previous studies have shown that the overall performance is highly sensitive to fabrication tolerance. As an alternative, we propose a composite floor system that supports multiple individual shells on a steel beam grid. The novel system covers the total floor area between columns with a collection of several identical rectangular segments that are covered by separate shells, while the corners of the shells are supported by a grid of steel beams. For a given column grid, several variations of the proposed floor solution can be designed by dividing the total floor area into different numbers of equal sections, each to be designed as an individual shell. This paper presents the conceptualisation and preliminary structural design of the composite system with concrete shells and steel beams. For the same column spacing, the embodied carbon and floor height of three possible variations of the novel system are compared herein against two designs treated as benchmarks: a design with a single shell and a conventional flat slab design. As the span of the individual shells decreases, the embodied carbon attributed to concrete decreases. However, despite the increased number of beams needed for sectioning the total area into shells with shorter spans, variations in applied loads and loading points also affect the design of supporting beam grid. Therefore, relationship between the embodied carbon from the steel beams and the span of the individual shells is nonlinear, highlighting the importance of parametric optimisation. The proposed composite system can achieve embodied carbon reductions of up to 58% compared to a conventional flat slab, a level similar to that of a single-shell design but with almost one-third less floor height.

Keywords: thin shell floors, shape optimisation, embodied carbon, composite floor systems

1. Introduction

Increasing concerns about climate change force all sectors to reduce carbon emissions. The construction industry is responsible for a significant share of global carbon emissions resulting from human activities, with 6% attributed solely to cement production [1]. Embodied Carbon can be used to assess the environmental performance of the construction work by quantifying the carbon emissions arising from the activities throughout their life cycle [2]. In multi-story concrete buildings, up to 75% of the total embodied carbon of superstructure is from floors [3]. Concrete slab systems that transfer loads through bending essentially under-utilise the capacity of concrete in the volume below the neutral axis. Therefore, shell floor systems designed based on compressive membrane actions provide opportunities to improve material efficiency, in contrast to flexure-based slab designs. Previous studies have illustrated that novel shape-optimised shell floor systems offer greater potential for reducing embodied carbon compared to optimising slab designs within conventional construction practices [4].

Several previous studies illustrated the successful use of shells in floor systems to reduce embodied carbon and self-weight. Hawkins et al. [5] developed a floor system with textile-reinforced groin vaults and prestressed steel ties to reduce embodied carbon and self-weight by up to 58% and 53% respectively, compared to conventional concrete flat slab designs. Rippmann et al. [6] 3D printed a form-found compression-only shell with ribs using silica sand and reached weight reductions of up to 70% in contrast to a flat slab. While they did not present an estimation of embodied carbon due to the lack of reliable data at the time, they emphasised the potential to reduce embodied carbon with emerging low-carbon 3D printing materials in future. Oval et al. [7] illustrated the construction of a segmented form-found ribbed concrete shell with prestressed ties using concrete spraying, achieving a 75% reduction in self-weight and cutting embodied carbon by 50% compared to a flat slab. Hegger et al. [8] numerically compared several conceptual floor designs where textile-reinforced concrete shells act as either a single shell or a part of a hybrid floor system, to illustrate potential reductions of self-weight up to 70%. Likewise, novel construction techniques such as textile-reinforced concrete, 3D printing, and concrete spraying can be employed to fabricate shells for floor systems to reduce both embodied carbon and self-weight.

Despite the potential benefits of shell floor systems, previous studies have also highlighted various concerns that either need further research before practical implementation or present disadvantages compared to conventional solutions. The optimised curved geometries in previous studies were manufactured using novel construction methods [6], [7], which are more suited for prefabrication due to the required machinery and quality control. Therefore, segmented off-site prefabrication and subsequent on-site assembly can be a viable strategy to construct shell floors for long spans required in practice. However, the structural behaviour of a segmented shell is different to that of a continuous shell. Nuh et al. [9] tested a segmented shell structure assembled through half-joint shear keys and noticed imperfections in the dry joints due to fabrication tolerance. They observed that the behaviour at the joints heavily depends on the quality of the interface, whereas the experiments recorded collapse loads at less than half of the predictions from their finite element model. Rippmann et al. [6] used male-female interlocking features in their segmented 3D-printed ribbed shells and observed that the formation of hinges at the joints increased deflections. In terms of the floor height, Hawkins et al. [5] deduced that a shell height of span/10 was optimal for their shell floor systems, which is 140% higher than the height of an equivalent flat slab with a depth of span/24 [10]. Minimising the floor height of shell floor solutions is crucial for maximising the utilisation of space within the overall building structure, and subsequently reducing both the cost and embodied carbon per floor area. Therefore, a composite shell floor system with reduced overall height with no joints can be a promising compromise to reduce embodied carbon in concrete floors.

