**Structural Engineering and Mechanics**, *Vol. 63, No. 1 (2017) 77-88*
DOI: https://doi.org/10.12989/sem.2017.63.1.077


# Simplified sequential construction analysis of buildings with the new proposed method

Mohammad Jalilzadeh Afshari*, Ali Kheyroddin[a] and Majid Gholhaki[b]

*Faculty of Civil Engineering, Semnan University, Semnan, Iran*

*(Received July 7, 2016, Revised May 8, 2017, Accepted May 18, 2017)*

**Abstract.** Correction Factor Method (CFM) is one of the earliest methods for simulating the actual behavior of structure according to construction sequences and practical implementation steps of the construction process which corrects the results of the conventional analysis just by the application of correction factors. The most important advantages of CFM are the simplicity and time-efficiency of the computations in estimating the final modified forces of the beams. However, considerable inaccuracy in evaluating the internal forces of the other structural members obtained by the moment equilibrium equation in the connection joints is the biggest disadvantage of the method. This paper proposes a novel method to eliminate the aforementioned defect of CFM by using the column shortening correction factors of the CFM to modify the axial stiffness of columns. In this method, the effects of construction sequences are considered by performing a single step analysis which is more time-efficient when compared to the staged analysis especially in tall buildings with higher number of elements. In order to validate the proposed method, three structures with different properties are chosen and their behaviors are investigated by application of all four methods of: conventional one-step analysis, sequential construction analysis (SCA), CFM, and currently proposed method.

**Keywords:** sequential construction analysis (SCA) or staged analysis; conventional one-step analysis; differential column shortening; correction factor method (CFM); modified CFM; construction sequence

## 1. Introduction

Nowadays, in common structure analyses, the dead and live loads of all floors are applied instantaneously. In fact, it is assumed that the structure does not bear any load before the end of construction. This assumption could be valid for lateral loads or the dead loads of subsequently installed components, but it is unsuitable for the dead loads of the structural members and floors because these types of loads are gradually applied to the previously constructed members during the progress of construction which depends on technology and the planning of construction (Esmaili 2008, Chen *et al.* 2006). The deformations of the lower stories are already taken place under the self weight of their floors even before the upper floors are built. Therefore, in each stage of construction, the newly built members are installed on the previously deformed members of the structure. Thus, if it is assumed that each story is built in a particular stage of construction, then final deformation of structure is the cumulative outcome of deformations in construction of each story until the completion of the final stage of construction.

Besides, Structural members are added in stages as the construction of a building proceeds and hence their dead load is carried by the part of the structure completed at the stage of their installation. Therefore, it is clear that the distribution of displacements and stresses in the constructed part of the structure at any stage does not depend on the sizes, properties, or the presence of members composing the remainder of the structure (Kwak and Kim 2006). The correct distribution of the displacements and stresses of any member can be obtained by accumulating the results of analysis of each stage. Ignoring this fact and redistribution of stress caused by cumulative column shortenings in conventional one-step analysis where the construction sequences are neglected may lead to seriously incorrect analysis results, particularly at the upper floors of the multistory buildings and may cause unexpected damages on structural and nonstructural members (Esmaili *et al.* 2007, Park *et al.* 2013). On the other hand, it is known by research and experiment that concrete structures are subjected to larger displacements and stresses because of long term behavior and time dependent parameters of concrete such as creep and shrinkage. This brings about the increase in beam deflections, expansion of tensile cracks in members, excessive column shortenings (Kim *et al.* 2012a, Kim 2015), differential displacements of horizontal structural members such as beams (Kim 2013), caused by unequal and increasing axial displacements of adjacent frame members (Vafai *et al.* 2009, Njomo and Ozay 2014) and considerable redistribution of stress in structure. All these outcomes, directly or indirectly affecting on structure's response, must be considered by applying the loads according to the

*Corresponding author, Ph.D. Candidate
E-mail: jalilzadeh.afshari@semnan.ac.ir
[a]Professor
E-mail: kheyroddin@semnan.ac.ir
[b]Associate Professor
E-mail: mgholhaki@semnan.ac.ir


http://www.techno-press.com/journals/sem&subpage=7
ISSN: 1225-4568 (Print), 1598-6217 (Online)

sequences of construction and using the staged analysis in multistory buildings.

This research aims to modify the axial stiffness of the columns by using the correction coefficients of CFM and introduce an innovative method, named Modified CFM, to consider the effects of construction sequences in a single step analysis rather than time-consuming staged analysis. To do so, it is essential to study the literature and different methods of considering the construction sequences in analysis. Two most important techniques for this purpose are the active floor analysis and correction factor method (CFM) which are described in the following sections.

## 2. Literature review

### *2.1 Sequential construction analysis by using the concept of active floor*

One of the most important defects of conventional analysis, which highly affects its results and wastes the structural capacity of the building, is its inability to consider the real differential column shortening factor accurately. The exterior columns are designed for gravity loads approximately half as much as interior columns, but their cross sections become comparable after design process because the exterior columns need to resist the turnover moments caused by lateral loads. Therefore, there is a considerable difference between the ratios of gravity loads to cross section areas of the two groups of columns. Consequently, the column shortenings become different, and this generates shear forces and bending moments in members connecting these two groups of columns together. In conventional analysis, the largest cumulative differential column shortenings exist in upper stories of the building and, therefore, the largest induced bending moments and shear forces are developed in the beams connecting the two adjacent columns in those stories.

However, in construction operations, especially in concrete structures, since each floor is leveled at the time of its construction, the deformations occurred in the frame below, before the construction of the floor, are insignificant. Hence, the columns shortenings and induced shears and moments generated in related beams are, in fact, much smaller than the outcomes of the conventional one step analysis (Choi and Kim 1985). In general and in every structural system, the value of column shortening increases by elevation in one-step analysis. In staged analysis and progressive loading, however, its increasing trend slows down in higher levels, and it reaches its peak in middle stories. Eventually, it starts a decreasing trend and reaches a value at the top of building which is much lower than the result of conventional one-step analysis as shown in Fig. 1 (Choi and Kim 1985). In fact, with sequential loading, the vertical displacement on top story is derived from the displacements related to the loading of the same story solely.

The concept of active floor analysis is based on the definitions of active floor, inactive floor and deactivated floors, with a procedure in the reverse order of real construction sequence which moves from top down to the bottom of the building. In this method, when *r*th floor is analyzed, it is subjected to the gravity loads of the same floor plus the gravity forces of columns of the (*r*+1)th floor resulted from the previous stage of analysis. When the deflections of *r*th floor and the internal forces of its members are found, they would be used in the next stage of analysis. In each stage of analysis, the inactive floors are assumed weightless and their time-dependent deflections are neglected. In fact, the inactive floors have the role of elastic supports for the *r*th floor in its analysis. These assumptions about inactive floors, which are obviously constructed before *r*th floor, are made to establish a story by story structural modeling system which considers the sequential construction analysis in the structure design as shown in Fig. 2 (Choi and Kim 1985).

As an example, the last story of structure, the *n*th floor, is assumed active at the start of the procedure. Since there is no other story above, it deflects only under its own weight, and the rest of structure is considered as inactive floors.

