Embodied Energy and CO$_2$ Emission Reduction of a Column-Beam Structure with Enhanced Composite Precast Concrete Members

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Abstract

Green Frame is a column-beam system that uses composite precast concrete members. Previous studies have proven this system to be not only structurally safe, constructible, and economically feasible, but also environmentally friendly. However, the column and beam of the frame need to be improved further in terms of structural performance in order to reduce the CO$_2$ emissions. To this end, a more enhanced structural system than the existing Green Frame has been developed. The aim of this paper is to analyze the embodied energy and CO$_2$ reduction effect of a column-beam structure with enhanced CPC members. An apartment building project was selected as a case study, and the CO$_2$ reduction effect was compared between the existing and enhanced Green Frame. It was found that the improved system would result in a 3% reduction in CO$_2$ compared with the existing one.

Keywords: embodied energy; CO$_2$ reduction; Green Frame; composite precast concrete; CO$_2$ assessment

1. Introduction

Many countries have increased efforts to reduce the emission of greenhouse gases. Such efforts have led to the construction of green buildings throughout the world (Chung and Rhee, 2013; Lee and Yang, 2009; Yan et al., 2010). Korea is actively seeking to reduce CO$_2$ emissions by introducing the "Act of the construction and performance evaluation of environment-friendly apartment buildings" and arranging "Clause of the energy saving design and construction criteria of apartment buildings" (Chung and Rhee, 2012; Lee et al., 2012). However, these studies and regulations are rather concentrated on operation and maintenance phases, not on construction phases (Rey et al., 2007; Yaegashi et al., 2015; Kang and Rhee, 2012). As part of the effort to create a sustainable construction environment, investigation of alternative methods intended to reduce CO$_2$ emissions during the construction phase is deemed necessary (Lee et al., 2012, Tang et al., 2006). As a result, Green Frame was developed.

Green Frame is a column-beam system that uses composite precast concrete members (CPC) (Won et al., 2013). Green frame has proven through previous studies to have not only structural safety, constructability, and economic feasibility, but also environment-friendliness (SH Corporation, 2010; Hon et al., 2010a; Joo et al., 2012a; Kim et al., 2012). Hong et al. (2009) suggested the Green Frame concept, proving that it has a CO$_2$ reduction effect of approximately 18-23% compared to conventional methods. Lee et al. (2012b) improved the Green Frame and confirmed that it reduced CO$_2$ emissions by an additional 2.8%. In addition, analysis studies on the CO$_2$ reduction effect of Green Frame have been carried out by Hong et al. (2012a, 2012b), Kim et al. (2012) and Kim et al. (2013b).

The Green Frame was enhanced even further through elaborated engineering and structural analyses. The detail of CPC column was changed to the less use of steel than other types developed before. As a result, a more enhanced Green Frame is developed, and the aim of this paper is to analyze the embodied energy and CO$_2$ reduction effect of a column-beam structure with enhanced CPC members.

This research is carried out by the following process as shown in Fig.1. First, the enhanced Green Frame is introduced in comparison with the existing Green Frame. Second, methodology for assessment of CO$_2$ emission generated during the construction phase of the Green Frame was explained as a sum of the following: 1) CO$_2$ resulting from the production and transport of input resources and 2) the energy consumed in the construction phase. Third, an apartment building project was selected as a case study, and the CO$_2$ reduction effect was compared between the existing
and the enhanced Green Frame. The CO₂ emissions of future construction projects implementing the Green Frame could be promptly calculated using the results of this study.

2. Enhanced Green Frame

The Green Frame combines the structural advantages of reinforced concrete and steel structures, and is constructed using CPCs to improve the quality and productivity (Lee et al., 2012). The CPCs for the Green Frame are produced on site, which cuts down on the cost of material transport, factory fees, and so forth (Joo et al., 2012a). The CPCs of the Green Frame are composed of Green Beams (GBs) and Green Columns (GCs) (Ko et al., 2013).

The GC is a reinforced concrete column (one to three sections) and attached with joint steel (Joo et al., 2012a; Kim et al., 2012). Hong et al. (2010) proposed different column types depending on the joint method as shown on the left side of Fig.2. Lee et al. (2012) further suggested Type 4 (bolting type) as illustrated in Fig.2. Although less steel is used in Type 4 when compared to Type 3, more steel is needed when compared to Type 1 and Type 2. A reduction in input resources results in lower CO₂ emissions.

