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Design technology based on resizing method for reduction of costs and carbon dioxide emissions of high-rise buildings

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ABSTRACT

Construction materials are known to cause a considerable environmental impact during their manufacturing and construction phases. The environmental impact such as CO_2 emissions can be calculated based on the amount of materials used. To reduce CO_2 emissions, it is necessary to develop technologies that can reduce the amount of materials used in the design phase. This study proposes a design technology that applies a resizing method to reduce the cost and carbon dioxide emissions of high-rise buildings. This technique increases the natural frequency of the structure and decreases the structural weight by reducing the wind load acting on high-rise buildings. The proposed technique is applied to a 37-story real building in order to compare the cost and CO_2 emissions pre- and post-application of the technique. The cost and CO_2 emissions in the phases of material manufacturing, material transportation, and on-site construction are considered. As a result of the application, it was confirmed that the redesign obtained with the proposed technique reduces the cost by 29.2% and CO_2 emissions by 13.5%, when compared to the initial design.

1. Introduction

The Kyoto Protocol (1997) imposes obligations to reduce greenhouse gases (GHGs), which are the main cause of global warming. According to this Protocol, companies with high carbon dioxide (CO_2) emissions should either reduce them by developing technologies for energy reduction or buy the certified emission reductions (CERs) from other companies with less CO_2 emissions.

CO_2 accounts for approximately 77% of the entire GHGs, and the annual CO_2 emissions have been increased by 80% since the 1970s [1]. The construction industry is known to emit a considerable amount of CO_2. According to the International Energy Agency (IEA), about 24% of the CO_2 emissions are due to the energy consumed by buildings [2]. In the United States, CO_2 emissions from buildings account for 38% of the entire emission [3]. Thus, it is necessary that the construction industry develop technologies that reduce its environmental impact, which is expected to have a huge effect around the globe.

The environmental evaluation for buildings considers the effects of its entire life cycle, which is divided into material manufacturing, transportation, on-site construction, use/maintenance, and removal/disposal phases [4]. Various studies [5–8] for each phase have been conducted, aiming at generating technology developments that could reduce the environmental impact of buildings. As for the use/maintenance phase of the buildings, studies have been carried out to reduce the environmental impact by improving the energy efficiency of exterior and finishing materials, as well as the heating, ventilating, and air-conditioning (HVAC) systems [9–11].

CO_2 emissions prior to the use/maintenance phase of buildings (material manufacturing, transportation, on-site construction) are known to amount to over 32% of those produced during the life cycle of a building [4]. CO_2 emissions during such phases are mostly generated during the manufacturing phase of construction materials [4,5]. For example, 1445 Mt CO_2 emissions in 2014 were generated for the production of cement, and the cement production accounts for roughly 8% of global CO_2 emissions [12]. Therefore, in order to decrease the environmental effect prior to the use/maintenance phase of the buildings, it is necessary to develop environmentally friendly construction materials, like low-carbon materials, or to develop a sustainable structural design method [13–16].

In the field of sustainable structural design, several measures [17,18] are being considered to reduce the CO_2 emissions and energy consumption during material manufacturing, transportation, and on-site construction phases by decreasing the structural material required for buildings. This is possible because the CO_2