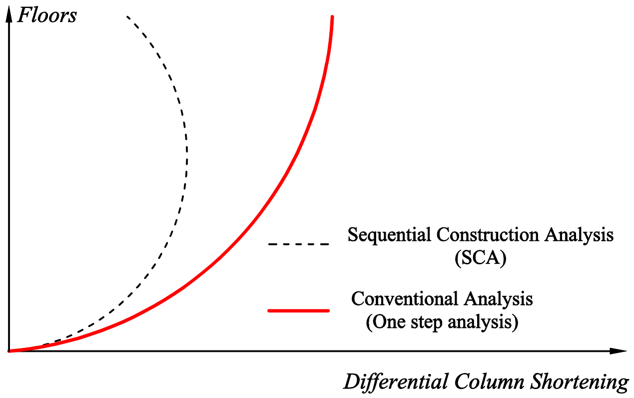



Fig. 1 Comparison of conventional one step analysis and staged analysis (Choi and Kim 1985)

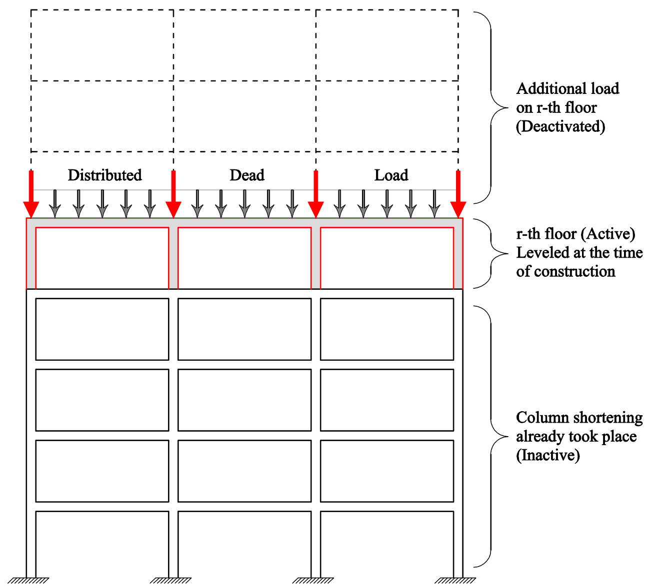
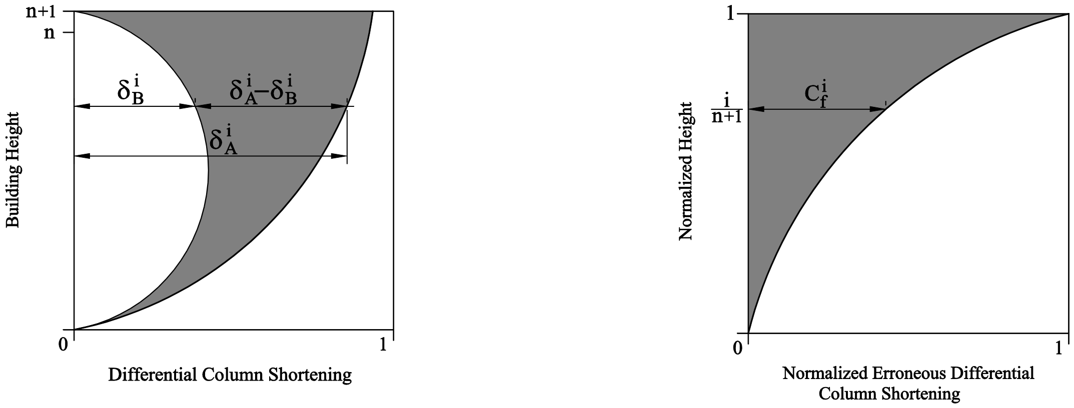
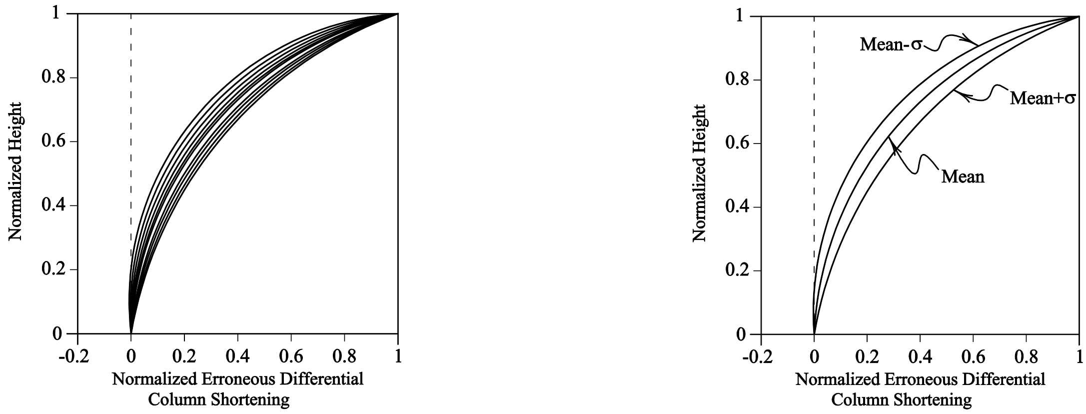



Fig. 2 Modeling for typical floor analysis (Choi and Kim 1985)




(a) Erroneous differential column shortening (b) Correction factor for *i*th floor

Fig. 3 Calculation of correction factor for normalized curves (Choi *et al*. 1992)




(a) Assembled normalized curves (b) Mean and Mean±σ curves

Fig. 4 Regression of Erroneous Differential Column Shortening (Choi *et al.* 1992)

After analysis and finding the deflections of the active floor, the internal forces of members are calculated, and the forces of columns are kept to be used in the next stage as the transferred loading from above floor. Then, the (*n*-1)th floor becomes active, and is analyzed under its own weight and the transferred axial column forces of the previous stage. This process continues until the first floor becomes active and is analyzed. The main equation for analysis of active floor is as Eq. (1)

$$K^r U^r = P^r \tag{1}$$

Where, $K^r = \sum_{m=1}^{r} K^m$ is the assembled stiffness matrix of the structure from first floor to *r*th floor, $P^r$ is loads vector consisting of the *r*th floor's weight and axial forces of the columns of the upper floor, and $U^r$ is the nodal displacement vector (Choi and Kim 1985). Obviously, for story by story analysis of an n-story structure, *n* stages of analysis is required which is time-consuming. To overcome this problem, sub-structuring technique could be of benefit (Kim *et al.* 2012b). In this process, a group of stories are assumed as active, instead of only one story. Thus, when analyzing the group of active floors, their weights are added to the axial forces of above columns as the reaction along the boundaries between the active group of floors and the above floor (Choi and Kim 1985).

### *2.2 Sequential Construction analysis by CFM*

The sequential application of dead load which corresponds to the nature of construction sequences, and differential column shortenings due to different tributary areas that exterior and interior columns support, are two essential factors in multistory structure design which are usually overlooked and therefore, are the cause for certain problems in structure analysis, especially in upper stories of the building. Choi and Kim (1985) are among those who focused on this matter and considered the stages of construction by introducing the concept of active floor in the analysis. Saffarini and Wilson (1983), without any knowledge of Choi and Kim's study, established a model to simulate the actual behavior and response of structures under the sequential gravity loads.

In their method, the stiffness matrix of the structure is regenerated in every stage according to progress of construction and addition of the new members, and the final level of stresses and displacements to account for in the design of a member that will be completely assembled at a certain stage is obtained by accumulating the effects of the weights added at that stage and at all subsequent stages. The two aforementioned methods, succeeded to consider the concept of construction sequences by utilizing the computing power of the modern computers. This progress was beneficial, but it required sophisticated engineers with deep knowledge of complex algorithms of programming. Correction factors method (CFM), which was developed by Choi, Chung, Lee and Wilson (1992), effectively considered the impact of construction stages in analysis by applying very simple correction factors to the analysis results, instead of complex and repeated analyses.

The correction factors can be obtained by the curve to be established statistically from the results of existing building analyses, whose basic concept is similar to the design response spectrum for seismic design. To develop the correction factor curve, several buildings with various properties in height and floor plan are analyzed by two different methods;

Method A: Analysis and design of structure by conventional one-step method.

Method B: The analysis of the structure considering the sequential application of dead loads such as the analysis by the method in Choi and Kim (1985).

