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Structural System Embodied Carbon Analysis for Super Tall Buildings

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Abstract

Building construction has been the main fields of energy consumption and greenhouse gas emission in the world nowadays. With the increase of building height, the amount of carbon dioxide discharged by the building has increased significantly during the entire life cycle. The impact of super tall buildings on the environment has drawn increasing attention due to the huge energy and material consumption. In the life cycle of the building, the carbon emissions are composed of three parts, say embodied carbon, operating carbon and demolition and disposal carbon. Embodied carbon of structural system contributes the most carbon emission during the construction stage of a supper tall building and thus is an important index to measure the environmental impacts of different structural systems for a given super tall building. The embodied carbons and environmental costs of typical super tall building structures for different structural systems are thoroughly analyzed in this study. The distribution of embodied carbons of critical structural members, such as the frame columns, central core walls, structural floors and outrigger trusses are also discussed. At last, this paper analyses the fundamental factors which influence the environmental costs, and the analysis results will provide a guide for the sustainable structural design of super tall buildings.

Keywords: Embodied carbon; structural system; environmental cost; sustainable structural design; super tall buildings.

1. Introduction

Due to the influence of human activity, the concentration of greenhouse gases and sulfide aerosol in the 21st century increase quickly, which lead to future global temperature rising rapidly in the next 100 years. The intergovernmental panel on climate change (IPCC) had predicted that by the end of this century, global temperatures will rise by 1.5 to 4.5 degrees Celsius as the carbon dioxide doubles, according to Reuters. Impacts brought about by climate changes were recognized as more and more serious in recent years.
Studies have shown that [1], the construction, operation and maintenance produce a large amount of carbon emissions which is accounted for about 1/3 to 1/2 of the total carbon emissions in England. According to the United Nations environment programme (UNEP), building energy consumption accounted for about 30%-40% of total energy consumption in the whole society [2]. Construction has been the main areas of the world energy consumption and greenhouse gas emissions. In recent years, with the economic development, the number of high-rise buildings is increasing rapidly, as well as the building height. According to the statistical results of Council on Tall Buildings and Urban Habitat (CTBUH) in 2014, there are more than 800 super tall buildings which are taller than 200 meters up to 2013. So it is of great significance to reduce the carbon emissions of super tall buildings for protecting the environment.

The impact of super tall buildings on the environment has drawn increasing attention due to the huge energy and material consumption. By taking two 40-story residential buildings in Hong Kong as models for research and statistics, Chen, et al. [3] found that embodied carbon of steel and aluminium in Hong Kong buildings was more than concrete buildings. The Council on Tall Buildings and Urban Habitat [4] found that embodied carbon of high-rise buildings is higher than that of low-rise buildings, but the growth trend is not obvious with the increase of the storeys. Zhao and Fang [5] proposed a new time-based life cycle model for assess and optimize the life cycle environmental cost of super tall buildings. Wang and Zhao [6] compared the economic costs and environmental costs between the existing building applying tube-in-tube system and framed tube system respectively, using embodied carbon index in the structural system selection of high-rise building structures. Li and Chen [7] developed a methodology for estimating the life-cycle carbon efficiency of a residential building.

The embodied carbons and environmental costs of a real 301.8 meter super tall buildings applying three different structural systems are thoroughly analyzed in this study. The distribution of embodied carbons of critical structural members, such as the frame columns, central core walls, structural floors and outrigger trusses are also discussed. At last, this paper analyses the fundamental factors which influence the environmental costs, and the analysis results will provide a guide for the sustainable structural design of super tall buildings.

2. Embodied carbon and environmental cost

2.1. Embodied carbon

A building' life cycle carbon emissions (see Fig.1)includes embodied carbon, operation carbon and end-of-life carbon. Among them, the end-of-life carbon includes the demolition carbon emissions and carbon emissions associated with recycling, operating carbon is the carbon emissions of building operation stage. There are three kinds of statistical scope for the calculation of embodied carbon. ICE database data are defined as ‘cradle-to-gate’[8],

![Fig. 1. Carbon emissions in different stages of a building’ life cycle](image)

which counts the energy and carbon emissions from the extraction of raw materials from the earth (the ‘cradle’) and all the manufacturing processes up until when it leaves the factory (the ‘gate’); AIA Guide to Building Life Cycle Assessment in Practice [9] think that embodied energy comes from the materials manufacturing and construction phases of the building project; Cole and Kernan think that embodied energy are made of the initial embodied energy, the recurring embodied energy associated with maintenance and repair, and operating energy. The embodied carbon system boundary of "from cradle to gate", covering the stage of production of materials and components which are most closely to structural design is used in this paper.
2.2. Calculation method of embodied carbon

Embodied carbon of production stage is calculated based on ICE database data, and the calculation formulas of commonly use structural material about embodied carbon are listed below:

(1) Concrete

\[ C_{\text{con}} = M_{\text{con}} \times W_{\text{con}} \]  

where \( C_{\text{con}} \) is the embodied carbon of concrete (t CO₂); \( M_{\text{con}} \) is the embodied carbon of concrete per ton (t CO₂/t); \( W_{\text{con}} \) is the weight of concrete (t).

