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Assessment of mitigation alternatives for differential shortening in high-rise reinforced concrete buildings

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Abstract

Selecting appropriate structural system for reinforced concrete (RC) buildings is essential in the design process to satisfy serviceability and strength requirements. Using ordinary analysis (OA) may result in inaccurate estimation of differential shortenings (DS) between vertical supporting elements which might lead to structural and architectural problems. Efficiency of staged analysis including time-dependent effects (SAT) has been recently recognized for the analysis of these buildings due to considering the sequential nature of construction. In this research, eight RC buildings with heights ranging between 35 and 175 m and various structural systems, namely rigid frames (RF), shear walls (SW), wall frames (WF), and tube in tube (TT), are analyzed. An assessment is conducted for the adequacy of three mitigation alternatives to decrease changes between DS estimated using OA and SAT. In Alternative 1, cross sections of all vertical elements (columns and shear walls) are increased by 50%. Alternative 2 is performed by iteratively proportioning the dimensions of internal columns without changing the cross sections of edge and corner vertical elements. One outrigger system is introduced along the height of buildings with WF and TT systems in Alternative 3. Analysis of the eight buildings is implemented by developing a numerical model considering the construction stages and time-dependent effects. The alternatives assessment is conducted by comparing differential displacements (DD), bending moments, and shearing forces before and after mitigation obtained from OA and SAT. The numerical results showed that Alternative 1 is not efficient in mitigating the differences between the OA and SAT for all the studied buildings. However, an optimum solution can be achieved using the Alternative 2 for all investigated systems. Also, Alternative 3 was found adequate in partially mitigating the differences between the two analyses for the buildings with WF and TT systems.

Keywords: Mitigation, Staged analysis, Ordinary analysis, Reinforced concrete, Shortening, Structural systems

Introduction

Reinforced concrete (RC) buildings become an excellent alternative due to material availability and low workmanship and maintenance cost compared to other building materials. A combination of columns, beams, walls, and/or cores are commonly structurally proportioned to carry gravity, wind, and seismic forces. Many researchers explored various considerations for analysis and design of buildings under seismic loading. Alaa et al. [1] proposed a set of equations to improve the accuracy of torsional irregularity design considerations in mid-rise dual system buildings under earthquake loading. Nonlinear dynamic analysis of 15 buildings was conducted, and new equations were proposed for the torsional amplifications. Shehata et al. [2] used a sub-structuring technique and the dual reciprocity boundary element method to analyze buildings on raft foundations considering soil-structure interaction. The superstructure was modelled using the boundary element method, while the substructure was simulated using the dual reciprocity boundary element method. Bao et al. [3] used the vertical pushover method to investigate the progressive collapse of base-isolated buildings using experimental and numerical simulations. It was concluded that nonuniformity of beams led to severe beam end damage under seismic loading. Progressive collapse resistance was not affected by the horizontal stiffness of the seismic isolation layer. Compared to the unstrengthen beams, Hemida et al. [4] reported that the CFRP strengthened beams showed higher load capacities and lower deflections which might not be adequate for earthquake resistance. The aforementioned researchers adopted the ordinary analysis (OA) approach where a completed building is subjected to all forces at one phase. This analysis methodology was found inaccurate since loads are applied sequentially during the building construction [5, 6]. Several research works determined the optimum structural system in RC buildings using OA [7, 8]. Taranath [7] analyzed RC buildings with rigid frame (RF) which consists of RC columns and beams. RF and shear wall (SW) systems were found suitable for RC buildings having less than 20 and 30 storeys, respectively. Some research attempts compared between OA and staged-construction analysis (SA) of RC buildings [5, 6]. FE simulation was developed by Elansary et al. [5] which considers the sequential nature of construction of RC buildings as well as the change in concrete properties with time. A comparison was conducted between the responses from the SA and OA analyses. Behavior of post-tensioned slabs was studied by Elansary et al. [6] considering SA. Noticeable variations were observed between straining actions and stresses from the SA and OA analyses. Time-dependent effects in RC building were investigated in various studies [9–11]. Metwally [9] reported that shrinkage and creep have a noticeable effect on RC column shortening. Considering the effect of temperature on analysis of RC buildings, Raksha et al. [10] concluded that the effect of differential shortening (DS) should be considered when for buildings higher than 20 storeys. Elansary et al. [11] studied six RC buildings with different structural systems (RF, SW, and WF). For buildings with RF, SA produced higher moments and shears than OA by 29.9 ~ 35.0% and 19.6 ~ 23.5%, respectively.

Methods

The current manuscript aims at investigating the adequacy of three various mitigation alternatives in reducing differences in shortenings and straining actions from OA and SAT. The efficiency of the alternatives is examined for eight concrete buildings having various number of storeys and structural systems (RF, SW, WF, and TT). The first and second alternatives include changing the dimensions of all or selected vertical elements, respectively, for all investigated RC buildings, while the third alternative includes introducing an outrigger system to RC buildings with WF and TT systems. Firstly, the previous investigations on mitigating column shortening in RC buildings are presented. These include formwork cambering, column shortening compensation, increasing column reinforcement, and using outrigger system. Secondly, the manuscript outlines the properties of analyzed RC buildings, material parameters, and loading procedure. Thirdly, details of the numerical model adopted in the analysis are reported. Fourthly, details of the proposed approaches for mitigating the differences between the column shortenings and internal forces from OA and SAT are reported. Finally, discrepancies between DS and internal forces from OA and SAT with/without the proposed mitigation are provided.

Column shortening mitigating techniques

Fintel et al. [12] determined the column and wall shortenings of two buildings having several storeys of 70 and 80 with WF and RF systems, respectively, using an analytical procedure. The study highlighted the efficiency of compensating the differential column shortenings in reducing straining actions in horizontal members. Avoiding the traditional trial-and-error compensation procedure, PARK [13] developed an optimization algorithm, using the simulated annealing technique, to compensate the differential column shortenings in high-rise building. Tilts in slabs were controlled in the optimization technique by limiting the compensation values for the columns.

Kim [14] proposed a method for increasing the axial stiffness of columns by placing additional reinforcement. The authors tested the proposed approach by analyzing three models (constant section, constant stress, and general method) and comparing reinforcement quantity and distributions in the columns. It was found that increasing the reinforcement ratio by 1%, 2%, 3%, and 4% reduced the max column shortening by 16%, 30%, 40%, and 52%, respectively. Instead of the time-consuming trials-based and optimization approaches, Kim and Shin [15] proposed an efficient approach for the analysis of high-rise RC buildings by lumping construction sequences for the column shortenings. The investigation showed that results like the exact model for design stage of RC buildings can be obtained by lumping more than two storeys into one constructing unit.

