Optimization of CO_2 Emissions and Cost for Composite Building Design with NSGA-Ⅱ

Ji Hyeong Park, Ji Hye Jeon, and Hyo Seon Park

***Abstract*—** Environmental pollution problems have been globally main concern in all fields including economy, society and culture into the 21st century. Beginning with the Kyoto Protocol, the reduction on the emissions of greenhouse gas such as CO_2 and SO_X has been a principal challenge of our day. As most buildings unlike durable goods in other industries have a characteristic and long life cycle, they consume energy in quantity and emit much CO_2. Thus, for green building construction, more research is needed to reduce the CO_2 emissions at each stage in the life cycle. However, recent studies are focused on the use and maintenance phase. Also, there is a lack of research on the initial design stage, especially the structure design. Therefore, in this study, we propose an optimal design plan considering CO_2 emissions and cost in composite buildings simultaneously by applying to the structural design of actual building.

***Keywords*—**Multi-objective optimization, CO_2 emissions, structural cost, encased composite structure

I. INTRODUCTION

WITH the progress of material civilization and rapidly industrialization, environmental pollution problems are getting very serious recently. Beginning with the Kyoto Protocol in 1997, environmental preservation has been a shared challenge all over the world, not the specific countries. In all fields of industry, various efforts have been made for reducing the environmental load.

In particular, in the construction industry, a representative environmental polluting industry, various studies for reducing CO_2 emissions and energy consumption have been actively conducted since the 2000s. These studies have included the development of Life-Cycle Assessment (LCA) model [1], development of facility system and material in green building [2,3] and green building design [4]. Most studies are focused on CO_2 emissions in the use and maintenance stage, because the largest amount of CO_2 is generated in that stage [5]. However, most buildings unlike durable goods in other industries have a characteristic and long life cycle and the reduction of CO_2 emissions is bound together in activities at each stage in the life cycle. In other words, the reduction of the environmental load and the effect of the environmental improvement cannot be possible by optimizing a part, not all [6]. In order to achieve environmentally friendly construction considering the LCA, the design should be derived to reduce CO_2 emissions from the early building design stage and structure engineers should be able to create a design plan considering the environmental friendliness and economic feasibility [7, 8].

Preceding studies that considered CO_2 emissions in the structural design stage typically used optimal design methods. Moon (2008) proposed an optimal design method that minimizes the quantity of the input materials for sustainable structural designs in the steel frame structure [9]. Paya et al. (2009) proposed the optimal design technique to reduce either CO_2 emission levels or structural cost of reinforced concrete frame structures using a Simulated Annealing (SA) method [10]. In addition, Paya et al. (2008) suggested a multi-objective design methodology applied to the four objective functions of the structural cost, environmental impact, constructability and overall safety of RC framed structures using the SA method [11]. Although these results show that suggested optimal design methodologies can effectively reduce CO_2 emission levels, there are material limitations that must be overcome before they can be applied to actual buildings. In fact, the height of buildings overall is increasing, and composite members are used for high-rise buildings in place of RC members [12]. Hence, a design technique that considers environmental friendliness and economic feasibility is necessary also for composite members.

Therefore, this study describes an optimal design technique that minimizes CO_2 emissions and cost generated in the material production stage simultaneously and that is applicable to actual high-rise buildings. Additionally, we applied the optimum design technique with NSGA-Ⅱ proposed here to the structural design of a 35-story building to evaluate the applicability and stability of the algorithm.

II. SCOPE AND METHOD OF THE STUDY

A. Scope of the Study

This study was aimed at encased composite columns supporting only the gravity load in the building frame system frequently applied for high-rise buildings. In the optimization process, the load on the columns and the axial force of the members were assumed to be constant because of the relatively minor variation of the load on the columns. Moreover, CO_2 emissions were limited to discharge in the material production stage.

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B. Research Methods

A large number of parameters in composite building design should be considered, including the composite cross-sectional area and the size of the steel frames, especially in high-rise building. Thus, in this study, we employed the NSGA-Ⅱ, known to be appropriate for complex numerical problems [13], to optimize the two objective functions of CO_2 emissions and cost at once.

