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Original Article

Impact of Seismic Design on Embodied Carbon and Construction Cost in Multi-Storey Reinforced Concrete Frame Buildings

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Abstract *- The building industry is a large contributor to global greenhouse gas emissions. The construction and building materials processes alone account for a large portion. While seismic design is imperative to keeping structures safe in regions that experience earthquakes, it often increases the volume of materials needed for construction, worsening the environmental and economic consequences. As a result, this research seeks to assess the degree to which seismic design impacts the Embodied Carbon (EC) and construction budgets of reinforced concrete structures of differing heights, enabling a more informed carbon-cost analysis for those carbon-conscious structural designs. Buildings of 2-, 4-, 6-, and 8-story height, and both seismic and non-seismic design scenarios, were analysed. All designs appropriately used SNI 2847-2019 and SNI 1726 for seismic provisions. The structural design for slabs, beams, and columns, and detailed structural modelling material constituted the core building blocks for material volume quantification. Construction cost was derived from the built-up method, and EC was derived from the legal provisions for concrete and steel. The total EC, cost, and their distribution by elements were used to derive prioritization to assist the cost optimization. The outcome illustrates the volumetric consequences of seismic design and how it diverges as height increases. In the case of the 8-storey building, the seismic design has 54% more Embodied Carbon (EC) and 79% more increased cost in comparison to the non-seismic design. For non-seismic buildings of all heights, slabs more than 50% of the time controlled the EC and cost. However, for the seismic buildings, the dominance of the slabs reduced as they got taller, and the columns started to take more due to the increased seismic detailing provisions. The carbon-cost trade-off analysis indicated a strong linkage between cost and EC, and the non-seismic mid-rise buildings provided the most balanced performance. This shows that the EC assessment in regions with a high seismic risk should be considered as a design criterion to mitigate the impact of economically and environmentally seismic detailing provisions in the code. Improvements in cost and sustainability can be achieved by controlling slabs in non-seismic designs and improving columns in seismic designs.*

Keywords *- Reinforced concrete buildings, Seismic design, Embodied carbon, Construction cost, Carbon–cost trade-off.*

1. Introduction

The building and construction industry has acknowledged greenhouse gases as pollutants and contributed to about 37% of the CO_2 emissions worldwide [1]. Building CO_2 emissions include operational and embodied emissions. Operational emissions, as defined by the IPCC and EPA, include heating, cooling, lighting, and operating equipment powered by construction electricity. Embodied emissions entail the extraction, manufacturing, and assembling of construction materials, as well as the construction activities themselves [2-4].

Emissions from construction operational factors will continue to decline with the new advancements of modern energy systems as decarbonisation progresses, whereas the construction industry will be largely dominated by embodied emissions. Most modern construction buildings will have about 50% of the total carbon in the deodorized building footprint, leaving the construction building to remain partially carbon-intensive as the construction materials will make. This construction footprint will remain between now and 2050 [5]. This shows how much work has to be put into tackling the carbon emissions left by buildings to reduce the adverse impact on the climate.

Identifying the source literature shows the degree of divergence in the contribution of embodied carbon to total emissions of buildings. Buchanan and Honey [6], Eaton and Amato [7], Dimoudi and Tompa [8], and Clark [9] have all documented proportions of 30% to 80% variations that have sources built on types and materials and sources energy performance standards. This also illustrates the complex nature of managing and assessing the embodied carbon in buildings, lacking clear and bounded analyses. These factors aid in creating a valuable framework for managing negative building impacts on the environment.

Many pieces of research have assessed the embodied carbon of different structural systems and materials and different construction practices, focusing on Reinforced Concrete (RC) buildings, mainly because of their popularity and heavy carbon influence. As part of their research, Khan et al. [10] did an environmental impact analysis of a three-storey commercial building in Pakistan using Building Information Modelling (BIM). This research elaborated on the main components/stuff that contribute to a building's total carbon footprint. As the combined total of embodied carbon emissions was over 80% the main contributors were: steel (33.51%), concrete (19.98%), brick (14.75%), aluminium (12.10%), and paint (3.22%). This research signifies the control that structural materials, and more especially, steel and concrete, have on a building's environmental efficiency. In the same fashion, Hellmeister [11] used the Athena Impact Estimator for Buildings to conduct a life cycle assessment (LCA) of a mass timber building versus a conventional steel–concrete structure in Boston, Massachusetts. Assuming 60 years of service life for both buildings, it was determined that the timber alternative used 52% less construction material, and embodied carbon emissions were 53% less. This is a prime example of how the mass timber alternative significantly reduces the carbon footprint of a building.

In an effort to optimise costs within various spans, Goodchild et al. [12] designed a few charts that described designs for elements of reinforced concrete frames. Most of the elements described in the charts are slabs. The study also used a parametric design while observing the strict controls on the limits of deflections as per the Eurocode 2[13], which also helped to produce some updated recommendations on the span-to-depth ratios. One of the more interesting points made in the study was that slabs could actually be made thinner, which also reduced the price of construction, by increasing the amount of reinforcement within the codified limits. This was also the case in a study by Ferreiro-Cabello et al. [14], where the design of flat slabs and a column grid construction was studied in the case of the carbon that was to be embodied. It was shown that in order to have minimal carbon use, the design slabs and the associated carbon had to be very close to the minimum thickness. It was also noted that this specific design needed more reinforcement; thus, a trade-off is clear in design. It is the proportion of the slab depth to the end. Trinh et al. [15] described the advancement in the optimization of flat slab systems. The authors examined the impact of various design parameters on the carbon footprint of low-carbon structural design, specifically column spacing, slab thickness, concrete grade, and reinforcement detailing. They determined that low carbon imprints on the design suggested the use of thinner slabs and closer column spacing, leading to even lower material usage. However, increasing the grade of concrete resulted in lower concrete volume requirements, albeit increasing the volume of embodied energy. This was due to the carbon footprint of higher-grade concrete. This illustrates the need for design in multiple parameters since optimal environmental performance has not been achieved. The most influential parameters on the embodied carbon for flat slab systems. This design focuses on column size and layout, concrete grade, slab thickness, and reinforcement ratio.

