Finite Element Based Optimization of Two-Way Concrete Slabs: A Comparative Study on Embodied Carbon and Cost Efficiency

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ABSTRACT

The building sector is a major source of Global Greenhouse Gas (GHG) emissions. The carbon embodied in construction materials has drawn attention in sustainable design. Reinforced concrete slabs, as core structural elements, contribute notably to both environmental and economic impacts. This study examines the use of Finite Element Modeling (FEM) in the design of two-way concrete slabs. The goal is to reduce the embodied carbon and material cost compared to the conventional design methods. A concrete slab system was analysed under typical office building loads. A structural design was developed using FEM and compared to the Marcus method. This traditional approach relies on empirical moment coefficients and is widely used in Indonesian engineering practice. The results showed that FEM consistently required less reinforcement for all slab thicknesses studied. This reduction in material led to carbon savings of up to 12%. It also resulted in cost savings of up to 15% per m², especially for slabs 150–180 mm thick. While the difference between the methods decreased with thicker slabs, FEM remained more efficient in all cases. Overall, the findings show that FEM improves the structural precision. At the same time, it supports both the environmental and economic goals in slab design. Performance-based methods, like FEM, can help achieve low-carbon construction without compromising safety or code compliance.

Keywords-low carbon structures; sustainable building; climate action; embodied carbon; sustainability

I. INTRODUCTION

The building sector is responsible for approximately 40% of the global energy consumption and contributes around 30% of the anthropogenic GHG emissions [1, 2]. When evaluating the energy demand and environmental impact of buildings across their life cycles, these impacts are typically categorized into operational and embodied impacts. Although progress has been made in reducing the operational impacts, primarily through technological innovation and regulatory frameworks, reducing the embodied impacts remains a significant challenge. This is largely due to the lack of standardized methodologies, comprehensive data, and regulatory guidance [3–6]. Without real progress in building efficiency, emissions from the construction sector could rise sharply, possibly doubling within two decades. This trend is mainly fueled by the urban expansion and increased development activity [7, 8].

Most academic studies on embodied carbon focus on case-specific assessments. However, life cycle evaluation methods are now gaining traction in professional practice. Despite this progress, there is still a lack of clarity about the data sources and assumptions used in these calculations. Authors in [9] used Building Information Modeling (BIM) to assess the environmental impact of a three-storey commercial building in Pakistan. Their results showed that steel, concrete, brick, aluminium, and paint were the main contributors to embodied carbon together accounting for over 80% of the total.

Authors in [10] applied the Athena Impact Estimator to compare a mass timber building with a traditional steel–concrete structure in Boston. Over a 60-year life span, the timber structure used 52% less material and had a 53% lower embodied carbon footprint. Authors in [11] used a national input–output database to estimate the energy use and emissions from construction materials in Japan. Their case study focused on a three-story reinforced concrete library and offered material specific insights across the building's life cycle.

While these studies highlight the role of materials in embodied carbon, they say little about how design methods affect the environmental impact. In particular, the potential of structural design tools, like FEM, remains underexplored. Economic aspects, and especially the material cost, are also often overlooked, even though they are critical for project viability.

This study addresses key gaps in the literature. It examines how FEM can optimize the design of two-way reinforced concrete slabs. The focus is on reducing both the embodied carbon and cost compared to conventional methods. Beyond structural performance, the study includes a combined assessment of the environmental and economic outcomes. This is achieved through FEM-based reinforcement optimization. It has been shown that FEM can improve the material efficiency [12]. However, few studies have considered both the cost and carbon impacts, especially in the ASEAN context.

II. METHODOLOGY

The current study explored how FEM can help reduce the embodied carbon in reinforced concrete slab design. The focus was on two-way slab systems typically used in office buildings. The performance of FEM based design was compared with that of conventional design methods to assess the potential benefits in terms of material efficiency and environmental impact.

