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Towards Sustainable Seismic Design: Assessing Embodied Carbon in Concrete Moment Frames

Abstract

The construction industry faces the imperative of reconciling structural integrity with environmental sustainability, urging a nuanced exploration of the material choices and design parameters. This study investigated the seismic design and embodied carbon implications of varying concrete grades and column spacing in concrete moment frames. A systematic approach was employed, conducting seismic design analyses and embodied carbon assessments for concrete moment frames with concrete grades of C25/30, C32/40, and C40/50 and column spacings of 4, 6, and 8 m. The results highlight the intricate influence of concrete grades on the resulting beam and column designs, with C32/40 emerging as the optimal choice, showing a substantial reduction in total embodied carbon. Additionally, column spacing is pivotal in shaping the beam design parameters, exhibiting a positive correlation between reduced column spacing and lower embodied carbon. This study contributes useful insights into the ongoing discourse on sustainable construction, offering a balanced perspective on the complex interplay between structural design choices and environmental implications.

Keywords: Building structures and design, Built environment, Concrete structures, Sustainability, UN SDG 13: Climate action

1. Introduction

The building and construction sector is a significant contributor to the prevailing environmental and climate crises. As of 2022, 37% of the global greenhouse gas emissions arising from human activities were ascribed to the construction and maintenance of buildings and infrastructure (UNEP, 2022). Notably, in 2020, the construction sector accounted for 20% of aggregate energy-related carbon dioxide (CO_2) emissions. These figures are anticipated to escalate in the ensuing years (UNEP, 2021). Recognising the urgency of mitigating climate impact, prominent international institutions are advocating immediate measures to curtail emissions by 78% by the year 2035. This reduction is pivotal for realising the targeted transition to a net-zero emissions scenario by 2050.

Reinforced concrete remains a key material in the construction industry, despite prevailing concerns regarding its environmental sustainability. Notably, cement production, a primary constituent of reinforced concrete, accounts for approximately 8-10% of global carbon emissions stemming from human activities (Monteiro, Miller and Horvath, 2017; Cao *et al.*, 2021). In view of this, the mitigation of the environmental footprint of concrete structures has become pronounced in the context of current climate emergencies. The quantification of environmental impacts in construction is effectively achieved through the assessment of embodied carbon, encompassing greenhouse gas emissions associated with raw material extraction, manufacturing, transportation, construction processes, repair and maintenance, and end-of-life activities (G. P. Hammond and Jones, 2008; RIBA, 2017; Gibbon *et al.*, 2022). Addressing the environmental ramifications of concrete structures requires a comprehensive understanding of embodied carbon (Mak and Lees, 2023).

Accordingly, the work presented here endeavours to contribute to sustainable construction practices by focusing on the mitigation of embodied carbon through the implementation of efficient design strategies.

In the context of seismic design of reinforced concrete (RC) buildings, design philosophies articulated in prevailing national codes and guidelines play a pivotal role in ensuring the construction of buildings with acceptable safety standards (FEMA, 2005; ASCE, 2016, 2017). The selection of an appropriate concrete frame system is pivotal for ensuring structural integrity and safety under seismic forces. Specifically designed for high-seismic regions, special reinforced concrete moment frames are a popular structural solution. This preference stems from their inherent flexibility and high ductility, which enables them to absorb and dissipate seismic forces (Kadarningsih *et al.*, 2014; I. Salama, 2015). The utilisation of such frames is strategically aligned with the unique challenges posed by high-seismicity areas, where the capacity to withstand and mitigate seismic loads is paramount.

Numerous studies have focused on the mitigation of embodied carbon in reinforced concrete buildings. Kaveh and Ardalani (2016) explored the discrete design optimisation of reinforced concrete frames using an enhanced colliding bodies algorithm. The proposed method incorporates a predetermined section database (DB) for design variables, specifically focusing on the area of steel and the geometry of cross-sections for beams and columns. Several benchmark test problems were subjected to optimisation to validate the efficacy of this approach. The analysis also highlighted the relevance of the two objective functions, emphasizing designs that effectively address CO_2 increments in practical applications. In another study, Kaveh et al. (2020) delved into the interplay between optimal cost and optimal carbon dioxide emissions in the design of reinforced concrete frames with varying heights. Utilising an automated computational process, three frames of different heights (four, eight, and twelve storeys) were modelled and subjected to optimisation. The results suggest that, through the optimisation process, buildings with lower heights exhibit greater reductions in CO_2 emissions compared to their taller counterparts.

