Optimal Compensation of Axial Shortening in Tall Buildings by Differential Evolution

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1 Introduction

In tall buildings, large axial shortenings occur in vertical elements like columns and walls since these elements carry huge vertical loads from many floors [4]. The amount of axial shortenings among the members is usually not the same because of the difference in stress levels and other aspects such as reinforcement ratios and volume-surface ratios. The difference in axial shortening of vertical members can result in redistribution of loads between vertical members and additional forces in horizontal elements. Besides effecting on structural elements, differential axial shortenings can also cause damages in nonstructural elements such as the interior partitions, cladding systems, and plumbing systems. Therefore, differential axial shortening is of primary concern in the structural design of tall buildings [1, 3].

To avoid negative effects on structural and nonstructural elements of the building, differential axial shortenings of vertical elements should be minimized. In the design stage, this can be carried out by achieving uniformity of compressive stress within vertical elements, increasing the stiffness of horizontal members [6], and increasing axial stiffness of vertical elements anticipated to be subjected to large magnitude of shortening (e.g. by means of providing additional reinforcement) [5]. Nevertheless, such approaches in the design stage may not guarantee that differential axial shortening can be fully controlled due to many other design aspects to be considered. An effective means for reducing differential shortening is to compensate for the change in lengths of the vertical elements at the construction stage. For example, during the construction of columns, the concrete can be 'overcast' to accommodate the anticipated axial shortening. In this approach, floors are often grouped and an

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equal compensation amount will be applied for every floor in a group [7–9, 11]. By restricting the errors between the calculated differential shortening and the compensation amount, the differential shortening can be controlled [9–11]. In practice, the number of lumped groups should be minimized for the sake of simplification of the compensation task.

In this study, the moving-optimal compensation method (MOC) is established to determine the optimal number of lumped groups as well as the optimal correction amounts for the compensation of differential axial shortening of the vertical elements in tall buildings. Instead of solving the optimization problem as a whole, which may be very costly, the current method successively solves a sequence of smaller optimization problems by a differential evolution algorithm. The method is examined for the compensation of the differential shortening of vertical elements in a 70-story building. The efficiency of MOC is compared with those of two other methods, including the optimal compensation technique (OC) [9] and the moving average correction technique (MAC) [11].

2 Compensation Strategy

2.1 Formulation of Moving Optimal Compensation

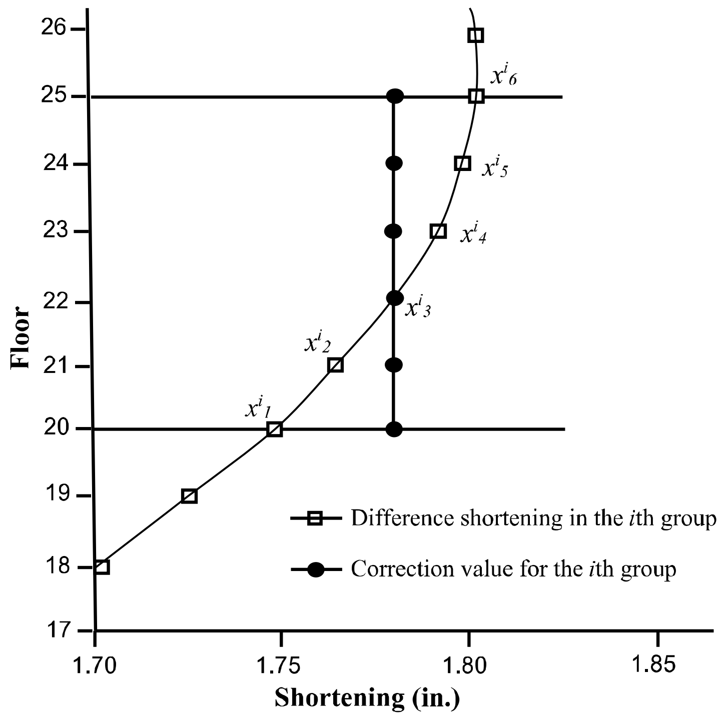
The moving optimal compensation method (MOC) in this study has a strategy similar to that of the MAC method proposed by Parket al. [11]. The floors are divided into groups with an equal correction amount for every floor in a group as described in Fig. 1. In Fig. 1, x_j^i is the calculated shortening of a vertical element of the jth floor in ith group.