Using outrigger systems was reported to have an efficient effect in controlling column shortening in tall buildings [16–18]. El-Leithy [16] investigated using RF, SW, WF, and TT in RC tall buildings subjected to gravity and wind loads. Sitapara and Gore [17] reviewed performance and feasibility of different configurations of outrigger systems. The authors reported some advantages of the outrigger systems such as the following: (1) they can be utilized with steel, concrete, or composite structures, and (2) the effect of external column spacing on the structural behavior of these buildings is negligible. On the contrary, disadvantages of this system include the following: (1) interfering with utility usable spaces and (2) increasing overturning moment on the foundation of the central core. Choi et al. [18] reviewed effect of using outrigger systems on the structural behavior and design of tall buildings. The authors concluded that no comprehensive and clear procedures are available for the design of outrigger systems due to the variety of challenges, solutions, and new concepts being developed.

Modelling attributes

The current study is conducted by analyzing eight concrete buildings with 10, 20, 30, 40, and 50 storeys each having a height of 3.5 m. All buildings have footprint area of 900 m^2 with a 6×6 m internal opening [5]. A slab thickness of 300 mm is utilized in all buildings to satisfy serviceability requirements. Table 1 shows the number of storeys and structural system for the analyzed buildings. A reinforcement ratio of 2% is adopted for all structural vertical elements. El-leithy [16] previously analyzed the same buildings using OA under the code-specified loads. A concrete density of 23.56 kN/m^3 was adopted to estimate the own weight of the structural elements, while flooring load which was 3 kN/m^2 was added. As recommended by the ASCE 7–05 code [19], the live load was assumed 2 kN/m^2. The concrete dimensions of the structural elements, as well as properties of concrete and reinforcing steel, can be found in [9]. The stiffness reduction factors were estimated according to the ACI 318–19 code [20]. Additional file 1 show details of the concrete dimensions of all structural elements for the investigated buildings.

The studied buildings are analyzed in the current paper using a 3D FEM previously developed by the same authors of the current paper [5]. The model includes 3D two-node beam elements to model the columns and beams and four-node 3D plate elements to simulate the slabs and walls. The FEM is developed using midas Gen [21] software to conduct both OA and SA for the eight buildings considering dead and live loads. Efficiency of midas Gen [21] was proven by various researchers [5, 6, 9]. More details about the utilized FEM can be found in [5, 9].

Procedure of the hybrid analysis including both SA including time-dependent effects (SAT) and OA is summarized as follows: (1) Draw the structural elements of the building in a three-dimensional environment, (2) define time-dependent parameters for concrete, (3) define construction stages, (4) conduct the SAT and OA, and (5) compare results of the SAT with those obtained from OA. In the current paper, the construction cycle time is assumed to be 7 days (5 days for formwork installation and 2 days for concrete casting). The shoring is placed on three levels, and the time of removal of lowest level of shoring from casting of top floor is 5 days. The shoring

Table 1 Parameters for analyzed buildings

Building	No. of floors	Structural system
B_{d1}	10	RF
B_{d2}	10	SW
B_{d3}	20	RF
B_{d4}	20	SW
B_{d5}	30	WF
B_{d6}	40	WF
B_{d7}	40	TT
B_{d8}	50	TT

is removed from the 1st storey after 22 days when the age of this storey becomes 19 days.

Mitigation alternatives

Slope of slabs or beams due to DS between columns and other supporting elements leads to increasing the straining actions in the horizontal members (beams and slabs). Differences between internal forces from OA and SAT due to the unequal differential displacements (DD) at the element ends lead to unsafe or uneconomic solutions in various zones of the slabs and beams. Columns cross-sectional dimensions are changed in Mitigation Alternatives 1 and 2. These changes should be coordinated with the architectural engineer to ensure satisfying building functionality. The change is applied using a dimension modification factor (DMF) calculated using following equation:

$$D_N = DMF.D_O \tag{1}$$

where D_O and D_N are the old and new dimensions in the original and modified models, respectively. Using this modified dimension reduces the column shortening and consequently decreases differential settlements between the modified columns and the adjacent vertical elements supporting the same horizontal member. This results in reducing the straining actions in the horizontal members. In Alternative 1, dimensions of all columns and shear walls are increased by a DMF of 1.5. In Alternative 2, dimensions of the internal columns only are changed using various DMF without changing the dimensions of the edge columns, corner columns, or shear walls. For practical purposes, a constant DMF is utilized for each five consecutive floors. The selected factors are guided by the curves of the differences between SAT and OA. A trial-and-error procedure is adopted to determine the adequate DMF. The trials are stopped when the differences between the modified and original models become less than 5%. To ensure adequate transition of loads from upper to lower floors, a constraint is applied on the conducted trials to avoid having cross sections of columns in upper floors larger than those for columns in lower floors. The objective function is based on reducing bending moments and shearing forces in the horizontal members in the modified model less than those in the original model. In Alternative 3, an outrigger system with several deep beams (width of 200 mm) is placed along the height of the building. The optimum location of outrigger system was investigated by many researchers to control building drift and straining action [22, 23]. One outrigger system is utilized for buildings with WF and TT systems. The outrigger system is located at mid-height of buildings B_{d5} and B_{d6} and at top of buildings B_{d7} and B_{d8}.

Results and discussions

In this section, DD from SAT before mitigation (SATb) and SAT after mitigation (SATa) for the three proposed mitigation alternatives are presented. In addition, the differences between the moments in slabs and beams before and after mitigation between OA and SAT are plotted along the height of the eight analyzed buildings. Straining actions of (B1, B2) beams and (S1, S2) strips are presented where extreme values are observed (Fig. 1). Figure 1a and c shows that B1 is supported on columns C4 and C2. B2 is supported on

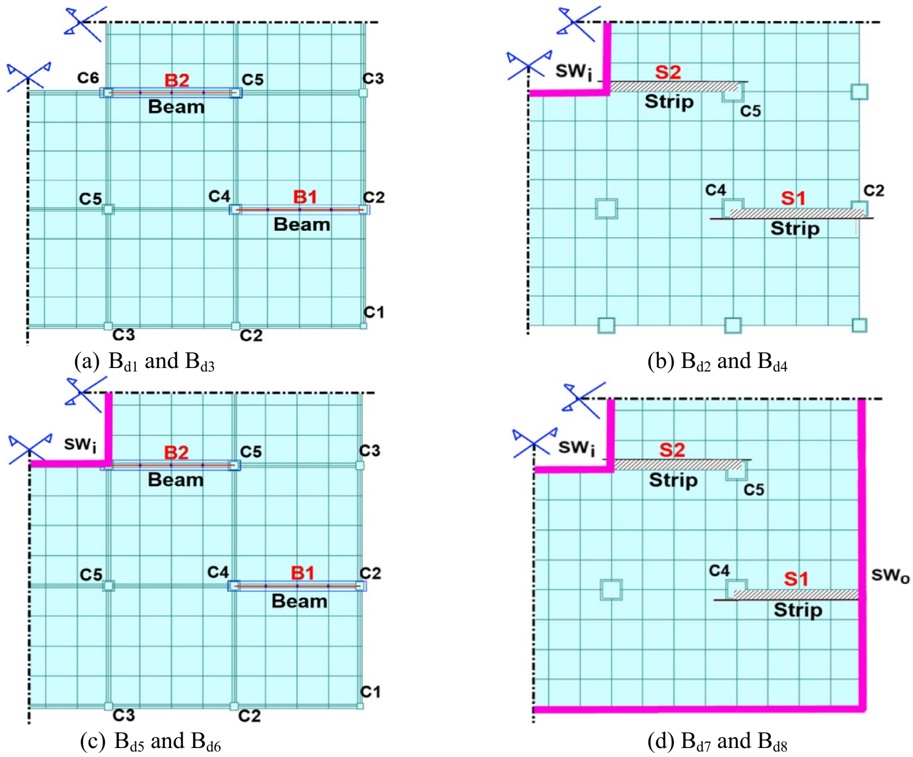

Fig. 1 Plans of the analyzed buildings. **a** B_{d1} and B_{d3}. **b** B_{d2} and B_{d4}. **c** B_{d5} and B_{d6}. **d** B_{d7} and B_{d8}