By plotting the column shortenings along with the building heights for each method and then considering the difference of results, the normalized erroneous differential column shortening is obtained for every structure under study as presented in Fig. 3 (Choi *et al.* 1992). Then the normalized erroneous differential column shortening for each structure is plotted on one graph as shown in Fig. 4(a) so the mean curve and mean plus/minus the standard deviation curves could be obtained by statistical methods as in Fig. 4(b).

The correction factor for *i*th floor $(C_f^i)$ which is the ratio of erroneous differential column shortening of *i*th floor to that of the top floor, is obtained by Eq. (2)

$$C_f^i = \frac{(\delta_A^i - \delta_B^i)}{\delta_A^n} \tag{2}$$

Where $\delta$ is the differential column shortening; subscripts A and B indicate the type of analysis (conventional or staged); and subscripts $i$ and n indicate *i*th and *n*th floor respectively. Therefore, the erroneous differential column shortening caused by neglecting the construction stages for *i*th floor is calculated by multiplying its correction factor and the differential column shortening of the top floor obtained by method as shown in Eq. (3)

$$\delta_e^i = \delta_A^i - \delta_B^i \approx \delta_A^n \times C_f^i \tag{3}$$

Then, based on elastic theory, the amounts of correction for moment and shear forces of beams of *i*th floor are calculated using the Eqs. (4)-(5), respectively

$$M_c^i = \frac{6EI}{L^2(1+2\beta)} \times \delta_e^i \tag{4}$$

$$S_c^i = \frac{12EI}{L^3(1+2\beta)} \times \delta_e^i \tag{5}$$

Where $\beta = \frac{6EI}{L^2 AG}$, $L$ is beam length, $E$ is Young's modulus, $I$ is the moment of inertia, $A$ is the effective shear area and $G$ is shear modulus. The final amounts of moment and shear of the members, after considering the effect of construction stages, are calculated by subtracting the results of Eqs. (4)-(5) from the amounts obtained by conventional analysis as shown in Eqs. (6)-(7), respectively

$$M_f^i = M_0^i - M_c^i \tag{6}$$

$$S_f^i = S_0^i - S_c^i \tag{7}$$

Where $(M_f^i)$ and $(S_f^i)$ are final corrected moment and shear, respectively. $(M_0^i)$ and $(S_0^i)$ are the moment and shear obtained by method A analysis, respectively. The correction factor of *i*th floor could be obtained either graphically by using Fig. 4(b) or numerically by the equation obtained by regression for n-story building or by the Eq. (8)

$$C_f^i = \left(\frac{i}{n+1}\right)^{\alpha} \tag{8}$$

Where α is a variable related to structure's height. For structures of the mean curve, α is 2.8, and for those of (Mean+σ) and (Mean-σ) curves, α is 2.3 and 3.3 respectively. It should be noted that in the above classification, (Mean-σ) curve, Mean curve and (Mean+σ) curve belong to tall structures (over 31 stories), moderately tall structures (16 to 30 stories) and low-rise structures respectively. The principle advantage of this method, is that it does not rely on complex and time-consuming staged analyses, and the effect of construction stages is considered simply by applying the correction factors to the conventional, one-step analysis results.

## 3. Procedure description of the proposed method

As explained before about CFM, this method is able to correct the results of conventional one-step analysis by application of correction factors to consider the effects of construction stages on the forces of structural members. The final and corrected values of bending moments and shear forces of the beams, caused by column shortenings in construction stages, has an acceptable accuracy when obtained by this method according to elastic theory. However, the column forces obtained from the equilibrium of corrected moments in column-beam joints has considerable inaccuracy in higher stories of the structures, especially in presence of a bracing member in connection joint. The proposed method of the present study is developed to reduce or eliminate this inaccuracy by a process that derives the final results from the software rather than applying the correction factors afterwards manually. This method modifies the axial stiffness of the columns by using the column shortening correction factors of CFM (Eq. (8)), to reflect the construction sequence in the analysis.

Analyzing the structure with corrected axial stiffness of the columns helps the final forces of the members to be directly derived from software without the aforementioned error. Besides, the effects of construction stages are taken into account by application of correction factors of CFM in one sequence of analysis and hence it is concluded much faster than the staged analysis. On the other side, using the coefficients of CFM method in the present paper makes all the basic assumptions and the limitation of application of the proposed method identical to the CFM method. Story by story construction of structures is among the most basic assumptions of the mentioned methods. To explain this new method, named modified CFM, and introduce its parameters and properties, a column-based analysis is applied where the columns are modeled by equivalent springs as displayed in Fig. 5.

According to this figure, the total amount of shortening in a particular column at the top floor, regardless of the analysis method, is obtained by accumulation of axial deflections in all floors as shown in Eq. (9)

$$\delta^n = \sum_{i=1}^{n} \delta^i \tag{9}$$

Where $\delta^i$ is the column shortening (axial deflection of the column) of $i$th floor and is calculated by Eq. (10).

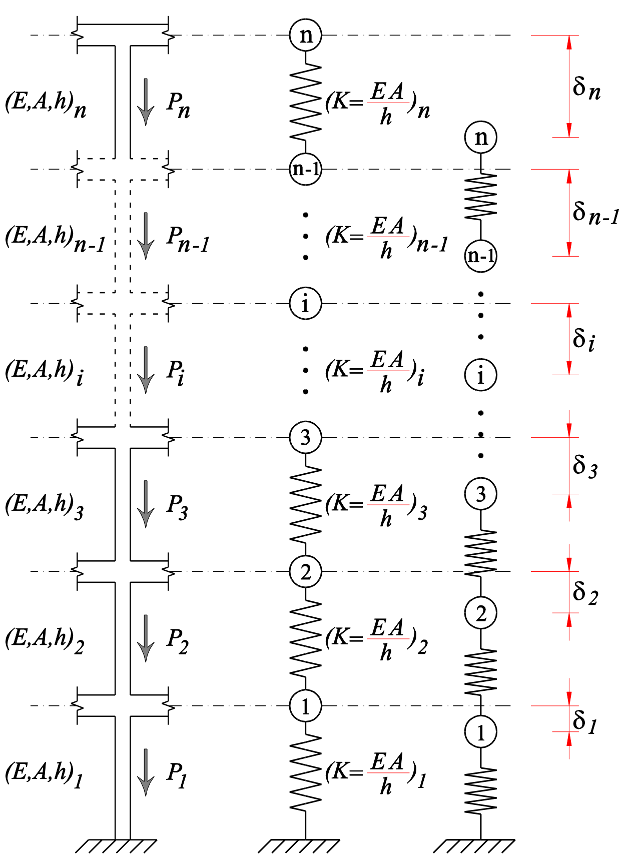



Fig. 5 Column shortening analysis by equivalent springs model

$$\delta^i = \frac{P^i}{K^i} \tag{10}$$

Where, $P^i$ is the axial force of the column and $K^i$ is the axial stiffness of the column of $i$th floor. $K^i$ is calculated using Eq. (11)

$$K^i = \left(\frac{E.A}{h}\right)_i \tag{11}$$

Where, $E$ is the modulus of elasticity of the column, $A$ is the column's cross section area, and $h$ is the column length of $i$th floor. On the other hand, considering Eq. (3), the actual column shortening obtained by staged analysis could be calculated by Eq. (12). The actual value of shortening in first floor's column obtained by staged analysis could be calculated according to Eq. (13) by putting the subscript value as 1

$$\delta_B^i = \delta_A^i - \delta_A^n \times C_f^i \tag{12}$$

$$\delta_B^1 = \delta_A^1 - \delta_A^n \times C_f^1 \tag{13}$$

By substituting $\delta^i$ from Eq. (10) in Eq. (13), as shown in Eq. (14), the stiffness of the column in staged analysis $(K_B^1)$ becomes a function of correction factors of CFM and unmodified axial stiffness of the column in conventional analysis (Eq. (15))

$$\frac{P_B^1}{K_B^1} = \frac{P_A^1}{K_A^1} - \delta_A^n \times C_f^1 \tag{14}$$

$$\Rightarrow K_B^1 = \frac{P_B^1 \times K_A^1}{P_A^1 - K_A^1.C_f^1.\delta_A^n} \tag{15}$$