GC Type 5 was developed in this study for further reduction of the resources needed and thus the CO₂ emissions. GC Type 5 has different methods of joining the columns together. Couplers are used to connect the columns, which is similar to Type 2 and Type 3. Type 2 requires less steel, but its constructability and safety are relatively low since the GCs should be installed before placing slab concrete. The steel used for Type 3 differs because the GCs are installed after placing slab concrete. This enhances the constructability and safety, but decreases the economic efficiency due to the excessive amount of steel required, in turn generating a tremendous amount of CO₂.

Couplers for bamboo type rebar have some disadvantages in that they make it difficult to respond to construction errors and require quite a large working space. On the other hand, the main rebar in Type 5 GCs is replaced with threaded rebar, which enables easier handling of construction errors and installation of couplers compared to the couplers for the bamboo type rebar.

For GBs, an upper or a lower flange that contributes minimally to the bending moment is removed from the conventional beams based on preliminary studies of the application of H-shape steel, which leads to a decrease in the quantity of steel needed while still ensuring the efficiency of the members (Lee et al., 2012; Kim et al., 2013c). GBs are superior with regard to quantity reduction, decreasing the construction cost, and reducing CO₂ emissions (Hone et al., 2009, 2010).

GBs can be applied not only in GCs, but also in steel-reinforced concrete and steel columns (Lee et al., 2012). T-shape steel is inserted into both ends of the GB as described in a study conducted by Lee et al. (2012). In the previous study, the steel was inserted to 1/3 of the beam's length as shown in Fig.3., but the
present study adopts 1/8 of the length of the beam. Structural examinations of safety indicate the amount of rebar needs to be increased slightly when inserted to 1/8 of the beam length.

![Diagram](image)

**Fig.3. Comparison of GBs**

3. Assessment of CO₂ Emission in Green Frame Construction

To evaluate the CO₂ emissions associated with the Green Frame, Hong et al. (2009, 2010) and Lee et al. (2012) applied the CO₂ unit to quantity resources using Equation (1). This CO₂ unit is the production CO₂ of resources, and is not included in the CO₂ generated during the material transportation and construction phases. Each material generates CO₂ according to the equipment used to transport it. In addition, CO₂ is generated from the consumption of energy such as fuel and electricity due to equipment operation in the construction phase (Kim et al., 2004). Therefore, these CO₂ emissions should be included in the CO₂ assessment by using Equations (2) and (3).

\[
\begin{align*}
\text{Production CO}_2 &= \sum (Q_i \times \text{CO}_2\text{em}) \\
\text{Transportation CO}_2 &= \sum (N_e \times D_i \times \text{CO}_2\text{em}) \\
\text{Installation CO}_2 &= \sum (E_i \times \text{CO}_2\text{em})
\end{align*}
\]

Here,

- \(Q_i\): the quantity of resources such as form, rebar, concrete, etc.
- \(\text{CO}_2\text{em}\): the CO₂ emission rate of resources production
- \(N_e\): the amount of transportation equipment
- \(D_i\): the transportation distance
- \(\text{CO}_2\text{em}\): the CO₂ emission rate of the transportation equipment per kilometer
- \(E_i\): the quantity of energy used
- \(\text{CO}_2\text{em}\): the CO₂ emission rate associated with the energy use.

![Diagram](image)

**Fig.4.** illustrates the construction CO₂ assessment process. First, CO₂ units are applied to the estimated resources' quantity using the methods described by Hong et al. (2009, 2010) and Lee et al. (2012) and the production CO₂ is estimated. Second, installation CO₂ is estimated based on the energy consumption of the equipment used for installation. Third, transportation CO₂ is limited to the CO₂ generated in the transport of material from the supply site to the construction site. Based on the estimated resources' quantity, the CO₂ is estimated after calculating the amount of equipment.

Kim et al. (2004) analyzed the transport distance and velocity of transportation equipment for major materials in order to set the delivery distance and standard carrying capacity in 20 cities in Korea. This study used the data and methods reported by Kim et al. (2004) to estimate transportation CO₂. In addition, the regression equations were applied for estimating the quantity of CO₂ emitted from the use of oil and electrical energy at the construction phase.

The authors used the oil and electrical energy data surveyed by Kim et al. (2004) to build the regression equations. The total floor area and the quantity of diesel and gasoline used in 29 projects were analyzed to build the regression equation for estimating the quantity of CO₂ emitted from the use of oil energy.

