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Minimising embodied carbon in reinforced concrete flat slabs through parametric design

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ABSTRACT

Minimising carbon emissions from the building construction industry is of paramount importance in the present context due to the rising concerns of climate change. This paper explores the potential of minimising embodied carbon in reinforced concrete flat slabs by parametrically varying the slab thickness, grade of concrete, column spacing, column size, and reinforcement details. A parametric design algorithm was developed to generate a range of one storey structural frames with flat slabs and to calculate their 'cradle-to-gate' embodied carbon per unit floor area while identifying the viable design space and relevant limiting criteria. Also, a parametric finite element model is parallelly developed to estimate non-linear long-term deflection and to investigate the possibility of further reducing embodied carbon by scrutinising the deflection related design limits. The effect on the optimum designs by the adopted carbon coefficients is also quantified. The flat slab design with minimum embodied carbon for a given design load and column spacing corresponds to the minimum allowable thickness, largely insensitive to adopted carbon coefficients. Relaxing the deflection limit can reduce embodied carbon but only by around 20% of the required percentage increase in the deflection. The possibility of reducing embodied carbon by providing more reinforcement to further reduce slab depths allowed by the deflection criteria is sensitive to the adopted carbon coefficients. Minimising embodied carbon in flat slabs require optimising column spacing, using lower grades of concrete, and minimising slab depth based on deflection checks.

1. Introduction

Reinforced concrete is widely used in the construction industry despite its concerns regarding environmental sustainability. Cement production alone is responsible for around 6% of global carbon emissions due to human activities [1]. Therefore, minimising the environmental impact from concrete buildings is crucial in the present context due to the climate emergency. Reinforced concrete flat slabs are popular as a floor system due to their simple arrangement without beams which leads to a flat soffit with presumed easy and fast construction [2,3]. Embodied carbon can be used to quantify the environmental impacts of construction activities as the amount of greenhouse gas emitted due to raw material extraction, manufacturing, transportation, construction process, repair and maintenance, and end of life activities [4–6]. Hence, this paper explores the potential of reducing embodied carbon in reinforced concrete flat slabs through parametric design.

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For a given column grid and a set of design loads, there can be several viable flat slab designs with different slab depths and grades of concrete. Such discrete designs may have different quantities of steel and concrete with different carbon intensities. Scanning such a design space can potentially identify the designs with minimum embodied carbon for given design criteria. Furthermore, column spacing and column sizes can have a direct impact on the overall embodied carbon of flat slab designs due to the different flexural and shear stresses imposed on the slab, and column design itself. Therefore, this study investigates the potential of reducing the embodied carbon of flat slab designs by parametrically varying slab thickness, grade of concrete, column spacing, column size, and reinforcement design.

Parametric design of slab thickness essentially deviates from conventional span-to-depth ratios for deflection control. Hence, the parametric optimisation in this study is coupled with a parametric finite element model to estimate the long-term nonlinear deflection of flat slabs. The model is used to explore the possibility of minimising embodied carbon of flat slabs by pushing the boundaries of conventional span-to-depth ratios and conventional deflection benchmarks.

The sustainability of construction activities can be studied by quantifying the environmental impact into different stages of the life cycle, as standardised by BS EN 15978 [7]. As per the standard, the life cycle stages A1 to A3 known as 'cradle-to-gate' represent the Product stage which includes raw material supply, transportation of materials, and manufacturing. London Energy Transformation Initiative [8] highlights that the cradle-to-gate embodied carbon can be up to 50% of whole life carbon, while the construction stage contributes to 5%. Sansom and Pope [9], Wen et al. [10] and Gan et al. [11] also studied life cycle embodied carbon in several cases and concluded that the contribution from transportation and construction activities have a contribution within 1%–15% from. The scope of this study is limited to parametric optimisation of reinforced concrete flat slabs, having the construction methods the same for all the solutions. Therefore, 'cradle-to-gate' embodied carbon is a reasonable performance indicator in this study.

Several researchers have attempted to minimise embodied carbon in reinforced concrete flat slabs. Due to the similarity of the research methodology, previous studies which optimised cost or embodied energy are also discussed in the literature review. Sahab et al. [12] minimised the cost of flat slabs in three levels by optimising the column layout, slab thickness, and reinforcement design, emphasising the importance of optimising the column layout for significant cost savings. They illustrated that increasing the reinforcement ratios to reduce thickness in designs that were governed by the deflection criteria can reduce overall cost. Goodchild et al. [2] developed a set of design charts for flat slabs and listed the slab depths which gives minimum cost for each span, based on a series of parametric designs. Controlling the deflections of their designs referring to Eurocode 2 [13] adjusted span-to-depth ratios, they also found that providing more reinforcement to further reduce the allowable slab thickness can reduce overall cost. Ferreiro-Cabello et al. [14] designed a set of flat slabs varying the thickness for three different column grids and highlighted the importance of reducing spans in reducing embodied carbon. Furthermore, they illustrated that designs with minimum embodied carbon approached the minimum feasible slab thickness, having a marginal potential to trade-off between slab depth and amount of reinforcement. Eleftheriadis et al. [15] also developed a BIM-based genetic algorithm to optimise flat slabs which varied the size and reinforcement of slabs and columns, along with the column layout. They also concluded that the designs with the least embodied carbon approached shorter column spacings and thinner slabs. Again, they observed that increasing the slab thickness to reduce reinforcement ratios could reduce overall embodied carbon. Trinh et al. [16] optimised flat slabs considering column spacing, grade of concrete, slab thickness, and reinforcement details as variables and observed that most sustainable designs converged towards thinner slabs and denser column grids. They demonstrated that increasing the grade of concrete could not reduce overall embodied energy despite the possibility of reducing the amount of concrete. Therefore, it is worthwhile to explore the potential of reducing embodied carbon of flat slabs through parametric design varying slab thickness, reinforcement ratios, column layout, column size, and grade of concrete. Moreover, scrutinising the relationship between Ultimate Limit State and Serviceability Limit State with regards to embodied carbon has the potential to result in observations useful in design optimisation.

The guidelines by Brooker [17] and IStructE [18] for Eurocode 2 (BS EN 1992-1-1) [13] suggest beginning the design process of flat slabs based on recommended span-to-depth ratios. Also, Eurocode 2 presents a set of equations to calculate limiting span-to-depth ratios based on the grade of concrete, provided reinforcement ratio, and stress level to omit calculating deflections. Peiretti et al. [19] conducted a series of parametric analyses for ranges of load histories, additional reinforcements, environmental conditions, and grades of concrete to support the development of limiting span-to-depth ratios in Eurocode 2. However, on the one hand, Stewart [20] conducted a probabilistic study and warned that the conventional span-to-depth ratios produce a significant risk of exceeding the limiting deflection. Vollum [21] also alerted that the span-to-depth ratios in Eurocode 2 can underestimate the long-term deflection for different patterns of stress levels and load histories. On the other hand, different standards suggest different levels of limiting deflection, even in cases where deflections are to be estimated. The Concrete Centre [22] listed limiting deflection prescribed by several standards which varied from span/500 to span/250 while some specifying 20 mm. Orr et al. [23] surveyed the opinion of engineering practitioners and revealed that 47% of them were comfortable with allowing deflection limits to be exceeded for a few minutes per week or more. On a different note, Brooker [24] noted that estimated deflections of concrete structures are expected to have a variation within $+15\%$ to -30% from the actual deflections even if the method of calculation is the most sophisticated. Therefore, it is beneficial to explore the viability of pushing the boundaries of limiting span-to-depth ratios and limiting deflections in the context of minimising embodied carbon.

The 'cradle-to-gate' embodied carbon of the structural frame of flat slabs depends on the amount of concrete and reinforcing steel in the design. Databases such as Inventory of Carbon and Energy by Circular Ecology [25] recommend embodied carbon coefficients for construction materials to facilitate calculating 'cradle-to-gate' embodied carbon. Since the shares of embodied carbon from concrete and steel depend on the adopted carbon coefficients, designs with minimum embodied carbon for given design criteria also depend on the coefficients. However, Hammond and Jones [5] and De Wolf et al. [26] explained the inherently uncertain nature of embodied carbon. Dixit et al. [27] and Pomponi and Moncaster [28] described how the values can vary depending on the method of calculation, manufacturing technology, data source, temporal representation, geographical location, and project-specific aspects. Also, Oh et al. [29] reported that the ratio of carbon coefficients of concrete to steel from several sources ranged from 0.0208 to 0.4545, and illustrated how the details of the optimum design vary accordingly. Marsh et al. [30] modelled the uncertainty of embodied carbon estimations and observed that the values can vary from 50% to 140% of the original results for the extremes of their Monte-Carlo simulation. Therefore, it is essential to connect a sensitivity analysis to the optimisation procedure to observe the dependability of optimum design on the adopted carbon coefficients.

2. Methodology

Flat slabs of 3 × 3 bays are designed by parametrically varying slab thickness, grade of concrete, column spacing, column size and the ratio of Asprov/Asreq (Asprov – Provided amount of reinforcement, Asreq -Required amount of reinforcement for ULS design) to study the variation of embodied carbon per unit floor area, assuming the conditions for an office building. A MATLAB [31] code was developed for the parametric design of flat slabs. Simultaneously, a parametric Finite Element Model was developed using SOFiSTiK FEA and Rhino – Grasshopper [32,33], to estimate non-linear long-term deflections (Fig. 1).

2.1. *Parametric design of flat slabs*

Flat slabs were designed according to Eurocode 2 (BS EN 1992-1-1) [13], referring to guidelines by The Concrete Centre [34] and IStructE [18]. The following parameters were input in the design programme.

- Column spacing – square-shaped grids are considered in this scope (4 m–10 m with 0.25 m intervals)
- Slab thickness (across the whole slab - 200 mm–400 mm with 5 mm intervals)
- Grade of concrete (C20/25, C30/37, and C40/50)
- Column width – square columns are considered (300 mm, 450 mm, and 600 mm)
- Increase in provided reinforcement (Asprov/Asreq - 1.00, 1.10, 1.20 and 1.30)
- Design loads (superimposed dead load of 1.5 kN/m^2, imposed load of 2.5 kN/m^2, and perimeter loading of 10 kN/m for cladding)
- Floor to floor height (3.5 m)

The design programme output the following.

