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Tooba Arshad, Syed Majid Hashmi, Mohd. Nazim Raza, Abdullah Shariff

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Study of torsion and combined shear stresses in the central core of tall twisting buildings

Tooba Arshad*

Structural Engineering,
Muffakham Jah College of Engineering and Technology (MJCET),
Hyderabad, India
Email: toobaarshad99@gmail.com
*Corresponding author

Syed Majid Hashmi

KMH Engineering,
Bldg. No. 1749, Banjara Hills, Rd no. 12, Hyderabad, India
Email: majid.hashmi@kmhengineering.com

Mohd. Nazim Raza and Abdullah Shariff

Department of Civil Engineering,
Muffakham Jah College of Engineering and Technology (MJCET),
Hyderabad, India
Email: nazim.raza@mjcet.ac.in
Email: abduallahshariff@mjcet.ac.in

Abstract: Twisted building features gradually rotating floors throughout its height and serves as a picturesque addition to a city's skyline. However, it is important to acknowledge the risks associated with its structural performance due to the torsion induced in these structures as a consequence of its twisting nature. There is also an increase in shear stresses in structural elements, especially in the vertical members. Elevated shear stresses can lead to shear failures, which are critical for the overall integrity of the building. Thus, this research aims to study the torsion generated in a twisted building due to gravity and lateral loads using CSI ETABS 20. The study was conducted on several models that varied in terms of angle of twist and height of the building. Additionally, a manual calculation of torsion developed in the core of twisted building is also worked out to verify the results obtained from the software. When comparing straight building models to twisted building models, it was evident that the latter experienced notably increased torsion when exposed to gravity and seismic loads, however, twisted buildings demonstrated superior performance against wind loads, attributed to their aerodynamic helical shape.

Keywords: twisting building; circular core wall; torsion; shear stress; gravity load; wind load; seismic load; base shear; storey displacement.

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Biographical notes: Tooba Arshad is a dedicated and passionate engineer, who has successfully embarked on a successful career in structural engineering. driven by her interest, she pursued her Bachelor's in Civil Engineering from Deccan College of Engineering and Technology, Hyderabad, graduating with first-class honours. She then pursued a Master's in Structural Engineering at Muffakham Jah College of Engineering and Technology, Hyderabad, securing outstanding grades in her class. Following a successful internship at KMH Engineering, she was appointed as a Structural Engineer at the firm, marking the beginning of a promising career.

Syed Majid Hashmi is a renowned tall building design expert with 33 years of global experience. He spent 20 years in Dubai, designing over 200 tall buildings and 15 supertall buildings, including the Guinness World Record-holding Princess Tower, which stood at 413 m. He has designed towers of 300 m and 400 m heights. Returning to India in 2011, he worked as the Technical Director for BuroHappold in Mumbai, before establishing his own consultancy, KMH Engineering, in Hyderabad in 2018. He holds a gold medal in Master's in Structural Engineering from Osmania University and is a licensed Professional Engineer from the USA.

Mohd. Nazim Raza is working as an Assistant Professor in Civil Engineering Department of Muffakham Jah College of Engineering and Technology. He received his Bachelor of Engineering in Civil Engineering from Muffakham Jah College of Engineering and Technology, Hyderabad and Master's in Structural Engineering from Deccan College of Engineering and Technology, Hyderabad. Currently, he is pursuing his PhD from Osmania University and has been publishing papers in national and international journals and conferences. He has guided many ME students in their projects.

Abdullah Shariff is a renowned faculty member in the Civil Engineering Department of Muffakham Jah College of Engineering and Technology. With over three decades of experience, he has been actively contributing to the research field and a life member of ISTE. He has authored over 40 research papers, which are published in esteemed national and international journals and conferences. He has guided over 50 Master's projects and guiding PhD students in their research endeavours. His area of specialisation is structural engineering.

1 Introduction

Architects and engineers worldwide have always aimed to create structures that are both aesthetically striking and functionally robust. Enhanced computer modelling capability is now a commonplace in our profession enabling architects to formulate three-dimensional images that often appear to defy gravity (De Simone et al., 2015). One such innovation is the twisted building, which can be regarded as an engineering marvel. These structures feature floors that rotate around their vertical axis as the building ascends; leading to a visually captivating twisted geometry.

While the design of twisted buildings is impressive, it brings significant engineering challenges. The inclination of the columns and the rotation of the slabs introduce substantial torsion, which unrestrained would cause the building to come spinning down to the ground (Shukla and Kumar, 2020; De Simone et al., 2015; Abdelrazaq, 2010). Consequently, the cores – serving as the sole vertical elements – must be constructed

with significant thickness to handle the large torsional moments directed toward them (Erkoç and Torunbalci, 2023; Fawzy and Ghobarah, 2014). Additionally, the intricate architecture of these buildings makes them susceptible to seismic activity (Paulay and Priestley, 2012; Alsharqawi and Kumar, 2021; Navya et al., 2020), often resulting in their construction in areas of low seismicity.

Despite these complexities, twisted buildings have notable advantages, particularly regarding wind forces. An aerodynamic twisted shape has the advantage of disturbing the form of wind impact around a building to effectively reduce wind excitation (Abdelrazaq et al., 2020; Hedayat and Kwon, 2020; Golasz-Szolomicka and Szolomicki, 2019). However, gaps remain in our understanding of how these structures behave under various lateral and gravity loads and for increased irregularities in architecture.

In this present study, the floor plan resembles a five petal flower that rotates around a vertically straight circular central core. The structure design features rotated floor slabs with a reinforced concrete frame supported by a central mega core and ten columns. It has continuous beams that connect the core to the outer spiralling columns. The building starts rotating from the 6th floor to the top of the structure. Multiple models are created and the degree of rotation in each model is varied in increments of 2° , for the sake of research, i.e., 0° , 2° , 4° and 6° .

The irregular plan and an even wider range of rate of twisting of the models help us elaborately analyse the optimal rate of twisting that complies with the existing codal restrictions and ensures the safety, stability and sustainability of these structures.

The geometry or shape of the building contributes greatly in inducing torsion at the core of the building and hence, the role of gravity loads is studied with much scrutiny. Therefore in this study, the objectives would be to calculate and observe the torsion that takes place due to gravity loads and provide a comprehensive analysis of the effect of vertical loads on twisted structures. It will also be verified whether the shear stresses induced due to the twisting nature of the building are within safe limits. Additionally the behaviour of twisted structure would be studied under lateral loads, i.e., seismic and wind loads.