Mak and Less (2023) investigated a novel approach for enhancing the environmental and mechanical performance of reinforced concrete structures. The investigation targeted shear-critical elements by employing a unique methodology that incorporated functionally graded concrete and voids to engage a preferential internal resistance mechanism reliant on internal arch action. Through failure testing, the study demonstrated notable improvements in the performance of the specimens compared to conventional designs, achieving increased resistance and reduced embodied carbon. A comparative analysis was conducted by Bechman and Weidner (2021) on a standard multi-storey concrete building, an optimised concrete structure, and a hybrid timber tower, each comprising 29 floors. The optimised concrete building incorporated specific adjustments, including a tailored concrete mix, optimised structural systems, and refined material manufacturing processes. The hybrid timber building was designed with a foundation, underground levels, and a rigid core composed of concrete, while the upper floors featured 200-millimeter timber panels with 100-millimeter concrete topping slabs. The findings of this study revealed significant potential for carbon emission reduction, with the adoption of a hybrid timber design resulting in emission reductions of up to 78% compared to conventional concrete structures. Moreover, the study indicated that an optimised concrete approach could yield substantial carbon emission reductions of 47%.

Goodchild et al. (2009) developed a set of design charts for reinforced concrete frame elements, focusing on slabs and providing insights into optimal cost considerations for various spans. The charts were prepared in accordance with Eurocode 2 guidelines (CEN, 2014), leading to optimised span-to-depth ratios and rebar quantities for given floor loads. Their findings suggested that augmenting reinforcement to achieve a reduction in allowable slab thickness could contribute to an overall cost reduction. Another relevant contribution to the literature comes from Ferreiro-Cabello et al. (2016), who investigated flat slabs with various thicknesses across different column grids. Their study underscores the importance of minimising embodied carbon by reducing spans. Additionally, their research demonstrated that designs with the lowest embodied carbon approached the minimum feasible slab thickness, revealing a nuanced trade-off between the slab depth and reinforcement content.

Eleftheriadis et al. (2018) utilised a building information Modelling (BIM)-based genetic algorithm to optimise flat slabs and systematically manipulate the dimensions, reinforcement, and column layout. Their investigation revealed that designs exhibiting the least embodied carbon favoured shorter column spacing and thinner slabs. Notably, the study revealed that increasing the slab thickness to achieve a reduction in the reinforcement ratios proved to be an effective strategy for diminishing the overall embodied carbon content. The findings provide valuable insights into the optimisation of reinforced concrete elements for enhanced sustainability in construction.

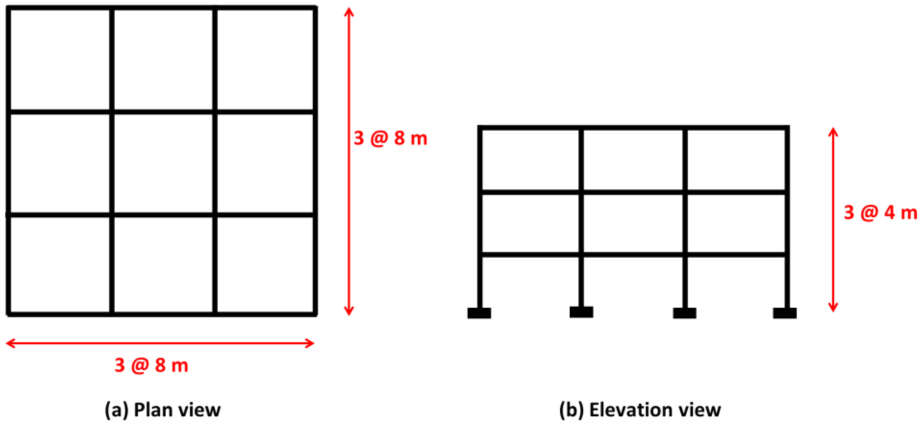
Based on an extensive review of the existing literature, it is evident that there is a substantial opportunity to mitigate the embodied carbon footprint within concrete structures, primarily through the implementation of optimised design strategies. The exploration of optimal design configurations presents a promising avenue for achieving significant reductions in the environmental impacts associated with concrete construction. However, the current body of research reveals a noteworthy gap in the investigation of embodied carbon, specifically within the context of seismically designed concrete moment frames. Despite the acknowledged importance of these structural elements, there is a paucity of studies delving into the intricate nuances of their embodied carbon, thereby warranting focused attention and inquiry in this domain.

The work presented in this paper aims to bridge a critical knowledge gap by conducting a thorough exploration of the potential for minimising embodied carbon in seismically designed reinforced concrete moment frames. This study aims to scrutinize and compare the embodied carbon of reinforced concrete moment frames, specifically focusing on the varying parameters of the concrete grade and column spacing. Through this exploration, this research seeks to provide insights into the efficiency of design strategies in reducing the carbon footprint of concrete structures across seismic zones. The emphasis on seismic considerations adds practical relevance by highlighting the significance of environmentally conscious choices in areas prone to seismic activity. The overarching goal is to contribute to sustainable construction practices by identifying the optimal design considerations that enhance structural performance while minimising embodied carbon. This research not only addresses a pressing environmental concern but also offers practical implications for architects, engineers, and policymakers committed to advancing more sustainable building practices in diverse seismic contexts.

2. Methodology

This study investigates the embodied carbon profiles of reinforced concrete frame structures, focusing on three-storey buildings with a consistent plan arrangement featuring three bays, as shown in Figure 1. The selected building configurations, with a standard storey height of 4.0 m and a concrete slab depth of 150 mm across all levels, align with practical construction norms to ensure the relevance and applicability of the study's findings to realistic architectural and engineering considerations.

