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Research Article

Cost and CO_2 Emission Reduction Effects of a Partially Encased Composite Precast Concrete Beam

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In order to study the performance of partially precast partially encased assembled composite beam (PPECB) in reducing costs and reducing carbon dioxide (CO_2) emissions, this paper obtained the bearing capacity of PPECBs by a static test. Considering the load conditions and beam height conditions as constraints, the steel-concrete composite beam (SCCB) and reinforced concrete beam (RCB) were optimized and designed based on the principle of fully utilizing the advantages of steel and concrete. On the basis of investigating the quantity of different materials, the cost and CO_2 emissions of the three different types of beams were analyzed. The cost and CO_2 emission of the PPECB are the lowest, and SCCBs have the highest cost and CO_2 emissions. This paper can provide reference for design choice and further research from the perspective of cost and CO_2 emission and lay a solid foundation for the realization of economic and environment-friendly buildings.

1. Introduction

Global warming is a severe environmental challenge facing mankind. The greenhouse effect caused by CO_2 emission is a major factor contributing to global warming. According to the Intergovernmental Panel on Climate Change (IPCC) report, the construction industry consumed 40% of the world's energy and produced 36% of CO_2 emissions [1]. Construction activity is one of the main human activities that leads to the increase of CO_2 concentration in the global atmosphere [2]. Many countries have increased efforts to reduce greenhouse gases. Such efforts have led to the construction of green buildings throughout the world [3–5]. But in the construction of green buildings, the cost and benefit of additional investment in the process of design and construction have become a concern. Some scholars had analyzed 33 green buildings in California; the results showed that the buildings that reach the Leadership in Energy and Environmental Design (LEED) basic certification of the American Green Building Committee cost 1.84% more than the conventional buildings on average. The additional cost of LEED gold certification is about 2%–5% [6]. The increase in costs is detrimental to any economic behavior, especially in the real estate industry. Therefore, some scholars put forward the concept of green frame in view of the construction process from the perspective of the whole life cycle, expecting to achieve low-cost construction and low CO_2 emissions in the construction stage [7–10]. At present, there is no report about green structure in China. From the perspective of green frame, this paper proposes a partially precast partially encased assembled composite beam (PPECB) in order to achieve a low-cost and low CO_2 emission green frame, and comparative analysis of RCBs and SCCBs commonly used in China to clarify the effect of three types of beams on cost and CO_2 emissions was performed. It can provide reference for design choice and further research from the perspective of cost and CO_2 emission.

2. Methodology

2.1. Introduction of the PPECB. As we all know, the SCCB is a kind of composite beam slab system with relatively fast construction speed (Figure 1(a)), which has been applied in the world. In order to improve the mechanical properties of

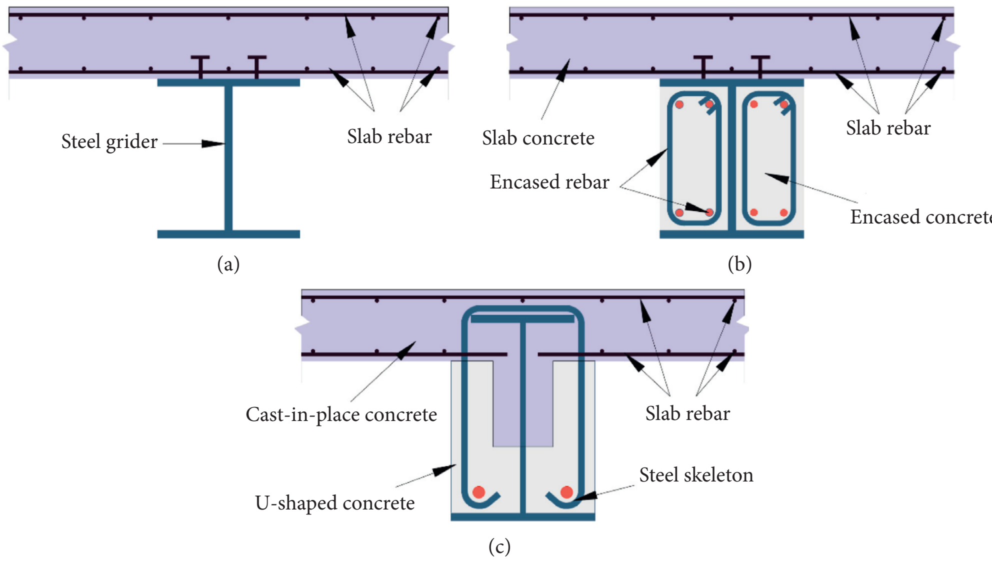

Figure 1: Evolution of the PPECB. (a) SCCB. (b) PECB. (c) PPECB.

