Comparative Analysis of Embodied Carbon Associated with Alternative Structural Systems

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ABSTRACT

The structural system of a building is usually selected by comparing the structural performance, costs and ease of construction of different alternative systems. Other sustainability criteria including carbon footprint have been overlooked traditionally in making such a decision. This paper aims to highlight the important effect of the choice of structural system on embodied carbon of buildings. A set of 15 alternative steel and concrete structural systems including moment resisting frames, braced frames, shear walls and dual systems were designed for 3, 10 and 20 storey buildings. A process-based analysis was conducted to estimate the carbon emissions incurred in material extraction, transportation and construction phases of these 15 structural system alternatives. The results highlight the importance of considering carbon footprint on top of other conventional criteria when selecting the structural system of a building.

Keywords –

Structural Systems; Embodied Carbon; Extraction and Manufacturing Phase; Transportation; Construction

1 Introduction

Structural engineers, in collaboration with architects and owners check the viability of architectural aspects of a building and make important decisions regarding its structural features including material choice, layout and lateral load resisting system. Based on the various concerns that each of the parties involved in the decision making process have, different parameters are considered when deciding about the building's structure. The cost of the project is of great importance for the owner; availability of material and technology can significantly affect the cost of the structure. Rate and easiness of construction are also common concerns for different parties. For structural engineers the structural behaviour, which is a combination of strength and stiffness, is the main issue. Having access to information about the intensity of wind or earthquake in the area that the building will be located, the soil characteristics of the site, and the dead and live loads associated with different architectural details and occupancies respectively, can provide an idea about the type of material and lateral load resisting system that should be adopted. On the other hand, architects are concerned with architectural aspects such as span lengths, storey heights, lateral load resisting elements layout and size etc. The environmental impacts of the projects are not commonly a priority in this conventional structural design procedure. However, the increased awareness about importance of sustainability in construction calls for consideration of other sustainability criteria on top of the above conventional criteria in design of structures. One of these important sustainability concerns is the considerable carbon footprint of buildings. According to the Fourth Assessment Report of the Intergovernmental Panelon Climate Change (IPCC), the share of the construction industry in the total annual GHG emission is 30% which is significant and demand preventive measures [1].

Embodied and operating carbon are parts of the terminologies that are frequently used by the sustainability and climate change professionals but are new to a structural engineer's lexicon [2]. Embodied carbon is referred to all carbon emission incurred in material extraction and manufacturing phase, transportation of material to the construction site and construction phase. On the other hand, operating carbon refers to all carbon emitted during the operation phase of a building due to heating, cooling and providing proper lightening for its interior. Given the continued improvement in the operational carbon efficiency of buildings and the development of the net zero carbon building's idea, the role of the embodied carbon becomes more significant in the life cycle environmental impacts of buildings [3]. A structural engineer knowledgeable in the life cycle characteristics of materials and construction activities can significantly decrease the embodied carbon associated with buildings [4].

The contribution of structural materials and elements in the embodied carbon of a building has been previously investigated. Dimoudia and Tompa [5] studied the role of various construction materials on embodied energy in contemporary office buildings in Athens, Greece. Results showed that, for the case building, the highest contribution in the embodied energy of the building belongs to the structural building materials (concrete and reinforcement steel), accounting for 66.73% to 59.57% of the total embodied energy of the building [5].

The study conducted by Cole [6]was one of the first attempts to estimate the energy and greenhouse gas emissions associated with the construction of alternative structural systems. In this study, a detailed examination of the energy and greenhouse gas emissions associated with the on-site construction of a selection of alternative wood, steel and concrete structural building assemblies was performed to investigate the share of the construction process in the total initial embodied carbon and the effects of different structural alternatives on the latter. Results of this study showed considerable differences between the GHG emissions associated with construction of alternative wood, steel and concrete structural assemblies and highlighted the construction of the concrete assemblies as the highest GHG emitter [6]. A number of studies have also focused on estimating the carbon emissions incurred in the construction phase and comparing the effects of different construction processes on the latter by collecting the fuel and electricity consumption data of different equipment functioning on the construction site [7-10].