In order to make the CO₂ emission data, for reference, the quantity of diesel and gasoline was converted to the TOE, ton of oil equivalent, according to Article 5 Paragraph 1 of the Energy Law in Korea, and the TOE was converted to the CO₂ emission according to the guidelines of the Intergovernmental Panel on Climate Change (IPCC, 2006).

The regression equation was built as equation (4) that has the independent variable of the total floor area and the dependent variable of CO₂ emission. Table 1. shows the descriptive statistics of Equation (4), and Table 2. shows the regression model summary.

\[
Q_{\text{CO}_2\text{f}} = 0.0053A_f + 88.217 \tag{4}
\]

Here,

- \(Q_{\text{CO}_2\text{f}}\): CO₂ emissions from fuel used during the construction phase [T-CO₂],
- \(A_f\): the total floor area [m²]

**Table 1. Descriptive Statistics for Equation (4)**

| Variables | No. | Min. | Max. | Mean | Standard deviation |
|-----------|-----|------|------|------|--------------------|
| Total floor Area (m²) | 29 | 29,264 | 340,560 | 92,677 | 73,387 |
| CO₂ emission (T-CO₂) | | 29 | 19 | 1,689 | 576 | 429 |

**Table 2. Regression Model Summary of Equation (4)**

| Items | R Square | F | Sig. |
|-------|----------|---|------|
| Regression equation | 0.809 | 11.148 | 0.000 |

The total floor area and the consumption of electrical energy used in 34 projects were analyzed to build the regression equation for estimating the quantity of CO₂ emitted from the use of electrical energy.

In order to make the CO₂ emission data, the consumption of electrical energy was converted to the CO₂ emission according to the guidelines of the
The regression equation was built as equation (5) with the independent variable of the total floor area and the dependent variable of CO\textsubscript{2} emission. Table 3. and Table 4. show the descriptive statistics of Equation (5) and the regression model summary respectively.

\[ Q_{CO2e} = 0.0028A + 87.179 \]  
Here,  
\[ Q_{CO2e} : \text{CO}_2 \text{ emissions due to electricity consumed during the construction phase} \ [T-CO}_2]. \]

**Table 3. Descriptive Statistics for Equation (5)**

| Variables              | No. | Min. | Max. | Mean  | Standard deviation |
|------------------------|-----|------|------|-------|--------------------|
| Total floor Area (m\textsuperscript{2}) | 34  | 29,264 | 111,275 | 57,636 | 22,158 |
| CO\textsubscript{2} emission (T-CO\textsubscript{2}) | 34  | 80 | 469 | 250 | 83 |

**Table 4. Regression Model Summary of Equation (5)**

| Items                | R Square | F   | Sig.    |
|----------------------|----------|-----|---------|
| Regression equation  | 0.566    | 41.743 | 0.000 |

### 4. Case Application of Enhanced Green Frame

An apartment building project was selected as a case study. The CO\textsubscript{2} reduction effect was compared between the existing and enhanced Green Frames. The case project involved a bearing wall type apartment building in Korea that was redesigned in order to examine the feasibility of the Green Frame. A 15-story building with a total floor area of 6,534 m\textsuperscript{2} was selected from among the eight buildings comprising the project in order to calculate the quantity of resources used. The foundation and underground structure were excluded. The quantity of materials was calculated by dividing the parts into concrete work, reinforcement work, formwork, partitioning panel, and PC installation. GBs embedded with T-shape steel (1/3 length of the beam length) and Type 4 GCs were used for the existing Green Frame, as in the study by Lee et al. (2012). The GBs embedded with T-shape steel (to 1/8 the length of the beam) with Type 5 GCs proposed in this study were applied to the enhanced Green Frame for comparison.

The quantities calculated for the existing and enhanced Green Frames are given in Table 5.

First, the quantity of materials used for the concrete work was calculated by including the materials used for cast-in-place, PC, and grouting. The quantity of cast-in-place concrete was calculated to be 1,923.54 m\textsuperscript{3} for the existing Green Frame and 1,888.49 m\textsuperscript{3} for the enhanced one. This is because twice as much grouting of the part connecting the columns is required for the enhanced Green Frame compared to the existing one. The quantity of concrete required for the CPCs was 429.38 m\textsuperscript{3} for both the existing Green Frame and the enhanced one.