C5 and C6 (Fig. 1a) or supported on C5 and shear wall SW_i (Fig. 1c). Strip S1 extends between C4 and C2 (Fig. 1b) or between C4 and SW_o (Fig. 1d), while strip S2 extends between SW_i and C5 (Fig. 1b and d).

The difference in moment or shear is estimated as follows:

$$\text{Diff.b\%} = \frac{X_{SATb} - X_{OSAb}}{X_{OSAb}} \times 100\% \tag{2}$$

$$\text{Diff.a\%} = \frac{X_{SATa} - X_{OSAa}}{X_{OSAa}} \times 100\% \tag{3}$$

where Diff.b and Diff.a are the difference before and after mitigation, respectively. X_{OSAb} and X_{OSAa} are the parameters obtained from OA before and after mitigation. X_{SATb} and X_{SATa} are the parameters obtained from SAT before and after mitigation.

Mitigation Alternative 1

This section outlines the effect of increasing all cross sections of vertical elements by 50% (i.e., $DMF = 1.5$) on DD and internal forces.

Differential Displacement (DD)

Noticeable differences are observed between the DD from SATb and SATa for the eight buildings (Fig. 2). It is noted that nonlinear DD are obtained from SATb where the

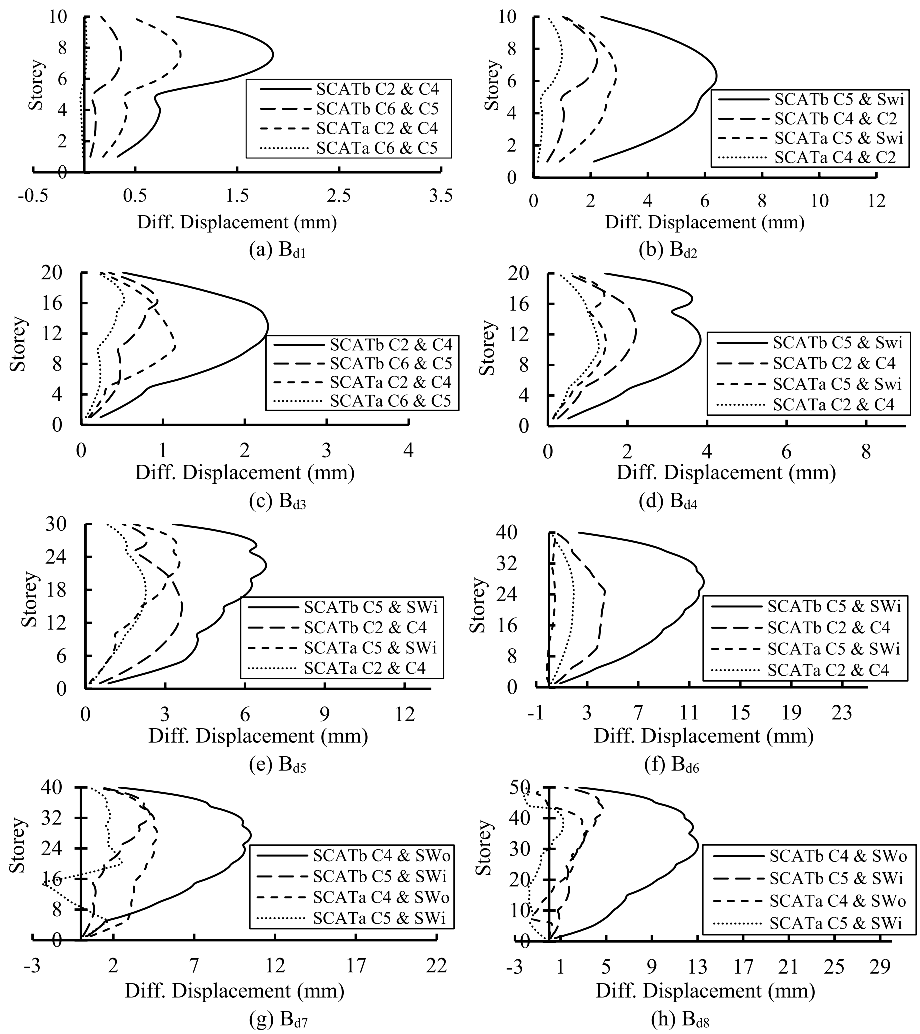

Fig. 2 Differential displacement due to SATb and SATa. **a** B_{d1}. **b** B_{d2}. **c** B_{d3}. **d** B_{d4}. **e**. B_{d5}. **f** B_{d6}. **g** B_{d7}. **h** B_{d8}

Table 2 Maximum DD from SATb and SATa

Building	Max. DD from SATb, mm	Storey	Max. DD from SATa, mm	Storey	% reduction
B_{d1}	1.82	8	0.93	7	49
B_{d2}	6.37	6	2.86	6	55
B_{d3}	2.28	13	1.14	10	50
B_{d4}	3.83	11	1.46	11	62
B_{d5}	6.76	22	3.53	23	48
B_{d6}	12.13	27	1.94	24	84
B_{d7}	10.48	27	4.70	27	55
B_{d8}	13.03	31	3.06	33	77

maximum DD are located near the middle storey. Also, the SATa produced a nonlinear trend for the DD, and the maximum values are located near the upper quarter of each building. Table 2 shows the maximum DD of all buildings before and after mitigation and their locations. Reductions of 48 ~ 84% in the DD are observed due to increasing the cross sections of all columns by 50%.

