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Wind-induced response of half-storey outrigger brace system in tall buildings

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In all previous studies, the outrigger arms are symmetric with respect to the centre line of the core. Hence, each outrigger involves two arms at the same level which usually occupy one, two or three stories. In this communication, the innovative idea is to implement the outrigger arms asymmetrically. One main purpose of this study was to investigate the feasibility study of four half-storey outriggers system instead of the corresponding two-storey outrigger system. To study the effects of the newly defined configurations on the global performance of tall buildings, some 30-, 45- and 60-storey two-dimensional steel frames with braced core systems at centre have been analysed and designed under gravity and wind load without outriggers. Later, the outrigger trusses were added in different arrangements at the optimum locations. The results show that the new idea will improve the system efficiency.

Keywords: Half-storey-outrigger, inter-storey drift, steel frame, wind load.

IN tall buildings, there are many points and design criteria which should be considered by structural engineers. The most important design criteria may be strength, serviceability, stability and human comfort. The goal of the designer is to attain convenient schemes, to satisfy these criteria, and achieve the lowest weight per unit area for the structure[1]. Mendis *et al.*[2] recommend that a limit of $H/500$ should be used for the maximum inter-storey drift (IDR) to assure serviceability under wind load (H is the total height of the building). This value is consistent with a recommendation given in the National Building Code of Canada and survey results which indicated that designers of steel-framed buildings in USA use a drift limit ranging from $H/600$ to $H/200$.

While 35 to 40-storey buildings can conventionally rely solely on shear wall and braced core systems, the resistance of these systems to lateral displacement decreases approximately with the cube of building height. Thus, braced core systems become highly inefficient for taller buildings[3,4]. The outrigger system is capable of providing up to 25–30% additional stiffness compared to a system without such trusses[5]. Taranath[6] studied the optimum location of a single outrigger added to the structural system with the aim of reducing the building roof displacement under the wind load and presented an

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approximate method of analysis. In that study, the cross section of the structure and components such as columns and braces were identical along the height of the building.

Smith and Salim[7] considered the flexural action of outriggers and presented some graphs which give the optimum location of the outriggers of a multi-outrigger building with a uniform cross-section of structure along the height, subjected to the uniform lateral load. Also, as a simple approximate guideline for the optimum performance of a multi-outrigger structure with *n* outriggers, the location of the outriggers should be determined at $1/(1 + n)$, $2/1 + n)$ up to $(n)/(1 + n)$ height location.

In all the studies carried out by other researchers, the frames have some outrigger arms which are symmetric with respect to the centre line of the core. The new idea in this communication is to locate arms only at one side of the core in each level while their directions are switched alternatively along the height of the frame. Hence, utilizing some half-storey outriggers builds an asymmetrical configuration as shown in Figure 1. The performance of such systems has not been studied previously by other researchers.

The main purpose of this study is to define the feasibility using of two-half-storey and four-half-storey outrigger systems in lieu of corresponding one- and two-outrigger systems. Some two-dimensional frames which have braced core systems at centre and have the same height to width ratio (aspect ratio) of 6.3, have been analysed and designed under the gravity and wind load without outriggers (reference models). The roof displacement, the maximum inter-storey drifts of the frame and the base moment of the core have been obtained. As the aim is to evaluate the effect of newly defined configurations on the performance of the systems, the structural design of elements is carried out only for strength criteria, and not for displacement criteria. Subsequently, outriggers are added in different arrangements. Firstly, a one-storey outrigger is placed at an optimum location for minimizing the roof displacement. The calculation of optimum location of outriggers is explained below. Later, the one-storey outrigger is removed and two half-storey outriggers are placed at two approximate optimum levels.