This study introduces a composite floor system where individual shells are mounted on a grid of steel beams, as illustrated in Figure 1. Each shell transfers the applied loads through compressive membrane actions to the beam grid which provides adequate lateral restraints. In contrast to a floor system with a segmented shell spanning across the column spacing, this system avoids dry joints within shells and potentially has reduced floor height due to shorter spans of individual shells. The proposed novel system also promotes the circular economy because the individual concrete shells and the steel beams can be dismantled and reused in another structure. However, the material consumption of the proposed system may be higher due to additional steel beams needed for the supporting grid. For a given column spacing, the proposed system can offer multiple viable variations with different spans for individual shells, such as dividing the floor area into different numbers of sections. Therefore, the objective is this paper is to understand how the variations of the proposed system compare with floor systems with a single shell and conventional flat slabs, in terms of embodied carbon and floor height.

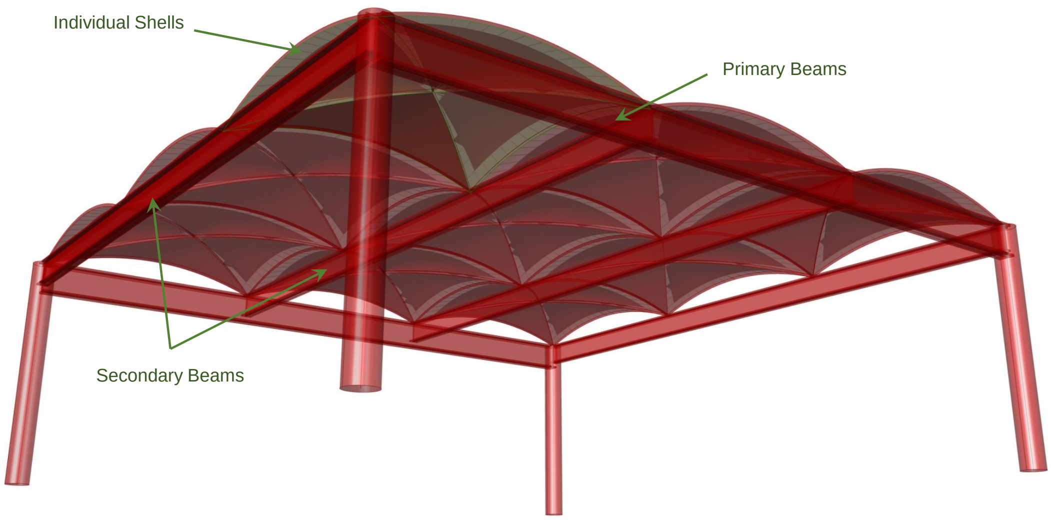
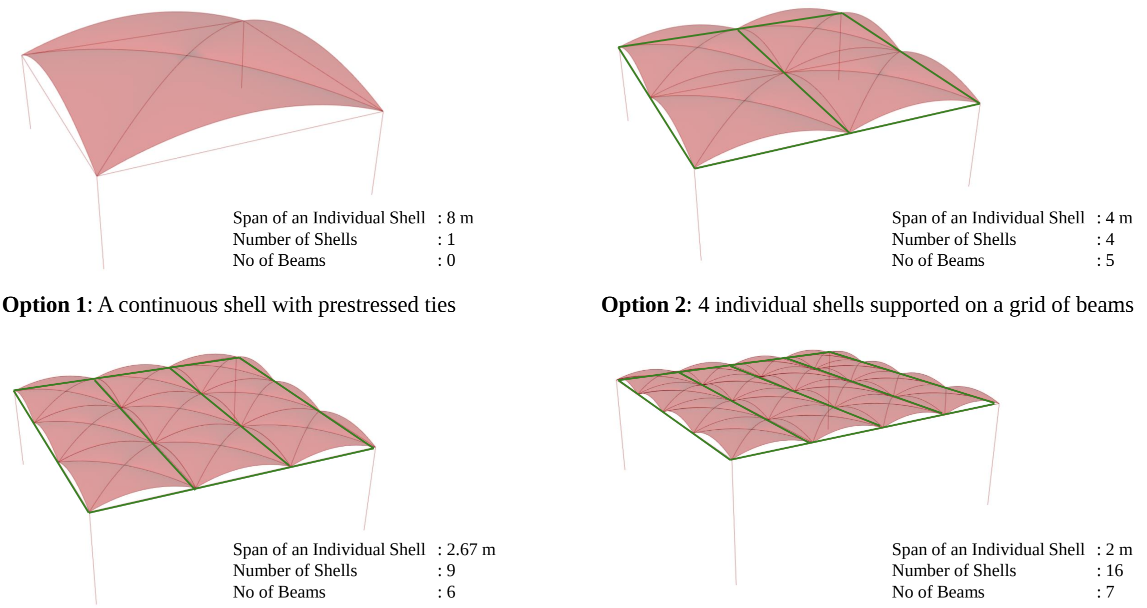