The structural system considered in this study consisted of a two-way reinforced concrete slab supported by beams arranged in a 3×3 bay configuration, as shown in Figure. 1. Each bay was modeled with equal spans in both directions, representing a typical office floor layout. This configuration is chosen to reflect common practice in medium-rise office buildings and to allow for a realistic structural behavior under gravity loads. The structural materials used in the slab design include normal-weight concrete with a specified compressive strength of f_c'=20 MPa [13] and reinforcing steel bars conforming to BjTS 420A with a yield strength of 420 MPa [14].

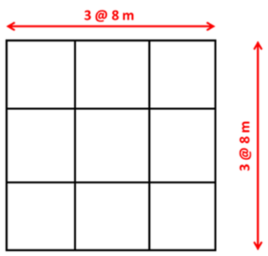

Fig. 1. Selected building plan.

The gravity loads applied to the slab system were defined based on [15]. The dead load was set at 2.0 kN/m² to account for the weight of non-structural elements, finishes, and ceiling systems. A live load of 2.5 kN/m² was used, representing typical office occupancy.

Finite element analysis was carried out using ETABS [16], a widely employed tool for structural modeling. The two-way slab was modeled with shell elements to capture both the in-plane and out-of-plane bending behavior under gravity loads. To ensure accurate results, the mesh size was limited to a maximum of 1m.

The model also included supporting beams with realistic stiffness values. Boundary conditions were applied to reflect actual restraints, such as the slab continuity and the interaction between the beams and slabs. The bending moment distributions obtained from the FEM analysis were used as the basis for reinforcement design, in accordance with the relevant code provisions. These results are illustrated in Figure 2, where the moment contours across the slab surface are demonstrated.

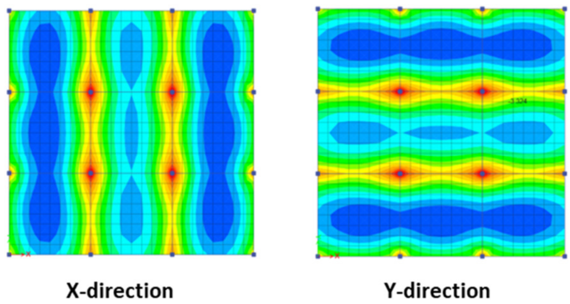

Fig. 2. Moment diagram.

For the comparison, the slab was also designed using the Marcus method, a conventional approach commonly deployed in Indonesian engineering practice for two-way reinforced concrete slabs. This method relies on empirical moment coefficients derived from the elastic plate theory, with adjustments based on experimental results to better reflect the real-world slab behavior under uniformly distributed loads. The design bending moment in each direction M_i is calculated using:

$$M_i = 0.001 C_i q l_x^2 \quad (1)$$

where C_i is the empirical moment coefficient, which depends on the aspect ratio of the slab and the boundary conditions, q is the ultimate uniformly distributed load and l_x is the shorter span of the slab panel. These simplified assumptions allow for practical and efficient design without the need for numerical modeling. However, they often lead to conservative reinforcement estimates, especially in slabs with more complex support conditions.

For both the FEM-based and conventional design approaches, the internal forces obtained from the analysis were used to design the slab according to [17]. Reinforcement was placed in both orthogonal directions, based on the maximum positive and negative bending moments identified in each method. The required steel area was calculated through standard flexural design procedures, following the code guidelines. In addition, the FEM-based designs were carefully checked to ensure that all slab sections met the requirements for both the ultimate strength and serviceability limit states.

The designed flexural strength of the slab section (ϕM_n) is calculated using:

$$\phi M_n = 0.9 A_s f_y \left(d - \frac{a}{2}\right) \quad (2)$$

where A_s is area of tensile reinforcement, f_y is the yield strength of the reinforcement steel, d is the effective depth from the compression face to the centroid of the tensile reinforcement, and a is the depth of the equivalent rectangular stress block calculated according to:

$$a = \frac{A_s f_y}{0.85 f_c' b} \quad (3)$$

where f_c' is the concrete compressive strength and b is the width of the slab strip considered (typically 1 m for design per m width).

