Research on Carbon Emissions from Urban Bridge Construction based on LCA

Qianqian Liang[1, 2 *], Yexun Li [1, 2,a], Laifa Wang[1, 2,b], Wei Zhang[1, 2,c], Wenxuan Duan[3,d]

[1] CCCC THIRD HARBOR ENGINEERING CO, Ltd, Shanghai 200030, China
[2] Key Laboratory of Engineering Structures, CCCC Group, Shanghai 200030, China
[3] CCCC THIRD AVIATION BUREAU NINTH ENGINEERING CO, Ltd, Chongqing 400012, China

*Corresponding author's e-mail: liang_qqian@163.com
[a] 370189173@qq.com, [b] laifa.wang@163.com
[c] 464728373@ qq.com, [d] 824492257@qq.com

Abstract. This study considered the unique complexity of urban bridge construction environments and established a carbon emissions model applicable to such activities. Based on the Life Cycle Assessment (LCA) method, the model divided the construction process into material production, transportation, and construction. The construction phase was further subdivided into multiple components. Application to a Shanghai urban bridge case study demonstrated that: (1) In the construction phase, the contribution of water usage was less than 1% to the carbon emissions in all sub-projects. This factor could be ignored to simplify the model. (2) From the perspective of carbon emission proportions, the material production phase was the primary emission source, accounting for over 90% in all sub-projects. The use of recycled materials had significant potential for reducing carbon emissions. (3) In terms of carbon emissions from sub-projects, the carbon emissions from main beam construction were significantly higher than those from main tower and cable construction, making it a key focus area for future carbon reduction efforts.

Keywords: Urban bridges, Construction, Carbon emissions, LCA

1 Introduction

With the continuous growth of urban population density and the increasing severity of traffic pressure, the demand for urban bridge construction and maintenance has risen significantly. The construction of urban bridges involves a large amount of resource and energy consumption, making it particularly important to accurately calculate the carbon emissions associated with urban bridge construction activities. Currently, scholars both domestically and internationally have widely focused on carbon emissions research throughout the Life Cycle Assessment (LCA) of bridge engineering[1][2]. For example, Wang used the LCA method to analyze the carbon emissions of six different types of bridges from the perspectives of materialization, operation and maintenance,

S. Sing et al. (eds.), *Proceedings of the 2025 7th International Conference on Civil Architecture and Urban Engineering (ICCAUE 2025)*, Atlantis Highlights in Engineering 43,
https://doi.org/10.2991/978-94-6239-682-1_2

and demolition and scrapping. This revealed the differences in carbon emissions between different types of bridges throughout their entire life cycle[3]. However, current research mainly focuses on direct carbon emissions from different bridge types, materials, or construction stages. Research on the complexity of the urban bridge construction environment and the diversity of factors affecting carbon emissions has been insufficient. Especially in urban environments, bridge and road construction often causes traffic delays around construction sites, resulting in additional carbon emissions. Huang et al used the SUMO model to simulate traffic delays around urban road maintenance areas and found that traffic delays can cause additional carbon emissions of between 80 ~ 180 kg/h[4]. In addition, green plants in urban road areas absorb CO_2 through photosynthesis to form carbon sinks, which can offset carbon emissions during the entire life cycle of bridges to a certain extent[5].

Therefore, this article aims to fully consider the special nature and complexity of the construction environment of urban bridges and establish a carbon emission model applicable to urban bridge construction activities.

2 Life Cycle Assessment (LCA)

2.1 Scope and Purpose of Carbon Emissions Research

Greenhouse gases mainly include six gases, such as CO_2, CH_4, and N_2O. Among them, CO_2 accounted for over 90% of total emissions and was the dominant contributor. Therefore, the term carbon dioxide equivalent (CO_{2e}) referred specifically to CO_2 in this study. this study constructed a carbon emission calculation model applicable to the entire process of urban bridge construction and achieved the following objectives. First, through on-site surveys and resource verification, the system boundaries of urban bridge construction were clarified, a carbon emissions inventory was systematically compiled, and a targeted carbon emissions calculation model was constructed. Second, the main sources of carbon emissions during the construction process, key influencing factors[6], and their interactions were thoroughly investigated to identify key carbon emission stages. Finally, by quantifying carbon emissions from construction activities, we provide contractors with quantitative reference data on the carbon emission levels of various sub-projects, enabling them to comprehensively assess the carbon contributions of all construction activities.

