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NUMERICAL STUDY ON BEHAVIOUR OF NON-TOWER BUILDING ATTACHED WITH TOWER

Md Taqiuddin[1], Dr V. Lakshmi Shireen Banu[2]

[1] Post Graduate Student, Department Of Civil Engineering, Malla Reddy Engineering College (Autonomous), Hyderabad-500100, India.
[2] Associate Professor, Department of Civil Engineering, Malla Reddy Engineering College (Autonomous), Hyderabad-500100, India.

ABSTRACT:- *Podium surrounding tower walls are often widely preferred for multifaceted functionality of Tall buildings. Horizontal offset buildings constitute a class of structures that are particularly prone to in-plane floor deformation and torsion occurring simultaneously. It is found from previous studies that podium can impose significant differential restraint on coupled tower walls, these walls displaces under lateral loads contributing to the generation of in-plane strutting forces in podium floors leading to its un-conservative design. The in-plane rigid diaphragm assumption commonly adopted in practice can significantly suppress these strutting forces. Key parameters contributing to these in-plane strutting forces and drift at top of tower are analysed by way of parametric studies on representative models of the podium-tower assemblage by incorporating in-plane flexibility in modelling for different sizes of podium with beam-column frame and flat slabs structure, introducing extended blade walls and outriggers in podium to minimize the effect of strutting forces and study the contribution of podium in controlling tower displacement.*

Keywords: Podium-tower buildings, Backstay effect, In-plane Strutting forces, Floor diaphragms, Jump-formwork, Connectrix boxes.

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1. INTRODUCTION

Modern architectural design of mixed use complex has introduced a building system which consists of multiple high-rise towers sitting on a common podium. Podiums are augmented floor area at the lower level of a high rise building surrounding it as shown in (Fig. 1.1). These are common in metropolitan areas in regions of low-to-moderate seismicity. A podium may be permitted in plot admeasuring 1000 sq.m or more. The podium provided with ramp may be permitted in one or more level, total height not exceeding 32 m above ground level [*DCR-2034*].

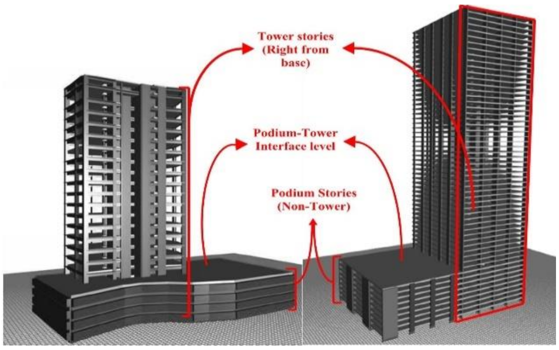

Figure 1.1

At the podium-tower interface, horizontal forces are transferred from the tower to the podium. Reactive forces are developed at the podium-tower interface to resist the overturning actions (Fig. 1.2). This reacting mechanism is similar to the backstay phenomena. It can induce high intensity shear force in the structural (tower) wall within the podium. The amplitude of the induced shear force is dependent on the in-plane flexibility of the floor structure connecting the pair of walls. This was recently studied by Mehair Yacobian et al.[1]. Avigdor Rutenberg [2] studied the prevalence of incompatibility (strutting) forces in slabs and beams connecting structural walls of different base dimensions. The Lateral load displaces tower walls and is responsible for generation of in-plane strutting forces in podium floors leading to its un-conservative design. But the in-plane rigid diaphragm assumption commonly adopted in practice can significantly suppress compatibility forces generated within the podium floor. Therefore, this strutting action can only be reported accurately if the horizontal in-plane deformation of the floor diaphragm has been incorporated into the modelling. This was stated by Gardiner et al. [3]. Therefore, podium slabs are defined as semi-rigid Shells in modelling and casted monolithic on site. [Refer Table 1]

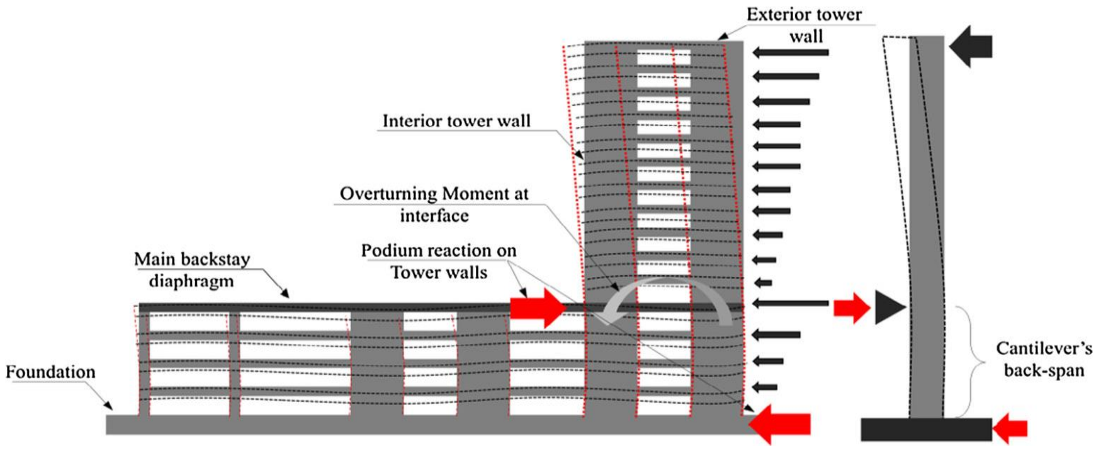

Figure 1.2

These reactive forces are *strutting forces* as shown in (Fig 1.3). One of the objectives of this study is to reduce strutting forces at podium-tower interface level.

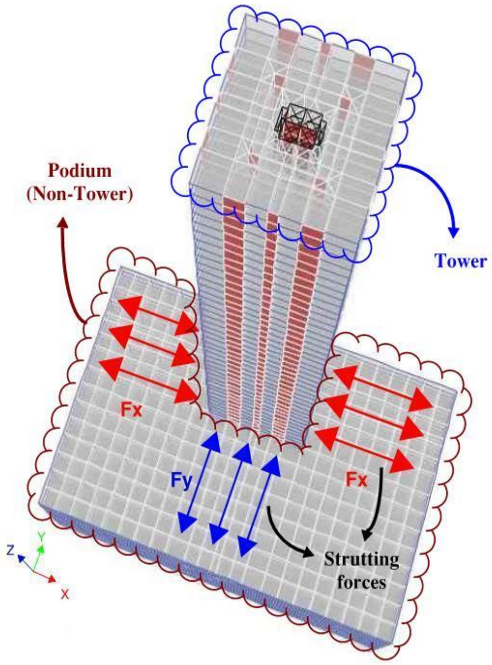

Figure 1.3

IS 16700-2017(Criteria for Structural Safety of Tall Concrete Buildings), clause 7.3.11 *"Stiffness of flat slab frames (that is, slab-column frames) shall be ignored in lateral load resistance, in all seismic regions".* Tall building code suggests that stiffness of slabs is ignored in all seismic zones, i.e., Slabs in tall buildings are infinitely stiff and lateral load is transferred 100% to vertical structural elements without any membrane deformation. Therefore, no in-plane stresses and no out of plane bending moments are reported in slabs of tower structure. To make this happen in software (ETABS) and practically on site, the slabs in tower are dealt as follows:

Software (ETABS): As discussed above, with reference of Table-1, we have to define modelling type of slab as 'membrane' (as it has no out of plane bending moments) and assign a 'rigid' diaphragm (as it has no in-plane stresses).

Practically on site: In order to satisfy the guidelines of code, stiffness of slab for lateral loads is ignored by implementing the latest construction practice of *"Jump formwork with* Connectrix *boxes"*

Table-1

Property of diaphragm/slab	In-plane stresses	Out of plane bending
Rigid	No	Yes
Semi-rigid	Yes	Yes
Membrane	Yes	No
Shell	Yes	Yes

Rigid diaphragms are infinitely stiff; therefore relative displacement between any two points/joints is zero. These diaphragms don't report shell stresses and in-plane forces, but reports out of plane bending, whereas Semi-rigid diaphragms report both in-plane stresses and out of plane bending. Membranes transfers load directly to supporting structural objects and do not take part in load bearing; load is transferred 100% to the vertical members (based upon their own stiffness). In shells, the stiffness of diaphragm and associated members contributes in load transfer; therefore resist a portion of the load through flexural deformation.

Jump formwork system (also referred as self-climbing or self-lifting) to construct the central core walls. The central core is typically constructed ahead of the residential wings by using a climbing formwork system as shown in Figure 1.4. The formwork supports itself on the concrete cast earlier so does not rely on support or access from other parts of the building or permanent works.

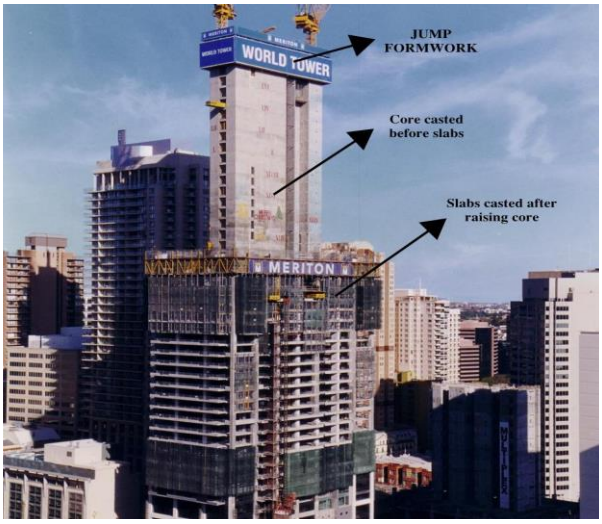

Figure 1.4

Connectrix connection box is used to eliminate/reduce the moment transfer from slab to vertical elements. Box installation is as shown in Figure 1.5 and is widely suitable for:

- Wall to Slab Connections
- Slab to Slab Connections
- Wall to Wall Connections
- Stair Landing Connections

Figure 1.5

2. NUMERICAL STUDY

The structural model adopted for the study is a tall building with 50 storeys, the plan area is 30 m x 30 m. The structural configuration is a 'tube in tube' lateral load resisting system. Later podium structure is attached to the existing tower and the studies are carried out on 18 models by changing the structural configuration of podium structure.