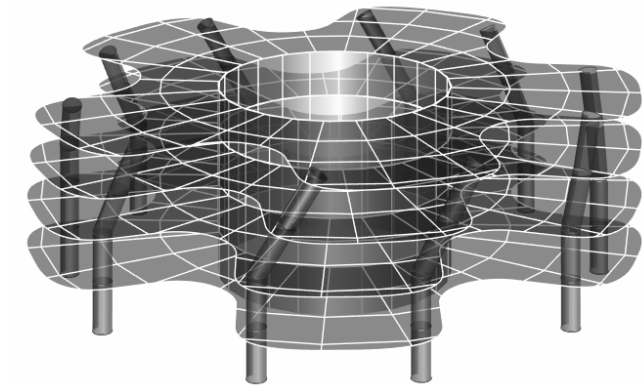
1.1 Torsion in twisted structures

A twisted structure is formed when the slabs of the building rotates in increments about a fixed vertical axis. This rotation gives rise to the columns being oriented in an inclined manner in order to maintain the continuity between the slabs (Figure 1). Therefore, the vertical gravity loads acting on the columns (which is now inclined) gives rise to internal reaction force components that are acting;

- 1 along axis of the column
- 2 in the horizontal direction.

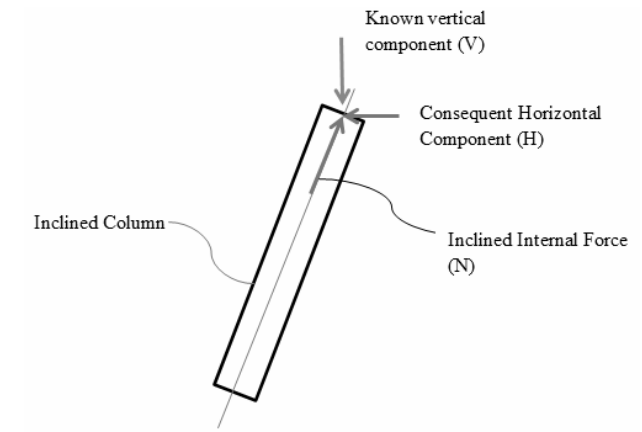
The horizontal force component here arises due to the sloped nature of the column and acts in resistance to the vertical gravity loads. A combined action of all the horizontal forces at the top of each column in a particular storey generates a twisting force about the axis of the entire building, i.e., the core of the building.

Figure 1 Inclined column in twisted building



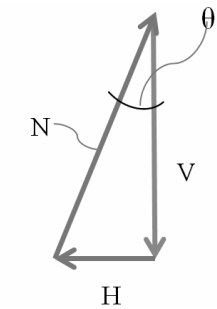
Source: KMH Engineering

Figure 2 Force components in an inclined column



Source: Johns Hopkins University (n.d.)

Figure 3 Force polygon



Source: Johns Hopkins University (n.d.)

The axial force in the columns is the inclined force shown acting along the axis of one column (Figure 2). This force is equal to the combination of a vertical and a horizontal component. The gravity loads and reactions are vertical and create the vertical component; the horizontal component develops because the vertical forces are carried in an inclined column, i.e., for the columns to be in equilibrium there must be a horizontal component of the axial force. These three forces create a ‘force polygon’, which, drawn head to tail, form a closed shape (Figure 3). The magnitudes of the horizontal components and the axial force can be found from the vertical force and the angle of the column axis with trigonometry (Johns Hopkins University, n.d.).

1.2 Manual calculation of torsion

θ is the slope of the inclined column which can be calculated by simple geometry. For each angle of twist the different values of θ are:

- 2° rotation per floor, $\theta = 11.32^\circ$
- 4° rotation per floor, $\theta = 21.82^\circ$
- 6° rotation per floor, $\theta = 31^\circ$.

As mentioned earlier, the magnitude of the inclined force and the horizontal component can be calculated from simple trigonometric equations.

Therefore,

$$\text{Internal inclined force, } N = V \div \cos \theta \quad (1)$$

$$\text{Horizontal force component, } H = N \times \sin \theta \quad (2)$$

The horizontal component of force is responsible for the torsion at the central core wall.

$$\therefore \text{Torsion} = H \times n \times R \quad (3)$$

where

n no. of columns

R distance from pivot point of plan to outermost column.

2 Literature review

Erkoç and Torunbalci (2023) evaluated the adaptability, drawbacks, and sustainability of twisted architectural designs within modern regulations, highlighting key considerations for design and construction. Marmar et al. (2021) conducted a study on twisted towers and highlighted that these towers not only reduced material usage but also showcased enhanced aerodynamic properties, reducing the effect of wind loads and improving energy efficiency. Navya et al. (2020) compared twisted and straight structures with varying heights and twist angles and produced results that indicated that the conventional structures outperformed twisted ones in terms of seismic response, emphasising the importance of structural configuration of twisted buildings under seismic actions. Hanna Golasz-Szolomicka and Szolomicki (2019) in their study emphasised that twisted shapes

help disrupt the impact of wind around the building, effectively reducing wind-induced excitation and the risk of resonance-related issues. Tanaka et al. (2012) in their study reiterated that vortex shedding behaviours, particularly in models with helical exterior displayed irregularly shed weak vortices throughout its height, which contributed to its improved aerodynamic performance.

3 Methodology

In order to meet the objectives of the present study, G+25 and G+35 structures were modelled as per Indian Standards using CSI ETABS. The structures were of the same plan and comprised a circular central core and the floors of the tower started rotating from the sixth storey at the rate of 0° per floor, 2° per floor, 4° per floor and 6° per floor. The columns therefore are inclined from the sixth storey till the topmost storey.

Once the tower was modelled, gravity and lateral loads were defined in the program and the results for torsion due to the specified loads were noted down. Additionally the base shears and storey displacements were also observed. As the study progressed it was observed that the torsion at the core due to gravity loads in all models were significantly high and therefore a check for shear stresses at the central core was carried out to ensure that the stresses developed were within limits.

The study was carried out by varying angle of twist and comparing the twisted models to their respective parametric twin. The different models that were fabricated, the load cases and combinations that were considered are tabulated in Tables 1, 2, 3 and 4. The load combinations used in the study are in accordance with IS 456:2000 and IS 1893:2016 (Part I). The seismic analysis method used in the study was response spectrum method. The wind and seismic load parameters are presented in Table 3.

