Reducing the carbon emissions of building construction using thin-shell concrete floors

Steel and concrete are consumed in vast quantities as the global population continues to grow, develop and urbanise. Both these materials are carbon-intensive to produce, and construction therefore represents one of the hardest sectors of the economy to decarbonise. This project reimagines one of the most common uses of steel and concrete: floor slabs in multi-storey buildings. An innovative vaulted system is proposed, which takes inspiration from historical structures whilst utilising modern materials and construction methods. It is shown to offer significant carbon savings over today's typical floor structures.

Author: ***PhD, Dr, Dr, Meng,*** **Will Hawkins**

Background

The manufacture of building materials currently contributes 11% of the world's carbon emissions [1]. This is largely due to the carbon-intensive production of cement, the key component of concrete, and steel. Over the next four decades, a doubling of existing floor area will be required to meet the needs of continued population growth and urbanisation [2]. This increasing demand, combined with limited opportunities to improve the efficiency of material production, means that construction is often considered to be the hardest sector of the economy to decarbonise.

Most steel and concrete is used to construct buildings, of which floors are the dominant component [3]. These are typically made of reinforced concrete slabs and beams: prismatic structures which resist load through bending. When concrete bends, it cracks, and steel reinforcing bars must therefore be included to provide tensile resistance. In fact, most of the concrete is a typical floor slab is cracked, and therefore makes only a marginal contribution to strength and stiffness. Could we re-imagine floor structures to make better use of materials? How much carbon might we save in the process?

Learning from the past

Before the widespread use of steel, the only means of creating spanning structures from durable, fireproof, yet brittle materials such as stone, brick or concrete was to use curved forms such as arches, domes and vaults. This curvature enables shells to resist load through compressive membrane forces, rather than bending, so reinforcement can be avoided. The need for metals or timber is eliminated, creating highly durable structures which can survive for millennia, such as the unreinforced concrete dome of the Pantheon in Rome and the intricate masonry rib-vaulting of Gothic cathedrals (Figures 1a and 1b).

The fireproof and aesthetic qualities of brick and ceramic tiles led to the development of elegant vaulted floor structures, such as those pioneered by the Guastavino Company in Spain and North America (Figure 1c). In the middle part of the 20th century, long-span concrete shells with remarkably low thicknesses became popular, thanks in part to the high cost of steel, but also the innovation of engineers including Eduardo Torroja, Piere Luigi Nervi and Heinz Isler

(Figure 1d). These examples demonstrate the effectiveness of geometry to create elegant and durable structures despite material restrictions.

Figure 1 – Curved structures have been used to make use of brittle materials for millennia. Examples include a) the Roman Pantheon (completed 125AD), b) Ely Cathedral (1349), c) Boston Public Library (1895) and d) Heinz Isler's Deitingen motorway service area (1968).

Today, historical shell-building techniques are unfortunately lost, but the need to minimise material consumption is greater than ever. This has led to growing research interest in highly efficient vaulted structures, using modern computational techniques to maximise structural performance. Tile vaults have been proposed as a low-tech and low-carbon floor system [4], however their slow and labour-intensive construction process prohibits large scale application. Geometrically intricate precast concrete units have also been shown to offer significant material reductions [5], albeit relying on high-carbon concrete mixes and advanced computational manufacturing methods.

A modern thin-shell flooring system

In today's construction industry, the relative cost of labour is much higher than that of materials, and a successful solution must therefore be simple and quick to build. This project proposes textile-reinforced concrete shells of uniform thickness supported by columns at each corner (Figure 2). Additional strength and robustness are provided by two layers of glass fibre mesh reinforcement, allowing the shell thickness to be minimised. Each unit is pre-cast and craned into position before being covered by a non-structural fill material such as recycled rubble, excavation waste or an alternative low-carbon, locally-sourced, bulk material. As well as creating a level top surface, the fill distributes concentrated floor loads to the shell, reduces vibration by adding mass and damping, and acts as an acoustic and thermal barrier between floors. Lateral thrust from the shells is resisted by a network of steel ties, which are prestressed to control uplift.