Figure 1: Composite floor system with individual shells supported by a beam grid.

2. Methodology

The embodied carbon and floor height of five different floor designs for a column spacing of 8 m × 8 m are estimated to understand the potential of the proposed composite shell floor system with steel beams. A reinforced concrete flat slab design according to Economic Concrete Frame Elements for Eurocode 2 is considered as a conventional benchmark [11]. Figure 2 shows the configuration of the four solutions with shells compared in this paper. As a benchmark for the design with a single shell, Option 1 is recreated according to the design proposed by Hawkins et al. [5] with a groin vault spanning between columns supported by prestressed steel ties. Option 2, 3, and 4 illustrate the variations of the proposed system where the 8 m $\times$ 8 m floor area is divided into 4, 9, and 16 equal areas respectively, to be covered by individual shells. The different options of the composite system entail differences in required span and thus shell thickness, the number of beams needed for the supporting grid, and the points at which loads are applied to the grid. Hence, the material consumption for shells and the supporting beam grid may differ across various options, resulting in variations in total embodied carbon, even if the total span is the same.

The optimum material properties, quantities, and geometries for shells in this paper are estimated for each option referring to the design tables developed by Hawkins et al. [12], assuming the individual shells are shaped as groin vaults. The groin vaults are reinforced with two layers of bi-directional GFRP textile, and a recycled aggregate fill is used to level the top surface of the floor system, as the aforementioned study had conceptualised. A superimposed dead load of 1.5 kN/m^2 and an imposed load of 2.5 kN/m^2 are considered in this paper to represent the loading conditions of a typical office floor. While the design of prestressed ties in Option 1 is also extracted from the above design tables, the supporting steel



Option 1: A continuous shell with prestressed ties

Option 2: 4 individual shells supported on a grid of beams

Option 3: 9 individual shells supported on a grid of beams

Option 4: 16 individual shells supported on a grid of beams

Figure 2: Variations of the shell-beam composite floor system.

beam grid is assumed to provide equivalent support conditions for individual shells in the composite options. Figure 3 labels different structural elements of the hybrid system in this study and illustrates the load path. The supporting beam grids are designed as a collection of universal beams according to BS EN 1993-1-1 [13]. The effects of lateral forces on the beam grids from shells and the deflection of beams on the overall behaviour are not investigated at this early stage of the study. Embodied carbon of each system is estimated for the life cycle stages of A1 to A3 (i.e. cradle-to-gate) in this scope [14]. Table 1 presents the adopted embodied carbon coefficients here according to the Circular Ecology database [15], except for GFRP textile reinforcement, for which the value is taken from the review by Hawkins et al. [5].

