A comparative study of environmental performance between CFST and RC columns under combinations of compression and bending

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ABSTRACT

To better understand the environmental performance of columns and assist construction designers in achieving a balance between structural requirements and environmental protection, this paper assessed and compared the EI of columns constructed with two concrete types (CFST and RC) and three cross-sections (circular, rectangular and square) under different combinations of compression and bending. The BEPAS model categorized the columns' EI into two safeguard areas—ecological damage and natural resources, and then expressed the impacts using the EIV index in unit of “yuan”. Based on the assessment results and M-N interactive curves, M-N-EI interactive curves were developed to present the EI of columns under various combinations of axial force (N value) and bending moment (M value). Thus, structural performance and environmental performance can be shown in a single figure to conveniently contribute decision-making. The M-N-EI interactive curves were also compared to optimize choices of environmentally friendly concrete types and cross-sections to satisfy structural bearing capacity requirements. Moreover, the influences of

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various parameters, the H/B of rectangular columns, steel ratio of RC columns, steel strength, steel recycling rate and solid waste recycling rate, were analyzed. An engineering scenario was served as a case study to test the application and operation of the assessment methodology and M-N-EI interactive curves. The results indicate that the new curves can effectively express the EI of columns under different combinations of compression and bending and can potentially be used by the construction industry to achieve environmental goals and provide clear implications for practice.

Keywords: environmental impact (EI); concrete-filled steel tube (CFST); reinforced concrete (RC); compression and bending; life cycle assessment (LCA)

Nomenclature

CFST	Concrete-filled steel tube
CFSTc	Concrete-filled steel tube with a circular cross-section
CFSTr	Concrete-filled steel tube with a rectangular cross-section
CFSTs	Concrete-filled steel tube with a square cross-section
RC	Reinforced concrete
RCc	Reinforced concrete with a circular cross-section
RCr	Reinforced concrete with a rectangular cross-section
RCs	Reinforced concrete with a square cross-section
D	Outer diameter
B	Outer width
M	Moment
N	Axial load
f_y	Yield strength of the steel
ρ	Steel ratio
t	Thickness of the steel tube
LCA	Life cycle assessment
EI	Environmental impact
EIV	Environmental impact value

1. Introduction

RC and CFST columns are widely used building components in China's construction industry. RC columns consist of a mixture of concrete and steel to overcome concrete's relatively low tensile strength and ductility by including reinforcement. In contrast, CFST columns are composite material systems and are constructed of steel tubes filled with concrete (Choi and Xiao, 2009) and this type of column is often described as "1+1>2" (Han, 2007). CFST columns have a number of distinct advantages over RC columns regarding structural performance (Nethercot, 2003; Wardenier and Met Staal, 2002). The concrete infill is confined by the steel tube, resulting in a triaxle state of compression that increases the strength and strain capacity of the concrete and delays local buckling of the steel tube by preventing inward buckling. Besides, CFST columns can be constructed easily and rapidly without formwork, which also reduces construction costs (Nie et al., 2008; Wang et al., 2013). Because of their better mechanical performance and lower cost, CFST columns have been increasingly employed in a variety of buildings, bridges, tower structures, and large-span structures over the past several decades (Han, 2007; Yu et al., 2010).

Research on CFST and RC columns is currently focused on their mechanical behaviors and includes experimental studies, theoretical models, finite element models, fiber beam-column models and other analyses (Gourley et al., 2001; Wang et al., 2013; Yu et al., 2010). Roeder et al. (2010) addressed combined axial and flexural loading and predicted the stiffness and resistance of circular CFST columns based on 122 specimens. An and Han (2014) developed a finite element analysis model to analyze the performance of concrete-encased CFST columns under combination of compression and bending. Yang et al. (2014) investigated the experimental behavior of 12 CFST members, 4 reference hollow structural section members and 4 reference plain concrete

members under local bearing forces. These works explored the mechanical performance and constructional properties of columns using many methods, and their results lay a foundation for our study.

There is a lack of awareness regarding the EI of columns and its relationship with the bearing capacity, although the importance of the environmental performance of structural members in building design has been highlighted (Nadoushani and Akbarnezhad, 2015). The existing building EI assessment studies have compared different building types, construction technology methods and some important construction materials. Dodoo et al. (2012) analyzed the life cycle primary energy balances of a concrete-frame building and a wood-frame building. Nadoushani and Akbarnezhad (2015) assessed the life cycle carbon footprint of concrete-frame and steel-frame buildings. Mao et al. (2013) calculated and compared the characteristics of the greenhouse gas emissions of prefabrication and conventional construction methods. Rodríguez-Alloza et al. (2015) assessed the EI of warm mix asphalt mixtures. Li et al. (2011) evaluated the environmental performances of commonly used commercial concretes with 6 different strength grades. The EIs of CFST and RC columns have not yet been studied or elucidated, let alone an integration assessment of structure and environment performances. This paper attempts to fill this gap to help easily know about the EI of columns as well as its relationship with the bearing capacity, further help structure design and selection.