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Nomenclature

A	the area for the cross section
$a(z_i)$	the maximum acceleration at ith floor
a_{peak}	the maximum acceleration response
B	the width of a building
C_i^j	the capacity of the jth vehicle transporting the ith material (m^3/EA or ton/EA)
C_i^k	the capacity of the kth equipment for the ith material (m^3/h)
$\bar{C}'$	the mean wind load coefficient
DC_d^k	the diesel consumption per hour of the kth equipment for the ith material (l/h)
DC_d^j	the diesel consumption per hour of the jth vehicle transporting the ith material (l/h)
E	the modulus of elasticity
EF_d	the CO_2 emission factor of diesel of the jth vehicle transporting the ith material (kg-CO_2/l)
EF_i	the CO_2 emission factor of the ith construction material (kg-CO_2/kN)
F	the member forces (axial forces, shear forces) due to the wind load
f	the member forces (axial forces, shear forces) due to the unit load
f_1	the first natural frequency
G	the shear modulus of elasticity
g	the peak factor
H	the height of a building
I	the moment of inertia for the cross section
l_i	the length of the ith member
M	the member forces (moments) due to the wind load
M_1	the generalized mass and the height of a building
m	the member forces (moments) due to the unit load
m_i	the mass of ith floor
Q_i	the quantity of the ith construction material (kN)
q_H	the unit velocity pressure at the top of a building
$S_M(f_1)$	the moment power spectrum value of wind load at the first natural frequency
SM_i^j	the standard movement per hour of the jth vehicle transporting the ith material (km/h)
TD_i^j	the transportation distance of the jth vehicle transporting the ith material (km)
UC_i	the unit cost of the ith construction material (EUR/kN)
UC_i^j	the unit cost per unit hour of the jth vehicle transporting the ith material (EUR/h)
UC_i^k	the cost per unit hour of the kth equipment for the ith material (EUR/h)
$W_F(z_i)$	the total wind load
$W_{Fm}(z_i)$	the mean wind load
$W_{Fr}(z_i)$	the resonance wind load
W_i	the weight of ith member
X	the direction of X-axis
Y	the direction of Y-axis
Z	the direction of Z-axis
z_i	the height of ith floor
β	the vertical distribution coefficient of wind load
β_i	the sectional control factor of the ith member
γ	the total weight control factor
δ	the lateral displacement at the top of the building
δ_i	the DPF of the ith member
η_1	the damping ratio
λ	the lagrange multiplier
σ_M	the root mean square value of base moment
ϕ_i	the first mode shape value at ith floor

emissions and energy consumption during these phases are calculated based on the amount of materials used [19–21]. Danatzko and Sezen [22], Anderson and Silman [23], Moon [24] described minimizing material use as the sustainable structural design strategy that can reduce the environmental impacts. Pongiglione and Calderini [25] provided a comprehensive state-of-the-art overview of sustainable structural design.

Yeo and Gabbai [26], Park et al. [27] and Oh et al. [28] performed a parametric analysis about the environmental effects of structural design parameters for reinforced concrete (RC) beams, columns, and composite columns, respectively, and proposed guidelines for structural design that minimize the CO_2 emissions. The results of these studies show that a decrease in CO_2 emissions as well as of the required structural materials is indeed possible, under identical loads, by proposing appropriate sectional sizes, reinforcement ratios, etc. Likewise, Miller et al. [29] and Fraile-Garcia et al. [30] compared the embodied energy or CO_2 emissions, among other factors, for each slab type in order to select structural alternatives.

While these studies [26–30] focused on structural design on the member level, several studies [31–33] proposed optimal structural design methodologies for RC frames on the building level. There are only a few factors influencing the structural design of structural members (i.e., section size, material strength, etc.) [34–36], and thus there are not many alternatives. For this reason, it is possible in the existing studies to develop parametric analyses focusing on the member level [26–28]. However, numerous members are involved on the building level, and all members must be simultaneously considered because of the interaction between them. Therefore, limitations do exist for proposing measures to reduce the environmental effect by applying parametric analyses on the building level.

On the other hand, the existing studies [31–33] that proposed optimal structural design methods on the building level have used simulated annealing (SA) and big bang-big crunch (BB-BC) algorithms as heuristic methods. These studies proposed values for the design variables that satisfied the constraint conditions for safety and minimized CO_2 emissions at the same time. They are widely used in studies for structural optimization because of their high convergence speed, despite its repetitive structural analysis and evaluation. However, the optimization technique based on heuristic methods as in these studies [31–33], tends to have a decreasing convergence speed as the number of design variables increases. Thus, the optimization method based on a heuristic method is difficult to apply to real buildings. The existing studies [31–33] have only been applied on 2D-based academic examples (maximum of 8-story, 2-span with 40 members).

Meanwhile, Foraboschi et al. [37] proposed a sustainable structural design technique that conserves environmental resources on a building level. Without using a structural optimization technique, a design method to reduce the embodied energy was proposed by comparing design alternatives. It was suggested that selecting a proper floor type is the most effective method for reducing the embodied energy of a building [37].

This study proposes a structural design technique to reduce cost and CO_2 emissions for a high-rise building. This technique computes the displacement participation factor (DPF) of each member of a high-rise building. Then the cross-sectional sizes of members are re-determined based on DPF. With the redesign process using DPF, the stiffness and natural frequency of the structure increase