Bending moments

Compared to SAT, OA produces uneconomic design because of using overestimated moments in beams or slabs and produces unsafe design at the other zones because of utilizing underestimated moments. This section investigates the effect of applying Mitigation Alternative 1 on decreasing the deviations in moments between OA and SAT at ends of the horizontal members with unsafe design. Figure 3 shows the differences between the moments from OA and SAT with/without mitigation. It is observed that differences in moments dramatically vary with/without mitigation. Table 3 presents the

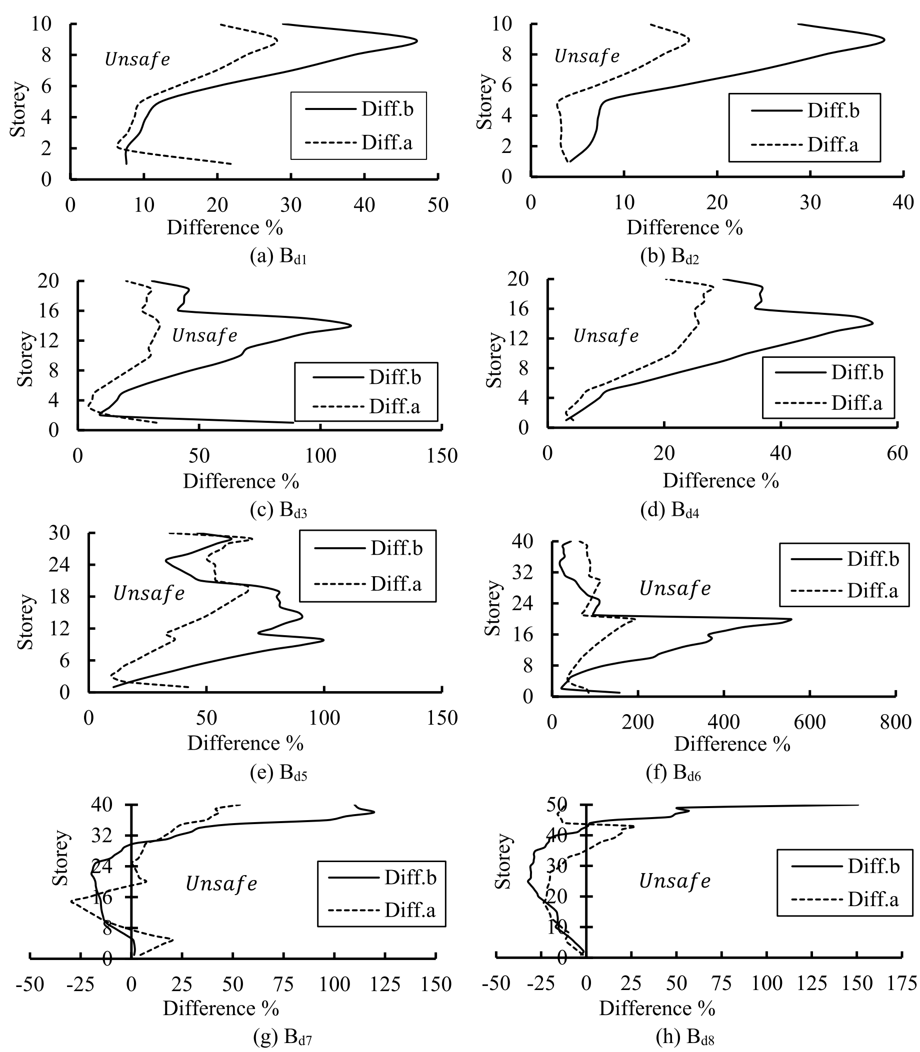

Fig. 3 Differences in moment for horizontal members between OA and SAT before and after mitigation. **a** B_{d1}. **b** B_{d2}. **c** B_{d3}. **d** B_{d4}. **e** B_{d5}. **f** B_{d6}. **g** B_{d7}. **h** B_{d8}

Table 3 Maximum differences between moments from OA and SAT with/without mitigation

Building	Max. diff. % bet. OSAb & SATb	Storey	Max. diff. % bet. OSAa & SATa	Storey	% reduction
B_{d1}	47	9	28	9	40
B_{d2}	38	9	17	9	55
B_{d3}	113	18	34	14	70
B_{d4}	56	19	28	19	50
B_{d5}	99	29	71	20	28
B_{d6}	554	38	97	21	82
B_{d7}	119	39	53	40	55
B_{d8}	151	50	26	46	83

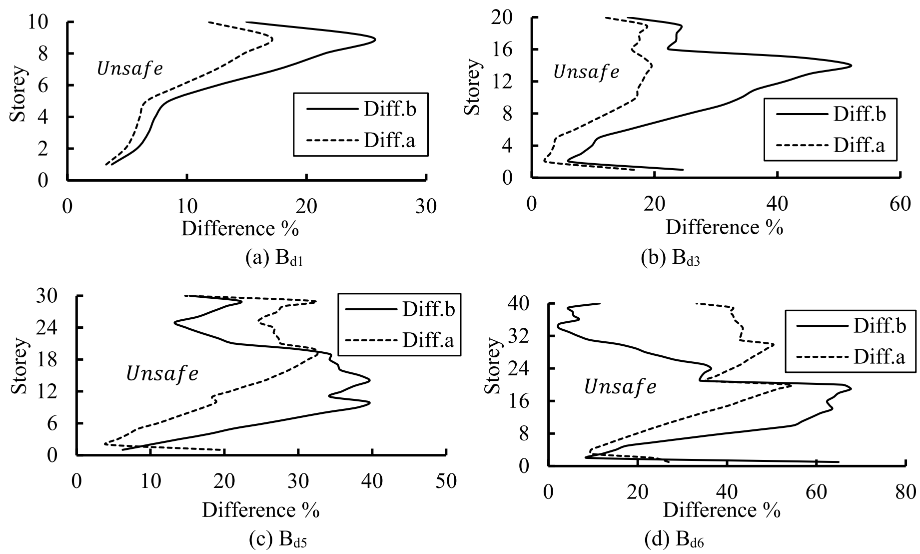

Fig. 4 Differences in shearing forces at beam ends between OA and SAT. **a** B_{d1}. **b** B_{d3}. **c** B_{d5}. **d** B_{d6}

maximum deviations in moments from SAT and OA and their locations with/without mitigation. The proposed mitigation alternative reduces the differences between SAT and OA by 28 ~ 83%. Although this alternative reduces the differences between SAT and OA by quite large percentages, none of the obtained solutions completely mitigated all unsafe members.

Shearing force

Effect of utilizing Mitigation Alternative 1 on decreasing the differences in shearing forces between OA and SAT at the beam end zones with unsafe designs. Figure 4 shows the differences between the shearing forces from OA and SAT with/without mitigation for the eight buildings. Significant changes along the building height are observed in the differences between shearing forces obtained before/after mitigation from SAT and their corresponding values from OA. Table 4 shows the maximum variations between shearing forces from SAT and OA for the buildings and their locations with/without mitigation. A reduction of 20 ~ 62% is noted in the differences between SAT and OA.

Table 4 Maximum differences between shearing force from OA and SAT with/without mitigation

Building designation	Max. diff. % bet. OSAb & SATb	Storey	Max. diff. % bet. OSAa & SATa	Storey	% reduction
B_{d1}	26	9	17	9	35
B_{d3}	52	14	20	14	62
B_{d5}	40	14	32	20	20
B_{d6}	68	19	54	19	21

None of the obtained solutions mitigated all unsafe beams in shear, although significant decreases in the variations between SAT and OA are achieved. More importantly, one can note that this alternative increased the level of unsafety of upper floors of buildings B_{d5} and B_{d6}.