Therefore, the present study aimed to quantify and compare the EIs of CFST and RC columns satisfying structural bearing capacity requirements. Previous research addressing columns' structural performance (M-N interactive curves) and building environmental assessment model (BEPAS) provides a basis for our study. The EIV index was calculated to express the

quantified EI values of columns from an economic perspective. M-N-EI interactive curves were first developed to explore the relationship between the structural performance and the environmental performance of columns, and the influences of certain parameters were discussed. Finally, an engineering scenario served as a case study to illustrate the function of the M-N-EI interactive curves and test their application. The newly developed M-N-EI interactive curves enable designers to consider environmental sustainability in addition to cost and quality when designing columns.

2. Methodology

2.1 M-N interactive curve

The M-N interactive curve is often used in construction design to express the bearing capacity of the axial force (N value) and bending moment (M value) of a column. Fig. 1 shows a typical M-N interactive curve. Generally, balance failure occurs when the column bears the maximal M value, and it divides the M-N interactive curve into two stages: First, a decrease in N leads to an increase in M, the point at which the compression-controlled failure occurs. During this stage, the initial yielding of the extreme tensile fiber of the steel does not occur when the compressive concrete is crushed. In the other stage, tension-controlled failure takes place, in which a decrease in N leads to a decrease in M. During this stage, the initial yielding of the extreme tensile fiber of the steel tube occurs before the compressive outer concrete is crushed.

(Fig. 1)

M-N interactive curves consist of the combinations of N and M a column can bear and are often employed to analyze columns' structural performance. An and Han (2014) applied this

method to determine the behavior of a concrete-encased CFST column under different combinations of compression and bending and further explored how the M-N interactive curves change when some parameters, such as concrete strength, steel strength and diameter of the cross-section, vary. In addition, some investigators developed a set of curves to assist in structure design. Nie and Tao (2009) compared the M-N interactive curves of CFST columns with different cross-sectional types and areas and then offered a practical optimization method to aid the cross-section choice. The “Concrete Structure Calculation Manual” (Wu, 2002) summarizes the M-N interactive curves of many structural members (beams, columns and slabs) with different cross-sectional dimensions to make design rapid and simple. These two studies yielded results are especially applicable to Chinese construction projects because they comply with the major Chinese design codes and construction standards for structural members, such as “Code for design of concrete structures” (MOHURD and AQSIQ, 2010) and “Code for design of steel structures” (MOHURD and AQSIQ, 2003). These M-N interactive curves were used here to measure the column structural performance and provide a foundation for assessing EI.

2.2 LCA-based EI assessment model

Many building EI assessment methods, such as ESGB (MOHURD, 2014) and ESGCB (MOHRUD, 2011), have been developed within the last ten years attaching great importance to construction industry in China. These methods are qualitative scoring methods, although easy to use, their assessment criteria are sometimes subjective. Hence, it is difficult to provide in-depth and comparable results with these methods (Li et al., 2010). LCA is a well-known analytical framework for assessing EI over the building’s lifespan, and quantitative tools based on the LCA approach are considered an entirely different group of EI assessment tools apart from qualitative tools. These

methods can provide comprehensive quantitative results and potentially facilitate decision-making at the design phase. BEPAS (Building Environmental Performance Analysis System) (Zhang et al., 2006) is an LCA-based assessment model funded by the Ministry of Housing and Urban-Rural Development (MHURD) that served as a methodological basis for a newly published construction industry standard in China: the Standard for the Sustainability Assessment of Building Projects (MHURD, 2011). This study used BEPAS to assess the columns' EI and involved the following steps: goal and scope definition, inventory analysis, classification, characterization and weighting according to the International Organization for Standardization (ISO) (ISO, 2006), as shown in Fig.

2.

(Fig. 2)

- Goal and scope definition

CFST and RC columns were the evaluated objects in this study, and the goal was to quantify their EI values and express them in a unified unit to facilitate comparison. More detailed information regarding the evaluated objects, including cross-section types and material parameters, will be presented in section 3. The research scope included raw material extraction, the manufacture and transportation of building materials and on-site construction, and is collectively referred to as the pre-use phase (Azari, 2014; Heinonen et al., 2016; Keoleian et al., 2000) or materialization stage (Luo et al., 2016; Zhang and Wang, 2015). In this paper, the authors employed the term “pre-use phase” and show it in Fig.3 to make the research boundary clear. Only the pre-use phase was studied because the involved parties and responsibilities in this phase were identified clearly, and the proposed management measures based on the results could be used more effectively to facilitate decision-making (Li et al., 2015). Besides, the energy use in pre-use stage

has been identified as increasing for energy efficiency buildings (Sartori and Hestnes, 2007) and makes up a considerable part of the total energy use in low energy buildings (Thormark, 2002). Notably, steel formwork consumption during the on-site construction of the RC columns was also considered in the assessment because steel formwork is a necessary ancillary material. Furthermore, the formwork can be recycled 100 times according to engineering practice and previous research (Cao et al., 2015).

(Fig. 3)

- Inventory analysis

During inventory analysis, the inputs of raw materials and energy necessary to realize the appropriate function and the outputs of pollutants emitted to the air, water, soil and other environmental media in one functional unit are quantified. According to the ISO 14040 standard (ISO, 2006), a functional unit is the reference unit through which a system's performance is quantified via LCA. This study defined the functional unit as "the cross-sectional area of a column that bears a certain combination of compression and bending". This functional unit was chosen to obtain information about the cross-sectional dimension required to bear a given combination of compression and bending according to the column's structural properties and bearing functions. This functional unit was defined to meet the study objectives and similar definition has previously been applied in certain LCA studies of building materials (Ardente et al., 2008; Pargana et al., 2014).