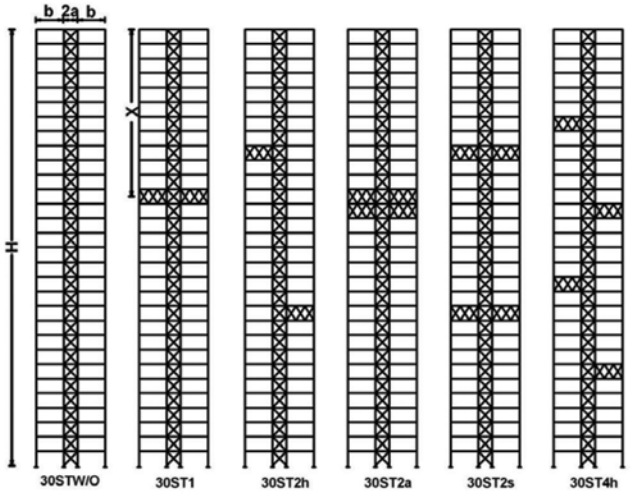

Figure 1. Elevation of the 30-storey frames and different arrangements of the outrigger(s).

Secondly, one outrigger consisting of a two-adjacent-storey truss is placed at the optimum location in the reference model, then, it is separated by two one-storey outriggers at two approximate optimum levels, as well as separated by four half-storey outriggers at the approximate optimum levels. In all the models, the explained response parameters, mentioned for reference models, are measured. Finally, the results of the systems are evaluated and compared.

Because of the scope limit, lateral load is supposed to be the wind load, the behaviour of the systems is expected to be linear elastic. It is worth mentioning that in tall buildings to reduce the effects of motion perceptibility due to wind loads, perhaps one of the most important design criteria is serviceability and human comfort. Furthermore, in low and moderate seismic regions, the design of the lateral resisting system will likely be governed by wind rather than seismic forces[8]. In this paper the limit of H/500 is assumed as a criterion merely to assess the results and to get intuition.

To study the effect of the newly defined configurations on the global performance of the tall buildings, finite element (FE) models of 30, 45 and 60-storey steel frames are made. The height of the stories in all of them is 3.7 m. The yielding stress of the steel is 2400 kg/cm^2. Figure 1 shows the general elevation of frames and the various arrangements of outriggers for the 30-storey building. In all models, the beam connections to the columns and the columns connections to the foundation are of pinned type. Table 1 represents the value of the parameters used in the models. The descriptions of the abbreviated names are explained in Table 2.

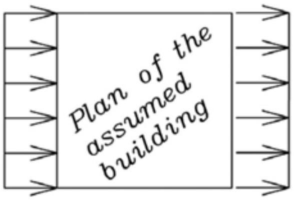

Figure 2. Wind load case.

Table 1. Descriptions of the models

No. of stories	2*a* (m)	*b* (m)	*H* (m)	Aspect ratio
30	3.5	7	111	6.34
45	5.25	10.5	166.5	6.34
60	7	14	222	6.34

Table 2. Abbreviation descriptions of the models

Model	Description
NSTW/O*	N-storey frame without any outrigger
NST1	N-storey frame with *a*1-storey outrigger at the optimum location
NST2H	N-storey frame with 2 half-storey outriggers along the height at the approximate optimum locations
NST2A	N-storey frame with 2 adjacent storey outrigger at the optimum location
NST2S	N-storey frame with 2 separated storey outriggers along the height at the approximate optimum locations
NST4H	N-storey frame with 4 half-storey outriggers along the height at the approximate optimum locations

*N is the total Number of the stories.