To simplify the compensation or the construction process in practice, the number of lumped groups should be minimized. This can be achieved by maximizing the number of floors, N_i, in each group. On the other hand, there will be errors between the compensation amounts and the prediction amounts. The correction amount, δ_i, used for the ith group, therefore, should be chosen such that the cumulative error between the predicted differential shortening and the correction amounts is minimum. Thus, the objective function for the optimal compensation of the ith group is formulated in the following form:

$$\text{Minimize } f(N_i, \delta_i) = -N_i + w \times \left| \sum_{k=1}^{i-1} \varepsilon_k + \sum_{j=1}^{N_i} \left(x_j^i - \delta_i \right) \right| \tag{1}$$

where w, $(w \geq 1)$ is a weighted factor; ε_k is the cumulative error between the compensation amount and the predicted differential shortening in the kth group

Fig. 1 Concept of the moving average correction method [11]



$$\varepsilon_k = \sum_{j=1}^{N_k} \left(x_j^k - \delta_k \right), k = 1, \ldots, i - 1 \tag{2}$$

To control the slab tilt caused by the axial shortenings, an allowable error value, θ_i, is introduced [9]. Moreover, the cumulative error is limited to a tolerance, ϵ_i. These constraints are written in the following forms [11]:

$$\left| x_j^i - \delta_i \right| \leq \theta_i \tag{3}$$

$$\left| \sum_{k=1}^{i-1} \varepsilon_k + \sum_{l=1}^{j} \left(x_l^i - \delta_i \right) \right| \leq \epsilon_i \tag{4}$$

The optimal number of floors, N_i, together with the correction amount δ_i for the ith group is determined by solving the above constrained optimization problem. The steps of the moving optimal compensation method are as followings:

1. Predict the differential shortenings of vertical elements and set the tolerances for the compensation errors, θ_i and ϵ_i.
2. Solve the optimization problem described in Eq. 1 with the constraints in Eq. 3 and Eq. 4 to obtain the optimal number of floors, N_i, and the optimal correction amounts, δ_i, for the ith group.
3. Set $i = i + 1$, and move to the next group.

The optimal compensation solutions are found by using differential evolution (DE) [12]. DE is simple, easy to use and applicable for different optimization problems. The basics of DE are described in the following.

2.2 Differential Evolution

DE utilizes a population of N_P candidate vectors of the design variables, $\mathbf{a}_k, k = 1, \ldots, N_P$ (individuals), and an individual is defined as $\mathbf{a}_k, = a_{k1}, a_{k2}, \ldots, a_{kD}$, where $\mathbf{a}_{ki}, i = 1, \ldots, D$ are D design variables.

Initially, a population is randomly sampled from the solution space. For each individual $\mathbf{a}_k$ (named the target vector) of the current population, a trial vector $\mathbf{c}_k$ is generated by the 'mutation' and 'crossover' operators as follows.

Mutation: A mutant vector $\mathbf{b}_\mathrm{k}$ is first created as:

$$\mathbf{b}_k = \mathbf{a}_{r1} + F \times (\mathbf{a}_{r2} - \mathbf{a}_{r3}) \tag{5}$$

where $\mathbf{a}_{r1}$, $\mathbf{a}_{r2}$ and $\mathbf{a}_{r3}$ are different individuals randomly chosen from the population;F is a scaling factor chosen in the interval [0, 1].

Crossover: the mutant vector is then exchanged with the target vector $\mathbf{a}_k$, producing the trial vector $\mathbf{c}_k$ as:

$$c_{ki} = \begin{cases} b_{ki} & \text{if } (\text{rand}[0, 1] \leq C_r) \text{or} r = i \\ a_{ki} & \text{otherwise} \end{cases} \tag{6}$$

where r is a randomly chosen integer in the interval $[1, D]$; C_r is the crossover parameter given in the interval [0,1].

Then, the trial vector $\mathbf{c}_k$ is compared with the target vector $\mathbf{a}_k$ and the better one will survive in the next generation. The evolution stops when a termination criterion is satisfied.

2.3 Handling Constraints and Comparison of Solutions

The considered optimization problem has inequality constraints, which can be expressed in the form

$$c_j(\mathbf{a}_k) \leq 0, j = 1, \ldots, n_C \tag{7}$$

where n_C is the number of constraints and $c_j(\mathbf{a}_k)$ is the jth constraint function. The constraint violation of an individual $\mathbf{a}_k$ is given by

$$C_k = \max\left\{\max_j\{0, c_j(\mathbf{a}_k)\}\right\}, j = 1, \ldots, n_C \tag{8}$$

Deb's rules [2] are applied in this constrained optimization problem to compare two individuals. Deb's constraint rules are described as:

1. A feasible individual is better than any infeasible one.
2. Of two feasible individuals or two individuals with equal constraint violations, the smaller objective function value is the better.
3. Of two infeasible individuals, the smaller constraint violation is the better.