Table 1: Embodied Carbon Coefficients

Material	A1-A3 Embodied Carbon Coefficient (kgCO_2e/kg)
Concrete C30/37 (Flat Slab)	0.132
Concrete C35/40 (2 m Shell)	0.146
Concrete C40/50 (2.7 m Shell)	0.159
Concrete C50/60 (4 m & 8 m Shells)	0.180
Steel Rebar	1.20
Steel Section	1.21
Fill	0.0061
Glass Fibre	3.00

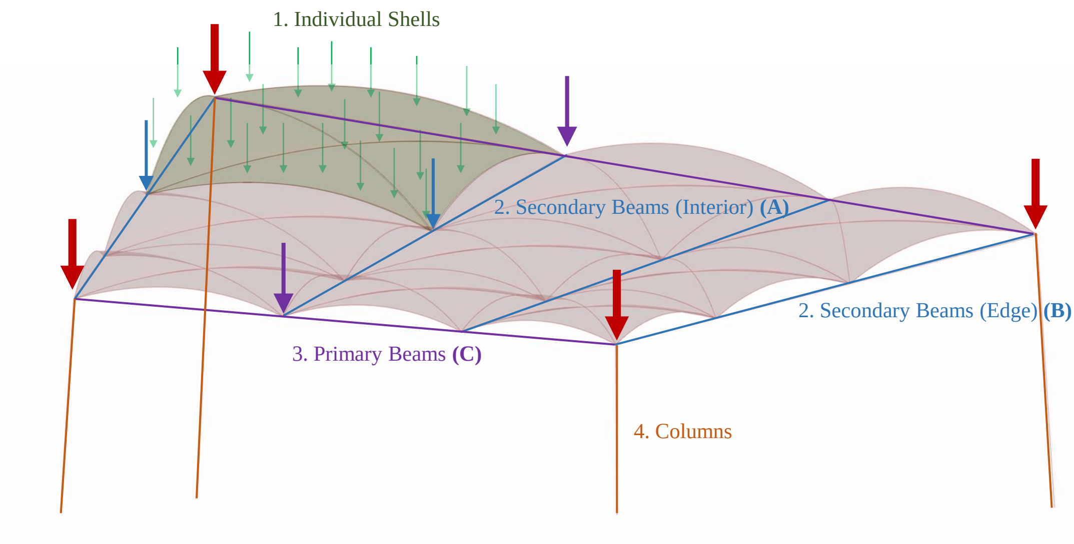


Figure 3: Elements in the proposed composite floor system.

3. Results and Discussion

The design details of the shells for Options 1 to Option 4 are listed in Table 2. The required shell thickness, reinforcement area, concrete strength, and fill volume decrease as the design span decreases, reducing the material consumption for shells in the composite system. Table 3 presents the design details of the supporting beams. The notation used to identify beams with different loading conditions is labelled in Figure 3 accordingly. Although the number of beams required is higher when the total area is sectioned as shells with shorter spans, the loading points of beams also change. As a result, the design forces and, hence the sizes of the beams required do not always proportionately vary with the design span of the individual shells. For example, Option 3 has the beams loaded at third points whereas Option 4 has the beams loaded in 3 points including at the midspan. Hence, although certain point loads in Option 4 may be lower than those in Option 3, the design moments in some beams in Option 4 exceed those of Option 3, requiring larger beams.

Table 2: Design details of the shells in the composite floor systems

Span of Individual Shells	Option 1 8m	Option 2 4m	Option 3 2.67m	Option 4 2m
Shell Thickness (mm)	76	42	27	18
Reinforcement Area (mm^2/m)	202	148	97	65.3
Tie Diameter (mm)	44	20	16	12.9
Concrete Strengh (MPa)	50	50	42	35
Total Depth (mm)	876	442	294	218
Concrete Volume (m^3/m^2)	0.07698	0.04256	0.02733	0.01800
Reinforcement Volume (m^3/m^2)	0.00107	0.00059	0.00039	0.00026
Steel Volume (m^3/m^2)	0.00075	0.00031	0.00028	0.00026
Fill Volume (m^3/m^2)	0.15208	0.08104	0.05742	0.04552
Self Weight (kN/m^2)	3.84	2.08	1.10	0.50

