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Cost optimization and estimation of embodied carbon in reinforced concrete frame structure.

Optimización de costos y estimación del carbono incorporado en una estructura de marco de hormigón armado.

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ABSTRACT

Reinforced Concrete (RC) structures are common structures all around the globe. Measures are being taken to reduce the greenhouse emission contribution from construction industries. The contribution of embodied energy of structures is also considered for more efficient operation of buildings. The study investigates the embodied carbon content for various grades of concrete used in the design and an optimization approach for an economic design. Analysis and design of RC frame structures are done using Staad-Pro software and cost optimization is done using Genetic Algorithm (GA) in Matlab software. The design constraints considered are geometry, strength, and areas of reinforcement confirming Indian Standard codes. The optimized result is used to model the RC structure in Revit software to determine its embodied carbon content. Candidate structures are then evaluated to compute embodied energy using individual relationships. This paper studies the possibility to reduce the embodied carbon content in RC frames and to propose an optimum design model to design commercial buildings to provide reliable, economical, time-saving, and practical designs.

Keywords: Reinforced Concrete, Genetic Algorithm, Cost Optimization, Carbon Content, Embodied Carbon.

RESUMEN

Las estructuras de hormigón armado (CR) son estructuras comunes en todo el mundo. Se están tomando medidas para reducir la contribución de las industrias de la construcción a las emisiones de gases de efecto invernadero. También se considera el aporte de energía incorporada de las estructuras para un funcionamiento más eficiente de los edificios. El estudio investiga el contenido de carbono incorporado para varios grados de concreto utilizados en el diseño y un enfoque de optimización para un diseño económico. El análisis y diseño de estructuras de marcos RC se realizan utilizando el software Staad-Pro y la optimización de costos se realiza utilizando el algoritmo genético (GA) en el software Matlab. Las limitaciones de diseño consideradas son la geometría, la resistencia y las áreas de refuerzo que confirman los códigos estándar indios. El resultado optimizado se utiliza para modelar la estructura RC en el software Revit para determinar su contenido de carbono incorporado. Luego se evalúan las estructuras candidatas para calcular la energía incorporada utilizando relaciones individuales. Este artículo estudia la posibilidad de reducir el contenido de carbono incorporado en los marcos RC y proponer un modelo de diseño óptimo para diseñar edificios comerciales para proporcionar diseños confiables, económicos, prácticos y que ahorren tiempo.

Palabras clave: Hormigón Armado, Algoritmo Genético, Optimización de Costos, Contenido de Carbono, Carbono Incorporado.

INTRODUCTION

Reinforced Concrete (RC) is a widely used building material in developed and developing countries for constructing civil engineering structures. Concrete is good for its compression strength, resistance, and durability to damage from fire and water. RC frames have horizontal beam elements and vertical column elements connected by rigid joints cast in a single operation to act in unison. The design of conventional RC structures is cater only to safety criteria and needs excessive materials. Much research has been done for the optimized design of RC structural elements for minimum cost but only minimal work has been done on the study of embodied carbon content and its optimization.

Optimization of the embodied carbon content of RC frames is extra challenging than in steel frames because of the complexity related to concrete, reinforcement, and formwork. The unit cost of these materials is different so the overall cost of the frame also changes accordingly. This makes the problem complex and combinatorial which depends on the combination of the selection of design parameters such as beam sections and column sections, areas of reinforcement, type of material, and spacing of columns and beams and their orientation to reduce the cost of the frames. The frames may be cast in situ or precast depending on the construction methods and practices. It also depends on the width of the beam at a given level and the smaller dimensions of the columns at upper levels. By considering the actual size of the reinforcing bars to avoid rounding off values to the next promising values.

A Genetic Algorithm (GA) method offers optimal design models to make them practically feasible. GA is used in structural optimum design for the last few decades as it can deal with complex and large parameter problems. GA-based optimization design of RC members based on multi-criterion objectives has been carried out in recent years. The process starts with an initial population and then using the three operations: reproduction, crossover, and mutation, it generates successive populations. The objective function defines the aim, i.e., to minimize or maximize what the user intends using GA. To minimize the cost of an objective function, minimize the cost of steel, concrete, and beam and columns sections.