III. The Optimization Algorithm

A. Optimization Algorithm

Fig. 1 shows a process of the optimization algorithm using Pareto optimal solution applied in this study. First, the member forces are secured through a structural analysis and the parameters necessary for the genetic algorithm. Then, the early population is formed. As the procedure of NSGA-Ⅱ is repeated until the terminal condition is satisfied, we obtain the non-dominant first-order optimal solution set that does not violate the constraints.

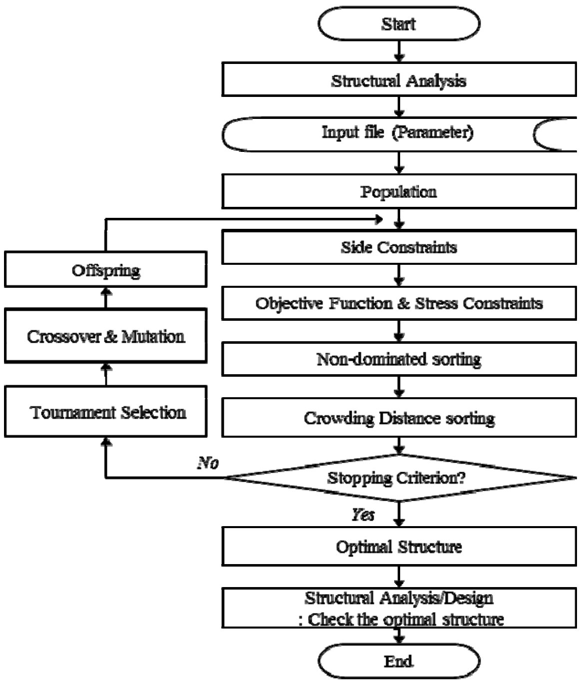

Fig. 1 Flowchart of the optimization algorithm with NSGA-II

B. Design Variables

This study use discrete design variables to find the optimal solutions using a GA and establish databases consisting of both section properties and material properties of the SRC column. The 512 SRC section database is made up of 23 SM-490 rolled beams, 31 SM-490 built-up, 132 SM-490TMCP, 163 SM-520TMCP and 163 SM-570TMCP members per one type of strength of concrete. There are seven types of strength of concrete (21, 24, 27, 30, 35, 40 and 50*MPa*), so the member can be selected from a database that contains a total of 3854 data.

The five types of 512 SRC column database, as the design variables in this study, can be divided into rolled H beams and welded H beams depending on the processing method. When calculating the unit price (C_{stl}) of the SM-490, SM-490TMCP, SM-520TMCP and SM-570TMCP in the form of a welded H beam, the unit price is sum of the price of the thick plate for the beams (\/ton) and the fabrication cost α(\/ton). When calculating the unit CO_2 emission (E_{stl}) of the material, the CO_2 emission from welding β(kg·CO_2/kg), should be taken into consideration, not considered in this study.

C. Objective Functions

The purpose of this study is to minimize the total CO_2 emission and cost of the column line simultaneously using the unit CO_2 emission and price of material depending on the strength levels of the concrete and the steel. Therefore, the objective functions were defined with respect to CO_2 emission and cost of the column line of the subject building, as expressed by Eq. (1-a) and Eq. (1-b):

$$Minimize\ f_1 = \sum_{i=1}^{M} A_{stl}^i L^i \rho_{stl} C_{stl} + A_{con}^i L^i \rho_{con} C_{con} \quad (1\text{-a})$$

$$Minimize\ f_2 = \sum_{i=1}^{M} A_{stl}^i L^i \rho_{stl} E_{stl} + A_{con}^i L^i \rho_{con} E_{con} \quad (1\text{-b})$$

Eq. (1-a) is the function for the structural cost of the column line. Eq. (1-b) is the function for the CO_2 emission of the column line. A and L denote the member cross-sectional area and the member length, respectively. ρ denotes the density of the material. C and E denote the unit price and CO_2 emission in the column cross-sections depending on the design parameters, respectively. The subscripts *stl* and *con* refer to the steel material and concrete, respectively. The superscript i refers to the ith member, and M denotes the total number of members included in one column line.