Gravity loads, including self-weight, an additional superimposed dead load of 2 kN/m², and a live load of 2.4 kN/m², were computed following ASCE 7-16 (2016). Seismic considerations were integrally incorporated into the analysis, and the seismic load was determined following the provisions outlined in ASCE 7-16 (2016). Specific seismic parameters were precisely defined for this study, including a Peak Ground Acceleration (PGA) of 0.46 g, 0.2 Second Spectral acceleration (S_S) at 1.03 g, 1 Second Spectral acceleration (S_1) at 0.46 g, and a Site Class designation of SD. Notably, the wind load was omitted from the analysis, prioritising the seismic load owing to its higher criticality in this study.



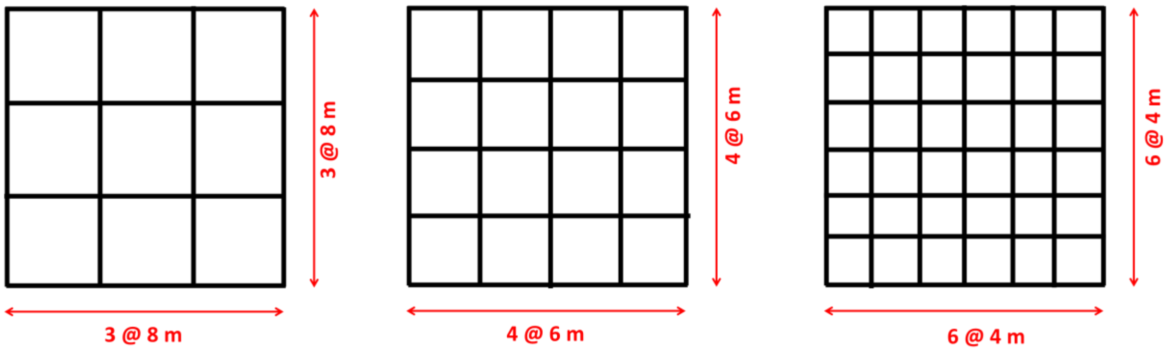
(a) Plan view

(b) Elevation view

Figure 1 Generic concrete frame building

The well-established commercial finite element software package ETABS (2023) was employed to conduct structural analysis and design. The design procedures implemented in this study conformed to ACI 318-19 (2019), which serves as a comprehensive guide for the design of concrete structures. The primary emphasis of this investigation is the examination and optimisation of the main structural elements, beams, and columns. Adhering to the rigorous standards set forth in ACI 318-19 (2019) ensures that the structural design is not only in compliance with industry-recognised codes but also adheres to established principles and practices governing the design of concrete elements. This methodical approach guarantees the reliability, safety, and structural integrity of the studied elements, contributing to the robustness and scientific rigour of the research.

To achieve the study objectives, the frames were designed as special moment-frame configurations. This design approach was chosen to meticulously explore the structural behaviour and performance of special moment frames under varying conditions, specifically considering different concrete grades (C25/30, C32/40, and C40/50) and column spacings (4 m, 6 m, and 8 m), as shown in Figure 2. These variations represent common concrete specifications and practical construction scenarios, allowing for a comprehensive exploration of the influence of different parameters on the embodied carbon profiles of specially designed moment-frames.



(a) Column spacing of 8 m (b) Column spacing of 6 m (c) Column spacing of 6 m

Figure 2 Frame floor plans with different column spacing

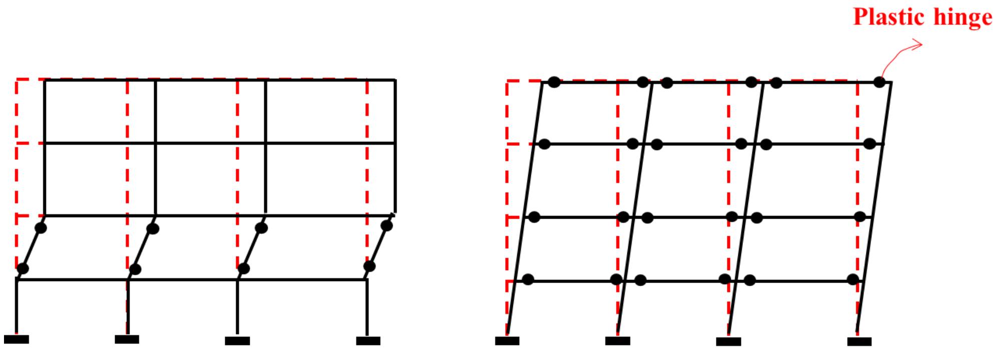
2.1 *Seismic design of concrete moment frame*

Concrete moment frames are fundamental and extensively utilised structural systems in civil engineering and play a crucial role in ensuring building stability, particularly in seismic regions. Their key feature lies in their ability to provide both strength and ductility, and effectively absorb and dissipate seismic energy. Their widespread use is grounded in the assurance of reliable structural performance and averting catastrophic failures during seismic events.