Table 3: Design details of the supporting beams in the composite floor systems

Span of Individual Shells	Option 2 4m	Option 3 2.67m	Option 4 2m
Design loads:			
Self weight from Shells (G_k) (kN/m^2)	2.08	1.10	0.50
Imposed (Q_k) + Superimposed dead loads (G_k) (kN/m^2)	2.5 +1.5	2.5 +1.5	2.5 +1.5
ULS design loads (W = 1.35G_k+1.5Q_k) (kN/m^2)	8.59	7.27	6.46
Design moments:			
Secondary beams in the middle (A)	275 kNm (WL^3/16)	138 kNm (WL^3/27)	207 kNm (WL^3/16)
Secondary beams at the ends (B)	137 kNm (WL^3/32)	69 kNm (WL^3/54)	103 kNm (WL^3/32)
Primary beams (C)	275 kNm (WL^3/16)	207 kNm (WL^3/18)	207 kNm (WL^3/16)
(L- Total span between columns (8 m))			
UB Sections (S275):			
A -Secondary beams (interior)	UB406×140×53	UB305×127×37	UB356×171×45
B- Secondary beams (edge)	UB305×127×37	UB203×133×25	UB254×146×31
C - Primary beams	UB406×140×53	UB356×171×45	UB356×171×45
Beam Arrangement	A+2B+2C	2A+2B+2C	3A+2B+2C

The Embodied Carbon of each floor option considered in this paper is presented in Figure 4, illustrating how different constituents contribute to the total embodied carbon. In all options, steel and concrete emerge as the primary materials accountable for embodied carbon, whereas the contribution of fill material and textile reinforcement is negligible. Regarding the floor options with shells, the embodied carbon attributed to concrete reduces when the design span of the shell reduces. Options 2, 3, and 4 have much higher embodied carbon attributed to steel due to the need for beams, in contrast to Option 1 where only the prestressed ties are needed. Embodied carbon of the beam grid is the lowest in Option 3, as the optimum compromise of the number of beams, the magnitude of point loads, and the loading points. As a result, both Option 1 where a single shell is spanning across the column spacing supported by prestressed ties, and Option 3 where nine individual shells are mounted on a grid of steel beams have a similar embodied carbon. In contrast to the conventional flat-slab design, the proposed options with composite shell-beam solutions also have the potential to be dismantled and reused in another structure at the end of life, presenting opportunities for circular construction practice. Compared to a conventional reinforced concrete flat slab design, Option 1 and Option 3 have 58% less embodied carbon for a floor area of 8 m × 8m.

Variation of the floor height of the shell floor systems designed in this study is shown in Figure 5, compared with a conventional flat slab design. All the floor options with shells have more than double the floor height of the flat slab, but Options 3 and 4 have around one-third less height than Option 1. Therefore, the proposed hybrid system with shells and beams has a lower floor height compared to the design with a single shell but still has a higher floor height than conventional slab solutions. Although the overall depth of shell floors is much higher than flat slabs, the services can be incorporated within the area to be filled for levelling, whereas additional space is usually needed for the slabs. The floor height of the composite options presented in this study is calculated assuming the individual shells are mounted on the beam grid. Conceptually, there is an opportunity to further reduce floor height by fixing the shells in between the beams. Further studies are needed to understand the feasibility of such a system in terms of constructability and connection details.

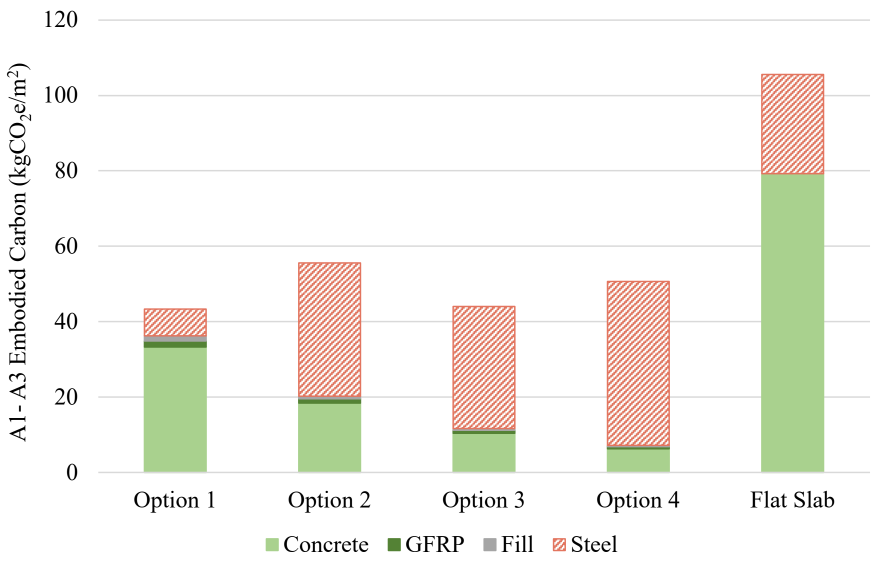


Figure 4: Embodied carbon of different floor options.