Overall, it was determined that the two types of Green Frames needed the same quantity of concrete, 2,388.58 m\textsuperscript{3}. This implies that the columns and beams are enhanced within a range in which the overall structural system is not greatly affected. The total concrete quantity was converted into the quantity per unit area, 0.366 m\textsuperscript{3}/m\textsuperscript{2}. This is similar to the one (0.346 m\textsuperscript{3}/m\textsuperscript{2}) calculated by Lee et al. (2012). The quantity computed in the present study included the core, which may have caused the difference of 0.02 m\textsuperscript{3}/m\textsuperscript{2}.

Second, the quantity of resources needed for the reinforcement work was calculated for rebar and steel. The figures computed for each material were aggregated based on the diameter of the rebar and the number of columns and beams for steel. The quantity of rebar was 262.95 tons for the existing Green Frame and 272.15 tons for the enhanced one. The amount of steel was 81.00 tons and 43.61 tons, respectively. The enhanced Green Frame required approximately half the steel and 4% more rebar than that used in the existing Green Frame system. Overall, it was predicted that the enhanced Green Frame had a higher structural efficiency, even with the approximately 8% reduction in reinforcement. The quantity of reinforcement per unit area was calculated to be 0.036 ton/m\textsuperscript{2} by Lee et al. (2012), while this study calculated 0.053 ton/m\textsuperscript{2} for the existing Green Frame and 0.048 ton/m\textsuperscript{2} for the enhanced one.

Third, the quantities of resources for the formwork and partitioning panel were found to be the same for both types of Green Frame because the columns and beams under consideration are for the same building.
In the study by Lee et al. (2012), the quantity of formwork materials per unit area was 1.1 m²/m², whereas it was 2.767 m²/m² in this study. This is because the study scope and items included in the calculations carried out for the present study differ from those specified by Lee et al. (2012). First of all, Lee et al. (2012) did not take the core part of the structural frame into account when calculating material quantities. Also, the plywood form was applied to slabs. On the other hand, the present study assumed that deck plates were used for housing slabs and plywood forms were used for the core slabs. Along with these differences, this study assumed that the CPCs of the Green Frame were produced on site, with the addition of steel forms for in-situ production.

Fourth, the greatest quantity differences were noted for the PC installation work. The amount of high-tensile bolts used for column-beam joints, column-column joints, and couplers for column-column joints in the enhanced Green Frame were calculated. The quantity of resources for PC installation was not considered in the studies conducted by Hong et al. (2009, 2010) and Lee et al. (2012). The change in the method used to connect columns from bolting to coupling in the enhanced Green Frame led to a difference in the quantity. Approximately 1/3 of the high-tensile bolts used in the conventional Green Frame system were replaced with 702 couplers.

In general, there is a difference in the grouting for the concrete work between the two systems, but the total quantity is the same. In the case of the formwork and partitioning panel, the same quantities are required, even for the detailed items. This is due to the fact that the same structural system – Green Frame – beams were enhanced. However, when it comes to the reinforcement work, the quantity of rebar is about 4% greater and that of steel which is about 46% lower for the enhanced Green Frame system. This results in an overall decrease in material quantity of approximately 8%. This implies that the structural performance of the enhanced Green Frame is more efficient than that of the existing one. Furthermore, unlike in previous studies, the number of bolts and couplers required for the PC installation are included in the calculations.

5. Analysis of CO₂ Emission Reduction

CO₂ emission was calculated using the methods introduced in Section 3. The production CO₂ was first calculated. Hong et al. (2009, 2010) and Lee et al. (2012) calculated the CO₂ emissions generated during the construction phase of a building. Table 6. shows the CO₂ emission rate for major construction materials. This data was collected from "The Environmental Load Unit Composition and Program Development R&D Program, Korea Institute of Construction & Transportation Technology Evaluation and Planning"