The seismic design of the moment frame involves several key principles, as follows:

a. Strong-Column/Weak-Beam Frame

This principle aims to avoid the formation of storey mechanisms (Figure 3a), where the columns and joints in one or a few storeys fail before the beams, leading to large storey drifts and possible collapses. Instead, the design should ensure that the beams yield in flexure before the columns (Figure 3b), resulting in a more uniform and ductile damage distribution over the height of the structure.



(a) Storey mechanism **(b) Beam mechanism**

Figure 3: Schematic of frame behaviour in response to seismic action

In addition to satisfying the basic strength design requirement for combined axial and flexural forces, each column section must satisfy the strong-column weak-beam requirement. According to ACI 318-19 (ACI, 2019), a critical strength check must be conducted for all beam-to-column connections.

$$\sum M_{nc} \geq (6/5)\sum M_{nb} \tag{1}$$

where M_{nc} is the sum of the nominal flexural strength of the columns framed into the joint, and M_{nb} is the sum of the nominal flexural strengths of the beams framed into the joint.

b. Avoiding Non-ductile Failures

Achieving a ductile response in structural members necessitates flexural yielding while concurrently preventing non-ductile failure modes, such as shear and axial failure. A strategic capacity design approach is typically employed to circumvent non-ductile failures. This method involves identifying regions prone to flexural yielding, designing these areas to meet the code-prescribed moment strengths, and subsequently computing other design forces through equilibrium considerations. Figure 4 illustrates the approach applied to the beam and column. The calculation of the design shear force (V_e) involved a comprehensive evaluation of the forces acting on the segment of the beam between the faces of the joints. Notably, the probable moment (M_{pr}) is derived by considering the dimensions and reinforcement at the joint, assuming a tensile strength of 1.25 times the yield strength ($1.25f_y$)

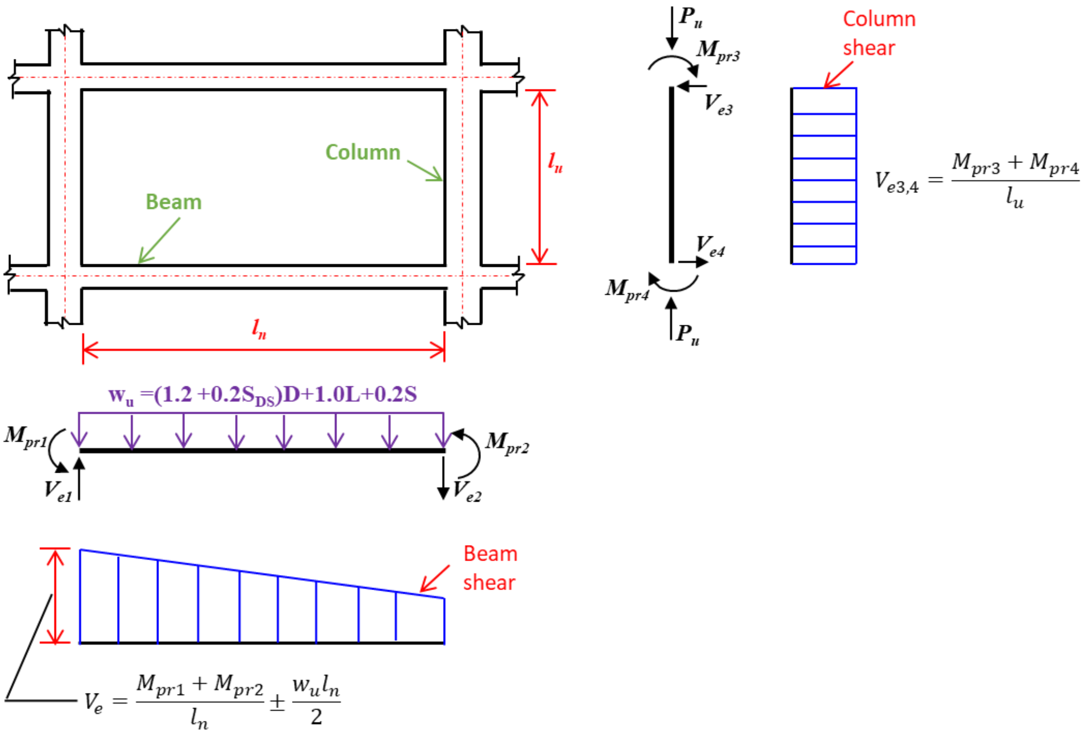


Figure 4: Design shear for beam and column

c. Ductile Flexural Behaviour

The optimal yield mechanism envisions uniform yielding of the beams throughout the entire height of the structure, accompanied by yielding of the base columns. However, in practical terms, it is prudent to anticipate some degree of column yielding along the height of the structure, unless columns significantly exceed beams in strength. Consequently, specific attention should be paid to detailing the end regions of both beams and columns at each beam-column joint. This ensures that they can undergo an inelastic flexural response without experiencing critical strength deterioration.