the steel girder, some scholars filled the concrete between the top and bottom flange of the steel girder to form a partially encased composite (PEC) beam slab system (Figure 1(b)), and systematically studied the static mechanical behavior of PEC beams [11–13]. In order to reduce the influence of beams on the indoor space, simplify the construction process, and further improve the performance of beams, some scholars have made further improvements, put forward a PPECB (Figure 1(c)), and studied the short-term mechanical behavior of PPECBs [14], laying a foundation for its engineering application.

This improved PPECBs consist of two parts: prefabricated part and cast-in-place part. Its detailed cross-section is shown in Figure 2.

The characteristics of cross-section of PPECBs are as follows:

(i) The precast part is made up of precast concrete, longitudinal reinforcement, and unequal width flange I-steel girder

(ii) semiclosed stirrup is placed on the unequal width flange I-steel girder

(iii) The longitudinal reinforcement is bound to the hoop hook of a semiclosed stirrup

(iv) The cast-in-place concrete is poured in a U-shaped groove

2.2. Research Process of This Paper. First, the PPEC beam shall be designed and subjected to a static load test to obtain the moment constraint condition and failure mode. Next, on the basis of considering the failure mode, the SCCB and RCB would be designed through the bending moment constraint condition and the beam section height constraint condition, and then the quantity of material for three kinds of beams would be calculated.

Second, from the perspective of the whole life cycle, the cost and CO_2 emissions of three different types of beams would be calculated by the material conversion rate in the materialization stage.

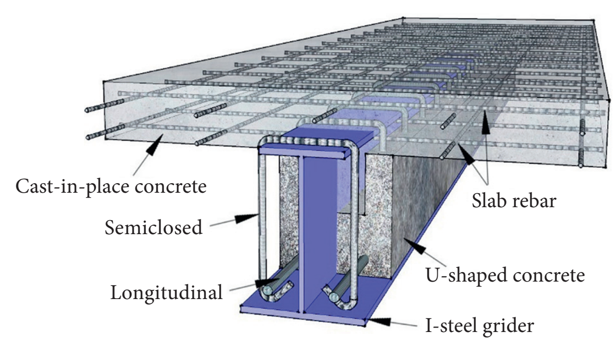

Figure 2: Schematic diagram of the PPECB.

Finally, the conclusion shall be drawn from the calculated cost and CO_2 emissions.

The procedures of this research are as shown in Figure 3.

2.3. The PPEC Beam Test. According to the purpose and test conditions of this paper, a PPECB specimen was designed with reference to BS EN 1994-1-1 [15], and the size details of the cross-section are shown in Figure 4. The top flange width of I-steel was 100 mm, the width of the bottom flange was 150 mm, the flange thickness was 8 mm, and the web thickness was 6 mm. The mechanical properties of the material were tested. The results are shown in Table 1.

The test was completed on a 500-t pressure-testing machine. The test specimen was simply supported beam. The test used a four-point symmetrical loading method, and the test loading device is shown in Figure 5. During the loading process, the load increment of each stage was 10 kN. When the steel was close to yield, the load increment of each stage was reduced to 5 kN per step. When approximately 90% of the estimated ultimate capacity was reached for the specimens, the load was reduced to 5 kN per step. When the

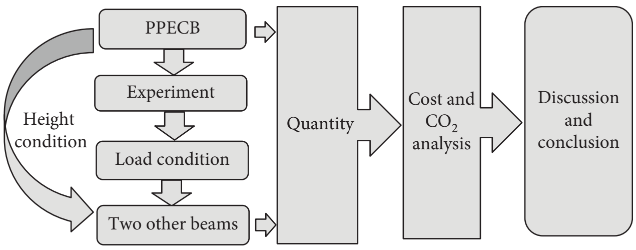

FIGURE 3: Procedures of this study.