In this step, M-N interactive curves were selected to facilitate determining the cross-sectional dimension of the assessed columns under a given combination of compression and bending. Using

the cross-sectional size, the amounts of consumed concrete and steel were determined and subsequently converted into the amounts of pollutant discharged, natural resources consumed and energy used in each project using the inventory database. The database used here was derived from previous investigations and “eBuilding” software (Li et al., 2010; Li et al., 2011; Wang, 2015; Wu, 2005), and the recycling levels of steel and solid waste were considered.

- Classification

Classification connects the input-output data with EI categories. BEPAS allocated the EI to two safeguard areas—ecological damage and resource depletion—and divided ecological damage into 9 sub-categories and resource depletion into 3 sub-categories, as shown in Fig. 2.

- Characterization

Characterization assesses the contributions of each input and output to its assigned impact categories. Usually, many pollutants can cause the same impact, e.g., SO_2 , NO_x and NH_3 can cause acidification. Therefore, inventory results in the same category must be integrated in this step. The characterization factor data in this model were obtained from previous studies (Kong, 2010; Li et al., 2010; Zhang et al., 2006).

- Weighting

The weighting step aims to evaluate the relative severity of categories and summarize the different impacts into a single value to facilitate comparison and decision-making. BEPAS used a monetary approach, WTP, to calculate impact weights and thereby enhance the assessment's objectivity and express the EIV results in “yuan”. The weighting factors used in this study were proposed by previous research [31] based on the green taxes levied on emissions and natural resources.

3. Evaluated columns

CFST and RC columns are the evaluated objects in this study, and the assessment extends to different cross-sectional shapes. Concrete columns have various cross-sectional types, and circular, rectangular and square are three common shapes in practical applications. Generally, circular concrete columns exhibit better mechanical behavior than square and rectangular columns and result in more effective confinement (Han et al., 2011). However, square and rectangular columns are favored by engineers because of their simple joint configuration, good stability, suitable shape for architectural designs and current popularity (Yang et al., 2014). Some researchers (Porsch and Hanswille, 2004; Yang and Han, 2009, 2011) have investigated the behavior of and design methods for locally loaded CFST columns with different cross-sections. To optimize cross-section selection regarding environmental protection, this paper assessed and compared the EIs of columns with different cross-sectional shapes.

Figures 4 and 5 summarize the dimensional parameters of the columns. Fig. 4 depicts three CFST column cross-sections (CFSTc, CFSTr and CSFTs), where D , B , d and b are the outer diameter, outer width, inner diameter and inner width, respectively; t is the steel tube wall thickness. The parameters of RCc, RCr and RCs are presented in Fig. 5, where D , B , and H are the diameter, width and height, respectively.

(Fig. 4)

(Fig. 5)

The main building materials used in CFST and RC columns are concrete and steel, but their grades and types vary and thus affect the EI assessment results of columns. Because of space limitations, this study did not cover all parameter combinations and instead only focused on

common parameter combinations that are suitable to most engineering applications and tested the operability of the framework and methodology. The influences of different parameters are discussed in section 4.3 to define their roles.

The parameters, including the steel strength, cross-section and steel ratio, of six concrete columns are summarized in Table 1. This study was developed based on structural performance studies, and the parameters applied were in accordance with those investigations. For CFST columns, the adapted concrete grade was C50, and the steel was Q345 based on the literature (Nie and Tao, 2009). C50 and Q345 have been widely used in the Chinese construction industry; their strengths were suitably matched to improve their structural performance, and these materials were recommended by the “Technical Specifications for Concrete-Filled Steel Tubular Structures” (Nie and Tao, 2009). The thicknesses of the steel tube followed the relationship $t/D=0.028$, which represents an average value that satisfies the design specification ($t/D \geq \frac{f_y}{150 \times 235}$ for CFSTc and $t/D \geq \frac{1}{60} \times \sqrt{\frac{f_y}{235}}$ for CFSTr and CFSTs) and has been used in many related studies (Elremaily and Azizinamini, 2002; Fujimoto et al., 2004; Gupta et al., 2007). For the RC columns, the concrete grade was C50, and the steel was HRB400 based on the literature. The steel ratio was 1%, which satisfies the “Code for design of concrete structures” (MOHURD and AQSIQ, 2010) and has been widely used in practical engineering and theoretical studies. The H/B of the rectangular columns evaluated in this study was 1.5.

(Table 1)

4. Results and discussion

4.1 M-N-EI interactive curves

M-N-EI interactive curves were developed to present the compression-bending capacities and EI of concrete columns in a single figure. This study employed M-N interactive curves to identify the cross-sectional area, applied BEPAS to quantify the impacts of columns, and presented the accompanying EI on M-N interactive curves, thereby generating M-N-EI interactive curves. In the following sections, the assessed column length is assumed to be 1 m (unit length), and all calculation results presented are the EI values of unit-length columns. Thus, the EIV of columns with different lengths could be easily determined.