2.2 System Boundary

System boundaries were one of the fundamental components of the LCA scope. In this study, based on the specific circumstances of urban bridge construction, carbon emissions were categorized into direct carbon emissions and indirect carbon emissions. Direct carbon emissions mainly involved material production, transportation, and construction during the construction period[7]. Indirect carbon emissions were caused by land use and traffic delays. Indirect carbon emissions were caused by construction, so they were included in the carbon emissions of the construction phase. The specific content was shown in Figure 1.

Material production carbon emissions referred to greenhouse gas emissions generated throughout the entire upstream production phase, from raw material collection and processing to the creation of the final product. Carbon emissions from vehicle transportation mainly included carbon emissions generated by fuel consumption or electricity consumption of construction machinery during the transportation phase. On-site construction carbon emissions mainly originated from construction materials, temporary materials, construction machinery, construction water, artificial, land use, and transportation delays. Construction materials referred to consumable materials used during the construction process, such as welding materials and iron parts. Temporary materials were tools that could be used multiple times during construction, such as steel-wood composite formwork panels and steel pipe scaffolding. Land use referred to changes in land use in the original area during urban bridge construction, which might result in a reduction in carbon sink areas, a decrease in the carbon sequestration capacity of the region, and an indirect increase in carbon emissions caused by construction activities. Transportation delays caused by road closures and detours around construction sites on urban bridges during construction periods can lead to traffic congestion and result in additional carbon emissions.

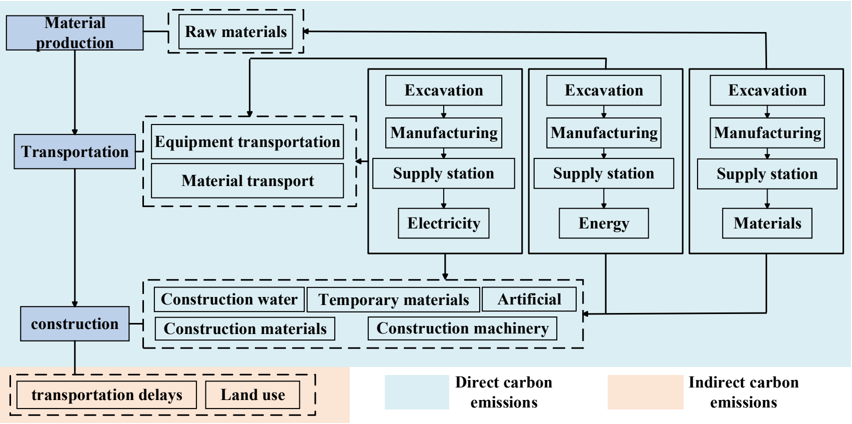


Fig. 1. Carbon system boundary for urban bridge construction

2.3 Inventory Analysis

2.3.1 Material Carbon Emission Factor.

After comprehensively considering the characteristics of construction in China's construction industry, this research systematically compiled carbon emission factors applicable to primary bridge construction materials. The specific values were shown in Table 1.

Table 1. Inventory of material carbon emission factors

Number	Material category	Carbon emission factor
1	concrete	320.00 kg CO_{2e}/m^3

2	Steel	2120.00 kg CO_{2e} /t
3	wood	73.90 kg CO_{2e} /m^3
4	Welding rod	2050.00 kg CO_{2e} /t
5	Zinc	1500.00 kg CO_{2e} /t
6	Iron	2280.00 kg CO_{2e} /t
7	Gravel	4.02 kg CO_{2e}/m^3
8	Water	0.17 kg CO_{2e} /t

2.3.2 Carbon Emission Factors for Vehicles and Machinery.

Energy served as a critical power source for vehicles and machinery, with its emissions playing a significant role in material production, transportation, and mechanical construction. According to the *General Principles for Comprehensive Energy Consumption Calculation*, emission factors were 3.50 kg CO_{2e}/kg for gasoline and 3.67 kg CO_{2e}/kg for diesel. According to the announcement by the *Ministry of Ecology and Environment* and *the National Bureau of Statistics* on the release of the 2021 power sector carbon dioxide emission factors, the carbon emission factor for electricity was determined to be 0.60 kg CO_{2e}/kWh. Referencing the *Highway Engineering Machinery Shift Costs*, machinery operated on an 8-hour daily shift standard. Daily carbon emission factors for construction machinery were detailed in Table 2.