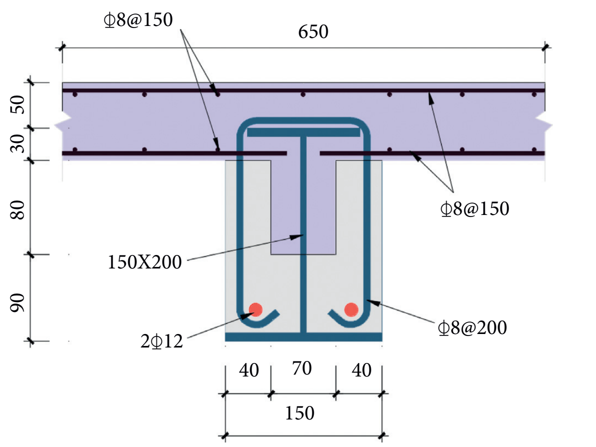

FIGURE 4: Cross-sectional feature information of the PPEC beam.

TABLE 1: Mechanical properties of materials.

Material	f_{cu} (MPa)	f_y (MPa)	f_u (MPa)
Concrete	23.9	—	—
I-steel-Q235	—	287.0	442.0
Rebar	—	360.3	475 .2

f_{cu}, concrete compressive strength; f_y, tensile yield strength; f_u, tensile ultimate strength.

ultimate load was reached, the specimen was continuously loaded to failure. During the loading process, the vertical load, displacement, and strain of the concrete and steel were mainly monitored.

The specimen was a typical bending failure, and its final state is shown in Figure 6. The failure process of the test specimen is as follows: first, the short vertical cracks appeared in the midspan of the specimen. With the increase of the load, the cracks extended upward and increased continuously, and then the lower flange, longitudinal rebars, and some webs yield successively. Finally, the concrete in the compression zone was crushed, the deformation increased sharply, and the bearing capacity decreased.

Figure 7 depicts the load-deflection curve of the specimen. The specimen experienced three stages: elastic, elastoplastic, and plastic failure. In the plastic failure stage, the concrete at the top of the specimen was partially crushed, and the effective compression zone was reduced, which was reflected in the load-deflection curve, that is, the sudden drop in the plastic failure stage, and then the neutral axis moved down, and the bearing capacity was improved. With

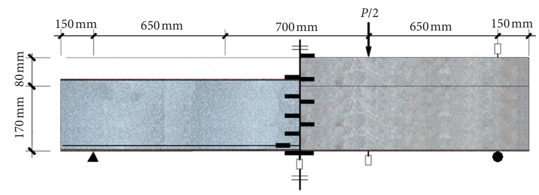

FIGURE 5: Test setup and measuring points layout.

FIGURE 6: Failure mode of the PPEC beam.

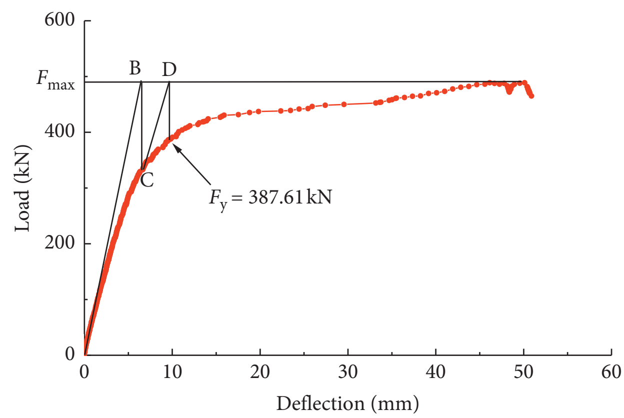

FIGURE 7: Load-deflection curve of the PPEC beam.

the continuous loading, more concrete was crushed, and the specimen gradually lost its bearing capacity. The yield load Fy is determined by the method shown in Figure 7 [16]. Then, the yield bending moment was obtained, and its value is 125.97 kN m.

The strain distribution of steel in midspan is shown in Figure 8. It can be seen from Figure 8 that the specimen basically conforms to the plane section assumption in the elastic and elastoplastic stages. But near the failure, the plane section assumption is not satisfied. In the elastic and elastoplastic stages, the neutral axis is basically distributed at the bottom of the concrete slab through observation (Figure 8).

2.4. Constraint Condition. As a vertical load transfer member of a building structure, the beam is mainly subjected to the bending moment. Therefore, the bending moment is a major constraint. In addition, the failure mode must also be considered, and the specimen needs to be designed as a flexural failure mode. In the case where the height of the building is determined, reducing the beam height can effectively increase the net space of the building.