The M-N-EI interactive curves of CFST and RC columns with different cross-sections are displayed in Fig. 6. We found the following: (1) There are significant differences in EIV across different cross-sectional types of CFST columns and RC columns, indicating that the cross-sectional type affects columns' EI. (2) For a column, small N and M usually require a small cross-sectional area; thus, fewer materials consumed, and the column exhibits better environmental performance. (3) Given specific N and M values, the EIVs of columns with different cross-sectional types can be rapidly obtained from the curves. Thus, these curves have the potential to be a convenient tool to assess the EI of concrete columns for engineering applications.

(Fig. 6)

4.2 Comparison

In practical engineering design, engineers and designers require more information about the differences between columns constructed using different concrete types and cross-sectional shapes to choose the appropriate column to minimize EI and satisfy capacity demands. Here, M-N-EI interactive curves are compared among columns with the same EIV (46.25 yuan, which is the EIV of a common RCr column with the cross-sectional area of 1200 mm*800 mm) but different

concrete types and cross-sections to better elucidate their differences. The concrete types considered in this study included CFST and RC, and the cross-sectional types included circular, rectangular and square.

(1) Comparison between columns with different concrete types

Fig. 7 (a)(b)(c) compares the M-N-EI interactive curves between CFST and RC columns with three cross-sections. All CFST columns have better bearing capacity performances than RC columns, regardless of their cross-section type; thus, CFST columns exhibit better environmental performance than RC columns under the same combination of compression and bending. Therefore, CFST columns have advantages not only in their structural performance but also in their environmental friendliness. Furthermore, CFSTc columns outperform RCc columns to a greater extent than the other two types of cross-sections. For rectangular and square columns, the difference is slight in compression-controlled situations but significant in tension-controlled situations. Therefore, the advantages of CFST columns are much more obvious when the tension is controlled.

(Fig. 7)

(2) Comparison among columns with different cross-sections

Fig. 8 (a)(b) compares the M-N-EI interactive curves of CFST and RC columns with different cross-sections. For CFST columns, two critical points divide the graph into three periods, which are denoted A, B and C. In period A, which corresponds to the compression-controlled situation with small M, the CFSTc column performs better than the CFSTr column, followed by the CFSTs column. As the M value increases, CFSTc's advantage decreases, but CFSTr performs better. When the M value is sufficiently large, as in period C, the performances are ranked as follows:

CFSTr, CSFTc and CFSTs. Table 2 summarizes and compares the compression-bending capacity performances of columns in these 3 periods. This comparison indicates that cross-sectional type significantly influence the structural performance of CFST columns and that different cross-sections should be chosen based on period to which the engineering scenario corresponds. The situation is much simpler for RC columns; rectangular columns always perform better than square and circular columns, regardless of the combination of N and M. Consequently, when bearing the same N and M, RCr will bring out the smallest EI and is the best choice, followed by RCs and RCc columns.

(Fig. 8)

(Table 2)

(3) Comprehensive comparison

Fig. 9 presents the M-N-EI interactive curves of six concrete columns for comprehensive comparison. Overall, CFSTc and CFSTr bear high loadings well, and CFSTr bears large moment well; RCc and RCs have difficulties bearing large N and/or M. Fig. 9 is divided into 7 periods, which are denoted D, E, F, G, H, I and J, and the performances of columns and the recommended choices are markedly different in these periods. In D, E and J, the columns' performances exhibit clear orders, while the situations are more complex in F, G, H and I, as summarized in Table 3. In D, CFST columns exhibit better performance than RC columns; specifically, CFSTc is the best, followed by CFSTr and CFSTs, and RCr is a better choice than RCs and RCc. In E, with the increases of M value, the RCr column shows better performance than CFSTs, and the six columns are ranked as follows: CFSTc, CFSTr, RCr, CFSTs, RCs and RCc. According to the performance in I and J, rectangular columns generally have a better M capacity than circular and square columns

because of their large section inertia. Therefore, the rectangular cross-section should be considered first for practical engineering situations requiring low N and high M.

(Fig. 9)

(Table 3)

4.3 Sensitivity analysis

The bearing capacity performance and environmental performance of columns are affected by many parameters, and this study conducted a sensitivity analysis of some most important parameters to better elucidate their roles: H/B (varied from 1 to 2), steel ratio (varied from 0.22% to 2.01%), steel strength (HRB335 and HRB400), steel recycling rate (varied from 20% to 95%) and solid waste recycling rate (varied from 5% to 100%). The former three parameters are structural characteristics, and columns' bearing capacity and EI will change as these parameters change. The sensitivity analysis was conducted by comparing the M-N-EI interactive curves of columns with different parameter values and the same EI (46.25 yuan), as shown in Fig. 10. The latter two parameters are external factors; they have fixed values in a specific region and exhibit no relationship to the structure capacity and cross-sectional design. The sensitivity analysis was performed by comparing the EIVs of columns with different parameter values, as shown in Figures 11 and 12.