Table 1 Models

<i>Model no.</i>	<i>Description</i>	<i>Height (m)</i>	<i>Rotation per floor</i>	<i>Total rotation</i>
1	Straight 25 floors	75	0°	0°
2	2° rotation 25 floors		2°	40°
3	4° rotation 25 floors		4°	80°
4	6° rotation 25 floors		6°	120°
5	Straight 35 floors	105	0°	0°
6	2° rotation 35 floors		2°	60°
7	4° rotation 35 floors		4°	120°
8	6° rotation 35 floors		6°	180°

Table 2 Gravity load definition

<i>S. no.</i>	<i>Load patterns</i>	<i>Load definition</i>	<i>Code</i>
1	Dead	Self wt. of the structure	-
2	Floor finish	1.5 kN/m ²	IS 875 (Part I):1987
3	Partition wall load	1 kN/m ²	
4	Live load	3 kN/m ²	IS 875 (Part II):1987

Table 3 Wind and seismic load parameters

<i>Wind load according to IS 875 (Part III) 2015</i>	
Basic wind speed	47 m/s
Terrain category	4
Topography (k3)	1
Importance factor	1
Risk coefficient factor (k1)	1
<i>Seismic load according to IS 1893 (Part I): 2016</i>	
Seismic zone	3
Importance factor (I)	1.2
Response reduction factor R	4
Site type	I

Table 4 Load combinations

<i>S. no.</i>	<i>Load combinations</i>	<i>Code</i>
1	Ultimate (1.5DL + 1.5LL)	IS 456:2000
2	1.5DL + 1.5Wind	
3	1.5DL + 1.5Seismic	
4	1.2DL + 1.2LL + 1.2Wind	
5	1.2DL + 1.2LL + 1.2Seismic	
6	1.2(DL + LL ± (EQx ± 0.3EQy))	IS 1893:2016 (Part I)
7	1.5(DL + LL ± (EQx ± 0.3EQy))	
8	0.9DL ± 1.5(EQx ± EQy)	

3.1 Manually calculated torsion

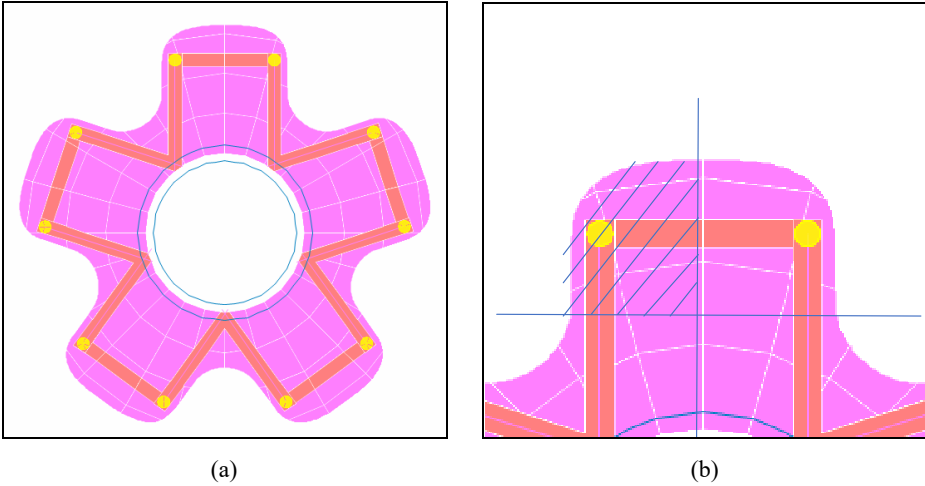
A derivation based on the basic principles of mechanics was worked out to roughly estimate the magnitude of torsion that can be generated at the core. Although the hand calculations do not consider the intricate workings within the structure and its load path, it still gives us an expected magnitude of torsion that needs to be studied. By comparing the manually calculated torsion and the torsion values obtained from ETABS, the aim of this study does not focus on which method gives a more accurate value, rather it helps us understand that a rough hand calculation gives a very close value to the software results and works as a great tool when similar structures need to be analysed.

The steps that were followed to come up with magnitude of torsion are discussed in Section 1.2.

The derivation of the known vertical force component (V) in G+35 models is shown below. Similar procedure is adopted to calculate the torsion at the core in G+25 models as well.

The plan used and the tributary area for which the loads on columns were calculated is shown in Table 5.

Figure 4 (a) Plan (b) Tributary area (see online version for colours)



Area of the shaded region

- Slab area = $(6.1 \times 6.15) = 37.515$.