It should be noted that in all equations of this study, superscripts determine the number of story, and subscripts indicate whether the parameter comes from the conventional one-step analysis or the staged analysis. By expanding Eq. (12) for column shortenings in 2nd and 3rd floors, the modified stiffness of the column related to the staged analysis in 2nd $(K_B^2)$ and 3rd $(K_B^3)$ floors would be obtained as shown in Eqs. (16) to (21)

$$\delta_B^2 = \delta_A^2 - \delta_A^n \times C_f^2 \tag{16}$$

$$\frac{P_B^1}{K_B^1} + \frac{P_B^2}{K_B^2} = \frac{P_A^1}{K_A^1} + \frac{P_A^2}{K_A^2} - \delta_A^n \times C_f^2 \tag{17}$$

$$\Rightarrow K_B^2 = \frac{P_B^2 \times K_A^2}{P_A^2 + K_A^2.(C_f^1 - C_f^2).\delta_A^n} \tag{18}$$

$$\delta_B^3 = \delta_A^3 - \delta_A^n \times C_f^3 \tag{19}$$

$$\frac{P_B^1}{K_B^1}+\frac{P_B^2}{K_B^2}+\frac{P_B^3}{K_B^3}=\frac{P_A^1}{K_A^1}+\frac{P_A^2}{K_A^2}+\frac{P_A^3}{K_A^3}-\delta_A^n\times C_f^3 \quad (20)$$

$$\Rightarrow K_B^3=\frac{P_B^3\times K_A^3}{P_A^3+K_A^3.(C_f^2-C_f^3).\,\delta_A^n} \quad (21)$$

By developing this process for all floors of the building, the final equation is established for calculation of the modified stiffness of the column in *i*th floor regarding the effect of construction stages as shown in Eq. (22)

$$K_B^i=\frac{P_B^i\times K_A^i}{P_A^i+K_A^i.(C_f^{i-1}-C_f^i).\,\delta_A^n} \quad (22)$$

If the axial forces of the columns in two methods of conventional and staged analysis are assumed to be equal $(P_A^i\approx P_B^i)$, then the final equation for modified axial stiffness of the columns due to staged analysis would be as Eq. (23)

$$K_B^i=\frac{P_A^i\times K_A^i}{P_A^i+K_A^i.(C_f^{i-1}-C_f^i).\,\delta_A^n} \quad (23)$$

After modifying the axial stiffness of all columns by Eq. (23), the effects of construction stages are included in the analysis, and the model is ready for one-step analysis. Therefore, all final forces of the members could be obtained directly from common analysis and design programs. For evaluation and verification of the proposed method, three structures are chosen as the numerical examples to be studied under 4 methods of conventional analysis, staged analysis, CFM and the proposed method. Finally, the proposed method is compared to the other methods from the aspect of processing speed.

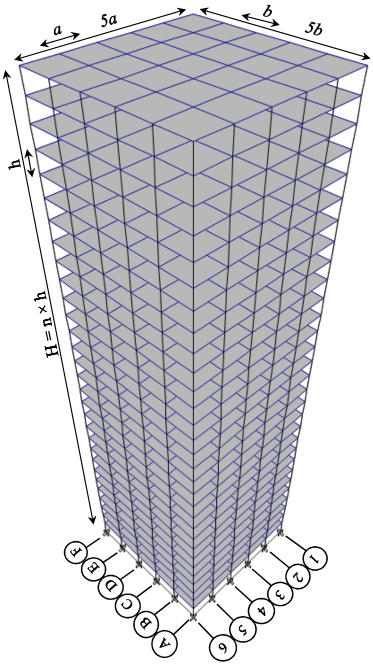



Fig. 6 Scheme of structure 1 and 2

## 4. Numerical examples

To evaluate the functionality of proposed method, three structures with different dimensions, materials and load resisting systems are considered. Structures 1, 2 and 3 are 30-story moment resisting steel frame, 20-story moment resisting concrete frame and 15-story concrete dual system of moment frame and shear walls in the form of central concrete core, respectively. The general properties of these 3 structures are presented in Table 1. The general and parametric layout of the structures 1 and 2 are displayed in

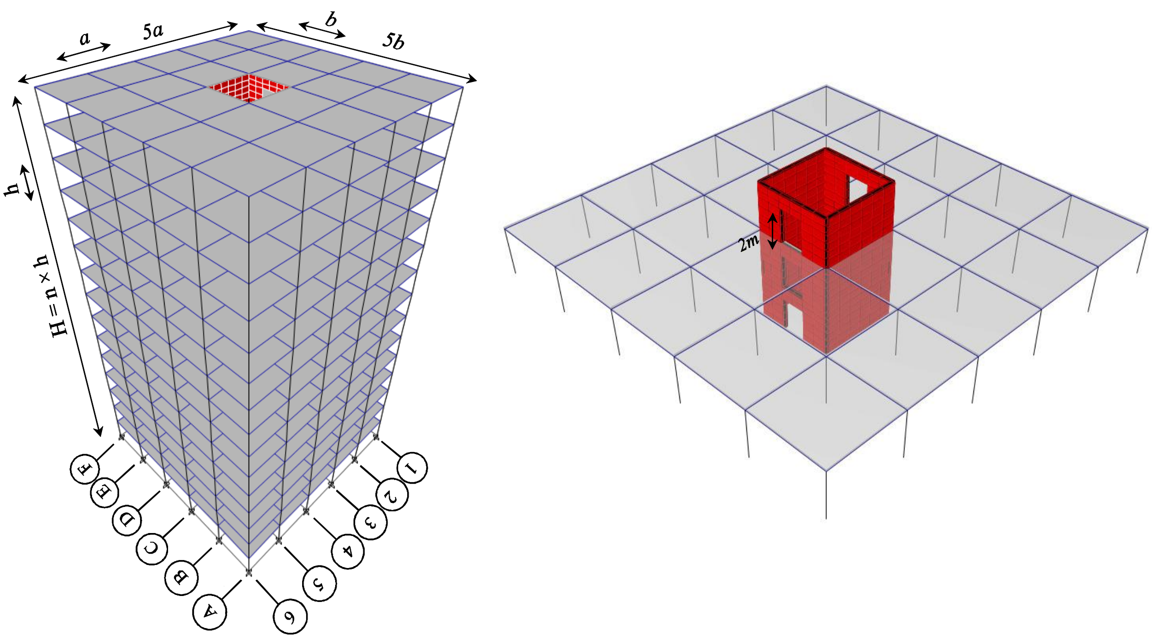



Fig. 7 Scheme and wall layout of structure 3

Fig. 6 and the cross section properties of their members are presented in Tables 2-3, respectively. The layout of shear walls and coupled shear walls forming the concrete core of structure 3 are displayed in Fig. 7 and its cross sectional properties are presented in Table 4. After an optimized design of each structure, the important criteria, such as member's forces and column shortenings, would be compared under 4 methods of conventional one-step analysis, staged analysis, CFM analysis and currently proposed modified CFM.