Case (I) : Independent tower model.

In order to understand the contribution of podium, we need to identify the analysis results of an individual tower model independent of podium.

Case (II) : Podium-tower with 10 m podium width.
Case (III): Podium-tower with 20 m podium width.
Case (IV): Podium-tower with 30 m podium width.
Case (V): Podium-tower with 40 m podium width.

From Case – II to Case – V, Podium (a non-tower structure) is attached to the tower on its three sides with 10 m, 20 m, 30 m and 40 m width. Tower is at one side of podium. The sensitivity study is done by varying structural configuration of podium as following options:

i. Slab with beams of 10 m span.
ii. Flat Plate with columns at 10 m distance.
iii. Flat Plate with columns at 5 m distance .
iv. Flat Plate with columns at varying distance.

Case (VI): Outrigger in podium.
Case (VII): Extended blade walls in podium.

2.1 Description of Building Model

The podium-tower assemblage adopted is as follows for loading in Table-2

– Number of floors = 3B+G+50 *(**153** m)*
– Number of podium floors = 3B+G+9 (***30****m)*
– Storey height = 3 m *(3.5 m for basements)*
– Grade of concrete
  Base to G+20 = M60
  G+21 to G+40 = M55
  G+41 to G+50 = M50
– Sectional properties changed for every 10 floors
– Cracking of elements (as per IS 16700-2017)
  Beams = 0.7 (M.O.I about 2 and 3 axis)
  Slabs = 0.35 (Bending M11 and M22)

Table-2

Type of load	**Intensity**
SDL(Finishes, ceiling and services)	1.5 (kN/m^2)
Live load	2.0 (kN/m^2)
Partition wall load	2.0 (kN/m^2)
Facade (Glass)	4.0 (kN/m)
Wind speed	44 m/sec (Hyderabad)
Terrain category - Structure class -	2 C

Table-3: Sectional properties

Structural elements		Sectional Properties
Tower columns	G+41 – G+50	450 x 450
	G+31 – G+40	600 x 600
	G+21 – G+30	700 x 700
	G+11 – G+20	850 x 850
	B – G+10	1000 x 1000
Tower walls	G+41 – G+50	300
	G+31 – G+40	350
	G+21 – G+30	400
	G+11 – G+20	450
	B – G+10	500
Retaining wall		400
Depth of tower peripheral beams		750
Peripheral beams of tower in podium		400 x 1200
Beams in podium		400 x 1200
Peripheral beams in podium		300 x 800
Columns in podium		800 x 800
Tower slabs (rigid membrane)		250
Podium slabs (semi rigid shell)		270
Outriggers		7500 x 500
Blade walls		3500 x 600

2.2 Analytical Models

P-Delta effect is considered for analysis, which is a non-linear effect and studied for wind forces in X and Y directions to compare following results.

a) Displacement at the roof level.
b) Moment contributed by outer core, inner core and retaining wall at the base.
c) Moments in slab at podium-tower interface.
d) Stresses in slab at podium-tower interface.
e) Strutting forces in slab at podium-tower interface.

Case (I) : Independent tower model

An independent tower with plan and elevation views as shown in Figures 2.1 and 2.2. The tower has 3 basements and G+50 floors, total height of building above G.L is 150 m. Table-4 shows the results from analysis, it is observed that the tower displacement is exceeding the allowable limit.

Allowable displacement is **H/500**

=> (153000)/500 = **306 mm.**

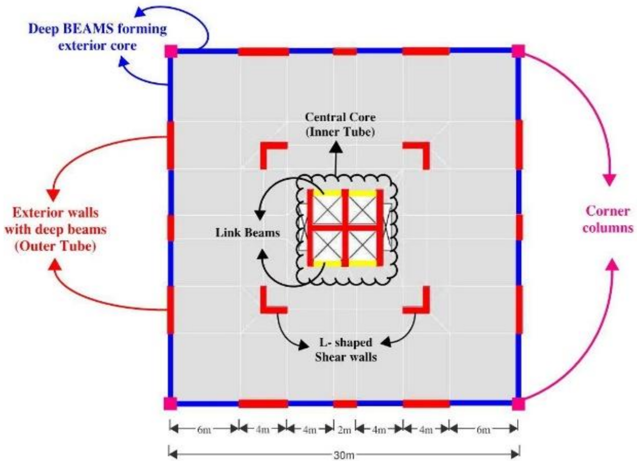

Figure 2.1

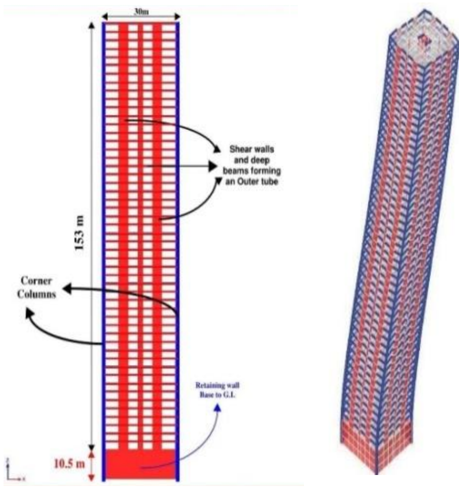

Figure 2.2

Table-4: CASE – I Independent Tower

Displacements (mm)	Wind X	488
	Wind Y	517
	Allowable (H/500)	306
	% reduction for Wind X	-37.3
Total moment	My for Wx (kN-m)	1766013
	Mx for Wy (kN-m)	1787986
Moment contribution (Wind X)	Outer core (kN-m)	1607642
	%	91.0
	Inner core (kN-m)	158370.6
	%	9.0
	Retaining wall (kN-m)	included with outer core
	%	-
Moment contribution (Wind Y)	Outer core (kN-m)	1745442.9
	%	97.6
	Inner core (kN-m)	42543.24
	%	2.4
	Retaining wall (kN-m)	included with outer core
	%	-
Stresses/Moments/Axial forces	-	-

Case II - Podium-Tower with 10 m Podium Width

Option – (i) Slab with beams of 10 m span:

Podium (a non-tower structure) is attached to the tower on its three sides with 10 m width. Tower is at one side of podium as shown in Figure 2.3

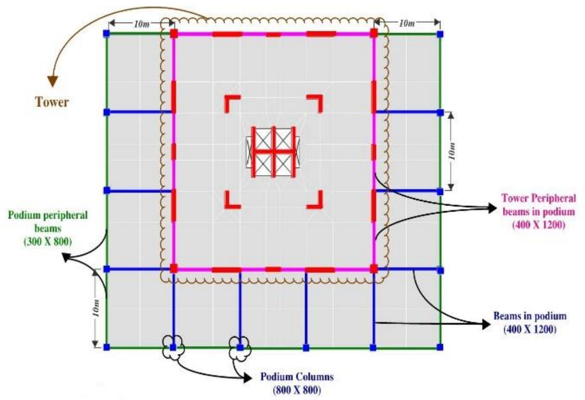

Figure 2.3

Table-5: Case II – (Option - i)

Displacements (mm)	Wind X	360
	Wind Y	384
	Allowable (H/500)	306
	% reduction for Wind X	-26.2
Total moment	My for Wx (kN-m)	1788293
	Mx for Wy (kN-m)	1814857
Moment contribution (Wind X)	Outer core (kN-m)	552582
	%	30.9
	Inner core (kN-m)	71531
	%	4.0
	Retaining wall (kN-m)	851227
	%	47.6
	Podium columns **(%)**	17.5
Moment contribution (Wind Y)	Outer core (kN-m)	662422
	%	36.5
	Inner core (kN-m)	29037
	%	1.6
	Retaining wall (kN-m)	878390
	%	48.4
	Podium columns **(%)**	13.5
Stresses in podium diap.	S11 for Wx (MPa)	2.2
	S22 for Wy (MPa)	2.1
Moments in podium diap.	M11 for Wx (kN-m)	29
	M22 for Wy (kN-m)	31
Axial forces in podium diap.	F11 for Wx (kN/m)	147
	F22 for Wy (kN/m)	133

From Table-5, the drift at top of tower is controlled by 26%, even though the allowable limit is not satisfied. On the other hand, depth of beams in podium is reducing the storey height. Simultaneously, axial forces are generated in beams and interface level slab of podium model, which makes the design complicated and requires more steel. Hence, there is a need to study with flat slabs instead of beam-slab.

Option – (ii) Flat slab with columns at 10 m distance:

The podium comprises of flat slabs with peripheral beams as shown in Figure 2.4. The interior beams in podium structure are eliminated because such deep beams are reducing the floor height.

