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# Optimal lateral stiffness design of composite steel and concrete tall frameworks

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ABSTRACT

This paper presents the optimal lateral stiffness design of composite steel and concrete tall frameworks subject to overall and interstorey drift constraints as well as member sizing limits using an efficient numerical approach developed based on the Optimality Criteria (OC) method. Taking into account the composite interaction between the structural steel and concrete materials, the stiffness-based optimal design problem is first formulated according to the European Code 4 (EC4). The necessary optimality criteria are then derived for the design followed by the construction of an iterative scheme to satisfy these optimality conditions while indirectly optimizing the design problem with multiple constraints. The recursive OC process is then carried out with the initial member sizes obtained from a closed-form solution developed for the similar problem with a single drift constraint. The effectiveness and practicality of the developed optimization approach is further illustrated through a series of framework examples.

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## 1. Introduction

Progress in the modern design and construction of high-rise composite frame construction has been very dramatic since its first introduction in the United States in the late 1960's [1,2]. The type of composite framing system, as shown in Fig. 1, consisting of steel beams acting interactively with metal deck-concrete slab and concrete encased composite columns, has been as a viable alternative to the conventional steel or reinforced concrete system in the high-rise construction. Such a system has the desired characteristics including high strength and stiffness, good ductility and fire resistance, and promising cost effectiveness for a wide range of building heights under various design conditions.

During the design of high-rise buildings, the control of the lateral deflection due to wind or seismic loads has been of prime importance in order to prevent both structural and non-structural damages. The design of the structural members in such a system is thus not governed by the strength criteria in the member, but rather and more dominantly, by serviceability lateral stiffness criteria of the structure expressed in terms of the maximum lateral displacement and interstorey drift limits. Violations of strength requirement are often found in very few members, i.e., only a relatively small number of strength constraints is critical to a whole structural design. Moreover, the sizing of structural members in a tall framework to satisfy the system level serviceability limit is more difficult to achieve when compared with the local strength criteria. Considering such strength criteria simultaneously during the OC-based stiffness optimization process is still possible except that it will significantly increase the size of this already highly-nonlinear problem and the solution-solving process might be very time-consuming and less efficient. These strength criteria are not considered in the current study. However, one possible way to handle this problem is to carry out the element strength design process first and then take resulting member sizes as the lower-size bounds on the design variables for the current optimization cycle [3]. In most building codes, these lateral serviceability (drift) criteria are commonly specified or recommended as the ratio of the building overall or storey height, for example, 1/400.

Composite steel and concrete construction is well known for its efficient utilization of most desirable attributes of both materials, i.e., the economy, high rigidity and fireproofing of concrete combined with the lightness, spannability and the speed of construction of structural steel. However, in order to distribute the materials efficiently within a framework building while satisfying the lateral stiffness criteria, the traditional "trial-and-error" design approach is generally inevitable. The analysis-design loop is typically repeated until all the design performance criteria are met and the economical requirements are satisfied. Notwithstanding, this approach would not necessarily provide the optimal solution to the design, and it is oftentimes rather time-consuming due to its nature of the "trial-and-error" based manual design process.

Structural optimization, on the other hand, provides a numerical tool that can replace the traditional "trial-and-error" design ap-

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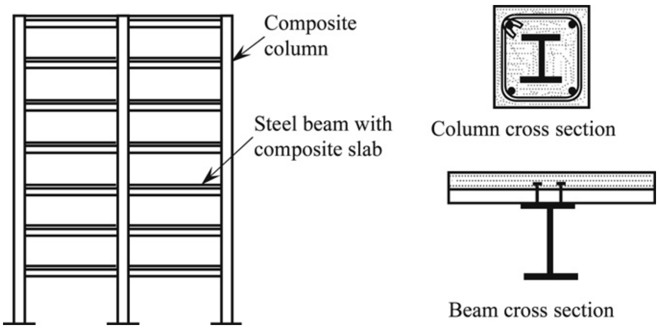


**Fig. 1.** Type of composite building framework under study.

proach with a systematic and automated design process. For practical structural application purposes, Mathematical Programming (MP) and Optimality Criteria (OC) method have been two major viable approaches to structural optimization problems [4]. The MP method aims at obtaining information from conditions around the current design point in design space, going from point to point to best reduce the weight or cost directly. Although general, the efficiency of this method highly depends on the number of design variables. The OC method, on the other hand, heuristically derives conditions that characterize the optimum design, and changes the design to satisfy those conditions while indirectly optimizing the structure. It tends to be insensitive to the number of design variables, thus significantly reducing iterations required for convergence to an optimum design [5,6]. Although this Optimality Criteria technique is quite efficient for the member sizing design of practical tall frameworks [6,3,7], their applications are still limited to structures consisting of pure steel, pure concrete and mixed steel and concrete members [8–11]. To date, very little work has been done on the optimal design of composite steel and concrete tall frameworks constructed from the systems similar to the one shown in Fig. 1 with the composite interaction between the two materials in structural members fully accounted for.