Within the plane of a moment frame, it is essential to maintain the continuity of the column longitudinal reinforcement at all floor joints and the beam longitudinal reinforcement at all interior joints. An exception to this continuity is permissible only if the splices sustain multiple post-yielding cycles. Transverse reinforcement is crucial for confining the core concrete and offering restraint against the buckling of the longitudinal reinforcement. This transverse reinforcement must extend from the joint face along a sufficient length to encapsulate the anticipated yielding region at the ends of the beams and columns. Figure 5 provides an illustrative representation of the requisite details near a typical beam-column connection.

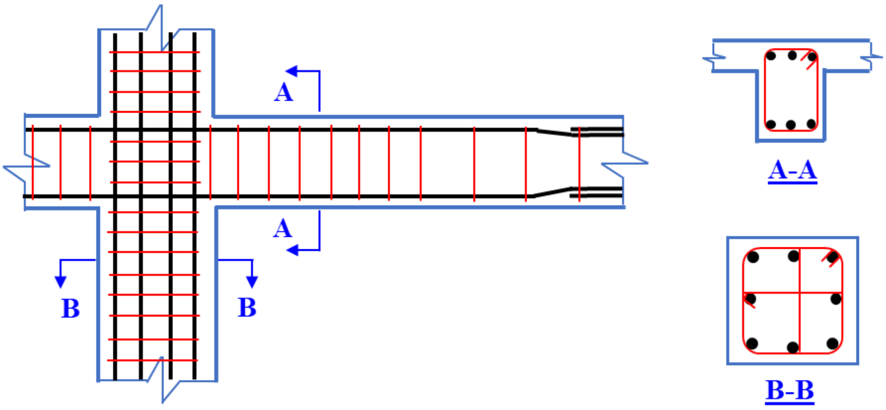


Figure 5: Typical reinforcement details required for ductile flexural behaviour

2.2 Embodied carbon calculation

An assessment of construction sustainability requires a thorough investigation of its environmental impact throughout the distinct stages of its life cycle, as stipulated by BS EN 15978 (BS 15978: 2011, 2011). According to this standard, stages A1–A3 collectively form the 'cradle-to-gate' phase, known as the product stage. This encompasses activities ranging from raw material extraction and transportation to manufacturing (Gibbon *et al.*, 2022). Notably, the London Energy Transformation Initiative (2020) emphasizes the significant contribution of embodied carbon in this phase, often constituting up to 50% of the entire life cycle carbon footprint, as depicted in Figure 6. This is in contrast to the comparatively smaller share in the construction phase, typically approximately 5% of the total. Researchers, such as Sansom and Pope (2012), Wen et al. (2015), and Gan et al. (2017), have conducted case studies exploring embodied carbon across the life cycle, consistently finding that transportation and construction activities collectively contribute within the range of 1% to 15%. Hence, employing 'cradle-to-gate' embodied carbon as a performance indicator is reasonable. This approach allows for a focused examination of the environmental implications linked to variations in the concrete grade and slab thickness while keeping construction methods constant.

Total embodied carbon (EC) was calculated using the following equation:

$$EC = \Sigma (C \times CF) \tag{1}$$

where C is the quantity of materials utilised and CF represents the carbon factor, signifying the quantity of carbon per unit weight or volume. This methodological approach adheres to recognised standards and enables a comprehensive evaluation of the carbon footprint attributed to concrete structures. The specific carbon factors for various materials are listed in Table 1, providing a valuable reference for the assessment of their environmental impact.