Mitigation Alternative 2

Effect of increasing concrete dimensions of internal supporting members by the DMF in Table 5 on DD and internal forces of structural members are presented in the current section.

Differential Displacement (DD)

Figure 5 shows the DD between the ends of the horizontal members where noticeable deviations are seen between the DD from SATb and SATa for all studied buildings. It is noted that the DD obtained from SATb vary nonlinearly where the maximum DD is located at the mid-height, approximately. Also, distribution is nonlinear for DD from SATa where the maximum DD is located near the upper half of the buildings. These values approach zero or turn to a negative value. Table 6 shows the maximum DD of all buildings before and after mitigation and their locations. Markable decreases in the DD are observed due to increasing cross section of internal columns without changing all other vertical elements. The reductions for the studied buildings range from 10 to 115%.

Bending moments

This section investigates the effect of increasing concrete dimensions of internal vertical members by the DMF in Table 7 on decreasing the deviations in moments between OA

Table 5 Dimension factor, DMF at each floor of studied buildings

Storeys	Building							
	B_{d1}	B_{d2}	B_{d3}	B_{d4}	B_{d5}	B_{d6}	B_{d7}	B_{d8}
5	1.45	1.45	1.10	1.43	1.47	1.89	1.09	0
10	1.38	1.38	1.41	1.53	1.41	1.88	1.10	0
15			1.20	1.33	1.33	1.81	1.05	0
20			1.33	1.50	1.38	1.80	1.06	0
25					1.36	1.71	1.07	0
30					1.27	1.52	1.23	0
35						1.68	1.45	0
40						1.85	1.78	1.15
45								1.36
50								1.67

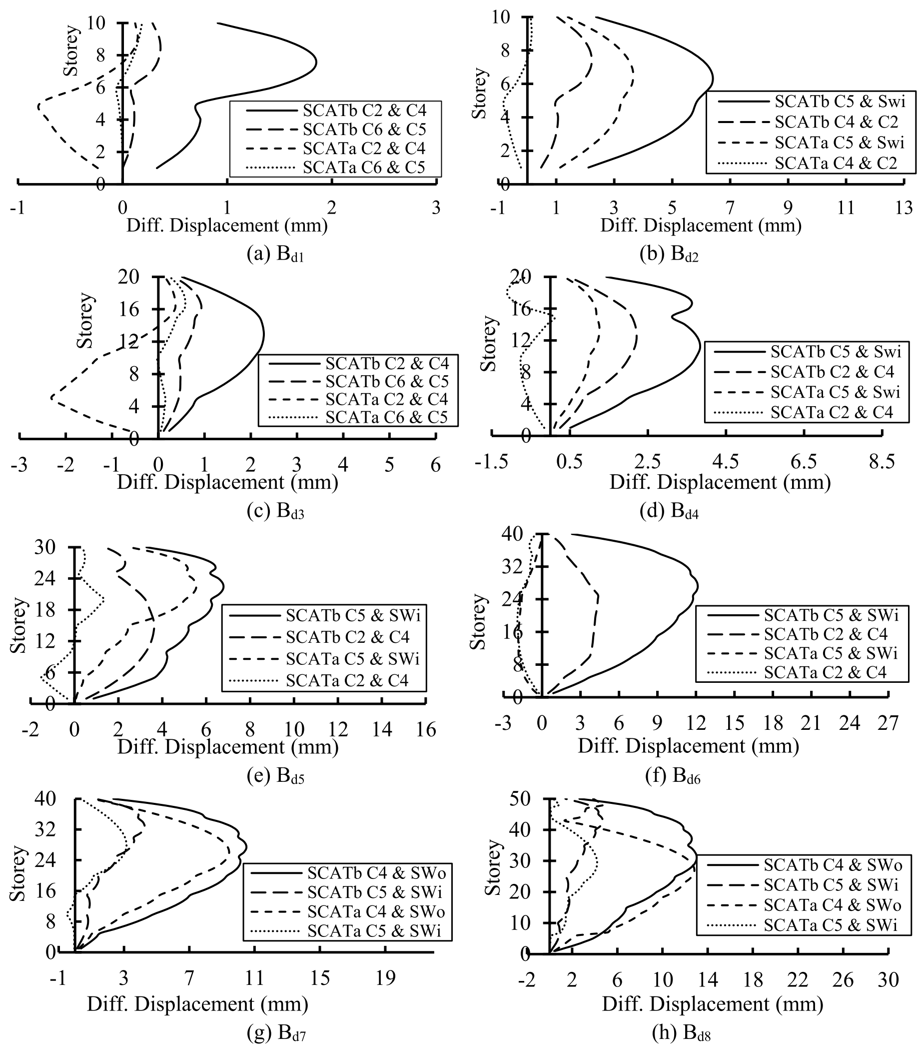

Fig. 5 Differential displacement in investigated members due to SATa and SATa. **a** B_{d1}. **b** B_{d2}. **c** B_{d3}. **d** B_{d4}. **e** B_{d5}. **f** B_{d6}. **g** B_{d7}. **h** B_{d8}

Table 6 Maximum DD from SATb and SATa

Building	Max. DD (SATb), mm	Storey	Max. DD (SATa), mm	Storey	% reduction
B_{d1}	1.82	8	0.14	9	92
B_{d2}	6.37	6	3.61	6	43
B_{d3}	2.28	13	0.36	16	84
B_{d4}	3.83	11	1.25	14	67
B_{d5}	6.76	22	5.53	22	18
B_{d6}	12.13	27	−1.78	24	115
B_{d7}	10.48	27	9.40	27	10
B_{d8}	13.03	31	11.72	29	10

and SAT at ends of beams and slabs having unsafe designs. The difference percentages before and after mitigation along the building heights are plotted in Fig. 6. These differences are observed to significantly change along the building height before or after

Table 7 Maximum differences between moments from OA and SAT before applying mitigation alternative 2

Building designation	Max. diff. % bet. OSAb & SATb	Storey
B_{d1}	47	9
B_{d2}	38	9
B_{d3}	113	18
B_{d4}	56	19
B_{d5}	99	29
B_{d6}	554	38
B_{d7}	119	39
B_{d8}	151	50