- Flexural reinforcement design as detailed four layers (T1, T2, B1 and B2)
- Shear link design for three columns (internal, corner and side)
- Column reinforcement design for three columns (internal, corner and side)
- Checks whether input criteria are feasible in terms of
  - o No compression reinforcement needed – ductile failure (unfeasible if fails)
  - o The maximum area of flexural reinforcement (unfeasible if fails)
  - o Shear failure at column perimeter (unfeasible if fails)
  - o Column design unfeasible with input column size (unfeasible if fails)
  - o Limit Span/Effective Depth ratio for deflection according to Eurocode 2 using Equation (1) (only checks the status)

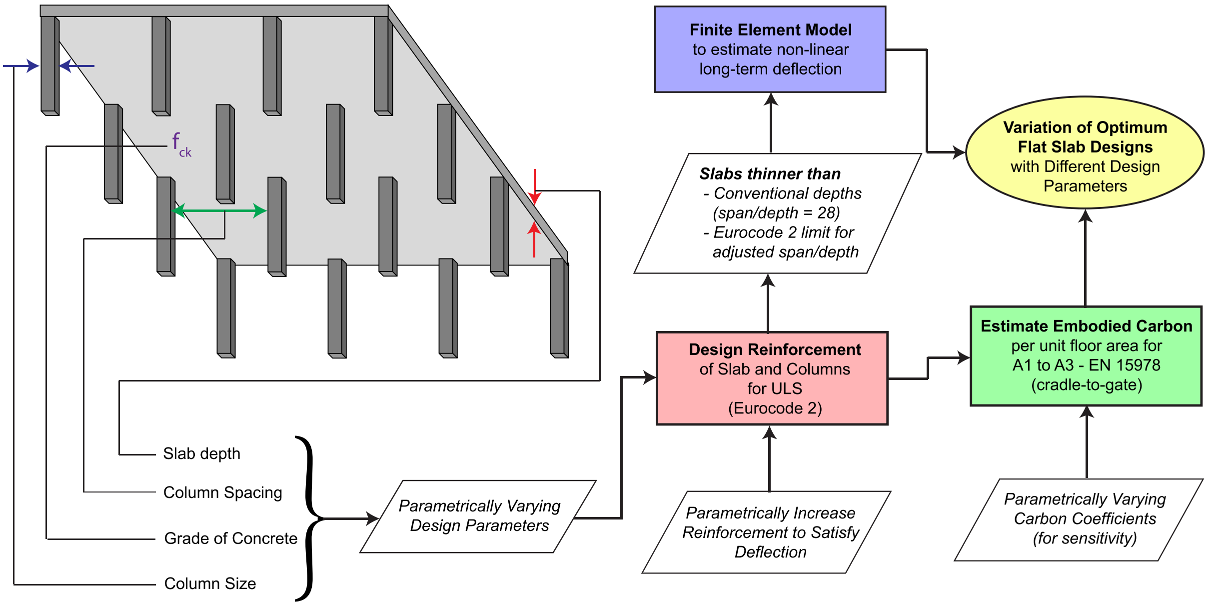


Fig. 1. Approach to parametrically optimise the design of flat slabs.

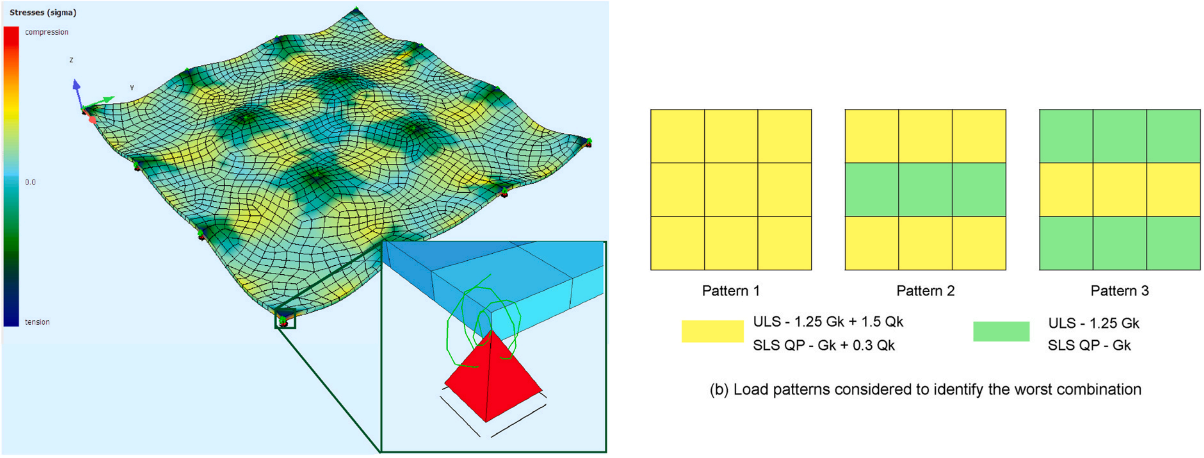
The following equations (Equation (1)) in Eurocode 2 are used in this study to compare with the results of the finite element model. These equations calculate adjusted Span/Effective Depth ratios to justify omitting calculations for deflection control.

$$\frac{l}{d}=K\left[11+1.5\sqrt{f_{ck}}\ \frac{\rho_0}{\rho}+3.2\sqrt{f_{ck}}\left(\frac{\rho_0}{\rho}-1\right)^{3/2}\right]\ if\rho\leq\rho_0 \tag{Equation 1a}$$

$$\frac{l}{d}=K\left[11+1.5\sqrt{f_{ck}}\ \frac{\rho_0}{\rho-\rho'}+\frac{1}{12}\sqrt{f_{ck}}\sqrt{\frac{\rho'}{\rho}}\right]if\rho>\rho_0 \tag{Equation 1b}$$

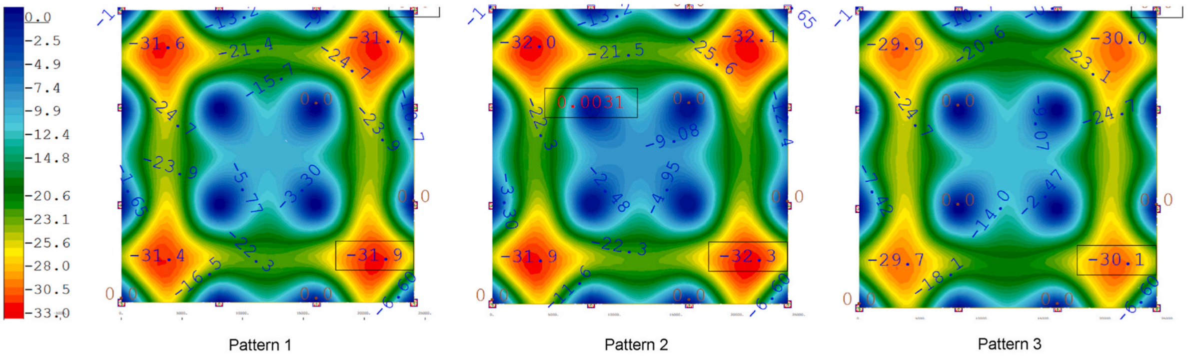
l/d – limit span/effective depth
K - factor to take int account the different structural systems
ρ_0 – reference reinforcement ratio = $10^{-3}\sqrt{f_{ck}}$
ρ - required tension reinforcement ratio at mid-span to resist the moment due to the design loads
ρ’ – required compression reinforcement ratio at mid-span to resist the moment due to the design loads
f_{ck} - Characteristic strength of concrete in MPa
* Multiply l/d by Asprov/Asreq
* Multiply l/d by 8.5/leff for leff>8.5 where leff – effective span (in meters)

The characteristic yield strength of reinforcement is taken as 500 MPa. Durability concerns related to an office building environment require C30/37 or higher grade of concrete according to Eurocode 2. However, this study explores whether lower grades of concrete can reduce embodied carbon than the conventional choices. Further research may be required if the use of C20/25 is proven to reduce embodied carbon of flat slabs. The minimum thickness of flat slabs considered in the design space is limited to 200 mm assuming a fire rating of R90. Imposed load of 2.5 kN/m^2 and superimposed dead load of 1.5 kN/m^2 were considered. Also, 10 kN/m was considered in the perimeter for cladding. Reinforcement cover is taken as 30 mm (assuming 20 mm diameter reinforcement +10



(a) Finite Element Model of the flat slab (support conditions enlarged)

(b) Load patterns considered to identify the worst combination



(c) Non-linear long term deflection plots of 250 mm slab with C30/37 on 8 mx 8 m column grid for different load patterns under quasi-permanent load

Fig. 2. Finite element model of flat slab for estimating non-linear long-term deflection.

mm for deviations).

The moments were calculated considering the slab strips as beams and apportioning the moments to column and middle strips using the tables in design guides by The Concrete Centre. Detailing requirements of reinforcement at columns were also considered. A moment redistribution of 15% was adopted. The reinforcement areas were considered as a continuous variable in mm^2/m, while the provided amount of reinforcement was equal to the required reinforcement. The designs were limited to singly reinforced slabs with ensured ductile behaviour by limiting $K = M/bd^2f_c$ to 0.168. The designs which required reinforcement to be more than 4% of the area were considered unfeasible, while at least minimum reinforcement was provided everywhere, following Eurocode 2 recommendations. Curtailing of flexural reinforcement was approximated referring to simplified guidelines by The Concrete Centre [34], and reduced as a percentage from the amount of steel when calculating embodied carbon. The amount of steel after curtailing at the top layers was approximated to have 100% of the designed reinforcement within 0.15 of the span, and 50% within 0.3 of the span from the face of the support, and at least the minimum reinforcement everywhere. The bottom layers were not curtailed.

Three types of supports were designed for shear links, internal, corner and side columns. Shear forces were also calculated using the same tables used in the flexural analysis. Amounts of flexural reinforcement calculated in the previous steps were used in estimating the shear capacity of slabs without shear reinforcement. The designs were considered unfeasible when the shear stress in the column perimeter exceeds the shear capacity of the slab without links ($V_{Rd,max}$). Punching shear links were also separately designed for internal, corner and side columns using the recommended β values by NA to BS EN 1992-1-1 [35] to account for the unbalanced moment transfer due to eccentricity. The ratio of v_{ed}/v_{rdc} for punching shear performance was noted in all the designs without limiting to a specific number. While Eurocode 2 [13] limits the value to 1.5, NA to BS EN 1992-1-1 [35] extends the limit to 2.0, and The Concrete Centre has increased the limit to 3.0 [2]. The values in this study were later observed to be under 3.0 for all the design scenarios. While the size of the link was treated as a continuous variable, the minimum size was set to be H8. The number of shear links was calculated by providing the links for the required area, adhering to the spacing limitations.