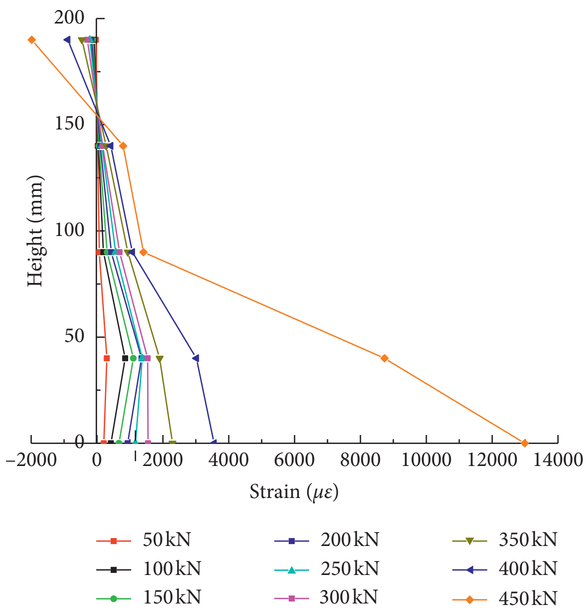

FIGURE 8: Strain distribution of steel in midspan.

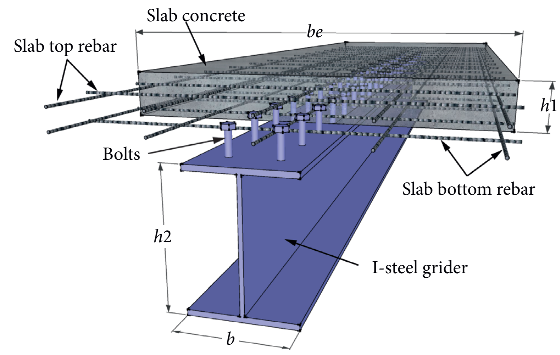

FIGURE 9: The schematic design of SCCBs.

In other words, under the premise of maintaining a net height, the smaller the beam height, the lower the story height, and then reducing the use of building materials, thereby reduces the cost and CO_2 emissions. The height of the beam is another important constraint condition.

Through the analysis in the previous section, it is found that the neutral axis of the PPECB is basically located at the bottom of the concrete slab, which indicates that the designed beam section can fully exert the performance of concrete and steel. Therefore, the full utilization of both steel and concrete materials is also an important constraint condition.

2.5. Design of SCCBs. Under all constraints, the schematic design of SCCBs is shown in Figure 9. In order to ensure the yield of steel before concrete crushing, the cross-section design is obtained by equations (1) and (2) according to the code JGJ138-2016 [17]:where f_c is the design compressive strength of concrete, f_y is the yield strength of steel, the value of f_c is according to Chinese code GB5010-2010 [18] and f_y is according to Chinese code GB 50017-2017 [19], A_c is the effective pressure area of concrete, A_s is the area of steel, h_1 and h_2 are the flange thickness of the slab and the height of I-steel, respectively, and M_y is the flexural capacity, and its value is 162 kN m.

$$f_c A_c \geq f_y A_s, \tag{1}$$

$$M_y = f_y A_s \times 0.5 h_2 \leq f_c A_c \times 0.5 h_1, \tag{2}$$

According to the size of h_1 and h_2, it can be divided into three kinds of designs. For each of the three cases, a beam section was designed. The detailed design results are shown in Table 2.

TABLE 2: Design parameters of SCCBs.

Item	*tw*	*tf*	h_2	*b*	*be*	h_1	Bolts	Slab rebar
SCCB1	12	14	150	200	1400	100	2∗*D8*@100	Bottom: *X&Y D8*@200 Top: *X&Y D8*@200
SCCB2	14	18	125	160	1200	125	2∗*D8*@100	Bottom: *X&Y D8*@200 Top: *X&Y8*@200
SCCB3	18	16	100	180	1000	150	2∗*D8*@100	Bottom: *X&Y D8*@200 Top: *X&Y D8*@200

Note. The design value of the steel yield strength is 315 MPa (Q345); *D*, diameter of reinforcement; @, representative spacing; *X&Y*, horizontal and vertical.

2.6. Design of RCBs. Section design is carried out under restricted conditions. In order to design conformable beam with steel yielding before concrete failure, it can be designed as T-shaped and rectangle-shaped section (Figure 10). The design principle is to satisfy the minimum design value of concrete cross-section. The strength of the material and the design method reference the code GB5001-2010. The detailed parameters of RC beams are listed in Table 3.