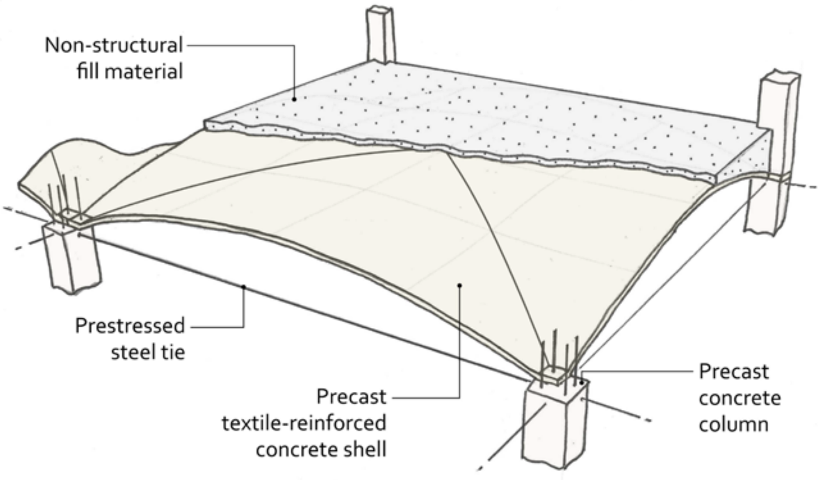


Figure 2 – Overview of the proposed structural system.

Design, analysis and construction

A range of candidate shell geometries were investigated in a computational investigation, including hypars, spherical patches, and those form-found using dynamic relaxation [6], [7]. Groin vaults, which are comprised of two singly-curved barrel vaults intersecting at right-angles, were identified as having a strong structural performance across deflection, vibration and buckling criteria. Each of the four main surfaces comprising the groin vault is singly-curved and developable, greatly simplifying the construction of formwork; this is the basis of the groin vault's ubiquity in historical masonry structures.

The groin vault geometry is defined by the span l, rise h and edge curve profile. Historically, this might have taken the shape of a circular arc, or the catenary formed by a hanging chain. Today, however, we can use parametric optimisation to maximise structural efficiency. The geometric optimisation process developed for this project is illustrated in Figure 3. A Bezier curve is defined by four control points and the two dimensionless parameters a and b. The internal forces throughout the shell are calculated for each trial geometry using a linear finite element analysis, under a variety of worst-case loading patterns which might be experienced by the floor. From these forces, the total bending strain energy is found. This is a proxy for the structural efficiency of the shell, since bending implies large stresses, greater deformations, a higher required shell thickness, and mode embodied carbon. Using a genetic algorithm, the optimal values of a and b are found which minimise the envelope of maximum bending energy across all loading patterns.

After the optimal vault geometry has been determined, the required shell thickness, reinforcement quantity and concrete strength is found using an analytical model of textile-reinforced concrete strength [8], which was developed during this project and builds upon the work of Scholzen et al. [9].

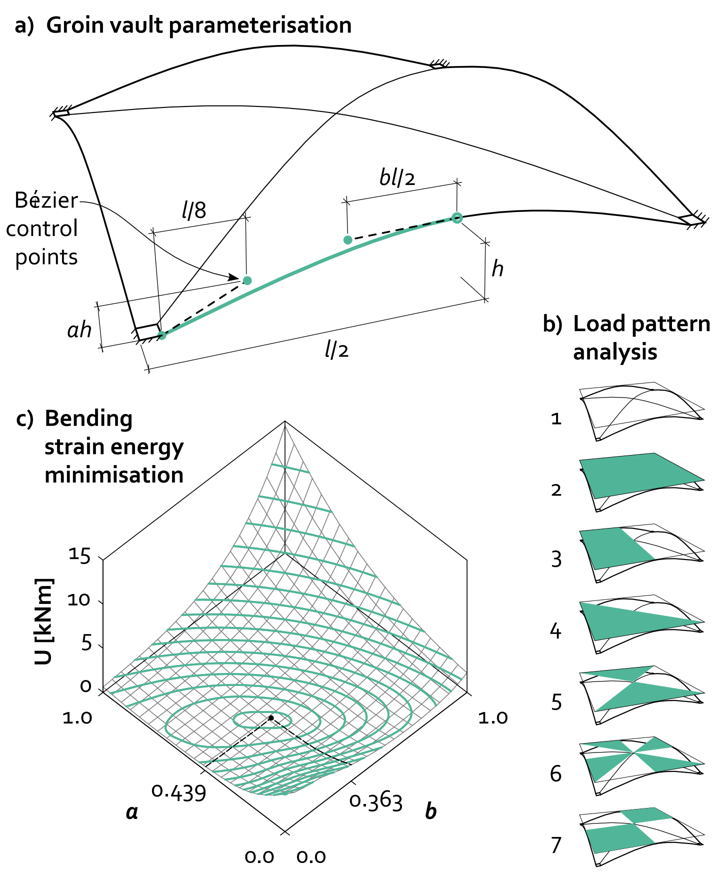


Figure 3 – Parameterisation, analysis and optimisation of groin-vault geometry.