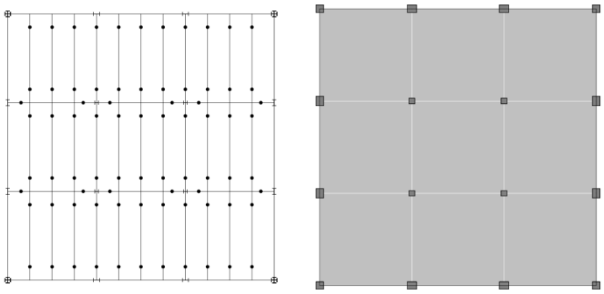
Collings [11] investigated the embodied carbon of alternative combinations of structural materials and systems for bridges. Moon investigated the minimum weight of steel members needed as the only sustainability factor (minimum material used) to meet the stiffness requirement of tubular systems as well as the impact of different geometrical configurations on that minimum amount. [12]. Ji et al. also presented the design results of 9 concrete buildings with alternative concrete and rebar strength with a focus on comparing different available cost-environmental decision making processes and without giving detailed information on their designs and considering the viability of the alternative assumed strength combinations. [13] Other studies also highlighted the importance of investigating the role of structures in environmental impacts of buildings [2, 4]. However, the focus of all previous studies has been on comparing the embodied carbon of a particular structure made with two different materials or two structural systems for a given material. The overlapping effects of the structural system, height of the building and material used have not been yet investigated. This paper aims to highlight the importance of considering embodied carbon as a decision making criterion, together with conventional criteria including performance, costs and ease of construction, for selection of structural system. The considerable effect of the choice of structural system on the embodied carbon of the structure is investigated by considering the carbon invested in the materials as well as the carbon emissions associate with the construction process. Five different structural systems were designed for three different building heights. All 15 structures were subjected to process-based analysis to determine their associated embodied carbon. The results are compared to evaluate the effects of variations in the embodied carbon of structures with changes in the lateral load resisting system used. In addition, the effects of the height of the building and structural material used, i.e. concrete vs steel, on the embodied carbon of different structural systems are compared.

2 Methodology

Structural engineers currently have very limited guidance on how to incorporate sustainability concepts in their designs. To show the considerable impact of choice of material and load resisting system on the embodied carbon of buildings, 15 structures were designed for a case building by varying the material type and structural systems. Two different materials, i.e. steel and concrete, and different lateral load resisting systems including, i.e. sway and non-sway, were considered. The design and life cycle analysis details are explained in the following sections.

2.1 Frame Design Details

Being the most commonly used materials in structures, steel and concrete were chosen as frame materials for this comparative study. Alternative systems chosen from two general sway and non-sway categories were designed for a square shape plan with three bays in orthogonal directions, each five meter in length (Figure 1). Besides the type of material (e.g. concrete and steel) and lateral load resisting system which affect the stiffness of the structure, the height of the building also has a considerable effect on its stiffness and behaviour, influencing several aspects of the design. Therefore to study the parameter of buildings height, three different buildings of 3-, 10-, and 20- stories, representing short, medium and tall buildings with the storey height of 3.6 m, were considered. For each of these heights 3 different steel structural systems including moment resisting frame in E–W and N–S directions (Figure 2a), braced frame in E–W and N–S directions (Figure 2b) and a combination of these systems, i.e. moment resisting frame in N–S direction and braced frame in E–W direction, were designed. Composite slabs were chosen for the flooring system of the steel buildings as this is one of the common flooring systems used. The slabs are composed of a 9 cm thick concrete slab and steel joist spaced at 125 cm spacing centre to centre. In addition, 2 concrete structural systems including moment resisting frame in E–W and N–S directions (Figure 2a) and a dual system of moment resisting frame and reinforced concrete shear wall in E–W and N–S directions (Figure 2c) were also designed. For concrete structures a concrete slab with 12 cm thickness was chosen and drop panels were considered to increase the punching shear capacity at column-slab joints.



(a) (b)

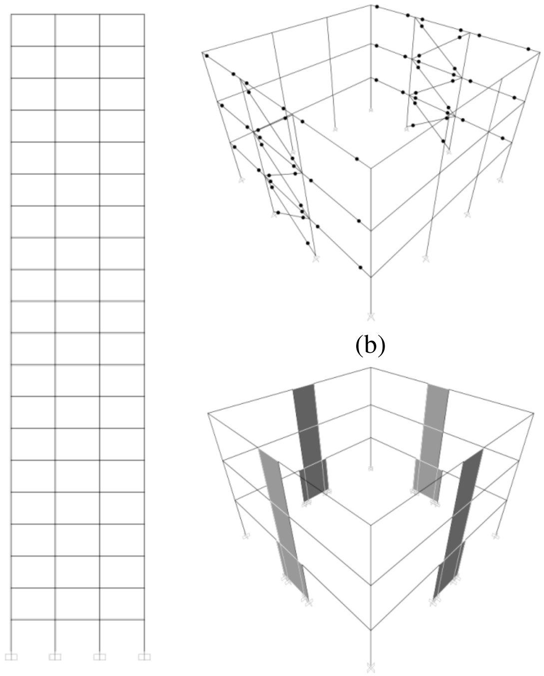
Figure 1. Plan view of the designed buildings for (a) steel buildings (steel frames with composite slabs) (b) concrete buildings (concrete frames with concrete slabs)