Since the slab designs depend on span and the size of the columns, considering the carbon contribution from columns is of vital importance. In practice, determining the column sizes depends on the number of stories and the column grid. Taller office buildings will have larger columns marking shear capacity for the slab less critical. Therefore, the design loads of the columns were calculated for three stories, a reasonable minimum to study the effect of the column size for the design of flat slabs. Column height was taken as 3.5 m. Three types of columns were designed as in the shear design. The reinforcement design was based on interaction charts given in the guides by The Concrete Centre. The chart for rectangular columns with $d_2/h = 0.15$ (d_2 -distance to the centroid of the bars in half section, h-column width) was considered on average, for a rough estimation. Biaxial bending was also considered by doubling the design moment, assuming worst-case symmetry, multiplying the design moment by a factor of 2.

2.2. Parametric finite element model for deflection

Parametric geometry of the at slab was created in Rhino-Grasshopper [32,33] interface and input to SOFiSTiK FEA [36] (Fig. 2). The following parameters were kept as variable input.

- Column spacing
- Slab thickness
- Column size
- Grade of concrete
- Creep and shrinkage coefficients
- Average reinforcement density of top layer and maximum reinforcement density of the bottom layer (as per MATLAB design programme)

The slab was modelled using quadrilateral shell elements (QUAD in SOFiSTiK) (Fig. 2). The columns were not directly modelled, but the effects were introduced using pin supports and two orthogonal rotational springs with constants 2x3EI/L at each column. Three different load patterns (fully loaded, and two alternate bay loadings) for imposed loads were analysed for each design to understand the worst combination of loads, considering the symmetry. Quasi-permanent loads for deflection estimation were calculated using $\psi_2 = 0.3$. The built-in design tool in SOFiSTiK FEA is a bit different from the output of the MATLAB design programme since the highly detailed design matching moment contours is based on linear analysis without moment redistribution. Thus, the reinforcement for the nonlinear analysis was approximated to the design from MATLAB by limiting the minimum values of reinforcement at the top layer as the average density and the bottom layer as the maximum. Creep and shrinkage were considered in the FEA programme to represent long term effects, referring to Eurocode 2. The coefficients were varied with the grade of concrete and slab thickness, considering relative humidity of 50% and age at loading 28 days.

The objective of estimating deflection is to explore the relationship between embodied carbon and the serviceability performance of the flat slabs. This study investigates whether it is possible to further reduce embodied carbon of flat slabs by optimising the design for the target limit deflection and even relaxing the limiting deflection. If the possible carbon reductions are encouraging, further research may be required to justify relaxing conventional benchmarks for limiting deflection, in a context in which the state-of-the-art shape optimised curved structural members are encouraged. Due to the expected variations and uncertainties as discussed in the literature review, the estimated deflections in this study will be approximations to facilitate the discussion.

2.3. Estimating embodied carbon

Embodied carbon of flat slabs was estimated for ‘cradle-to-gate’ i.e. A1-A3 according to BS EN 15978 [7]. Following values were adopted in this study, referring to Inventory of Carbon and Energy by Circular Ecology.

- Reinforcing steel – 1.20 $kgCO_2e/kg$
- Concrete C20/25–0.112 $kgCO_2e/kg$
- Concrete C30/37–0.132 $kgCO_2e/kg$
- Concrete C40/50–0.159 $kgCO_2e/kg$

Due to the uncertain and tentative nature of carbon coefficients, the effect on the suggested optimum designs by the adopted coefficients was also studied. As an indicator of the sensitivity of the optimum designs to carbon coefficients, the required change of the ratio of carbon coefficients of steel/concrete to change the optimum design was calculated (Equations (2) and (3)).

$$Required\ S\Big/C = \frac{V2Concrete - V1\ Concrete}{V1Steel - V2Steel} \times 100(\%) \qquad \text{(Equation 2)}$$

$$Required\ Variation\ in\ S\Big/C = \frac{Required\ S/C - Original\ S/C}{Original\ S/C} \times 100(\%) \qquad \text{(Equation 3)}$$

- S/C – Carbon Coefficient of Steel/Carbon Coefficient of Concrete
- V2Concrete – Volume of Concrete in Design 2
- V1Concrete – Volume of Concrete in Design 1
- V2Steel – Volume of Steel in Design 2

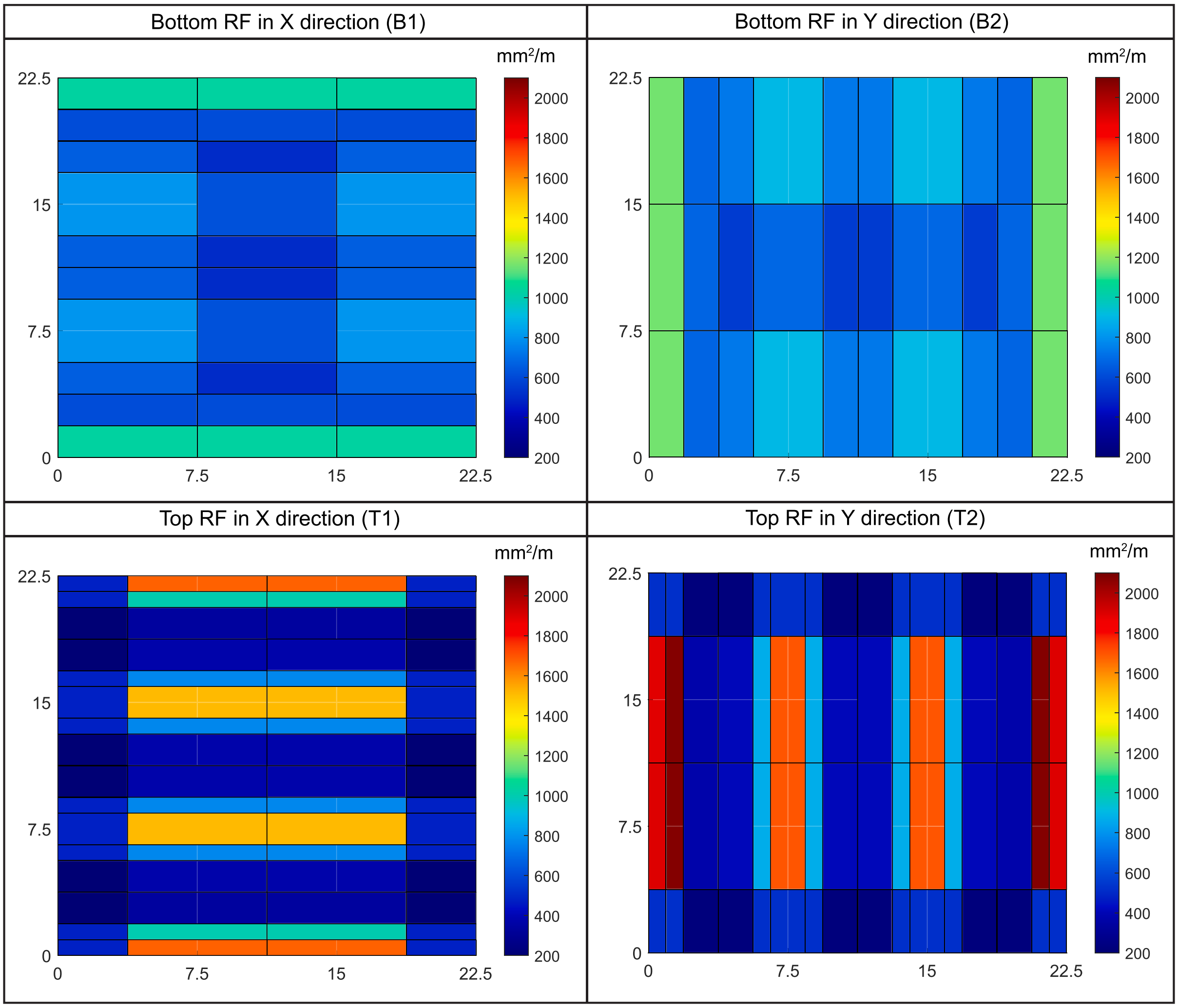


Fig. 3. Four reinforcement layers designed for 250 mm thick slab with C30/37 with 7.5 m × 7.5 m column grid with 600 mm square columns (curtailing was considered separately in embodied carbon calculations).

- V1Steel – Volume of Steel in Design 1
- Design 1 – Slab design with minimum embodied carbon with original carbon coefficients
- Design 2 – Slab design with potentially minimum embodied carbon if S/C is changed (Slab design 5 mm thicker than Design 1 for investigating the effect of slab depth, slab design with Asprov/Asreq >1 for investigating the effect of increasing reinforcement)

3. Results

Fig. 3 shows the output reinforcement maps for four layers of reinforcement for an example case.

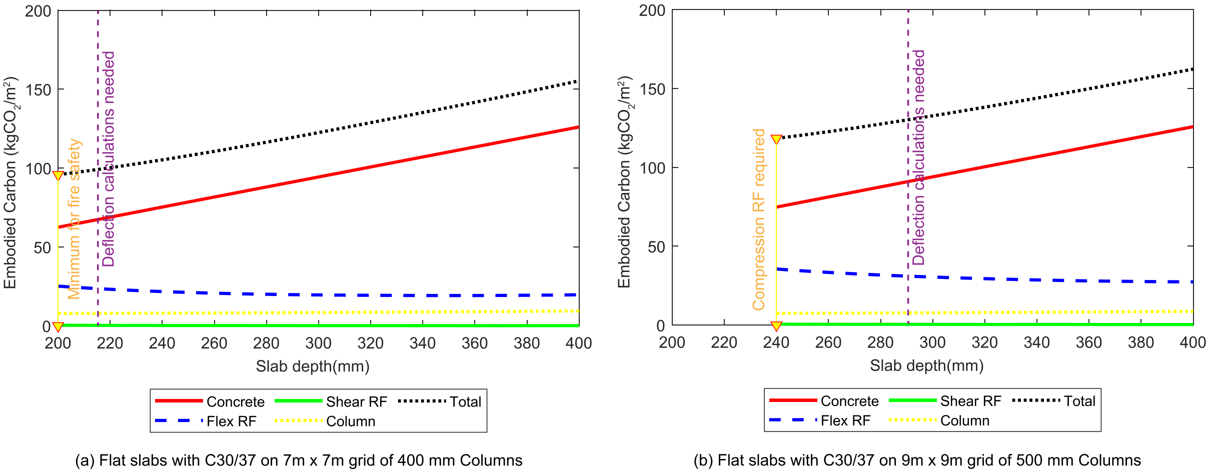
Fig. 4 describes the variation of embodied carbon per unit floor area with slab thickness, for two scenarios. While the share of embodied carbon from concrete, flexural reinforcement, shear reinforcement and columns are separately shown, the factors which limit the design space are also noted. Different scenarios had different criteria limiting the design space, while some of the designs needed verification for satisfying deflection requirements.