Quarter-scale physical prototypes were constructed in order to explore materials, manufacturing methods, and verify the structural performance of the proposed system [10]. Two shells were constructed, the first with no fill material and the second with a foamed concrete fill with a density of 800kg/m^3. Both had a span of *l*=2000mm, rise of *h*=200mm, thickness of 18mm and threaded steel ties of 16mm outer diameter. A modular timber formwork system was constructed (Figure 4a), onto which the shell was cast by hand (Figure 4b). A fine-grained concrete was used, with a maximum aggregate size of 2mm and low cement content (434 kg/m^3) to further reduce embodied carbon.

The prototype shells were loaded using four hydraulic jacks, each distributed onto four contact patches, using the arrangement shown in Figure 4c. The jacks were controlled independently in pairs, allowing both uniform and asymmetric loads to be applied. After initial loading, prestressing of ties and then loading and unloading uniformly, the shells were tested to destruction under a worst-case asymmetric load (pattern 3 in Figure 3). Load-displacement results for each test phase are shown in Figure 5. The presence of the fill can be seen to increase the stiffness moderately, but has only a minor effect on ultimate strength. Ignoring the fill for analysis purposes can then be recommended as a simplifying assumption.

The shells were found to support the required loading for a new office or residential building, both with and without fill material. Moreover, they exhibited controlled and ductile behaviour at the peak load, as shown by the large deformation and distributed cracking in Figure 4d. This is critical for the safety of thin shells in modern buildings, since large displacements provide ample warning of failure in the case of accidental damage or severe over-loading.

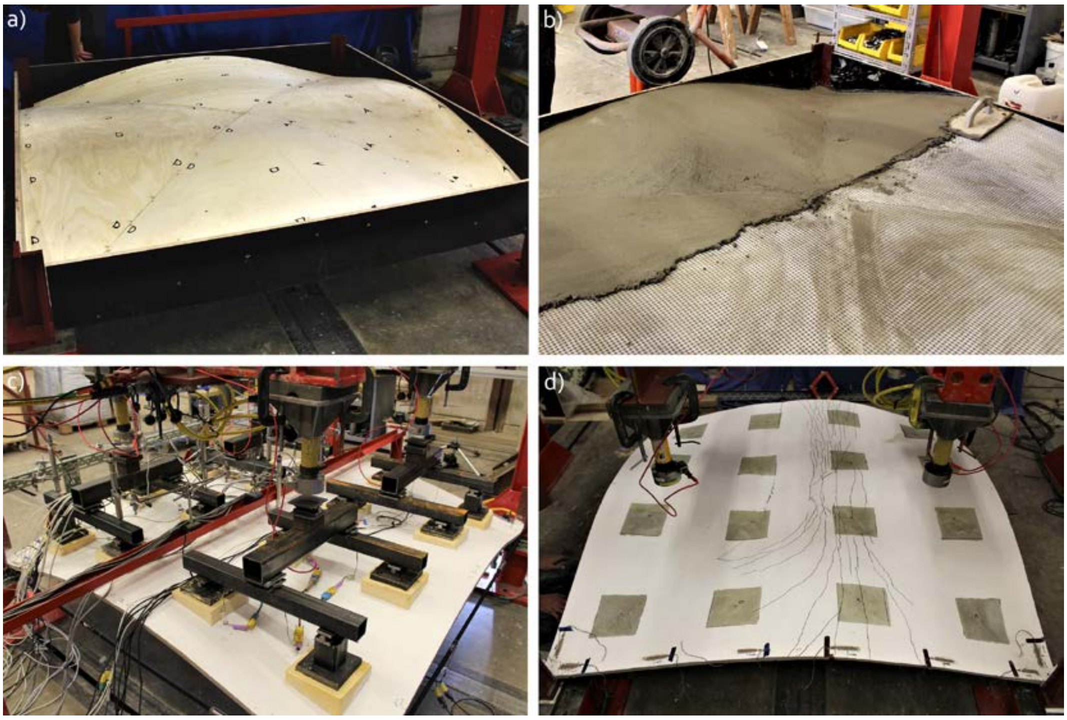


Figure 4 – Physical prototyping, showing a) timber formwork, b) shell construction, c) loading apparatus and d) shell crack patterns after testing.