All prevailing requirements for gravity, wind, and seismic design were considered. The buildings were designed for a moderate seismic risk region, Seismic Design Category C (Atlanta, Georgia), as defined in the American Institute of Steel Construction (AISC) Seismic Provisions (ASCE, 2005). The buildings were modelled using ETABS 9.7.0 and a pseudo dynamic analysis was carried out on them. The design loads on the buildings are also determined based on (ASCE) 7-05 "Minimum Design Loads for Buildings and other Structures". The design standards used in the design of members and their connections were AISC and ACI, for steel and concrete building respectively. For typical floors, the dead load consists of the self-weight of the slabs being 216 kg/m^2 and 288 kg/m^2 for the composite and concrete ones respectively, and a super-imposed dead load of 370 kg/m^2; while the design live load is assumed to be 200 kg/m^2. For the roof, the super-imposed dead load is 260 kg/m^2; and the design live load is 150 kg/m^2. The yield stress (F_y) were considered to be 400 MPa and 240 MPa for steel members and reinforcement respectively. The characteristic compressive strength of concrete f'_c is assumed to be 30 MPa.

The subgrade soil modulus and its allowable compressive strength are considered to be 3 kg/cm^3 and 2.5 kg/cm^2, respectively. Based on these properties, for each of the 3- and 10- story buildings a combination of spread and strip footings and for the 20 storey buildings, mat footings were designed. All foundations were designed using SAFE 8.1.0.

2.2 Estimation of the Embodied Carbon of the Frames

Once the design of the previously discussed structures was completed, using quantity takeoffs from the design software, the amounts of materials needed (steel, concrete, reinforcement bars) were determined. Based on these quantities, the carbon footprint of different phases of construction was calculated [14]. The following sections review the methods used for estimating the carbon footprint of different phases of the building life cycle by evaluating the processes leading to carbon emissions. The important parameters to be considered in performing the analysis and the interpretation of the results of analysis are discussed.



(b)

(a) (c)

Figure 2.(a) Elevation view of 20 storey steel or concrete moment resisting frames;3D view of (b) 3 storey steel braced frame and, (c) 3 storey concrete reinforced shear wall

2.2.1 Material Extraction and Manufacturing

Each building is a complex combination of tens, if not hundreds, of different materials. The carbon emissions due to extraction, production and processing of construction materials constitute a significant proportion of the total life cycle carbon of buildings. Available literature shows that depending on the type of structure and the function of building the embodied carbon may account for between 40% to 50% of the total life cycle carbon of buildings[15]. The energy use and carbon emissions incurred during production and processing of different building materials have been estimated in a number of previous studies. Among these studies, Hammond and Jones, under the Carbon Vision Buildings Program at the University of Bath, England, are establishing a large and comprehensive database of energy and carbon embodied in building materials [16, 17]. The advantage of this database is its compliance with International Standardization Organization (ISO) [18] for Life Cycle Assessment [19]. The carbon emission factors of this database are used in this study (Table 1).

The following equation is used to calculate the total embodied carbon footprint of materials used in the designed buildings (concrete, bars, steel): [7]

$$E_M = \sum M_j^M . f_j^M / 1000 \qquad (1)$$

Where E_M is the total embodied carbon of all building materials (in tons CO2-e) (CO2-e: CO2-equivalent); M_j^M is the amount of building material j (in kg) obtained from quantity takeoffs tables from design software ; and f_j^M is the carbon emission factors for building material j (in kg CO2-e/kg) shown in Table 1.