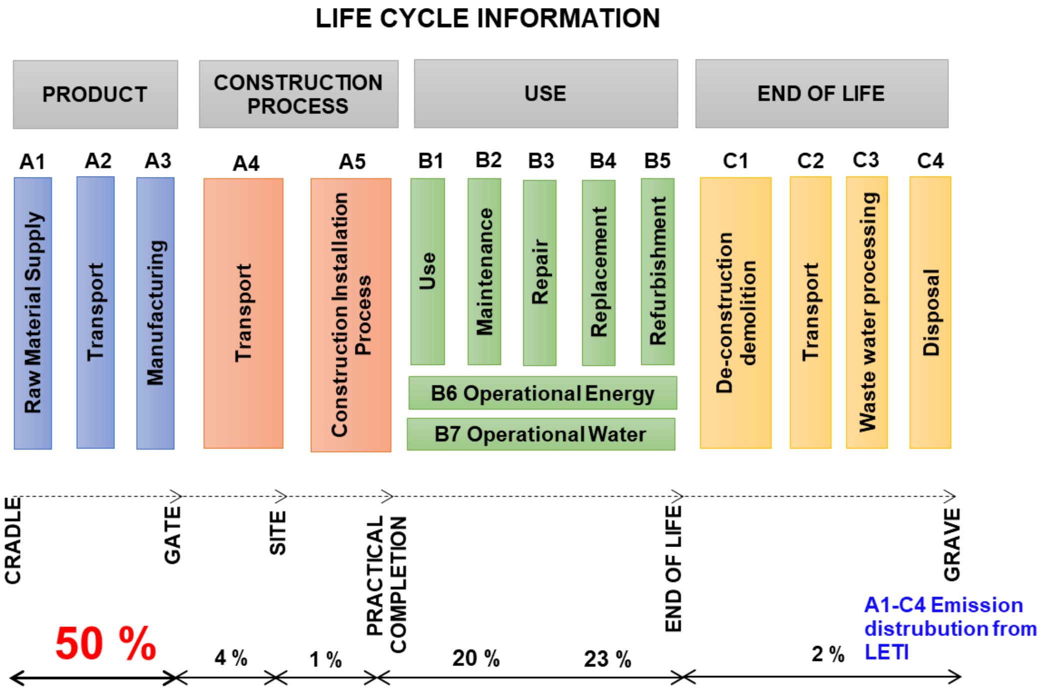


Figure 6. Life cycle stages (based on BS 15978: 2011, 2011)

Table 1 Carbon factors (CF) for various materials (Hammond and Jones, 2008)

Materials	Carbon Factor (CF)
Reinforcing steel	1.99 kg CO2e/kg
Concrete grade C25/30	284 kg CO2e/m^3
Concrete grade C32/40	330 kg CO2e/m^3
Concrete grade C40/50	380 kg CO2e/m^3

3. Results and discussions

3.1 Effect of concrete grade

This section provides an in-depth exploration of the influence of different concrete grades on both the seismic design and the embodied carbon of concrete moment frames. The design outcomes for the concrete moment frames, categorised by different concrete grades for the beams and columns, are detailed in Tables 2 and 3. These results provide insights into the structural configurations and specifications of each concrete grade.

Examining the beam design results, a notable observation emerged: the concrete grade exhibited a minimal influence on the flexural reinforcement. This suggests that the strength requirements for the bending moments were adequately met across the considered concrete grades. However, a distinct impact is evident in the shear reinforcement. C25/30 requires a shear reinforcement spacing of 100 mm, whereas C32/40 requires a spacing of 150 mm. Intriguingly, C40/50, despite having higher strength characteristics, is constrained by the ACI 318-19 (2019) requirement of 150 mm shear reinforcement spacing, maintaining parity with C32/40.

In contrast to the beam design, the concrete grade significantly affects the dimensions and flexural reinforcement in column design. For C25/30, the designed column requires a dimension of 0.55 m x 0.55 m with 16D25 reinforcement. In contrast, C32/40 allows for a reduction in dimension to 0.5 m x 0.5 m with less reinforcement, specifically 12D25. Surprisingly, C40/50 exhibited dimensions and reinforcements similar to those of C32/40. This apparent anomaly stems from the overarching principle of achieving strong weak column beams, where the design prioritises maintaining the column's strength relative to the beam, ensuring overall structural integrity.

However, the concrete grade does not significantly affect the shear reinforcement in the column design. Higher concrete grades enhance the shear capacity of the column. However, the adoption of a capacity design approach in shear design introduces unique dynamics. Although higher concrete grades improve the shear capacity, the design force is concurrently influenced by the probable moment, as discussed previously. Consequently, although the shear capacity of the column increases with higher concrete grades, the design force also increases, aligning with the capacity design principles to prevent nonductile failure.

Table 2 Resulting beam design for moment frame with different concrete grades

Concrete grade	***Dimension***		***Flexural reinf.***				***Shear reinf.***	
	B (m)	***H (m)***	***End span***		***Mid span***		***End span***	***Mid span***
			Top	***Bottom***	***Top***	***Bottom***		
C25/30	0.3	0.7	4ϕ25	2ϕ25	2ϕ25	2ϕ25	2ϕ10-100	2ϕ10-300
C32/40	0.3	0.7	4ϕ25	2ϕ25	2ϕ25	2ϕ25	2ϕ10-150	2ϕ10-300
C40/50	0.3	0.7	4ϕ25	2ϕ25	2ϕ25	2ϕ25	2ϕ10-150	2ϕ10-300

Table 3 Resulting column design for moment frame with different concrete grades

Concrete grade	***Dimension***		***Flexural reinf.***	***Shear reinf.***	
	B (m)	***H (m)***		***End span***	***Mid span***
C25/30	0.55	0.55	16ϕ25	2ϕ13-50	2ϕ13-150
C32/40	0.5	0.5	12ϕ25	2ϕ13-50	2ϕ13-150
C40/50	0.5	0.5	12ϕ25	2ϕ13-50	2ϕ13-150

These design results underscore the nuanced influence of the concrete grade on various aspects of moment-frame design. Although the impact on flexural reinforcement in beams and shear reinforcement in columns is evident, the design is remarkably consistent for shear reinforcement in beams and flexural reinforcement in columns across the considered concrete grades. These results also emphasize the significance of aligning design choices with code requirements, particularly when constraints such as shear reinforcement spacing are dictated by standards such as ACI318-19. The observed variations in shear reinforcement spacing due to the concrete grade underline the importance of meticulous compliance with code provisions.