In this paper, an automatic resizing approach for the minimum cost design of composite steel and concrete tall frameworks subject to top and interstorey drift as well as fabrication sizing constraints is presented. The design optimization problem is first defined in an explicit formula using the effective sectional properties of structural members based on the Eurocode 4 [12,13]. Under the consideration of composite interaction between structural steel and concrete, the formulation yields to a highly nonlinear mathematical model in terms of member sizing design variables. The rigorously derived Optimality Criteria method is then employed to determine the optimal solution. A closed-form solution is exploited for a similar single-constraint optimization problem, which is used as the initial pre-processor for the iterative OC process of the multiple-constraint optimization problem in the study. Several multi-storey framework examples are presented to illustrate the effectiveness and practicality of the developed optimal design approach.

## 2. Explicit design problem

The formulation of a structural design problem is of first crucial importance for the success of the optimal design synthesis. For a skeletal composite framework with the predefined topology as shown in Fig. 1, the basic sizing variables include the cross-sectional area of both the steel beams ($A_{aB}$) and columns ($A_{aC}$), the thickness of the concrete slabs ($h_c$), the width ($B$) and the depth ($D$) of the column sections. The design optimization problem is usually associates with a set of design constraints related to lateral stiffness in terms of lateral displacement and interstorey drifts. For a general composite framework having $M$ storeys and $N$ structural members ($N = N_B + N_C$, where $N_B$ and $N_C$ are the numbers of composite beams and columns, respectively), the drift constraints defined by drift ratio $d$ can be expressed as

$$\begin{cases} \text{for interstorey drift, } d_j = \left(\delta_j - \delta_{j-1}\right)/h_j \le d_j^U, \\ \quad (j = 1, 2, \ldots, M) \qquad \text{(a)} \\ \text{for top deflection, } d_M = \delta_M/H \le d_M^U \qquad \text{(b)} \end{cases} \tag{1}$$

in which $\delta_j$ and $\delta_{j-1}$ are the lateral displacements at two adjacent storeys of $j$ and $j-1$ ($j = 1, 2, \ldots, M$); $h_j$ and $H$ are the height of the $j$th storey and the overall height of the building; $d_j^U$ and $d_M^U$ represent the allowable drift limit of the $j$th storey and the top of the building, respectively.

By utilizing the principle of virtual work, the displacement of interest $\delta$ in a building can be expressed as:

$$\delta = \sum_{i=1}^{N} \int_0^{l_i} \left( \frac{F_x f_x}{EA_x} + \frac{F_y f_y}{GA_y} + \frac{F_z f_z}{GA_z} + \frac{M_x m_x}{GI_x} + \frac{M_z m_z}{EI_z} + \frac{M_y m_y}{EI_y} \right)_i dx, \quad (i = 1, 2, \ldots, N) \tag{2}$$

where $l_i$= length of the member $i$; $E$ and $G$ = Young's modulus and shear modulus; $A_x, A_y$, and $A_z$ = axial and shear areas for the composite cross section; $I_x, I_z$, and $I_y$ = torsional and flexural moments of inertia for the composite cross section; $F_x, F_y, F_z, M_x, M_z$, and $M_y$ = member forces and moments due to the actual load; $f_x, f_y, f_z, m_x, m_z$, and $m_y$ = member forces and moments due to a unit virtual load applied at the location corresponding to $\delta$.

For the composite beams and columns, the effective sectional properties $A_x, A_y, A_z$ and $I_x, I_z, I_y$ need to be properly determined to fully take into account the interaction between the structural steel and concrete in the members. The report [14] carefully examines the currently available formulations in the literature on the effective stiffness design of composite beams and columns using elastic interaction theory (e.g., Newmark–Siess–Viest theory [15]) and code-based design recommendations (e.g., ACI, AISC–LRFD, European Code, etc.). According to these findings, the European model code (Eurocode 4, [13]) is found to provide more comprehensive procedures for strength and stiffness design of composite columns as well as beams when compared with the American Specifications (i.e., ACI, AISC-LRFD) and others (e.g., German Standards). In accordance with the EC 4, the effective sectional properties for composite beams can be determined as [13,16,17]:

$$A_x = A_a \left(b_{eff} h_c/n\right) / \left(b_{eff} h_c/n + A_{aB}\right), \quad A_y = A_{ay}, \quad A_z = A_{az} \tag{3a,b,c}$$

$$I_x = I_{ax}, \quad I_z = A_a \left(h_c + 2h_p + h\right)^2 /4\left[1 + nA_a/(b_{eff} h_c)\right] + b_{eff} h_c^3/(12n) + I_{az}, \quad I_y = I_{ay}. \tag{3d,e,f}$$

The effective sectional properties for concrete encased composite columns can be obtained as

$$A_x = A_a + (BD - A_a)/n, \quad A_y = A_{ay}, \quad A_z = A_{az} \tag{4a,b,c}$$

$$I_x = k_1 B^3 D/n + (1 - 1/n) I_{ax}, \quad I_z = (1 - 0.8/n) I_{az} + BD^3/(15n), \quad I_y = (1 - 0.8/n) I_{ay} + B^3 D/(15n), \tag{4d,e,f}$$

where $A_a$, $A_{ay}$, and $A_{az}$ = axial and shear areas for standard steel section; $I_{ax}$, $I_{az}$, and $I_{ay}$ = torsional and flexural moments of inertia for standard steel section; $n = E_a/E_c$; $h_p$ = height of the metal deck profile; $b_{eff}$ = effective breadth of the concrete slab (equal to