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# Sustainable design model to reduce environmental impact of building construction with composite structures

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ABSTRACT

Thanks to advances in technologies related to zero energy buildings, reducing $CO_2$ emissions during the design and construction phase becomes more and more important to reduce environmental impact from building construction. Even though more than half of high-rise buildings over 200 m completed in 2014 employed steel reinforced concrete (SRC) composite structures, most of sustainable design to reduce $CO_2$ emissions were limited to reinforced concrete (RC) buildings. Since SRC is a composite structure consisting of three component materials of concrete, steel shape, and rebar, $CO_2$ emissions can be effectively reduced by applying eco-friendly design strategies for determining the proportions of those components in SRC members.

In this study, the sustainable design model for SRC composite structures is developed for optimal combination of construction materials with minimized $CO_2$ emissions. The model is used to provide comprehensive analyses of variability of $CO_2$ emissions in the building construction. The results indicates that increasing the cross-sectional area of steel shape is more advantageous for reduction of $CO_2$ emissions than increasing the cross-sectional area of concrete for composite structures subjected to high axial loads required in high-rise building constructions based on the analysis of the contribution of each component to strength of column. Sensitivity analysis reveals that the environmental impact can be significantly reduced by using high strength materials in SRC structures. Further, through the application of the model to the design of an actual high-rise building, it is confirmed that derived SRC columns have excellent performances in terms of environmental impact and space utilization.

## 1. Introduction

The average temperature at the earth's surface has increased by approximately 0.6°C over the last 30 years due to global warming (Carnesale and Chameides, 2011) which is caused by the changes in the concentration of greenhouse gases (GHGs) in the atmosphere (Pachauri and Reisinger, 2007). GHGs have continuously increased since pre-industrial times as a result of human activities (Pachauri and Reisinger, 2007). Of the anthropogenic GHGs, the largest proportion is carbon dioxide ($CO_2$). Therefore, reducing $CO_2$ emissions is very important to reduce anthropogenic GHGs.

According to a research (Hong et al., 2015), GHG emissions generated from construction related human activity accounted for 385 $tCO_2e$. Dong and Ng (2015) reported that construction consumes 16% of total iron and steel production annually, where the steel industry is responsible for 6.7% of total $CO_2$ emissions. Also, Portland cement manufacturing is accompanied by large emissions of $CO_2$ (Mehta, 2002). The $CO_2$ emissions generated in the cement industry account for approximately 5% of the global anthropogenic $CO_2$ emissions (Worrell et al., 2001). Recently, it was stressed that materials and building systems for building construction can cause significant environmental pressures (Chou and Yeh, 2015). It was reported that approximately 38.5% of all U.S. $CO_2$ emissions were generated from the use of buildings (Zhang et al., 2011; Zhang, 2015) and $CO_2$ emissions of buildings around the world are anticipated to significantly increase (USEIA, 2016). Therefore, the $CO_2$ emissions generated during the manufacturing phase for building materials cannot be ignored.

Accordingly, significant effort and research have aimed to reduce the $CO_2$ emissions in the building and construction sectors since the 2000s. Most studies have focused on reducing the $CO_2$ emissions generated during the operation and maintenance phase

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of buildings (Zhang et al., 2006; Yang et al., 2008; Radhi, 2010; Kibert, 2012) because this phase generally produces the largest amount of $CO_2$ emissions (Sartori and Hestnes, 2007). However, some studies have also been conducted to minimize the $CO_2$ emissions in the design and construction phase (Azhar et al., 2011; Zhang et al., 2012, 2013) including structural design stage dimensioning structural members and combining various construction materials (Moon, 2008; Yeo and Gabbai, 2011; Park et al., 2014; Yang et al., 2015; Yeo and Potra, 2015) based on life cycle assessment (De Benedetto and Klemes, 2009; Cucek et al., 2012; Downie and Stubbs, 2013). As previously mentioned, the $CO_2$ emissions generated during the building material manufacturing and construction phases are not negligible (Worrell et al., 2001; Mehta, 2002). In particular, thanks to the advancement of technologies related to zero energy buildings, which have been actively studied in recent years (Musall et al., 2010; Marszal et al., 2011; Marszal and Heiselberg, 2011; Attia et al., 2012), reducing $CO_2$ emissions during the design phase has been more important than ever before.

However, most of these studies were limited to reinforced concrete (RC) structures consisting of two component materials of concrete and steel rebar. Few studies have been conducted on composite structures such as steel reinforced concrete (SRC) structures. SRC composite members are mainly used in large scale buildings such as high-rise buildings (Saw and Liew, 2000; Shanmugam and Lakshmi, 2001; Spacone and El-Tawil, 2004); 54% of high-rise buildings over 200 m completed in 2014 employed composite members, which is the largest proportion to date and is still increasing according to a report (Safarik and Wood, 2014). Because SRC is a composite member consisting of three component materials of concrete, steel shape, and steel rebar, its performance and $CO_2$ emissions are dependent on the proportion or combination of each component material. Consequently, sustainable design of composite members based on the previous experience of engineers is not easy for eco-friendly SRC members while also satisfying structural performance. In contrast to steel and RC buildings, $CO_2$ emissions can be effectively reduced by applying eco-friendly design strategies for determining the proportions of three component materials in SRC members.