Table 5 Procedure to calculate torsion acting at the core due to gravity loads

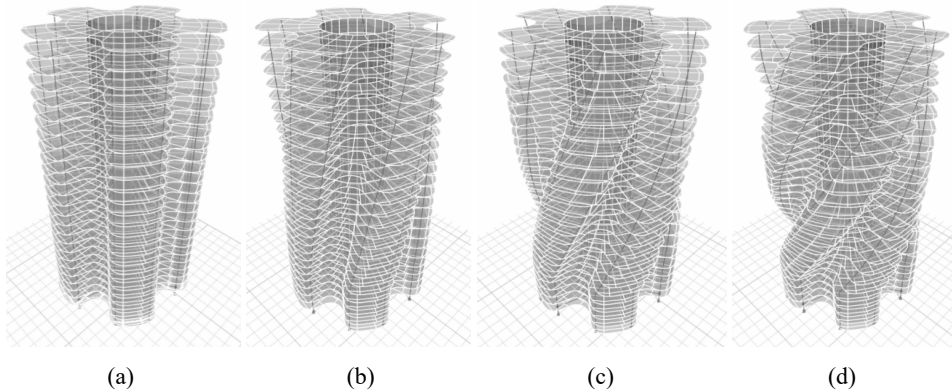
Steps	Description	Zone 3	Zone 2	Zone 1
S1	Wt due to slab = Panel area (FF + PwL + LL + (thk of slab $\times$ density of conc.)	$37.515(1.5 + 1 + 3 + (0.15 \times 25)) = 347 \text{ kN}$	347 kN	347 kN
S2	Self Wt of column = vol of column $\times$ density of conc.	$= (\pi \times 0.4^2) \times 3 \times 25 = 37.699 \text{ kN}$	$= (\pi \times 0.5^2) \times 3 \times 25 = 58.905 \text{ kN}$	$= (\pi \times 0.6^2) \times 3 \times 25 = 84.823 \text{ kN}$
S3	Self Wt of beam = $(L \times W \times D \times \text{density})$	$= (11 \times 1.3 \times 0.45 \times 25) = 160.875 \text{ kN}$	$= (11 \times 1.3 \times 0.45 \times 25) = 160.875 \text{ kN}$	$= (11 \times 1.3 \times 0.45 \times 25) = 160.875 \text{ kN}$
S4	Total load in each zone	No. of floors = 5 Load = $(347 + 37.699 + 160.875) \times 5 = 2,728 \text{ kN}$	No. of floors = 15 Load = $(347 + 58.905 + 160.875) \times 15 = 8,502 \text{ kN}$	No. of floors = 10 Load = $(347 + 84.823 + 160.875) \times 10 = 5,927 \text{ kN}$
S5	Total vertical load on column	$= 2,728 + 8,502 + 5,927$ $\therefore V = 17157 \text{ kN}$		
S6	From equation (1), axial load in the column (N) is $= V \div \cos \theta$	Factored load $V' = 1.5 \times 17,157 = 25,735.5 \text{ kN}$ 2° rotation per floor = $25,735.5 \div \cos (11.32^\circ) = 26,246 \text{ kN}$ 4° rotation per floor = $25,735.5 \div \cos (21.82^\circ) = 27,721.6 \text{ kN}$ 6° rotation per floor = $25,735.5 \div \cos (31^\circ) = 30,023.8 \text{ kN}$		

Table 5 Procedure to calculate torsion acting at the core due to gravity loads (continued)

Steps	Description	Zone 3	Zone 2	Zone 1
S7	From equation (2), horizontal force component (H) is $= N \times \sin \theta$	2° rotation per floor = $26,246 \times \sin (11.32^\circ) = 5,151.8 \text{ kN}$ 4° rotation per floor = $27,721.6 \times \sin (21.82^\circ) = 10,303.9 \text{ kN}$ 6° rotation per floor = $30,023.8 \times \sin (31^\circ) = 15,463.4 \text{ kN}$		
S8	From equation (3), torsion developed at sixth storey in the core $= H \times n \times R$	2° rotation per floor = $5,151.8 \times 10 \times 17.26 = 889,200 \text{ kNm}$ 4° rotation per floor = $10,303.9 \times 10 \times 17.26 = 1,778,453 \text{ kNm}$ 6° rotation per floor = $15,463.4 \times 10 \times 17.26 = 2,668,982.8 \text{ kNm}$		

4 Scope of the study

In order to compare the results between the models, the sizes of structural members are assumed to be same in all models irrespective of the rate of twist present in them.

Figure 5 3D view of G+25 models, (a) 0° per floor (b) 2° per floor (c) 4° per floor (d) 6° per floor**Table 6** Structural details of the models

Models	Zones	Concrete grade	Storeys	Column diameter (mm)	Core wall thickness (mm)	Slab thickness (mm)
G+25	Zone 1	M60	1–10	800	1,000	150
	Zone 2	M50	11–20	700	900	150
	Zone 3	M40	21–25	600	800	150
G+35	Zone 1	M60	1–15	1,200	1,500	150
	Zone 2	M50	16–30	1,000	1,400	150
	Zone 3	M40	31–35	800	1,300	150

Figures 5 and 6 show the 3D view of the models with varying rates of twist and heights; used in the study. The first case is of the G+25 floor straight model. The second case is the twisted version of the first case, wherein the rate of twist per floor starts at 2° from the 6th storey. The third and fourth cases are the twisted models with rate of twist per floor being 4° and 6° respectively. The details of the structural elements are presented in Table 6. The common details of all the models are tabulated in Table 7.

Figure 6 3D view of G+35 models, (a) 0° per floor (b) 2° per floor (c) 4° per floor (d) 6° per floor

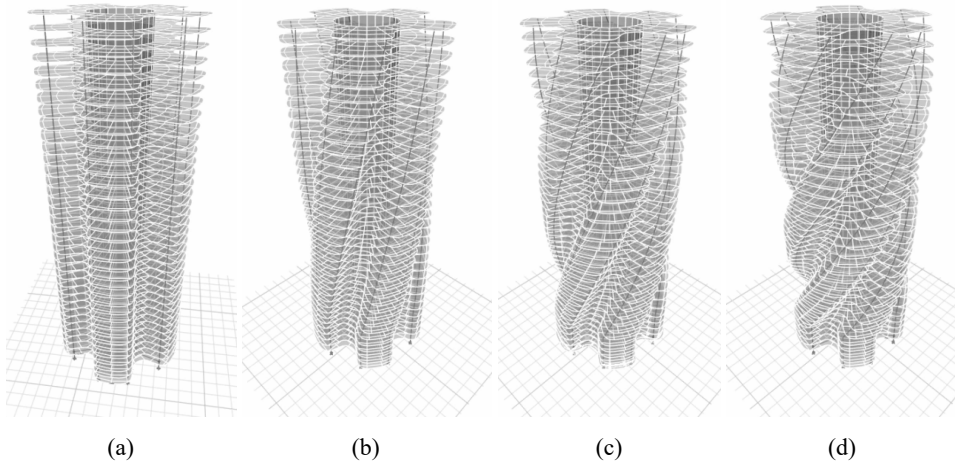


Table 7 Common details in all models

Plan area	1485.5 m ²
Storey height	3 m
Rotation of floor in twisted buildings initiates from	Storey 6
No. of columns on each floor	10
Beam size	1,300 mm $\times$ 600 mm
Distance from pivot point of plan and column	17.26 m
Building type	RCC
Grade of steel	Fe500

5 Results and discussion

5.1 Torsion diagram in core by floor due to gravity loads (ultimate)

5.1.1 G+25

We can observe from the torsion graphs of G+25 models Figures 7(a), 7(b), 7(c) and 7(d), that the torsion in straight buildings due to gravity loads is of negligible magnitude with the maximum torsion being 261 kN-m whereas the torsion in twisted buildings spiked at the sixth floor, where the twisting of the models start, and gradually decreased as it

gained height. This trend is due to the fact that there is a decrease in the gravity loads as the models gain height. The maximum torsion in the 2° , 4° and 6° rotation per floor was noted at the sixth storey as 648,869 kN-m, 1,242,102 kN-m and 1,852,405 kN-m respectively.