Table 1 Properties of studied structures

| Specification | Structure 1 | Structure 2 | Structure 3 |
|---|---|---|---|
| Structural system | Intermediate steel moment frame | Intermediate concrete moment frame | Concrete dual system with intermediate moment frame |
| Number of stories | 30 | 20 | 15 |
| Building height (H), *meter* | 108 | 72 | 54 |
| Story Height (h), *meter* | 3.6 | 3.6 | 3.6 |
| Bay length in each direction (a-b), *meter* | 6 | 6 | 6 |
| Number of bays in each direction | 5 | 5 | 5 |
| Young's Modulus (E), *GPa*- member | 25.3-slab | 25.3 | 25.3-frame, 35.4-wall |
| Compressive Strength ($f_c$), *MPa*- member | 25-slab | 25 | 25-frame, 55-wall |
| Floor system | Composite slab | concrete slab | concrete slab |
| Structure's fundamental period, *second* | 3.35 | 2.164 | 1.743 |

Table 2 Properties of members of structure 1

| Story | Beams (I Shaped) Dimension in mm | Columns (Box) Dimension in mm |
|---|---|---|
| 1 to 11 | PL 600×10 *web* + 2PL 240×20 *flange* | Box 600×600×60 |
| 12 to 16 | PL 600×10 *web* + 2PL 240×20 *flange* | Box 500×500×50 |
| 17 to 22 | PL 600×10 *web* + 2PL 240×20 *flange* | Box 500×500×40 |
| 23 to 30 | PL 600×10 *web* + 2PL 240×20 *flange* | Box 400×400×40 |

Table 3 Properties of members of structure 2

| Story | Beams Dimension (B×H), mm | Columns Dimension (B×H), mm | |
|---|---|---|---|
| 1, 2 | 500×600 | 1000×1000 | 28Φ32 |
| 3 to 6 | 500×600 | 900×900 | 24Φ28 |
| 7, 8 | 400×550 | 800×800 | 24Φ28 |
| 9 to 12 | 400×550 | 700×700 | 20Φ28 |
| 13, 14 | 400×550 | 600×600 | 20Φ25 |
| 15 , 16 | 400×400 | 600×600 | 20Φ25 |
| 17 to 20 | 400×400 | 500×500 | 16Φ25 |

Table 4 Properties of members of structure 3

| Story | Beams | Walls | | | Columns | |
|---|---|---|---|---|---|---|
| | B×H (mm) | $\rho_L$ (%) | $\rho_T$ (%) | Thickness (mm) | B×H (mm) | Longitudinal Reinforcement |
| 1, 2 | 400×350 | 1.84 | 1.5 | 500 | 700×700 | 32Φ32 |
| 3, 4 | 400×350 | 1.82, 2.04 | 1.5 | 450 | 700×700 | 32Φ32 |
| 5, 6 | 400×350 | 1.64, 2.05 | 1.5 | 400 | 700×700 | 28Φ28 |
| 7 | 350×300 | 1.87 | 1.5 | 350 | 700×700 | 28Φ28 |
| 8 | 350×300 | 1.87 | 1.5 | 350 | 600×600 | 20Φ25 |
| 9 | 350×300 | 1.27 | 1.5 | 300 | 600×600 | 20Φ25 |
| 10 | 350×300 | 1.27 | 1.5 | 300 | 500×500 | 16Φ25 |
| 11 | 350×300 | 1.52 | 1.5 | 250 | 500×500 | 16Φ25 |
| 12, 13 | 350×300 | 0.81 | 1.5 | 250 | 400×400 | 16Φ18 |
| 14, 15 | 350×300 | 1.02 | 1.5 | 200 | 400×400 | 16Φ18 |

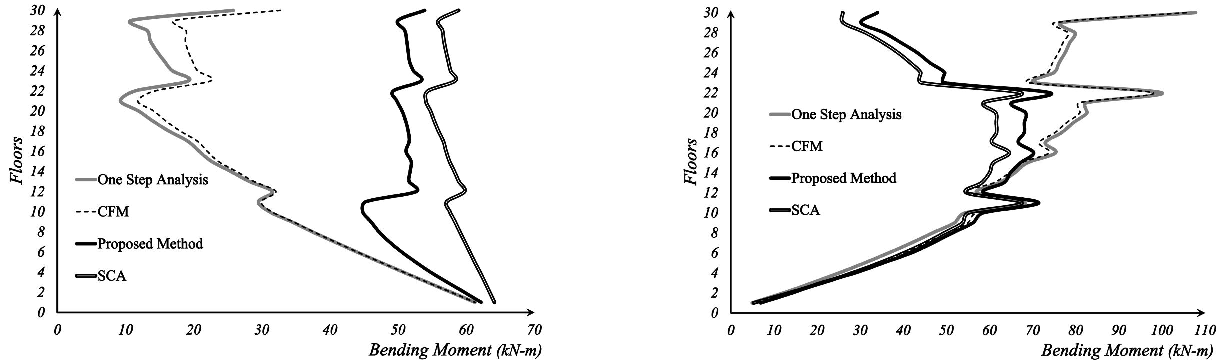
After confirming the results of modified CFM in comparison with the staged analysis, its efficiency in terms of analysis speed and total duration of process would be compared to the staged analysis. It should be considered that the optimized and accurate design of all three structures have been carried out according to the results of conventional analysis. This gives us the option to discuss the conservativeness or the incompetence of this kind of design in comparison with 3 other analysis methods and this would be a valid comparison due to the maximum utilization of members' capacities in the optimized design. The gravity and lateral loads are applied to the structures according to Minimum Design Loads for Buildings and Other Structures (ASCE7 2010) and the structure design is conducted using the Specification for Structural Steel Buildings (AISC-ASD 1989) and the Building Code requirements for Structural Concrete (ACI318 1999). The yield strength and the ultimate tensile strength of steel material of the structure 1 are 240 and 370 MPa, respectively, and yield stresses of longitudinal and transverse reinforcement in concrete structures are assumed 400 and 300 MPa, respectively. All three structures are considered residential and located in severe seismic zone. the load combination for staged analysis is $D_L$+0.2$L_L$.

It should be noted that ($\rho_L$) and ($\rho_T$) in Table 4, are the ratio of area of distributed longitudinal and transvers reinforcement to gross concrete area perpendicular to that reinforcement, Respectively.

## 5. Evaluation of results

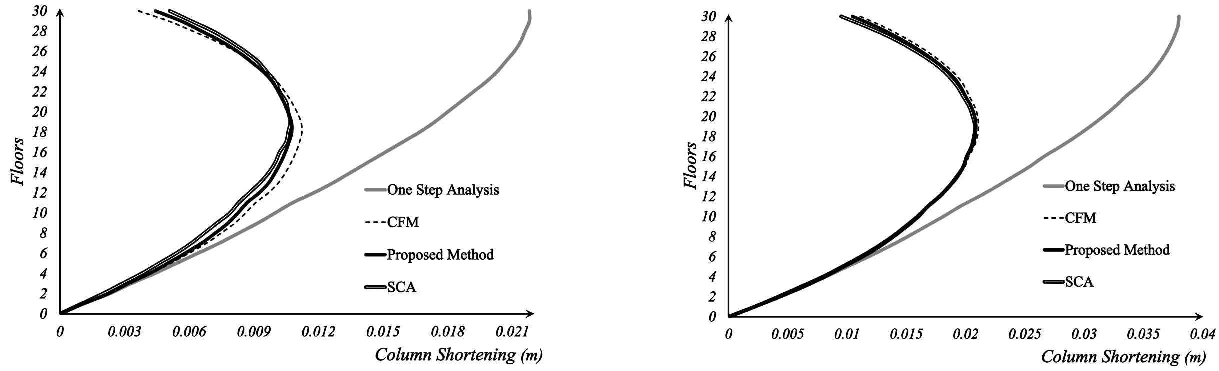
### *5.1 Structure 1 (30-story Steel moment frame)*

To evaluate the column shortenings and internal forces of the members resulted from four different methods of analysis, some members are selected as samples. The beam on axis 3, between two axes of D and E and the column located on axes 4 and E junction are considered to study the



