Impact of Seismic Design on Embodied Carbon in Steel Buildings: A Structural Element-based Assessment

Militia Keintjem
Civil Engineering Department, Faculty of Engineering, Bina Nusantara University, Jakarta, 11480, Indonesia
militia.marchella@binus.ac.id

Riza Suwondo
Civil Engineering Department, Faculty of Engineering, Bina Nusantara University, Jakarta, 11480, Indonesia
riza.suwondo@binus.ac.id (corresponding author)

Made Suangga
Civil Engineering Department, Faculty of Engineering, Bina Nusantara University, Jakarta, 11480, Indonesia
suangga@binus.ac.id

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ABSTRACT

The building and construction sector is a major contributor to global carbon emissions, with Embodied Carbon (EC) from material production, transportation, and construction gaining increasing attention. Although seismic design enhances structural safety, it also leads to a higher material consumption, thereby increasing the EC footprint of the buildings. This study examines the impact of seismic design on EC in steel buildings, focusing on columns, beams, and floors. A two-story steel-framed building was analyzed under low, moderate, and high seismic intensities. The EC assessment followed BS EN 15978, considering cradle-to-gate emissions (stages A1–A3) using industry-standard Inventory of Carbon and Energy (ICE) database values. Structural modeling was conducted using ETABS to determine the material demands. The results showed that the total EC increased by approximately 51% from non-seismic to high seismic conditions. Columns and beams exhibited the highest proportional increase owing to the larger cross-sectional sizes required for seismic stability, while concrete slabs contributed the most absolute emissions. Steel components, however, exhibited the greatest relative rise in carbon intensity. To reduce the EC in seismic design, structural optimization methods, high-strength steel utilization, and material reuse strategies should be explored. This study provides a scientific foundation for integrating sustainability into seismic regulations, thus contributing to low-carbon structural solutions for earthquake-prone regions.

Keywords-embodied carbon; seismic design; sustainable construction; steel structure

I. INTRODUCTION

The building and construction sectors are major sources of Greenhouse Gas (GHG) emissions worldwide. Estimates indicate that the latter is responsible for 37–39% of the global energy-related CO_2 emissions [1, 2]. Within this total:

- 10–15% stems from EC (emissions generated during material production and construction processes).
- The remainder arises from operational carbon (emissions associated with heating, cooling, and powering buildings during use).

The World Green Building Council reports that 28% of the global building sector emissions are due to operations and 11% are due to materials and construction processes. As operational energy use is reduced through the efficiency and decarbonisation of the energy supplies, the relative importance of EC is increasing. It is projected that the "upfront" carbon emissions (materials and construction) will account for approximately 50% of the total carbon footprint of new construction between now and 2050 [3]. This makes addressing EC in buildings a critical part of climate mitigation strategies for the built environment.

Several studies have examined the role of EC in buildings, emphasizing the need for sustainable construction practices. Authors in [4] utilized Building Information Modelling (BIM) to evaluate the environmental impact of a three-story commercial building in Pakistan. Their findings revealed that the materials contributing most significantly to the overall carbon footprint were steel (33.51%), concrete (19.98%), brick (14.75%), aluminum (12.10%), and paint (3.22%), which in combination accounted for over 80% of the total emissions. Similarly, authors in [5] applied the Athena Impact Estimator for Buildings to conduct a Life Cycle Assessment (LCA) comparing a mass timber building with a conventional steel–concrete building in Boston, Massachusetts. The analysis assumed a 60-year lifespan for both structures and demonstrated that the timber building required 52% less construction materials, while achieving a 53% reduction in EC compared with its steel-concrete counterpart.

Authors in [6] adopted an Input-Output National Database approach to estimate the energy consumption and greenhouse gas emissions of construction materials over their life cycle in Japan. Their study assessed a three-story reinforced concrete library building covering a site area of 849 m² and a total floor area of 2,413 m². The findings indicated that the total emissions from the construction phase to the end-of-life phase amounted to 1,367,120 kg of CO_2e. Authors in [7] employed a hybrid LCA methodology to analyze the carbon footprints of residential and commercial buildings in the United States. Their study highlights the dominant role of the operational phase, accounting for 91% of the total EC contribution. This finding highlights the need for strategies that not only minimize EC at the construction stage, but also enhance energy efficiency during building operations. Authors in [8] conducted a comprehensive review of EC assessment methodologies in buildings, synthesizing findings from 48 published articles. Their review identified four main approaches used in EC LCAs: BIM, the Athena Impact Estimator for buildings, Input-Output Databases, and Hybrid Input-Output LCA. They also highlighted the challenge of missing data in existing methodologies and proposed the integration of machine learning models to address this issue. Furthermore, they emphasized the necessity of standardizing protocols and guidelines for EC assessments to ensure consistency and comparability across projects and regions. The implementation of these recommendations can significantly enhance the reliability of EC evaluations and facilitate their adoption in the construction industry.