Mergos [16] evaluated the use of rocking footings in the seismic design of RC frames to improve resistance and aid in sustainability. With the use of rocking isolation, embodied carbon decreases by 40% and the reductions increase in value in areas with greater seismic intensity. In addition, Mergos [17] developed optimum RC frame designs for minimum cradle-to-gate embodied CO_2 emissions and compared them to cost-optimal designs. The results emphasized the extent to which ductility class affects embodied emissions. In high seismic zones, low-ductility designs produce up to 60% more CO_2 emissions than medium- or high-ductility designs. The study also noted that minimum carbon designs tended to coincide with minimum cost designs more often than expected, which balances out until the costs of concrete and reinforcing steel have disparate impacts. The latter findings demonstrate the importance of seismic resilience and sustainability, underscoring the integrated carbon–cost assessments done in the study.

Design optimisations will continue to provide opportunities to improve the reductions in the embodied carbon of concrete structures. Studies have shown that the carbon footprint of structures can be greatly reduced through techniques such as reducing slab thickness, optimising column spacings, varying the ratios of reinforcement, and choosing suitable concrete grades. However, in seismic regions, it becomes more challenging to realise such reductions due to the tightened constraints demanded by seismic-resilient design. High seismic zone buildings must follow seismic design regulations, which usually result in the requirement of more robust structures to be built. Consequently, more steel and concrete are used, which increases the embodied carbon, contrary to buildings in non-seismic regions. This illustrates the need to assess the embodied carbon of a whole structure in view of the constraints of seismic design and the necessity of cohesive design paradigms that harmonise the structural and ecological aspects.

While there has been some research into embodied carbon in buildings, there still seems to be a gap in research with detailed analysis at the component level with respect to how embodied carbon changes with building height, seismic design requirements, and construction cost at the component level. A lot of the previous work seems to miss out on structural elements like beams and slabs, and additional materials needed to be designed for seismic codes. In addition to this, the relative lack of research on the integration of economic factors to level the embodied carbon and cost for practical assessments still focuses on the carbon component of sustainability. The focus, especially in the case of unsustainable earthquake regions, may be on the seismic design.

In response to this gap, this study assesses the embodied carbon and the construction cost of multi-storey reinforced concrete frame buildings (2-, 4-, 6-, and 8-storey) with and without seismic loading. The integrated approach of this study is what makes it unique. Whereas most of the previous works focused either on embodied carbon on its own or the cost alone, this study considers both parameters simultaneously on the level of building components (slabs, beams, and columns) of multi-storey reinforced concrete buildings (2-, 4-, 6-, and 8-storey). By comparing seismic and non-seismic designs, this study demonstrates how seismic requirements affect the volume of materials used, the environmental cost, and the construction cost. The unique dual focus provides an unprecedented carbon–cost trade-off, showing possible design combinations where structural safety is compromised for profitability and environmental efficiency-elements that previous studies generally ignored.

2. Methodology

2.1. Building Configuration and Structural Layout

This research examines the embodied carbon as well as the construction costs of Reinforced Concrete (RC) frame buildings of different heights, 2-, 4-, 6-, and 8-story buildings, while keeping the structural and architectural design the same, as illustrated in Figure 1. All buildings had a standard storey height of 4.0 metres. The structural system used was reinforced concrete moment-resisting frames, as they are commonly used in mid-rise buildings for their structural efficiency, architectural adaptability, and construction economy.

Gravity and seismic loads for this study follow the Indonesian regulations. For the gravity loads, the weight of the structural elements is automatically considered, and the imposed dead load, as well as the live load, are provided in the project specifications, which are 1.0 kN/m^2 and 2.0 kN/m^{2,} respectively, which were based on and referenced on SNI 1727:2020 [18] for residential purposes. In SNI 1726:2019 [19], it is mentioned that seismic loading should be included, and for this study, I assumed the values for high-seismicity. The assumed seismic parameters are *PGA* of 0.37 g, medium-stiff soil (Site Class *SD*) with short-period spectral acceleration (S_S) of 0.78 g, 1-second spectral acceleration (S_1) of 0.38 g, and response spectrum. These parameters define the design response spectrum for the lateral load-resisting system design. In various studies, it was recorded that the wind loading is negligible, which is applicable in this scenario as well. In this scenario, the lateral design is predominantly influenced by the seismic effects.

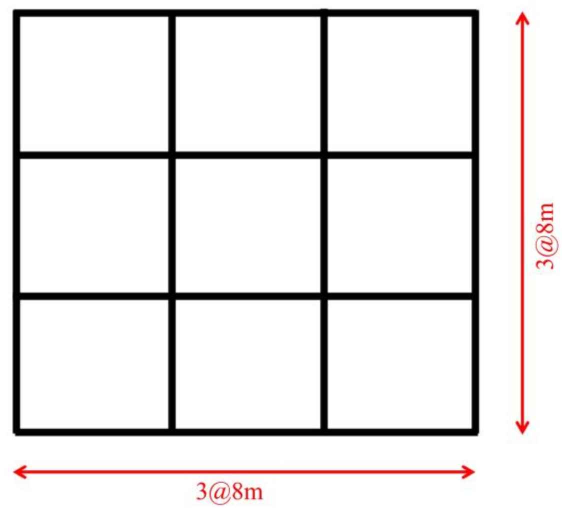


Fig. 1 Plan view of the building layout used in this study

All structural components, such as columns, beams, and slabs, were constructed with K300 concrete, which has a compressive strength of 25 MPa. For the reinforcement, the design used BjTS 420A steel of 420 MPa yield strength and 420 MPa yield strength steel [20]. All design processes were carried out in accordance with SNI 2847:2019 [21] and the Indonesian standard for reinforced concrete structures. In structural design, vertical and horizontal structural elements were of primary importance, specifically, the slabs, beams, and columns, which constitute the major components of the load-bearing system for the building.

The structural analysis and design were carried out using the ETABS [22] software, which is an industry-standard for finite element analysis. In building design, the models were given fixed base support, which assumes full restraint at the foundation. Assemblies of frames were used for beams and columns, and shells were built for the concrete slabs. To model accurate in-plane stiffness, slabs were constructed with a rigid floor diaphragm system that maintains uniform lateral movement for the entire slab. A linear static analysis was carried out, as it is the most common analytical approach used in the engineering of mid-rise reinforced concrete frame buildings.

Each building configuration in this study was designed under two structural scenarios: non-seismic and seismic. To understand the effect of seismic design requirements on material quantities, embodied carbon, and construction costs. The seismic design of the reinforced concrete moment-resisting frame was developed according to the ductility and detailing provisions of SNI 2847:2019 [21], which prioritizes three principles: (1) establishing a strong-column/weak-beam hierarchy, (2) preventing non-ductile failure modes, and (3) facilitating ductile flexural behaviour.