(Fig. 10)

(Fig. 11)

(Fig. 12)

(1) Effect of H/B of rectangular column

Fig. 10 (a) shows the variation characteristics of M-N-EI interactive curves as H/B changes

from 1 to 2 (using a CFST column composed of C50 concrete and Q345 steel as an example). When EIV remains constant, the N-bearing capacity of the column is slightly influenced by H/B; in contrast, the M-bearing capacity increases as the H/B value increases. The value of H/B affects the section inertia and further the M value a column can bear. Fig. 10 (a) clearly demonstrates that columns with $H/B > 1$ perform better than those with $H/B = 1$, which means that a rectangular column is better than a square column at bearing moment. This finding is in agreement with the conclusion drawn in section 4.2.

(2) Effect of steel ratio

Fig. 10 (b) compares the M-N-EI interactive curves of RCr columns with different steel ratios. The M, N and EI values with higher steel ratios are larger than those with lower steel ratios, and the shapes of the curves are similar. Steel contributes more to N and M bearing and yields a higher EI than an equal amount of concrete.

(3) Effect of steel strength

RC columns with different steel strengths (HRB 400 and HRB 335) are compared in Fig. 10 (c). A column with a higher steel strength exhibits better bearing capacity performance than other columns with the same EIV. To bear the given N and M, a column with HRB 400 will yield a lower EI and is a better choice regarding environmental protection.

(4) Effect of steel recycling rate

Fig. 11 illustrates the influence of steel recycling rate on the EIVs of a CFSTr column and an RCr column bearing 750 KN·m and 8000 KN. The EIV decreases as the steel recycling rate increases, and this trend is relatively obvious for CFSTr columns because steel plays a more important role in the EI of CFSTr columns than RCr columns because of the steel's larger proportion.

Currently, the steel recycling rate in China is 70% (MC et al., 2015), and as a result, CFSTr columns have a slight advantage (0.76 yuan) over RCr columns. In developed countries, recycling technology is more advanced, and the steel recycling rate is higher. For example, the recycling rate in the US has reached 80% (SRI, 2014), and thus, the EIV of CFSTr columns (12.01 yuan) is 26.18% lower than that of RCr columns (16.27 yuan). Therefore, increasing the steel recycling rate is an effective way to decrease columns' EIs and protect the environment. With the development of recycling technology, the advantages of CFST columns have become increasingly distinct.

Practically, the steel used in CFST columns can be easily separated from concrete and relatively readily recovered, whereas the steel encased by concrete in RC columns is much more difficult to separate. This finding is well supported by statistical data from the US (SRI, 2014): the recycling rate of structural steel (97.5%) is much higher than that of steel reinforcement (72%). If we adopt values of 97.5% and 72% to assess the environmental performance of CFSTr and RCr columns, respectively, the EIV of CFSTr (4.90 yuan) is only approximately a quarter of that of RCr (16.73 yuan). Because of the data available in China, the rate applied in this study is the overall steel recovering rate, and thus, the advantages of CFST columns are underestimated to some extent. Therefore, CFST columns exhibit better performance and should be increasingly considered for construction projects.

(5) Effect of solid waste recycling rate

Fig. 12 shows the influence of the solid waste recycling rate on the EIVs of a CFSTr column and an RCr column bearing 750 KN·m and 8000 KN. Similar to the trend observed for the recycling rate, the EIV decreases as the solid waste recycling rate increases, and this trend is relatively obvious for CFSTr columns. The EIV difference between CFSTr and RCr columns goes up as the

solid waste recycling rate increases, growing from 0.76 yuan to 5.30 yuan as the rate grows from 5% to 100%.

According to national planning (MST et al., 2012), the recycling rate of construction waste in China is less than 5%, indicating a huge gap compared with certain developed countries, such as the US (75%) and England (90%). Similar to many investigations (Zhang et al., 2015), this study applied 5% as the recycling rate because of the lack of an exact figure. If the recycling level reaches 75%, similar to that in the US, the EIVs of CFSTr and RCr will decrease by 31.28% and 9.98%, respectively; furthermore, CFSTr's advantage will increase to 4.11 yuan. If the rate increases to 90%, as in England, the EIVs of CFSTr and RCr will decrease by 38.00% and 12.11%, respectively, and CFSTr's advantage will increase to 4.83 yuan. The development of recovery technology increases the significance of the advantages of the CFST columns. Thus, it is important to raise the recycling rate, possibly via building level technological innovations and design modifications, to increase the release of occupied space and decrease environmental damage.

4.4 Application

A typical engineering situation served as a case study to illustrate the application of M-N-EI interactive curves and test their operation. It is currently a residential building in Beijing City, and the assessed columns are 3 m long, bearing loadings of 750 KN·m and 8000 KN. Based on previously developed M-N-EI interactive curves, we rapidly determined the EIVs of 6 columns, as summarized in Fig. 13. Additionally, we applied the assessment model described in section 2.2 in a stepwise fashion and calculated the EIV of each category, as summarized in Table 4. According to Fig. 13 and Table 4, we arrived at the following conclusions:

(1) The environmental performances of the 6 concrete columns are markedly different, and the total EIVs are ranked as follows (from high to low): RCc, RCs, RCr, CFSTs, CFSTr and CFSTc. The highest total EIV (RCc, 59.67 yuan) is 9.55% higher than the second-highest value and 34.85% higher than the lowest value. Such significant differences highlight both the importance of considering EI in the design phase and the practicality of this work.