Table 5. Comparison of Material Quantities

| Classification       | Work          | Item           | Unit | GF         | EGF         | Q'ty per unit area |
|----------------------|---------------|----------------|------|------------|--------------|--------------------|
| Concrete work        | Cast-in-place | m³             | 1,924| 1,888      | 0.294        | 0.289              |
|                      | PC            | m³             | 429  | 429        | 0.066        | 0.066              |
|                      | Grouting      | m³             | 36   | 71         | 0.005        | 0.011              |
|                      | Total         | m³             | 2,389| 2,389      | 0.366        | 0.366              |
| Rebar                | HD10          | ton            | 69   | 72         | 0.011        | 0.011              |
|                      | HD13          | ton            | 41   | 43         | 0.006        | 0.007              |
|                      | HD16          | ton            | 16   | 16         | 0.002        | 0.002              |
|                      | HD19          | ton            | 106  | 110        | 0.016        | 0.017              |
|                      | HD25          | ton            | 31   | 32         | 0.005        | 0.005              |
|                      | Sub-total     | ton            | 263  | 272        | 0.040        | 0.042              |
| Steel                | Column        | ton            | 38   | 28         | 0.006        | 0.004              |
|                      | Sub-total     | ton            | 81   | 44         | 0.012        | 0.007              |
|                     | Total (rebar + steel) | ton      | 344  | 316        | 0.053        | 0.048              |
| Formwork             | Form for int. wall | m²              | 4,530| 4,530      | 0.693        | 0.693              |
|                      | Form for slab  | m²             | 225  | 225        | 0.034        | 0.034              |
|                      | Joint form    | m²             | 540  | 540        | 0.083        | 0.083              |
|                      | Steel form    | m²             | 4,346| 4,346      | 0.665        | 0.665              |
|                      | Deck plate    | m²             | 6,821| 6,821      | 1.044        | 1.044              |
|                      | Total         | m²             | 18,080| 18,080    | 2.767        | 2.767              |
| Partitioning panel   | Ext. wall     | m²             | 3,465| 3,465      | 0.530        | 0.530              |
|                      | Int. wall     | m²             | 5,616| 5,616      | 0.860        | 0.860              |
|                      | Total         | m²             | 9,081| 9,081      | 1.390        | 1.390              |
| PC installation      | High-tensile bolt | EA              | 36,864| 24,576    | 5.642        | 3.761              |
|                      | Coupler       | EA             | -    | 702        | -            | 0.107              |

In general, there is a difference in the grouting for the concrete work between the two systems, but the total quantity is the same. In the case of the formwork and partitioning panel, the same quantities are required, even for the detailed items. This is due to the fact that the same structural system – Green Frame – beams were enhanced. However, when it comes to the reinforcement work, the quantity of rebar is about 4% greater and that of steel which is about 46% lower for the enhanced Green Frame system. This results in an overall decrease in material quantity of approximately 8%. This implies that the structural performance of the enhanced Green Frame is more efficient than that of the existing one. Furthermore, unlike in previous studies, the number of bolts and couplers required for the PC installation are included in the calculations.
Since CPCs are produced on site, the same CO₂ emission rate for ready-mixed concrete applies to the cast-in-place and CPCs. Emissions for rebar and steel were calculated using the CO₂ emission rates of high strength reinforcement bars and structural steel, respectively. In the case of high-tensile bolts, the CO₂ emission unit of the bolt and nut was converted from ‘per kg’ to ‘per EA,’ for the couplers, there was no matching data so the unit was calculated based on high-tensile bolts.

Based on the drawings, the material quantity was calculated as shown in Table 5. The CO₂ produced in the construction of the case project with the CO₂ emission rate is illustrated in Table 6, and the material quantities are summarized in Table 7.

Unlike the existing studies, different items were included in the CO₂ emissions calculation based on the input resources, which resulted in overall emission differences. However, the CO₂ emissions per unit area for detailed items were similar to previously reported values. It is safe to conclude that CO₂ emissions were accurately calculated. In terms of the detailed items, the quantity of materials required for reinforcement work was decreased by around 8% in the enhanced system, reducing CO₂ emission by around 10%. This is because more CO₂ is emitted when manufacturing steel than the same weight of rebar. Bolts and couplers were not taken into account in previous studies, whereas they were accounted for in this study. However, it was determined that the bolts and couplers that are critical in the construction phase have very little impact on the total CO₂ emissions.

However, as indicated in Section 3, the production CO₂ is not equivalent to the construction CO₂. When a building is being constructed, fuel and electricity are used to run the equipment, which generates CO₂ (Kim et al., 2004). Thus, this study considered CO₂ emission generated from the transportation of materials and from fuel and electricity used so as to accurately calculate the CO₂ emission during the building's construction process.

