CO2 Optimization of Concrete-Filled Steel Tube Columns in Buildings

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Abstract: Much attention has been given to environmental issues around the world in recent years, and continuous efforts have been made to reduce greenhouse gases (GHGs). Carbon dioxide (CO2), which is the largest portion of GHGs, is produced from various industrial sectors including building relevant sector. Thus, the necessity to manage and reduce CO2 emissions in buildings has been raised. In addition to the building construction and operation phases, the building design phase has also been investigated to reduce CO2 emissions through sustainable structural design. Although a concrete-filled steel tube (CFT) column, which has its excellent structural performance, economic feasibility, and good space utilization, is widely used for high-rise buildings, researches on sustainable structural design have focused on the reinforced concrete (RC) structures. With regard to CFT columns, which have a high potential to reduce CO2 emissions because of combining two heterogeneous materials, this study proposes an optimum sustainable structural design model with the minimum CO2 emissions using genetic algorithm (GA). The results of the optimum designs for CFT columns obtained from the proposed model were examined in terms of the environmental performance, economic feasibility and space utilization.

Keywords: sustainable structural design; embodied carbon dioxide; genetic algorithm; CFT column.

1. Introduction

The building energy consumption has increased CO2 emissions, which are the main cause of GHGs. Much effort has gone into reducing the CO2 emissions produced during the building operation and maintenance phases which are the largest CO2 emission phases in buildings [1-2]. However, buildings consume CO2 not only in the operation and maintenance phase, but also prior to this, such as in the design and material production phase, and the material transport and construction phase, which are also generally considered in attempts to reduce CO2 emissions [3]. In the design and material production phases of a building, the amounts and layout of the structural materials are determined to satisfy the safety and serviceability requirements of the building. To maximize environmental performance of the buildings while satisfying safety requirements of the buildings, various approaches minimizing the CO2 emissions produced during the manufacture and construction of structural materials have been conducted. Such methods are called sustainable structural design. This design method aims to satisfy all of the structural constraints while minimizing the CO2 emissions calculated in accordance with a life-cycle assessment (LCA) database and the strength of the structural material. Studies on minimizing the CO2 emissions of building structures have mainly focused on RC structures with optimization techniques [4-5].

A CFT column is composed of two materials (concrete and steel). The strength of each complements the weakness of the other, which provides a superior load resistance performance. The CFT columns have been widely used as the main columns of various buildings, including high-rise buildings, for a lateral force resistance system [6-7]. The material costs and CO2 emissions vary considerably during the production of the two materials for composite columns [8-9], depending on the strengths of the materials. Therefore, it is possible to derive the optimum design to reduce the CO2 emissions through the appropriate combination of the two heterogeneous materials.

This research suggests an optimization method minimizing CO2 emissions of the CFT columns in buildings. In the optimum design process, the section type of CFT column, diameter of the section, and thickness of the steel tube are set as structural design parameters. The objective function established as the CO2 emissions of the CFT column is minimized using GA. The optimum solution is searched while satisfying structural safety constraints. For load scenarios constructed by increasing the required axial load, the optimum designs were obtained by the proposed design method. The derived optimum designs were discussed in terms of the CO2 emissions, material costs, and characteristics of cross-sections. Furthermore, the optimum designs of CFT
column for various loading conditions constructed by increasing the required axial and moment load were conducted and the CO2 emissions function, which can be used to assess the environmental performance of the design of the CFT column, was obtained.

2. Optimum design model for CFT columns

2.1 Design parameters

The CFT columns are classified as circular and square CFT columns, as shown in Fig. 1. The cross-section of a CFT column is composed of two component materials, the concrete and steel tube, which have compressive strength \( f_{ck} \) and yield strength \( F_y \) values. As shown in Fig. 1, the steel tube has a width \( D_s \) and thickness \( t_s \), while the concrete has a sectional dimension or diameter \( D_c \). The cross-section of a CFT column is designed by combining structural parameters such as the cross-section type, \( D_s, t_s, D_c, f_{ck}, \) and \( F_y \). Among those structural parameters, the cross-section type, \( D_s, t_s, \) and \( D_c \) are considered as design parameters during the optimum design process. It is assumed to be used 325MPa and 27MPa strengths for steel and concrete materials, respectively. The ranges of structural design parameters listed in Table 1 are determined based on actual design results for CFT columns in buildings.