Sustainable construction is favorable for environmental, economic, and social requirements. Over the last decade, the environmental costs of construction are a concern. A large amount of concrete being used for economic feasibility and sturdiness in construction materials and high consumption of cement leads to more and more greenhouse gas CO_2 emissions. Optimizing these RC structures can scale down the amount of concrete and/or steel used in the structure which lowers the discharge of CO_2 emissions, moreover environmental costs, and costs related to construction. Efforts are to be made to decrease and control CO_2 emissions during the service life of the frames. The embodied energy due procurement of raw materials, transport, processing, distribution, and construction needs to be considered. The minimization of the embodied carbon in building materials may be a main constituent within the delivery of sustainable designs. Revit software is used to create the model, measure, and determine the carbon footmark of the materialization stage. Embodied carbon footprint buildings and construction require the analysis of a large number of materials, products, and assemblies and this can be a difficult task, as a result, embodied carbon calculators may be considered. An environmental consultant formed an embodied carbon calculator for concrete, as a part of the able embodied carbon databank for ingredients called an Inventory of Carbon and Energy (ICE) database.

In the present study analysis, design, and optimization of different RC frame structures are carried out the embodied carbon content for these different RC frame structures is calculated and compared.

From literature ,it is observed that a huge number of variables are involved in the optimization of RC frames and are found to be infeasible. However cost constituents of concrete, steel, and formwork are considered. Due to the difference in unit price, even a slight variation of one item will change the overall cost of the frame in large. So, the problem is complex, which finally needs the choice of a group of suitable design parameters for beam and column sections and the amount of reinforcement. Structural designs are normally optimized for the total cost in view of sustainability and embodied energy. The concrete grades also vary the CO_2 footprint in the design of RC frames. The high concrete grades have the best mechanical properties, which gives high CO_2 emissions. So, the changes in CO_2 footprint between the optimal designs with concrete grades are less, and not many comparative studies of these have been done.

MATERIAL AND METHODOLOGY

The variables of optimization are not connected and also the number of acceptable solutions is finite. A genetic algorithm offers the optimal design model that generates solutions that are practically feasible by considering the actual reinforcement in the optimal design model and avoids the round of values to the next size after the final solution has arrived. The objective function is the total cost of concrete, steel, and formwork of all columns and beams. The cost of components is the material, fabrication, and labor. The cost is only construction costs and the cost of the building life cycles such as maintenance and demolition is not included. The construction costs and embodied carbon content for the structures of the higher grade of concrete are considerably greater than the nary concrete. Also, the percentage of reinforcement is high and it is difficult to decide the grade of concrete suitable for a given structure in advance.

The purpose of this study, an optimization technique on a Genetic algorithm with constraints and objective functions for a frame structure under gravity load are considered and compare the embodied carbon content in the optimized frame structures of different grades of concrete. To safeguard the reliability of the results on the type of economic environmental favor for RC structures. Variants of a four-four-story frame structure are considered, two-span variants of column space of 4m and 8m, and four concrete grade variants of M30, M40, M50, and M60. In this study, eight variants of the four-story RC frame structure are independently optimized. The optimization program is done using the global optimization toolbox in Matlab software. Secondly, the optimization results are saved and used to model the eight variants four-story structure in Revit software, and the estimate of embodied carbon content for each of the eight variants is compared.

The objectives of the research work are to analyze and design the RC frame structure of eight variants of a four-story RC frame structure, two-span variants, and four concrete grade variants. To optimize eight variants of the four-story RC frame structure, two-Spann variants, and four concrete grade variants of the Genetic algorithm. To model the eight variants of four-story structure, two-span variants, and four concrete grade variants in Revit software and to estimate the total cost and embodied carbon content and to compare the cost and estimated embodied carbon content of the eight variants of four-story RC frame structure, two-span variants, and four concrete grade variants.

Structural Analysis: Eight variants of a four-story RC frame structure are considered, two-span variants of column spacing of 4m and 8m, and four concrete grade variants of M30, M40, M50, and M60. The structures are modeled by providing suitable dimensions for beams and columns materials, cross sections, and support conditions are described. The input parameters such as the structural details have been taken based on the codal provisions of IS 456:2000, load condition based on IS 875 (Part 1) for dead load and IS 875 (Part II) for live load The bending moment, shear force and reinforcement details obtained from the analysis are considered for the optimization process. To reduce the complexity of optimization, the grouping of beams and columns has been done based on the position and loading conditions. The grouping of beams and columns given in Table 1 has been done based on the results obtained.