Table 2. Inventory of material carbon emission factors

Mechanical type	Energy type	Unit	Energy consumption	Carbon emission factor kg CO_{2e}/ unit
Hoist	Electricity	kWh	37.58	22.55
Box culvert jacking equipment	Electricity	kWh	42.24	25.34
AC spot welder	Electricity	kWh	101.77	61.06
AC arc welding machine	Electricity	kWh	87.63	52.58
Vibratory pile hammer	Electricity	kWh	352.13	211.28
Concrete pump	Electricity	kWh	463.11	277.87
Electric multistage pump	Electricity	kWh	238.09	142.85
Steel strand stretching equipment	Electricity	kWh	19.36	11.62
Intelligent grouting system	Electricity	kWh	80	48.00
Steel strand threading machine	Diesel fuel	kg	70.97	42.58
Truck crane	Diesel fuel	kg	113.15	350.77
Crawler crane	Diesel fuel	kg	113.15	350.77

The main transport vehicles were cargo trucks and flatbed trucks. Freight truck was mainly used to transport materials related to bridge construction, with carbon emissions of 251.53 kg CO_{2e} /truck. The flatbed truck was mainly used to transport construction machinery, with a carbon emission factor of 183.50 kg CO_{2e} /truck.

2.3.3 Land Use Carbon Emission Factors.

Land use carbon emission factors were estimated based on carbon dioxide absorption data for different types of green spaces in Taiwan[8], as shown in Table 3.

Table 3. Inventory of land-use carbon emission factors

Land category	Site greening	Park	Farmland	Forest
Carbon emission factor ($kg\ CO_{2e}/m^2 \cdot day$)	-9.04E-04	-6.68E-03	-1.26E-02	-1.36E-02

3 Carbon Emission Calculation Model for Urban Bridge Construction Activities

Carbon emission calculations required comprehensive coverage of emission sources while prioritizing key analytical areas and excluding factors contributing less than 1% of emissions in any given phase[9]. For instance, when traffic delays accounted for less than 1% of on-site construction phase emissions, their contribution to urban bridge construction carbon emissions was excluded from the model and not analyzed further. The overall carbon emissions calculation was as shown in Formula (1):

$$E = \sum_{i=1}^{n} Q_i f_i + \sum_{j=1}^{n} N_j f_j + E_{SG} \tag{1}$$

In the formula, E is the total carbon emissions from bridge construction. Q_i is the total consumption of the i-th material. f_i is the carbon emission factor for the i-th material. N_j is the number of shifts for the j-th type of vehicle. f_j is the carbon emission factor for the j-th vehicle. E_{SG} is carbon emissions during the construction phase, including seven components: construction machinery, turnover materials, construction materials, land use, artificial, construction water, and transportation delays. It has seven parts: construction machinery, temporary materials, construction materials, land use, labor, construction water, and traffic delays. As shown in Formula (2):

$$E_{SG} = \sum_{k=1}^{n} N_k f_k + \sum_{i=1}^{n} Q_i f_i + \sum_{s=1}^{n} Q_s f_s \lambda_s - \sum_{m=1}^{5} A_m f_m U + Q_p f_P + Q_w f_w + Q_{yw} r_a \tag{2}$$

$$Q_{yw} = F_m D q \tag{3}$$

In the formula, N_k is the number of shifts for the k-th type of machinery. f_k is the carbon emission factor for the k-th type of machinery. Q_w is the amount of construction water used. f_w is the carbon emission factor for water. Q_p is an artificial number. f_p is the artificial carbon emission factor. Q_s is the total consumption of the s-th type of temporary materials. f_s is the carbon emission factor for the s-th type of temporary materials. λ_s is the carbon emission conversion coefficient for the s-th type of temporary materials. It is the ratio of the amount of time that turnover materials were used during construction to the amount of time specified in the turnover material quota. In this study, the ratio was set at 0.25. A_m is the area of the m-th land type. f_m is the carbon emission factor for the m-th land type. U is the length of the construction. Q_{yw} is the total additional fuel consumption in the construction work area. r_a is the carbon emission factor for the a-th type of energy. F_m is vehicle fuel consumption per hundred kilometers, the fuel for the vehicle is all gasoline. D is the detour distance. q is the daily traffic volume in the construction section.