Figure 7 Torsion diagram by floor in G+25 models due to gravity loads, (a) straight building (b) 2° rotation per floor (c) 4° rotation per floor (d) 6° rotation per floor (see online version for colours)

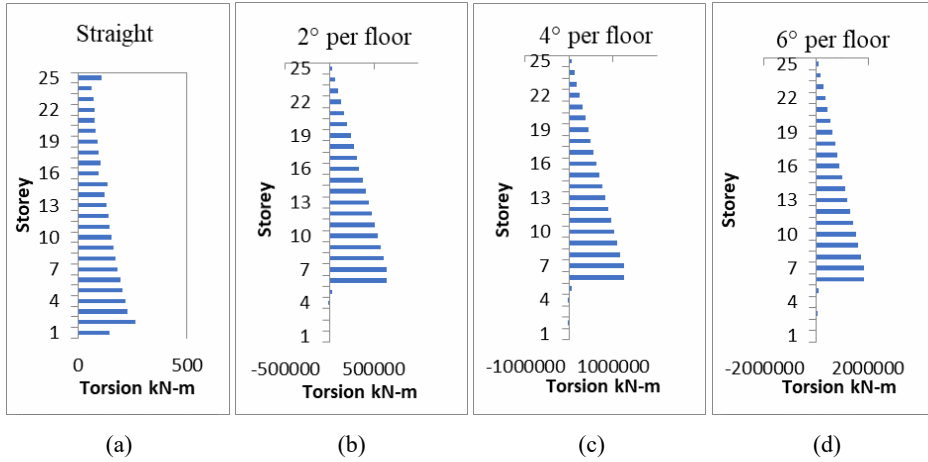
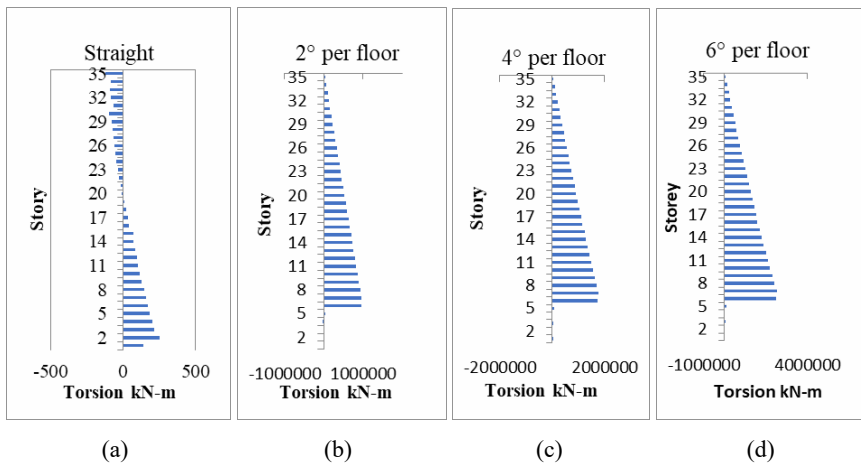


Figure 8 Torsion diagram by floor in G+35 models due to gravity loads, (a) straight building (b) 2° rotation per floor (c) 4° rotation per floor (d) 6° rotation per floor (see online version for colours)



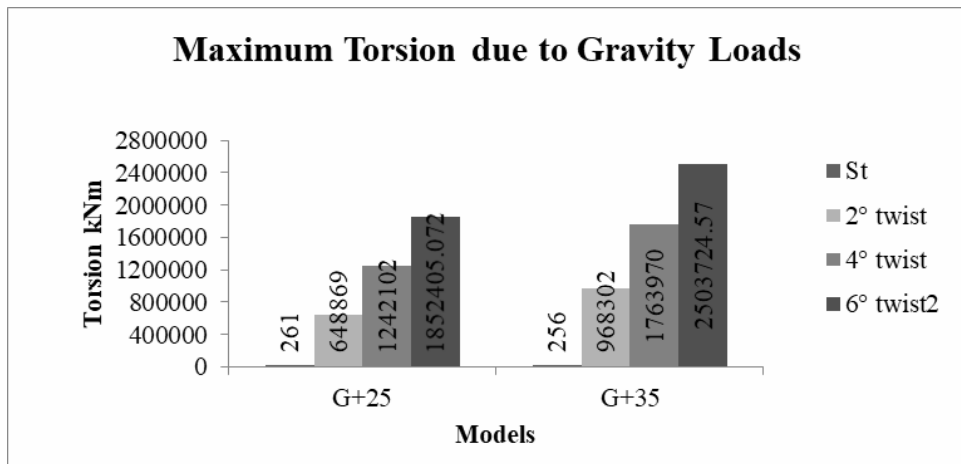
5.1.2 G+35

A similar trend is observed in the G+35 models. The maximum torsion in the twisted buildings is observed at the 7th storey as 968,302 kN-m, 1,763,970 kN-m and 2,503,725 kN-m for 2° [Figure 8(b)], 4° [Figure 8(c)] and 6° [Figure 8(d)] rotation per floor respectively, and the torsion in the straight building is about 256 kN-m.

5.2 Maximum torsion due to load combination (ultimate)

The torsional moments generated due to gravity loads rose with the increase in angle of twist and elevation and the torsion due to gravity loads in straight models was negligible when compared to that of the twisted models.