To satisfy the strong-column/weak-beam requirement, a critical flexural strength check was performed at all beam-to-column joints. This condition is expressed as follows:

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

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. This ensures that plastic hinges form in the beams rather than in the columns during seismic events.

To prevent non-ductile failure, particularly shear failure, the design shear force (V_e) in beams is calculated based on probable moment capacities (M_{pr}), which consider enhanced tensile strength using a multiplier of 1.25 times the yield strength ($1.25f_y$). This ensures that the shear design reflects the potential overstrength of flexural members. Figure 2 shows the key parameters and internal force demands for the seismic design of both the beams and columns.

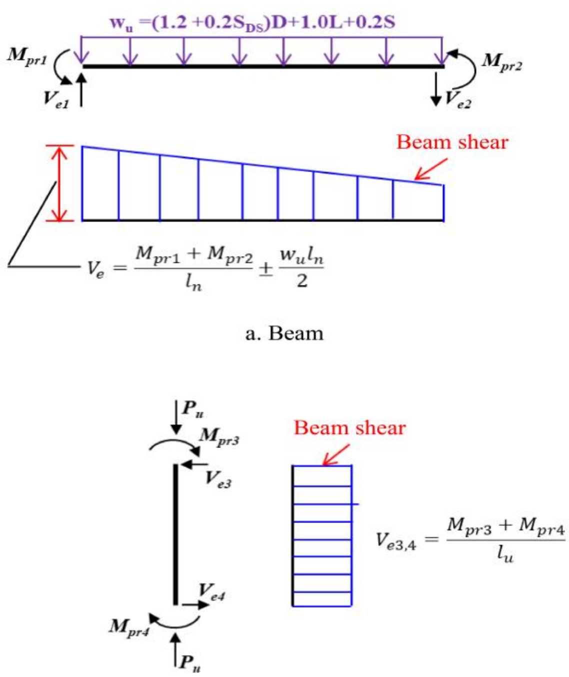


Fig. 2 Beam and column shear force design checks in seismic frames

For ductile flexural behaviour, the continuity of the longitudinal reinforcement is maintained in both columns and beams at all joints. Splices are only permitted when it can be demonstrated that they can sustain multiple cycles of post-yielding deformation. Additionally, transverse reinforcement was provided to confine the core concrete and prevent the buckling of the longitudinal bars. This reinforcement must extend from the joint face along the expected length to undergo inelastic deformation during an earthquake.

2.2. Embodied Carbon Calculation

The evaluation of construction sustainability requires a comprehensive assessment of the environmental impacts across all stages of the building lifecycle, as defined in BS EN 15978 [23]. This standard categorises the life cycle into distinct phases, with Stages A1 to A3 collectively referred to as the 'cradle-to-gate' phase or the Product Stage, encompassing raw material extraction, transportation to manufacturing facilities, and material production processes. London Energy Transformation Initiative (LETI)[24] shows that the cradle-to-gate phase is critical in that it can account for almost 50% of the total lifecycle embodied carbon. This is in stark contrast with the construction phase (Stages A4 and A5), which only contributes a small portion of the total emissions at about 5%.

This perspective is corroborated in empirical studies conducted by Sansom and Pope [25], Wen et al. [26], and Gan et al. [27] that consistently report transportation and on-site construction activities together contribute between 1 and 15% of the total embodied carbon. Therefore, it is reasonable to adopt cradle-to-grave embodied carbon as a key performance metric [28]. The calculations for the Embodied Carbon (EC) of every structural element use the following equation:

$$EC = \sum Q_i \times CF_i \tag{2}$$

Where Q_i is the quantity of material used (in mass or volume) and CF_i is the carbon factor, defined as the carbon dioxide equivalent emissions per unit of material. Table 1 shows the carbon factors used in this study, obtained from the Inventory of Carbon and Energy (ICE v3.0) that was developed by Hammond and Jones [29].

Table 1. Carbon Factor (CF) of materials used in this study [29]

Materials	Carbon Factor (CF)
Reinforcing steel	1.9 kg CO_2e/kg
Concrete grade K300	284 CO_2e/m^3

2.3. Cost Estimations

The economic performance of the building was assessed through construction cost analysis, focusing on the initial cost associated with material procurement and on-site implementation. This is complementary to the evaluation of embodied carbon, for which the construction cost provides the basis for assessing the carbon-cost trade-off in structural design. A unit cost-based approach was used to reflect normal engineering practices in Indonesia.

The total construction cost was calculated using the following equation:

$$EC = \sum Q_i \times UP_i \quad (3)$$

Where, UP_i denotes the unit price of material i obtained from the regionally available construction cost database as published by the Indonesian Ministry of Public Works. This ensures compliance with nationally regulated prices and current market conditions. The unit prices utilised in this study are presented in Table 2. These values were consistently applied across all variations of the building to facilitate a uniform comparison of differing design heights and seismic design variations.

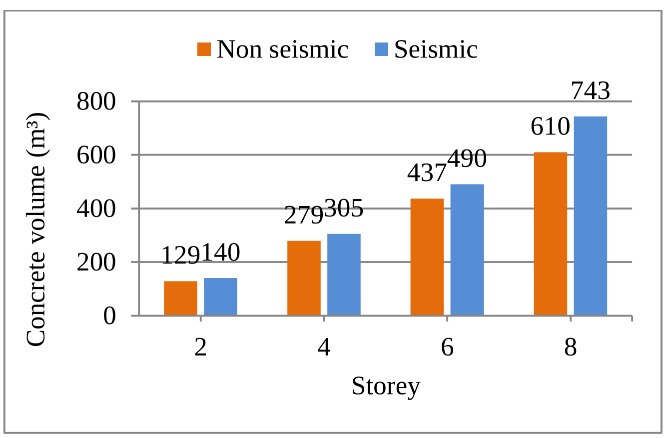
Table 2. Unit prices of materials (1 US$ = IDR 16,000. -)

Materials	Unit price
Reinforcing steel	US$1.51/kg
Concrete grade K300	US$72.7/$m^3$