2.7. The Quantity of Materials of Different Beams. Assuming that all beams length is 2 meters, all material quantities can be calculated. The quantity of calculated results is listed in Tables 4, 5, and 6.

3. Results

3.1. Cost Analysis. In China, due to the vast area, the cost of building materials varies slightly from place to place, but in general it is not much different. In this paper, the cost of unit materials provided by the local government of Ningbo City, Zhejiang Province, in November 2019 is used as the basis for data calculation and analysis, and the price converted to USD of unit materials is shown in Table 7 [20].

As shown in Table 8, the cost of each material of each specimen can be obtained by Tables 4–7. In order to present visual contrast of data, Table 8 is made into an intuitive

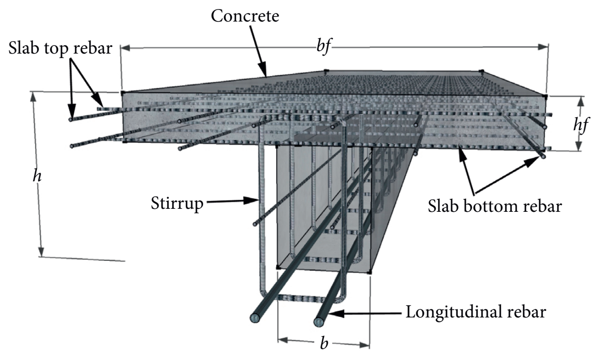

Figure 10: The schematic design of reinforcement concrete beams.

Table 3: Design parameters of RCBs.

Item	*Bf*	*Hf*	*b*	*h*	Longitudinal rebar	Stirrup
RCB1	700	100	300	250	5∗*D*25	*D*8@100(4)
RCB2			500	250	6∗*D*22	*D*8@120(4)

Note. D, diameter of reinforcement; @, representative spacing.

Table 4: Quantity survey of PPECBs.

Item		Unit	PPECB
Concrete		m^3	0.15
Steel		kg	40.31
Screwed rebar	Stirrup	kg	2.17
	Longitudinal rebar	kg	3.55
	Slab rebar	kg	11.10

Table 5: Quantity survey of SCCBs.

Item	Unit	SCCB1	SCCB2	SCCB3
Steel	kg	89.26	91.24	90.92
Concrete	m^3	0.28	0.30	0.30
Bolts	kg	1.44	1.44	1.44
Screwed rebar	kg	24.37	24.45	27.70

Table 6: Quantity survey of RCBs.

Item		Unit	RCB1	RCB2
Screwed rebar	Slab rebar	kg	5.65	—
	Stirrup	kg	11.38	15.19
	Longitudinal rebar	kg	38.53	38.53
	Constructional rebar	kg	3.55	10.81
Concrete		m^3	0.23	0.25

Table 7: Unit cost of resources.

Item	Unit	Unit price
Concrete	USD/m^3	87.26
Steel-Q235	USD/kg	0.57
Steel-Q345	USD/kg	0.58
Rebar	USD/kg	0.60
Bolts	USD/kg	0.78

Table 8: The cost of different beams.

Material	PPECB	SCCB			RCB	
		SCCB1	SCCB2	SCCB3	RCB1	RCB2
Concrete	13.32	24.43	26.18	26.18	20.07	21.82
I-steel-Q235	22.83	—	—	—	—	—
I-steel-Q345	—	51.84	52.99	52.80		
Rebar	10.02	14.51	14.56	16.49	35.19	38.41
Bolts	—	1.13	1.13	1.13	—	—
Total	46.16	91.91	94.85	96.60	55.26	60.23

Note. The bolts are classified into I-steel during statistics.

histogram. The material cost of each specimen is shown in Figure 11, The cost of different beams is shown in Figure 12.

Analysis (Figure 11) shows that in the cost composition of each beam, the cost of steel (I-steel and rebar, same bellow) accounts for a large proportion, while the cost of concrete accounts for a small proportion. In SCC beams, when the height is determined, the size of h_1 and h_2 will affect the distribution of the neutral axis and then the change of the amount of constituent materials and finally the cost. However, as the neutral axis decreases, the cost of steel (I-steel and rebar) will gradually increase in the total cost. In the PPEC beam and RC beam, steel (I-steel and rebar) accounts for a large proportion of the total cost.