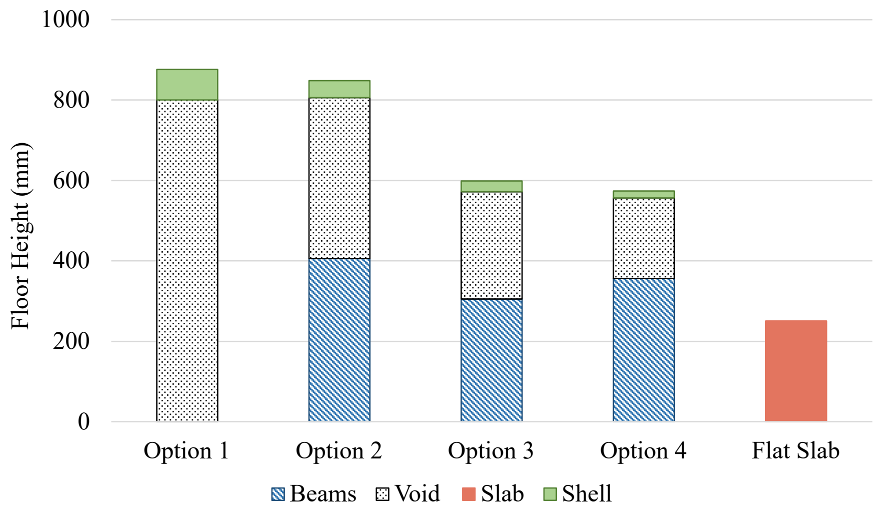


Figure 5: Floor height of different floor options.

This paper investigated the feasibility of a composite floor system that supports a set of shells on a grid of steel beams, as an alternative to floor systems with a single segmented shell. The motivation behind the proposed system was to reduce overall floor height and eliminate the necessity for dry joints within shells for long spans that would otherwise require segmentation in prefabricated shells. Although having additional flexural elements can be seen as a step backwards from shell floors that work predominantly through membrane actions, their embodied carbon is shown to be similar to solutions with a single shell. Floor height could also be reduced with the proposed system compared to designs with single shells.

Therefore, the proposed composite floor system is a promising way forward to use shells in floors considering possible savings of embodied carbon, potential for prefabrication while avoiding dry joints, and overall floor height.

Future studies are needed to understand how beams and individual shells behave in the proposed composite floor system, which can be interdependent. The results presented herein did not consider horizontal reaction forces exerted by the shells for the design of beams, and also did not address how the deflection of beams affects the performance of individual shells. These effects can have the potential not only to significantly alter the structural behaviour but also to change the optimum composite solution, rather than designing shells and beams separately. Furthermore, this study considered only groin vaults as a shell geometry for the proposed system due to readily available data in the literature. Alternative shell forms may be more suited for the context and offer further reductions in embodied carbon, considering the opportunities presented by supporting beam grids. For example, single-curvature shells continuously supported on beams (i.e.: Barrel Vaults) can be a promising solution for further investigation.

4. Conclusions

As the design span of individual shells decreases in the composite system, shell thickness, reinforcement area, concrete strength, and fill volume decrease, reducing concrete consumption. All the variations analysed in the proposed system have considerably higher embodied carbon attributed to steel due to the need for beams, in contrast to options with only the prestressed ties. However, while sectioning the total area into shells with shorter spans requires more beams, changes in applied loads and loading points can cause nonlinear variations in required beam sizes relative to individual shell spans. As a result, the design option with a single shell supported by prestressed ties and a parametrically optimised composite option with several discrete shells mounted on a steel beam grid can have similar embodied carbon, by up to 58% less than a conventional flat slab. While the floor height of any shell-based floor design may exceed double that of a flat slab, the composite system can reduce it by up to one-third compared to a single-shell design. The proposed shell-beam composite floor system is a feasible strategy to reduce embodied carbon in floors and overall floor height by feasibly incorporating shells in concrete floors while avoiding segmentation and subsequent dry joints.

Acknowledgments

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