4 Case Study

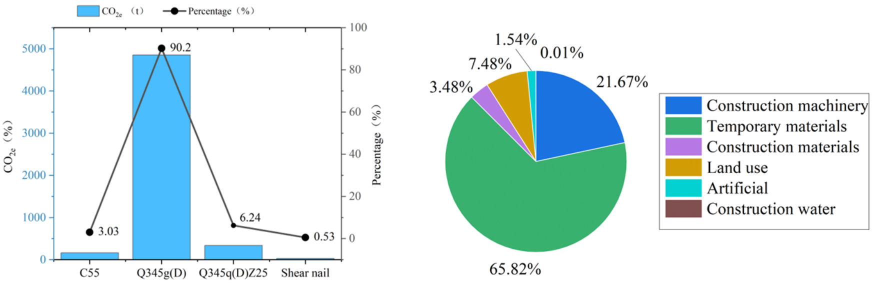
4.1 Project Overview

This study focused on the construction of a low-rise cable-stayed bridge in Shanghai. The main girder adopted a hybrid beam structure design, consisting of a 7-meter-long steel-concrete composite segment, and a 105-meter-long steel beam segment. The steel tower columns used a single-box, single-chamber steel box section. The external dimensions of the tower base structure were 3.5 m (longitudinal) × 5.4 m (transverse). The tower top section dimensions were 3.5 m (longitudinal) × 2.04 m (vertical). The intermediate section was designed to vary linearly. The thickness of the wall panel steel plate was 20~40 mm. The cables were arranged in a fan-shaped pattern on both sides. Six pairs of stay cables were arranged on each side of the arch tower in the longitudinal direction of the bridge, with a cable spacing of 1.2~1.6 m. The cable spacing on the side span beams was 7.5 m. The cable spacing on the center span beams was 9 m, and there were a total of 48 stay cables on the entire bridge. During the construction process, due to the extremely short diversion section and the detour distance of less than 10m, the impact on the surrounding traffic was almost negligible. In addition, the project occupied 6,400 m^2 of forest land and 4,000 m^2 of farmland during construction. In addition, the project occupied 6,400 m^2 of forest land and 4,000 m^2 of farmland during construction. The construction periods for the main beams, main towers, and cable stays were estimated to be 120 days, 50 days, and 30 days, respectively.

4.2 Carbon Emissions Calculation and Analysis

4.2.1 Main Beam.

The carbon emissions from the main beam construction activities amounted to 5,378.10 t. The carbon emissions from material production primarily originated from C55, Q345g(D), Q345q(D)Z25, and shear nails, with the emission quantities and proportions for each material shown in Figure 2(a). Construction carbon emissions reached 220.67 t, with the specific proportions shown in Figure 2(b). Among these, water use emissions were 0.02 t, accounted for less than 1% of total construction carbon emissions. The transportation vehicles amounted to 134.03 t, with material transportation and mechanical transportation accounting for 40% and 60% of total transportation carbon emissions, respectively.

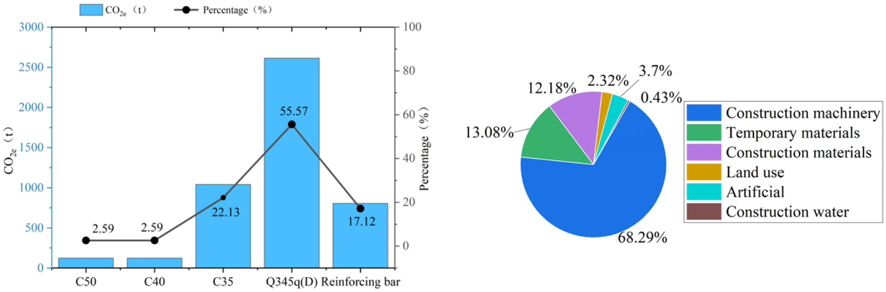


(a) material production (b) construction

Fig. 2. Carbon emissions from main beam material production and construction

4.2.2 Circular Tower.

The carbon emissions from the construction of the circular tower amounted to 4,847.57 t. Material production primarily originated from C50, C35, Q345q(D), reinforcing bars, and shear nails, with the emission quantities and proportions of each material shown in Figure 3(a). Construction phase emission proportions were as shown in Figure 3(b). Among these, carbon emissions from construction water use amounted to 1.28 t, accounting for less than 1% of total construction emissions. The transportation vehicles emissions were 198.67 t, with material transportation and mechanical transportation accounting for 38% and 62% of total transportation carbon emissions, respectively.