As illustrated in Figure 12, the cost of the PPEC beam is the lowest and the cost of SCCBs is the highest. Among all the SCCBs, the lowest cost is the SCCB1. The cost of RCB1 is lower than that of RCB2. The cost of PPECB, SCCB1, and RCB1 is \$323.5, \$644.08, and \$387.24, respectively. Compared with the three beams of PPECB, SCCB1, and RCB1, the cost of PPECB is 19.7% lower than that of RCB1 and nearly half lower than that of SCCB1. The cost of RCB1 is 39.88% lower than that of SCCB1. With the decrease of the neutral axis along the section height, the cost of SCCBs increases gradually. The cost of RCB1 is 8.25% lower than that of RCB2, which shows that the cost of T-shaped beams is lower than that of rectangular beams under the same load and height.

3.2. CO_2 Emission Analysis. In China, there is no national standard CO_2 emission rate at the materialization stage. Refer to [21–24], and unit CO_2 emission rates of materials are listed in Table 9 without considering material recovery. The CO_2 emissions of different materials in each beam are obtained through Tables 4–7, as shown in Table 10. For visual representation, the contents of Table 10 are drawn as a histogram. The CO_2 emission of each specimen material is shown in Figure 11. The CO_2 emission of each beam is shown in Figure 12.

As shown in Figure 13, in each beam, the main source of CO_2 emissions is steel (I-steel and rebar). The CO_2 emissions from concrete and steel in the PPECB are 60.86 kg and 207.84 kg, respectively. Whether it is concrete or steel, the CO_2 emission of PPECB is the lowest of all beams. As mentioned in the previous analysis of cost, h_1 and h_2 will also

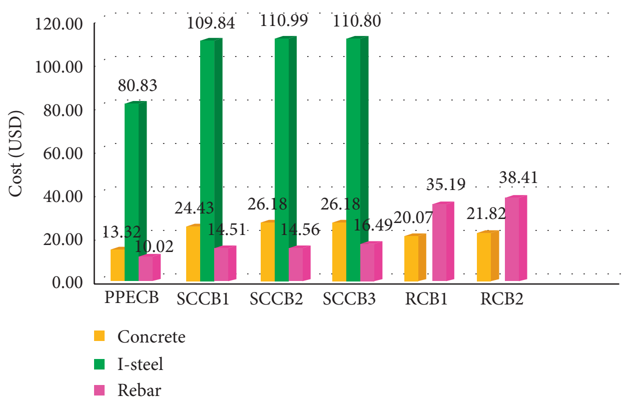

FIGURE 11: The cost of material for different beams.

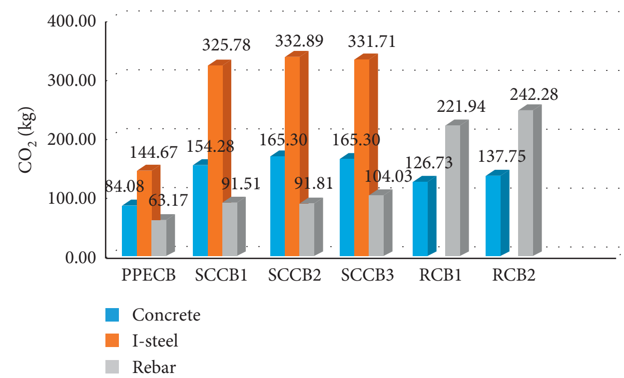

FIGURE 13: CO_2 emission from materials of different beams.

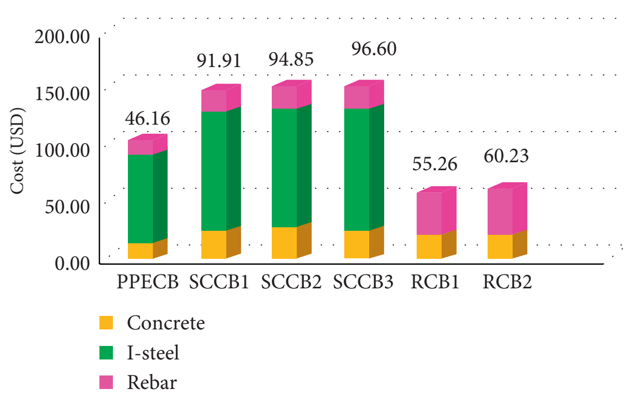

FIGURE 12: The cost of each beam.