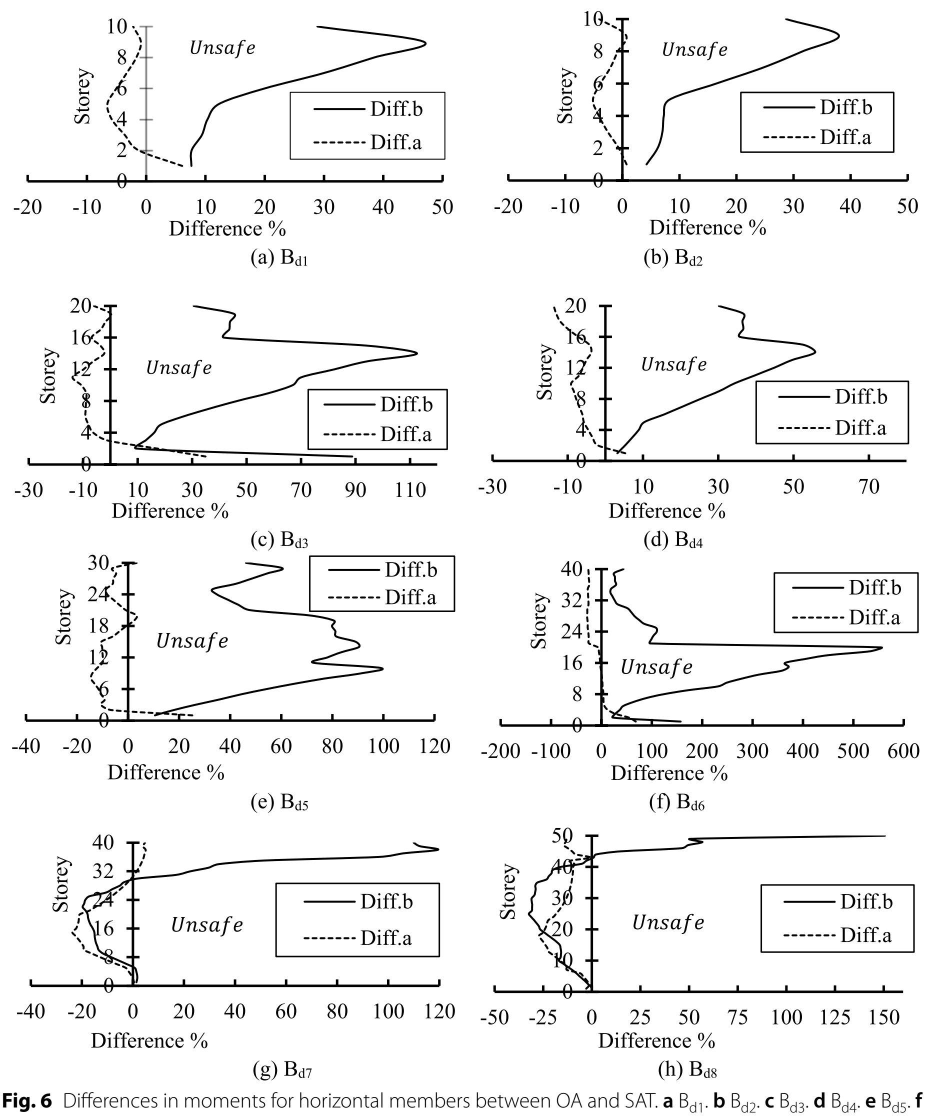

Fig. 6 Differences in moments for horizontal members between OA and SAT. **a** B_{d1}. **b** B_{d2}. **c** B_{d3}. **d** B_{d4}. **e** B_{d5}. **f** B_{d6}. **g** B_{d7}. **h** B_{d8}

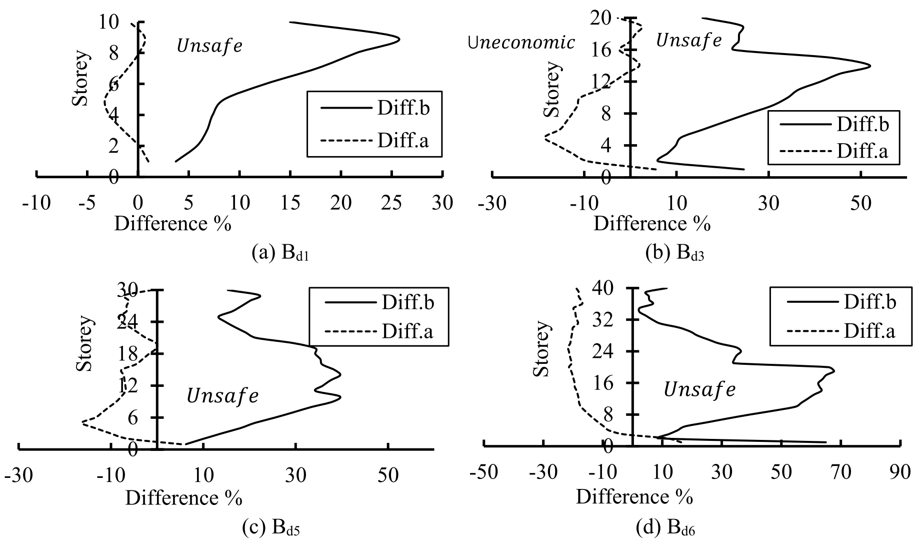

Fig. 7 Differences in shearing force at beam ends between OA and SAT. **a** B_{d1}. **b** B_{d3}. **c** B_{d5}. **d** B_{d6}

Table 8 Maximum differences between shearing forces from OA and SAT before applying mitigation alternative 2

Building designation	Max. diff. % bet. OSAb & SATb	Storey
B_{d1}	26	9
B_{d3}	52	14
B_{d5}	40	14
B_{d6}	68	19

mitigation. Table 7 shows maximum differences in bending moments between SAT and OA and their locations for the considered beams and slab strips before applying Mitigation Alternative 2. However, all these differences have been reduced to less than 5% along the height of the eight buildings after applying the proposed mitigation alternative.

Shearing forces

This section examines the effect of adopting Mitigation Alternative 2 on decreasing the differences in shearing force between OA and SAT at the beam ends with unsafe designs. Figure 7 shows the differences between the shearing force from OA and SAT with/without mitigation along the height of the studied buildings. Differences in shearing forces remarkably change throughout the building height before or after mitigation. Table 8 shows maximum differences in shearing force between SAT and OA and their locations for the considered beams before applying Mitigation Alternative 2. This indicates that OA produces unsafe designs at certain elements. However, the differences in shearing force obtained from the two analyses after mitigation do not exceed 5% for all considered buildings.

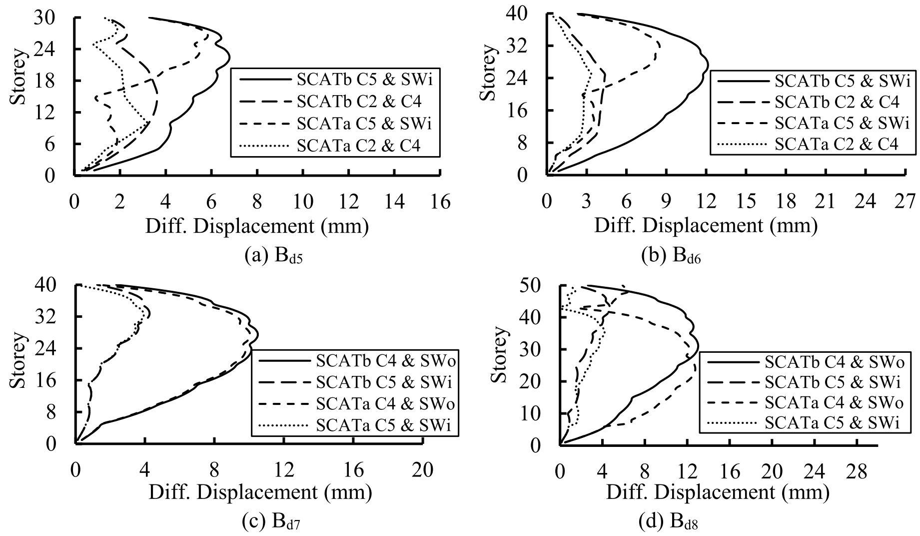

Fig. 8 Differential displacement in members due to SATb and SATa. **a** B_{d5}. **b** B_{d6}. **c** B_{d7}. **d** B_{d8}