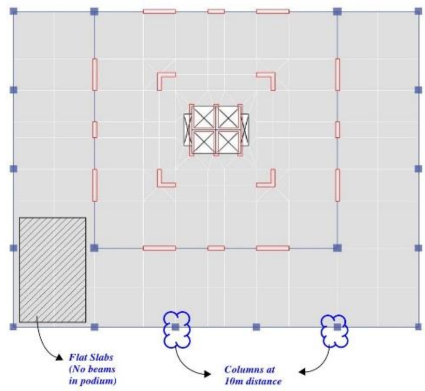

Figure 2.4

Table-6: Case II – (Option - ii)

Displacements (mm)	Wind X	385
	Wind Y	404
	Allowable (H/500)	306
	% reduction for Wind X	-21.1
Total moment	My for Wx (kN-m)	1788293
	Mx for Wy (kN-m)	1814857
Moment contribution (Wind X)	Outer core (kN-m)	763601
	%	42.70
	Inner core (kN-m)	80473
	%	4.5
	Retaining wall (kN-m)	661668
	%	37.0
	Podium columns **(%)**	15.8
Moment contribution (Wind Y)	Outer core (kN-m)	820315
	%	45.20
	Inner core (kN-m)	29037.712
	%	1.6
	Retaining wall (kN-m)	787647
	%	43.4
	Podium columns **(%)**	9.8
Stresses in podium diap.	S11 for Wx (MPa)	2
	S22 for Wy (MPa)	1.9
Moments in podium diap.	M11 for Wx (kN-m)	32
	M22 for Wy (kN-m)	37
Axial forces in podium diap.	F11 for Wx (kN/m)	136
	F22 for Wy (kN/m)	128

From Table-6 it is observed that around 21% drift is reduced, though axial forces at interface diaphragm are less but tower is not meeting the allowable drift. Therefore, the column spacing in podium is reduced from 10 m to 5 m and the effect of framing action on drift and diaphragm forces are noted.

Option – (iii) Flat Plate with Columns at 5 m design:

In this model column spacing in podium structure is 5 m as shown in Figure 2.5

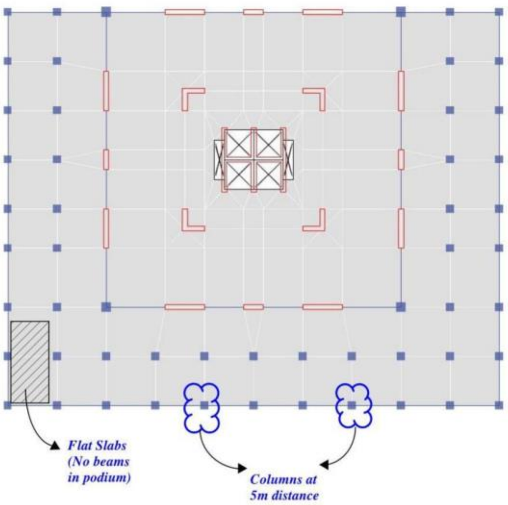

Figure 2.5

Table-7: Case II – (Option - iii)

Displacements (mm)	Wind X	362
	Wind Y	387
	Allowable (H/500)	306
	% reduction for Wind X	-25.8
Total moment	My for Wx (kN-m)	1788293
	Mx for Wy (kN-m)	1814857
Moment contribution (Wind X)	Outer core (kN-m)	581195
	%	32.50
	Inner core (kN-m)	69743
	%	3.9
	Retaining wall (kN-m)	706375
	%	39.5
	Podium columns (%)	24.1
Moment contribution (Wind Y)	Outer core (kN-m)	658793
	%	36.30
	Inner core (kN-m)	30852
	%	1.7
	Retaining wall (kN-m)	793092
	%	43.7
	Podium columns (%)	18.3
Stresses in podium diap.	S11 for Wx (MPa)	3.3
	S22 for Wy (MPa)	3.6
Moments in podium diap.	M11 for Wx (kN-m)	38
	M22 for Wy (kN-m)	41
Axial forces in podium diap.	F11 for Wx (kN/m)	256
	F22 for Wy (kN/m)	291

From Table-7 it is observed that with the increase of framing action in podium around 26% of displacement is reduced which is similar to that of Case – II (Option - i) i.e., beam-slab system. Simultaneously there is around 60% increase of strutting forces at interface diaphragm when compared to Case – II (Option – ii) model.

Case III - Podium-Tower with 20 m Podium Width

Option – (i) Slab with beams of 10 m span:

The assemblage is shown in Figure 2.6, Here width of podium is increased by10 m for previous case. Total width of podium from face of tower is 20 m.

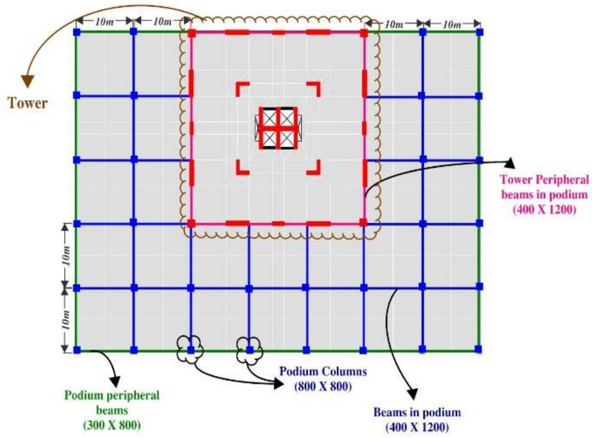

Figure 2.6

Table-8: Case III – (Option - i)

Displacements (mm)	Wind X	353
	Wind Y	377
	Allowable (H/500)	306
	% reduction for Wind X	-27.7
Total moment	My for Wx (kN-m)	1819357
	Mx for Wy (kN-m)	1872185
Moment contribution (Wind X)	Outer core (kN-m)	520336
	%	28.60
	Inner core (kN-m)	61858
	%	3.4
	Retaining wall (kN-m)	851459
	%	46.8
	Podium columns (%)	21.2
Moment contribution (Wind Y)	Outer core (kN-m)	634670
	%	33.90
	Inner core (kN-m)	35571
	%	1.9
	Retaining wall (kN-m)	962303
	%	51.4
	Podium columns (%)	12.8
Stresses in podium diap.	S11 for Wx (MPa)	2.85
	S22 for Wy (MPa)	3.25
Moments in podium diap.	M11 for Wx (kN-m)	21
	M22 for Wy (kN-m)	23
Axial forces in podium diap.	F11 for Wx (kN/m)	235
	F22 for Wy (kN/m)	267

Table-8 shows the lateral displacement of tower is reduced by around 28%, this is just 2% more than that of Case – II (Option – i) which was 26%. Though one more bay of 10 m width is added, there is not much change in tower drift. On the other hand, the axial forces are increased by around 45%. Retaining walls at the base are sharing moments around 46% in X-direction and 51% in Y-direction.

Option – (ii) Flat slab with columns at 10 m distance:

This model has flat slabs in podium with 10 m column spacing as shown in Figure 2.7.

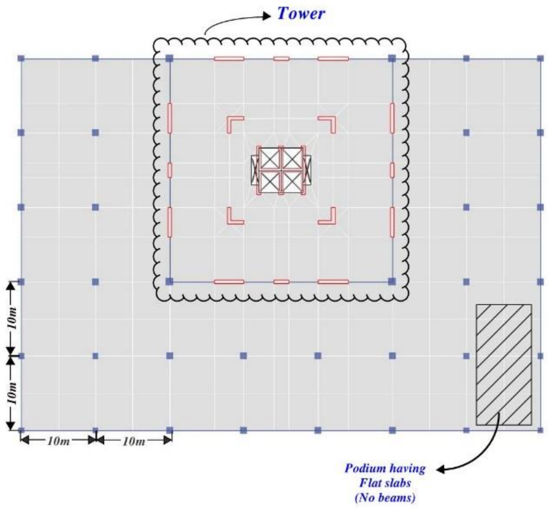

Figure 2.7

Table-9: Case III – (Option - ii)

Displacements (mm)	Wind X	382
	Wind Y	398
	Allowable (H/500)	306
	% reduction for Wind X	-21.7
Total moment	My for Wx (kN-m)	1819357
	Mx for Wy (kN-m)	1872185
Moment contribution (Wind X)	Outer core (kN-m)	764129.94
	%	42.00
	Inner core (kN-m)	78778.1581
	%	4.3
	Retaining wall (kN-m)	673162.09
	%	37.0
	Podium columns (%)	16.7
Moment contribution (Wind Y)	Outer core (kN-m)	748874
	%	40.00
	Inner core (kN-m)	33699.33
	%	1.8
	Retaining wall (kN-m)	926731.575
	%	49.5
	Podium columns (%)	8.7
Stresses in podium diap.	S11 for Wx (MPa)	2.2
	S22 for Wy (MPa)	2.3
Moments in podium diap.	M11 for Wx (kN-m)	30
	M22 for Wy (kN-m)	33
Axial forces in podium diap.	F11 for Wx (kN/m)	190
	F22 for Wy (kN/m)	163

From Table-9, analysis results show there is no change in contribution of podium in tower drift control when compared with Case - II (Option - ii). As there is no framing action in podium-tower, lateral drift is not reduced and less strutting forces are reported in diaphragm at interface level. This reveals that the podiums with flat slabs having columns at far distances has less framing action and no contribution in tower drift control beyond its first bay.