Expanding the scope of Figs. 4 and 5 presents the variation of embodied carbon per unit floor area for a range of scenarios. While the two axes represent slab depth and column spacing, scenarios with three different column sizes and three different concrete grades are analysed. Furthermore, the factors which limit the design space are also plotted. The design space was limited for ULS conditions, considering the requirement of compressive reinforcement, shear failure at column perimeter, and failure of column design. The designs corresponding to Span/Depththe adjusted Span/Effective Depth ratios according to Eurocode 2 for deflection control are marked on the viable design space. As conventional benchmarks, the designs for Span/Depth ratio of 28 are also marked on the same plot, referring to the design guidelines by Brooker et al. [17]. The designs which satisfy ULS criteria but need verifications for SLS criteria were noted to be separately explored via the parametric finite element model.

Fig. 6 presents the variations of embodied carbon in the design space when the size of the columns is varied proportional to the column spacing. The column sizes are approximated based on the required area for the load from three stories, assuming the average design stress of 17 N/mm^2 for C30/37 columns with 1% reinforcement, based on IStructE preliminary design guidelines [18]. Based on the rough estimate, column sizes were adopted as 6% of the column spacing in this scope, limiting to a minimum of 300 mm considering fire performance. Fig. 6(a) shows the variation of embodied carbon per unit area for C30/37 flat slabs for a range of slab thicknesses and column spacings when column size is 6% of the span. Fig. 6(b) breaks down the composition of the embodied carbon of the optimum designs for each column spacings, extracting from Fig. 6(a). The shares of the embodied carbon of the optimum design for ULS criteria, the design recommended for Eurocode 2 adjusted Span/Effective Depth ratio, and the slab with Span/Depth = 28 are shown in the same plot. Fig. 6(c) and (d) illustrate the variation of optimum depths and optimum embodied carbon with column spacing for three grades of concrete. The rest of the results in this paper were generated assuming column sizes as 6% of the span, with a minimum of 300 mm.

Following Figs. 5 and 6, the designs which satisfy ULS criteria but need verification for SLS were input to the finite element model to estimate their non-linear long-term deflections to be compared with conventional benchmarks. Fig. 7 illustrates the variation of deflection with slab thickness for four different column grids. Deflection resulting from linear, non-linear short term, and non-linear with creep and shrinkage analyses for three load patterns considered are plotted for each case. P1, P2 and P3 in Fig. 7 correspond to the three load patterns analysed, as illustrated in Fig. 2. Deflections were estimated for the slab thicknesses from the minimum possible for ULS to Span/Depth = 28. Also, deflection corresponding to span/250 is also marked as a conventional benchmark for limiting deflection. Furthermore, slab depths corresponding to the adjusted Span/Effective Depth ratios for each span according to Eurocode 2 (from Equation (1)) are also marked on the same plots as ‘EC2 limit’.

Repeating Fig. 7 for other concrete grades and extracting the maximum values, Fig. 8 presents the variation of long-term non-linear deflections of flat slabs along with the ULS minimum, span/28, conventional benchmark, and Eurocode 2 adjusted Span/Effective



(a) Flat slabs with C30/37 on 7m x 7m grid of 400 mm Columns

(b) Flat slabs with C30/37 on 9m x 9m grid of 500 mm Columns

Fig. 4. Variation of the embodied carbon of flat slabs per unit area with slab thickness for two example cases.

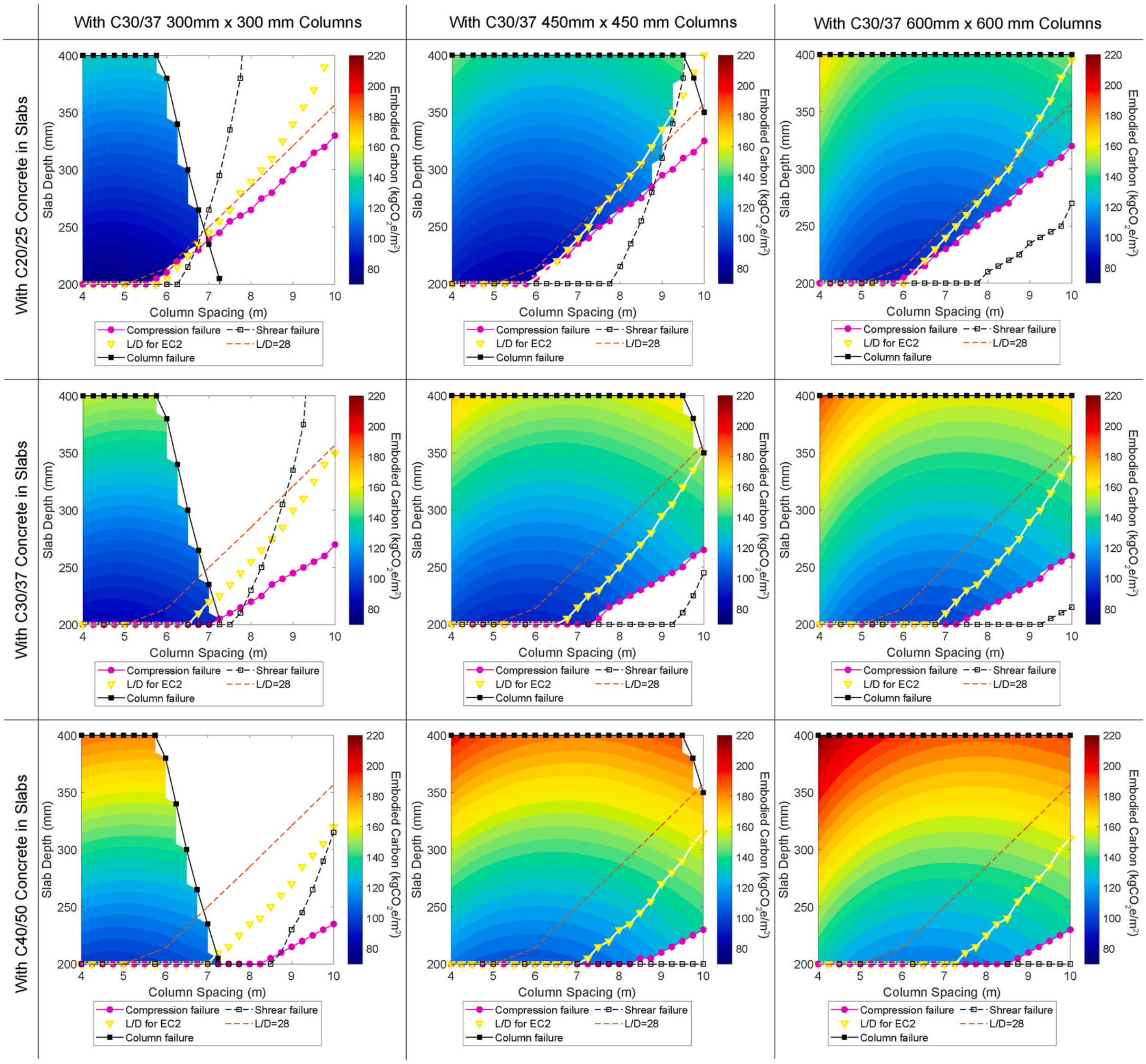


Fig. 5. Variation of the embodied carbon of flat slabs per unit area with slab thickness and column spacing for different concrete grades and column sizes.

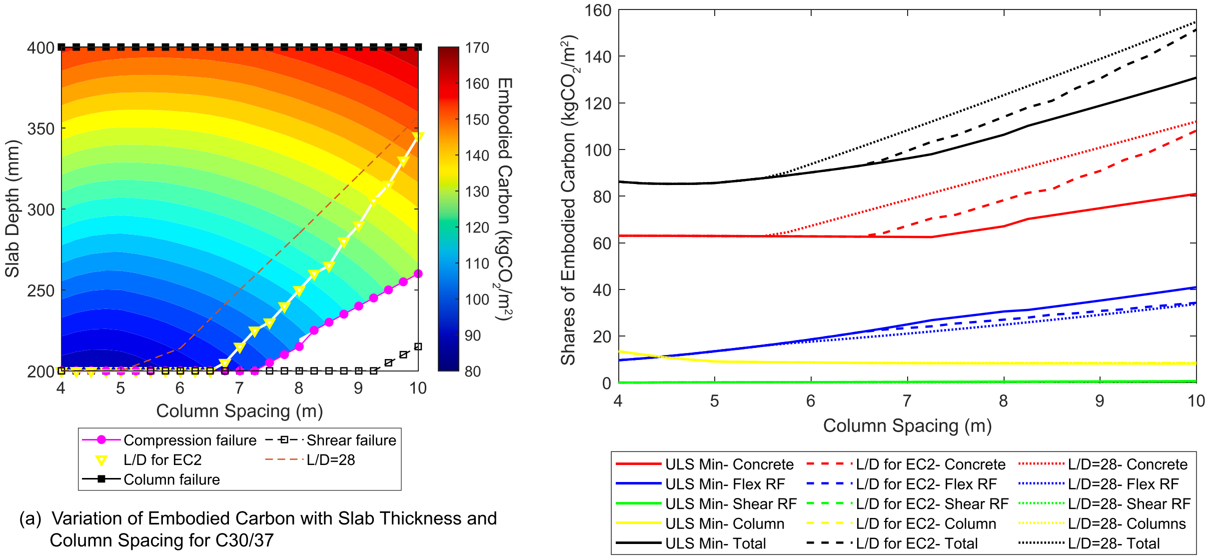
Depth.

Fig. 9 shows the variation of possible savings of embodied carbon with estimated long-term deflection. The savings were calculated for each design compared to the design with C30/37 for Span/Depth = 28. The positive values for savings correspond to designs with less embodied carbon than the benchmark, while negative values correspond to designs with higher embodied carbon. Embodied carbon for a particular deflection value in Fig. 9 has similar ULS and SLS performance because all the designs satisfy ULS criteria.