Table 1.Embodied energy and carbon coefficients of major construction material

material	embodied energy coefficients (MJ/kg)	embodied carbon coefficients (kgCO$_2$-e/kg)
steel	21.5	1.53
concrete	0.78	0.113
bars	17.4	1.4
plywood	15	0.45

2.2.2 Transportation

Transportation is considered as an important origin of carbon emissions related to construction. This includes both on-site transportation and off-site transportation of materials, equipment and personnel [6]. EPA report shows that the construction sector accounts for 6% of light on-road truck use and 17% of medium/heavy truck use in the U.S. transportation system while the contribution of the transportation section to the overall GHG emissions is 28% [20, 21]. If the impacts of these transportations were also included in the 1.7% share of the construction industry in the total U.S. GHG emissions, this figure would double. [22]

The type and size of transportation vehicles differ depending on the size and type of construction materials. For instance, ready-mixed concrete (RMC) requires concrete mix trucks, while long and heavy materials, such as steel shapes or concrete piles, require trailers. Likewise, other materials, like cement and aggregate, require dump trucks. According to the type and size of the vehicles, the type of fuel and fuel efficiency are different [7]. The emission factors for different type of vehicles can be deduced from databases like MOVES Model [23] and EMFAC [24]. Once the emission factors for different type of vehicles are determined or deduced from available emission inventories, the GHG emissions from transportation of building materials or equipment can be calculated by the following equation:

$$E_T = \sum_j \sum_k M_j^T \times (T_j^k \times f_k^T) 1000 \qquad (2)$$

Where E_T is the total GHG emissions from fuel combustion of transportation for all building materials, waste and equipment (in tons CO$_2$-e); M_j^T is the amount of building materials, waste and equipment j (in tons); T_j^k is the total distance of transportation for the item j by vehicle k (in km); and f_k^T is the GHG emission factor for transportation (in kg CO$_2$-e/ton km).

In this study, the average distance between materials stockpile (factory gate) to the construction site was assumed to be 40 km. Since the trucks and trailers return to the manufacturing site empty, a roundtrip was considered in which the transportation vehicles travel to the construction site loaded and return unloaded.

Table 2.Energy consumption and GHG emission factor of considered transportation vehicle

equipment	size	weight	energy consumption (MJ/ton.km)	GHG emission (kgCO$_2$-e/ton.km)
concrete mixer truck	6	m3	12	2.06
Trailer 20t	20	ton	5	0.97
Truck 15t	15	ton	16.5	0.94

2.2.3 Construction

The erection of a building entails using various materials and equipment. The latter is usually accompanied with considerable energy consumption and thus carbon emissions. This is on the top of the emissions due to extraction and manufacturing process discussed before. The embodied carbon of permanent construction materials is generally not considered in estimation of carbon footprint of construction phase and is dealt with separately. However, apart from the materials used permanently in structure and envelope of the building, a significant amount of materials is used temporarily during the construction process to support and facilitate construction activities. Thus, the carbon footprint of construction phase includes the emission incurred in manufacturing and transportation of temporary materials, such as formwork as well as transportation of equipment to and from the job site and equipment use [8, 25]. Calculating the embodied carbon of temporary materials may be informed using the similar methodology described for permanent materials (Section 2.2.1). Moreover, the carbon footprint of on-site and off-site transportation in the construction phase may be estimated using the procedure described in Section 2.2.2.

Different emission inventory models are available for estimating the carbon footprint of non-road equipment, namely NONROAD model, OFFROAD model as well as a model developed by Lewis [26]. Regardless of the estimation method used, once the emission factors for different types of equipment are determined, the GHG emissions from fuel and electricity consuming construction equipment can be calculated using the following equation:

$$E_C = \sum F_j^C . f_j^{Cf} / 1000 + \sum E_j^C . f_j^{Ce} / 1000 \qquad (3)$$

where E_C is the total GHG emissions from fuel and electricity combustion of construction equipment (in tons CO_2-e); F_j^C is the amount of fuel j consumed by construction equipment j (in litres) and f_j^{Cf} is the quantity of purchased electricity from power company k (in kWh); E_j^C is the GHG emission factor for fuel j consumed by construction equipment j (in kg CO_2-e/litre) and f_j^{Ce} is the emission factor for power company j (in kg CO_2-e/kWh).