Option – (iii) Flat Plate with Columns at 5 m design:

As there was less framing action in previous model, we are trying to induce more framing action by maintain column distances at 5 m as shown in Figure 2.8

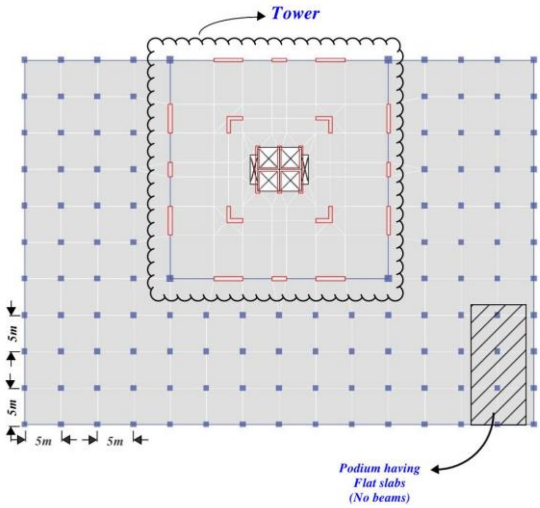

Figure 2.8

Table-10: Case III – (Option - iii)

Displacements (mm)	Wind X	354
	Wind Y	380
	Allowable (H/500)	306
	% reduction for Wind X	-27.5
Total moment	My for Wx (kN-m)	1819357
	Mx for Wy (kN-m)	1872185
Moment contribution (Wind X)	Outer core (kN-m)	564000.67
	%	31.00
	Inner core (kN-m)	65496.852
	%	3.6
	Retaining wall (kN-m)	764129.94
	%	42.0
	Podium columns (%)	23.4
Moment contribution (Wind Y)	Outer core (kN-m)	651520.38
	%	34.80
	Inner core (kN-m)	33699.33
	%	1.8
	Retaining wall (kN-m)	939836.87
	%	50.2
	Podium columns (%)	13.2
Stresses in podium diap.	S11 for Wx (MPa)	3.9
	S22 for Wy (MPa)	4.7
Moments in podium diap.	M11 for Wx (kN-m)	37
	M22 for Wy (kN-m)	47
Axial forces in podium diap.	F11 for Wx (kN/m)	354
	F22 for Wy (kN/m)	406

From Table-10, it is observed that podium is contributing around 27.5% in drift control, just 1.5% increase from that of Case – II (Option – iii).

Simultaneously there is around 30% increase in strutting forces at interface level diaphragm. Retaining walls at base has 50% of moment contribution. There is still a need for such configuration that reduces strutting forces.

Option – (iv) Flat Plate with Columns at varying Distance:

Podium columns are spaced by varying distances, first two bays are at 5 m and third one at 7.5 m making total width of podium as 17.5 m from face of tower as shown in Figure 2.9.

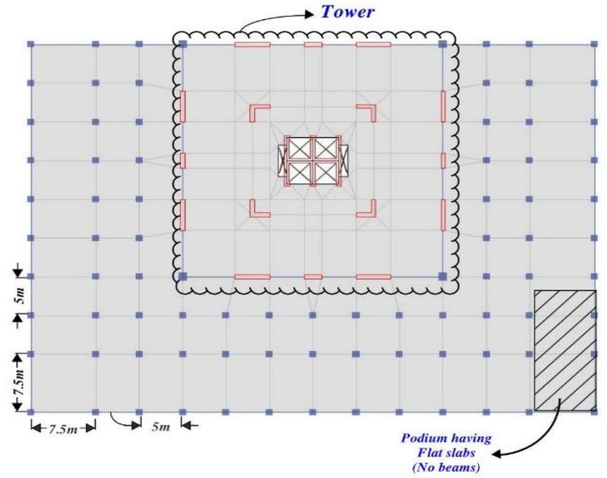

Figure 2.9

Table-11: Case III – (Option - iv)

Displacements (mm)	Wind X	358
	Wind Y	383
	Allowable (H/500)	306
	% reduction for Wind X	-26.6
Total moment	My for Wx (kN-m)	1812716
	Mx for Wy (kN-m)	1850703
Moment contribution (Wind X)	Outer core (kN-m)	543814.8
	%	30.00
	Inner core (kN-m)	67070.492
	%	3.7
	Retaining wall (kN-m)	696082.944
	%	38.4
	Podium columns (%)	27.9
Moment contribution (Wind Y)	Outer core (kN-m)	662551.674
	%	35.80
	Inner core (kN-m)	35163.357
	%	1.9
	Retaining wall (kN-m)	886486.737
	%	47.9
	Podium columns (%)	14.4
Stresses in podium diap.	S11 for Wx (MPa)	3.55
	S22 for Wy (MPa)	3.8
Moments in podium diap.	M11 for Wx (kN-m)	40
	M22 for Wy (kN-m)	47
Axial forces in podium diap.	F11 for Wx (kN/m)	326
	F22 for Wy (kN/m)	348

It is observed from Table-11, that there is decrease in contribution (tower drift control) by 0.9% and around 15% reduction in strutting forces when compared with previous Option – iii. This option with columns at varying distances is quiet productive in displacement and in-plane forces but the allowable displacement limit is still not achieved.

Case IV - Podium-Tower with 30 m Podium Width

Option – (i) Slab with beams of 10 m span:

Further proceeding the case study by adding more 10 m wide podium to the existing one. Total width of podium is 30 m with 3 bays of 10 m width as shown in Figure 2.10.

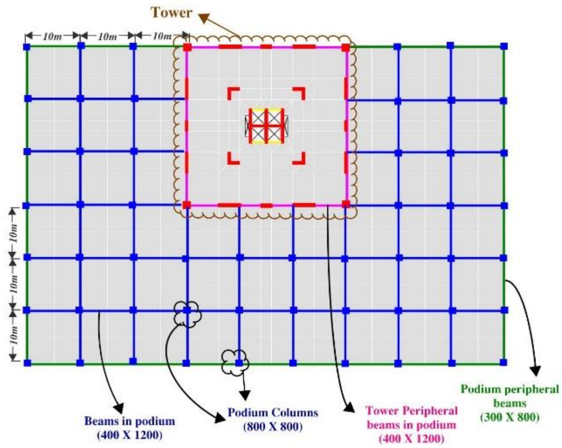

Figure 2.10

Table-12: Case IV – (Option - i)

Displacements (mm)	Wind X	345
	Wind Y	371
	Allowable (H/500)	306
	% reduction for Wind X	-29.3
Total moment	My for Wx (kN-m)	1846422
	Mx for Wy (kN-m)	1926114.0
Moment contribution (Wind X)	Outer core (kN-m)	553926.6
	%	30.00
	Inner core (kN-m)	51699.816
	%	2.8
	Retaining wall (kN-m)	899207.514
	%	48.7
	Podium columns (%)	18.5
Moment contribution (Wind Y)	Outer core (kN-m)	659694.045
	%	34.25
	Inner core (kN-m)	34670.052
	%	1.8
	Retaining wall (kN-m)	1088254.41
	%	56.5
	Podium columns (%)	7.5
Stresses in podium diap.	S11 for Wx (MPa)	3.38
	S22 for Wy (MPa)	3.88
Moments in podium diap.	M11 for Wx (kN-m)	21
	M22 for Wy (kN-m)	25
Axial forces in podium diap.	F11 for Wx (kN/m)	269
	F22 for Wy (kN/m)	337

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From Table-12, it is observed that around 29% of tower displacement is reduced. Only 1.3% more than Case – III (Option – i), which was around 27.7%. Increase in size of podium has very nominal contribution in tower displacement; on the other hand, as framing action is increased around 21% strutting forces are increased.

Option – (ii) Flat slab with columns at 10 m distance:

Revising the previous model by eliminating beams in podium structure and making it as flat slab-column frame as shown in Figure 2.11

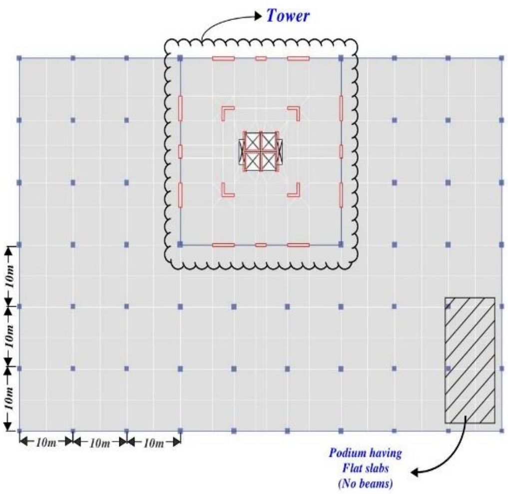


Figure 2.11

Table-13: Case IV – (Option - ii)

Displacements (mm)	Wind X	380
	Wind Y	396
	Allowable (H/500)	306
	% reduction for Wind X	-22.1
Total moment	My for Wx (kN-m)	1846422
	Mx for Wy (kN-m)	1926114.0
Moment contribution (Wind X)	Outer core (kN-m)	406212.84
	%	22.00
	Inner core (kN-m)	75703.302
	%	4.1
	Retaining wall (kN-m)	853046.964
	%	46.2
	Podium columns (%)	27.7
Moment contribution (Wind Y)	Outer core (kN-m)	494433.4638
	%	25.67
	Inner core (kN-m)	34670.052
	%	1.8
	Retaining wall (kN-m)	1016988.192
	%	52.8
	Podium columns (%)	19.7
Stresses in podium diap.	S11 for Wx (MPa)	2.89
	S22 for Wy (MPa)	2.7
Moments in podium diap.	M11 for Wx (kN-m)	35
	M22 for Wy (kN-m)	34
Axial forces in podium diap.	F11 for Wx (kN/m)	247
	F22 for Wy (kN/m)	217

From Table-13, it is observed that there is negligible contribution of podium on tower displacement when compared with Case – II (Option – ii), this is because flat slabs framing action depends upon spacing of columns, as columns are at far distance framing action is less and also strutting forces are reduced by around 36% when compared with previous Option - i.

Option – (iii) Flat Plate with Columns at 5 m design:

This model has column spacing of 5 m and remaining is same that of previous Option – ii model. Figure 2.12 shows the podium-tower assemblage.