Fig. 10 reports the percentage difference in embodied carbon of the optimum designs for each column spacing and grade of concrete from the design with minimum embodied carbon in the entire set. Each point corresponds to the design with minimum embodied carbon for the given span and grade of concrete while satisfying deflection requirement based on the adjusted Span/Effective Depth ratio according to Eurocode 2.

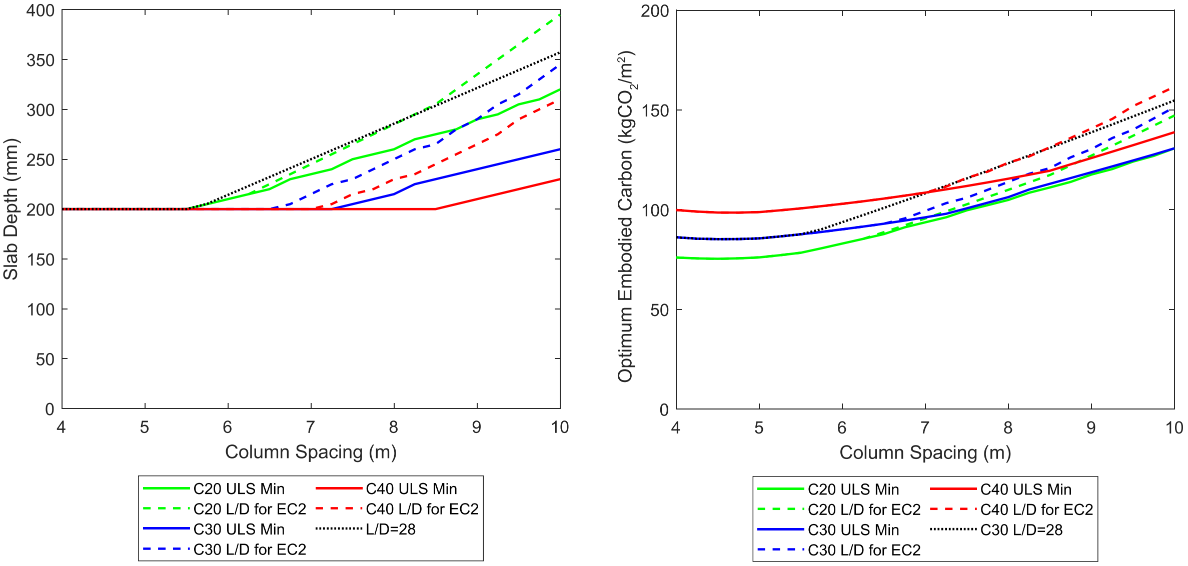
Fig. 11 shows the variation of optimum embodied carbon and the corresponding slab depth for C30/37 with different levels of increased reinforcement ratio for a range of column spacings.

Fig. 12 explores how the optimum designs of flat slabs with C30/37 depend on the carbon coefficients adopted. As illustrated in Fig. 5, the designs with minimum embodied carbon coincided with the minimum possible slab thickness in all the cases considered. However, if either the adopted carbon coefficient of steel is increased or that of concrete is decreased, the optimisation algorithm can suggest a thicker slab as the design with the lowest embodied carbon. Therefore, Fig. 12(a) shows the required increase in S/C (according to Equation (3)) to move the design with minimum embodied carbon away from the minimum possible thickness. As an example, the required increase in S/C for slabs spanning 7 m considering deflection criteria according to Eurocode is 267%. This means that the optimum slab thickness for 7 m spanning flat slabs will not coincide with the minimum allowable slab thickness if the adopted



(a) Variation of Embodied Carbon with Slab Thickness and Column Spacing for C30/37

(b) Variation of Shares of Embodied Carbon of the Optimum Design with Column Spacing



(c) Variation of Optimum Slab Depth with Minimum Embodied Carbon with Column Spacing

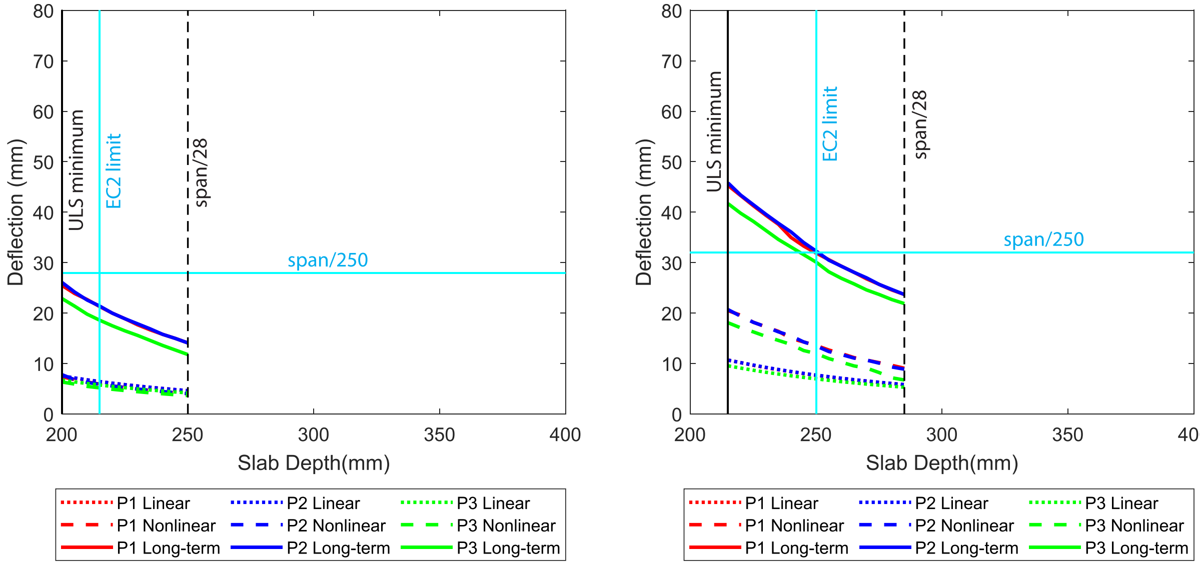
(d) Variation of Minimum Embodied Carbon vs Column Spacing for Different Grades of Concrete

Fig. 6. Variation of the embodied carbon, shares of embodied carbon and the optimum designs within through the design space.

carbon coefficient of steel is increased by 267% (or that of concrete reduced by 63% to have the same effect) compared to the values considered in this study. However, either the carbon coefficient of steel should decrease or that of concrete should increase to reduce overall embodied carbon by providing more reinforcement. Hence, Fig. 12(b) shows the required decrease in S/C for providing Asprov/Asreq >1 to be effective in reducing embodied carbon.

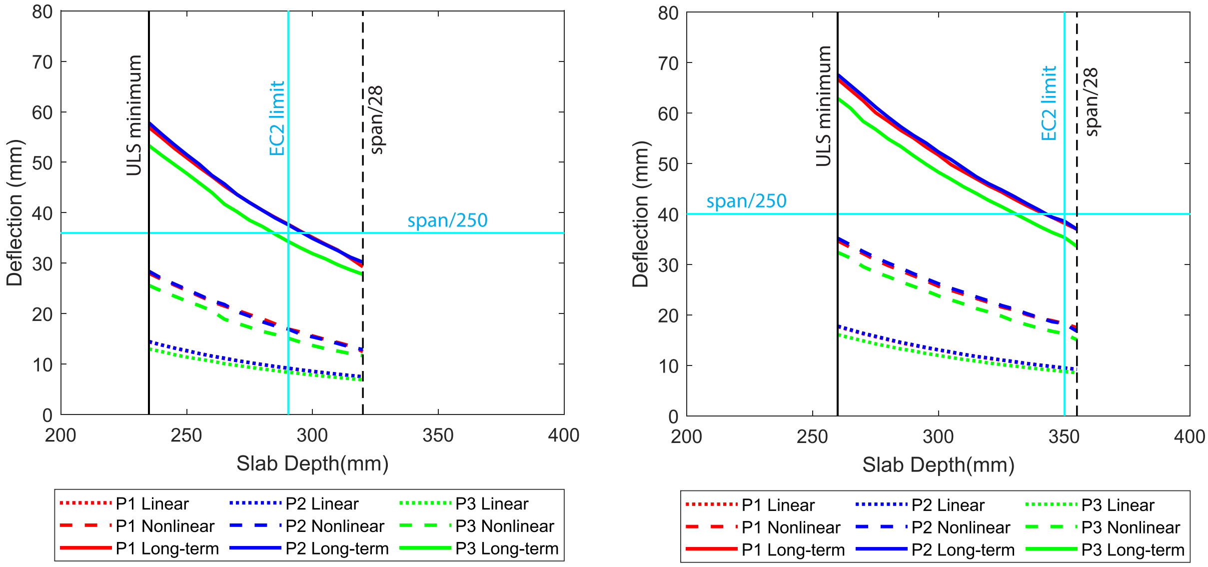
4. Discussion

This study explores the opportunities to minimise embodied carbon of reinforced concrete flat slabs by sweeping through the viable design space for a given set of design loads. The design slab thickness could be limited by fire safety, compression failure (instead of under-reinforced ductile failure), and deflection control. While the slab depths for denser column grids were governed by fire criterion, slabs with larger spans were mainly governed by the deflection demands according to Eurocode 2 adjusted Span/Effective Depth ratios. Only a few designs with C20/25 had designs governed by compression failure criterion instead of deflection benchmarks. Increasing the grade of concrete expanded the feasible design space by allowing thinner slabs to satisfy both deflection and ductile



(a) 7 m x 7 m Column Grid

(b) 8 m x 8 m Column Grid



(c) 9 m x 9 m Column Grid

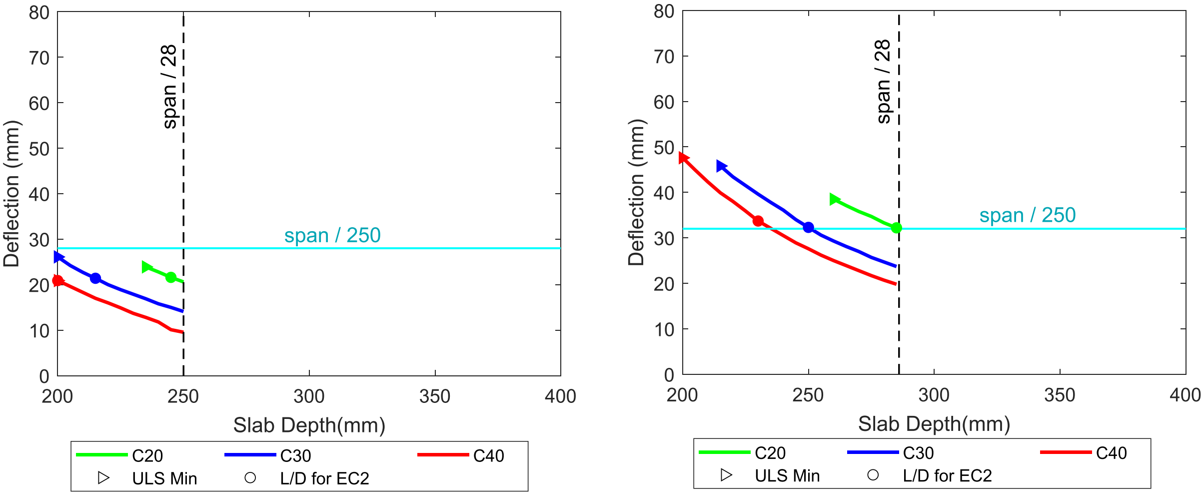
(d) 10 m x 10 m Column Grid

Fig. 7. Variation of deflection with slab depth for C30/37 for different column grids.

failure demands. In all the cases considered for different spans, grades of concrete, and column sizes, the optimum slab thickness converged to the design with minimum allowable thickness.