Buildings in seismic zones often require more robust structures to withstand earthquakes, which can increase the quantity of steel and other materials, and thus the EC impact. Seismic design codes (e.g., those applicable to seismic zones) typically mandate additional reinforcement, ductile detailing, and redundancy—all of which tend to increase material usage compared to non-seismic designs. Studies have found that the choice of the structural system for lateral force resistance significantly affects EC. For steel structures, using braced frames, which carry seismic loads through axial member action, can reduce the required steel tonnage compared with moment-resisting frames. One comparison showed a 20% reduction in EC when switching from moment frames to steel-braced frames for a building of a similar size and seismic design criteria [9]. This is because braced frames typically use less steel mass, but more braces, to achieve the same strength and stiffness, whereas moment-resisting frames rely on heavy beams and columns, and rigid connections.

Despite these advancements, a notable gap exists in the understanding of how seismic design influences the EC of individual structural elements, such as columns, beams, and floors. There has been limited research specifically addressing the impact of seismic design on EC. Seismic codes often require additional reinforcement and material to enhance structural resilience, which can increase the EC footprint of a building. To address this gap, this study aims to investigate the EC contribution of each structural element in steel buildings and compare the differences between seismic and non-seismic designs. By quantifying these variations, this study aims to provide insights into optimizing steel building designs for both sustainability and structural safety.

II. METHODOLOGY

The current study investigated a two-story steel building with a consistent plan arrangement featuring three bays, as illustrated in Figure 1. The building had a standard story height of 4.0 m and concrete slab depth of 150 mm. Two different spans, 6 m and 8 m, were investigated, with gravity loads having been considered based on the recommendations of ASCE 7-16 [10]. The applied loads included a self-weight, an additional superimposed dead load of 0.5 kN/m², and a live load of 2.0 kN/m². These loading conditions represent realistic serviceability requirements for typical steel-frame buildings.

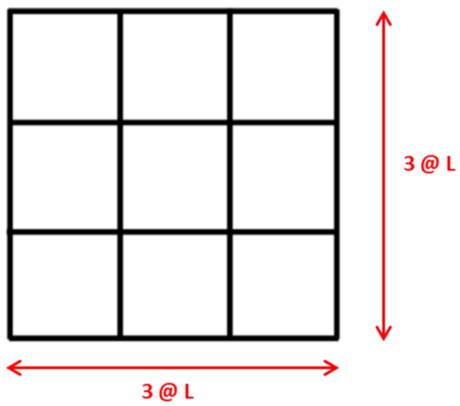

Fig. 1. Selected building plan.

Seismic loads were incorporated into the analysis based on ASCE 7-16 provisions [10]. To evaluate the impact of seismicity on EC, three seismic zones were considered.

- Low seismicity: Seismic coefficient of 0.027
- Medium seismicity: Seismic coefficient of 0.137
- High seismicity: seismic coefficient of 0.222.

For the steel structures, JIS G 3101 SS400 steel with a yield strength of 245 MPa was selected. The structural system was designed in accordance with AISC 360-16 [11] for strength and serviceability, and AISC 341-16 [12] for seismic performance. This study adopts an Intermediate Moment-Resisting Frame (IMRF). The H-sections were used for the columns, whereas the I-sections were utilized for the beams. This configuration ensures that the structural elements provide optimal performance under both gravitational and lateral loading conditions, thereby contributing to the overall structural stability of the building. Concrete C20/25 was used for the concrete slabs, which were designed based on ACI 318-19 [13]. Structural analysis and design were conducted employing the well-established commercial finite element software package ETABS [14].

The EC assessment followed the framework established in BS EN 15978 [15], which outlines the methodology for evaluating the environmental performance of buildings. This study focused on stages A1–A3, collectively known as the 'cradle-to-gate' phase. This phase encompasses raw material extraction, transportation, and manufacturing [16]. Research by the London Energy Transformation Initiative [17] underscores the significance of this phase, noting that it can contribute up to 50% of a building's total life cycle carbon footprint. Consequently, employing ' cradle-to-gate-EC as a key performance indicator is a logical approach for assessing the environmental impact of structural design choices.