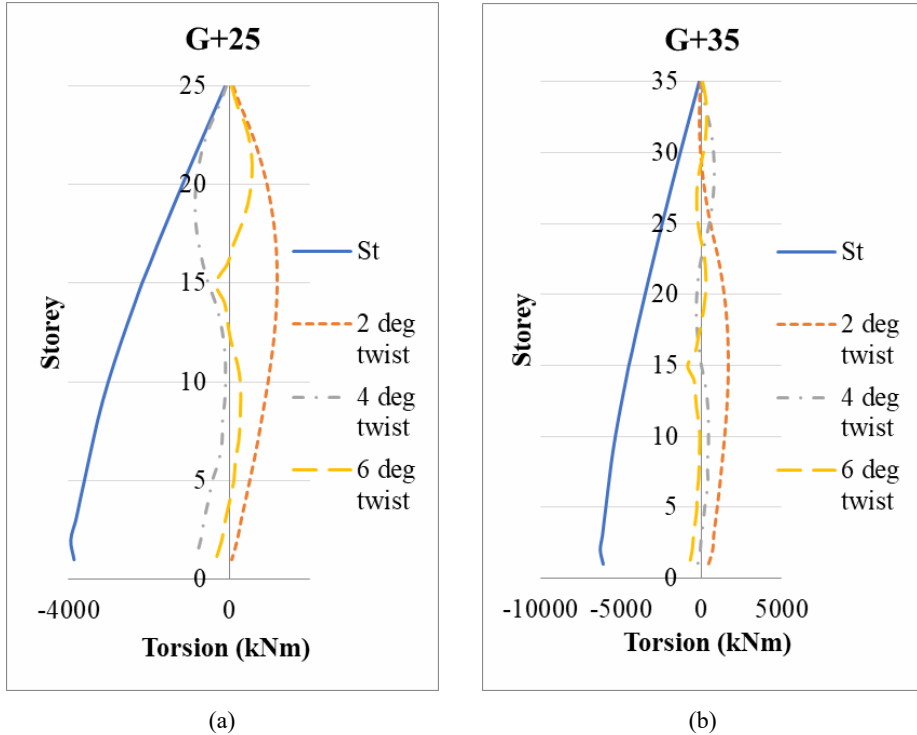
Figure 9 Max torsion in G+25 and G+35 models



5.3 Torsion due to wind loads

The graphs of torsion due to wind loads in the straight and twisted models of G+25 and G+35 stories are represented below in Figure 10. The variation in the torsion induced due to wind loads is evident as the torsion in straight models is constantly decreasing as the height increases. However the 2° models show a decreased magnitude of torsion when compared to straight model for wind loads. In the 4° and 6° models the torsional response due to wind loads was observed to be irregularly distributed along the height and an overall decrease in the magnitude of torsion from straight to 6° models was also noted. The observations in the torsional response of the models with G+35 storeys are similar to those noticed in G+25 models. The magnitude of torsion increased with height of the models as observed from the graphs below. The torsional response of G+35 models was similar to that of G+25 models in nature but not in magnitude. This variation in torsion values based on the difference in the rates of twist of the models highlights the vortex shedding properties of twisting buildings. The increase in irregularities of the models are contributing to the vortices being shed more effectively.

Figure 10 Torsion diagram by floor due to wind loads, (a) G+25 models (b) G+35 models (see online version for colours)

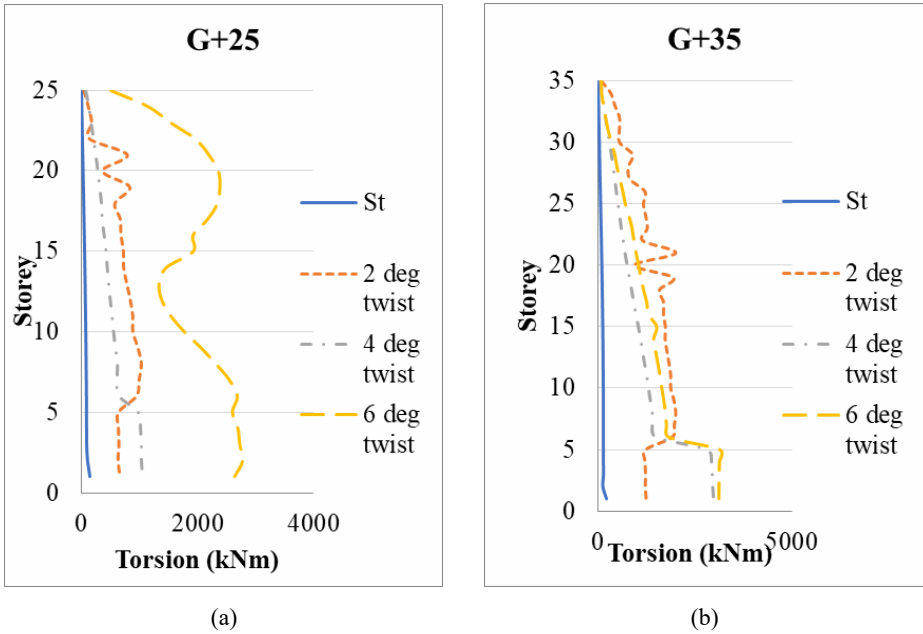


5.4 Torsion due to seismic loads

The magnitude of torsion was the highest at the ground storey in straight models of both heights, and decreased at the upper storeys. This variation in torsion for straight models is negligible in comparison to that of twisted models. In twisted building models, the maximum torsion developed at the core was at storey 6 or 7, the magnitude of which was significantly higher than straight models. A consistent increase in torsion at the 6th storey was noted as the twisting of the models advanced.

The rotation of floors starts from the sixth storey in the present study, implying that the rotated floor caused an escalation in the magnitude of torsion at the central core. It is important to note that the magnitude of torsion increases significantly with the rate of twist. This highlights that twisted buildings are not as stiff as conventional buildings when subjected to seismic loads and it is important to note whether the torsion being developed in the core wall are within limits.

Figure 11 Torsion diagram by floor due to seismic loads, (a) G+25 models (b) G+35 models (see online version for colours)



5.5 Shear stresses developed at core due to gravity and lateral loads

5.5.1 Shear stress due to gravity and lateral loads

Table 8 presents the load combinations utilised to validate compliance with shear stress limits. These combinations are referenced throughout the study by their corresponding serial numbers.