Table 9 Maximum DD from SATb and SATa

Building	Max. DD (SATb), mm	Storey	Max. DD (SATa), mm	Storey	% reduction
B_{d5}	6.76	22	6.18	25	9
B_{d6}	12.13	31	8.45	31	30
B_{d7}	10.48	27	10.01	27	4
B_{d8}	13.03	31	12.72	23	2

Mitigation Alternative 3

The impact of locating one outrigger system at the mid-height of buildings B_{d5} and B_{d6} as well as at top of buildings B_{d7} and B_{d8} on DD between vertical supporting elements is discussed in the following subsections. Also, the influence of including this outrigger system on internal forces of slabs and beams in these buildings is presented. These locations are selected based on the location of maximum deviations in internal forces between OA and SAT.

Differential Displacement (DD)

Figure 8 shows the DD between end zones of the considered beams and strips where remarkable deviations are noticed between DD from SATb and SATa for buildings B_{d5}, B_{d6}, B_{d7}, and B_{d8}. The curves show that DD from SATb vary nonlinearly where maximum DD is located in the building middle storey. Moreover, distribution of DD from SATa is nonlinear, and the maximum DD is located at the upper storeys. Table 9 shows the maximum DD of these buildings before and after mitigation and their locations. Noticeable decreases in DD (2 ~ 30%) are observed due to locating one outrigger system along the height of the considered buildings.

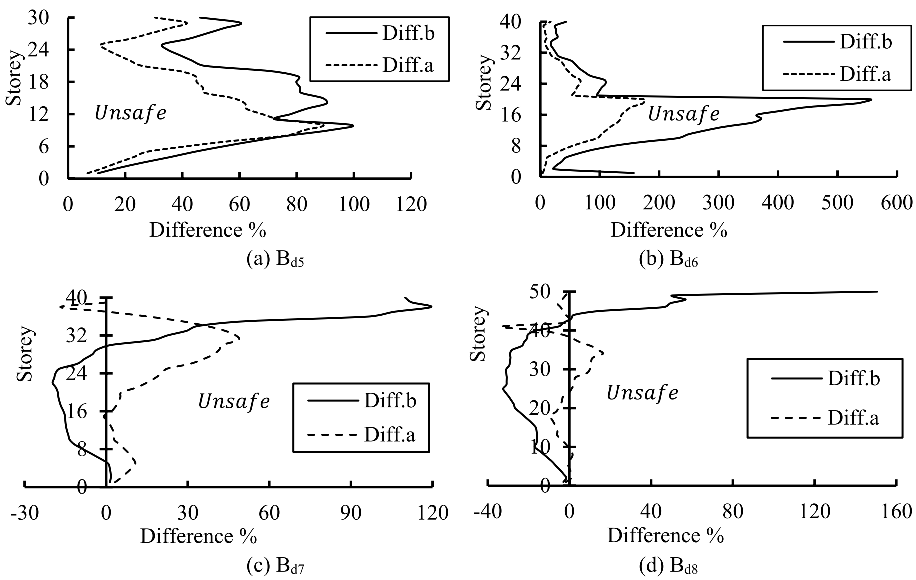

Fig. 9 Deviations in moments for horizontal members between SATb and SATa. **a** B_{d5}. **b** B_{d6}. **c** B_{d7}. **d** B_{d8}

Table 10 Maximum differences between moments from OA and SAT with/without mitigation

Building	Max. diff. % bet. OSAb & SATb	Storey	Max. diff. % bet. OSAa & SATa	Storey	% reduction
B_{d5}	99	10	90	10	9
B_{d6}	554	20	175	20	68
B_{d7}	119	39	49	31	59
B_{d8}	151	50	16	34	89

Bending moments

This section investigates the effect placing one outrigger system at the previously selected locations along the height of buildings B_{d5}, B_{d6}, B_{d7}, and B_{d8} on decreasing the deviations in moments between OA and SAT at ends of the horizontal members with unsafe designs. The original design of these ends is classified as "unsafe" where the SAT yields moments larger than those obtained from the OA. Figure 9 shows deviations between the moments from OA and SAT with/without mitigation for the four buildings. The deviations in moments are noted remarkably change throughout the building height with/without mitigation. Table 10 shows the maximum deviations between moments from SAT and OA and corresponding positions with/without mitigation. The table shows that the decreases in the deviations between SAT and OA are between 9 and 89% due to introducing one outrigger system along the building height. However, a change in the differences is observed in the lower two-third of the buildings B_{d7} and B_{d8} from uneconomic differences of 19% and 32% to unsafe differences of 49% and 16%, respectively. This indicates that the proposed location of the outrigger system might need to be adjusted to better mitigate these increases in the differences between the OA and SAT.

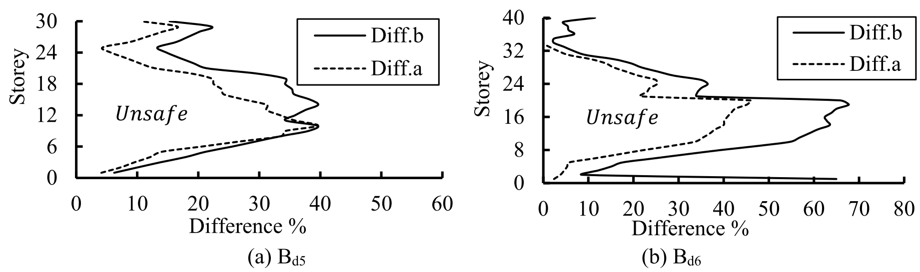

Fig. 10 Deviations in moments for beams between SATb and SATa. **a** B_{d5}. **b** B_{d6}

Table 11 Maximum deviations between shearing forces from OA and SAT with/without mitigation

Building	Max. diff. % bet. OSAb & SATb	Storey	Max. diff. % bet. OSAa & SATa	Storey	% reduction
B_{d5}	40	14	38	10	1
B_{d6}	68	19	46	20	32

Shearing forces

This section examines the impact of applying Mitigation Alternative 3 on buildings B_{d5} and B_{d6}, which have beams, on decreasing the differences in shearing force from OA and SAT at beam ends with unsafe designs. Figure 10 shows the deviations between the shearing forces from OA and SAT with/without mitigation for the two buildings. Deviations in shearing force remarkably vary throughout the building height before or after introducing the outrigger system. Table 11 shows the maximum deviations between shearing forces from SAT and OA for the two buildings and corresponding positions with/without mitigation. The decreases in the deviations between SAT and OA due to utilizing the outrigger system reach 1 ~ 32% for building B_{d5} and B_{d6}, respectively. The proposed mitigation alternative does not totally mitigate the differences in shear forces between the two analyses.