The EC total was calculated using:

$$\mathrm{EC} = \sum Q_i \times CF \quad (1)$$

where Q_i is the quantity of the material and *CF* is the EC factor derived from well-established ICE databases [18], and is expressed as:

- Steel section: 1.55 $kgCO_2e/kg$
- Reinforcing bar: 1.99 $kgCO_2e/kg$
- Concrete: 267 $kgCO_2e/m^3$

A comparative analysis was conducted to assess the variations in EC resulting from seismic design requirements. This approach provides valuable insights into the environmental impacts of structural decisions in both seismic and non-seismic regions.

III. RESULTS

The steel design results obtained from the structural analysis and design are summarized in Table I. The results demonstrate a progressive increase in beam and column sizes with higher seismic intensity, primarily due to higher lateral force and strong-column–weak-beam requirements according to AISC 341-16. The columns experienced the most significant increase in cross-sectional area and weight, particularly in high seismic zones, where additional stiffness and strength are required to mitigate the P-delta effects and ensure ductility. Beams also increased in size, but to a lesser extent because they were designed to accommodate plastic hinging and improve energy dissipation.

EC analysis was conducted to determine the EC per square meter of floor area. Figure 2 presents the EC values for both the 6 m and 8 m spans under varying seismic intensities. The effect of the span length on EC provides additional insights into the material efficiency in seismic design. The results indicate that the 8 m span structure exhibits higher EC compared to the 6 m span structure, primarily because of the increased material requirements for larger beam spans. Furthermore, the findings revealed a strong correlation between seismic intensity and EC, with higher seismic demands requiring larger section sizes for beams and columns, thereby increasing the material consumption. For both span configurations, the total EC increased by approximately 51% when transitioning from a non-seismic to a high-seismic design condition. These results emphasize the significant impact of seismic design on material usage and EC, highlighting the need for optimized structural solutions to enhance both seismic performance and environmental sustainability.

TABLE I. STEEL DESIGN RESULTS

Condition	Span 8 m		Span 6 m	
	Column	Beam	Column	Beam
No EQ	H250	I250	H200	I200
Low EQ	H300	I250	H250	I200
Moderate EQ	H350	I300	H300	I250
High EQ	H400	I400	H350	I250

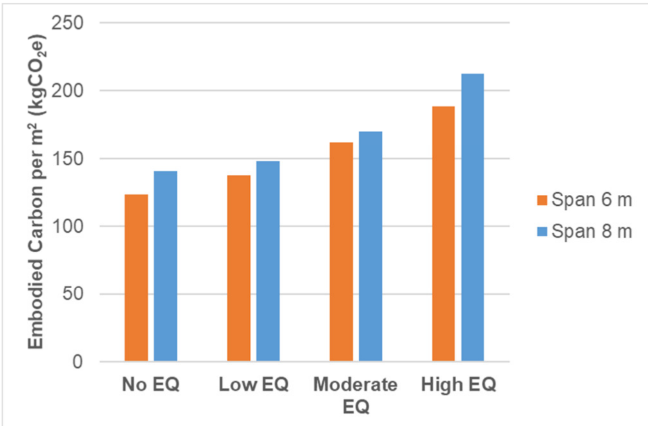

Fig. 2. EC/m².

A detailed breakdown of the EC contributions by structural element, as presented in Figure 3, highlights the relative impact of each component on the overall carbon footprint of the structure. The concrete slab remains the largest single contributor to EC given its extensive use across the entire floor area. However, the effect of seismic reinforcement is most noticeable in steel components, particularly columns and beams, which experience significant material increases to satisfy seismic stability, ductility, and strength requirements. Under non-seismic conditions, the columns and beams collectively accounted for approximately 40% of the total EC. However, as the seismic demand escalates, these structural elements undergo substantial size increases, causing their contribution to increase beyond 60% in high seismic zones. This shift demonstrates the direct correlation between seismic design and increased steel consumption, as additional sectional reinforcement, moment capacity enhancements, and lateral force resistance mechanisms are required to maintain structural integrity.

The increased EC in steel elements can be primarily attributed to two key factors: (1) the strong-column-weak-beam requirement, which dictates a proportional increase in the column strength relative to the beam plastic hinge capacity, and (2) the additional steel mass required to resist amplified lateral loads and P-delta effects in seismic regions. These findings highlight the critical role of seismic design in shaping material efficiency and EC emissions, reinforcing the need for innovative structural optimization strategies, such as high-strength steel, alternative section profiles, and hybrid construction methods, to minimize environmental impact while ensuring seismic resilience.