Table 1: Grouping of Beams and Columns

Sl.No.	Description	Designation
1	Plinth Beam	PB
2	First Floor Beam	B1
3	Second Floor Beam	B2
4	Third Floor Beam	B3
5	Fourth Floor Beam	B4
6	Corner Column	C1
7	Exterior Column	C2
8	Interior Column	C3

Structural optimization

The structural optimization problem is stated mathematically:

Minimize, f(x)

Subject to,

gi (x) ≤ 0 i = 1,..., p

hj (x) = 0 j = 1,...,m

xl ≤ x ≤ xu

where,

f(x) →Objective function

gi (x) → Set of inequality constraints

hj (x) → Set of equality constraints

x = xi, ,i→ 1,...,n is the vector of design variables

xl = xli , i→ 1,...,n is the lower bound of design variables

xu = xui , i→ 1,...,n is the upper bound of design variables.

The flow diagram of the research methodology is given in Figure 1.and the group of beams and columns is shown in Table 1.

The 3D model and the different loads acting on the first variant of the RC frame structure with column spacing of 4m and concrete grade of M30 are shown in Figure 2.

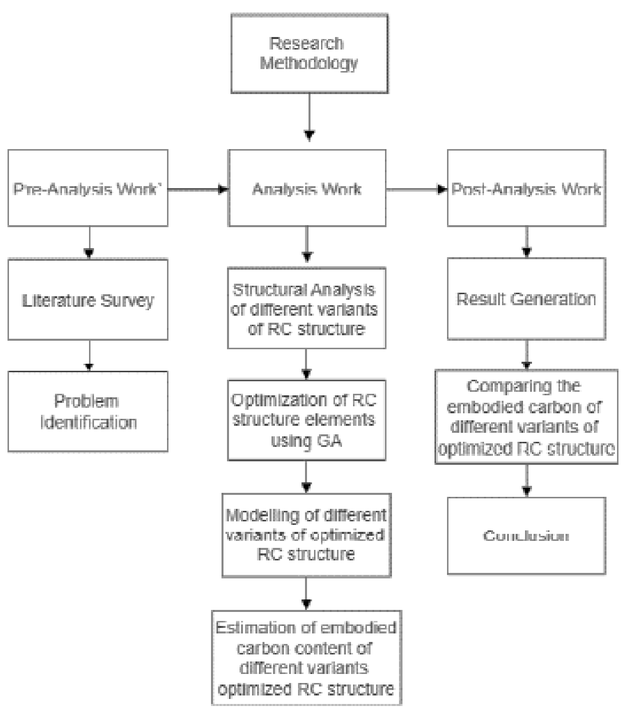


Figure 1: The flowchart of the research

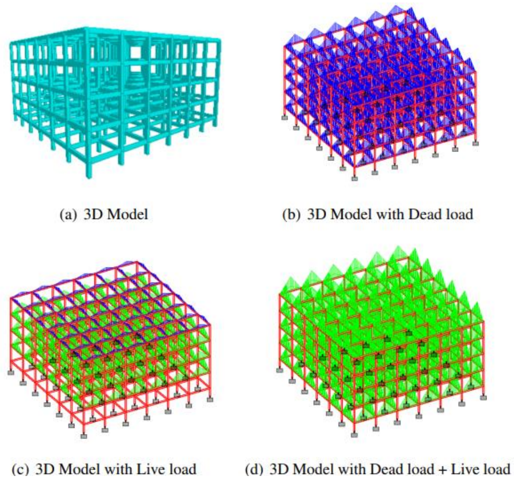


Figure 2: RC frame structure (4m span and M30 Grade concrete)

A. Optimization

Optimization is done using Genetic Algorithm in Matlab software for RC frame structure consisting of beam and column elements. The objective function is to minimize the cost of the RC frame structure. Width, depth, and area of reinforcements are considered design variables in both beam and column optimization. The cost of structural elements consists of the cost of concrete, steel, and formwork in the construction of the member. Hence minimizing the cost of the elements is expressed as:

Minimize (CostBeam) = (Concrete cost+ Steel cost + formwork cost)Beam ….. (1)

Minimize (CostColumn) = (Concrete cost+ Steel cost + formwork cost)Column ….. (2)

Constraints for this optimization problem are the following IS 456: 2000.