To satisfy the serviceability requirements, a minimum slab thickness was adopted based on empirical code provisions. This ensures an adequate control of the deflections under service loads. The minimum thickness (h_{min}) is calculated using:

$$h_{min} = \frac{l_n(0.8 + \frac{f_y}{400})}{36 + 9\beta} \quad (4)$$

where l_n represents the clear span length measured face-to-face between the supports, f_y is the yield strength of the reinforcement, and β is the ratio of the longer to the shorter slab dimension. By adopting this minimum thickness, it can be reasonably assumed that the slab deformations remain within acceptable limits, which is in line with the serviceability requirements of [17]. As a result, excessive deflection is effectively controlled, and additional deflection checks are inherently satisfied as part of the design process.

The embodied carbon assessment for the reinforced concrete slab designs was carried out using a "cradle-to-gate" life cycle approach, covering stages A1-A3 as defined in [18]. These stages include the extraction of raw materials, transportation to manufacturing sites, and the production processes of construction materials.

- A1: Raw material supply.
- A2: Transport to manufacturing facilities.
- A3: Manufacturing processes.

This system boundary excludes the transportation to the construction site, on-site construction activities, maintenance, and end-of-life processes. As such, the assessment strictly focuses on the environmental impact associated with material production. The total embodied carbon (EC) of the concrete slab was calculated using [19]:

$$EC = \sum_{i=1}^{n} (Q_i \times EF_i) \quad (5)$$

where Q_i is the quantity of material i (e.g. volume of concrete and mass of reinforcement), and EF_i is the emission factor of the material i (kgCO_2e/unit). The emission factors (EF) used in this study were sourced from [20], which provides widely accepted values for construction materials based on circular ecology principles. Table I summarises the emission factors used for the concrete and reinforcement steel in this study.

TABLE I. EMBODIED CARBON FACTORS FOR CONSTRUCTION MATERIALS

Material	Emission factor (kgCO_2e/kg)
Concrete (20 MPa)	0.112
Rebar	1.9

The cost analysis in this study is based on typical construction material prices relevant to the Indonesian context [21], as shown in Table II. The unit cost factors, expressed per m³ for concrete and per kg for reinforcement steel were used to assess the economic impact of each slab design alternative.

TABLE II. MATERIAL UNIT COST (US $ 1 = RP. 17,000)

Material	Cost (Rp)	Cost (US$)
Concrete (kg)	1,500,000	88.5
Rebar	25,000	1.5

Incorporating local construction costs ensures that the analysis reflects the real-world pricing. This enhances the practical relevance of the results. By using actual market conditions, the economic evaluation becomes more grounded. Thus, the study provides insights that are both environmentally and financially meaningful. These findings are particularly useful for decision-makers and professionals in the Indonesian construction industry.

III. RESULTS AND DISCUSSION

This section presents and discusses the results of two-way reinforced concrete slab designs, developed using both the FEM approach and the conventional Marcus method. The analysis focuses on three key aspects: structural performance, embodied carbon, and material cost. First, the slab thicknesses and reinforcement demand from each method were compared to assess the structural efficiency of the FEM-based design. Then, the embodied carbon of each slab configuration was evaluated. This was calculated using material quantities and cradle-to-gate emission factors. Finally, the study examined the cost implications of each design alternative. This was based on local unit prices for concrete and reinforcement steel. In combination, these analyses offer a well-rounded comparison of the environmental and economic performance. The findings aim to support more informed and sustainable decisions in structural engineering practice.

A. *Concrete Slab Design Results*

Figure 3 demonstrates how the reinforcement ratio (in kg/m³) varies with slab thickness for both design methods. The slab thicknesses considered range from 150 to 250 mm, which are typical values for office building floors. The results indicate that the FEM-based design consistently requires less reinforcement than the conventional method. This trend is maintained across all thicknesses. The difference is most noticeable in thinner slabs, particularly in the 150–180 mm range. In these cases, the Marcus method applies higher reinforcement levels to compensate for its simplified assumptions about moment distribution. In contrast, the FEM approach captures the actual behavior of the slab more accurately under load. This allows reinforcement to be placed only where it is structurally necessary. Therefore, it achieves greater material efficiency without overdesign.