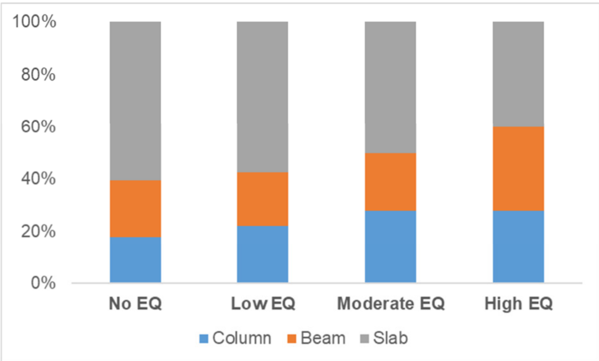

Fig. 3. EC contribution by structural elements.

IV. DISCUSSIONS

This study offers a unique contribution by providing an element-level assessment of EC in steel buildings under varying seismic conditions, a level of detail that is often missing in prior research, which typically focuses on whole-building analysis or material substitution strategies. While previous studies [4, 7] have examined EC across different building typologies or structural materials, they have often overlooked the influence of seismic code requirements on the material demands of individual structural components. By isolating the EC contributions from columns, beams, and slabs, this study revealed how seismic intensity directly affects each element, particularly steel components, owing to the need for enhanced strength and ductility.

The comparison of results across seismic zones highlights a clear trade-off: while seismic design is essential for life safety and structural resilience, it results in notable increases in EC, particularly in steel-intensive elements. This reinforces the need for more refined seismic design strategies that incorporate sustainability objectives rather than solely focusing on safety. Furthermore, the analysis across the two span lengths contributes new insights into how structural layout decisions influence embodied emissions, providing a more comprehensive understanding for engineers who are seeking to balance performance and environmental impact.

By integrating seismic design provisions with EC assessment, this study contributes to the emerging field of sustainable seismic design, laying the groundwork for future investigations into design optimization, alternative structural systems, and whole-life carbon performance in earthquake-prone regions. To advance this agenda, future research should adopt a holistic LCA framework that accounts for both embodied and operational carbon emissions over the entire building life cycle. Furthermore, the development of strategies for material reuse, recycling, and recovery, along with the application of performance-based design, high-strength steel, and hybrid systems, is essential for minimizing EC while maintaining compliance with seismic performance standards. Ultimately, the integration of sustainability principles into seismic design practices is critical for advancing low-carbon construction in seismically active regions and contributing to broader global decarbonization goals.

V. CONCLUSIONS

This study systematically evaluated the Embodied Carbon (EC) footprint of steel buildings under varying seismic design requirements, thereby providing key insights into the relationship between seismic intensity, material consumption, and environmental impact. The results demonstrated that seismic design significantly increased the EC, with the most pronounced effects observed in steel structural components, particularly columns and beams. This increase is attributed to the larger section sizes and additional reinforcement necessary to satisfy the seismic stability and ductility requirements, as mandated by AISC 360-16 and AISC 341-16. This study further highlights that EC increases by approximately 51% from non-seismic to high-seismic conditions, underscoring the substantial environmental implications of seismic design provisions.

A detailed breakdown of EC contributions reveals that, while the concrete slab remains the largest single contributor, the relative increase in EC is most evident in steel elements because of their critical role in lateral force resistance. The enforcement of seismic design principles, particularly the strong-column-weak-beam ratio and lateral stiffness requirements, results in a notable increase in steel consumption, thereby emphasizing the trade-off between structural resilience and sustainability. These findings highlight the need for material-efficient design approaches that balance seismic safety with carbon-reduction strategies.

This study builds upon and extends the existing research on EC in buildings by offering an element-level analysis under varying seismic design conditions, which often lacks in the current literature. Although previous studies have explored material substitution or whole-building carbon assessments, they have rarely examined how seismic requirements influence the EC of individual structural components. By addressing this gap, the present study provides a more granular insight into the relationship between seismic performance requirements and embodied emissions, supporting the development of integrated structural-environmental design frameworks for steel buildings.

To mitigate the environmental impact of seismic design, future research should focus on holistic Life Cycle Assessments (LCAs) that evaluate both embodied and operational carbon emissions throughout the lifespan of a building. Additionally, structural optimisation techniques, such as high-strength steel utilisation, performance-based design, and hybrid construction systems, should be explored to minimise material consumption while ensuring compliance with seismic performance requirements. The integration of material recovery, recycling, and reuse strategies can further contribute to reducing the carbon footprints of seismic-resistant structures.

Overall, this study underscores the necessity of integrating sustainability principles into seismic structural design and advocating the development of innovative low-carbon engineering solutions. By optimizing material efficiency and adopting advanced design methodologies, the construction industry can move towards more environmentally responsible seismic-resistant buildings, ultimately contributing to global carbon reduction targets and sustainable development goals.

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DATA AVAILABILITY

The utilized data can be found at: https://zenodo.org/records/14954743

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