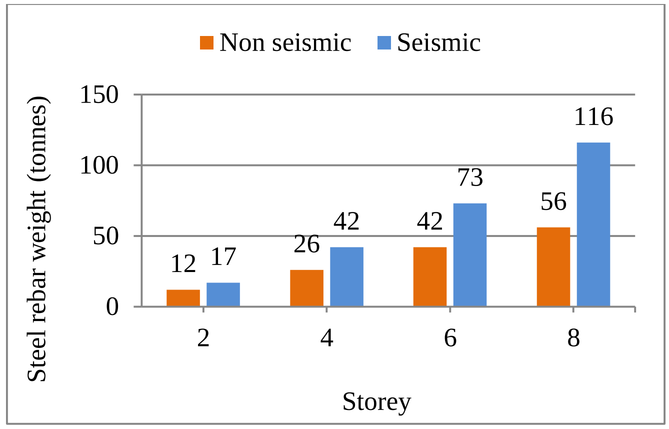
3. Results and Discussion

3.1. Design Axial Load-Carrying Capacities

As seen in Figure 3, the total material quantities for concrete and steel reinforcements show, as expected, a considerable increase with building height. The reason for this is that taller buildings exert greater structural demands. The impact of the seismic design provisions, however, appears to be more significant in the quantities of steel reinforcements for both materials. Overall, concrete volumes increase with storey count in both the seismic and non-seismic designs. For the 2-storey building, the required concrete volume was 129 m^3 in the non-seismic case and 140 m^3 in the seismic case, an increase of about 9%. This difference is more significant in the case of taller buildings. For the 8-storey configuration, concrete volume increased for the non-seismic design to 610 m^3 and 743 m^3 for the seismic design, an increase of 22%. The greater concrete requirement in seismic buildings is due to the larger member sizes (especially the columns) needed to meet the lateral load resistance, drift control, and ductility provisions in the seismic design codes.



(a) Concrete



(b) Steel rebar

Fig. 3 Total concrete volume and steel reinforcement weight for seismic and non-seismic designs in 2-, 4-, 6-, and 8-storey buildings

Reinforcement Steel quantities exhibit a greater divergence, as illustrated in Figure 3(b). The weight of steel in non-seismic buildings rises only slightly, from 12 tonnes for 2-storey buildings to 56 tonnes for 8-storey buildings, while seismic designs entail significantly greater quantities of steel. A 2-storey seismic building has 17 tonnes of steel, but for the 8-storey building, it rises to 116 tonnes—thus, the seismic design used over twice the amount of steel as the non-seismic design. Such an increase is a result of the design and detailing for ductile seismic performance, which requires the use of closely spaced stirrups and confinement reinforcement, as well as larger longitudinal bars in both beams and columns.

Figure 4 illustrates how an understanding of the steel-to-concrete ratio helps to gauge the magnitude of reinforcement. For non-seismic buildings, this ratio averages to a constant value of about 91-97 kg of steel per m^3 of concrete, which means the proportion of steel to concrete was relatively constant regardless of the building height. In contrast, seismic designs showed an increase in the proportion of steel to concrete. The ratio of starting values of 125 kg/m^3 for 2-storey buildings progressively increases to 155 kg/m^3 for 8-storey buildings. This is indicative of the increasing need for reinforcement, in proportion to concrete, as the seismic forces for taller structures become dominant. The increases in steel proportion in seismic buildings signify the adoption of crucial seismic design fundamentals, which include the strong-column/weak-beam provision.

3.2. Embodied Carbon Assessment

The data on embodied carbon presented in Figure 5 indicates that taller buildings experience an increase in the embodied carbon for both seismic and non-seismic designs. This increase is the result of the structural demands of taller buildings, which require more concrete and steel. Across all configurations, the seismic designs have more embodied carbon compared to the non-seismic design, and this difference grows as the buildings increase in height.

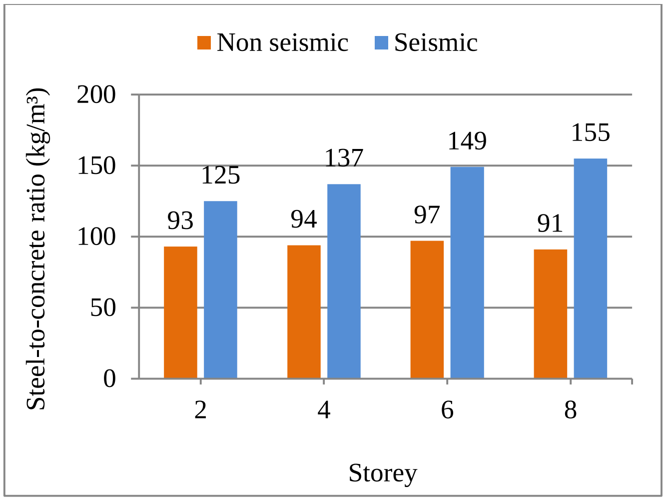


Fig. 4 Steel-to-concrete ratio for seismic and non-seismic designs in 2-, 4-, 6-, and 8-storey buildings

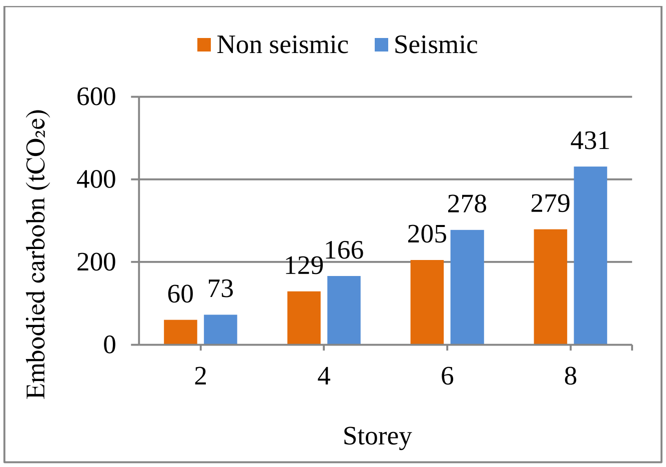
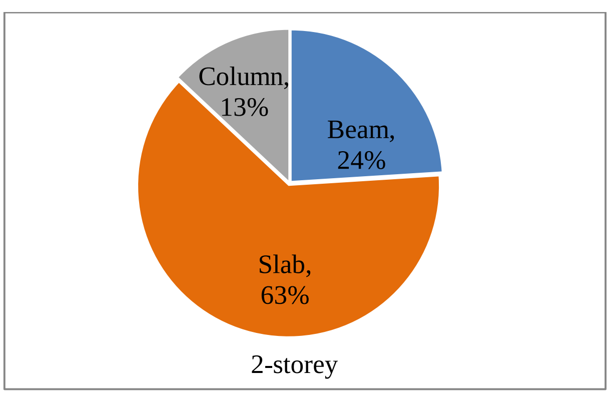