D. Constraint Conditions

The constraint functions consist of the main constraint for the resisting capacity of the cross-section and the sub-constraints for the constructability. For the main constraints, we used the P-M diagram, which was also used as the constraint in the optimal design of a RC structure using a GA by Lee and Ahn (2003) [14]. The main constraint can be expressed as Eq. (2) with L_m and L_u representing the distance between the origin and load point and the distance between the origin and cross point, respectively:

$$\frac{L_u}{L_m} \le 1 \quad (2)$$

The remaining constraints for the constructability are that the total cross-section, the inside dimension of the steel frame, the outside dimension of the steel frame, the yield strength of the steel and the concrete compressive strength of the upper members should not be greater than those of the lower members,

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as expressed by Eq. (3-a), (3-b), (3-c), (3-d) and (3-e). Here, i refers to the ith member, ranging from the first member to the (M-1)th member.

$$\frac{A_g^{i+1}}{A_g^{i}} \leq 1.0 \quad (3\text{-a}) \qquad \frac{S_{stl\_i}^{i+1}}{S_{stl\_i}^{i}} \leq 1.0 \quad (3\text{-b}) \qquad \frac{S_{stl\_o}^{i+1}}{S_{stl\_o}^{i}} \leq 1.0 \quad (3\text{-c})$$

$$\frac{F_{ys}^{i+1}}{F_{ys}^{i}} \leq 1.0 \quad (3\text{-d}) \qquad \frac{f_{ck}^{i+1}}{f_{ck}^{i}} \leq 1.0 \quad (3\text{-e})$$

The constraint for constructability is considered as a sub-constraint because when the constraint is violated, the software properly corrects the cross-section of the upper member by selecting the member that satisfies all of the constructability constraints.

IV. Example Analysis

A. Application Example

In this section, we applied the proposed optimization algorithm to a mixed-use residential building with 29 floors above ground and 6 floors in the basement as Fig.2 and then analyzed the environmental friendliness and economic feasibility of the suggested design plan. The building consists of a total of 57 SRC column lines that are divided into 19 SRC column lines according to the location on the plane and the shared load, one of which was analyzed in this study.

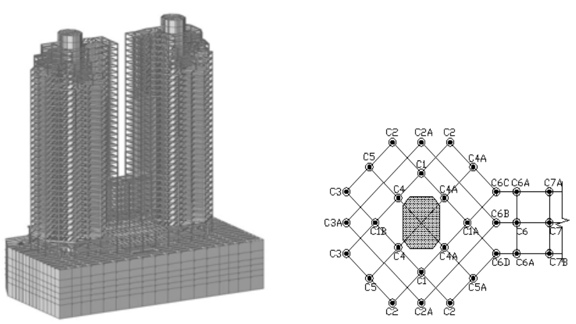

Fig. 2 Framework and the typical floor plan in example building

TABLE Ⅰ represents the unit price and the CO_2 emission values of the concrete depending on the material strength, and TABLE Ⅱ represents those of the steel types included in the SRC database. But, the unit price for the welded H beams was applied by adding the fabrication cost to the price of the thick plate.

TABLE I
The Unit Price and the CO_2 Emission on the Concrete Strength

f_{ck} (*MPa*)	21	24	27	30	35	40	50
Price (\/m³)	51,800 (100%)	54,300 (104.8%)	56,800 (109.6%)	59,700 (115.3%)	61,800 (119.3%)	73,300 (141.5%)	87,000 (167.9%)
CO_2 emissions (kg·CO_2/m^3)	321.57 (100%)	325.80 (101.3%)	346.14 (107.6%)	370.51 (115.2%)	405.73 (126.2%)	391.03 (121.6%)	453.15 (140.9%)