(2) For CFST and RC columns, ecological damage constitutes a significant percentage of the EI values (nearly 80% and 87%, respectively) and makes substantially larger contributions than resource depletion. The three major EI categories of CFST and RC are the same, but they have different levels of importance. For CFST columns, the three major EI categories (in order) are solid waste (approximately 42%), global warming (approximately 29%) and water resource depletion (approximately 11%). For RC columns, the three major EI categories (in order) are global warming (approximately 58%), solid waste (approximately 14%) and water resource depletion (approximately 7%). The difference is attributable to the different material compositions. CFST columns have higher steel content, and many technologically demanding steps involved in the production of steel (including iron ore mining, iron ore beneficiation and sintering) produce considerable quantities of solid wastes (Gong, 2004), resulting in high solid waste EIV. In contrast, RC columns have higher concrete content, and their EIs mainly depend on cement (Wang, 2009). Cement emits large amounts of CO₂ during its transportation and electrical production (Chen et al., 2014; Gong, 2004; Ishak and Hashim, 2015), and the resulting global warming impact contributes substantially.

(3) CFST columns are a better choice for engineering applications and are highly recommended, especially CFSTc columns in this engineering situation. Given a specific

combination of compression and bending, CFST columns generally have smaller cross-sectional areas. Thus, these columns use fewer materials, cost lower expense, utilize less space and exhibit lower EI values. Therefore, from the economic and environmental perspectives, CFST columns are better than RC columns.

(Fig. 13)

(Table 4)

5. Conclusion

This paper quantified the EIs of columns constructed using different concrete types and cross-sectional shapes (CFSTc, CFSTr, CSFTs, RCc, RCr and RCs) subjected to combinations of compression and bending. Based on M-N interactive curves and an EI assessment model, M-N-EI interactive curves were generated to present the environmental performance of columns in a single plot and help identify correct balance. The environmental performances of columns were also compared across concrete types and cross-sectional types, and sensitivity analyses were performed to better elucidate the performance characteristics of different columns and identify the major influencing factors. The results revealed the following: (1) Considerable environmental performance differences were observed among different concrete types and cross-sections, highlighting the importance of considering EI in the design of structural columns. (2) In most cases, CFST columns exhibited obvious advantages regarding environmental protection over RC columns and were highly recommended for engineering applications. (3) The environmental performances of the columns were affected by many parameters, and increasing the steel recycling rate could effectively reduce the environmental burdens incurred by the columns, especially CFST

columns. Finally, an engineering case was analyzed to demonstrate the functionality of M-N-EI interactive curves.

The assessment results and conclusions presented in this study have important scientific and practical implications. This study first attempted to present a column's N value, M value and EIV in a single figure and thus achieve an integrated assessment to realize an appropriate balance between structural performance and environmental performance. These curves may serve as a pre-construction decision-making tool to guide contractors in choosing the appropriate concrete type and cross-section during the design phase to satisfy both environmental and loading capacity requirements. Moreover, the assessment results allow measurement of the green and economic advantages of CFST columns over RC columns, contributing knowledge of CFST columns from another perspective. Additionally, the assessment results enrich the environmental performance database of building materials and structural components, laying a foundation for future EI assessments in construction industry.

More research is needed to better elucidate columns' EIs. For example, the influences of more parameters, such as t/D and concrete grades, could be analyzed. Furthermore, M-N-EI interactive curves involving additional parameter values (e.g., concrete grades, steel grades and steel ratios) could be drawn and studied to generate a set of graphs that would offer a convenient reference during construction design.

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References

- An, Y., Han, L., 2014, Behaviour of concrete-encased CFST columns under combined compression and bending. *J Constr Steel Res* 101, 314-330.
- Ardente, F., Beccali, M., Cellura, M., Mistretta, M., 2008, Building energy performance: A LCA case study of kenaf-fibres insulation board. *Energy Build* 40, 1-10.
- Azari, R., 2014, Integrated energy and environmental life cycle assessment of office building envelopes. *Energy Build* 82, 156-162.
- Cao, X., Li, X., Zhu, Y., Zhang, Z., 2015, A comparative study of environmental performance between prefabricated and traditional residential buildings in China. *J Clean Prod* pp.1-13.
- Chen, W., Hong, J., Xu, C., 2014, Pollutants generated by cement production in China, their impacts, and the potential for environmental improvement. *J Clean Prod* 103, 61-69.
- Choi, K., Xiao, Y., 2009, Analytical model of circular CFRP confined concrete-filled steel tubular columns under axial compression. *J Compos Constr* 14, 125-133.
- Dodoo, A., Gustavsson, L., Sathre, R., 2012, Effect of thermal mass on life cycle primary energy balances of a concrete-and a wood-frame building. *Appl Energ* 92, 462-472.
- Elremaily, A., Azizinamini, A., 2002, Behavior and strength of circular concrete-filled tube columns. *J Constr Steel Res* 58, 1567-1591.
- Fujimoto, T., Mukai, A., Nishiyama, I., Sakino, K., 2004, Behavior of eccentrically loaded concrete-filled steel tubular columns. *J Struct Eng* 130, 203-212.
- Gong, Z., 2004. A Quantitative method to the assessment of the life cycle embodied environmental

profile of building materials (Master dissertation). Tsinghua University, Beijing (in Chinese).

