Dynamic Analysis of Vertical Irregular Tall Structural System

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Abstract. The behaviour of any structural depends upon the structural element present in it. The critical aspect on which the structural configuration depends are shape, length and geometry of the building. In the present study the performance of vertical geometric irregular tall structures under the wind load is evaluated as per IS 16700: 2017 provisions. Three type of vertical geometric irregular tall reinforced concrete buildings having different plan dimensions with cantilevered offset length varying from 11% to 15% of the building lateral dimension with increment of 0.5% are modelled. Modal analysis and wind analysis are performed using structural analysis software ETABS to assess the behaviour of vertical geometric irregular tall structural system with cantilevered offset. Parameter such as time period, frequency, storey displacement and storey drift are studied and compared with the regular building. Multiple linear regression analysis is carried out to formulate a general expression for the responses of the vertical irregular tall buildings.

1. Introduction
The population growth of large cities is increasing due to relocation of individuals from rural to urban areas for employment and to raise their living standards. The limited construction area available in the heart of the city leads to the design and construction of tall buildings. In many cases the design of tall building is governed by the stiffness requirement rather than strength demand. The strength requirement can be easily achieved by modern methods, but these buildings are mainly affected by the lateral loads so there should be sufficient lateral stiffness of the building. The strength requirement can be easily achieved by modern methods, but these buildings are mainly affected by the lateral loads so there should be sufficient lateral stiffness of the building.

The stiffness to the lateral load can be achieved by selecting the proper structural system and proper structure design to the lateral loads. Structural engineer should choose the structural system wisely to design the building economically. There are mainly two types of lateral load, wind loads and seismic loads. Behavior of the structure to lateral loads can be studied by numerical analysis as well as from experiments. Wind tunnel test is carried out to study the behavior of structures to wind loads and shaking table test is conducted to study the response of the structure to ground motions. Static and dynamic analysis is carried out in numerical analysis, these methods includes linear and
nonlinear analysis. Tall buildings situated in high wind speed location are more affected by the wind forces, so the tall structures need to be analyzed by selecting the proper analysis method for these forces.

There are many factors which affect the behavior of the high-rise building such as height of the building, plan aspect ratio, slenderness ratio, building geometry, damping of the building etc. Proper analysis method should be adopted for analysis purpose according to building type, environmental conditions and all the parameters which will affect the behavior of high-rise building should be considered while designing.

In many cases, it is very difficult to estimate wind load and their associated structural behavior by analytical methods. For example, uncommon aerodynamic shape of the building or the building is flexible so that motion of the building affects the forces acting on it. Wind tunnel test is carried out in those cases to find the wind loads and study the behavior of the structures to wind action. The tall buildings having square geometric configuration are studied for dynamic responses for interference excitation [1] and stated that the kinetic energy is the main factor observed to be in upstream buildings which will alter the response induced along the wind and cross wind for the interference excitation. Wind tunnel test has been conducted to identify the source of error which arises when the mode shape of the buildings is non-ideal and methods of applying correction which include 2 adjustment factors. The first adjustment factors is related to static load and second one is relate to displacements and accelerations [2]. Shielding and channeling effects between two or more buildings are studied [3]. Upstream interfering buildings will decrease the mean wind load on downstream building by providing certain shielding effect. The vertical geometric irregularity structures are studied for their performances [4]. The parameter studied are as base shear, time period, inter storey drift ratio and maximum displacement. The results of regular structures are then compared to the results of the irregular structure. Nonlinear static approach is carried out with used defined hinges for different setback ratios. From the study they have conclude that performance of vertical irregular structure when designed conferring to IS code provisions are inferior related to regular structure. Five different structural systems of tall buildings are compared, and optimal structural system was determined for a certain building height [6]. The ratio of building height to the minimum base width is called as slenderness ratio. The maximum slenderness ratio of the building for different structural system and seismic zones are given in code [5]. Building with different slenderness ratio from 2 to 8 has been studied [7] and the design governing factor for all the configuration has been specified. High strength RC buildings performance and their cost utilization are studied [8]. The parameters considered for the cost analysis are utilization of steel, concrete and formwork. The static analysis and dynamic analysis of tall buildings are studied. From the study they have concluded that steel is the main parameter which contributes to the increase the cost. Member size can be reduced by adopting high strength concrete, the behavior of high strength concrete structure is same as that of equivalent normal strength concrete with respect to top displacement, base shear and maximum inter storey drift ratio. The damped outrigger concept for high rise buildings to increase damping of the structure are proposed [9]. In this concept lateral design force will be reduced so there will be a reduction in the member size of the structure and cost of construction can be saved. Damped outriggers are introduced to reducing dynamic wind effects. Performance based design using nonlinear pushover analysis is carried out [10]. Steel reinforcement is used to control the lateral drift beyond the limit, and it provides ductility to the RC building. Pushover analysis is carried out using “SAP2000” software. Principle of virtual work and Taylor series approximation are used for the inelastic performance-based design.