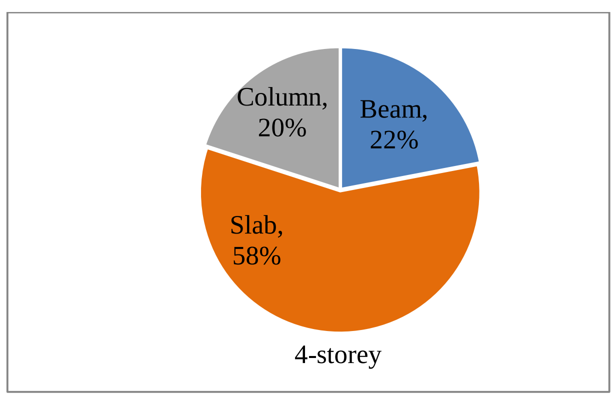
Fig. 5 Embodied carbon for seismic and non-seismic designs in 2-, 4-, 6-, and 8-storey buildings

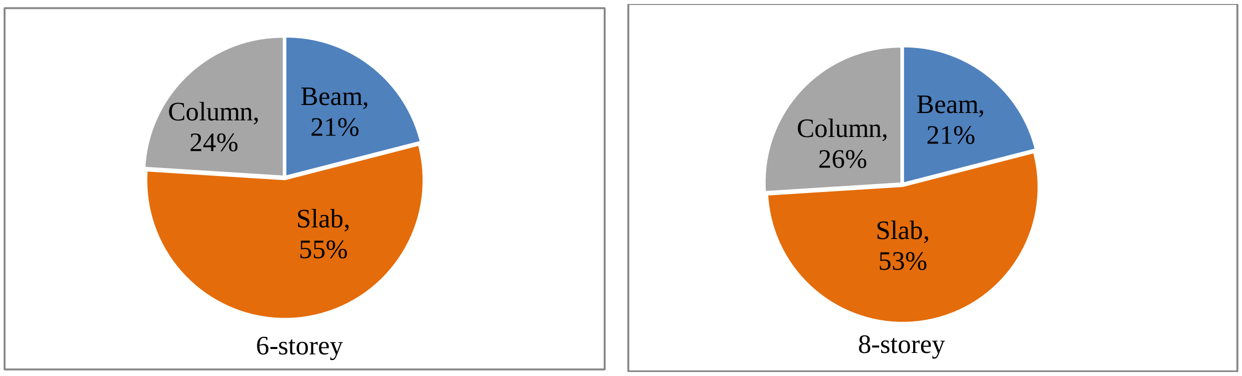
For the 2-storey building, the embodied carbon increased from 60 tCO_2e in the non-seismic design to 73 tCO_2e in the seismic design, which is an increase of 22%. For 4-storey buildings, the values increase from 129 tCO_2e to 166 tCO_2e, which is an increase of 29%. The difference is even greater for tall buildings; for 6-storey buildings, the embodied carbon increases from 205 tCO_2e to 278 tCO_2e (a 36% increase). For 8-storey buildings, the increase is from 279 tCO_2e to 431 tCO_2e, which is an increase of 54%.

As noted before, the primary cause of the increasing demand for reinforced steel for seismic buildings is the rapid divergence. Moreover, reinforced steel is more carbon-intensive than concrete, so this disparity in growth for seismic design will dominate the overall embodied carbon. The need for larger concrete columns and beams also results in more concrete and, consequently, more carbon emissions. The size and number of columns, as well as the number and size of beams, will have to be even greater than for buildings of the same volume and use.

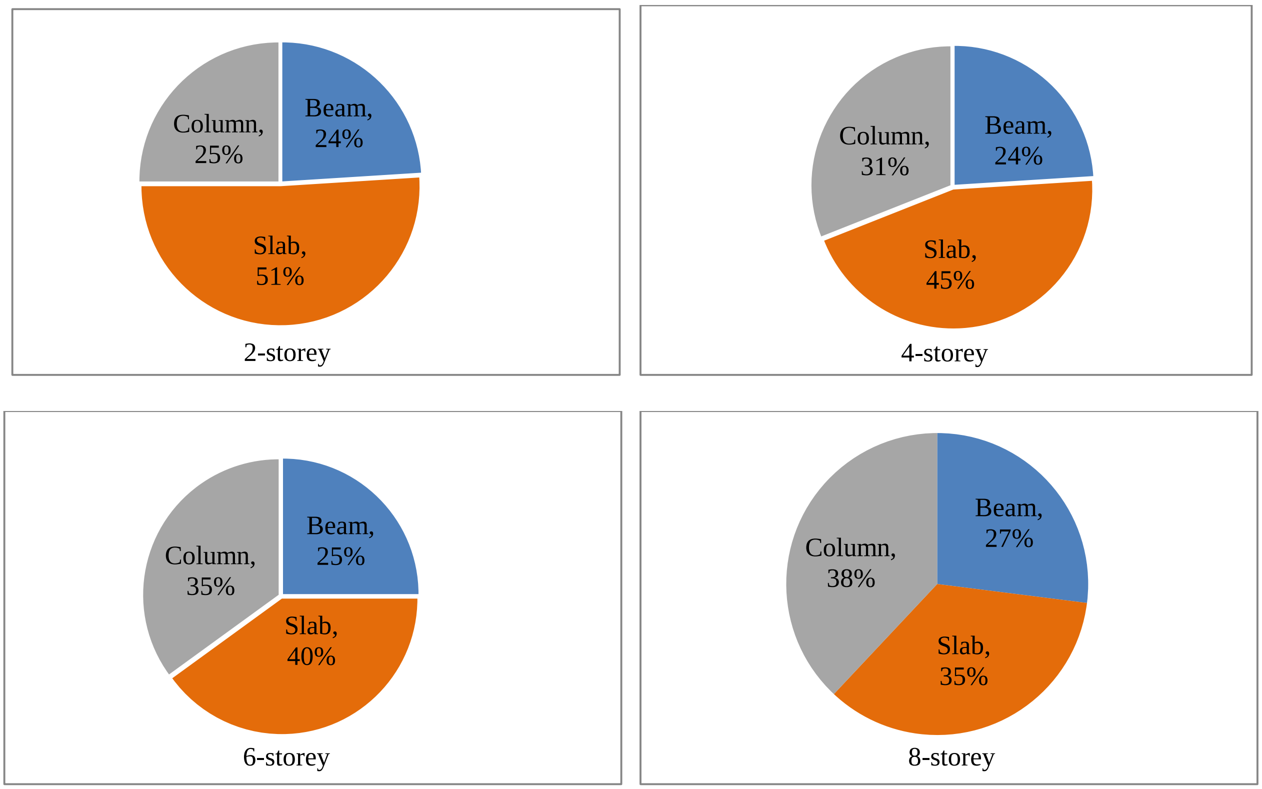
The breakdown of the EC by structural elements is presented in Figure 6 under both non-seismic and seismic designs. In non-seismic buildings, slabs consistently dominate the total EC, which is greater than 50% for all building heights. A large concrete volume and surface area, for slabs, and the thickness and reinforcement density do not change much, even for tall buildings, account for this dominance. Beams contributed 21–24% and columns accounted for the smallest share (13–26%), showing only a small share increase when building height increased due to higher axial load concrete cross-sections, reinforcement, and greater shaft height. In seismic buildings, the distribution shifts notably with height. Slabs remain the dominant contributor only in lower buildings, 51% in the 2-storey and 45% in the 4-storey designs, but their share decreases substantially in taller configurations, falling to 40% in the 6-storey and 35% in the 8-storey buildings. The increase in columns from 25% in the 2-storey case to 38% in the 8-storey case provides the primary explanation for this change. The beam contribution remained relatively stable, ranging from 24% to 27% across all the seismic heights.