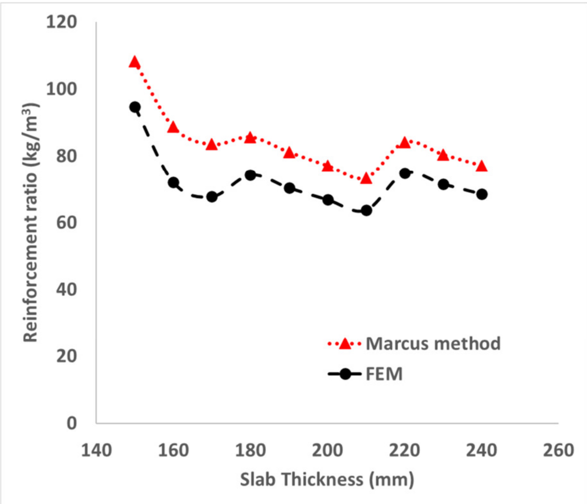

Fig. 3. Reinforcement ratios for different slab thicknesses.

As the slab thickness increased beyond 200 mm, the reinforcement ratios of both methods started to converge. This indicates that in thicker slabs, higher stiffness reduces the reinforcement demand. As a result, the benefit of FEM-based optimization becomes less pronounced. Even so, FEM still offers a clear advantage. In thinner slabs, a 20–25% reduction in reinforcement was observed. This aligns with [13, 14], where it was shown that the FEM-based design can achieve the same structural performance using significantly less steel. These gains come from FEM's ability to model the two-way load distribution and moment redistribution with greater accuracy. In contrast, conventional methods use simplified coefficients and provide only approximate solutions.

B. Embodied Carbon Assessment

Figure 4 displays the total embodied carbon per square meter ($kgCO_2e/m^2$) for slabs of different thicknesses. The results from the FEM are compared with those from the conventional Marcus method. As expected, the embodied carbon increases with the slab thickness. This is due to the larger amounts of concrete and steel needed in deeper slabs. In all cases, the FEM-based design resulted in lower embodied carbon than the conventional method. This is linked to the lower reinforcement requirements. The potential of FEM for material optimization was confirmed since greatest reductions were seen in thinner slabs, especially those between 150 and 180 mm. In this range, the Marcus method tends to overestimate moment demands due to its simplified assumptions. As a result, the embodied carbon savings reached 10–12%.

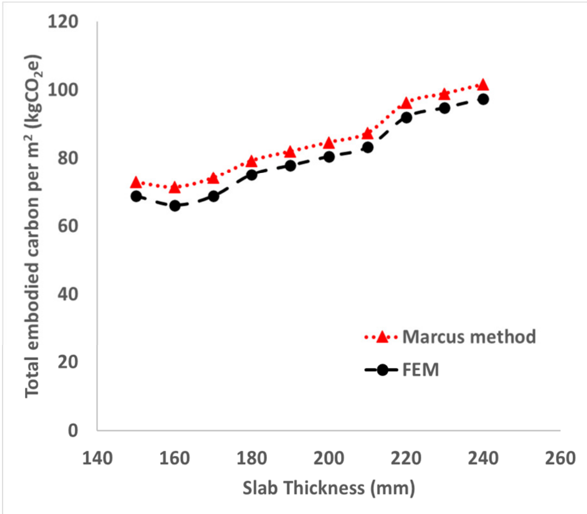

Fig. 4. Total embodied carbon per m^2 for different slab thickness.

As the slab thickness increased beyond 200 mm, the difference in the embodied carbon between the two methods became less noticeable. This is mainly because concrete volume, the main source of embodied carbon in thicker slabs, started to dominate the total impact. In such cases, the effect of reinforcement reduction becomes less significant. Even so, the FEM approach continued to perform better across all thicknesses. This confirms its value in achieving more sustainable structural designs.

Overall, the results stressed the environmental benefits of using FEM-based design methods in reinforced concrete slab construction. By promoting more efficient material use, FEM meets structural performance requirements while helping reduce the carbon emissions in the built environment. These findings also carry broader significance for sustainable construction in the ASEAN region. Countries like Indonesia are increasingly adopting green certification systems, such as EDGE and LEED. In this context, FEM-based optimization offers a practical way to improve the material efficiency and lower embodied carbon. By enabling more rational use of concrete and steel, FEM-based design contributes directly to certification credits for material optimization, resource efficiency, and carbon footprint reduction. Moreover, the method is highly scalable. Modern FEM tools are widely available and can be gradually integrated into everyday design workflows across the ASEAN construction industry.