Beam Constraints:

Deflection Constraint, $L/d \leq 26$

Flexural Capacity Constraint, $Mu - Mulim \leq 0$

Min. Area of Tensile Reinforcement, $Ast/bd=0.85/fy$

Max. Area of Reinforcement, $Ast \leq 0.04b(d + dc)$

Shear Strength, $(\tau v - \tau c)\ bd/0.87fyd=Asv/Sv$

Where, $Sv \leq 0.75d$ or $Sv \leq 300$

Column Constraints:

Geometric Constraints, $b \leq d$

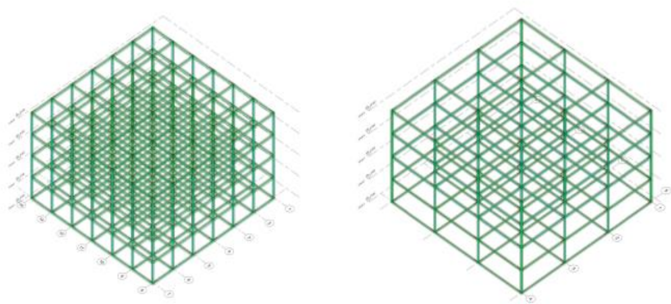
Axial Capacity, $P-Pu \leq 0$

Mini. Area of Reinforcement, $1-(As/0.008bd) \leq 0$

Max. Area of Reinforcement $(As/0.03bd) - 1 \leq 0$

B. Modeling

The dimensions and reinforcement data obtained from the optimization of beams and columns of RC frame structures with eight variants are modeled in REVIT 2022 software.3D model of the RC frame structure of concrete grade M30 and column spacing of 4m and 8m is given in Figure.3.



(a) RC Frame Structure 1 with Column Spacing 4m and concrete grade M30

(b) RC Frame Structure 2 with Column Spacing 8m and concrete grade M30

Figure 3: REVIT model of the First variant of RC frame structure

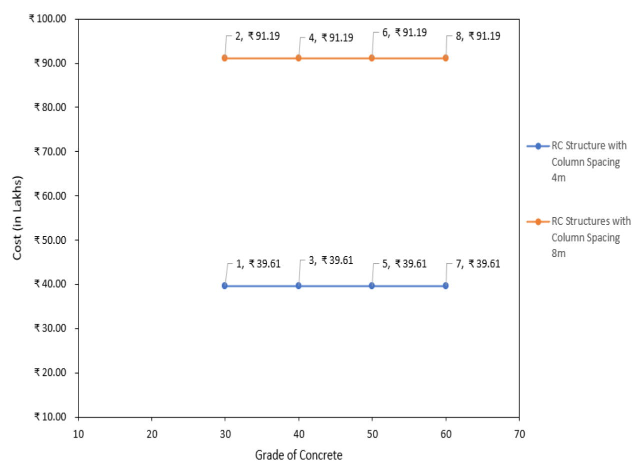


Figure 4: Construction Costs of Structures

The quantities of materials of, beams and columns were extracted from Revit 2022. These quantities were then fed to calculate the embodied carbon content of each RC frame structure.