Table 3. Specification of the elements cross-sections

		Beam section (cm)		Core column section (cm)		Outside column section (cm)		Outrigger section (cm)	
Frame stories		A (cm^2)	I (10^4 cm^2)	A (cm^2)	I (10^4 cm^2)	A (cm^2)	I (10^4 cm^2)	A (cm^2)	I (10^4 cm^2)
30 stories	0–5	360	12.7	3719	574	984	110	231	5.7
	5–10	360	12.7	2404	482	825	93	231	5.7
	10–15	360	12.7	2100	386	624	63	201	3.7
	15–20	360	12.7	1616	275	424	20	201	3.7
	20–25	360	12.7	1456	201	162	3	171	2.3
	25–30	360	12.7	1456	201	162	3	171	2.3
45 stories	0–5	450	24.2	7780	1400	3720	574	344	10.6
	5–10	450	24.2	8490	1403	3636	450	344	10.6
	10–15	450	24.2	6300	1050	3369	430	344	10.6
	15–20	450	24.2	5400	674	3192	400	261	8.2
	20–25	450	24.2	5400	674	2925	369	261	8.2
	25–30	450	24.2	1900	286	1719	261	261	8.2
	30–35	450	24.2	1456	201	1456	201	210	6.7
	35–40	450	24.2	1376	169	1376	169	210	6.7
	40–45	450	24.2	1141	126	1211	151	210	6.7
60 stories	0–5	540	41.0	12496	3406	3719	565	384	14.7
	5–10	540	41.0	11500	2860	3636	498	384	14.7
	10–15	540	41.0	10620	2430	3370	429	384	14.7
	15–20	540	41.0	10200	2170	3190	400	384	14.7
	20–25	540	41.0	9780	1940	2930	370	344	10.6
	25–30	540	41.0	7780	1400	1720	260	344	10.6
	30–35	540	41.0	6300	1050	1460	200	344	10.6
	35–40	540	41.0	5700	790	1380	170	344	10.6
	40–45	540	41.0	5700	790	1210	150	261	8.2
	45–50	540	41.0	5400	670	820	90	261	8.2
	50–55	540	41.0	5100	580	780	80	261	8.2
	55–60	540	41.0	5100	580	580	50	261	8.2

Note: A is the area and I is the moment of inertia of the cross-section.

The present study is aimed at considering the actual load. The wind load is therefore applied on models according to ASCE7-05 (ref. 9) and it is assumed that the depth of the wind load bearing face for all the models (perpendicular to the plane of the modeled frame) is 10 m wide. Furthermore, dead and live loads for this width are assumed to be 500 and 200 kg/m^2 respectively, which are all carried by the frame. Since the models are two-dimensional frames, only case 1 of the wind load cases, according to the figures 6–9 of ASCE7-05 (ref. 9), is assumed to be applied on the building, which can be seen in Figure 2.

The ETABS version 9.2 (ref. 10) software is used to apply the above mentioned loads and to perform the FE analysis and design the frames. First, the three systems without any outrigger have been designed based on AISC-ASD05 (ref. 11). The p–Δ effect has been considered in the analysis. The drift criteria have been ignored during design. After designing the systems without outrigger, outriggers are placed and the systems re-analysed. Since the outrigger systems are not designed and the outrigger may affect the force distribution among elements, during the design of non-outrigger systems the consideration is to take some elements a little overdesigned. This approach may require an iterative method of design. If all the models had been designed according to code requirements, the drift of the models would have been the same, so we would not be able to compare some of the most significant performance factors. It should be noticed that one of our intentions is to determine the reduction of the drift of the models by utilizing the new idea, so we are not supposed to design all the models; in this way the achieved results can be compared to each other. The designed specifications of the elements are represented in Table 3.

In 30ST1, 30ST2A, 45ST1, 45ST2A, 60ST1 and 60ST2A models, which have single belt, to find the best location of the outrigger to minimize the top displacement, the outrigger is moved from top to base level and the roof displacement is recorded for each level. This process and the results are represented in Figure 3. In this figure the horizontal axis is the roof displacement and the vertical axis shows the location of the truss belt along the normalized height. Optimum locations of the outrigger derived from this trial method and also from the graphical solution of Smith and Salim[7] as well as Chung[12], elaborated for triangular load and uniform cross-section elements, are compared in Table 4. In this table, it can be easily seen that these two methods have a good compatibility. It is noted that, because in the models of this communication, the sectional properties of elements are varying along the height, the average value of element cross-section properties is used to calculate the parameters needed to find the optimum location from graphical solution of the mentioned references. The optimum location of the outriggers is on an average 0.35 times the building height measured from the top for these models. This optimum location is only for the models and more study would be needed to generalize the results.