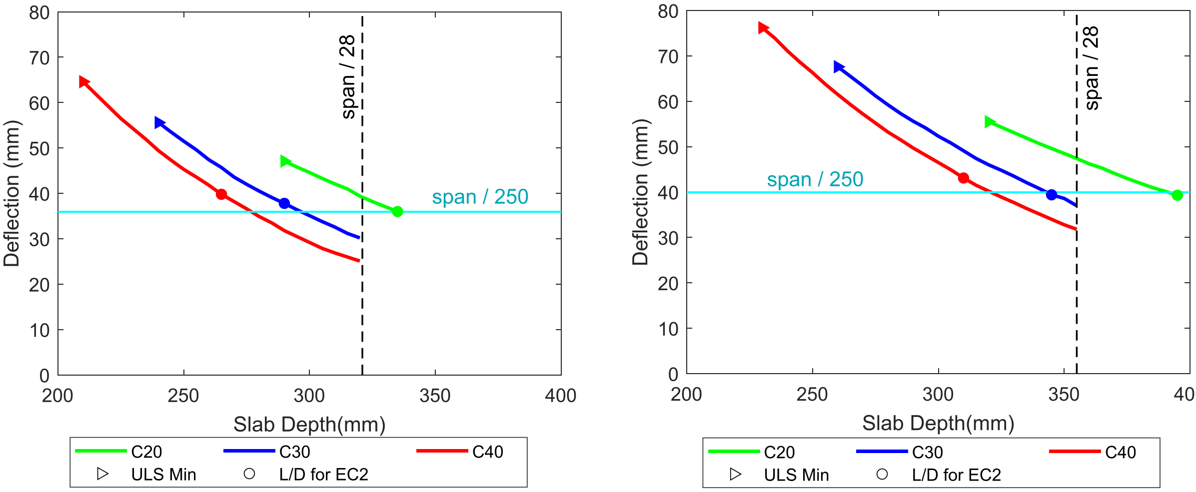
Reducing the column sizes limited the viable design space, not because of the shear failure of the slab at the perimeters but because the column design was unfeasible, even only with the load of three stories. Also, the share of embodied carbon from shear reinforcement was negligible compared to the total. However, the contour plots reveal that increasing the column sizes increased the embodied carbon per unit area while increasing the optimum column spacings. This highlights the importance of column sizes in the process of optimising flat slabs as a floor system, despite that the size of the columns was mainly governed by the column design itself, rather than the slab design. The optimum column spacing in this scope reached the minimum considered when the column sizes were varied proportionately.

Concrete contributed to a major share of the embodied carbon of the flat slabs. As the design slab depth increased for a given span and a grade of concrete, the share of embodied carbon increased while that of steel reduced at a lesser rate. For example, 220 mm flat slab design with C30/37 for 400 mm columns in a 7 m grid had a carbon intensity of 100 $kgCO_2/m^2$ where 69% was from concrete and 23% was from flexural steel. The overall embodied carbon increased to 122 $kgCO_2/m^2$ when the design depth was increased to 300 mm, where embodied carbon from concrete increased by 37% while that of steel dropped only by 15%. The variation of the shares of



(a) 7 m x 7 m Column Grid

(b) 8 m x 8 m Column Grid



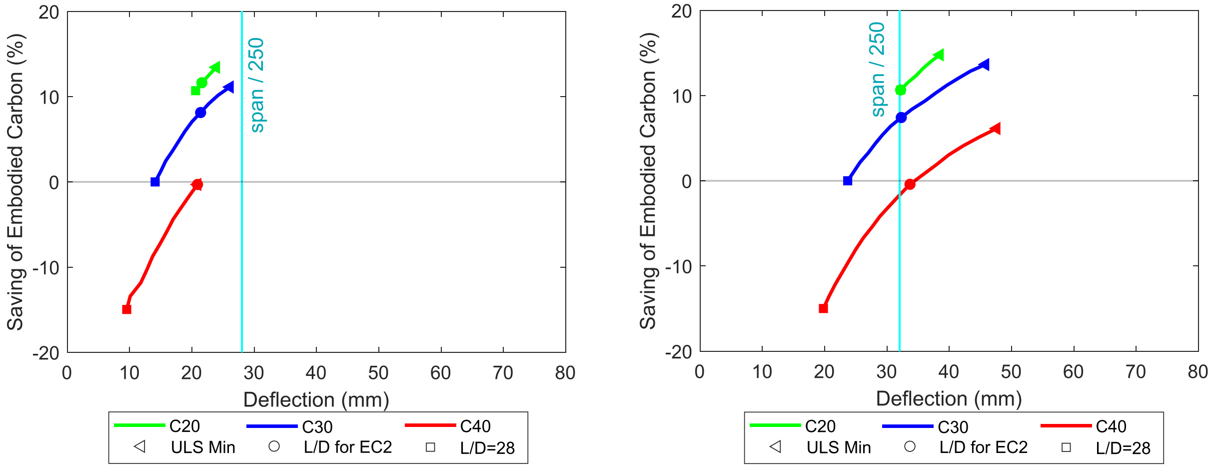
(c) 9 m x 9 m Column Grid

(a) 10 m x 10 m Column Grid

Fig. 8. Variation of estimated long-term deflections with slab depth for different spans.

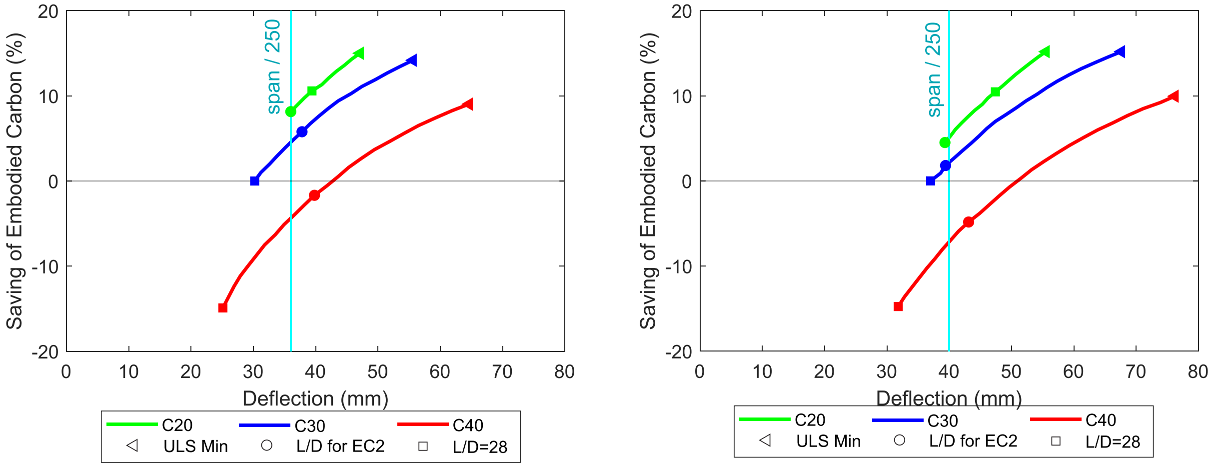
the embodied carbon of the optimum designs with the column spacing shows the effect of increased reinforcement ratios for higher spans. Even though the optimum designs for all the column spacings were pushed towards the minimum possible slab thicknesses, concrete was responsible for a major share of embodied carbon at around 70% on average.

The minimum allowable design depths of C30/37 slabs with column spacings more than 6.5 m were governed by deflection demands, rather than the Ultimate Limit State when the Eurocode 2 adjusted Span/Effective Depth ratios were adopted in deflection control in the flat slab designs. The depths suggested by Span/Depth = 28 were shown to be conservative for most cases except for slab designs with C20/25 for spans longer than 8.5 m, as expected. There was a range of slab depths with lower embodied carbon which satisfied the Ultimate Limit State but needed verification of deflection performance. The deflection estimations of the designs corresponding to limit Span/Effective Depth for Eurocode 2 from the parametric finite element model matched well with the conventional deflection limit of Span/250. Furthermore, the deflection plots reveal that the deflections were predominantly governed by the long-term effects which are associated with inherent uncertainties and project-specific conditions. Thus, relaxing the limiting deflection may be acceptable with further research if the resulting savings of embodied carbon is significant, referring to increasing interest on shape optimised structural members to minimise carbon emissions. However, the variation of embodied carbon showed a limited variation with the deflection. As an example, reducing the thickness from Span/Depth = 28 (285 mm) to Eurocode adjusted Span/Depth (250 mm) of the flat slab designs with C30/37 for 8 m column grid can reduce embodied carbon by 7.4% while approximately satisfying the deflection limit of span/250 = 32 mm. Allowing 13 mm more deflection than the conventional benchmark can further reduce embodied carbon only by 6.2% when the depth is reduced to 215 mm. Likewise, to reduce further 5% of the embodied carbon in the slab designs for 8 m, 9 m and 10 m column spacing with C30/37, the additional deflection allowed more than the benchmark has to be 29%, 27% and 23% respectively. Therefore, the trade-off between embodied carbon and estimated deflection is unfavourable in minimising embodied carbon of flat slabs. However, calculations for deflection checks even within conventional benchmarks can



(a) 7 m x 7 m Column Grid

(b) 8 m x 8 m Column Grid



(c) 9 m x 9 m Column Grid

(d) 10 m x 10 m Column Grid

Fig. 9. Variation of savings of embodied carbon with estimated long-term deflection compared to the design with C30/37 for Span/Depth = 28.

reduce embodied carbon in the slabs up to 8% by justifying the selection of lower depths than the depths suggested by conventional span-to-depth ratios.