(a) Non seismic



(b) Seismic

Fig. 6 Elemental contribution to embodied carbon for seismic and non-seismic designs in 2-, 4-, 6-, and 8-storey buildings

Stringent seismic design guidelines necessitate that columns in taller seismic structures be reinforced, confined, and stiffened to manage drift and ensure ductile behavior during a seismic event. Consequently, columns become larger in size with disproportionate increases in reinforcement compared to slabs and beams. Because concrete columns have a relatively low ratio of steel to concrete when compared to slabs and beams, additional steel in the columns increases the relative carbon emissions of the columns in comparison to the entire structure.

3.3. Cost Estimations

As shown in Figure 7, the construction costs for both seismic and non-seismic designs consistently increase with the building height. This is due to the greater material quantity for tall buildings. For all building heights, however, the seismic designs are more expensive due to larger member sizes, more reinforcement and detailing for the seismic standards, and additional construction complexities. For the 2-storey building, the total construction cost increased from US$28,000 in the non-seismic design to US$37,000 in the seismic design, an increase of 32%. The difference becomes progressively larger with height—42% for the 4-storey (US$60,000 to US$85,000), 52% for the 6-storey (US$96,000 to US$146,000), and 79% for the 8-storey configuration (US$128,000 to US$229,000). This pattern mirrors the embodied carbon results, highlighting the dual environmental and economic impacts of seismic design provisions, particularly in taller structures.

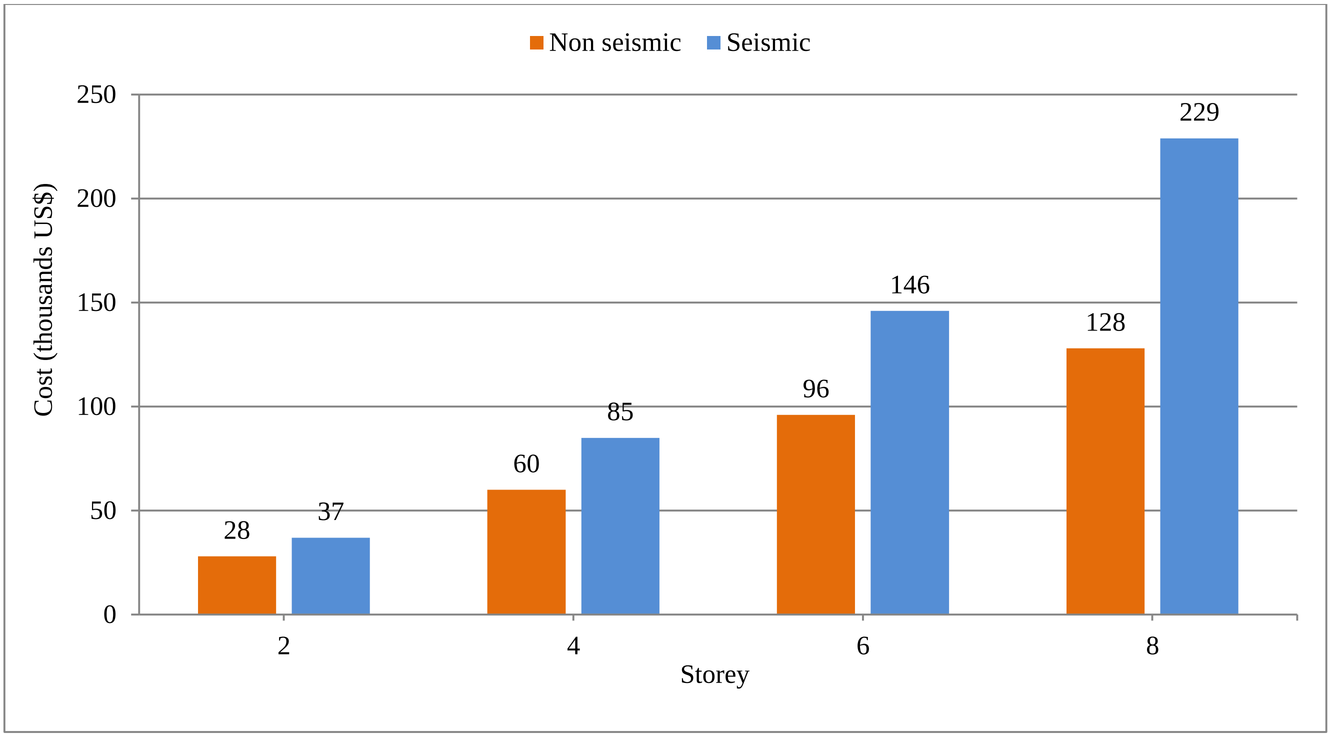
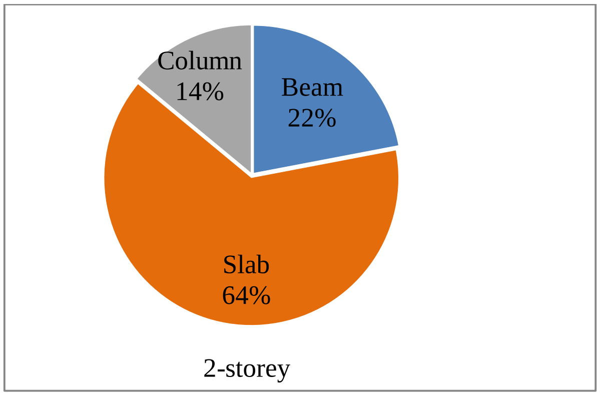