In the other models, the graphical solution of Chung[12] is used to find the optimum location of outriggers. However, those graphs are developed for the system with whole outrigger (trusses in entire storey). In this study, as was mentioned earlier, they are used to determine the approximate optimum location of the half-outriggers. Finally, the optimum locations of the outriggers can be observed in Table 5.

For the design of a tall building, the fulfilment of serviceability criteria may be carried out by limiting the maximum amount of drifts and displacements due to the wind load. Figures 4 and Figure 5 display the lateral displacement ratio and the inter-storey drift angle of the designated models. In Figure 4, the baseline of 1/500 has been drawn to make sense to compare the response of the models (Δ is the roof displacement in that figure). The roof displacement of the 60-storey frame comprising four half-outrigger separately (60ST4H) is 66% of the same model which has a two-storey outrigger (60ST2A). In these two models, the occupied bays by outriggers and the structural material weight are identical, but the lateral displacement has a distinct difference.

In Figure 5, it is obvious that the inter-storey drift angle of the stories is reduced rapidly around the outrigger level. This is because of the resistance of truss-belt against rotation of the core due to the axial action of outside columns. In other words, the core has a tendency for rotation, thus the outrigger should rotate, while the outside columns have axial stiffness, so they obviously resist the rotation of the outrigger and reduce the rotation of the storey containing outrigger. Accordingly, the inter-storey drift angle in the stories nearby the outrigger is reduced and overall, the lateral displacement of frames will be moderated. For example, the maximum inter-storey drift angle of the 60ST2A model is 0.0039 while this factor for the 60ST4H model is 0.0023 which is 59% of the first one. This fact is approximately true for the other models with 30 and 45 stories. Moreover, it seems that the drift ratio along height is most moderate for the 45ST4H model.

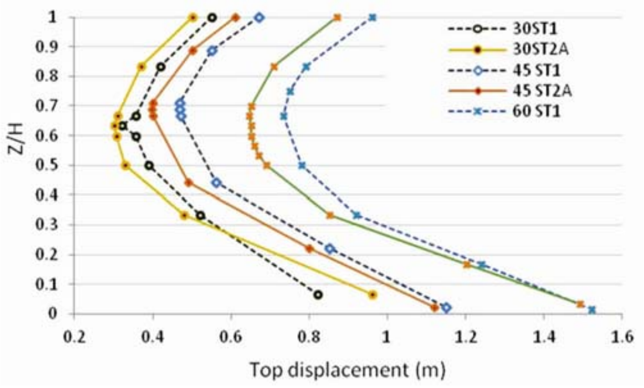

Figure 3. Determining the optimum location of the outrigger for one-outrigger models.

Table 4. The optimum location of the outriggers for multi-outrigger models

Type of frame	*X*/*H*			
30ST2H	0.280		0.620	
45ST2H	0.500		0.216	
60ST2H	0.210		0.457	
30ST2S	0.280		0.620	
45ST2S	0.500		0.216	
60ST2S	0.210		0.457	
30ST4H	0.184	0.400	0.580	0.760
45ST4H	0.148	0.332	0.500	0.632
60ST4H	0.132	0.316	0.416	0.584

Table 5. Optimum location of the outrigger for one-outrigger models

Type of frame	Optimum *X*/*H* from trial method	Optimum *X*/*H* from graph
30ST1	0.38	0.39
30ST2A	0.38	0.41
45ST1	0.32	0.30
45ST2A	0.32	0.38
60ST1	0.34	0.25
60ST2A	0.34	0.34
Average	0.35	0.34