C. Cost Evaluation

Figure 5 presents the total material cost per m^2 (in Indonesian Rupiah) for slabs of varying thicknesses. The comparison includes both the FEM and the conventional Marcus method. As expected, the material costs increase with slab thickness. This is due to the larger volumes of concrete and reinforcement required in thicker slabs. At every level of thickness, the FEM-based design resulted in a lower cost per m^2 than the conventional approach.

This cost advantage is mainly due to the reduced steel quantity in FEM designs. The greatest savings occurred in thinner slabs, particularly in the 150–180 mm range. In these cases, FEM reduced the material costs by 10-15% compared to the Marcus method.

The conventional method tends to overestimate the reinforcement needs in thinner slabs, which leads to overdesign and unnecessary cost. For slabs thicker than 200 mm, the cost difference between the two approaches became smaller. However, FEM remained slightly more economical.

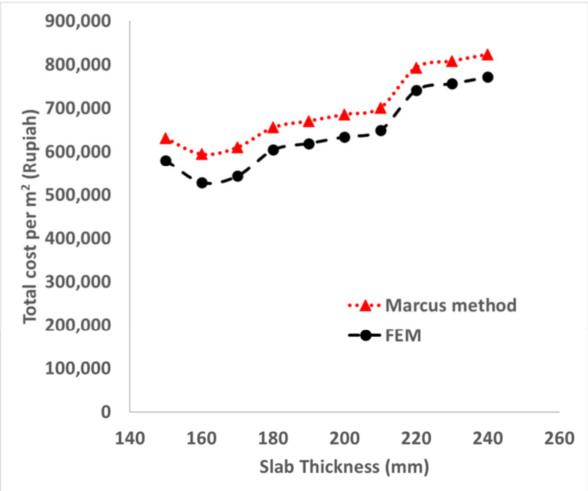

Fig. 5. Total cost per m^2 for different slab thickness.

These findings highlight the economic benefits of FEM-based slab optimization. This advantage is especially clear when thinner slabs are structurally feasible. In such cases, FEM not only reduces the embodied carbon, but also lowers the material costs. This makes it an attractive option for designers seeking to balance performance, sustainability, and budget constraints in structural systems.

IV. CONCLUSIONS

This study examined the use of Finite Element Modeling (FEM) in designing two-way reinforced concrete slabs. The analysis focused on the reinforcement efficiency, embodied carbon, and material cost. A FEM-based design was compared with the Marcus method, which is widely used in Indonesian engineering practice.

The results showed that FEM consistently required less reinforcement across all slab thicknesses. The most notable savings occurred in the 150–180 mm range, where material optimization was the most effective. This reduction led to meaningful environmental and economic benefits. In terms of the environmental impact, FEM reduced the embodied carbon by up to 12% per m^2. The difference was more significant in thinner slabs. From a cost perspective, the savings ranged from 10-15%, mainly due to the lower steel usage. Although the gap between the two methods narrowed for thicker slabs, FEM still offered advantages. It remained the most sustainable and cost-efficient option in all cases.

Beyond these results, the study contributes new insights by combining FEM-based optimization with embodied carbon and cost analysis. This integrated approach has received limited attention in earlier FEM slab studies, especially within the ASEAN context. By benchmarking against a method still widely used in Indonesia, this study provides relevant evidence to support a shift toward more sustainable practices.

Overall, FEM proves to be a reliable, environmentally friendly, and economically sound alternative to the conventional slab design. Its ability to optimize the material use without compromising safety makes it a valuable tool for promoting low-carbon, cost-effective construction. Future research could extend this work to other slab systems, such as flat or post-tensioned slabs, and include life cycle costs or construction-phase emissions for a more complete sustainability assessment.

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DATA AVAILABILITY

Data analysis https://zenodo.org/records/13668602.

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