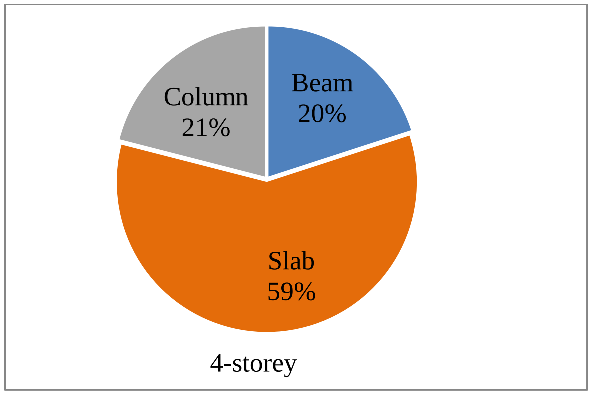
Fig. 7 Cost for seismic and non-seismic designs in 2-, 4-, 6-, and 8-storey buildings

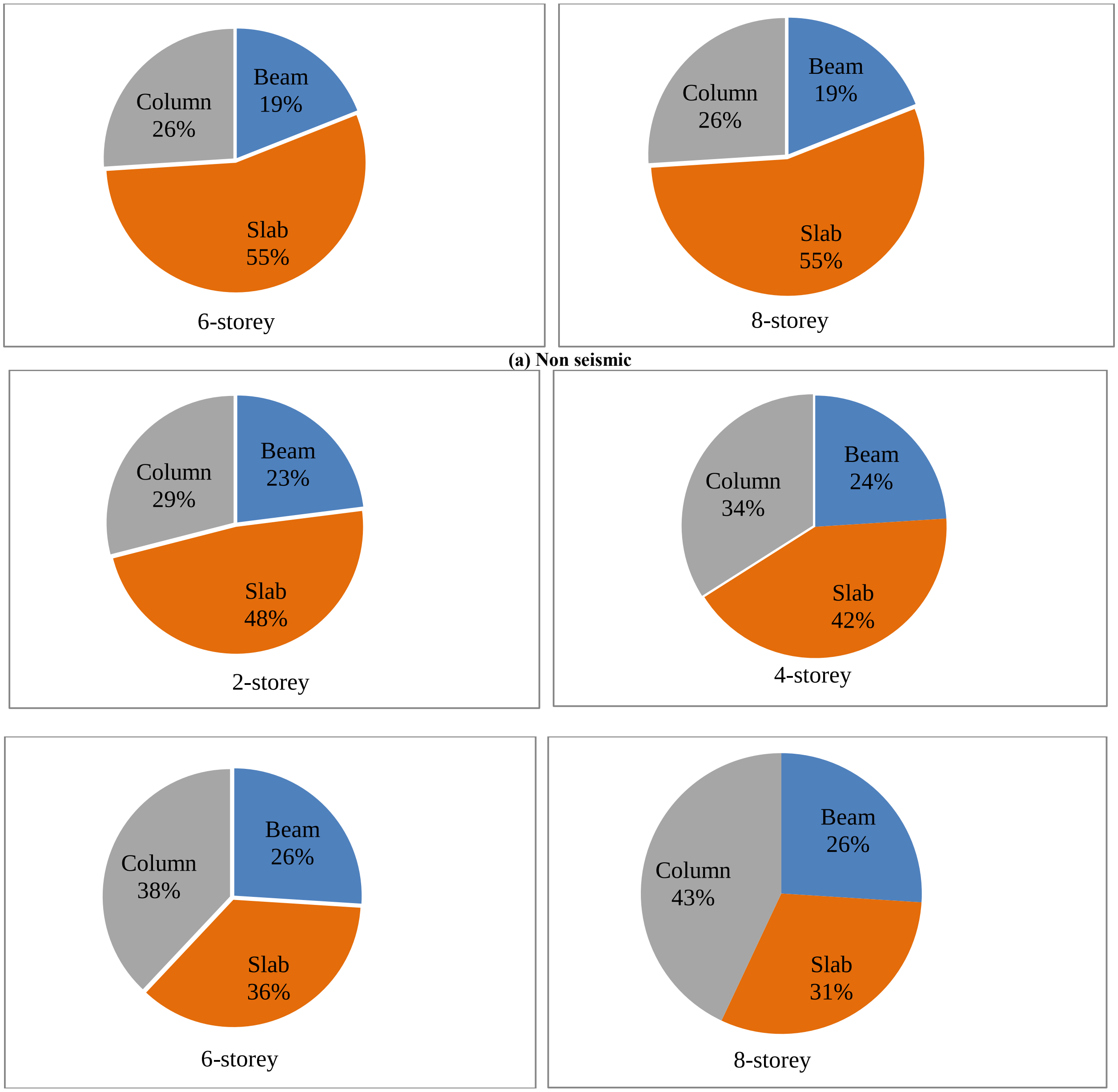
Examining construction costs further based on structural elements, as illustrated in Figure 8, uncovers more understanding. In non-seismic buildings, slabs are observed for every case to proportion the largest share of total costs (64% for the 2-storey case, then gradually decreasing to 55% in the 6 and 8-storey designs). Columns start off with a small share of 14% in the 2-storey case, then increase to 26% for the taller buildings, reflecting a moderate increase in their cross-sectional size and reinforcement demands. Beams stayed relatively stable throughout the range, 19% and 23%. In non-seismic designs, slab costs are dominant because of their extensive surface area, high formwork, and concrete volume demands.

In the case of seismic buildings, costs have an even more dramatic change in distribution with an increase in height. For shorter buildings, slabs still make the largest contribution (48% for 2-storey and 42% for 4-storey), but their share drops steeply to 36% and 31% for the 6 and 8-storey designs, respectively.

In contrast, the decline in slab contribution was counterbalanced by a large increase in column cost share, which rose from 29% in the 2-storey seismic design to 43% in the 8-storey configuration. There was also a small increase in beam costs, which ranged from 23 to 26%.