3 Illustration Example

In this section, a 70-story building [4] is considered to demonstrate the performance of the moving-optimal compensation method. Figure 2 shows the typical floor plan of the building. The differential shortening between the interior wall and the exterior column given in references [9, 11] is used as input data. The shortening of columns and walls includes both elastic and inelastic (creep and shrinkage) shortenings. The performance of the proposed method is compared with those of two other methods, the OC using simulated annealing (SA) [9] and the MAC method [11].

For the comparison, in the MOC method, the tolerance of 0.4 in is also given for both the compensation error and the cumulative correction error. Figure 3 depicts the compensation curves of the considered methods. The correction values for each group from the three methods are given in Table 1. The compensation error curves are depicted in Fig. 4 and the cumulative compensation error curves are shown in Fig. 5. It is seen from these results that the differential shortening values at every floor are controlled within the 0.4 in. limit. Considering the maximum accumulated compensation error, the OC using SA results in 1.07 in. on the 47th floor, whereas,

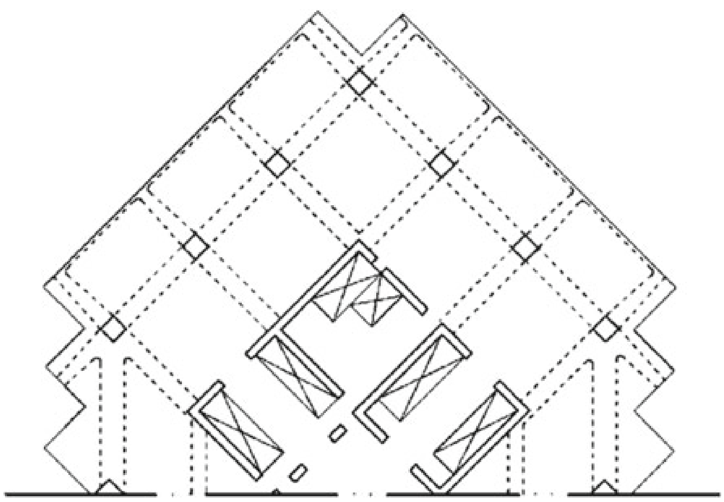


Fig. 2 Typical layout of the 70-storey building [4]

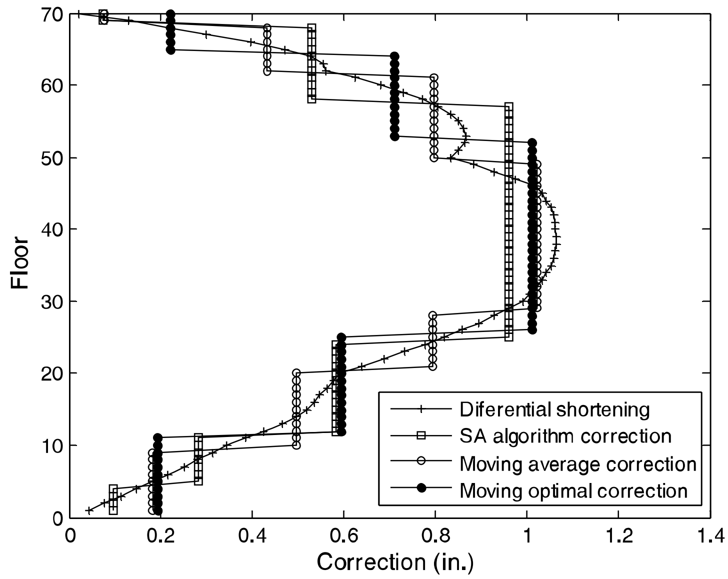


Fig. 3 Comparison of compensation curves from different correction methods for a 70-story building

Table 1 Comparison of compensation solutions of different methods

OC with SA			MAC			MOC		
Group	Floor	Correction (in.)	Group	Floor	Correction (in.)	Group	Floor	Correction (in.)
1	1–4	0.096	1	1–9	0.182	1	1–11	0.192
2	5–11	0.282	2	10–20	0.496	2	12–25	0.596
3	12–24	0.582	3	21–28	0.794	3	26–52	1.012
4	25–57	0.962	4	29–49	1.023	4	53–64	0.712
5	58–68	0.530	5	50–61	0.798	5	65–70	0.221
6	69–70	0.075	6	62–68	0.433	–	–	–
–	–	–	7	69–70	0.076	–	–	–