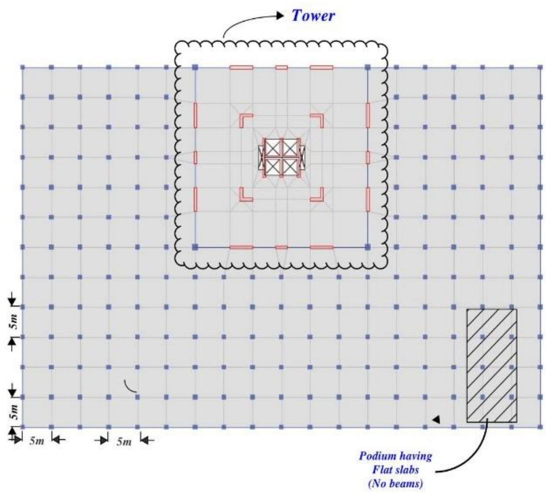


Figure 2.12

Table-14: Case IV – (Option - iii)

Displacements (mm)	Wind X	349
	Wind Y	374
	Allowable (H/500)	306
	% reduction for Wind X	-28.5
Total moment	My for Wx (kN-m)	1846422
	Mx for Wy (kN-m)	1926114.0
Moment contribution (Wind X)	Outer core (kN-m)	535462.38
	%	29.00
	Inner core (kN-m)	55392.66
	%	3.0
	Retaining wall (kN-m)	817964.946
	%	44.3
	Podium columns (%)	23.7
Moment contribution (Wind Y)	Outer core (kN-m)	609422.4696
	%	31.64
	Inner core (kN-m)	34670.052
	%	1.8
	Retaining wall (kN-m)	1020840.42
	%	53.0
	Podium columns (%)	13.6
Stresses in podium diap.	S11 for Wx (MPa)	4.96
	S22 for Wy (MPa)	5.51
Moments in podium diap.	M11 for Wx (kN-m)	41
	M22 for Wy (kN-m)	45
Axial forces in podium diap.	F11 for Wx (kN/m)	431
	F22 for Wy (kN/m)	486

The analysis results in Table-14. Shows that there is around 6% decrease in tower drift from Case – IV (Option – ii). Overall podium contribution in tower displacement is around 28.5% but need more to meet the allowable limit. Similarly, as we know the framing action is more than the previous model due to less column distance, there is huge increase in strutting forces by around 56%. Contribution of retaining wall in moments at base is 53%.

Option – (iv) Flat Plate with Columns at varying Distance:

As shown in the Figure 2.13, spacing of columns is varying. First two bays are of 5 m width; last two bays are of 7.5 m width.

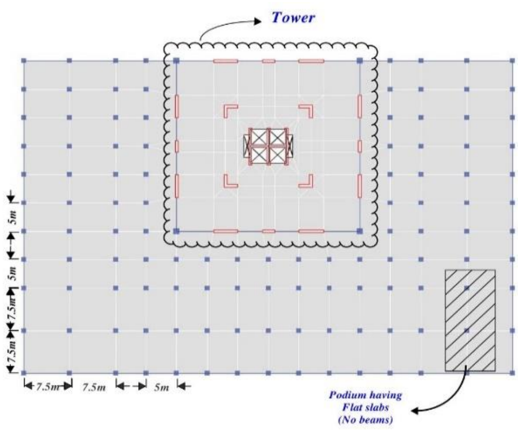


Figure 2.13

Table-15: Case IV – (Option - iv)

Displacements (mm)	Wind X	353
	Wind Y	378
	Allowable (H/500)	306
	% reduction for Wind X	-27.7
Total moment	My for Wx (kN-m)	1833139
	Mx for Wy (kN-m)	1895550.0
Moment contribution (Wind X)	Outer core (kN-m)	579271.924
	%	31.60
	Inner core (kN-m)	65993.004
	%	3.6
	Retaining wall (kN-m)	747920.712
	%	40.8
	Podium columns (%)	24.0
Moment contribution (Wind Y)	Outer core (kN-m)	664579.83
	%	35.06
	Inner core (kN-m)	36015.45
	%	1.9
	Retaining wall (kN-m)	1004641.5
	%	53.0
	Podium columns (%)	10.0
Stresses in podium diap.	S11 for Wx (MPa)	4.3
	S22 for Wy (MPa)	4.7
Moments in podium diap.	M11 for Wx (kN-m)	43
	M22 for Wy (kN-m)	48
Axial forces in podium diap.	F11 for Wx (kN/m)	363
	F22 for Wy (kN/m)	414

From analysis results as shown in Table-15, it is observed that around 15% of strutting forces are reduced by changing column positions at varying spans, but there is also decrease in tower displacement control by 2%.

Case V - Podium-Tower with 40 m Podium Width

Option – (i) Slab with beams of 10 m span:

In this case width of podium is further increased by 10 m, overall width of podium from face of tower is 40 m, column spacing is 10 m and slab is with beams as shown in Figure 2.14.

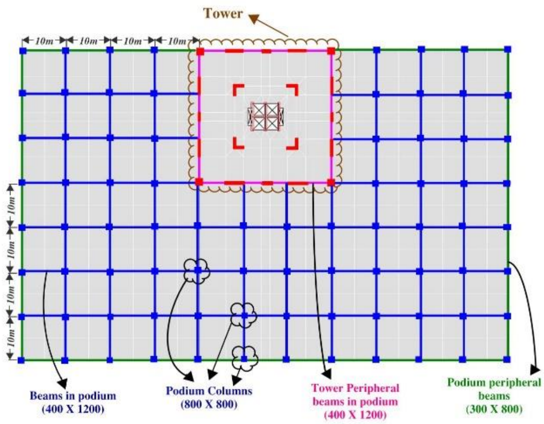


Figure 2.14

Table-16: Case V – (Option - i)

Displacements (mm)	Wind X	340
	Wind Y	365
	Allowable (H/500)	306
	% reduction for Wind X	-30.3
Total moment	My for Wx (kN-m)	1875986
	Mx for Wy (kN-m)	1962242
Moment contribution (Wind X)	Outer core (kN-m)	514020.164
	%	27.40
	Inner core (kN-m)	52527.608
	%	2.8
	Retaining wall (kN-m)	947372.93
	%	50.5
	Podium columns (%)	19.3
Moment contribution (Wind Y)	Outer core (kN-m)	588672.6
	%	30.00
	Inner core (kN-m)	35320.356
	%	1.8
	Retaining wall (kN-m)	1212665.556
	%	61.8
	Podium columns (%)	6.4
Stresses in podium diap.	S11 for Wx (MPa)	3.5
	S22 for Wy (MPa)	4.5
Moments in podium diap.	M11 for Wx (kN-m)	23
	M22 for Wy (kN-m)	26
Axial forces in podium diap.	F11 for Wx (kN/m)	309
	F22 for Wy (kN/m)	393

From analysis results as tabulated in Table-16, it is observed that podium is contributing by around 30% in tower displacement which is more than previous all cases, but this is an increase by just 1.7% from previous Case – IV (Option – i). Simultaneously the strutting forces are increased by 15%.

Option – (ii) Flat slab with columns at 10 m distance

Now in this model beams in podium are removed as shown in Figure 2.15

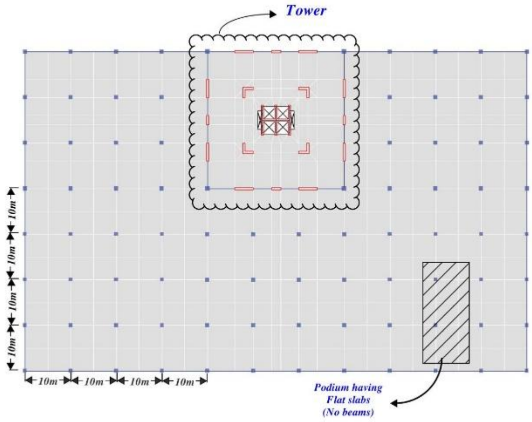


Figure 2.15

Table-16: Case V – (Option - ii)

Displacements (mm)	Wind X	378
	Wind Y	395
	Allowable (H/500)	306
	% reduction for Wind X	-22.5
Total moment	My for Wx (kN-m)	1875986
	Mx for Wy (kN-m)	1962242
Moment contribution (Wind X)	Outer core (kN-m)	761650.316
	%	40.60
	Inner core (kN-m)	71287.468
	%	3.8
	Retaining wall (kN-m)	769154.26
	%	41.0
	Podium columns (%)	14.6
Moment contribution (Wind Y)	Outer core (kN-m)	704444.878
	%	35.90
	Inner core (kN-m)	35320.356
	%	1.8
	Retaining wall (kN-m)	1110628.972
	%	56.6
	Podium columns (%)	5.7
Stresses in podium diap.	S11 for Wx (MPa)	3
	S22 for Wy (MPa)	3.1
Moments in podium diap.	M11 for Wx (kN-m)	33
	M22 for Wy (kN-m)	35
Axial forces in podium diap.	F11 for Wx (kN/m)	235
	F22 for Wy (kN/m)	260

It is observed from Table-16 that the tower drift is reduced by 22.5%, which is just 1% more than that of Case – II (Option – i). It is noted that increase in size of podium from 10 m width to 40 m width has effective contribution with its first bay only, further increase in number of bays with columns at 10 m distance has negligible contribution in tower displacement. Strutting forces are also reduced by 44% when compared with previous Option – i

Option – (iii) Flat Plate with Columns at 5 m design:

This model has columns at 5 m distance as shown in Figure 2.16, from this large sized podium model it is understood that in flat slabs framing action is more if columns are near.