(2) Rebar

\[ C_{\text{bar}} = M_{\text{bar}} \times W_{\text{bar}} \]  

where \( C_{\text{bar}} \) is the embodied carbon of rebar (t CO₂); \( M_{\text{bar}} \) is the embodied carbon of rebar per ton (t CO₂/t); \( W_{\text{bar}} \) is the weight of rebar (t).

(3) Shape steel

\[ C_{\text{steel}} = M_{\text{steel}} \times W_{\text{steel}} \]  

where \( C_{\text{steel}} \) is the embodied carbon of shape steel (t CO₂); \( M_{\text{steel}} \) is the embodied carbon of shape steel per ton (t CO₂/t); \( W_{\text{steel}} \) is the weight of shape steel (t).

(4) Profiled sheet

\[ C_{\text{sheet}} = M_{\text{sheet}} \times W_{\text{sheet}} \]  

where \( C_{\text{sheet}} \) is the embodied carbon of profiled sheet (t CO₂); \( M_{\text{sheet}} \) is the embodied carbon of Profiled sheet per ton (t CO₂/t); \( W_{\text{sheet}} \) is the weight of Profiled sheet (t).

2.3. Environmental cost

The relationship between economic and environmental cost can be reflected through the concept of the emission reduction cost. Emission reduction cost is extra cost in order to reduce the unit emission, which is a key factor affecting greenhouse gas emission reduction activity. The total cost \( TC \) in a building structure life cycle (in dollars) is given by:

\[ TC = AC + u_c \cdot C_f \cdot \beta \]  

where \( u_c \) is the emission reduction cost in a building structure life cycle (dollar/CO₂), \( C_f \) is the total carbon emission in a building structure life cycle, \( \beta \) is the conversion factor of carbon and carbon dioxide, \( AC \) is the economic cost of building structure, \( u_c \cdot C_f \cdot \beta \) is carbon emission cost in a building structure life cycle (in dollars).

Emission reduction cost of China in 2010 under different cost models are shown in Table 1.

| Model                  | Rate of emission reduction | Emission reduction cost (dollar/tCO₂) |
|------------------------|----------------------------|--------------------------------------|
| GREEN                  | 20%(30%)                   | 14(15)                               |
| Zhang’s CGE model      | 20%(30%)                   | 23(45)                               |
| China MARKAL-MACRO     | 20%(30%)                   | 59(75)                               |
| EPPA                   | 20%(30%)                   | 10(18)                               |
| GTEM                   | 20%(30%)                   | 18(30)                               |
3. Comparative study of different structural systems of a super tall buildings

3.1. Structure information

Three structural systems are compared for a real 301.8 meter super tall buildings in Changchun, Jilin province, China. It is a 69-story office building, which covers an area of 133000 m². There are three alternative structural systems, named system A, B, and C. System A uses frame-core wall structure, while the frame-core-outrigger lateral resisting system was applied in system B and C. One outrigger truss is set on the 44th floor along Y-axis in system B, and two outrigger trusses are set on the 44th floor and 57th floor along Y-axis in system C. The floor roof of system A uses cast-in-place reinforced concrete structure, while profiled sheet-concrete composite floor is applied in system B and C. Fig.2 shows the structure layout of system A, and Fig.3 shows the structure layout of system B and C. Besides, all of the three structural systems adopt steel reinforced concrete columns.

3.2. Material consumption of three structural systems

This project adopts C30 concrete for beams and slabs, C40-C60 concrete for walls and columns, with 15% fly ash added. The strength grade of rebar is HRB400, and the type of steel is Q345. DW76-688 profiled steel sheets are applied in profiled sheet-concrete composite floors, the thickness of which are 1mm.