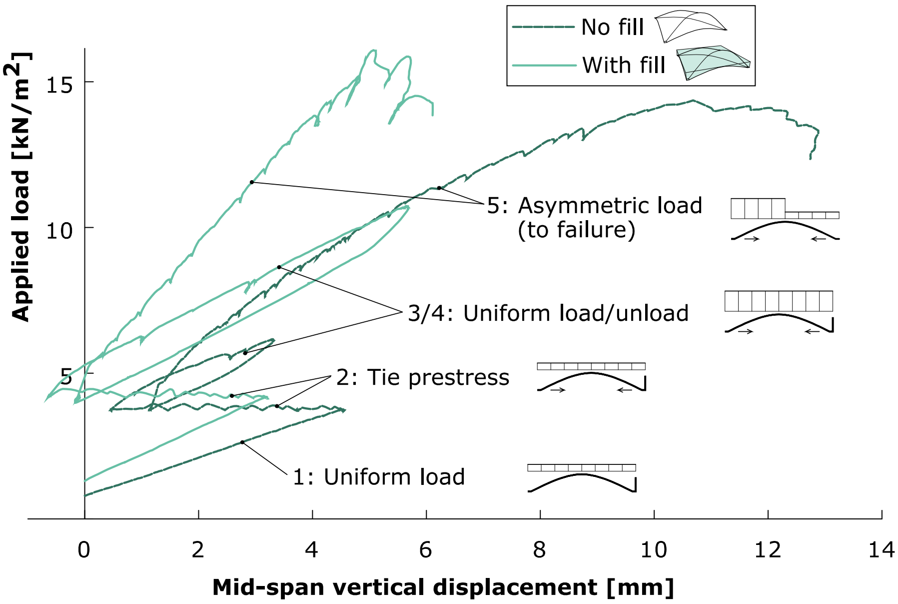


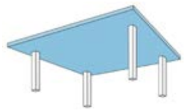
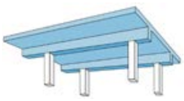
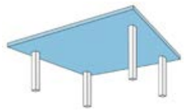
Figure 5 – Load vs displacement test results for prototype shells with and without fill

Comparison with typical concrete floor systems

A complete design methodology based around finite element modelling was been developed and, crucially, shown to safely underestimate the strength measured in the physical tests [11]. Using this, several full-scale designs were generated and compared to typical concrete flooring systems, including reinforced concrete flat slabs (two-way spanning), one-way slabs with beams, post-tensioned (prestressed) flat slabs and ribbed slabs, in approximate order of increasing construction complexity.

These designs were generated using a design guide [12] conforming to European building codes [13], for a typical office or residential application with live (variable) and dead (permanent) floor loads of 2.5kPa and 1.5kPa respectively. The span *l* is a key parameter influencing material quantities, and each system was therefore designed across its full range of typical spans. In all cases, these are equal in both directions. Table 1 shows the material quantities for each design, as and compares these to the thin TRC shell system proposed in this project.

Table 1 – Material quantities for each compared floor system across typical span ranges.

		Span [m]							
		4	6	8	10	12	14	16	18
	***RC flat slab***								
	Concrete strength [MPa]	30	30	30	30	30			
	Concrete mass [kg/m²]	470.0	484.1	587.5	806.1	1057.5			
	Steel mass [kg/m²]	10.0	14.0	22.0	28.0	36.0			
	Maximum depth [mm]	200	206	250	343	450			
	***RC one-way slab***								
	Concrete strength [MPa]	30	30	30	30	30			
	Concrete mass [kg/m²]	314.3	413.7	586.9	798.4	1116.3			
	Steel mass [kg/m²]	9.3	14.5	18.1	24.2	35.5			
	Maximum depth [mm]	242	348	602	737	907			
	***PT concrete flat slab***								
	Concrete strength [MPa]		32	32	32	32	32		
	Concrete mass [kg/m²]		470.0	470.0	585.2	747.3	1210.3		
	Steel mass [kg/m²]		10.0	15.0	20.0	26.0	36.0		
	Maximum depth [mm]		200	200	249	318	515		
	***RC ribbed slab***								
	Concrete strength [MPa]		30	30	30	30	30		
	Concrete mass [kg/m²]		342.0	391.6	505.2	654.7	965.3		
	Steel mass [kg/m²]		11.3	16.9	16.5	21.9	30.6		
	Maximum depth [mm]		340	548	971	923	970		
	***TRC shell***								
	Concrete strength [MPa]	40	45	45	45	50	50	50	50
	Concrete mass [kg/m²]	77.3	103.9	147.4	200.5	224.7	280.3	340.6	415.6
	Steel mass [kg/m²]	1.7	3.0	4.5	6.4	8.3	10.8	13.5	16.6
	Glass-fibre mass [kg/m²]	1.1	1.5	2.1	3.0	3.5	4.4	5.4	6.6
	Rubble fill mass [kg/m²]	113.5	169.9	213.1	273.3	322.3	371.0	413.7	450.2
	Maximum depth [mm]	432	643	861	1083	1293	1516	1741	1972