TABLE Ⅱ
The Unit Price and the CO_2 Emission on the Steel Type

Type of Steel	Steel plate thickness	Price of thick plate (\/ton)	CO_2 Emission (kg-CO_2/kg)
SM490	0<t≤25	727,100	0.4188
	25<t≤38	735,800	
	38<t≤50	743,700	
	60<t≤100	753,100	
SM490 TMCP	0<t≤25	749,700	0.4318
	25<t≤38	758,400	
	38<t≤50	766,300	
	50<t≤100	775,700	
SM520 TMCP	0<t≤25	758,400	0.4368
	25<t≤38	767,800	
	38<t≤50	775,700	
	50<t≤100	783,600	
SM570 TMCP	0<t≤50	867,600	0.4997
	50<t≤100	875,500	

B. The relation of CO_2 emissions and cost

The SRC column sections under the same load (=1000N) were variously designed with different strength levels of the materials and the different percentage of quantities. In that case, the CO_2 emission and structural cost of the SRC column were analyzed.

Fig. 3(a) shows a case in which the variation of the CO_2 emission of the SRC column depending on the percentage of concrete quantities was the smallest: the concrete whose compressive strength was 50MPa and the SM490 whose yield strength was 325MPa were used in the case. In contrast, Fig. 3(b) shows a case in which the variation of the CO_2 emission of the SRC column depending on the percentage of concrete quantities was the largest: the concrete whose compressive strength was 21MPa and the SM570TMCP whose yield strength was 440MPa were used in the case. Although the CO_2 emission from the designed column is different among the cases because materials of different strength levels were used, the same trend is found, in that the CO_2 emission from the columns increased as the percentage of the concrete quantity increases in the SRC columns. On the other hand, Fig. 4 show the cost generated in the same cases shown in Fig. 3. As shown in these figures, the cost of the SRC columns was governed by the ratio of the quantity of the steel. Consequently, Fig. 3 and Fig. 4 show that the CO_2 emission rates increased but the construction cost decreased as the concrete quantity ratio was increased in the SRC columns.

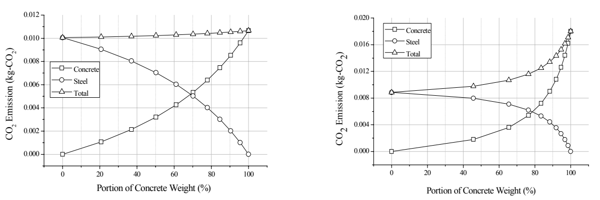

Fig. 3(a) (b) The smallest and the largest variation of CO_2 emission

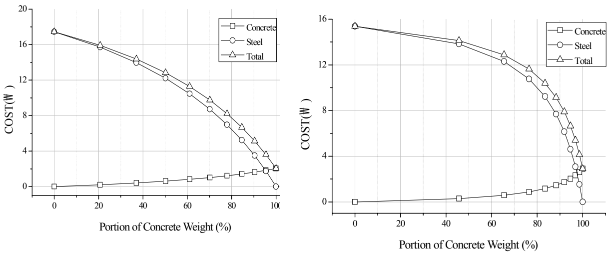

Fig. 4(a) (b) The cost variation in the same case as Fig. 3

C. Optimization Analysis

The optimization was performed for the case in which CO_2 emissions for concrete strength level and that for steel strength level were constant, at 321.57(kg- CO_2/m^3) and 0.4188(kg-CO_2/kg), respectively. The result in Fig. 5(a) shows that the optimal design plans are located on the left bottom side of the graph, indicating that both cost and CO_2 emissions decrease when compared to those of the initial design plan. Additionally, cost and CO_2 emissions of the individual cases were compared. The result showed that the CO_2 emission increased in the individual cases at a relatively low cost while the cost was increased in the individual cases with relatively less CO_2 emission. However, when the CO_2 emission for strength level was constant, the difference between the solution where the cost is the minimum and the CO_2 emission is the maximum and the solution where the cost is the maximum and the CO_2 emission is the minimum was approximately 1.9-2.4%, indicating that the range of the solution distribution was very narrow.