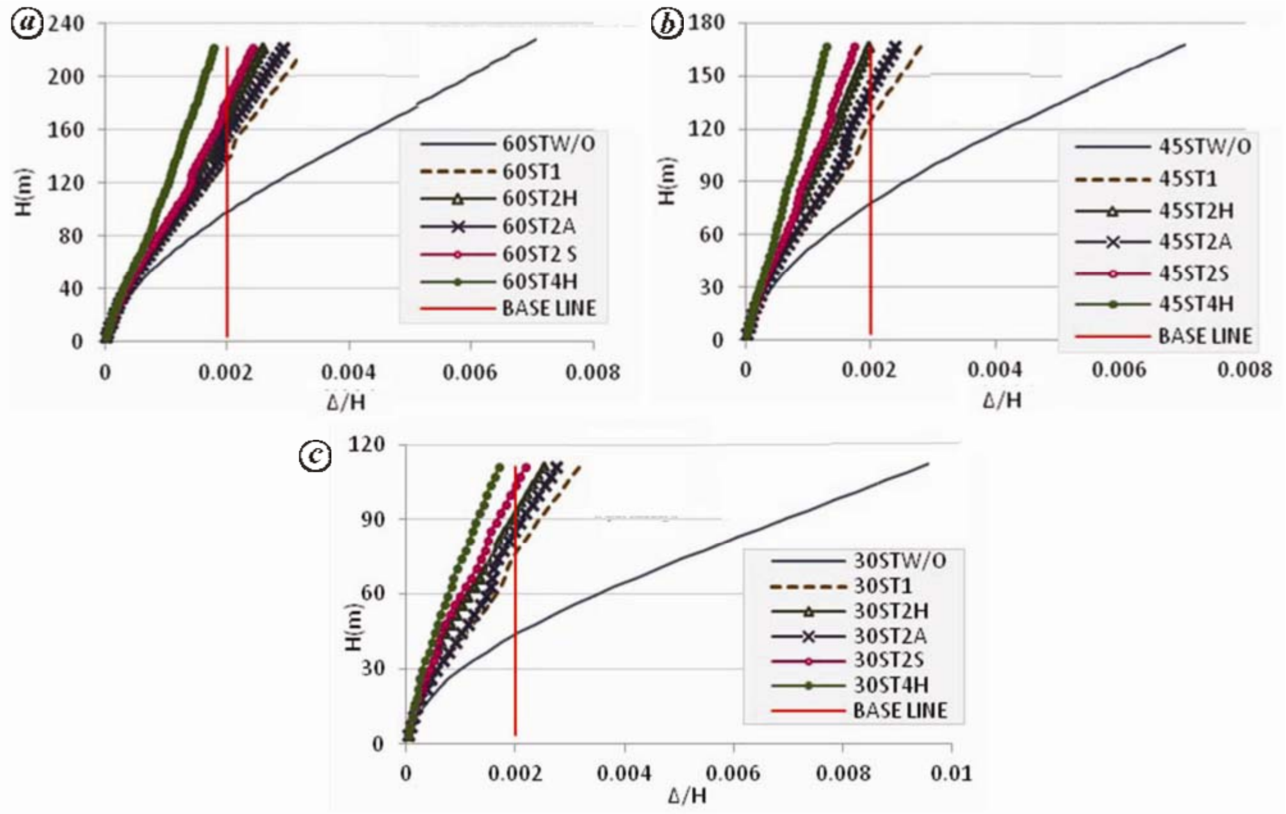

Figure 4. Lateral displacement of frames. ***a***, 60-storey, ***b***, 45-storey, ***c***, 30-storey.

