"COMPARATIVE STUDY OF CARBON FOOTPRINT IN RCC AND STEEL FRAMED BUILDINGS"

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ABSTRACT

The construction industry is a major contributor to global greenhouse gas emissions due to the extensive use of energy-intensive materials such as cement and steel. This study presents a comparative analysis of the embodied carbon of a G +2 storey commercial building designed using reinforced cement concrete (RCC) and steel-framed structural systems. Material quantities were obtained through Building Information Modelling (BIM) based estimation, and corresponding carbon emissions were calculated using standardized emission factors from the Inventory of Carbon and Energy (ICE) database.

The results reveal that steel-framed structures exhibit approximately 50% higher embodied carbon compared to RCC structures, primarily due to the high emission intensity associated with steel production. Despite this, steel construction offers significant advantages, including recyclability, prefabrication capability, reduced construction time, and lower material wastage, which enhance sustainability over the building life cycle.

The study emphasizes the importance of informed material selection, efficient structural design, and the integration of BIM-based methodologies in minimizing environmental impacts. The findings highlight that while RCC structures are advantageous in reducing initial embodied carbon, steel structures present considerable long-term sustainability benefits, making them a viable alternative for modern construction practices.

Keywords: Carbon Footprint, RCC, Steel Structure, Embodied Carbon, BIM, Sustainable Construction

1. INTRODUCTION

1.1 GENERAL

The rapid growth of the construction industry has led to a significant increase in global carbon emissions. Buildings require large quantities of raw materials such as cement, steel, sand, aggregates, and finishing materials. The production, processing, and transportation of these materials generate substantial greenhouse gas emissions, particularly carbon dioxide (CO_2), which is a major contributor to climate change.

In recent years, there has been a growing emphasis on sustainable construction practices to minimize the environmental impact of buildings. One of the key approaches used for evaluating environmental performance is carbon footprint analysis. The carbon footprint represents the total amount of greenhouse gases emitted directly or indirectly throughout the life cycle of a product or system.

Reinforced Cement Concrete (RCC) and steel-framed structures are two of the most widely used structural systems in modern construction. RCC structures primarily rely on cement and aggregates, whereas steel structures depend heavily on structural steel. Since both cement and steel production are energy-intensive processes, their usage significantly influences the total carbon emissions of a building.

1.2 ADVANTAGES

- RCC Structures Lower initial embodied carbon compared to steel structures
- Readily available materials and cost-effective construction
- Good fire resistance and durability

- Requires less skilled labour for construction
- Steel Framed Structures high strength-to-weight ratio
- Faster construction due to prefabrication
- Recyclability and reusability of steel
- Reduced material wastage and improved quality control

1.3 DISADVANTAGES

- RCC Structures high consumption of cement leading to CO_2 emissions
- Longer construction time
- Difficulty in recycling and higher demolition waste
- Heavier structural weight
- Steel Framed Structures higher initial embodied carbon due to steel production
- Susceptibility to corrosion if not properly protected
- Higher initial cost in some cases
- Requires skilled labour and precise fabrication

1.4 OBJECTIVES OF THE STUDY

- To calculate the embodied carbon of an RCC building and a steel-framed building
- To compare the carbon footprint of both structural systems
- To identify the major materials contributing to carbon emissions
- To evaluate the sustainability of RCC and steel structures

1.5 SCOPE OF THE STUDY

- The study focuses on a G +2 storey commercial building model
- Carbon emissions are calculated based on material quantities
- Emission factors are adopted from standard databases (ICE database)
- The analysis is limited to embodied carbon (construction phase only)
- Operational and demolition phase emissions are not included

2. LITERATURE REVIEW

2.1 GENERAL

Recent advancements in sustainable construction emphasize the importance of evaluating the environmental impact of building materials, particularly in terms of embodied carbon. The construction industry significantly contributes to global carbon emissions, with materials such as cement and steel being the primary contributors.

2.2 STUDIES ON PREVIOUS LITERATURES

Ailin Zhang, Xuechun Liu, Chen Tian, Xun Zhang, Yongqiang Tan. (2015), *"Design and Specification Compilation of a Modularized Prefabricated High-rise Steel Frame Structure with Inclined Braces – Part I: Integral Structural Design"*, *2015 MOC Summit*, ISSN 2562-5438. Zhang et al. (2015) presented a study on modularized prefabricated high-rise steel frames with inclined braces, highlighting how this structural system provides exceptional seismic performance and maintains flexibility even under rare earthquake conditions. Their research also emphasizes the significant reductions in construction time, with the system supporting rapid, industrial-scale development for high-rise applications, proving more efficient than most conventional modular approaches.