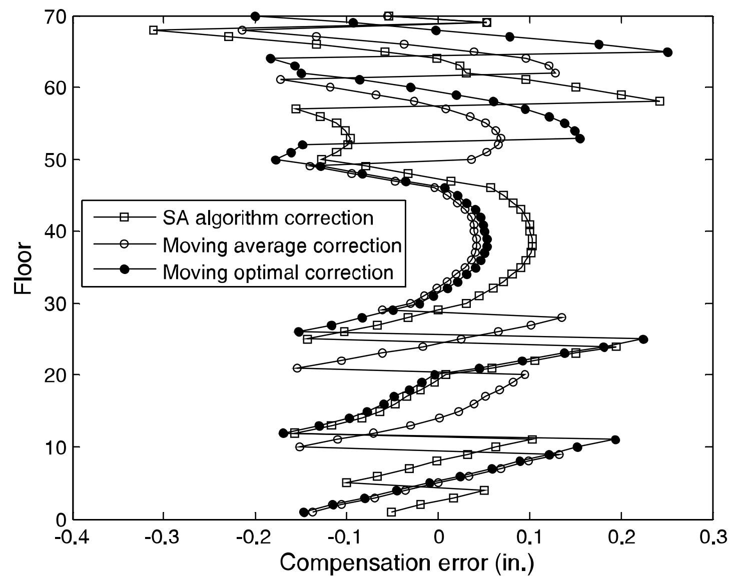


Fig. 4 Compensation errors from different correction methods for a 70-story building

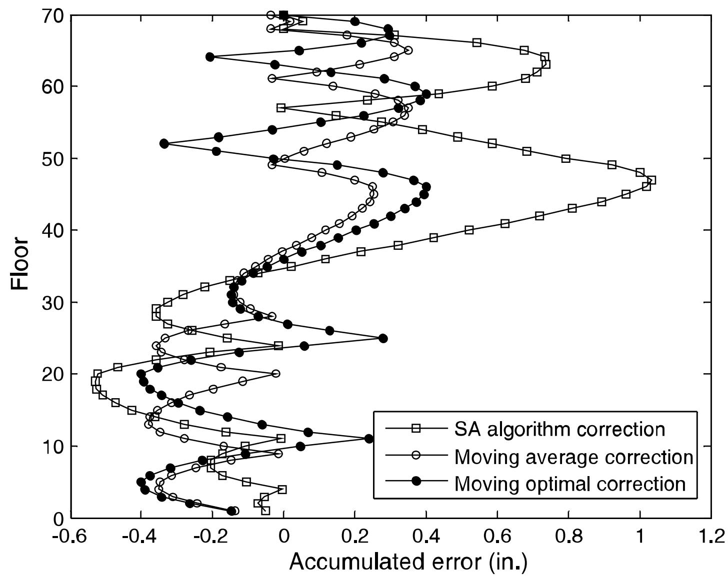


Fig. 5 Accumulated compensation errors from different correction methods for a 70-story building

the MOC method gives 0.4 in. at the 46th and 59th floors, which is similar to the MAC does (0.38 in. on the 65th floor).

The advantage of the MOC method is that it can give a smaller number of lumped groups in comparison with the OC using SA and the MAC methods. For this example, the number of lumped groups of the MOC method is five, whereas those of the OC using SA and the MAC method are six and seven, respectively. Another benefit of the proposed method is the low computational cost to produce the optimal solution since, in the moving optimization compensation, the optimization problem is performed in a sequence of small optimization problems with only two variables.

4 Conclusion

The moving optimal compensation method (MOC) for controlling the differential shortening of the vertical members in tall buildings is presented in this paper. Different from the existing methods, the proposed method determines the optimal compensation solution including the number of floor groups, the number of floors in each group and the average correction amount for each floor by solving a sequence of small optimization problems. The classical differential evolution algorithm is utilized as the optimizer. The MOC method is examined with a 70-story building example and its performance is compared with those of two existing methods previously reported in the literature. It is demonstrated that a smaller number of compensation groups can be found by the proposed method. By using the MOC method, the optimal solution for the compensation purpose can be derived systematically with low computational cost.

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