Concrete consumption of three structural systems is listed in Table 2. Steel consumption of three structural systems is listed in Table 3.

| Table 2. Concrete consumption of three structural systems |
|-------------------------------------------------------|
| member | System A (m³) | System B (m³) | System C (m³) |
| Wall   | C30 | C40 | C50 | C60 | C30 | C40 | C50 | C60 | C30 | C40 | C50 | C60 |
| Column | -   | 2964 | 10183 | 21619 | -  | 3970 | 6572 | 11797 | - | 3970 | 6572 | 11797 |
| Beam   | 18422 | - | - | - | - | 1765 | 3156 | 6222 | - | 1765 | 3156 | 6222 |
| Slab   | 15752 | - | - | - | - | 15758 | - | - | - | 15760 | - | - |
| Sum    | 34174 | 4011 | 13777 | 28287 | 15758 | 5735 | 9728 | 18019 | 15760 | 5735 | 9728 | 18019 |
### Table 3. Steel consumption of three structural systems

| member  | System A               | System B               | System C               |
|---------|------------------------|------------------------|------------------------|
|         | Rebar (t)  | Shape steel (t)       | Profiled sheet (m²)  | Rebar (t)  | Shape steel (t)       | Profiled sheet (t)  | Rebar (t)  | Shape steel (t)       | Profiled sheet (t)  |
| Wall    | 3897       | -                      | -                      | 4093       | -                      | -                      | 4095       | -                      | -                      |
| Column  | 2249       | 3677                   | -                      | 1923       | 3776                   | -                      | 2057       | 3776                   | -                      |
| Beam    | 4637       | -                      | -                      | 1060       | -                      | 13069                 | -                      | 11645      | -                      |
| Slab    | 1090       | -                      | -                      | -          | -                      | 150690                | 1059       | -                      | 150690                |
| Outrigger | -          | -                      | -                      | 60         | -                      | -                      | 120        | -                      |
| Sum     | 11873      | 3677                   | -                      | 7077       | 16906                  | 150690                | 7211       | 15541                  | 150690                |

### 3.3. Embodied carbon analysis

The distribution of embodied carbons in members and materials for different structural systems are calculated and analyzed based on ICE database in this section.

The unit embodied carbon of plan concrete is concerned with concrete strength and the kind and content of mineral admixtures. The unit embodied carbon of C30-C60 concrete with 15% fly ash added are shown in Table 4. It should be noted that the unit embodied carbon of C60 concrete isn't given in ICE database, and it is obtained through the liner interpolation method.

| Concrete grade | Unit embodied carbon (t Co²/t) | Note               |
|----------------|--------------------------------|--------------------|
| C30            | 0.130                          | 15% fly ash added  |
| C40            | 0.152                          | 15% fly ash added  |
| C50            | 0.174                          | 15% fly ash added  |
| C60*           | 0.196*                         | 15% fly ash added  |

The unit embodied carbon of steel is concerned with the recycling rate of steel. ICE database has listed the unit embodied carbon of steel with recycling rate of 0, 35.5%, 39%, 59%, 100%, respectively. According to the statistics and analysis of literature [10], the recycling rate of steel in China is only 38%, while the world's average recycling rate of steel is 82.5%, and developed countries' average recycling rate of steel is 90%. 38% recycling rate of steel is adopted for the calculation of embodied carbon of different structural systems. The unit embodied carbon of steel with recycling rate of 38% is shown in Table 5, and the data are obtained through polynomial fitting method.

| Material       | Unit embodied carbon (t Co²/t) | Note               |
|----------------|--------------------------------|--------------------|
| Rebar          | 1.885                          | Recycling rate 38% |
| Shape steel    | 2.056                          | Recycling rate 38% |
| Profiled sheet | 2.239                          | Recycling rate 38% |

The distribution of embodied carbons in members is shown in Fig. 4. The distribution of embodied carbons in materials is shown in Fig. 5. Some conclusions can be obtained from Fig. 4 and Fig. 5:

1. For System A without outrigger trusses, the distribution of embodied carbons in members have the rule: Wall > Column > Beam > Slab; the distribution of embodied carbons in materials have the rule: Concrete > Rebar > Shape steel.

2. For System B and C with outrigger trusses, the distribution of embodied carbons in members have the rule: Beam > Wall > Column > Slab > Outrigger; the distribution of embodied carbons in materials have the rule: Shape steel > Concrete > Rebar > Profiled sheet.
(3) Because outrigger trusses are set in System B and C, there is a decrease in the embodied carbon of wall.

(4) Due to the use of steel beams and profiled sheets in System B and C, there is a decrease in the embodied carbons of concrete and rebar, followed by a remarkable increase in the embodied carbon of shape steel. Compared with System A, the embodied carbons of beam and slab have a increase for System B and C.

(5) Due to the low recycling rate of steel in China, the embodied carbons of System A are the least.