RC = reinforced concrete
PT = post-tensioned
TRC = textile-reinforced concrete

These material quantities were converted to total embodied carbon using factors for material production only. These are detailed in a previous publication [11]. The variation of embodied carbon with span for each floor system is shown in Figure 5.

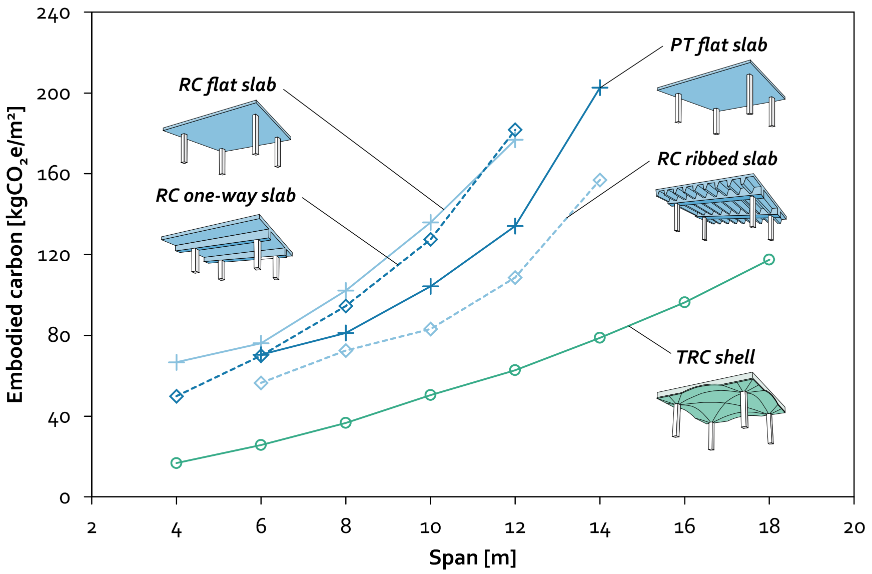


Figure 6 – Comparison of material embodied carbon between common concrete floor systems and thin TRC shells.

The traditional floor systems show a reduction in embodied carbon with increasing construction complexity, either through geometry (beams and ribs) or the addition of prestressing tendons. This implies a trade-off between construction cost and material efficiency. In contrast, the thin-shell floor system achieves significantly lower carbon despite its geometric and construction simplicity. This demonstrates the inherent efficiency of curved shell structures. The thin-shell system can also be used at much longer spans without a significant carbon cost. This is because the traditional systems are loaded in bending under an increasingly large proportion of their own self-weight, whereas the thin-shell system can accommodate this easily though efficient membrane action.

However, the efficiency advantage of the thin shell system comes at the cost of an increased total structural depth. As highlighted in Table 1, post-tensioned slabs have the lowest structural depth whilst the TRC shells have the highest. This is important for high rise buildings, where a minimal structural floor depth can increase the number of storeys possible within a permissive building height. However, whilst the maximum depth of the shells is large, the average depth is actually smaller than an equivalent slab, meaning that the headroom is, on average, greater. There is also scope to incorporate building services (lighting, ventilation, etc.) within the structural depth, which is not possible with traditional slabs and beams. The practicalities of this, and the effect of variable ceiling height on the user perception of indoor space, require further investigation.

Conclusions and outlook

This article has highlighted the significant impact the construction of buildings has on global carbon emissions, and the opportunity to reduce this through innovation in structural design of floor systems. Although successful modern buildings must be simple and cheap to produce, we can find inspiration from past designs where sparing use of materials was a necessity.

A system of precast textile-reinforced shells with a non-structural fill and steel ties is proposed, which harnesses the efficiency of membrane action. Through design optimisation, physical prototyping, and the development of a safe design methodology, it has been shown that this vaulted system drastically reduces material consumption and embodied carbon compared to typical concrete floors which act in bending, and are correspondingly highly cracked and require large quantities of steel reinforcement.

This project shows that innovative structural design has a considerable potential to reduce carbon emissions, although this requires new ways of thinking about how buildings are designed and constructed.

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