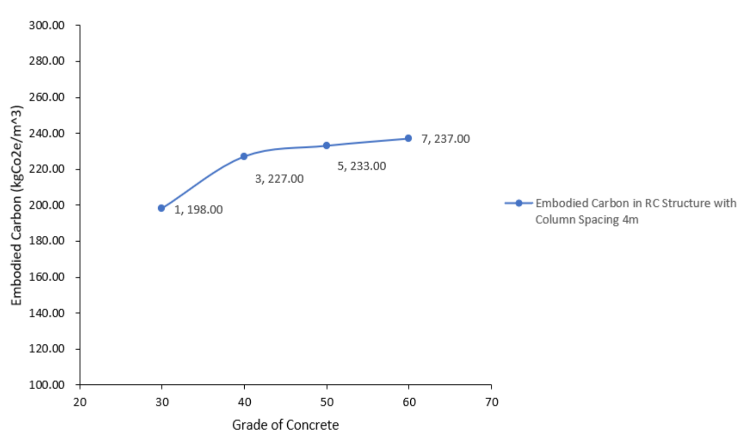


Figure 5: Embodied carbon for structures with column spacing 4m

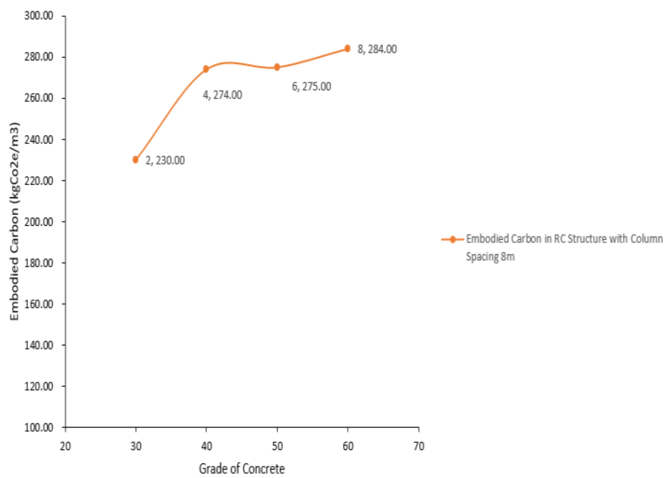


Figure 6: Embodied Carbon for Structures with Column Spacing of 8m

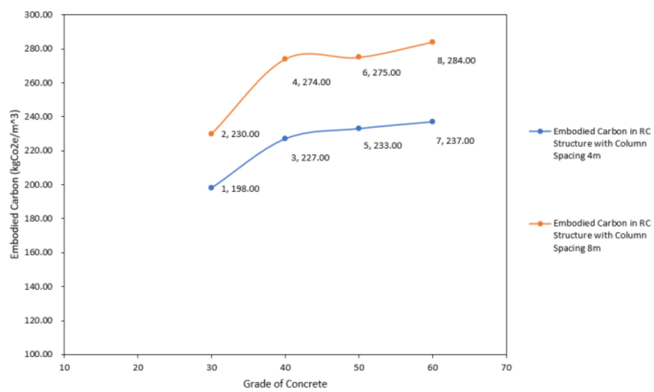


Figure 7: Embodied Carbon of RC Structures

RESULTS AND DISCUSSION

The analysis and design of eight variants of RC frame structures were carried out in Staad-Pro software. The analysis details of each beam and column group are considered input parameters in the optimization part. The optimization for beam groups and column groups is done separately to avoid complexity in the process. The design parameters considered i.e., the dimensions and reinforcement details of each of the beam groups and column groups are collected accordingly for all the eight variants of the considered RC frame structures. The optimization results of the beam and column groups are given in Table 2 and Table 3:

The construction cost of each variable was calculated, and Figure 4 shows variations in the construction costs for each variable. The column spacing has an important role in the variation of the construction cost. It is observed that for alternates with a column spacing of 8m the construction cost is greater compared to alternatives with a column spacing of 4m. It is witnessed that in some elements, the use of high-strength concrete gives reduced dimensions of beam and column elements and invariantly reduction the quantity of concrete, and not the steel. Reduction of cross-section also decreases the internal forces among the concrete and the steel, and this will be waged for by increased stresses in both materials. As a result, the quantity of steel reinforcement required becomes more. The results of the embodied carbon valuation are planned into two sections according to the column spacing as shown in Figure 5 and Figure. 6. The results are presented for each frame with different grades of concrete. These structures with different grades are compared and summarized and graphically expressed. The outcomes of the embodied carbon assessment in Figure 7 show that the embodied carbon increases with the greater grade of concrete. The concrete with M30 grade was found to be less impact and the maximum impact for M60 grade concrete. The environmental impact is strongly influenced by the amount of steel reinforcement, as well as the cement content.

Table 2: Grouping of Columns

Sl No	Structure	Group	b (mm)	d (mm)	A_s (mm^2)	A_t (mm^2)
1	RCFS1	C1	300	300	1000	110
	M30, 4m	C2	300	300	1000	110
		C3	250	300	1000	100
2	RCFS2	C1	300	300	1100	110
	M30, 8m	C2	250	250	1000	100
		C3	300	300	1000	120
3	RCFS3	C1	300	300	1000	110
	M40, 4m	C2	300	300	1000	100
		C3	250	300	1000	100
4	RCFS4	C1	300	300	1000	110
	M40, 8m	C2	300	300	1000	120
		C3	300	300	1000	110
5	RCFS5	C1	300	300	1000	100
	M50, 4m	C2	300	300	1000	100
		C3	250	300	1000	110
6	RCFS6	C1	300	300	1000	100
	M50, 8m	C2	250	250	1000	110
		C3	300	250	1000	100
7	RCFS7	C1	300	300	1100	110
	M60, 4m	C2	300	300	1000	100
		C3	300	300	1100	120