In this study, variability of $CO_2$ emissions in the construction of buildings with SRC composite members is investigated for mitigating environmental impacts of building construction. To analyze influence of combination of construction materials on $CO_2$ emissions, $CO_2$ emission minimization model for SRC composite column members is developed and the effectiveness of derived optimal designs for various loading scenarios are evaluated based on the contribution of component in the SRC column to the compressive and moment strength. Furthermore, the influences of the variations in the strengths of materials on $CO_2$ emission and space utilization are analyzed by defining the relationships between $CO_2$ emissions and strengths of three component materials such as concrete, steel shape, and rebar. Finally, the presented optimum design for SRC column is applied to sustainable design of a high-rise building. Environmental performance and space efficiency of the derived solutions are evaluated and compared with the RC column design results.

## 2. $CO_2$ emission minimization model for SRC composite columns

### 2.1. Design parameters

As shown in Fig. 1, the cross-section of an SRC column consists of three component materials: concrete, steel shape, and rebar. Each of these components materials can have various strengths and sectional dimensions, which are denoted as design parameters in this paper. There are numerous possible designs for an SRC column with various combinations of design parameters, and each of these has its own unique design strength and $CO_2$ emissions.

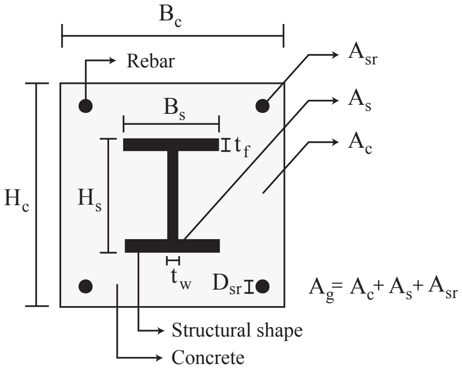

**Fig. 1.** Design variables of SRC column.

The design parameters in the cross-section of the SRC column are divided into two categories: design variables and design constant values. The design variables are varying values during design and design constant values are considered to be fixed constants. In this study, the variables related to the cross-sections of the concrete and steel shape were set as the design variables, which are shown in Fig. 1.

In Fig. 1, $B_c$ and $H_c$ are the width and the depth of the concrete, respectively. $B_s$, $H_s$, $t_f$, $t_w$ are the width, the depth, the thickness of the flange, and the thickness of the web of the steel shape, respectively. The material strength of each component material and the number and diameter of the rebar were set as the design constant values, which are listed in Table 1. In Table 1, the concrete compressive strength is$f_{ck}$, the yield strength of the steel shape is $F_{y,s}$, the yield strength of the rebar is $F_{y,sr}$, the number of rebars is $N_{sr}$, and the diameter of the rebar is $D_{sr}$; these are the design constant values in the cross-section design process. In Section 4, the material strengths of $f_{ck}$, $F_{y,s}$, and $F_{y,sr}$ of each component material are also considered to be design variables to analyze the influences of the changes in the strengths of materials on $CO_2$ emission.

The range of variable $B_c$ was set to 200–1000 mm, with 10 mm increments, which was set as a discrete design variable. This study sets a column cross-section with a square-shape as a target design because columns with a $B_c$ to $H_c$ ratio of 1:1 are commonly used in designs; therefore, the concrete depth $H_c$ had the same value as $B_c$. For the steel shape, commercially available H-shapes in the KS D 3502 standard (KATS, 2013) was used. Because the width to depth ratio of the H-shapes, $H_s/B_s$, used in columns is generally about 1:1, this study used H-shapes whose $H_s/B_s$ was close to one. Accordingly, the cross-section database of steel shapes used in this study consisted of 27 H-shapes. The concrete compressive strength $f_{ck}$, which was set as a constant, was 24 MPa, while the yield strength $F_{y,s}$ of the steel shape was 235 MPa. In addition, the rebar yield strength $F_{y,sr}$ was 400 MPa, the rebar diameter $D_{sr}$ was 28.6 mm (D29), and the total number of rebars $N_{sr}$ was set to four.

**Table 1**
Design constant values.

| Material | Design constant values |
|---|---|
| Concrete | Compressive strength, $f_{ck}$ |
| Steel shape | Yield strength, $F_{y,s}$ |
| Rebar | Yield strength, $F_{y,sr}$ |
| | Diameter, $D_{sr}$ |
| | Number, $N_{sr}$ |