Avendaño, J. I., Zlatanova, S., Domingo, A., Pérez, P., Correa, C. (2022), *"Utilization of BIM in steel building projects: A systematic literature review"*, Buildings, 12(6), p. 713. Avendaño et al. (2022) conducted a systematic literature review on the application of Building Information Modelling (BIM) in steel construction projects. The study highlights that BIM improves project coordination, design accuracy, clash detection and quantity take-off. Their research shows that BIM significantly enhances efficiency in planning, design and management of steel building projects.

Soliman, S. M., Mahdi, I. M., Dessouki, A. K., Rashid, I. A. (2023), *"BIM application in steel structures – Case study"*, International Journal of Research in Engineering & Management. Soliman et al. (2023) presented a case study on the application of BIM in steel structure projects. The study highlighted that BIM improves design coordination, clash detection and construction efficiency, leading to better project management.

Hammond, G., Jones, C. (2011), *"Inventory of Carbon and Energy (ICE) Version 3.0: Embodied Energy and Carbon Database for Construction Materials"*, University of Bath, United Kingdom. Hammond and Jones (2011) developed the Inventory of Carbon and Energy (ICE) database which provides embodied energy and carbon emission factors for a wide range of construction materials. The database compiles data from various research studies and industrial sources and is widely used for estimating the carbon footprint of buildings. In the present study, emission factors from the ICE database were used to calculate the embodied carbon of construction materials.

Ramesh, T., Prakash, R., Shukla, K. K. (2010), *"Life Cycle Energy Analysis of Buildings: An Overview"*, Energy and Buildings Journal, ISSN0378-7788. Ramesh et al. (2010) reviewed the life cycle energy consumption of buildings, including both embodied energy in construction materials and operational energy during the building life cycle. The study highlights that materials such as steel and cement significantly contribute to the total carbon emissions of buildings. The research emphasizes the importance of life cycle assessment in reducing the environmental impact of construction projects.

Mohammed, A., Elmasoudi, I., Ghannam, M. (2025), *"Life cycle environmental impact assessment of steel structures using building information modelling"*, Innovative Infrastructure Solutions. Mohammed et al. (2025) analysed the environmental impacts of steel structures using BIM-based life cycle assessment methods. The study shows that BIM can effectively estimate environmental impacts and help in selecting sustainable construction materials.

From the reviewed literature, it is evident that steel structures offer advantages such as recyclability, prefabrication, and faster construction, while RCC structures tend to have lower initial embodied carbon. However, both systems require careful evaluation using standardized methodologies such as the ICE database to ensure sustainable construction practices.

However, limited studies have compared embodied carbon between RCC and steel structures using BIM-based quantity estimation, which forms the motivation for the present study.

2.3 SUMMARY OF LITERATURE

- Prefabricated steel structures provide better seismic performance, flexibility, and faster construction compared to conventional methods.

- BIM technology improves design accuracy, coordination, and quantity estimation, which is essential for cost and carbon analysis.
- BIM-based approaches help in reducing construction errors and optimizing resource utilization.
- The ICE database is a standard and reliable source for calculating embodied carbon of construction materials.
- Construction materials significantly contribute to life cycle energy consumption and carbon emissions.
- Life Cycle Assessment (LCA) is an effective tool for evaluating the environmental impact of buildings.
- Steel structures offer benefits like recyclability, prefabrication, and reduced construction time.
- RCC structures generally have lower initial embodied carbon compared to steel structures.
- There is a lack of comparative studies using BIM-based quantity estimation for RCC and steel structures.

3. METHODOLOGY

A BIM-based approach was adopted for accurate material quantification and carbon estimation. The workflow involved 3D modeling, quantity take-off, and application of emission factors from standard databases.