Transportation CO₂ was computed using the amount of equipment used for each material and the corresponding CO₂ emission rate. The equipment assumed for transporting the concrete was a cement mix truck, a 20-ton truck for the rebar, steel, steel form and deck plates, and 8-ton trucks for form and partitioning panels. High-tensile bolts and couplers were accompanied with the rebar and steel.

The delivery distance used in this study was the average of each material delivery distance reported by Kim et al. (2004). The CO₂ emission rate used for the transportation equipment was the value suggested by the Ministry of Environment. However, since the CO₂ emission rate was estimated for 30 km, the rate was recalculated in this study. As shown in Table 8, the CO₂ emitted during material transportation for the existing Green Frame was 22,101 kg and was 22,063 kg for the enhanced system. CO₂ emissions during building construction due to the use of fuel in the construction phase were computed as shown in Eq. (4) (Kim et al., 2004). The total floor area of the case project to which the Green Frame was applied in this study was 6,534 m². Q_{CO₂} was 122.85 T-CO₂.

CO₂ emissions during the construction phase owing to the electric power consumption were computed as shown in Eq. (5) (Kim et al., 2004). Q_{CO₂} was 104.47 T-CO₂. Since the total floor area was the basis for calculating CO₂ emissions from fuel and electricity use, the same was applied to the existing and enhanced Green Frame.

Table 9. shows the total CO₂ emission by the resources and energy used. The enhanced Green Frame was approximately 3.23% more effective than the existing Green Frame in terms of reducing CO₂ emissions according to the resources used. There was approximately a 0.2% reduction in the CO₂ emitted during transportation. In addition, the total CO₂ emissions including that from energy usage was effectively reduced by approximately 3.02%.

The studies by Hong et al. (2009, 2010) and Lee et al. (2012) only calculated the production CO₂ whereas both transportation and installation CO₂ were estimated in this study. As shown in Table 9., the transportation and installation CO₂ emissions were less effective than construction CO₂. However, by applying these CO₂ categories, the total CO₂ emissions can be calculated more accurately than before.

### Table 6. The CO₂ Emission Rate for Key Materials Used in Green Frame Construction

| Qty item                   | Name of CO₂ emission rate     | CO₂ emission rate |
|----------------------------|-------------------------------|-------------------|
| Concrete                   | Ready-mixed concrete          | 140.43 kg-CO₂/m³ |
| Rebar                      | High strength reinforcement bar| 3,500.00 kg-CO₂/t |
| Steel                      | Structural steel              | 4,166.00 kg-CO₂/t |
| Outer form of ext. wall    |                               |                   |
| Form for int. wall         | Formwork                      | 3.83 kg-CO₂/m²   |
| Form for slab              |                               |                   |
| Joint form                 |                               |                   |
| Steel form                 | Steel plate                   | 169.60 kg-CO₂/m² |
| Deck plate                 | Gypsum board                  | 33.75 kg-CO₂/m²  |
| High-tensile bolt for steel connection | Bolt and nut | 0.0005 kg-CO₂/EA |
| Coupler for rebar connection | Bolt and nut | 0.0135 kg-CO₂/EA |
Table 7. Comparison of Production CO₂

| Classification | Total CO₂ emission (kg-CO₂) | CO₂ emission per unit area (kg-CO₂/m²) |
|----------------|----------------------------|--------------------------------------|
| Work           | Item | GF | EGF | GF | EGF |
| Concrete work  |        |    |     |    |     |
| Reinforcement work |        |    |     |    |     |
| Rebar          |        |    |     |    |     |
| Steel          |        |    |     |    |     |
| Total (rebar + steel) | 1,257,755 | 1,134,197 | 192 | 173 |
| Formwork       |        |    |     |    |     |
| Formwork       | 47,122 | 51,343 | 51 | 51 |
| Steel form     | 158,632 | 163,854 | 112 | 112 |
| Deck plate     | 1,156,790 | 1,156,790 | 177 | 177 |
| Total          | 1,920,289 | 1,920,289 | 294 | 294 |
| Partitioning panel | 306,484 | 306,484 | 47 | 47 |
| PC installation |        |    |     |    |     |
| High-tensile bolt | 17 | 11 | 0.003 | 0.002 |
| Coupler        | 9 | 9 | 0.001 |
| Total          | 3,819,972 | 3,696,417 | 585 | 566 |