Minimising slab thickness, changing the grade of concrete, and reducing the column spacing could reduce embodied carbon of the flat slab designs. The designs with C20/25 had lower embodied carbon than the designs with C30/37 and C40/50 for all the column spacings considered. The possible carbon savings by using C20/25 instead of C30/37 were up to 12%, but marginal for spans longer than around 7 m. Further research may be required to justify using C20/25 in flat slabs due to durability concerns. Even though the allowable slab depths could be reduced using C40/50 compared to C30/37, embodied carbon of optimum designs from C40/50 did not fall below C30/37 in any of the column spacings considered. This shows that adopting lower grades of concrete for thicker slabs can be effective in reducing embodied carbon rather than reducing slab thicknesses by using higher grades of concrete. Having the designs with minimum embodied carbon at 4 m–5 m columns spacings, around the minimum considered in this scope, embodied carbon always exponentially increased with the span. As an example, the carbon intensity per unit area of optimum slabs with C30/37 increased 76% from 86.2 $kgCO_2/m^2$ to 151.4 $kgCO_2/m^2$ when the span is increased from 4 m to 10 m. Reducing depth from Span/ Depth = 28 to adjusted Span/Effective Depth according to Eurocode 2 reduced embodied carbon up to around 8.6% for designs with C30/37. Therefore, column spacing is the most important parameter in minimising the carbon footprint of flat slabs, while minimising slab thickness than the conventional norms and adopting lower grades of concrete also can reduce embodied carbon.

Providing more reinforcement than the ULS flexural design can reduce deflections, allowing thinner slabs. The optimum slab thickness for a given span and a grade of concrete coincided with the minimum allowable thickness, where the limit is governed by deflection criteria for spans higher than 6.5 m. Even though increasing the provided reinforcement than the necessary amount for ULS reduced optimum slab depths for spans higher than 7 m, optimum embodied carbon did not reduce but increased instead. The reason is that the reduction in the share of embodied carbon by concrete is less than the increase in that of steel, keeping overall embodied carbon higher in the designs with Asprov/Asreq >1. Thus, providing more reinforcement to reduce allowable slab thickness did not

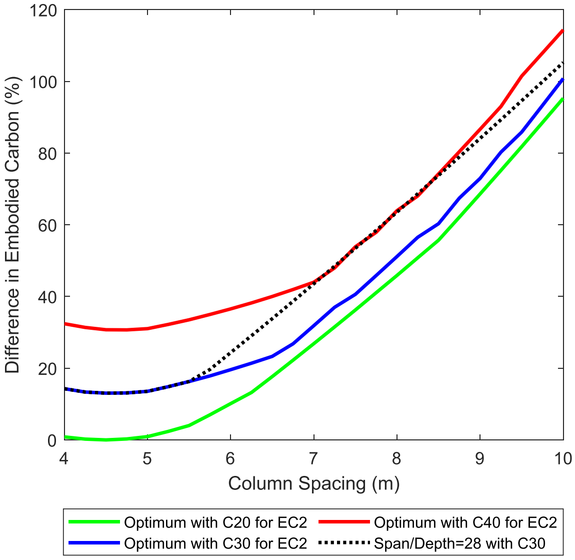
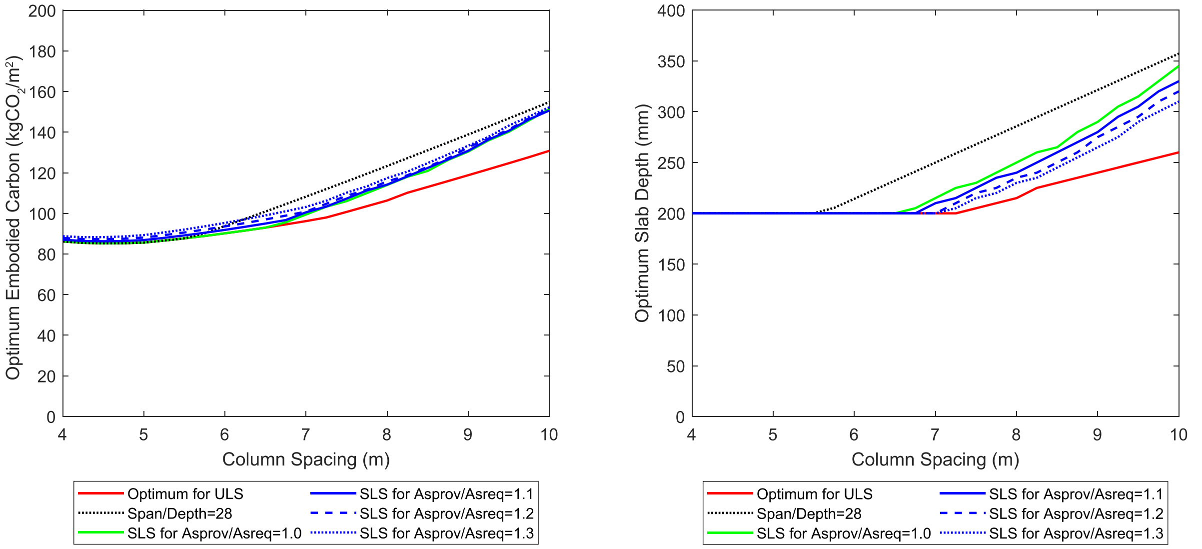


Fig. 10. Variation of difference in optimum embodied carbon with column spacing compared to the absolute optimum for different concrete grades.



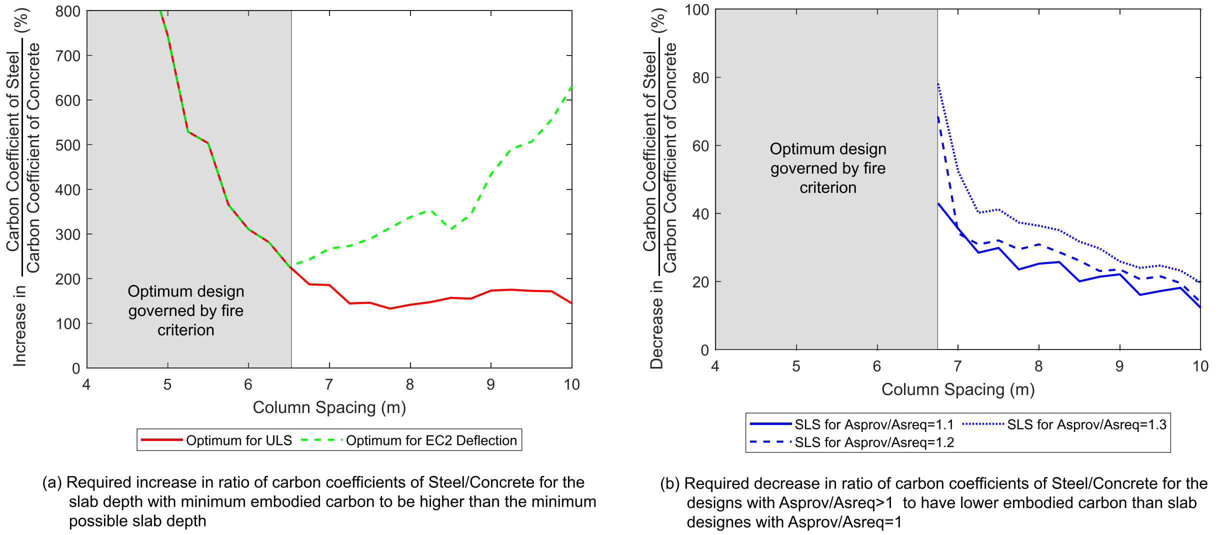
(a) Minimum Embodied Carbon vs Column Spacing

(b) Slab Depth with Minimum Embodied Carbon vs Column Spacing

Fig. 11. Effect of providing additional reinforcement to improve deflection performance for slabs with C30/37.

optimise embodied carbon with the adopted carbon coefficients.

The optimum designs depend on the adopted carbon coefficients of steel and concrete. The entire scope suggested minimising slab thickness as much as possible to minimise embodied carbon. Concrete with a lower carbon coefficient or reinforcing steel with a higher carbon coefficient can theoretically move the optimum towards deeper slabs. Changing the carbon coefficients of the constituents inevitably change the value for overall embodied carbon, but the interest in this scope is on the effect of such changes in the details of the optimum design. In all the column spacings considered in this scope, an increase in the ratio of carbon coefficients of steel/concrete by 200% was not sufficient for slab designs thicker than the minimum allowable depth to have the minimum embodied carbon. That means the designs with minimum embodied carbon will coincide with the minimum allowable slab thickness even if either the adopted carbon coefficient of concrete is quartered or that of steel is quadrupled. Therefore, the relationship between optimum slab thickness and minimum allowable slab thickness is largely insensitive to the adopted carbon coefficients. However, the ratio of carbon coefficients of steel/concrete should decrease for slab designs with Asprov/Asreq >1 to have lesser embodied carbon than the designs with Asprov/Asreq $= 1$. The required decrease in the ratio was around 60% on average for slabs with a span of 7 m and reduced to around 20% for spans of 10 m. Reinforcing steel with 20% less embodied carbon or concrete with 25% more can reduce overall



(a) Required increase in ratio of carbon coefficients of Steel/Concrete for the slab depth with minimum embodied carbon to be higher than the minimum possible slab depth

(b) Required decrease in ratio of carbon coefficients of Steel/Concrete for the designs with Asprov/Asreq>1 to have lower embodied carbon than slab designes with Asprov/Asreq=1

Fig. 12. Sensitivity of carbon coefficients on optimum slab designs with C30/37.

embodied carbon of slabs with a span of 10 m by increasing the provided reinforcement ratios to reduce allowable thickness. Hence, the outcome of designing slabs with Asprov/Asreq >1 to reduce embodied carbon can be sensitive to adopted carbon coefficients. Therefore, minimising embodied carbon require minimising slab depth mostly independent from adopted carbon coefficients, but further decreasing allowable depth with Asprov/Asreq >1 can be sensitive to the coefficients.