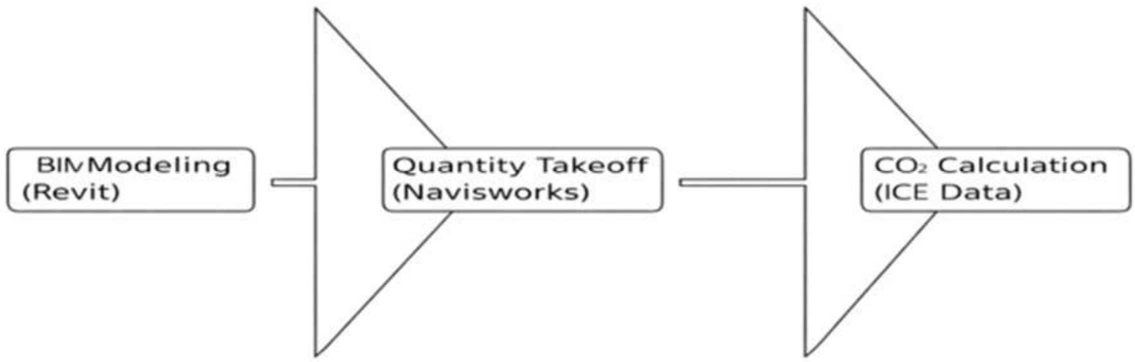


Figure 3.1: Methodology Flowchart

Figure 3.1 shows the digital workflow adopted in our project, beginning with BIM modelling in Revit, followed by Quantity Take-off in Navisworks, and concluding with CO_2 calculation using ICE data. Using material quantities extracted from the BIM model, the embodied carbon was calculated by multiplying each material's quantity with its corresponding emission factor from the University of Bath's ICE database. The analysis revealed that structural steel and cement are the largest contributors to emissions—steel due to its energy-intensive production and cement due to CO_2 released during clinker manufacturing. When compared with an equivalent RCC structure, the steel frame showed higher initial embodied carbon, but offered long-term sustainability benefits such as recyclability, reuse potential, faster construction, and reduced waste. Thus, while RCC may appear more economical in terms of emissions at the start, steel structures demonstrate greater environmental advantages over the building life cycle.

The study involves the following steps:

3.1 BUILDING MATERIAL ESTIMATION

The quantity of construction materials used in both RCC and steel framed buildings was obtained from the detailed material estimation of the project. Major materials considered in the analysis include:

- Cement
- Aggregates (20 mm, 12 mm, and 6 mm)
- Sand (M-sand and river sand)
- Solid blocks
- Paint
- Aluminium work
- Wood
- False ceiling materials
- Steel reinforcement

- Structural steel sections
- Glass and other finishing materials

3.2 EMISSION FACTORS

Each material has a specific carbon emission factor, which represents the amount of carbon dioxide emitted during the production of one unit of that material. Standard emission factors were used to estimate the carbon emissions.

Table 3.2: Carbon emission factors for building materials as per ICE

Sl No	Material	Carbon Emission Factor	ICE Typical Range
1	Cement	0.55 kg CO_2/kg	0.52–0.55 kg CO_2/kg
2	Steel (Fe500, ISMB, ISWB)	2.3 kg CO_2/kg	2.3–2.7 kg CO_2/kg (rolled steel)
3	Aggregates (20mm, 12mm, 6mm)	0.14 kg CO_2/cft	~0.14 kg CO_2/cft (≈ 0.005 kg/kg)
4	M Sand / River Sand	0.12 kg CO_2/cft	~0.12 kg CO_2/cft
5	Paint	0.25 kg CO_2/sqft	0.25–0.30 kg CO_2/sqft
6	Aluminium Work	3.5 kg CO_2/sqft	3.5–4.0 kg CO_2/sqft
7	Glass	1.2 kg CO_2/kg	1.2–1.4 kg CO_2/kg
8	Gypsum Ceiling	0.23 kg CO_2/sqft	0.22–0.25 kg CO_2/sqft
9	PVC Ceiling	0.28 kg CO_2/sqft	0.28–0.30 kg CO_2/sqft
10	SS Tube / Plate	3.5 kg CO_2/kg	3.5–4.0 kg CO_2/kg
11	Wood	18 kg CO_2/cft	17–20 kg CO_2/cft (Sal wood)

The Table 3.2 shows the standard ICE values were used to calculate material carbon emissions up to manufacturing stage.

3.3 CARBON FOOTPRINT CALCULATION

The carbon footprint of each material was calculated using the following formula:

Carbon Emission = Quantity of Material × Emission Factor

The total carbon footprint of the building was obtained by summing the carbon emissions of all materials used in the construction.

The BIM-based carbon footprint analysis shows that steel and cement are the dominant contributors, with steel producing higher emissions from energy-intensive manufacturing and cement from CO_2 released in clinker production. While steel frames have higher initial embodied carbon, they offer long-term sustainability benefits such as recyclability, reuse, faster construction, and reduced waste, whereas RCC structures show lower initial emissions but lack end-of-life sustainability advantages, underscoring the importance of informed material selection.