![Steel tube](image1)

![Concrete](image2)

(a) Circle CFT column

(b) Square CFT column

Figure 1 Design parameters of CFT columns

<table>
<thead>
<tr>
<th>Material</th>
<th>Design parameter</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel tube</td>
<td>Section type</td>
<td>Circular or Square</td>
</tr>
<tr>
<td></td>
<td>Width or diameter, ( D_s )</td>
<td>200–600 mm (with 20-mm increments)</td>
</tr>
<tr>
<td></td>
<td>Thickness, ( t_s )</td>
<td>1–25 mm (with 1-mm increments)</td>
</tr>
<tr>
<td>Concrete</td>
<td>Diameter, ( D_c )</td>
<td>( D_s - 2t_s )</td>
</tr>
</tbody>
</table>

2.2 Objective and constraint functions

In the proposed model for minimizing CO2 emissions of a CFT column, the objective function is established to the amount of the CO2 emissions and minimized. The function is defined by Eq.(1).

\[
\text{Min } f = h (\rho_c A_c C_c + \rho_s A_s C_s)
\]

Here, \( h \) refers to the length of the CFT column, \( \rho_c \) is the unit weight of the concrete, and \( \rho_s \) refers to the unit weight of the steel tube. In this study, \( \rho_c \) was considered to be 2300 kg/m³, and \( \rho_s \) was 7850 kg/m³. \( A_c \) and \( A_s \) are the cross-sectional area of concrete and steel tube of the CFT column and they are determined by structural design parameters. \( C_c \) and \( C_s \) refer to the CO2 emissions produced to manufacture the unit mass of the concrete and steel tube. The database for the CO2 emissions in this study are based on [8] and [9] for steel and concrete, respectively. The objective function refers to the CO2 emission generated from unit length of a
CFT column. Only the CO2 emissions produced during the manufacturing phase of the composite materials of the CFT column are considered in this study.

If the design strength of a CFT column determined by the combination of structural parameters described in section 2 is larger than the required load, the design of the CFT column cross-section is evaluated to be structurally safe. In this study, the structural safety of CFT column cross-sections is evaluated using the AISC [10] design method. The safety in this study was determined by whether the cross-section of the CFT column created by combining the structural parameters satisfied the constraints in [10]. The strength constraints for structural safety are defined by Eq.(2)-(3). Besides the strength constraint, constraints for the portion of steel tube area to gross-section area and compactness of steel tube are considered as Eq.(4)-(6) in the proposed design model.

\[
\frac{M_{\text{demand}}}{M_{\text{capacity}}} \leq 1.0
\]  \hspace{1cm} (2)

\[
\frac{P_{\text{demand}}}{P_{\text{capacity}}} \leq 1.0
\]  \hspace{1cm} (3)

\[
0.01 \frac{A_s}{A_g} \leq 1.0
\]  \hspace{1cm} (4)

\[
\frac{1}{0.15} \frac{F_s}{E} \frac{D_s}{t_s} \leq 1.0 \hspace{1cm} \text{for Circular CFT column}
\]  \hspace{1cm} (5)

\[
\frac{1}{2.26} \sqrt{\frac{F_s}{E} \frac{D_s}{t_s}} \leq 1.0 \hspace{1cm} \text{for Square CFT column}
\]  \hspace{1cm} (6)

In Eqs. (2) and (3), $M_{\text{demand}}$ and $P_{\text{demand}}$ are the required moment and axial load, respectively, and $M_{\text{capacity}}$ and $P_{\text{capacity}}$ are the design flexural strength and design compressive strength, respectively. Here, $A_s$ is the cross-section of the steel tube, and $A_g$ is the entire cross-section of the CFT column in Eq. (4). In Eqs. (5) and (6) $E$ refers to the modulus of elasticity of the steel tube. Eqs. (5) and (6) are constraints to evaluate the compactness values for the steel tubes used in the cross-sections of circular and square CFT columns, respectively.

2.3 Optimization

In the proposed optimum design model, for each design candidate be composed of structural design parameters listed in Table 1, the objective function defined by Eq. (1) is minimized while satisfying constraints. Because various design parameters are used and parameters have discrete values in the optimum design, a heuristic based optimization technique is appropriate for the problems. This study applied, a heuristic based optimization technique, GA [11] to the optimum design model. The GA evolves solution (design) candidates using genetic operators such as crossover, mutation and selection and finds a final optimum solution. In this study, the GA searches the best solution to minimize CO2 emissions of the CFT columns under given loading conditions.

The procedures of the proposed optimum design model are described as follow. First, for a given loading condition, required moment and axial loads acting a target CFT column are calculated. The LCA information of the CO2 emissions for steel and concrete used in the design of CFT column are provided. A population in the GA is initialized based on the ranges of the structural design parameters, as described in Section 2.1. The binary type number of the population converted to integer type number for discrete design parameters. Constraints described in Section 2.2 are calculated. If an individual violates a constraint, a penalty is calculated according to violation rate. Then, the objective function defined by Eq. (1) is calculated. And a fitness function is calculated using the violation ratio and the value of objective function. If termination condition is not satisfied, the current population is evolved by using genetic operators and procedures are repeated until end condition is satisfied. If termination condition is satisfied, a solution with the highest fitness value is represented as an optimum solution.
3. Application

Based on the optimum design model in Section 2, the optimum cross-sections for CFT columns were obtained according to the required load scenarios. During the optimum design, section type, width or diameter of section, and thickness of steel tube were established as structural design parameters. Material strengths of steel and concrete were excluded for design parameters and fixed to 325MPa and 27MPa, respectively. According to increases in the required axial load from 100kN to 10000kN in 100kN increments, under a constant required moment of 500kN-m, the optimum designs of the CFT columns were found. The CO2 emissions of the optimum designs for each section type are shown in Fig. 2.