5. Conclusion

The embodied carbon of reinforced concrete flat slabs can be reduced by parametric design varying slab thickness, column size, column spacing, grade of concrete, and reinforcement details, even within the present construction practice. The optimum slab thickness is often the minimum allowable slab thickness, mainly governed by the fire criterion for spans shorter than around 6 m–7 m and deflection for longer spans. The thinnest slab being the optimum is due to the predominant share of embodied carbon by concrete around 70% on average and is largely insensitive to the adopted carbon coefficients. The optimum size of the columns is practically governed by the column design itself rather than the shear performance of the slab but have an impact on overall embodied carbon per unit area and the optimum column spacing. Increasing the span of the slab exponentially increases the embodied carbon. Lower grades of concrete can further reduce embodied carbon up to 12% despite an increase in the slab thickness, but higher grades of concrete cannot reduce embodied carbon. Deflection checks can justify reducing slab depths than the suggestions from the conventional span-to-depth ratios and reduce embodied carbon up to 8%. Embodied carbon can be theoretically reduced by allowing larger deflections, but the reductions of embodied carbon can only be around 20% of the resulting percentage increase in the deflection. Increasing the provided reinforcement than the necessary limit for ULS design allows thinner slabs but may not reduce embodied carbon, but the outcome is sensitive to the carbon coefficients of steel and concrete. Therefore, embodied carbon in flat slabs can be reduced by optimising column spacing, adopting lower grades of concrete, and minimising slab thickness with deflection checks, while being cautious of the embodied carbon coefficients in certain circumstances.

6. Limitations and future work

The scope of this paper is limited to typical loading levels for office buildings. However, the conclusions may vary for building designs with different loading levels and will be addressed in future work. Also, post-tensioning has not been discussed in this scope but is an important aspect in minimising embodied carbon. Post-tensioning flat slabs can reduce slab thicknesses and improve deflection performance. The slab designs can be precambered to reduce the service deflections. Furthermore, post-tensioning flat slabs can be more feasible than passive reinforcements for longer spans to avoid deeper slabs in practice. Hence, a similar parametric analysis of post-tensioned flat slabs as the next step of this study would be explored in future. This study has mainly referred to British and European standards for concrete design and quantifying environmental impacts. Despite the basic similarities of the governing principles, there may be differences in the code requirements in other standards.

7. Data access statement

All data created during this research are openly available from the University of Cambridge data archive at http://doi.org/10.17863/CAM.80248.

CRediT author statement

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Declaration of competing interest

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References

[1] UNFCCC, Bigger Climate Action Emerging in Cement Industry | UNFCCC, UN Clim, Chang. News., 2017. https://unfccc.int/news/bigger-climate-action-emerging-in-cement-industry. (Accessed 8 July 2020).
[2] C.H. Goodchild, R.M. Webster, K.S. Elliott, Economic Concrete Frame Elements to Eurocode 2, The Concrete Centre, Surrey, 2009.
[3] The Concrete Society, Technical Report No. 64: Guide to the Design and Construction of Reinforced Concrete Flat Slabs, The Concrete Society, Surrey, 2007.
[4] J. Orr, O. Gibbons, How to Calculate Embodied Carbon, 2020. https://www.istructe.org/IStructE/media/Public/Resources/istructe-how-to-calculate-embodied-carbon.pdf.
[5] G.P. Hammond, C.I. Jones, Embodied energy and carbon in construction materials, Proc. Inst. Civ. Eng. - Energy. 161 (2008) 87–98, https://doi.org/10.1680/ener.2008.161.2.87.
[6] RIBA, Embodied and whole life carbon assessment for architects, London, https://www.architecture.com/-/media/gathercontent/whole-life-carbon-assessment-for-architects/additional-documents/11241wholelifecarbonguidancev7pdf.pdf, 2017.
[7] BSI, BS EN 15978, Sustainability of Construction Works - Assessment of Environmental Performance of Buildings Calculation Method, BSI, London, 2011, 2011.
[8] London Energy Transformation Initiative, Embodied Carbon Primer, 2020. January 20, London, https://www.leti.london/ecp.
[9] M. Sansom, R.J. Pope, A comparative embodied carbon assessment of commercial buildings, Struct. Eng. 90 (2012) 38–49. https://www.istructe.org/journal/volumes/volume-90-(2012)/issue-10/research-a-comparative-embodied-carbon-assessment/.
[10] T.J. Wen, H.C. Siong, Z.Z. Noor, Assessment of embodied energy and global warming potential of building construction using life cycle analysis approach: case studies of residential buildings in Iskandar Malaysia, Energy Build. 93 (2015) 295–302, https://doi.org/10.1016/j.enbuild.2014.12.002.
[11] V.J.L. Gan, C.M. Chan, K.T. Tse, I.M.C. Lo, J.C.P. Cheng, A comparative analysis of embodied carbon in high-rise buildings regarding different design parameters, J. Clean. Prod. 161 (2017) 663–675, https://doi.org/10.1016/j.jclepro.2017.05.156.
[12] M.G. Sahab, A.F. Ashour, V.V. Toropov, Cost optimisation of reinforced concrete flat slab buildings, Eng. Struct. 27 (2005) 313–322, https://doi.org/10.1016/j.engstruct.2004.10.002.
[13] BSI, BS EN 1992-1-1:2004+A1:2014, Eurocode 2 - Design of Concrete Structures: Part 1-1: General Rules and Rules for Buildings, BSI, London, 2015.
[14] J. Ferreiro-Cabello, E. Fraile-Garcia, E. Martinez de Pison Ascacibar, F.J. Martinez de Pison Ascacibar, Minimizing greenhouse gas emissions and costs for structures with flat slabs, J. Clean. Prod. 137 (2016) 922–930, https://doi.org/10.1016/j.jclepro.2016.07.153.
[15] S. Eleftheriadis, P. Duffour, P. Greening, J. James, B. Stephenson, D. Mumovic, Investigating relationships between cost and CO2 emissions in reinforced concrete structures using a BIM-based design optimisation approach, Energy Build. 166 (2018) 330–346, https://doi.org/10.1016/j.enbuild.2018.01.059.
[16] H.T.M.K. Trinh, S. Chowdhury, J.H. Doh, T. Liu, Environmental considerations for structural design of flat plate buildings – significance of and interrelation between different design variables, J. Clean. Prod. 315 (2021) 128123, https://doi.org/10.1016/j.jclepro.2021.128123.
[17] O. Brooker, Concrete Buildings Scheme Design Manual, The Concrete Centre, Surrey, 2009.
[18] IStructE, Manual for the Design of Concrete Building Structures to Eurocode 2, 1.2, The Institution of Structural Engineers, London, 2017.
[19] H.C. Peiretti, A.P. Caldentey, J.C.L. Agüí, J. Edtbauer, Pr, EN 1992-1-1 Chapter 7 - Serviceability Limit States- Deflections. Supporting Document, Grupo de Hormigón Estructural - ETSICCP - UPM, Madrid, 2003, https://doi.org/10.13140/2.1.2048.1606.
[20] M.G. Stewart, Serviceability reliability analysis of reinforced concrete structures, J. Struct. Eng. 122 (1996) 794–803. http://ascelibrary.org/doi/abs/10.1061/(ASCE)0733-9445(1996)122:7(794).
[21] R.L. Vollum, Comparison of deflection calculations and span-to-depth ratios in BS 8110 and Eurocode 2, Mag. Concr. Res. 61 (2009) 465–476, https://doi.org/10.1680/macr.2009.61.6.465.
[22] The Concrete Centre, Technical Report No.58- Deflections in Concrete Slabs and Beams, The Concrete Centre, Surrey, 2005.
[23] J. Orr, M.P. Drewniok, I. Walker, T. Ibell, A. Copping, S. Emmitt, Minimising energy in construction : practitioners' views on material efficiency, Resour. Conserv. Recycl. 140 (2019) 125–136, https://doi.org/10.1016/j.resconrec.2018.09.015.
[24] O. Brooker, How to Design Reinforced Concrete Flat Slabs Using Finite Element Analysis, The Concrete Centre, Surrey, 2006.
[25] G. Hammond, C. Jones, ICE (Inventory of Carbon & Energy) V3.0, 2019.
[26] C. De Wolf, F. Pomponi, A. Moncaster, Measuring embodied carbon dioxide equivalent of buildings: a review and critique of current industry practice, Energy Build. 140 (2017) 68–80, https://doi.org/10.1016/j.enbuild.2017.01.075.
[27] M.K. Dixit, J.L. Fernández-Solís, S. Lavy, C.H. Culp, Need for an embodied energy measurement protocol for buildings: a review paper, Renew. Sustain. Energy Rev. 16 (2012) 3730–3743, https://doi.org/10.1016/j.rser.2012.03.021.
[28] F. Pomponi, A. Moncaster, Embodied carbon mitigation and reduction in the built environment e what does the evidence say, J. Environ. Manag. 181 (2016) 687–700, https://doi.org/10.1016/j.jenvman.2016.08.036.
[29] B.K. Oh, S.W. Choi, H.S. Park, Influence of variations in CO2 emission data upon environmental impact of building construction, J. Clean. Prod. 140 (2017) 1194–1203, https://doi.org/10.1016/j.jclepro.2016.10.041.
[30] E. Marsh, J. Orr, T. Ibell, Quantification of uncertainty in product stage embodied carbon calculations for buildings, Energy Build. 251 (2021) 111340, https://doi.org/10.1016/j.enbuild.2021.111340.
[31] The MathWorks, MATLAB R2020b. https://uk.mathworks.com/products/matlab.html?s_tid=hp_ff_p_matlab, 2020.
[32] Robert McNeel & Associates, Grasshopper - algorithmic modeling for Rhino. https://www.grasshopper3d.com/, 2021.
[33] Robert McNeel & Associates, Rhino 7 for windows. https://www.rhino3d.com/, 2021.
[34] A.J. Bond, A.J. Harris, R.M. Moss, O. Brooker, T. Harrison, R.S. Narayanan, J. Burridge, A.E.K. Jones, R. Webster, A.S. Fraser, How to Design Concrete Structures Using Eurocode 2, second ed., The Concrete Centre, London, 2019.
[35] BSI, NA to BS EN 1992-1-1: UK National Annex to Eurocode 2 : Design of Concrete Structures - Part 1-2, General rules - Structural fire design, 2004.
[36] A.G. SOFiSTiK, Rhinoceros/grasshopper interface. https://www.sofistik.com/products/finite-elements/rhinoceros-interface, 2021.