Gourley, B.C., Tort, C., Hajjar, J.F., Schiller, P.H., 2001, A synopsis of studies of the monotonic and cyclic behaviour of concrete-filled steel tube beam-columns, University of Minnesota.

Gupta, P.K., Sarda, S.M., Kumar, M.S., 2007, Experimental and computational study of concrete filled steel tubular columns under axial loads. *J Constr Steel Res* 63, 182-193.

Han, L., 2007, concrete-filled steel tubular structures-theory and practice. 2nd ed., China Science Press, Beijing (in Chinese).

Han, L., Wang, W., Tao, Z., 2011, Performance of circular CFST column to steel beam frames under lateral cyclic loading. *J Constr Steel Res* 67, 876-890.

Heinonen, J., Säynäjoki, A., Junnonen, J.M., Pöyry, A., Junnila, S, 2016, Pre-use phase LCA of a multi-story residential building: Can greenhouse gas emissions be used as a more general environmental performance indicator? *Build Environ* 95, 116-125.

Ishak, S.A., Hashim, H., 2015, Low carbon measures for cement plant-a review. *J Clean Prod* 103, 260-274.

ISO, 2006. Environmental management life cycle assessment principles and framework. British Standards Institution, London.

Keoleian, G.A., Blanchard, S., Reppe, P., 2000, Life-cycle energy, costs, and strategies for improving a single-family house. *J Ind Ecol* 4, 135-156.

Kong, X., 2010. Research on the health damage assessment model of building during the life cycle (Master dissertation). Tsinghua University, Beijing (in Chinese).

Li, X., Su, S., Shi, J., Zhang, Z., 2015, An environmental impact assessment framework and index system for the pre-use phase of buildings based on distance-to-target approach. *Build Environ* 85,

173-181.

Li, X., Wang, S., Kong, X., Zhang, Z., 2011, Life cycle assessment of environmental impacts of ready-mixed concrete. *China Civil Eng J* 44, 132-138 (in Chinese).

Li, X., Zhu, Y., Zhang, Z., 2010, An LCA-based environmental impact assessment model for construction processes. *Build Environ* 45, 766-775.

Luo, Z., Yang, L., Liu, J., 2016, Embodied carbon emissions of office building: A case study of China's 78 office buildings. *Build Environ* 95, 365-371.

Mao, C., Shen, Q., Shen, L., Tang, L., 2013, Comparative study of greenhouse gas emissions between off-site prefabrication and conventional construction methods: two case studies of residential projects. *Energy Build* 66, 165-176.

MC, MDRC, MLR, MOHURD, ACFSMC, 2015. Long-term Plan for development of renewable resources recycling system (2015-2020).

<http://www.chinaacc.com/upload/html/2015/01/27/huc0bd77c2e08d4713ad2a5e490bffb75c.doc> (in Chinese).

MHURD, 2011. Standard for sustainability assessment of building project JGJ/T 222-2011, China Construction Industrial Press, Beijing (in Chinese).

MOHRUD, 2011. Evaluation Standard for Green Construction of Buildings GB/T 50640-2010, China Planning Press, Beijing (in Chinese).

MOHURD, 2014. Evaluation Standards for Green Building GB/T 50378-2014, China Architecture & Building Press, Beijing (in Chinese).

MOHURD, AQSIQ, 2003. Code for design of steel structures GB 50017-2003, China Planning Press, Beijing (in Chinese).

MOHURD, AQSIQ, 2010. Code for design of concrete structures GB50010-2010, Architecture & Building Press, Beijing (in Chinese).

MST, NDRC, MIIT, MEP, MOHURD, MC, CAS, 2012. Waste recycling technology engineering of the 12th Five-Year Plan.

<http://www.miit.gov.cn/n11293472/n11293832/n11293907/n11368223/n14784682.files/n14784429.pdf> (in Chinese).

Nadoushani, Z.S.M., Akbarnezhad, A., 2015, Effects of structural system on the life cycle carbon footprint of buildings. *Energy Build* 102, 337-346.

Nethercot, D., 2003, *Composite construction*, CRC Press.

Nie, J., Qin, K., Cai, C.S., 2008, Seismic behavior of connections composed of CFSSTCs and steel-concrete composite beams-experimental study. *J Constr Steel Res* 64, 1178-1191.

Nie, J., Tao, M., 2009, Study on comparison and optimization of section types of concrete-filled steel tube. *Building Structure* 38, 106-109 (in Chinese).

Pargana, N., Pinheiro, M.D., Silvestre, J.D., Brito, J.D., 2014, Comparative environmental life cycle assessment of thermal insulation materials of buildings. *Energy Build* 82, 466-481.

Porsch, M., Hanswille, G., 2004. Load introduction in composite columns with concrete filled hollow sections. In: *Composite Construction in Steel and Concrete V* (pp. 402-411). ASCE.