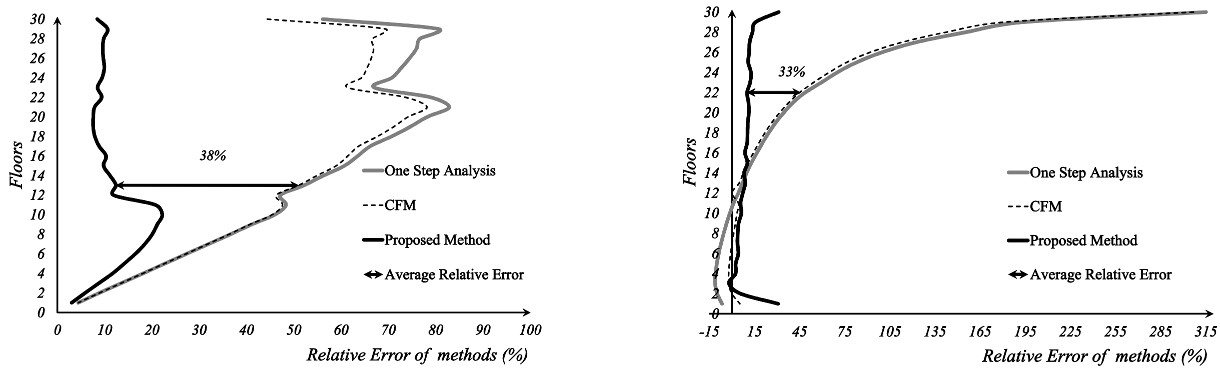

(a) Selected beam (b) Selected column

Fig. 8 Comparison of four analysis methods in estimating the bending moment




(a) Exterior column (b) Interior column

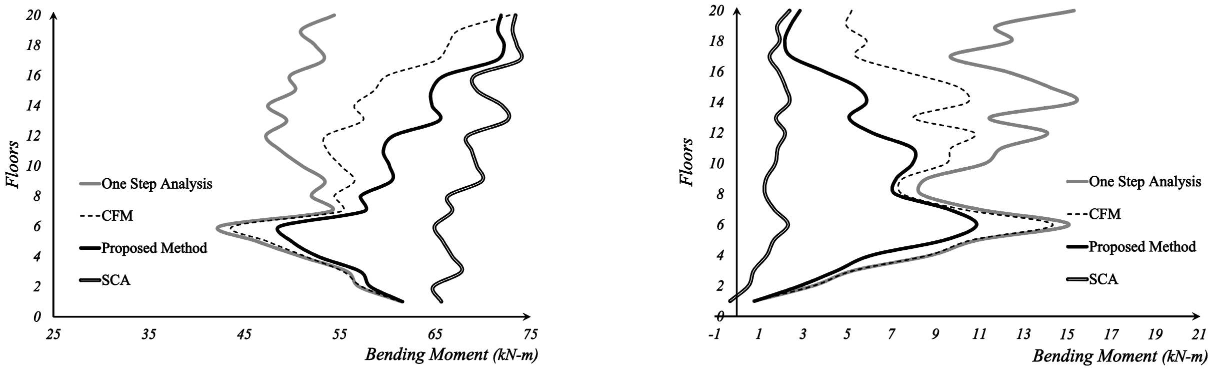
Fig. 9 Comparison of four analysis methods in estimating the column shortening




(a) Selected beam (b) Selected column

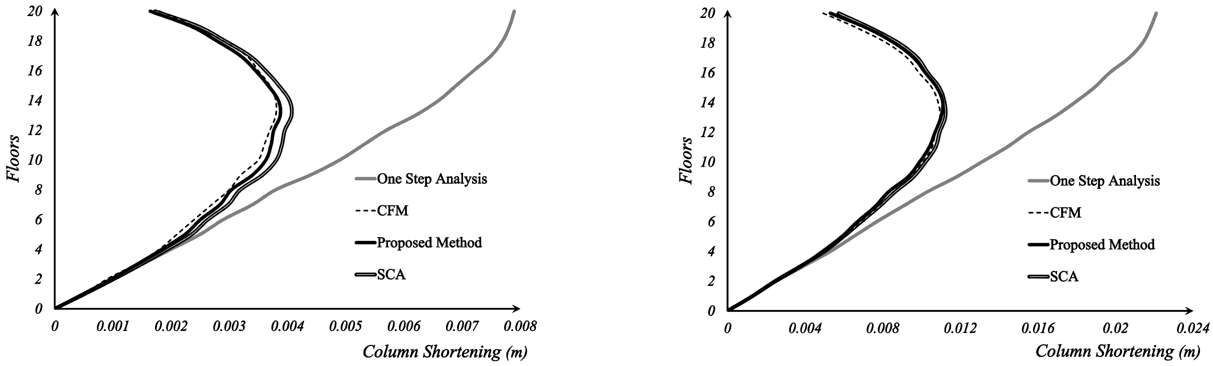
Fig. 10 Percentage error of methods in relation to the exact method in estimating the bending moments

induced bending moments of beams and columns on each floor due to the differential column shortenings. The column on the axes A and 1 junction is chosen as exterior column, and the column on the axes D and 4 junction is chosen as interior column to investigate the column shortenings. The graphs of induced bending moments of beam and column are displayed in Figs. 8(a)-(b), respectively. Also, the graphs of shortenings of exterior and interior columns are demonstrated in Figs. 9(a)-(b), respectively. It is understood from Figs. 8-9 that the proposed method has a proper performance in estimating the structure's response in accordance with the actual construction stages, and it is more successful than CFM in pushing the results of the conventional analysis to the exact values of staged analysis. To have a better understanding of the effectiveness of the proposed method, the percentage



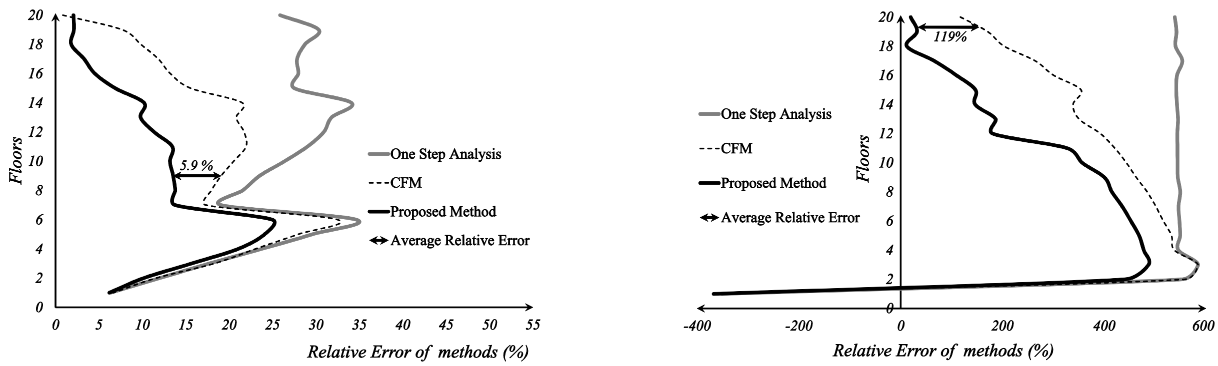

(a) Selected beam (b) Selected column

Fig. 11 Comparison of four analysis methods in estimating the bending moment




(a) Exterior column (b) Interior column

Fig. 12 Comparison of four analysis methods in estimating the column shortening




(a) Selected beam (b) Selected column

Fig. 13 Percentage error of methods in relation to the exact method in estimating the bending moments