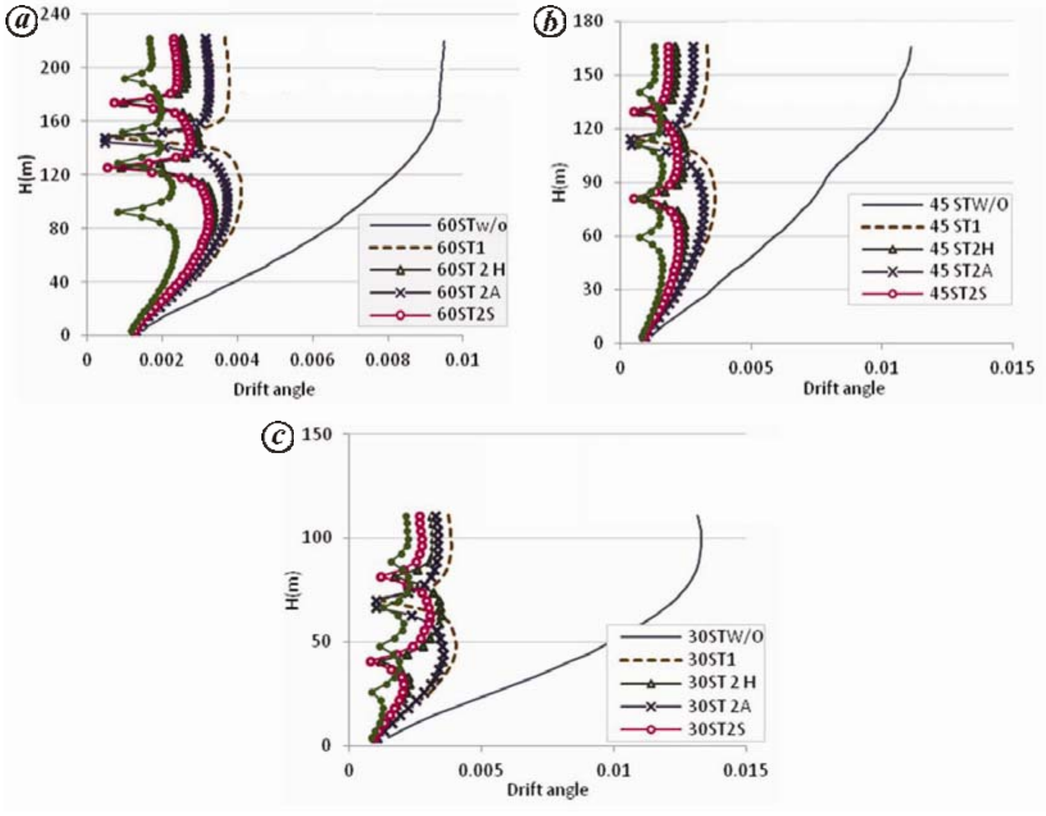

Figure 5. Inter-storey drift angle of frames. ***a***, 60-storey, ***b***, 45-storey, ***c***, 30-storey.