Rodríguez-Alloza, A.M., Malik, A., Lenzen, M., Gallego, J., 2015, Hybrid input - output life cycle assessment of warm mix asphalt mixtures. *J Clean Prod* 90, 171-182.

Roeder, C.W., Lehman, D.E., Bishop, E., 2010, Strength and stiffness of circular concrete-filled tubes. *J struct Eng* 136, 1545-1553.

Sartori, I., Hestnes, A.G., 2007, Energy use in the life cycle of conventional and low-energy

buildings: A review article. *Energy Build* 39, 249-257.

SRI, S.R.I., 2014. 2013 Steel Recycling Rates, Pittsburgh.

Thormark, C., 2002, A low energy building in a life cycle—its embodied energy, energy need for operation and recycling potential. *Build Environ* 37, 429-435.

Wang, L., 2015. Research on construction sustainability assessment system (Master dissertation). Tsinghua University, Beijing (in Chinese).

Wang, S., 2009. Research on the EIA of ready-mixed concrete during the life cycle (Master dissertation). Tsinghua University, Beijing (in Chinese).

Wang, Y., Nie, J.G., Fan, J., 2013, Theoretical model and investigation of concrete filled steel tube columns under axial force--torsion combined action. *Thin Wall Struct* 69, 1-9.

Wardenier, J., Met Staal, B., 2002, Hollow sections in structural applications, *Bouwen met Staal* Rotterdam, The Netherlands.

Wu, D.A., 2002, Concrete structure calculation manual, China Architecture & Building Press, Beijing (in Chinese).

Wu, X., 2005. Research on the environmental performance assessment system of buildings and its application (Master dissertation). Tsinghua University, Beijing (in Chinese).

Yang, Y., Han, L., 2009, Experiments on rectangular concrete-filled steel tubes loaded axially on a partially stressed cross-sectional area. *J Constr Steel Res* 65, 1617-1630.

Yang, Y., Han, L., 2011, Behaviour of concrete filled steel tubular (CFST) stub columns under eccentric partial compression. *Thin Wall Struct* 49, 379-395.

Yang, Y., Hou, C., Wen, Z., Han, L., 2014, Experimental behaviour of square CFST under local bearing forces. *Thin Wall Struct* 74, 166-183.

Yu, M., Zha, X., Ye, J., She, C., 2010, A unified formulation for hollow and solid concrete-filled steel tube columns under axial compression. *Eng Struct* 32, 1046-1053.

Zhang, X., Wang, F., 2015, Life-cycle assessment and control measures for carbon emissions of typical buildings in China. *Build Environ* 86, 89-97.

Zhang, Y., He, C., Tang, B., Wei, Y., 2015, China's energy consumption in the building sector: A life cycle approach. *Energy Build* 94, 240-251.

Zhang, Z., Wu, X., Yang, X., Zhu, Y., 2006, BEPAS—a life cycle building environmental performance assessment model. *Build Environ* 41, 669-675.

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Table 1

Information of the sampled concrete columns

Concrete type	Cross-section type	Concrete grade	Steel type	t/D	ρ	Abbreviation
CFST	Circular	C50	Q345	0.028	/	CFSTc
CFST	Rectangular (H/B=1.5)	C50	Q345	0.028	/	CFSTr
CFST	Square	C50	Q345	0.028	/	CFSTs
RC	Circular	C50	HRB400	/	1%	RCc
RC	Rectangular (H/B=1.5)	C50	HRB400	/	1%	RCr
RC	Square	C50	HRB400	/	1%	RCs

Table 2

Comparison of the compression-bending capacity performance in three periods

Period	Performance
A	CFSTc > CFSTr > CFSTs
B	CFSTr > CFSTc, CFSTs
C	CFSTr > CFSTc > CFSTs

Table 3

Comparison of the compression-bending capacity performance in different periods

Period	Performance
D	CFSTc > CFSTr > CFSTs > RCr > RCs > RCc
E	CFSTc > CFSTr > RCr > CFSTs > RCs > RCc
F, G, H	CFSTr > RCr, CFSTc, CFSTs
I	CFSTr > RCr, CFSTc
J	CFSTr > RCr

Table 4

EIVs of the impact categories of six concrete columns

Category	CFSTc	CFSTr	CFSTs	RCc	RCr	RCs
Ecological damage	35.17	38.31	40.10	51.92	43.95	47.40
Global warming	12.67	13.80	14.45	34.47	29.18	31.49
Eutrophication	1.57	1.70	1.78	2.32	1.97	2.12
Acidification	1.26	1.37	1.44	2.11	1.79	1.93
Airborne suspended particles	0.48	0.53	0.55	0.98	0.83	0.89
Solid waste	18.78	20.46	21.42	8.10	6.86	7.37
Photochemical smog	0.41	0.45	0.47	0.47	0.40	0.43
Waterborne suspended substances	0	0	0	3.46	2.93	3.17
Resource depletion	9.09	9.92	10.36	7.76	6.57	7.07
Water resource depletion	4.67	5.10	5.33	3.92	3.32	3.57
Fossil energy resource depletion	1.04	1.13	1.18	1.00	0.85	0.91
Other resource depletion	3.38	3.69	3.85	2.84	2.40	2.59
Total	44.25	48.23	50.47	59.67	50.52	54.47