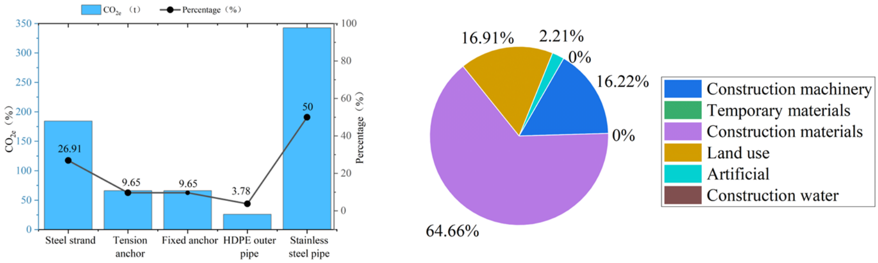


(a) material production (b) construction

Fig. 3. Carbon emissions from the production and construction of circular tower materials

4.2.3 Cable Tensioning.

The carbon emissions from the tensioning of the cable-stayed cables amounted to 726.16 t. Total material emissions were 477.57 t, primarily originating from steel strands, anchorages, HDPE outer casings, and stainless steel pipes. Material-specific emissions and proportions were shown in Figure 4(a). Construction phase emissions totaled 24.42 t, proportions in Figure 4(b).



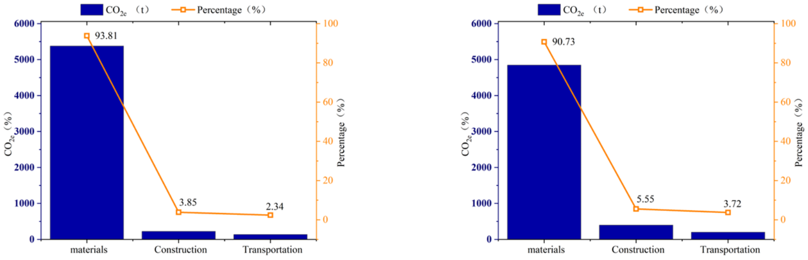
(a) material production (b) construction

Fig. 4. Carbon emissions from the production and construction of cable-stayed bridge tensioning materials

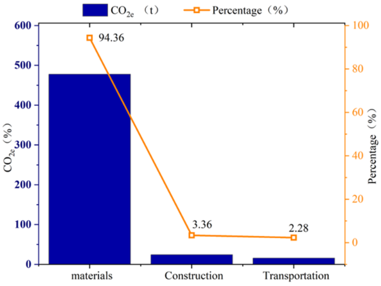
Among these, construction materials accounted for the highest proportion at 64.66%, with the primary material being grout (cement-based composite material). Additionally, this construction operation did not involve construction water or temporary materials. The total carbon emissions from transportation vehicles amounted to 198.67 t, with material transportation and mechanical transportation accounting for 55% and 45% of total transportation carbon emissions, respectively.

4.3 Comparison and Analysis of Carbon Emissions Results.

The carbon emissions and their proportions during the construction phases of the main beam, circular tower, and cable tensioning were shown in Figure 5.



(a) main beam (b) circular tower



(c) cable tensioning

Fig. 5. Carbon emissions comparison during construction of sub-projects cable tensioning

1. Among all sub-projects, main beam construction emissions were higher than other components, which should be a key focus for subsequent carbon reduction efforts. Given that concrete and steel were major sources of carbon emissions, the use of recycled steel and recycled concrete as an alternative to traditional materials had significant benefits in reducing carbon emissions.

2. In each sub-project, materials production accounted for more than 90% of the total, which was the main source of carbon emissions. Promoting green materials not only reduced emissions but advanced resource recycling and sustainable development[10].

3. Construction carbon emissions were mainly divided into seven categories: construction materials, temporary materials, construction machinery, construction water, artificial, land use, and transportation delays. While emission proportions varied across sub-projects, water usage emissions consistently accounted for less than 1% of total construction emissions and were consequently excluded from further analysis.

5 Conclusion

This research employed the LCA method to conduct a detailed analysis of the urban bridge construction process, which mainly included three major stages: material production, transportation, and construction. Given the complexity and diversity of urban bridge construction processes, this study further refined the sources of carbon emissions during the construction phase, which included construction machinery, construction materials, temporary materials, land use, transportation delays, construction water use, and artificial. Based on this framework, a targeted and widely applicable carbon emission quantification model for urban bridge construction was developed. To validate the model's effectiveness, urban bridges in Shanghai were selected as case studies for computational analysis. The model identified main beam construction as the sub-project with the highest carbon emissions. Construction water consumption accounted for less than 1% of the total, which can be ignored in order to focus on key sources of impact. The proportion of carbon emissions from material production accounted for more than 90% of the total carbon emissions for each sub-project. The use of recycled concrete and steel holds significant promise for reducing carbon emissions.

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