Table 8 Load combinations considered

S. no.	Load combinations
LC1	$1.5\text{DL} + 1.5\text{LL}$
LC2	$1.5\text{DL} + 1.5\text{WL}$
LC3	$1.5\text{DL} + 1.5\text{EQL}$
LC4	$1.2\text{DL} + 1.2\text{LL} + 1.2\text{WL}$
LC5	$1.2\text{DL} + 1.2\text{LL} + 1.2\text{EQL}$
LC6	$1.2(\text{DL} + \text{LL} \pm (\text{EQx} \pm 0.3\text{EQy}))$
LC7	$1.5(\text{DL} + \text{LL} \pm (\text{EQx} \pm 0.3\text{EQy}))$
LC8	$0.9\text{DL} \pm 1.5(\text{EQx} \pm \text{EQy})$

Table 9 Shear stress due to load combinations

Load combination	Shear stress (MPa)							
	G+25				G+35			
	S_t	2°	4°	6°	S_t	2°	4°	6°
LC1	0.3	1.47	2.71	4.02	0.43	2.15	3.76	5.4
LC 2	0.29	1.28	2.25	3.27	0.4	1.89	3.17	4.46
LC3	0.56	1.53	2.49	3.51	0.62	2.01	3.33	4.59
LC4	0.25	1.27	2.26	3.29	0.34	1.87	3.18	4.49
LC5	0.47	1.47	2.46	3.5	0.52	1.98	3.32	4.6
LC6	0.48	1.25	2.12	2.97	0.53	2.18	2.82	3.87
LC7	0.6	1.63	2.64	3.71	0.67	2.14	3.53	4.84
LC8	0.55	0.96	1.4	1.87	0.61	1.16	1.8	2.38

Shear stress in G+25 models for all load cases increased as the rate of twisting increased and a similar trend was observed for G+35 models. From the results it is observed that gravity loads induce greater shear stress in twisted models when compared to lateral loads. Core walls in straight models developed very low shear stresses due to gravity and lateral loads. As per codal provisions, it is recommended that the shear stress should not exceed 4MPa for concrete grades equal to or greater than M40. Clause 9.2.3 of IS 13920:1993 states that “the nominal shear stress in the wall, τ_v , shall not exceed τ_{cmax} , as per Table 14 of IS 456:1978” (Bureau of Indian Standards, 1993). Table 14 of IS 456:1978 is Table 20 in IS 456:2000, which states that “for concrete grades higher than or equal to M40, the shear stress must not exceed 4MPa” (Bureau of Indian Standards, 2000). This limit was constantly exceeded in six degree rotation models of G+35 models for majority of the load combinations. In a revised version of the code IS 13920:1993, i.e., IS 13920:2016, clause 10.2.3(a) states that “when nominal shear stress demand τ_v on a wall is, more than maximum design shear strength τ_{cmax} of concrete (given in Table 20 of IS 456), the wall section shall be re-designed” (Bureau of Indian Standards, 2016b).

An increase in the thickness of the core wall, may lead to various problems. The coordination between the architects and engineers may get disrupted due to the assignment of bulky members. There will also be an increase in the dead load of the structure which then gives rise to an increase in the magnitude of torsion being generated. Alternatively, composite core wall can be used in place of RCC. This will ensure that the strength of the member is not compromised and may even lead to an overall decrease in the thickness of the core wall (De Simone et al., 2015).

5.6 Base shears

Base shears due to wind and seismic loads, Figures 12 and 13 were observed to be almost equal in magnitude in models with same elevations.

Figure 12 Base shear due to wind

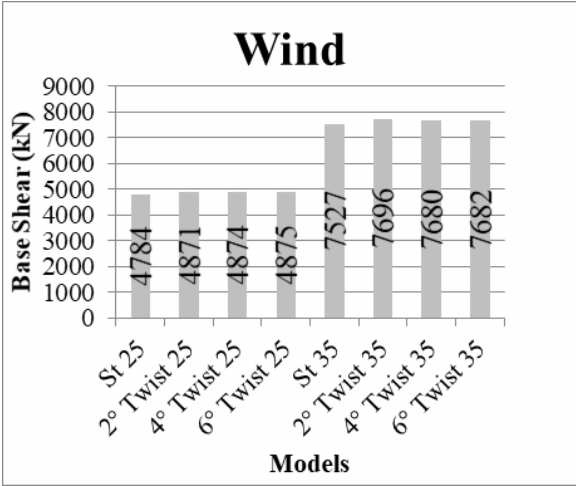
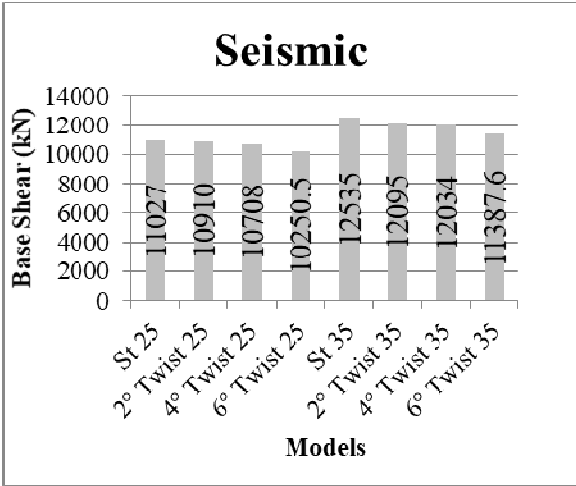


Figure 13 Base shear due to seismic



5.7 Maximum storey displacements (mm)

The displacements due to gravity loads in G+25 and G+35 models increased as the rate of twist increased. Displacement due to wind and seismic loads also showed similar a trend. This trend could be linked to the fact that as the rate of twist increased the stiffness of the models decreased.

Table 10 Displacements due lateral loads

Load combination	Displacements (mm)							
	G+25				G+35			
	S_t	2°	4°	6°	S_t	2°	4°	6°
LC1	0.026	4.1	5.26	7.72	0.17	10.9	11.75	16.2
LC2	6.45	7.5	10.22	12	25.66	24.5	33.6	37
LC3	19.94	21	23.48	24.5	37.5	35.67	46.5	47
LC4	5.15	6.18	8.95	11	20.5	21.78	28.35	32
LC5	15.94	16.96	19.56	21	30	31.7	39.41	40

6 Detailing of members

With the columns now being inclined, it is essential to observe how the reinforcement in columns would be placed. Although, there are no major differences between the placement of reinforcement in the straight or inclined column but, it is usually the case to provide more shear reinforcement in the inclined members. The shear reinforcement in inclined members is more tightly spaced to account for the effects due to the prominent horizontal force component acting at the column head.

As per Cl.26.5.3 of IS 456:2000, there are certain guidelines that need to be followed when designing a column, following which the reinforcement details in the straight and inclined column are presented below.