In this study, the carbon footprint of the construction phase was estimated based on common construction processes (series of construction operations) required to construct concrete and steel structures. Considering these processes and also taking into account the activity divisions of RSMeans [27], a work break down (WBS) of involved construction activities for each type of structure is developed. It should be noted that RSMeans is a widely used cost database in the United States and Canada which include detailed divisions for each type of activities involved in a construction project. For each activity the amount of work that a particular size and combination of crew can perform during a working day (8 hours) is shown under the title of ”Daily Output”. Some of the activity divisions used in this study, including the daily output, total cost and equipment used, are presented in Table 3. The included activities are major activities which require the use of fuel or electricity consuming equipment. The carbon emission factors of the used equipment are shown in Table 4. Using the quantity of material used from quantity takeoffs along other building properties, the work quantities are estimated and divided by daily output given by RSMeans to calculate the number of working days of individual equipment. The obtained results are multiplied by 8 (number of work hours defined in RSMeans) to calculate the work hours of equipment and multiplied by the carbon emission factors as indicated by equation 3.

3 Results and Discussion

The results of the life cycle analysis performed on the 15 different designed frames are presented in this section. Table 3 shows the material quantities per square meter of the buildings deduced from the design stage. Based on the quantities shown in this table and the CO_2 emission factors presented in Table 1, the embodied carbon of structures was calculated and results are shown in Table 3. As shown in Table 3, the embodied carbon per square meter of building area increases with the height of building. The reason for this increase is that for short and medium buildings (3 and 10 stories) an ordinary or intermediate frame system can be used but for tall buildings (20 stories) a special lateral load resisting system should be adapted. Special frame systems are required to fulfil additional conditions such as strong columns-weak beams. Moreover, for both medium and high rise buildings the conditions which limit the lateral deformation of frames are more influential when it comes to the design results compared to short buildings. All the extra conditions that should be checked and fulfilled for high and medium rise buildings compared to short ones increase the amount of material used in these buildings which leads to higher embodied carbon per square meter of the building.

Table 3.Material quantities extracted from the design stage and CO_2 emission due to different phase of the life cycle of the designed frames

Number of Stories	Type of Structure	Material quantities (kg/m^2)			Material extraction and manufacturing		Transportation		Construction		Embodied Carbon	
		steel	concrete	bars	CE (kg CO_2-e/m^2)	Potential saving in CE relative to best case	CE (kg CO_2-e/m^2)	Potential saving in CE relative to best case	CE (kg CO_2-e/m^2)	Potential saving in CE relative to best case	CE (kg CO_2-e/m^2)	Potential saving in CE relative to best case
3	S 3S MRF	59.4	371.8	13.9	152.4	15.6%	5.8	1.4%	9.7	0.0%	167.9	13.1%
	S 3S BF	46.2	371.8	14.1	132.4	0.5%	5.7	0.0%	10.3	5.9%	148.4	0.0%
	S 3S BF-MRF	49.5	371.8	14.0	137.3	4.2%	5.7	0.2%	10.0	2.9%	153.1	3.1%
	C 3S MRF	0.0	650.5	48.5	141.4	7.3%	9.4	65.0%	12.6	28.8%	163.3	10.0%
	C 3S SW	0.0	657.3	41.1	131.8	0.0%	9.4	65.0%	12.0	23.5%	153.2	3.2%
10	S 10S MRF	73.7	395.3	11.2	173.0	11.5%	5.9	0.2%	9.5	0.0%	188.5	4.4%
	S 10S 2D BF	71.4	395.3	11.2	169.5	9.3%	5.9	0.2%	10.6	10.9%	186.0	3.1%
	S 10S BF-MRF	69.3	395.3	11.2	166.3	7.2%	5.9	0.0%	10.1	5.4%	182.3	1.0%
	C 10S MRF	0.0	842.9	55.6	173.1	11.6%	11.6	97.7%	14.8	55.4%	199.6	10.6%
	C 10S SW	0.0	789.9	47.1	155.2	0.0%	11.2	90.4%	14.1	47.8%	180.5	0.0%
20	S 20S MRF	89.1	458.2	12.0	205.0	7.8%	6.8	0.0%	8.7	0.0%	220.5	3.9%
	S 20S BF	83.6	492.8	12.0	200.4	5.4%	7.2	6.2%	10.4	18.8%	218.0	2.7%
	S 20S BF-MRF	80.3	492.8	12.0	195.4	2.7%	7.2	6.5%	9.6	10.4%	212.3	0.0%
	C 20S MRF	0.0	947.8	73.2	209.6	10.2%	12.9	90.5%	14.8	69.3%	237.4	11.8%
	C 20S SW	0.0	868.8	65.7	190.2	0.0%	13.2	94.3%	14.0	59.7%	217.4	2.4%