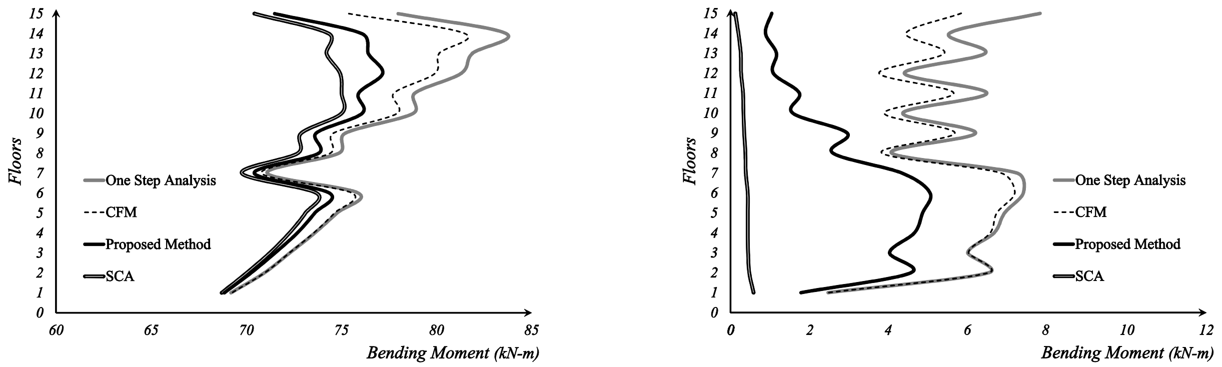
errors of the results of conventional method, CFM and currently proposed Modified CFM in relation to the exact results derived from the staged analysis are displayed in Figs. 10(a)-(b) for the selected beam and column of Figs. 8(a)-(b). As can be seen in Fig. 10, the proposed method has been able to increase the accuracy of the CFM in approximating the moments of selected beam and column by 38 and 33 percent, respectively, in average for all floors.

### *5.2 Structure 2 (20-story Concrete moment frame)*

The graphs of bending moments of beam and column, for the beam located on axis C between axes 1 and 2, and the column located on axes 4 and E junction, are displayed in Figs. 11(a)-(b), respectively. The graphs of shortenings of exterior column, located on the axes 1 and A junction, and interior column, located on axes 4 and D junction, are demonstrated in Figs. 12(a)-(b), respectively. Relative superiority of the current research method compared to the conventional and CFM methods in the estimation of actual results of the exact staged analysis proves the feasibility of applying this method to both concrete and steel frames. The percentage errors of the conventional method, CFM and proposed method in relation to the exact values of staged analysis in calculating the moments of the selected beam and column from Fig. 11(a)-(b), are displayed in Figs. 13(a)-(b), respectively. It is observed that the currently proposed Modified CFM is able to increase the accuracy of the CFM in estimating the moments of beam and column by 5.9 and 119 percent, respectively, in average for all floors.

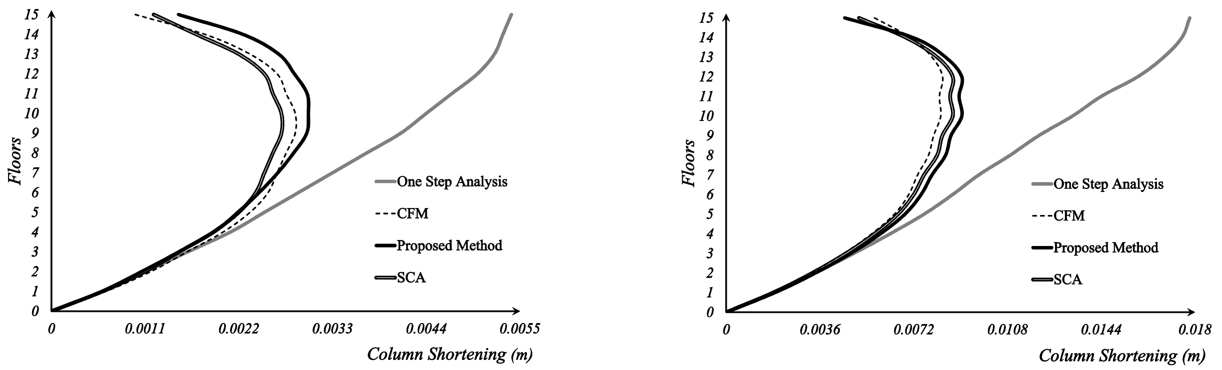
### *5.3 Structure 3 (15-story Concrete dual system)*

The graph of bending moment of beam located on axis D between axes 1 and 2 is displayed in Fig. 14(a). The



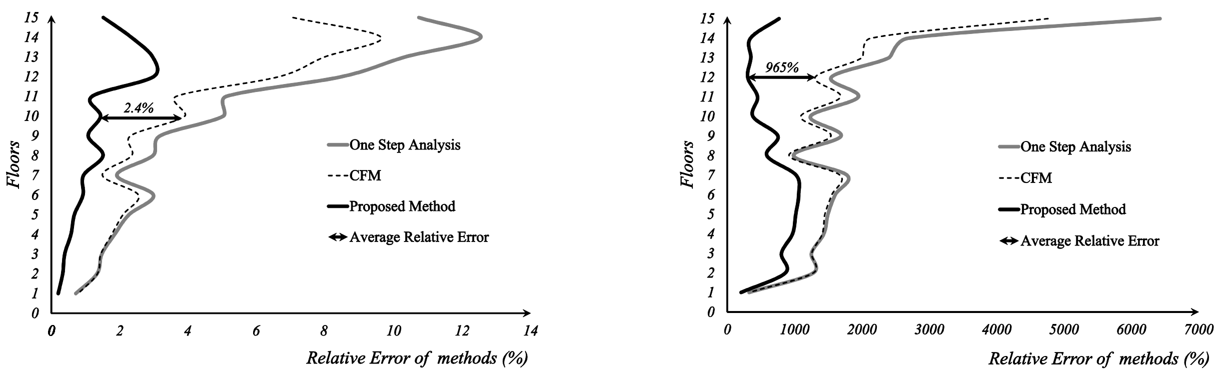

(a) Selected beam (b) Selected column

Fig. 14 Comparison of four analysis methods in estimating the bending moment




(a) Constrained column by shear walls (b) Unconstrained column of the frame

Fig. 15 Comparison of four analysis methods in estimating the column shortening




(a) Selected beam (b) Selected column

Fig. 16 Percentage error of methods in relation to the exact method in estimating the bending moments graph of bending moment of the column located on axes 1 and F junction is displayed in Fig. 14(b). To study the constraining effect of the shear walls on column shortening, the column located on the axes 3 and C junction is selected. The graph of its shortening resulted from four different methods of analysis is displayed in Fig. 15(a). The graph of shortening of the column located on the axes 2 and B junction, which is an interior column without the constraining effect of the shear walls, is displayed in Fig. 15(b). Better adaptation of the proposed method results of the current research compared to the conventional and CFM methods in assessment of the actual values of the staged analysis confirms the possibility of applying this method to dual systems of concrete shear walls-moment resisting frames. The percentage errors of the results of conventional analysis, CFM and proposed method in relation to the precise outcomes of the staged analysis in estimating the moments of the selected beam and column are displayed in Figs. 16(a)-(b), respectively.

The Modified CFM improves the accuracy of the CFM in estimating the moment of the selected beam by 2.4 percent in average for all floors. This improvement reaches to an impressive amount of 965 percent for the selected column's moment which further demonstrates the effectiveness of the currently proposed method. However, it is noteworthy that the relative error percentages of the proposed method compared to the exact staged analysis with approximate values of 1000% in Fig. 16(b) and 480% in Fig. 13(b), do not mean the inapplicability of the proposed method in structure design, because the aforementioned errors are calculated compared to the small values of column moment under staged analysis according to Fig. 14(b) and 11(b), respectively. Thereupon, the sensitivity of the estimated errors to small values of the bending moment, resulted in larger numbers, Whereas the difference between the bending moment values in the proposed method and nonlinear staged analysis, had no effect on the preliminary design of the desired columns sections. It is worth noting that for complex structures with different gravity load carrying system or an implementation schedule different from the story by story construction sequence, using the proposed method may be associated with error. In this regard, using nonlinear staged analysis will be a reasonable solution.