Figure 14 Column reinforcement from straight to inclined column (see online version for colours)

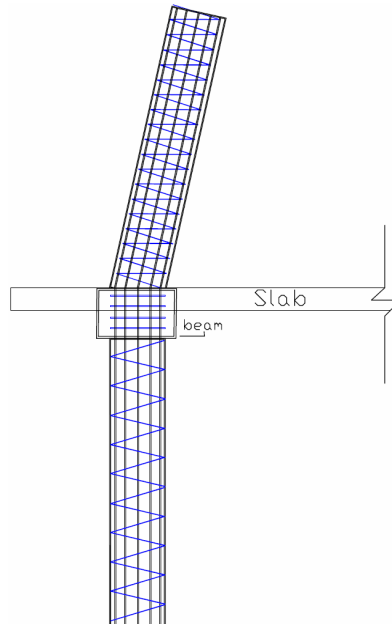


Figure 15 Detailing in straight column (see online version for colours)

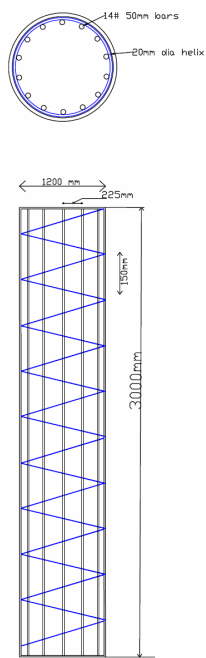
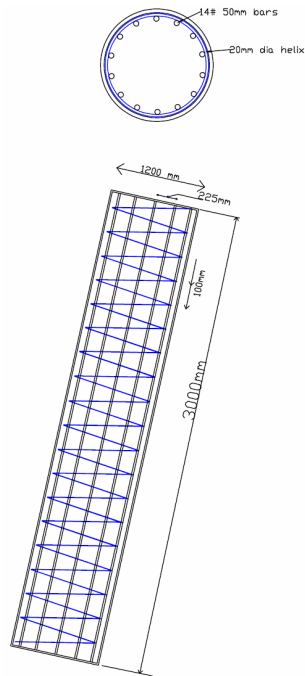


Figure 16 Detailing in inclined column (see online version for colours)



7 Manually calculated torsion vs. ETABS torsion

Detailed calculation of torsion, derived manually, is presented in Section 4.1. The results derived by manual calculations are only for gravity loads, i.e., dead and live loads.

Table 11 MCT vs. ETABS torsion for ultimate in G+25

G+25 models			% difference
Angle of rotation/floor	Torsion (kN-m)		
	Manual	ETABS	
2° rotation per floor	588,728.95	648,869.32	10.2
4° rotation per floor	1,177,490.06	1,242,102.343	5.5
6° rotation per floor	1,767,105.5	1,852,405	4.8

Table 12 MCT vs. ETABS torsion for ultimate in G+35

	<i>G+35 models</i>		<i>% Difference</i>
<i>Angle of rotation/floor</i>	<i>Torsion (kN-m)</i>		
	<i>Manual</i>	<i>ETABS</i>	
2° rotation per floor	889199.18	954952.98	7.4
4° rotation per floor	1778446.956	1735393.19	2.5
6° rotation per floor	2668985.139	2503724	6.6

The maximum torsion due to gravity loads, taken from ETABS, was developed in the 6th or 7th storey, as the inclination of the columns start from 6th storey. Therefore, manual calculations of torsion due to gravity loads are worked out at the 5th storey. The torsional values obtained manually and through ETABS showed a commendably close alignment, with a minimal deviation of only 3%, underscoring the high accuracy and reliability of ETABS in modelling torsional effects

8 Conclusions

- 1 The maximum torsion in the central core wall of twisted buildings, in G+25 and G+35 models, induced by gravity loads, was observed to occur at or near the storey where the twisting of the models commenced, i.e., the 6th storey. The magnitude of the straight models was negligible when compared to those observed in the twisted models. The torsion in the core wall induced by gravity loads increases proportionally with both the angle of twist and the height of the models.
- 2 Torsional response of twisting building when subjected to wind loads is comparatively better than that of its parametric twin. When subjected to wind loads, the observed lower torsion in twisted building models compared to straight models and the distribution of torsional moments along the height of the core wall, can be attributed, at least in part, to the phenomenon of vortex shedding.
- 3 When subjected to seismic loads, the straight models among all the elevations, i.e., G+25 and G+35 exhibited maximum torsion at the ground storey. However, in

twisted models, the torsion in the core wall escalated at the 6th storey, implying that the rate of twist has a significant effect on the stiffness of the building when subjected to seismic loads. Straight models outperformed their twisted counterparts under seismic loading conditions. Straight models consistently performed better as the rate of twisting in the models increased.

- 4 Shear stresses induced in the central core by both lateral loads and gravity loads were generally within acceptable limits for most models, except for 35 floor models with a 6° rotation per floor, where it exceeded acceptable limits, i.e., 4MPa.
- 5 In terms of displacements due to wind and seismic loads, the straight and twisted models at the same elevation exhibited an increase in the displacement values as the rate of twisting increased. This consistent trend can be attributed to the fact that as the rate of twist increased the stiffness of the models decreased.

In conclusion, the findings of this study provide compelling evidence that a rate of rotation of 6° per floor in the design of twisted structures, characterised by a circular central core wall and inclined columns, leads to a critical compromise in structural integrity as the shear stress in the core wall, surpasses the safety threshold, exceeding 4 MPa. These results underscore the importance of careful consideration in the design process, emphasising the need to ensure a balance between architectural innovation and structural validity.

The findings of this research on combined shear stresses in the central core of tall twisted buildings have significant practical implications for architects, engineers, and builders.

- Design considerations:
 - 1 rate of twist: a critical rotation rate of 6° per floor compromises structural integrity, exceeding acceptable shear stress limits (4 MPa).
 - 2 core wall design: circular central core walls with inclined columns require careful consideration to balance architectural innovation and structural validity.
 - 3 torsion estimation: manual calculation methods, validated by this study, can aid preliminary design decisions.
- Guidelines for twisted building design:
 - 1 limit rotation rate to $<6^\circ$ per floor
 - 2 ensure core wall stiffness through optimised design
 - 3 consider vortex shedding effects in wind load calculations
 - 4 prioritise seismic load performance in design decisions.

9 Scope for future work

- The effect of soil structure interaction could be studied for further understanding the response of twisted structures.
- The performance of twisted buildings with different core wall configurations could be studied.

- Exploring the use of stepped columns in twisted buildings as an alternative to inclined columns.
- Different plans for twisted structures can be used.

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