Table 3.3: Carbon footprint calculation of steel framed building

CARBON FOOTPRINT CALCULATION OF STEEL FRAMED BUILDING					
Sl No	**Material**	**Quantity**	**Unit**	**Emission Factor**	**CO_2 Emission (kg)**
1	Cement	177703	kg	0.55 kg CO_2/kg	97737
2	20 mm Aggregate	8310	Cft	0.14 kg CO_2/cft	1163
3	12 mm Aggregate	3954	Cft	0.14 kg CO_2/cft	554
4	6 mm Aggregate	1910	Cft	0.14 kg CO_2/cft	267
5	M Sand	10595	Cft	0.12 kg CO_2/cft	1271
6	River Sand	3435	Cft	0.12 kg CO_2/cft	412
7	Solid Block 8"	15099	Nos	0.18 kg CO_2/block	2718
8	Solid Block 4"	8831	Nos	0.15 kg CO_2/block	1325
9	Paint	34772	Sqft	0.25 kg CO_2/sqft	8693
10	Aluminium Work	180	Sqft	3.5 kg CO_2/sqft	630
11	Wood	50	Cft	18 kg CO_2/cft	900

Sl No	Material	Quantity	Unit	Emission Factor	CO_2 Emission (kg)
12	False Ceiling – PVC	686	Sqft	0.28 kg CO_2/sqft	192
13	False Ceiling – Gypsum	14063	Sqft	0.23 kg CO_2/sqft	3234
14	12 mm Square Rod	60	kg	2.3 kg CO_2/kg	138
15	MS Pipe with Square Tube	900	kg	2.3 kg CO_2/kg	2070
16	SS Tube	1062	kg	3.5 kg CO_2/kg	3717
17	Glass	1770	kg	1.2 kg CO_2/kg	2124
18	SS Plate	150	kg	3.5 kg CO_2/kg	525
19	Steel Fe 500	11570	kg	2.3 kg CO_2/kg	26611
20	ISMB 300	42000	kg	2.3 kg CO_2/kg	96600
21	ISWB 400	36750	kg	2.3 kg CO_2/kg	84525
22	Rolled Steel with Chequered Plate	8400	kg	2.3 kg CO_2/kg	19320
23	Deck sheet 1mm thick	11771	kg	2.7 kg CO_2/kg	31780
	Total				**386507 kg**

The Table 3.3 shows the embodied carbon emissions of major materials in the steel-framed structure, highlighting steel and cement as the dominant contributors to the overall footprint.

Table 3.3.1: Carbon footprint calculation of RCC framed building

CARBON FOOTPRINT CALCULATION OF RCC BUILDING					
Sl No	**Material**	**Quantity**	**Unit**	**Emission Factor**	**CO_2 Emission (kg)**
1	Cement	237354	kg	0.55 kg CO_2/kg	130544
2	20 mm Aggregate	11576	Cft	0.14 kg CO_2/cft	1621
3	12 mm Aggregate	6132	Cft	0.14 kg CO_2/cft	858

Sl No	Material	Quantity	Unit	Emission Factor	CO_2 Emission (kg)
4	6 mm Aggregate	1910	Cft	0.14 kg CO_2/cft	267
5	M Sand	13825	Cft	0.12 kg CO_2/cft	1659
6	River Sand	3435	Cft	0.12 kg CO_2/cft	412
7	Solid Block 8"	15099	Nos	0.18 kg CO_2/block	2718
8	Solid Block 4"	8831	Nos	0.15 kg CO_2/block	1325
9	Paint	34772	Sqft	0.25 kg CO_2/sqft	8693
10	Aluminium Work	180	Sqft	3.5 kg CO_2/sqft	630
11	Wood	50	Cft	18 kg CO_2/cft	900
12	False Ceiling – PVC	686	Sqft	0.28 kg CO_2/sqft	192
13	False Ceiling – Gypsum	14063	Sqft	0.23 kg CO_2/sqft	3234
14	12 mm Square Rod	60	kg	2.3 kg CO_2/kg	138
15	MS Pipe with Square Tube	900	kg	2.3 kg CO_2/kg	2070
16	SS Tube	1062	kg	3.5 kg CO_2/kg	3717
17	Glass	1770	kg	1.2 kg CO_2/kg	2124
18	SS Plate	150	kg	3.5 kg CO_2/kg	525
19	Steel Fe 500	41948	kg	2.3 kg CO_2/kg	96479
	Total				**258107 kg**

The Table 3.3.1 shows the embodied carbon emissions of major materials in the RCC structure, showing comparatively lower initial emissions than steel but reduced sustainability performance over the full life cycle. The analysis shows that the total carbon emission of the steel framed building is approximately 386,507 kg of CO_2, which is equivalent to 387 Tonnes of CO_2. Structural steel components such as ISMB beams, ISWB sections, deck sheets, and reinforcement steel contribute significantly to the total carbon emissions. The total carbon emission of the RCC building was calculated as approximately 258,107 kg of CO_2, which is equivalent to 258 Tonnes of CO_2. In RCC structures, cement and reinforcement steel were found to be the major contributors to carbon emissions.