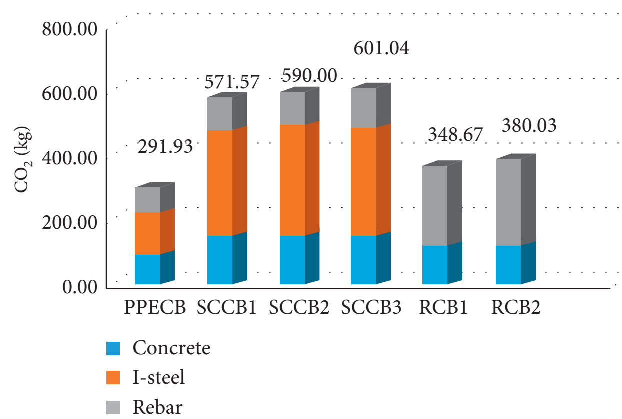

FIGURE 14: CO_2 emission from different beams.

TABLE 9: CO_2 emission rate.

Item	Unit	CO_2 emission rate
Concrete	kg-CO_2/m^3	398.84
Steel	kg-CO_2/kg	3.589
Rebar	kg-CO_2/kg	3.755

TABLE 10: The quantity of CO_2 emission of different beams.

Item	PPECB	SCCB			RCB	
		SCCB1	SCCB2	SCCB3	RCB1	RCB2
Concrete	84.08	154.28	165.30	165.30	126.73	137.75
I-steel-Q235	144.67	—	—	—	—	—
I-steel-Q345	—	320.37	327.48	326.30	—	—
Rebar	63.17	91.51	91.81	104.03	221.94	242.28
Bolts	—	5.41	5.41	5.41	—	—
Total	291.93	571.57	590.00	601.04	348.67	380.03

Note. The bolts are classified into I-steel during statistics.

affect the composition of SCCB materials and thus the composition of CO_2 emissions. When $h_1 = h_2$, the CO_2 emission ratio of steel in SCCB is 71.98%, which is the lowest among the three SCCBs. In RC beams, the CO_2 emission of T-section beams is 8.00% lower than that of rectangular beams, and the steel is 8.40% lower.

As shown in Figure 14, the CO_2 emissions of the PPECB, SCCB1, and RCB1 are 268.71 kg, 528.97 kg, 313.68 kg, respectively. Compared with the three, the CO_2 emissions of the PPECB are 14.34% lower than those of RCB1, and the emissions of RCB1 are 40.70% lower than those of SCCB1. In SCCBs, CO_2 emissions increase with the reduction of the height of the neutral axis along the section. In reinforced concrete beams, CO_2 emissions increase with the increase of a cross-section area. Overall, steel has a greater impact on CO_2 emissions.

4. Conclusion

In this paper, a PPECB is proposed and tested under static loading, and the corresponding constraints are given. According to the constraint conditions, two groups of five comparison specimens were designed and optimized. According to the amount of each specimen of materials, the cost of each specimen of materials and the emission of CO_2 were compared and analyzed. The conclusion is as follows.

First, a PPECB was proposed according to the basis of previous studies, and the section form and characteristics of the composite beam were introduced in detail. The relevant constraint conditions are determined through the test method. The material quantity of 6 specimens under constraint condition was calculated, which was used for cost and CO_2 emission analysis.

Second, under constraint conditions, the cost of PPECBs is lower than that of SCCBs and RCBs, and the cost of SCCBs is the highest. Compared with the three beams of PPECB, SCCB1, and RCB1, the cost of PPECB is 19.7% lower than that of RCB1 and nearly half lower than that of SCCB1. The cost of RCB1 is 39.88% lower than that of SCCB1. In all specimens, steel takes up most of the cost.

Third, under constraint conditions, the CO_2 emission of PPECBs is lower than that of SCCBs and RCBs, and the CO_2 emission of SCCBs is the highest. Compared with the three beams of PPECB, SCCB1, and RCB1, the CO_2 emissions of the PPECB are 14.34% lower than those of RCB1, and the CO_2 emissions of RCB1 are 40.70% lower than those of SCCB1. In all specimens, steel takes up most of the cost.

The PPECB has the advantages of low cost and low CO_2 emissions. From the perspective of cost and environment protection, the partially precast partially encased composite beam proposed in this paper is basically feasible. It can be a reference for further research on the green building structure system.

Data Availability

The experimental and computational data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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