![CO2 emissions of the optimum designs for circular and square section types](image)

**Figure 2 CO2 emissions of the optimum designs for circular and square section types**

Fig. 2 shows that, under relatively small required axial load scenarios, such as 2000kN or smaller, the CO2 emissions produced by the optimum square CFT columns were identical or smaller than those of circular CFT columns. On the other hand, under load scenarios where the required axial load was 2000kN or larger, the optimum square CFT columns generate much CO2 emissions rather than the optimum circular CFT column. The differences in the CO2 emissions between the two section types increase according to the increases in the required axial load when the required axial load was in the range of 2000–4800kN. Beyond approximately 2000kN, the increase rate of the CO2 emission of the square CFT column was 1.65 times larger than that of the circular CFT column. This result indicated that a circular CFT column efficiently resists axial loads with less CO2 emissions than a square CFT column for the loading conditions.

![Material costs, steel tube area, and diameters of cross-sections](image)

**Figure 3 Results of the optimum designs for CFT columns: (a) material costs, (b) steel tube area, (c) diameters of cross-sections**

Fig. 3 shows the results of a comparison of the material costs and diameters of the optimum designs according to increases in the required axial load. As indicated by Fig. 3(a), it was advantageous to use circular CFT columns rather than square CFT columns under most load scenarios in terms of structural costs. However,
the opposite result was also obtained in specific load cases, where the required axial load was in the 3000–4500kN. This was because expensive steel tubes were used more in the optimum designs of the circular CFT columns in the corresponding axial loads than in square CFT columns. A comparison of Fig. 3(a) and (b) shows that when the amount of steel tubes used was small, the material cost was also small, which implied that the material cost of the CFT columns was dominated by the amount of steel tubes used.

In contrast, as verified in Fig. 3(c), the diameter of a square CFT column, which had a greater material cost than a circular CFT column, was designed to be smaller than that of a circular CFT column under most load scenarios. A small column diameter means the cross-section of the column is small. This increases the utilized area of the building, which can deliver large economic benefits in some cases. In particular, it is very important for spaces where numerous buildings are densely constructed in cities to efficiently utilize small areas. Therefore, designers should consider not only CO2 emissions and material costs but also the cross-sectional areas or diameters of CFT columns when the section type of the CFT columns is selected under given load scenarios.

For the column design, there are considerably various loading conditions which are determined by required moments and axial forces according to the height, size, use, function and location of the building. For those possible loading conditions, designs for CFT columns can be derived by the optimum design model with the minimum CO2 emissions. In this Section, optimum designs were carried out for total 2500 loading conditions which were set by combining fifty required moment loads and fifty required axial loads. The optimum sustainable design results for the entire loading conditions were obtained. The CO2 emissions of each optimum design were provided, as shown in Fig. 4. Based on the CO2 emissions of the design results in Fig. 4, a CO2 emission function for sustainable CFT column design was established. The function was fitted using 4th order polynomial curve fitting and variables of the function were required moment and axial loads. Using the function, the amount of the minimum CO2 emissions can be estimated for a given loading conditions and a CFT column designed by a design philosophy can be assessed in terms of the sustainable structural design.

![Figure 4 CO2 emission function of the optimal designs for CFT columns under various loading scenarios](image)

**4. Conclusions**

In this study, an optimum design model was proposed to minimize CO2 emissions for the sustainable design of CFT columns in buildings. In the optimum design process, the section types of CFT columns and the dimensions were set as structural design parameters. In the model, objective function are established as the CO2 emissions of the CFT column design candidates and minimized using GA while satisfying constraints which are used to assess the structural safety of the CFT columns. For the derived optimum design results, the CO2 emissions, cost, and space utilization were analyzed with regard to section composition and section type. The results of a comparison of the optimum designs of circular and square CFT columns showed that as the required axial load increased, a design using a circular cross-section became more advantageous in terms of the environmental friendliness and material cost. However, the circular CFT column designs had larger diameters than the square cross-sections under both the axial load and moment load scenarios. Therefore, square CFT columns were better than circular CFT columns in terms of space utilization. The optimum design results obtained from the proposed model for possible great number of loading conditions provided a guideline for CFT column design with the minimum CO2 emissions in terms of section types, composition and dimension of...
structural materials. Further, the design results can be used to estimate CO2 emission for a given loading condition and evaluate a column design in the environmental performance aspect.

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6. References