8	RCFS8	C1	300	300	1000	110
	M60, 8m	C2	300	300	1100	120
		C3	300	300	1000	100

Table 3: Grouping of Columns

Sl No	Structure	Group	b (mm)	d (mm)	A_{st} (mm^2)	A_{sc} (mm^2)	A_{sv} (mm^2)	S_v (mm)
1	RCFS1	PB	250	250	300	300	100	180
	M30, 4m	B1	250	300	300	300	100	200
		B2	250	300	300	300	100	190
		B3	250	300	300	300	100	190
		B4	250	300	300	300	100	190
2	RCFS2	PB	200	200	300	300	100	200
	M30, 8m	B1	250	200	300	300	100	200
		B2	250	250	300	300	100	100
		B3	250	250	300	300	100	100
		B4	250	250	300	300	100	200
3	RCFS3	PB	250	250	300	300	100	170
	M40, 4m	B1	250	300	400	300	100	170
		B2	250	300	400	300	100	200
		B3	250	300	300	400	100	180
		B4	250	300	300	300	100	200
4	RCFS4	PB	200	200	300	400	100	100
	M40, 8m	B1	250	200	300	400	100	100
		B2	250	250	300	500	100	100
		B3	250	250	300	300	100	200
		B4	250	250	400	400	100	200
5	RCFS5	PB	250	250	400	300	100	170
	M50, 4m	B1	250	250	400	300	100	170
		B2	250	300	500	300	100	190
		B3	250	250	300	300	100	200
		B4	250	250	300	300	100	170
		PB	250	250	400	300	100	170
		B1	250	250	400	300	100	170
6	RCFS6	B2	250	200	300	300	100	200

	M50, 8m	B3	250	200	500	300	100	200
		B4	250	250	500	300	100	100
		PB	250	250	500	500	100	100
		B1	250	250	300	300	100	120
7	RCFS7	B2	250	300	400	400	100	190
	M60, 4m	B3	300	300	400	400	100	180
		B4	250	300	500	500	100	210
		PB	300	300	400	500	100	190
		B1	250	250	400	400	100	300
8	RCFS8	B2	300	450	400	300	100	300
	M60, 8m	B3	300	450	400	300	100	290
		B4	250	250	500	500	100	100
		PB	300	450	400	300	100	290
		B1	300	450	500	300	100	300

CONCLUSION

This investigation was done to do the optimization of RC frame frames. In total, eight different types of the RC frame were considered (two span variants and four concrete grade types) in terms of the construction costs and these optimized structures were modeled, and embodied carbon content is calculated and compared. The results of this study produced the following findings:

1. The optimization of beams and columns was performed separately to reduce the complexity of the optimization problem which gives realistic and constructible solutions. The construction cost of the RC frame depends on the span and not on the grade of concrete used. This investigation shows that the cost increases from Rs.39.61 lakhs to Rs. 91.19 lakhs as the span increases from 4m to 8m and no change is found with the change in grade of concrete from M30 to M60.
2. The cost of construction RC frame structure with column spacing of 4m and M30 grade of concrete is the lowest. For RC frame structures with column spacing of 8m, the variation in construction cost is 3% compared with the first variant.
3. The embodied carbon assessment shows that the first variant of the RC frame structure with column spacing of 4m and M30 grade of concrete has the lowest embodied carbon content. The carbon content increases around 5 times from M30 grade concrete to M60 Grade concrete. For RC frame structures with column spacing of 4m, the change of embodied carbon for different grades of concrete is 15% for M40, 18% for M50, and 20% for M60 compared with the first variant.

4. For RC frame structures with column spacing of 8m, the change of embodied carbon for different grades of concrete is 16% for M30, 38% for M40, 39% for M50, and 43% for M60 compared with the first variant. Variants of the RC frame structures with a column spacing of 4m show better results with the combination of M30 grade of concrete for both cost of construction and embodied carbon content.

A further study incorporating floor and roof slabs in the optimization to reduce the complexity can be done. Various load combinations incorporating seismic load and wind load along with dead load and live load can be considered for further optimization. Further study can be conducted for frames for large compressive forces, and high-rise buildings, the reduction of embodied carbon content can be significant. Unsymmetrical structures. Combination of RC structures with PSC structures.

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