(b) Seismic

Fig. 8 Elemental contribution to cost for seismic and non-seismic designs in 2-, 4-, 6-, and 8-storey buildings

The costs associated with columns in taller seismic buildings are increasingly influenced by the complexities of seismic design provisions that demand larger cross-sections, reinforced ratios, and more intricate confinement detailing. Due to the steep unit pricing of reinforcement steel compared to concrete, the reinforced columns increase the cost share of columns to the entire building. Also, higher labour costs are incurred due to complex detailing for ductility.

The importance of understanding the constituent and marginal costs on the economics and cost performance of the structural systems on the overall system performance remains vital and impressive. In the non-seismic and low-rise buildings, there are more opportunities to make cost savings with slab systems, while in the high-rise seismic buildings, it will be the column system design that will more greatly impact the total price of construction. This tells how much there will be in total savings focused on seismic safety if there is a column redesign and seismic performance revision to column layouts, effective redesign with lesser materials, and other specific reinforcement techniques.

3.4. Carbon–Cost Trade-Off and Design Implications

The integrated study of Embodied Carbon (EC) with construction cost showed a significant relationship with regard to environmental impact relative to economic performance across all building configurations. There is a positive correlation with building height, and it is comparatively high with designs that consider seismic activity.

The explanation for this alignment is that the primary drivers with regard to material quantities have a direct impact on EC and cost, which is influenced by reinforced steel. However, the faster rate of increase for the EC and cost of seismic buildings, especially taller ones, is likely due to the higher carbon market pricing, as well as the increased need for steel reinforcement, relative to the other building designs.

In contrast to the previous studies that focused on slabs or on whole building averages, which were not integrated with cost, the present work advances the studies by incorporating component-level analysis of slabs, beams, and columns. This is also in terms of contrasting seismic and non-seismic provisions, and integrating cost in the analysis of EC. These results enhance optimisation studies such as that of Mergos [17]. This work extends it by incorporating a carbon-cost dual framework to enable practical slab efficiency prioritisation in non-seismic regions and column optimisation in seismic zones.

From an optimisation perspective, results for non-seismic buildings imply the need for element-specific optimisation as slabs consistently dominate the EC and cost throughout the case studies. This suggests that reductions in cost and EC can be achieved through more aggressive optimisation approaches such as span reductions, improvements in slab thickness design, and the use of alternative, more cost-effective materials. On the other hand, in seismic buildings, particularly the taller ones, the columns dominate the carbon–cost profile and thus, require more aggressive optimisation as well.

There is a trade-off between the two objectives, particularly in regions of high seismicity. While additional seismic provisions are vital, as they facilitate life safety and the overall building's resilience, the additional costs and carbon impacts must be recognised early in the design process. This is why integrating carbon costs and carbon qualitative assessments during preliminary design is so critical for identifying configurations that address the safety, required level of carbon, and cost. Overall, they underscore the need for decision-making frameworks that combine structural responsiveness, carbon mitigation, and budgetary targets.

The findings have additional implications, beyond just the implications for policy and the industry. Considering the policies, the results show that although necessary for safety, the seismic code requirements can be a significant driver of embodied carbon. This means there is an opportunity for upcoming building policies and regulations on green building practices to focus on incorporating either embodied carbon limits or providing benefits for low-carbon seismic detailing practices. From the industry's perspective, the carbon cost analysis will be a useful tool for engineers and developers to pinpoint where moderated control practices to reduce cost could be implemented, like slab efficiency for non-seismic areas and column reinforcement for seismic areas. For carbon and cost evaluation, clients and contractors can facilitate their decision processes on feasibility studies and procurement to improve the overall sustainable and cost-effective nature of their processes.

4. Conclusions

This research determines how variations in building height impact the Embodied Carbon (EC), construction costs, and the carbon-cost trade-off of reinforced concrete buildings with and without seismic considerations and construction for seismic conditions. This work considered three primary structural components (slabs, beams, and columns), their different contributions to total materials, polymer concrete composite systems, costs, and the carbon-cost trade-off.

The main conclusions are as follows.

1. Material demand and building height: The concrete volume and the weight of the reinforcing steel for all design scenarios varied with building height, and all designs subsequently required more materials. Attention to materials required for designs with and without seismic considerations increased with height. This was especially the case with reinforced steel, indicating the effect of seismic design code details.
2. Embodied carbon trends: The EC of both seismic and non-seismic buildings increases with height. However, the EC of seismic constructions of taller buildings is more significant. For instance, 8 non-seismic design and 8-storey seismic design constructions are comparable, and the non-seismic design generated 54% less EC, chiefly because of the increased steel percentage in the columns and beams of the non-seismic design. The high emission factor for steel is the principal reason for the non-seismic design being a dominant factor in the EC growth.
3. Cost implications: Construction costs increased with building height and, like the EC, were still higher in seismic designs. For tall structures, the cost impact of steel-intensive seismic detailing is particularly pronounced.
4. Element-level contributions: In non-seismic buildings, slabs account for over 50% of the total ECM and cost for all building heights, underscoring their role as a primary element for optimisation. In seismic buildings, the dominance of slabs diminished with height, while the contributions of columns increased significantly, from 25% ECM share in 2-storey buildings to 38% in 8-storey buildings, owing to the requirements of seismic drift and ductility.
5. Carbon–cost trade-off: The relation of EC and cost was strongest for taller buildings with seismic design. These configured buildings were the worst in the carbon–cost spectrum. In the non-seismic design, lower- to mid-rise

buildings were the most balanced, attaining low EC per unit cost.

6. Design implications: In non-seismic contexts, the greatest potential for improvement revolves around slab optimisation. In seismic regions, the focus shifts to designing efficient columns and reducing steel. Evaluating the carbon embodied in structures built to seismic standards and resilient designs will satisfy the need for balanced structures.

This reinforces the need for a systematic and integrated structural design approach to focus on embodied carbon. The increased material usage for seismic design necessitates the need for balanced provisions that minimise environmental impact while preserving structural safety. Design standards with a carbon–cost trade-off balanced allow resilient construction to meet the decarbonisation targets of new builds without unnecessary safety and cost.

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Ethical Approval

This study did not involve human participants, animal subjects, or confidential data, requiring ethical approval. All analyses were conducted with respect to academic integrity. The authors affirm that the data presented are original and have not been manipulated or fabricated.

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Author Contribution

RS prepared the manuscript, MS reviewed the manuscript, and MK performed the analysis.

Data availability

Data analysis https://zenodo.org/records/16757666

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