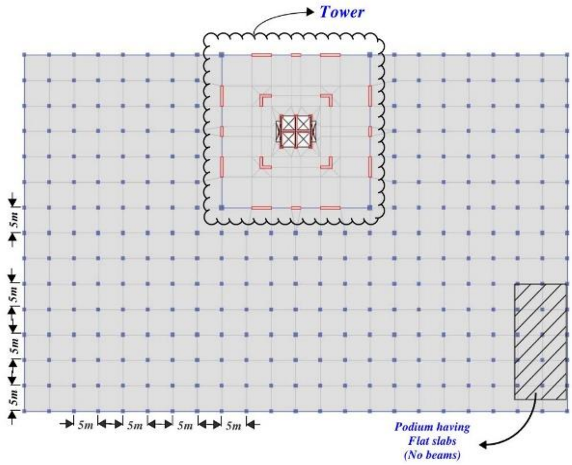


Figure 2.16

Table-17: Case V – (Option - iii)

Displacements (mm)	Wind X	343
	Wind Y	369
	Allowable (H/500)	306
	% reduction for Wind X	-29.7
Total moment	My for Wx (kN-m)	1875986
	Mx for Wy (kN-m)	1962242
Moment contribution (Wind X)	Outer core (kN-m)	510268.192
	%	27.20
	Inner core (kN-m)	50651.622
	%	2.7
	Retaining wall (kN-m)	874209.476
	%	46.6
	Podium columns (%)	23.5
Moment contribution (Wind Y)	Outer core (kN-m)	588672.6
	%	30.00
	Inner core (kN-m)	33358.114
	%	1.7
	Retaining wall (kN-m)	1008592.388
	%	51.4
	Podium columns (%)	16.9
Stresses in podium diap.	S11 for Wx (MPa)	4.49
	S22 for Wy (MPa)	6.5
Moments in podium diap.	M11 for Wx (kN-m)	37
	M22 for Wy (kN-m)	40
Axial forces in podium diap.	F11 for Wx (kN/m)	378
	F22 for Wy (kN/m)	546

From Table-17 it is observed that displacement is controlled by around 30%, which is just 1.2% more than the model in Case – IV (Option – iii). It shows that the contribution in displacement is increased by around 6% to 7% when compared with (Option – ii) of all cases. At the same time strutting forces are increased by around 55%. This is clearly because of more framing action.

Option – (iv) Flat Plate with Columns at varying Distance:

The assemblage of podium-tower is as shown in Figure 2.17. Columns in podium are at varying distances. First two bays are at 5 m distance, next two bays are at 7.5 m and last bay is at 10 m. Total width of podium is 35 m.

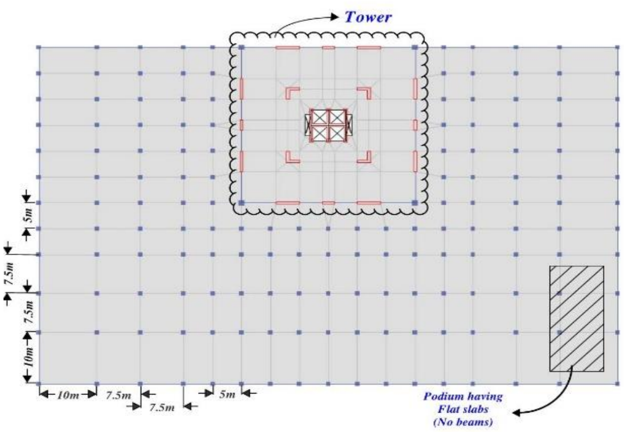


Figure 2.17

Table-18: Case V – (Option - iv)

Displacements (mm)	Wind X	347
	Wind Y	373
	Allowable (H/500)	306
	% reduction for Wind X	-28.9
Total moment	My for Wx (kN-m)	1862704
	Mx for Wy (kN-m)	1940678
Moment contribution (Wind X)	Outer core (kN-m)	541488.0528
	%	29.07
	Inner core (kN-m)	63331.936
	%	3.4
	Retaining wall (kN-m)	745081.6
	%	40.0
	Podium columns (%)	27.5
Moment contribution (Wind Y)	Outer core (kN-m)	641588.1468
	%	33.06
	Inner core (kN-m)	36872.882
	%	1.9
	Retaining wall (kN-m)	1036322.052
	%	53.4
	Podium columns (%)	11.6
Stresses in podium diap.	S11 for Wx (MPa)	4.6
	S22 for Wy (MPa)	4.9
Moments in podium diap.	M11 for Wx (kN-m)	39
	M22 for Wy (kN-m)	43
Axial forces in podium diap.	F11 for Wx (kN/m)	350
	F22 for Wy (kN/m)	418

From analysis results as shown in Table-18, it is observed that strutting forces are slightly reduced but there is also increase in tower displacement by 2%. This assemblage is having very nominal effect on displacement. Therefore, it can be suggested that size of podium can be restricted and some structural elements can be introduced in podium to limit tower displacement and reduce strutting forces.

Case VI – Podium with Outriggers in 9th and 10th floors at Podium-Tower Junction:

Outriggers are improvised form of frames which are very deep beams of single storey height between two columns. These are very effective in controlling drifts of tall buildings. As the study is about interface diaphragm, so the outriggers are introduced on 9th and 10th storeys of podium at podium-tower junction as shown in Figure 2.18. Size of podium is restricted to 17.5 m width.

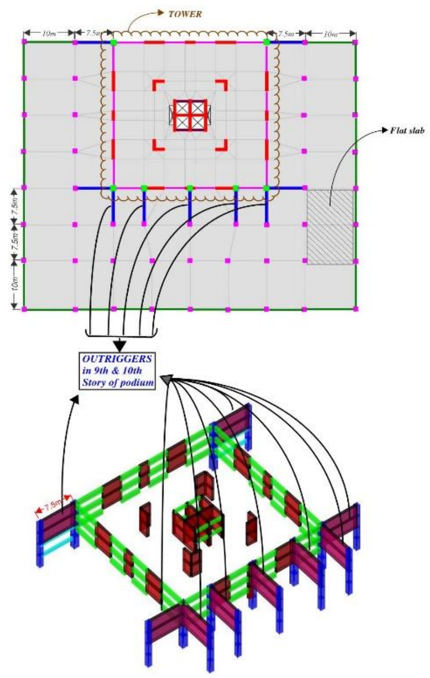


Figure 2.18

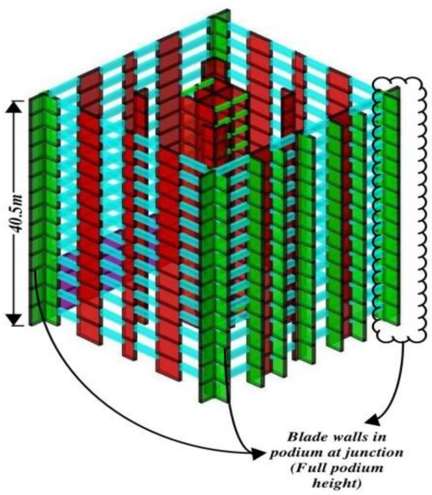
The analysis results from Table-19 revealed that the outriggers are very effective in controlling tower drift as it percentage contribution is around 32%, which is even not satisfying the allowable limit of displacement for lateral wind load. On the other hand, this podium configuration with outriggers has reported tremendous increase in in-plane strutting forces at interface level slab, which is 50% more than that of same podium size without outriggers as discussed in Case – III (Option – iv).

Table-19: Case VI

Displacements (mm)	Wind X	330
	Wind Y	344
	Allowable (H/500)	306
	% reduction for Wind X	-32.4
Total moment	My for Wx (kN-m)	1831418
	Mx for Wy (kN-m)	1867895.00
Moment contribution (Wind X)	Outer core (kN-m)	431452.6
	%	23.56
	Inner core (kN-m)	67799.3
	%	3.7
	Retaining wall (kN-m)	765826.3
	%	41.8
	Podium columns (%)	30.9
Moment contribution (Wind Y)	Outer core (kN-m)	413598.0
	%	22.14
	Inner core (kN-m)	29010.7
	%	1.6
	Retaining wall (kN-m)	1021458.6
	%	54.7
	Podium columns (%)	21.6
Stresses in podium diap.	S11 for Wx (MPa)	7.5
	S22 for Wy (MPa)	5.8
Moments in podium diap.	M11 for Wx (kN-m)	22
	M22 for Wy (kN-m)	33
Axial forces in podium diap.	F11 for Wx (kN/m)	610
	F22 for Wy (kN/m)	504

Case VII – Podium with Extended Blade Walls at Podium-Tower Junction

This case is studied by introducing structural walls in podium at podium-tower junction to minimize strutting forces in podium-tower interface level diaphragm and also meet the allowable tower displacement. These are extended walls from either columns or existing walls as shown in Figure 2.19. As these are extended, we can call it as extended blade walls. These walls are extended up to 3.5 m length away from tower in perpendicular direction to the face of podium casted right from base to last storey of podium.