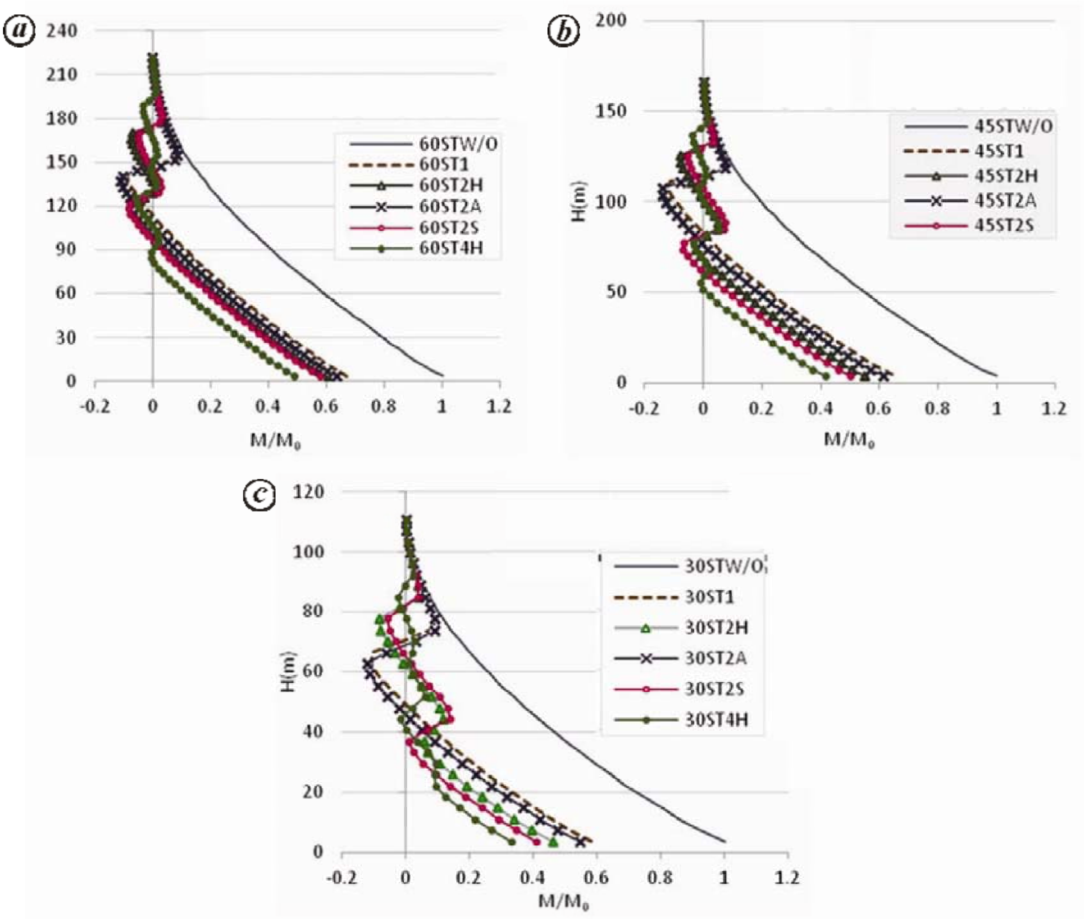

Figure 6. Core moment of frames. ***a***, 60-storey, ***b***, 45-storey, ***c***, 30-storey.

The action of the outrigger on the core is similar to applying an external moment on the core of the frame which is opposite to the direction of the moment induced due to the wind load. Hence, in Figure 6, reduction of the core moment happened abruptly at the outrigger level. The horizontal axis of this figure is the ratio of the moment of distinct model in each level to the core base moment of the system without any outrigger (M0). The more the number of separated half-outriggers, the smaller the amount of core moment at the base level. Besides, the direction of core moment changes alternatively in some models along the height, which would be interpreted as a more suitable performance of the systems. For example, the amount of the core moment at the base level of the 60ST4H model is 23% less than the amount of the core moment at the base level of the 60ST2A model.

The new concept of using two half-storey outriggers in lieu of a one-storey outrigger and also using four half-storey outriggers in lieu of one two-storey outrigger was studied here. To study the effect of the newly defined configurations on the global performance of tall buildings, modelling, analysing and designing of 30, 45 and 60-storey two-dimensional braced core systems without outrigger subjected to the gravity and wind load were carried out, then the outriggers with various arrangements placed at approximate optimum locations along the height. It was obvious that the idea of using two half-storey outriggers along the height instead of a one-storey outrigger system was more effective, while the number of braced bays for outrigger arms are the same for both of them. Also this fact is valid for a four-half-storey outrigger system instead of a two-storey outrigger system. The decrease in values of the roof displacement, the inter-storey drift, the core base moment and the fundamental time period of the models are demonstrated in Table 6. For example, a reduction of 39% in the top displacement, a reduction of 41% in the maximum inter storey drift and a reduction of 32% in the core base flexural moment for NST4H models (models contained four half-outriggers separately along the height which included the 30ST4H, 45ST4H and 60ST4H) compared to NST2A (models contained a two-storey outrigger at the optimum location which included the 30ST2A, 45ST2A and 60ST2A) are achieved using the new idea. These results are encouraging and the new configuration may be used to mitigate the motion of the tall buildings.

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