Table 8. Comparison of Transportation CO₂

| Classification | No. of equipment | Distance (km) | CO₂ emission rate (kg-CO₂/(Eq·30km)) | Total CO₂ emission (kg-CO₂) |
|----------------|-----------------|---------------|--------------------------------------|----------------------------|
| Work           | Item | GF | EGF | GF | EGF |
| Concrete work  |        |    |     | 20 | 25 |
| Reinforcement work |        |    |     | 31 | 307 |
| Rebar          |        |    |     | 8 | 31 |
| Steel          |        |    |     | 3 | 31 |
| Total (rebar + steel) | 11 | 422 | 383 |
| Formwork       |        |    |     | 24 | 2,310 |
| Formwork       | 21 | 24 | 2,310 |
| Steel form     | 9 | 9 | 31 |
| Deck plate     | 14 | 14 | 31 |
| Total          | 183 | 183 | 3,019 | 3,019 |
| Partitioning panel | 24 | 2,210 | 22,063 |

Table 9. Comparison of Construction CO₂

| Item                  | CO₂ emission (T-CO₂) |
|-----------------------|----------------------|
| Work                  | GF | EGF |
| Production CO₂        | 3,820 | 3,696 |
| Transportation CO₂    | 22 | 22 |
| Installation          |    |     |
| Oil use               | 123 | 123 |
| CO₂                   |    |     |
| Electricity use       | 105 | 105 |
| Total CO₂ emission    | 4,070 | 3,947 |

6. Discussion and Conclusion

A column-beam structure that enables flexible planning of apartment buildings while maximizing the use of construction resources and energy is becoming increasingly popular (Lee et al., 2012). The existing Green Frame needs to be continually improved to provide a reduction in cost and the requirement for skilled manpower, as well as an increase in safety, constructability and sustainability in the form of reducing CO₂ emissions. In this respect, this study analyzed the quantity of materials and CO₂ emissions for an apartment building designed with both the existing and the enhanced Green Frames.

It was found that the enhanced Green Frame results in a reduction in the quantity of structural materials, which translates into a decrease in CO₂ emissions. An apartment building was chosen as a case study in order to verify the feasibility of the enhanced Green Frame system the concomitant reduction in CO₂ emissions. The materials used as well as the transportation and installation costs were calculated to get an accurate picture of the true CO₂ emissions. As a result, an approximately 3% reduction in CO₂ emissions was seen when the enhanced Green Frame was adopted instead of the existing system. Most of the values for the material quantities and CO₂ emissions of specific items were similar to those calculated in previous studies. The reduction effect of CO₂ emission was found to be most prominent in the reinforcement work. These findings imply that a reduction in CO₂ emissions is possible when structural details are engineered by continuously enhancing conventional methods and developing new construction methods other than Green Frame.

Moreover, this study introduced an estimation model of the CO₂ emission at the construction phase that calculates it accurately and quickly when the structural system is changed. The CO₂ emissions of selected structure systems can be easily and promptly estimated in the design phase using the developed model. This study did not directly compare the CO₂ emission of a bearing wall structure, yet the reduction effect can be predicted using data from existing studies. According to data from the study conducted by Lee et al. (2012), the existing Green Frame adopted in this study demonstrates a 25% reduction in CO₂ emissions on average when compared to the bearing wall type structure. Thus, there may be an average 27% CO₂ reduction effect for the enhanced Green Frame when compared to the bearing wall structure.

This study was limited to a super structure. When the Green Frame is applied underground, it is expected that there may be a greater CO₂ emission reduction
effect due to the utilization of spaces and a reduction in floor height. For apartment buildings in Korea, the cost of underground structure accounts for about 40% of the entire structure. Therefore, it is expected that there is a potential for a greater reduction effect if the underground floors are constructed using the Green Frame and other existing methods are included for controlling CO\textsubscript{2} emissions.

This study assumed that the CPCs of the Green Frame were produced on site. When the CPCs are constructed as such, a reduction in CO\textsubscript{2} emissions is expected since it does not require transportation of PCs from factories or the installation of temporary materials (Joo et al., 2012b; Won et al., 2013). This study presumed that two types of CPCs were all produced on site. An analysis of the CO\textsubscript{2} emission reduction effect from in-situ production was not conducted; this could be done in a future study. It is expected that the model developed in this study could be used to easily predict the CO\textsubscript{2} emissions of construction projects to which the Green Frame system is applied.

Acknowledgement
This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korean Government (MSIP) (No. 2013R1A2A2A01068297).

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