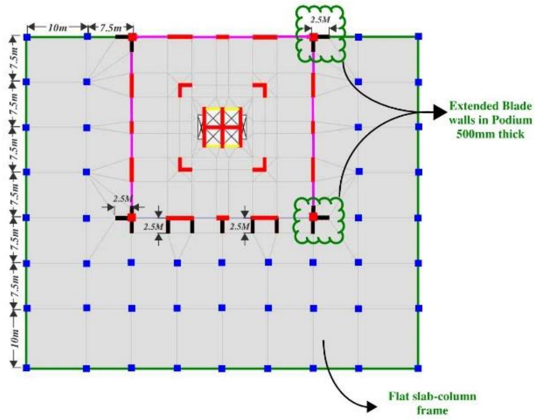


Figure 2.19

Table-20: Case VII

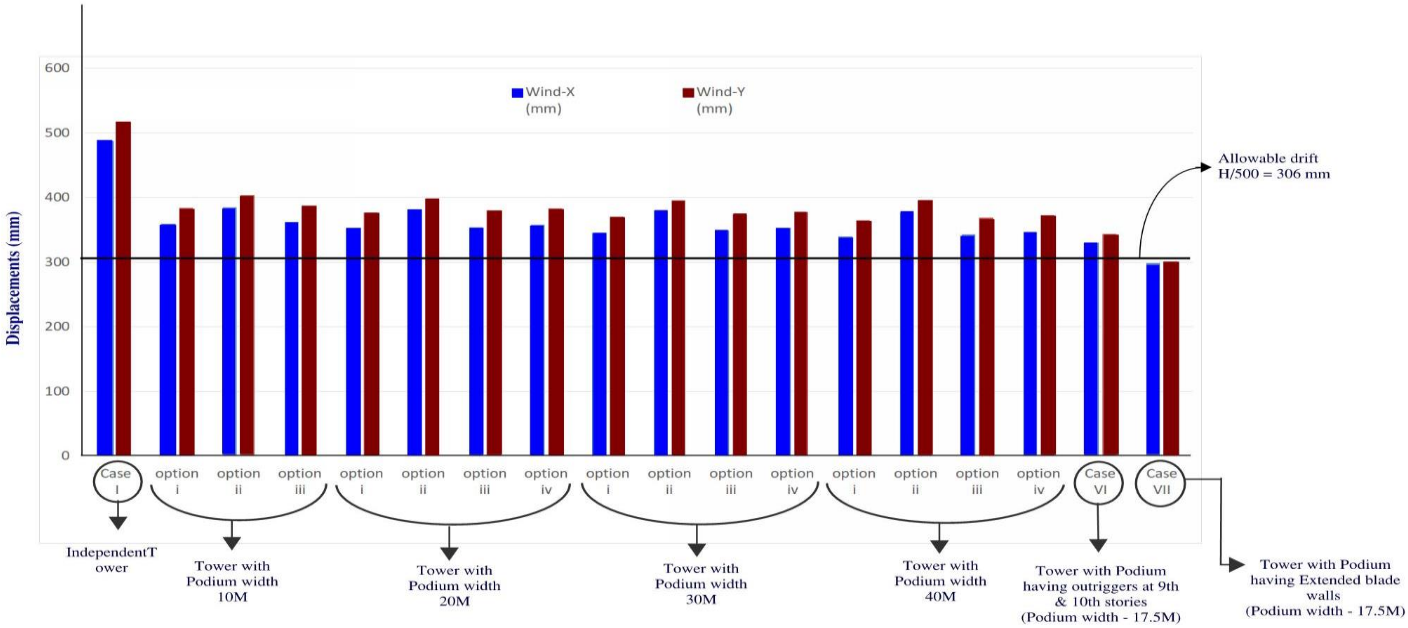
Displacements (mm)	Wind X	299
	Wind Y	301
	Allowable (H/500)	306
	% reduction for Wind X	-41.7
Total moment	My for Wx (kN-m)	1833706
	Mx for Wy (kN-m)	1857792.00
Moment contribution (Wind X)	Outer core (kN-m)	387518.2
	%	21.13
	Inner core (kN-m)	61510.6
	%	3.4
	Retaining wall (kN-m)	645814.7
	%	35.2
	Podium columns (%)	14.5
	Blade walls (%)	25.8
Moment contribution (Wind Y)	Outer core (kN-m)	297726.6
	%	16.03
	Inner core (kN-m)	26575.0
	%	1.4
	Retaining wall (kN-m)	974819.1
	%	52.5
	Podium columns (%)	3.1
	Blade walls (%)	27
Stresses in podium diap.	S11 for Wx (MPa)	2.33
	S22 for Wy (MPa)	2.2
Moments in podium diap.	M11 for Wx (kN-m)	30
	M22 for Wy (kN-m)	32
Axial forces in podium diap.	F11 for Wx (kN/m)	155
	F22 for Wy (kN/m)	135

The analysis results from Table-20 are satisfying both parameters, drift at top of tower and strutting forces at interface diaphragm. Tower displacement is under allowable limit and diaphragm forces are less comparatively with all the cases studied so far.

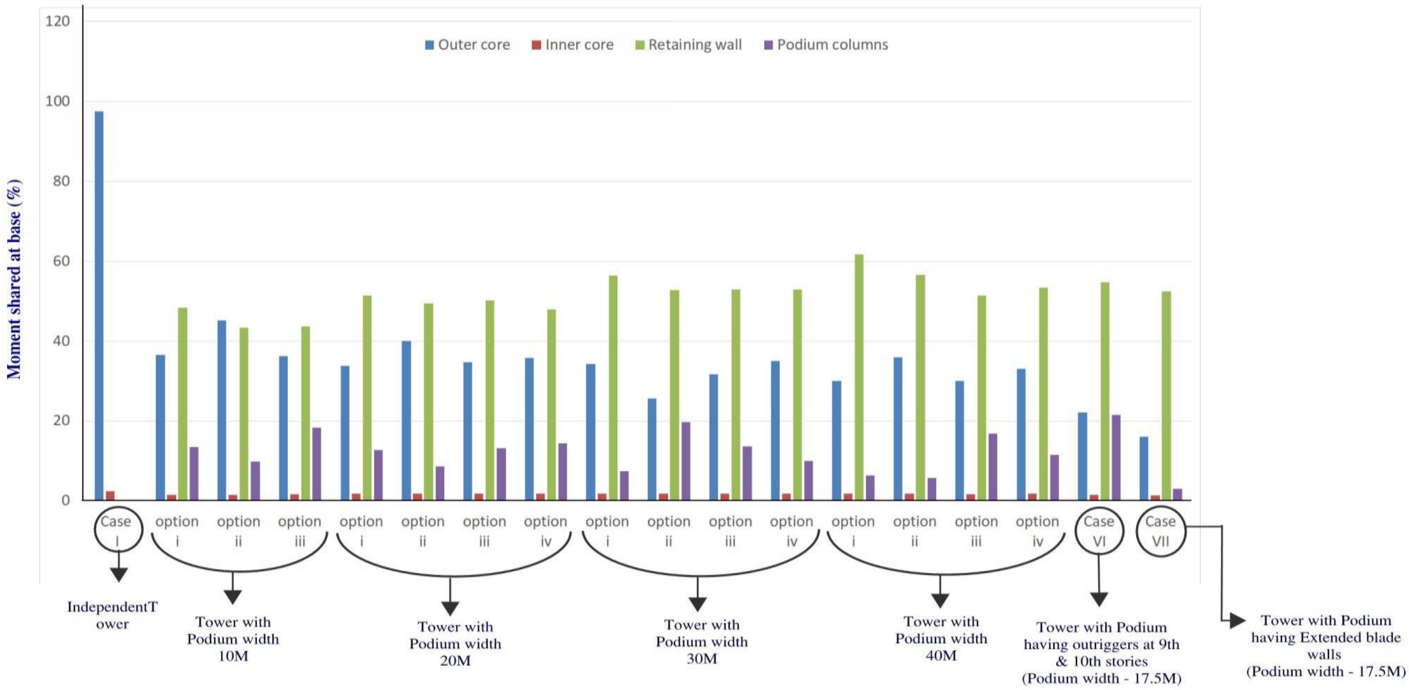
3. COMPARATIVE RESULTS

The comparative results after performing sensitivity analysis of podium-tower interaction emphasizing on podium structure are discussed in subsequent sections.

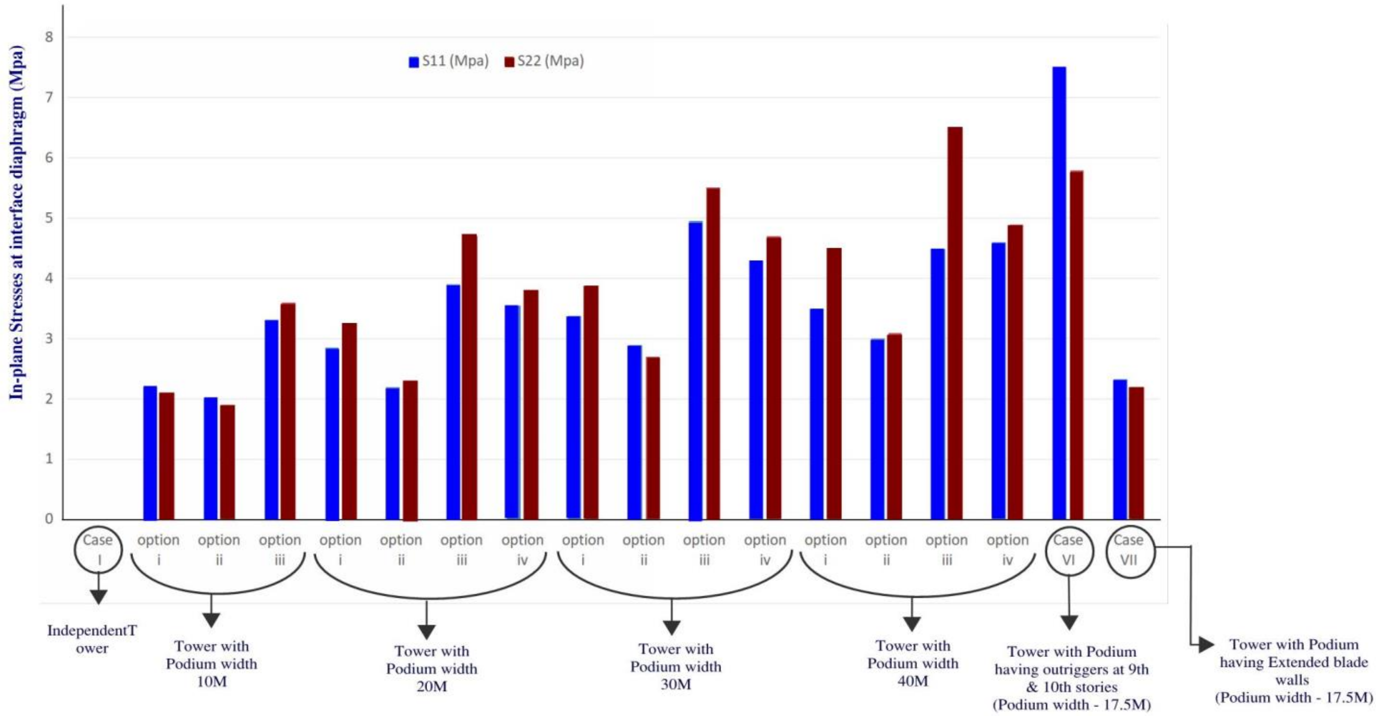
3.1 Comparison of displacements at top of tower