Conclusions

Efficiency of three mitigation alternatives is examined to decrease the differences between responses from OA and SAT. Dimensions for all internal vertical supporting elements are magnified in Alternative 1, while dimensions of selected internal vertical supporting elements are increased in Alternative 2. Alternative 3 is implemented by introducing one outrigger system along the building height. The three alternatives are examined by analyzing eight RC buildings having various number of storeys and different structural systems. A comprehensive FEM, which considers time-dependent effects, is utilized to conduct both OA and SAT for the analyzed buildings. One can conclude the following outcomes:

- When the cross sections of all vertical elements magnified by 50% (Alternative 1), DD between vertical elements decreased by 48 ~ 84%.

- Alternative 1 resulted in reductions in deviations between moments and shearing forces in beams and slabs from OA and SAT by 28 ~ 83% and 20 ~ 62%, respectively.
- Although significant reductions in deviations between SAT and OA are achieved due to adopting Alternative 1, none of the unsafe straining actions in beams and slabs was totally mitigated.
- Increasing the cross sections of internal columns by optimized dimension modification factor (DMF) (Alternative 2) reduced DD between vertical elements by 10 ~ 115%.
- When the studied buildings were mitigated using Alternative 2, deviations between moments and shearing forces in beams and slabs from OA and SAT did not exceed 5%.
- Locating one outrigger system on mid-height of buildings with WF system and at top of buildings with TT system (Alternative 3) reduced DD between vertical elements by 2 ~ 30%.
- Adopting Alternative 3 resulted in decreases in deviations between moments and shearing forces in beams and slabs from OA and SAT by 9 ~ 89% and 1 ~ 32%, respectively.

Derived outcomes in the current article are limited to the studied buildings' geometries and structural systems. Additional analyses should be performed to generalize these conclusions. Also, the study aimed at examining the efficiency of three mitigation alternatives in decreasing the differences between OA and SAT. An extension of the conducted research work is expected by investigating the behavior of the mitigated buildings under seismic loads.

Abbreviations

RC	Reinforced concrete
OA	One-step analysis
DS	Differential shortenings
SAT	Staged analysis including time-dependent effects
RF	Rigid frame
SW	Shear wall
WF	Wall frame
TT	Tube in tube
DD	Differential displacement
SA	Staged-construction analysis
DMF	Dimension modification factor
D_O	Old and new dimensions
D_N	New dimensions
B_d	Building
B	Beam
S	Slab strip
C	Column
Diff.	Differences
SATb	Staged analysis including time-dependent effects before mitigation
SATa	Staged analysis including time-dependent effects after mitigation

Supplementary Information

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Additional file 1. Dimensions of elements in analyzed buildings (cm).

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Authors' contributions

All authors have read and approved the manuscript. The following shows some details about the contribution of each author. AE, determined the research point, proposed modelling technique, and criticized the results. AE, criticized the results, revised the modelling technique, and revised the technical writing of the manuscript. MI, generated the models, wrote the draft of the paper, and implemented the required technical writing revisions.

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Declarations

Competing interests

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References

1. Alaa KM, El-Kashif KF, Salem HM (2022) New definition for torsional irregularity based on floors rotations of reinforced concrete buildings. J Eng Appl Sci 69:12. https://doi.org/10.1186/s44147-021-00061-5
2. Shehata OE, Farid AF, Rashed YF (2023) A suggested dynamic soil – structure interaction analysis. J Eng Appl Sci 70:63. https://doi.org/10.1186/s44147-023-00237-1
3. Bao C, Zhang Y, Lv D et al (2022) Study on mechanism and influential factors of progressive collapse resistance of base-isolated structure. J Eng Appl Sci 69:111. https://doi.org/10.1186/s44147-022-00157-6
4. Hemida OAR, Abdalla HA, Fouad HEE (2023) Flexural behaviour of recycled reinforced concrete beams strengthened/ repaired with CFRP laminates. J Eng Appl Sci 70:64. https://doi.org/10.1186/s44147-023-00235-3
5. Elansary AA, Metwally MI, El-Attar A (2021) Staged construction analysis of reinforced concrete buildings with different lateral load resisting systems. Eng Struct 242:112535
6. Elansary A, Mabrouk A, Zawam M, El-Attar A (2022) Staged-construction analysis of high-rise buildings with post-tension slabs. Arabian J Sci Eng 47:1–22
7. Taranath BS (2009) Reinforced concrete design of tall buildings. CRC Press, Boca Raton
8. Gunel MH, Ilgin HE (2007) A proposal for the classification of structural systems of tall buildings. Build Environ 42(7):2667–2675
9. Metwally MI (2020) Staged construction analysis of reinforced concrete buildings with different lateral load resisting systems. Ph.D. Thesis. Faculty of Engineering, Cairo University, Cairo
10. Raksha HL, Karthik S, Madhukeshwara JE (2016) Influence of axial shortening of vertical member in the tall structures. Int J Res Eng Technol 05:322–329
11. Elansary AA, Metwally MI, El-Attar A (2023) Structural system yielding minimum differences between ordinary and staged analyses. J Eng Appl Sci 70:1–18
12. Fintel M, Ghosh SK, Iyengar H (1987) Column shortening in tall buildings-prediction and compensation. Publ. EB108 D, Portland Cement Assoc Skokie 3:1–34
13. Park HS (2003) Optimal compensation of differential column shortening in high-rise buildings. Struct Design Tall Spec Build 12(1):49–66
14. Kim HS (2015) Optimum distribution of additional reinforcement to reduce differential column shortening. Struct Design Tall Spec Build 24(10):724–738
15. Kim HS, Shin SH (2011) Column shortening analysis with lumped construction sequences. Proc Eng 1(14):1791–1798
16. El-leithy NF (2010) Comparative study of structural systems for tall buildings. M.Sc. Thesis. Faculty of Engineering, Cairo University, Cairo
17. Sitapara KD, Gore NG (2016) Review on feasibility of high-rise outrigger structural system in seismically active regions. Int Res J Eng Technol 3(05):1427–1432
18. Choi HS, Joseph L (2012) Outrigger system design considerations. Int J High Rise Build 1(3):237–246
19. Institute SE (2006) Minimum design loads for buildings and other structures. ASCE/SEI 7–05. vol. 7. American Society of Civil Engineers, Reston, Virginia
20. Committee ACI (2019) Building code requirements for structural concrete (ACI 318–19) and commentary (ACI 318R-19). American Concrete Institute
21. Midas IT. Analysis for civil structures 2012:400. https://www.midasstructure.com/en/. Accessed Dec 2023
22. Kim HS (2017) Optimum design of outriggers in a tall building by alternating nonlinear programming. Eng Struct 150:91–97
23. Metwally MI, Elansary AA, El-Attar A (2020) Optimum location of outriggers in reinforced concrete buildings with tube in tube system using staged-construction analysis. Int J Adv Res Eng Technol 11(8):335–347

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