3.4. Comparison of economic and environment costs

The unit price of main structure materials is shown in Table 6.

| Material       | C30 (Yuan/m³) | C40 (Yuan/m³) | C50 (Yuan/m³) | C60 (Yuan/m³) | Rebar (Yuan/t) | Shape steel (Yuan/t) | Profiled sheet (Yuan/m²) |
|----------------|---------------|---------------|---------------|---------------|----------------|----------------------|--------------------------|
| Unit price     | 430           | 470           | 510           | 590           | 3700           | 8500                 | 124.6                    |

Take the emission reduction cost of $59/(tC) under a reduction rate 20% from China MARKAL MACRO model of 2010 and the Yuan’s exchange rate for dollars off for 1:6.2. Table 7 shows the economic and environment costs of three structural systems.

| member         | System A Economic cost (ten thousand) | Environment cost (ten thousand) | System B Economic cost (ten thousand) | Environment cost (ten thousand) | System C Economic cost (ten thousand) | Environment cost (ten thousand) |
|----------------|----------------------------------------|---------------------------------|---------------------------------------|---------------------------------|---------------------------------------|---------------------------------|
| Concrete       | 4030                                   | 4350                            | 2506                                  | 2707                            | 2506                                  | 2708                            |
| Rebar          | 4393                                   | 4614                            | 2618                                  | 2750                            | 2668                                  | 2802                            |
| Shape steel    | 3126                                   | 3200                            | 14370                                 | 14713                           | 13210                                 | 13526                           |
| Profiled sheet | -                                      | -                               | 1878                                  | 1913                            | 1878                                  | 1913                            |
| Sum            | 11548                                  | 12165                           | 21372                                 | 22084                           | 20262                                 | 20949                           |

According to the data of Table 7, We can conclude that:

(1) For System A without outrigger trusses, the economic and environment costs of materials have the same rule: Rebar > Concrete > Shape steel.
(2) For System B and C with outrigger trusses, the economic and environment costs of materials have the same rule: Shape steel > Rebar > Concrete > Profiled sheet.

(3) Compared with System A, in System B and C, there is a decrease in the economic and environment costs of concrete and rebar, followed by a remarkable increase in the economic and environment costs of shape steel for System B and C.

(5) Due to the low recycling rate and the high prices of steel in China, both the economic and environment costs of System A are the least.

3.5. The fundamental factors which influence the environmental costs

The factors which influence the environmental costs can be summarized as four categories: the factors which influence the material consumption, the factors which influence the unit embodied carbon, the unit price of main structure materials, and the emission reduction cost. Even though the latter two factors aren't controlled by engineers in general, but engineers can also take some effective measures to reduce the embodied carbons and the environment costs.

The material consumption is influenced mainly by the magnitude of load. The magnitude of load is affected by many factors, such as the location of structure, the shape of structure, structural system, the stiffness and mass distribution of the structure, and so on. Choosing the appropriate shape, structural system, and structural arrangement can reduce the magnitude of load, thus the material consumption and environmental costs can be reduced, too.

As previously mentioned, the unit embodied carbon of plan concrete is concerned with concrete strength and the kind and content of mineral admixtures. The more the mineral admixtures are mixed in concrete, the less the unit embodied carbon of plan concrete will be. We can also find that the unit embodied carbon of plan concrete with blast-furnace slag is less than that with fly ash at the same content of mineral admixtures. The recycling rate of steel has a great influence on the unit embodied carbon of steel, and then affect the embodied carbon and the environmental costs. Figure 6 shows the variation law of embodied carbons with the recycling rate of steel.

![Fig. 6. The variation law of embodied carbons with the recycling rate of steel](image)

As we can see in Figure 6, when the recycling rate of steel is greater than about 70%, the embodied carbons of System C on which two outrigger trusses are set, will be the least. We can conclude that, with the progress of steel making technique and the raise of recycling rate of steel, super tall buildings using more steel will produce less carbon emissions and be more environmentally friendly. Although we can't predict the unit price of steel in the future, but we can conjecture boldly that with the progress of steel making technique, both the economic and environment costs of buildings using more steel will be the least.
4. Conclusions

This paper introduces the Calculation method of embodied carbon and environmental costs based on ICE database data. This paper does not consider the embodied carbon and economic costs during construction stage and operation stage, because the embodied carbon and economic costs of materials production stage is most closely to structural design.

The embodied carbons and environmental costs of a real 301.8 meter super tall buildings applying three different structural systems are thoroughly analyzed in this study. The distribution regularities of embodied carbons of critical structural members and materials are find through the embodied carbon analysis in this paper. Both economic costs and environmental costs are used during the conceptual design stage of super tall buildings to help engineers choose a environmentally friendly structural system. At last ,this paper analyses the fundamental factors which influence the environmental costs to provide a guide for the sustainable structural design of super tall buildings. Through the analysis of the variation law of embodied carbons with the recycling rate of steel, we can conclude that, with the progress of steel making technique and the raise of recycling rate of steel, super tall buildings using more steel will produce less carbon emissions and be more environmentally friendly. With the progress of steel making technique, the unit price of steel will be certain to decrease sharply. We can conjecture boldly that with the progress of steel making technique, both the economic and environment costs of buildings using more steel will be the least.

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