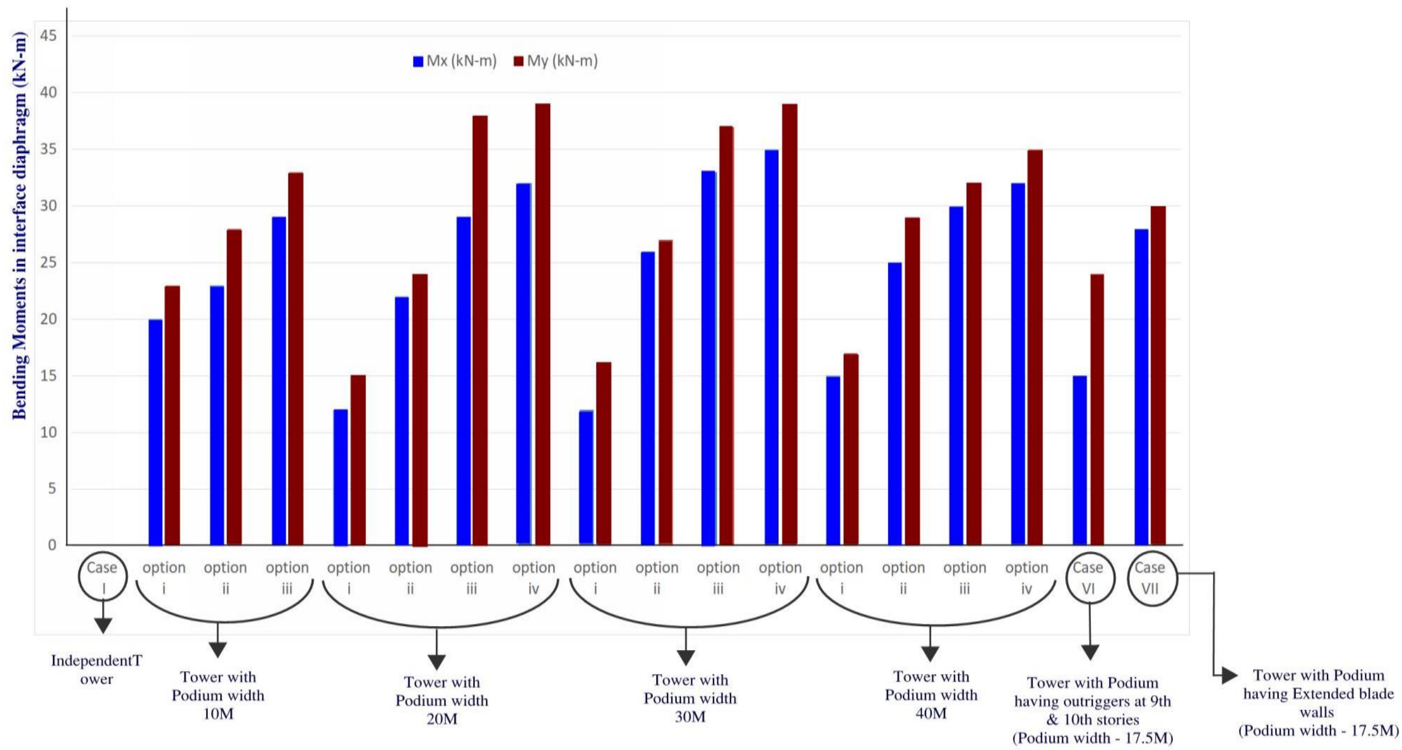
3.2 Moments shared at base of building



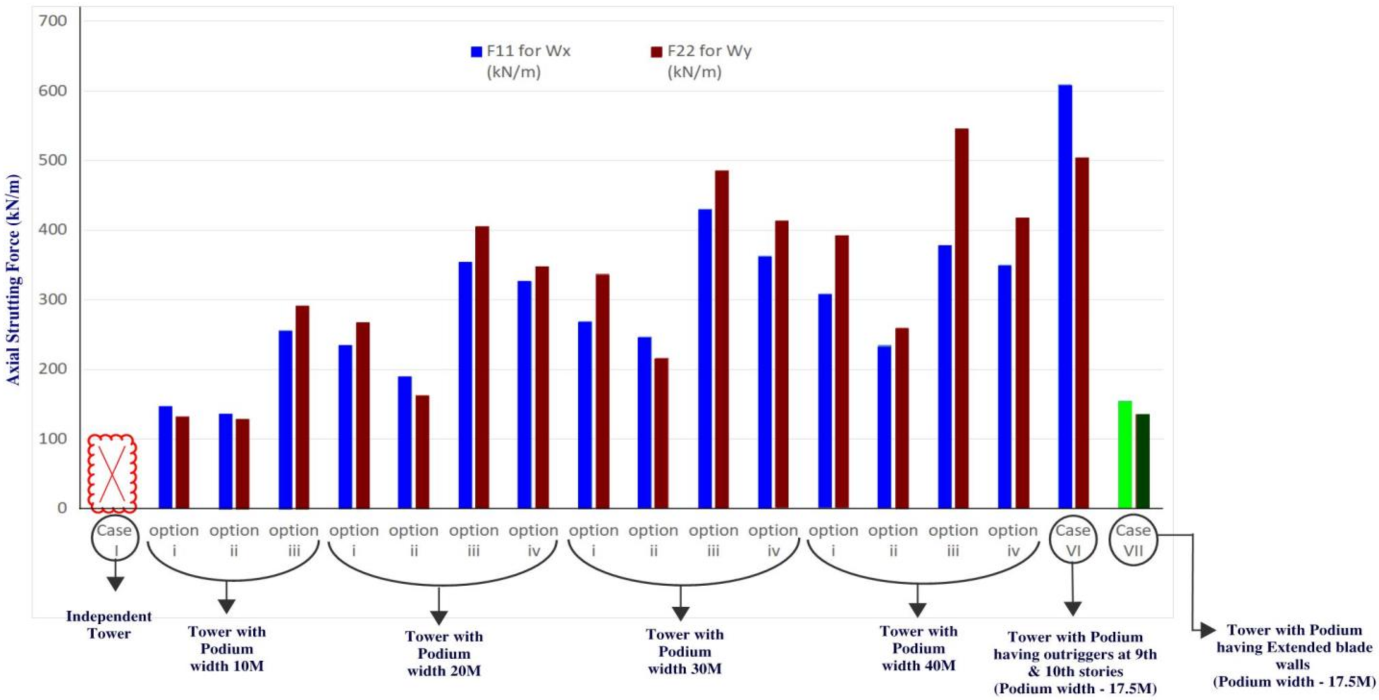
3.3 Comparison of stresses at interface level



3.4 Bending moments in interface diaphragm



3.5 Comparison of axial strutting forces in slab at podium-tower interface



4. CONCLUSIONS

The conclusions drawn from the numerical studies on podium structures are shown below. The results of linear analysis are varying from non-linear analysis, but the percentage difference of these results from model to model in linear analysis are almost similar to that of the non-linear analysis. Therefore, the specific conclusions are drawn from non-linear analysis, as it is recommended for tall buildings.

i. Podiums do contribute in reducing tower displacements. Almost 90% of this contribution is associated with its first bay around the tower.

ii. The increase in size of podium has nominal impact on tower drift. For Wind-Y tower displacement is 516 mm. Addition of first bay of podium reduced it to 384 mm (about 26.2%) and addition of next four bays reduced it to 360 mm (about 30.3%) which is 4% more reduction for 40 m wide podium.

iii. The strutting forces in podium diaphragm increase with increase in framing action. When columns are at 10 m distance the strutting forces are 260 kN/m and for 5 m distance it is 546 kN/m which is about 50% more.

iv. The flat slabs have less framing action than beam-slabs. Therefore, the flat slab system contributes less in control of tower displacement and also reports less strutting forces than the beam-column systems.

v. The outriggers in podium has reduced 32% of tower drift but increased strutting forces by 50%. This is due to increase in framing action.

vi. The extended blade walls in podium at podium-tower junction are very effective in controlling the tower drift to allowable limit (41.7% of displacement is reduced) and minimizing the framing actions at the same time, resulting in very less strutting forces of 135 kN/m at interface diaphragm.

vii. The moments shared by retaining walls at the base due to lateral loads is around 50%, which is more than any other structural element in the building for all cases.

viii. The podium columns in assemblage with outriggers exhibit more moment contributions at base than all other cases, which is around 22%.

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