It is notable that the constraining effect of the shear walls greatly reduces the column shortening when compared to an unconstrained similar interior column of the frame, as displayed in Fig. 17. Even though the axial stiffness of the column is modified in the proposed method, the calculated shortening is still accurate and close to the amount obtained by staged analysis.

### 5.4 Analysis durations

The time spent for carrying out the modified CFM for three sample structures are compared to the duration of staged analysis in Fig. 18.

This method, by applying the modified stiffness of the members as the input of analysis, and performing the analysis in one step, is able to consider the effect of

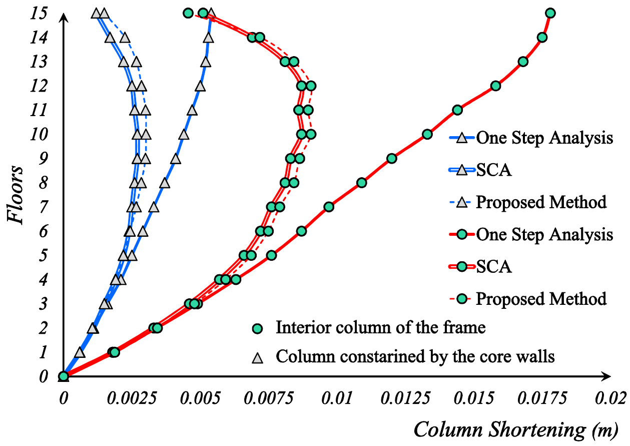



Fig. 17 Comparison of shortenings of the column constrained by shear walls and the unconstrained interior column of the frame

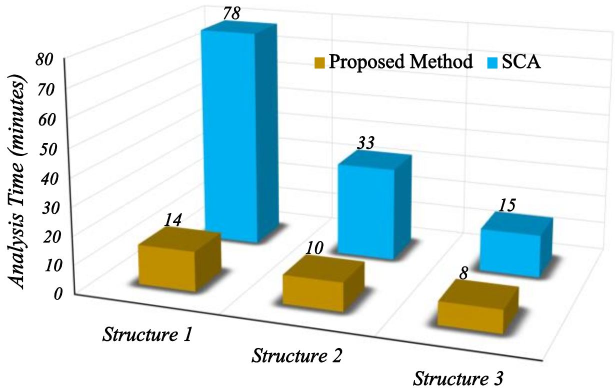



Fig. 18 Comparison of analysis time of proposed method and staged analysis

Table 5 Analysis time details of structures under study

| Model Number | SCA | Proposed method | |
|---|---|---|---|
| | Software time analysis (*minute*) | Stiffness Correction time (*minute*) | Software time analysis (*minute*) |
| Structure 3 | 15 | 7 | 1 |
| Structure 2 | 33 | 8 | 2 |
| Structure 1 | 78 | 10 | 4 |

construction stages successfully for structures 1, 2 and 3 in 18%, 30% and 53% of the time required for staged analysis, respectively, which proves its efficiency. However, it should be noted that analysis time of the proposed method, listed in Fig. 18, comprises the time spent to correct the axial stiffness of the columns and also the time required for software analysis. Details of the analysis times of the structures under the staged analysis and the proposed method of the present paper are shown in Table 5.

## 6. Conclusions

In this study, a novel method named modified CFM is proposed to consider the effects of construction stages, and eliminate the defect of the CFM which is its inaccuracy in obtaining the final internal forces of some columns or brace members by applying the correction factors to the analysis results. In the proposed method, the axial stiffness of all the columns of the structure are modified by applying the Eq. (23), to consider the effects of the construction stages. Then, the modified values of stiffness are used as the software's input to perform the one-step conventional analysis in much shorter time than the staged analysis. Moreover, it is not required to manually modify the software results after analysis by applying the correction factors as in CFM, which reduces the probability of errors. To evaluate the effectiveness of the modified CFM, three sample structures are studied with different geometries, materials and structural systems. Then, the differences in response of each structure due to sequential loading under four different methods of staged analysis, conventional analysis, CFM and modified CFM are assessed.

- The study indicates that the modified CFM obtains the most comparable results (member's forces and column shortenings) to the staged analysis.
- The results also proved that the modified CFM is capable of performing well for dual structural systems, and steel or concrete moment resisting frames because it predicts the analysis results more effectively towards their actual values, derived from staged analysis, when compared to the CFM.
- The method proposed in the current research which is an effective way to correct the results of the conventional analysis and apply the construction sequence effects to the structure analysis, can be effectively used in the preliminary design of structures assuming the story by story construction.

## References

ACI318 (1999), Building code requirements for structural concrete, American Concrete Institute; Farmington Hills, MI, USA.

AISC (1989), Specification for Structural Steel Buildings-Allowable Stress Design and Plastic Design, American Institute of Steel Construction; Chicago, IL, USA.

ASCE (2010), Minimum Design of Load of buildings and other structures (ASCE/SEI 7-10), American Society of Civil Engineers; Reston, VA, USA.

Chen, P., Li, H., Sun, S. and Yuan, M. (2006), "A fast construction sequential analysis strategy for tall buildings", *Struct. Eng. Mech*., **23**(6), 675-689.

Choi, C.K. and Kim, E.D. (1985), "Multistory frames under sequential gravity loads", *J. Struct. Eng*., ASCE, **111**(11), 2373-2384.

Choi, C.K., Chung, H.K., Lee, L.G. and Wilson, E.L. (1992), "Simplified building analysis with sequential dead loads-CFM", *J. Struct. Eng*., ASCE, **118**(4), 944-954.

Esmaili, O., Epackachi, S., Mirghaderi, R., Ghalibafian, M. and Taheri, A.A. (2007), "Evaluation of the construction sequence loading effects on seismic performance of high-rise buildings with different structural systems", *Proceedings of Ninth Canadian Conference on Earthquake Engineering*, Ottawa, Ontario, Canada, 729-738.

Esmaili, O. (2008), "Considering sequential construction methods of reinforced concrete high-rise buildings with material time-dependency effects", M.Sc. Dissertation, University Of Tehran, Iran.

Kim, H.S. (2013), "Effect of horizontal members on column shortening of reinforced concrete building structure", *Struct. Des. Tall Spec. Build*., **22**(5), 440-453.

Kim, H.S. (2015), "Optimum distribution of additional reinforcement to reduce differential column shortening", *Struct. Des. Tall Spec. Build*., **24**(10), 724-738.

Kim, H.S., Jeong, S.H., Shin, S.H. and Park, J.P. (2012a), "Simplified column shortening analysis of a multi-storey reinforced concrete frame", *Struct. Des. Tall Spec. Build.*, **21**(6), 405-415.

Kim, H.S., Jeong, S.H. and Shin, S.H. (2012b), "Column shortening analysis of tall buildings with lumped construction sequences", *Struct. Des. Tall Spec. Build.*, **21**(10), 764-776.

Kwak, H.G. and Kim, J.K. (2006), "Time-dependent analysis of RC frame structures considering construction sequences", *Build. Environ.*, **41**(10), 1423-1434.

Njomo, W.W. and Ozay, G. (2014), "Minimization of differential column shortening and sequential analysis of RC 3D-frames using ANN", *Struct. Eng. Mech.*, **51**(6), 989-1003.

Park, S.W., Choi, S.W. and Park, H.S. (2013), "Moving average correction method for compensation of differential column shortenings in high-rise buildings", *Struct. Des. Tall Spec. Build.*, **22**(9), 718-728.

Saffarini, H.S. and Wilson, E.L. (1983), "New approaches in the structural analysis of building systems", Research Report No. UCB/SEMM-83/08; Department of Civil Engineering, University of California, Berkeley, USA.

Vafai, A., Ghabdian, M., Estekanchi, H.E. and Desai, C.S. (2009), "Calculation of creep and shrinkage in tall concrete buildings using nonlinear staged construction analysis", *Asian J. Civ. Eng.*, **10**(4), 409-426.

*CC*