On the other hand, optimization was performed for the case in which the CO_2 emission rates for concrete strength level and that for steel strength level were not constant. Fig. 5(b) shows the algorithm application result obtained by applying the CO_2 emission values in Tables Ⅰ and Ⅱ. As in the previous case, the 15 optimal design plans are distributed on the left bottom side of the graph, indicating a trend in which CO_2 emissions increased in the individual cases at a relatively low cost and that the cost was increased in the individual cases with relatively less CO_2 emission. However, the ranges of the maximum and minimum values were wider than those in the previous case and the suggested solutions contain more variation. Thus, the users can select economic or environmental solution according to their preference. The result showed that the cost and CO_2 emission can be reduced by about 31-34% and 6.4-10.6% when compared to those of the initial design plan. The effect of the CO_2 emission reduction was smaller than that in the previous case because the minimum CO_2 emission value for each material strength level was applied in the previous case.

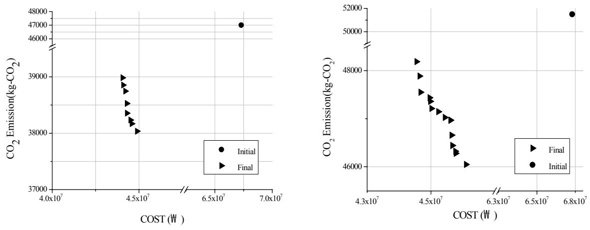

Fig. 5 (a) (b) CO_2 emission is constant and not constant on strength

Table Ⅲ compares the initial plan designed by the design office, the No. 1 optimal design plan where the CO_2 emission is the greatest and the cost is the lowest, and the No. 15 optimal design plan where the CO_2 emission is the lowest and the cost is the highest, among the optimal design plans shown in Fig. 5(b). Table Ⅲ shows that the SRC quantity of the optimal design plans No. 1 and No. 15 are less than that of the initial design plan by 2.7% and 1.9%, respectively, also showing that the CO_2 emission rates are less by 6.4% and 10.6%, respectively. That is the decrement of the CO_2 emission was not proportional to the decrement of the SRC quantity relative to the initial design plan. The SRC quantity of the No. 1 optimal design plan was less than that of the No. 15 optimal design plan by 1.58 t, while the CO_2 emission was greater by 2140 (kg- CO_2). This occurred because the CO_2 emission is determined by the ratio of the concrete and steel in the SRC columns where the two materials are used.

TABLE Ⅲ
THE ANALYSIS RESULTS OF THE CANDIDATE OPTIMAL DESIGN SOLUTIONS

		Steel	Concrete	SRC
Initial design	Quantity (ton)	67.34 (32.4%)	140.33 (67.6%)	207.68
	COST (Million-\)	64.13 (95.3%)	3.12 (4.7%)	67.30
	CO_2 Emission (Thousand-kg)	31.97 (62.1%)	19.53 (37.9%)	51.50
No.1	Quantity (ton)	41.06 (20.3%)	161.07 (79.7%)	202.13
	COST (Million-\)	38.75 (87.2%)	5.69 (12.8%)	44.44
	CO_2 Emission (Thousand-kg)	18.23 (37.8%)	29.96 (62.2%)	48.19
No.15	Quantity (ton)	43.57 (21.4%)	160.14 (78.6%)	203.71
	COST (Million-\)	41.38 (89.2%)	5.00 (10.8%)	46.38
	CO_2 Emission (Thousand-kg)	19.28 (41.9%)	26.77 (58.1%)	46.05

V. CONCLUSION

In this study, we proposed an optimization algorithm that is applicable to SRC columns considering the cost and CO2 emission simultaneously depending on the type of steel and the concrete strength levels. We applied the proposed optimum design technique to an actual column design to verify its economic feasibility and environmental friendliness. The following conclusions are reached:

1) The analysis was performed for the case where the CO_2 emission for each material strength level is constant and not constant. The result showed that the cost and the CO_2 emission of the optimal design plans for the two cases were decreased by 31-34% and 6.4-10.6%, respectively, when compared to those of the initial design plan for each case.

2) When the load condition is identical, the quantity ratio of each material affects the CO_2 emission and cost generated by the columns. If the design has a relatively large concrete quantity ratio, the entire cost may be decreased by reducing the quantity ratio of the steel that govern the cost of the structure, and the CO_2 emission from the cross-sections may be increased as the CO_2 emission of the concrete is increased.

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