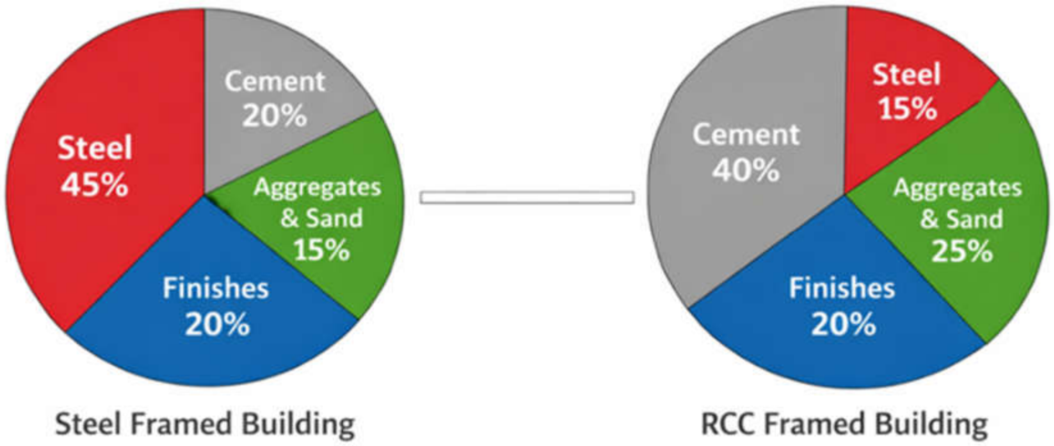
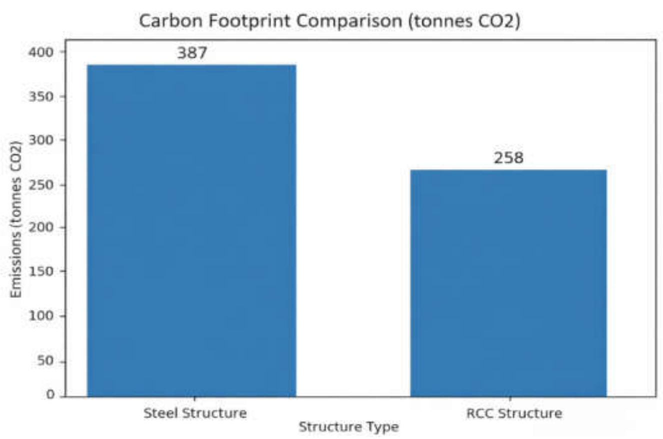


Figure 3.3: Percentage distribution of CO_2 emissions by material

This figure 3.3 shows the percentage distribution of CO_2 emissions by material type for steel-framed and RCC-framed buildings. It highlights that steel dominates emissions in steel-framed structures (45%), while cement is the largest contributor in RCC buildings (40%). Aggregates, sand, and finishes contribute moderately in both cases, emphasizing how material choice impacts the overall carbon footprint.

3.4 COMPARISON OF RESULTS

The total carbon emission of the steel-framed structure is approximately 387 Tonnes of CO_2, whereas the RCC structure emits 258 Tonnes of CO_2.



Graph 3.4: Comparison of total CO_2 Emissions between RCC and Steel Structures

The graph 3.4 shows a comparative analysis of total carbon emissions between steel-framed and RCC buildings. It clearly illustrates that the steel-framed structure emits 387 tonnes of CO_2, significantly more than the 258 tonnes emitted by the RCC structure. This visual supports the conclusion that while steel structures have higher initial embodied carbon, they may offer long-term sustainability advantages.