In the pursuit of balanced structural performance and environmental sustainability, this study examined embodied carbon analysis for concrete moment frames encompassing various concrete grades. As shown in

Figure 7, the results provide a holistic understanding of the environmental implications associated with different concrete grades in the context of concrete moment frame construction. Notably, the analysis revealed an interesting trend: embodied carbon from concrete increases with higher concrete grades, even though higher grades require less volume. This counterintuitive observation is attributed to the higher carbon factor associated with superior concrete grades. The carbon factor, which reflects the carbon emissions per unit weight or volume, is a critical determinant in assessing the environmental impact of concrete, and its increase with higher grades accentuates the need for a balanced consideration of both the volume and carbon factor in sustainability assessments.

The analysis further indicated that higher concrete grades resulted in lower carbon emissions from steel. This is primarily because high-grade concrete generally requires less reinforcement. However, a noteworthy exception is observed with concrete grade 40/50, which necessitates reinforcement similar to concrete grade 32/40. This deviation is mandated by the seismic design requirements outlined in ACI 318-19, emphasizing the importance of fulfilling the minimum steel requirements for structures subjected to seismic forces.

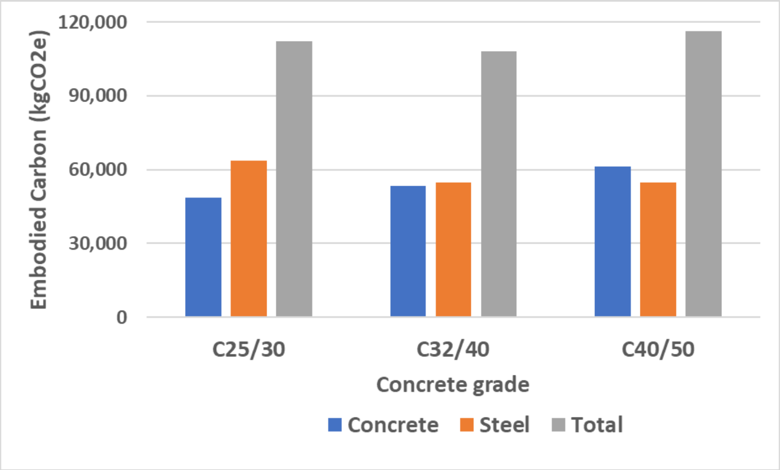


Figure 7 Embodied carbon of frame structure with different concrete grades

Despite the variations in the embodied carbon from concrete and steel across different grades, the overall influence of the concrete grade on the total embodied carbon for the concrete frame is substantial. Among the considered concrete grades, C32/40 was the optimal design choice, demonstrating a remarkable capacity to reduce embodied carbon by approximately 6%. This reduction represents as useful advancement in sustainable construction practices, showcasing the potential of thoughtful material selection for mitigating the environmental footprint of concrete structures. However, it is essential to acknowledge that the optimal design choice should be contextualised within the specific requirements of each project and the considerations of regional sustainability. The exploration of concrete grades in the context of embodied carbon highlights not only the considerable impact of material selection, but also the potential for substantial environmental gains through informed design choices.

3.2 Influence of column spacing

In this section, a detailed exploration is conducted to assess the influence of alterations in the column spacing on both the seismic design and embodied carbon of concrete moment frames. The study incorporates varying column spacings of 4, 6, and 8 m, utilising a consistent concrete grade of 25/30. This study sheds light on the design parameters of beams and columns, revealing the dynamic relationship between spacing configurations, structural demands, and environmental sustainability. The design outcomes for the concrete moment frames, distinguished by different configurations of column spacing for both the beams and columns, are outlined in Tables 4 and 5.

As anticipated, the column spacing plays a pivotal role in shaping the design parameters of beams within concrete moment frames. The results indicate that a shorter column spacing leads to a reduction in both the dimensions and the required flexural and shear reinforcement for beams. This outcome aligns with the expected behaviour, as a more closely spaced arrangement of columns necessitates beams to span shorter distances, resulting in decreased structural demands for both flexural and shear capacities.

In contrast, the influence of the column spacing on the column design parameters exhibited a more selective impact. A shorter column spacing was found to reduce the dimension and flexural reinforcement for columns, aligned with the principles of strong column weak beam design. However, it is noteworthy that the column spacing has no discernible effect on the shear reinforcement of the columns.