For all three considered heights, the lateral load resisting system that results in a lower embodied energy is the concrete reinforced shear wall system. The moment resisting frames, regardless of being concrete or steel, lead to higher embodied carbon. It should be noted that the weight of material used in steel buildings is much less than the weight of material used in concrete buildings but due to high embodied carbon coefficients of steel members compared to concrete, ultimately the embodied carbon of steel frames is in the same range as the concrete buildings. In the first column of Table 3, the amount of CO_2 produced in each phase of the building life cycle is displayed. The second column shows the amount of potential saving in the CO_2 emission that can be made by choosing the frame with the minimum amount of emitted CO_2. For the embodied carbon regarding the material usage in case of 3 storey buildings, a 15.6% saving in emitted CO_2 can be achieved by choosing concrete reinforced shear wall system instead of steel moment resisting frame. For 10 and 20 story buildings a maximum of 11.6% and 10.2% saving can be achieved respectively.

Other constituent parts of embodied carbon which include transportation and construction represent lower values compared to the material extraction and manufacturing part. For both transportation and construction phase, concrete frames render in higher embodied carbon due to higher fuel consuming vehicles and equipment such as concrete truck mixers and concrete pumps. This leads to significant savings in the amount of CO_2 emitted if steel structures are chosen for the buildings. Another influential parameter in the higher amount of CO_2 emitted during construction phase of concrete buildings is the embodied carbon of temporary material (formwork) used in the construction of these structures. Steel structures also have formwork placing activities in their foundations as well as their slabs but comparing to concrete structures the amount of formwork required for these structures is less.

Summing up the embodied carbon due to material extraction and manufacturing, transportation and construction phases, the embodied carbon of the alternative structural systems were calculated and presented in Table 3 and Figure 3. Based on these results, among the five alternative frames designed for 3 storey buildings, the maximum and minimum embodied carbon belong to steel moment resisting frame (S 3S MRF) and steel braced frame (S 3S BF) respectively. For the 10 and 20 storey buildings the maximum and minimum belongs to concrete moment resisting frame (C 10S MRF), concrete reinforced shear wall frame (C 10S SW), concrete moment resisting frame (C 20S MRF) and a combination of steel moment resisting frame and brace frame (S 20S MRF-BF), respectively. Table 3 also shows the maximum amount of reduction in the carbon footprint of a particular structure, with a given height, achievable through selection of structural material and system. As shown the maximum amount of reduction was 13.1%, 10.6% and 11.8% for 3-, 10- and 20- storey frames, respectively. By considering the relatively high carbon footprint of structures, such reductions in the embodied carbon could result in significant reductions in the environmental impacts of the building. This highlights the important effect of considering the carbon footprint as an important criterion when selecting the structural system for a particular building.

4 Conclusion

In this study, 5 alternative structural systems were designed for 3-, 10- and 20- storey buildings representing short, medium and tall buildings. The carbon footprint of all structure alternatives was estimated. The results showed that choice of structural system can affect the embodied carbon of the structure by as much as 13%. This highlights the importance of considering the embodied carbon on top of other conventional criteria and requirements including structural performance, costs and ease of implementation when selecting the structural system. Results also indicated that the embodied carbon associated with a particular structural system varies considerably with the height of the building as well as the choice of material for the structure. It should be noted that the results presented here are for illustration of importance of considering the embodied carbon in the design of structure and should not be generalize to make conclusions about superiority of a structural system over another.

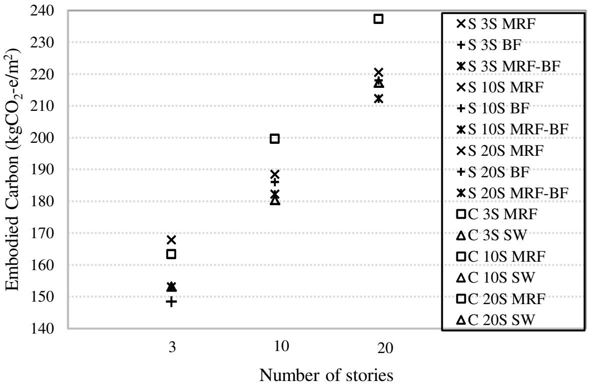


Figure 3.Overall embodied carbon of different frame systems for 3, 10and 20 storey buildings

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