Table 3.4: Comparative CO_2 emissions of steel-framed and RCC buildings

Sl No	Category	Steel Framed Building	RCC Framed Building	Key Observation
1	Total Emissions	387 tonnes CO_2	258 tonnes CO_2	Steel emits ~50% more overall
2	Steel	~45% (≈174 t)	~15% (≈39 t)	Steel dominates in steel frames
3	Cement	~20% (≈78 t)	~40% (≈103 t)	Cement dominates in RCC frames
4	Aggregates & Sand	~15% (≈58 t)	~25% (≈65 t)	Higher share in RCC
5	Finishes	~20% (≈77 t)	~20% (≈51 t)	Similar contribution

The table 3.4 shows that steel frames have higher overall embodied carbon, while RCC frames record lower initial emissions but lack sustainability advantages at end of life.

$$Percentage\ difference = \frac{387 - 258}{258} \times 100 = 50\%$$

The carbon footprint of the steel structure is approximately 50% higher than that of the RCC structure, indicating relatively higher embodied carbon emissions in steel construction.

3.5 KEY FINDINGS:

- Steel structure has ~50% higher initial carbon footprint
- RCC has lower initial emissions but less sustainability flexibility
- Steel offers better lifecycle sustainability advantages

3.6 DISCUSSION

The results clearly indicate that structural steel and cement are the dominant contributors to carbon emissions. While steel structures have higher initial embodied carbon, they provide long-term environmental benefits such as:

- Reusability and recyclability
- Reduced construction time
- Lower material wastage
- Efficient prefabrication techniques

Thus, sustainability assessment should not be limited to initial carbon emissions but must consider the entire life cycle of the building. The results indicate that optimizing steel usage and incorporating recycled materials can reduce the embodied carbon difference between RCC and steel structures by up to 10–15%.

3.7. CONCLUSION

The project primarily highlights the comparative evaluation of RCC and steel framed structures using BIM-based quantity take-off integrated with embodied carbon (ICE) assessment. The study clearly demonstrates the significant impact of material selection on the environmental performance of buildings. Although steel structures exhibit higher initial embodied carbon approximately 50% more than RCC due to energy-intensive manufacturing processes, they provide considerable long-term sustainability benefits such as high recyclability, reuse potential, reduced construction time, and lower material wastage.

In contrast, RCC structures show lower initial carbon emissions mainly due to the comparatively less energy-intensive production of concrete. However, their limitations in terms of recyclability, higher demolition waste, and longer construction duration reduce their sustainability performance over the entire life cycle. This highlights the importance of evaluating not only initial emissions but also lifecycle impacts in construction projects.

The integration of BIM tools such as AutoCAD, Revit, and Navisworks played a crucial role in improving accuracy and efficiency in quantity take-off, model coordination, and visualization. BIM-based workflows enabled precise estimation of material quantities, which were further used for reliable carbon emission calculations using ICE data. This approach ensures transparency, minimizes manual errors, and supports data-driven decision-making.

Overall, the study proves that the combination of BIM technology with carbon assessment tools provides a powerful framework for sustainable construction analysis. It enables engineers and designers to make informed choices by balancing structural performance, cost, and environmental impact. The project concludes that while RCC may be preferable for lower initial emissions, steel structures offer better long-term sustainability advantages, making them a viable solution for modern construction when lifecycle considerations are taken into account.

REFERENCES

[1]. Zhang, A., Liu, X., Tian, C., Zhang, X., & Tan, Y. (2015). Design and specification compilation of a modularized prefabricated high-rise steel frame structure with inclined braces – Part I: Integral structural design. MOC Summit.

[2]. Avendaño, J. I., Zlatanova, S., Domingo, A., Pérez, P., & Correa, C. (2022). Utilization of BIM in steel building projects: A systematic literature review. Buildings, 12(6), 713.

[3]. Soliman, S. M., Mahdi, I. M., Dessouki, A. K., & Rashid, I. A. (2023). BIM application in steel structures – Case study. International Journal of Research in Engineering & Management, 6(3), 13–18.

[4]. Hammond, G., & Jones, C. (2011). Inventory of Carbon and Energy (ICE) Version 3.0: Embodied energy and carbon database for construction materials. University of Bath, UK.

[5]. Ramesh, T., Prakash, R., & Shukla, K. K. (2010). Life cycle energy analysis of buildings: An overview. Energy and Buildings.

[6]. Mohammed, A., Elmasoudi, I., & Ghannam, M. (2025). Life cycle environmental impact assessment of steel structures using building information modelling. Innovative Infrastructure Solutions.

[7]. Bureau of Indian Standards. (2007). IS 800:2007 – General construction in steel – Code of practice. BIS, New Delhi.

[8]. Bureau of Indian Standards. (2000). IS 456:2000 – Plain and reinforced concrete – Code of practice. BIS, New Delhi.

[9]. Bureau of Indian Standards. (2016). National Building Code of India. BIS, New Delhi.