Table 4 Resulting beam design for moment frame with different column spacing

Column spacing	***Dimension***		***Flexural reinf.***				***Shear reinf.***	
	B (m)	***H (m)***	***End span***		***Mid span***		***End span***	***Mid span***
			Top	***Bottom***	***Top***	***Bottom***		
8 m	0.3	0.7	4ϕ25	2ϕ25	2ϕ25	2ϕ25	2ϕ10-100	2ϕ10-300
6 m	0.25	0.6	4ϕ19	2ϕ19	2ϕ19	2ϕ19	2ϕ8-100	2ϕ10-250
4 m	0.2	2.5	2ϕ19	2ϕ19	2ϕ19	2ϕ19	2ϕ8-100	2ϕ10-250

Table 5 Resulting column design for moment frame with different column spacing

Concrete grade	***Dimension***		***Flexural reinf.***	***Shear reinf***	
	B (m)	***H (m)***		***End span***	***Mid span***
C25/30	0.55	0.55	16ϕ25	2ϕ13-50	2ϕ13-150
C32/40	0.5	0.5	12ϕ25	2ϕ13-50	2ϕ13-150
C40/50	0.4	0.4	8ϕ25	2ϕ13-50	2ϕ13-150

The embodied carbon analysis for the concrete moment frames encompassing various column spacings is shown in Figure 8. The results indicate a noticeable influence of column spacing on the embodied carbon of the concrete moment frames. A discernible reduction in embodied carbon from both concrete and steel was observed as the column spacing decreased from 8 m to 6 m. This reduction signifies a positive correlation between the reduced column spacing and a more environmentally sustainable outcome in terms of embodied carbon.

However, the subsequent increase in embodied carbon at a 4 m column spacing prompted a nuanced analysis of the complex interplay between design choices and their environmental consequences. However, it is crucial to note that the current embodied carbon assessment focuses on a concrete frame. A previous study by Ferreiro-Cabello *et al.*, (2016) indicated that column spacing significantly influences embodied carbon in concrete slabs. Changes in the spatial distribution of the material within the slab can have a direct impact on embodied carbon. Alterations in thickness, reinforcement patterns, and material composition affect the overall carbon intensity of the slab. Although optimising the column spacing may reduce the embodied carbon in the frame, the subsequent impact on the slab configuration must be carefully considered. The interdependence of these elements requires a balanced and comprehensive design strategy.

The embodied carbon results underscore the need for a thorough evaluation of design choices. While 6 m column spacing emerges as the most optimal in terms of frame-embodied carbon, considerations related to the total embodied carbon, encompassing the influence on the slab, may reveal a more nuanced perspective. This discussion emphasizes the iterative nature of sustainable design, urging continual exploration and refinement of practices to achieve a delicate balance between structural efficiency and environmental responsibility.

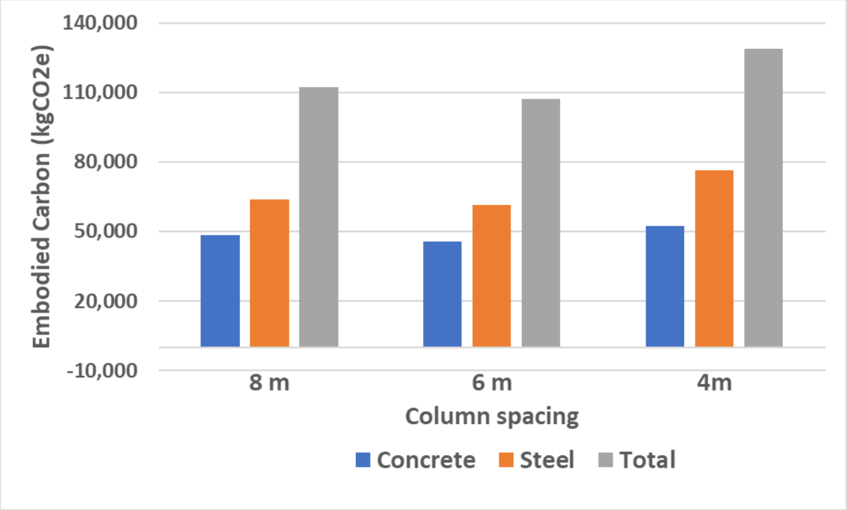


Figure 8 e Embodied carbon of frame structure with different column spacing

4. Conclusion

This study has explored the intricate interplay of concrete grades and column spacing in seismic design and embodied carbon of concrete moment frames. The examination of various concrete grades reveals nuanced influences on beam and column design parameters, emphasizing the importance of meticulous compliance with code provisions. Concrete grade C32/40 is the optimal design choice, showing a remarkable reduction of approximately 6% in the total embodied carbon, thus underlining the significance of thoughtful material selection in sustainable construction practices.

The examination of column spacing elucidates its pivotal role in shaping beam design parameters, with a discernible reduction in embodied carbon from both concrete and steel as the column spacing decreases from 8 m to 6 m. However, a counterintuitive increase in embodied carbon at 4 m column spacing prompted a closer examination. This contradiction emphasizes the need for a balanced and comprehensive design strategy that considers not only the frame but also its impact on the slab configuration.

Throughout this study, the iterative nature of sustainable design is underscored, urging the continual exploration and refinement of practices to strike a delicate balance between structural efficiency and environmental responsibility. As the construction industry navigates the challenges of optimising both performance and sustainability, the insights gained from this research contribute to a broader understanding of the complexities involved, offering valuable guidance for future endeavours to advance eco-friendly structural solutions.

Statements and Declarations

Conflict of interest: The authors have no conflict of interest to declare.

Ethical approval: The paper is neither published nor under review elsewhere. There are no human or animal participants involved in the conducted study.

Informed consent: All authors are aware of the paper.

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