The objectives of this study are to evaluate the performance of vertical irregular tall structures under wind loads as per IS 16700: 2017 provisions, to assess behaviour of vertical geometric irregular tall structural system with cantilevered offset to wind loads and development of correlation for responses using regression analysis.
2. **IS 16700: 2017**

In 2017 bureau of Indian standards has published a new code IS 16700: 2017 “Criteria for structural safety of tall concrete buildings” which address the issues associated with the reinforced concrete (RC) tall buildings design. According to this code buildings which are having height between 50 m to 250 m are considered as tall buildings. The following are the salient features addressed by this standard:

a) Different structural systems that can be adopted
b) General requirement such as maximum height of the building that can be adopted for different structural systems and for different seismic zone, plan aspect ratio, lateral drift, storey stiffness and strength, vertical acceleration, floor systems, material properties and progressive collapse mechanism
c) Loads and load combinations
d) Structural design parameters
e) Foundation design parameters

Buildings exceeding the specifications provided by this standard (for example, buildings height greater than 250 m, buildings height exceeding the height specified for particular structural system, or using of other structural systems which are not specified by this standards) and buildings which are not covered in this standards are called as code exceeding tall building. Such building requires an approach of performance-based design to meet defined performances of the structure. All code exceeding high rise buildings should go through two processes, review by structural design reviewer and review by an expert review panel.

3. **Vertical geometric irregularity**

Now a days, buildings shapes are becoming more complex because of its aesthetic architecture and function. Vertical geometric irregularity is the common type of irregularity in the buildings. In the code [11] they have given the definition of irregular buildings, where vertical geometric irregularity is a type in the vertical irregularities. According to the code this irregularity should be considered when the lateral dimension of lateral force resisting system at any storey is greater than 125 percent of the storey below. Different type of vertical geometric irregularity are given in the code are as shown in figure 1.

![Vertical geometric irregularities](image_url)

**Figure 1.** Vertical geometric irregularities
4. Structural modeling

Three type of symmetric building Type A, Type B and Type C having 3, 4 and 5 bays respectively are considered for the present study where cantilever projection is provided in the plan at 18th, 19th, 20th and 21st stories and the projection length is doubled for the 22nd, 23rd, 24th and 25th stories. In each type of building one reference building without vertical geometric irregularity (without any cantilevered offset) and nine vertical irregular buildings are modelled. The reference models are considered as base models to study and compare the responses of vertical geometric irregular buildings. Similar member properties are considered for both regular and irregular buildings. The building data considered for the present study are as shown in Table 1.

As per IS 1893:2016, the building having lateral dimension of the lateral force resisting system in any storey greater than 125 percent of the storey below are considered as vertical geometric irregular building. For the buildings having cantilevered offset in the top stories, lateral dimension in any storey is more than 120 percent of the storey below then they are considered as vertical geometric irregular buildings. The length of the cantilevered offset in each side of the plan is varied from 11 percent to 15 percent of the building horizontal length with the increment of 0.5 percent. Cantilevered offset length considered for Type A, Type B and Type C buildings are as shown in Table 2. Moment frame with structural wall system is selected as the structural system for modelling the tall RC buildings and L shaped structural wall is positioned at the opposite corners of the building so that the location of the shear wall can be maintained same for all models.

Table 1. Building data

| Type of Building | Components     | Details               |
|------------------|----------------|-----------------------|
| Type A           | Plan dimension | 9 m × 9 m             |
|                  | Storey height  | 3 m                   |
|                  | Building height| 75 m (25 storey)      |
|                  | Column spacing | 3 m                   |
|                  | Number of bays | 3                     |
| Type B           | Plan dimension | 12 m × 12 m           |
|                  | Storey height  | 3 m                   |
|                  | Building height| 75 m (25 storey)      |
|                  | Column spacing | 3 m                   |
|                  | Number of bays | 4                     |
| Type C           | Plan dimension | 15 m × 15 m           |
|                  | Storey height  | 3 m                   |
|                  | Building height| 75 m (25 storey)      |
|                  | Column spacing | 3 m                   |
|                  | Number of bays | 5                     |
Table 2. Cantilevered offset length

| Model no. | Cantilevered offset length – A (m) | Model no. | Cantilevered offset length – A (m) | Model no. | Cantilevered offset length – A (m) |
|-----------|-----------------------------------|-----------|-----------------------------------|-----------|-----------------------------------|
|           | Type A                            | Type B    | Type C                            |
| M-1       | Regular                           | M-11      | Regular                           | M-21      | Regular                           |
| M-2       | 0.110 × L                         | 0.990     | M-12                               | 0.110 × L | 1.320                             |
| M-3       | 0.115 × L                         | 1.035     | M-13                               | 0.115 × L | 1.380                             |
| M-4       | 0.120 × L                         | 1.080     | M-14                               | 0.120 × L | 1.440                             |
| M-5       | 0.125 × L                         | 1.125     | M-15                               | 0.125 × L | 1.500                             |
| M-6       | 0.130 × L                         | 1.170     | M-16                               | 0.130 × L | 1.560                             |
| M-7       | 0.135 × L                         | 1.215     | M-17                               | 0.135 × L | 1.620                             |
| M-8       | 0.140 × L                         | 1.260     | M-18                               | 0.140 × L | 1.680                             |
| M-9       | 0.145 × L                         | 1.305     | M-19                               | 0.145 × L | 1.740                             |
| M-10      | 0.150 × L                         | 1.350     | M-20                               | 0.150 × L | 1.800                             |
| M-11      | Regular                           | M-21      | Regular                           |
| M-21      | 0.110 × L                         | 1.650     | M-22                               | 0.110 × L | 1.725                             |
| M-22      | 0.120 × L                         | 1.80      | M-23                               | 0.125 × L | 1.875                             |
| M-23      | 0.120 × L                         | 1.875     | M-24                               | 0.130 × L | 1.950                             |
| M-24      | 0.125 × L                         | 2.025     | M-25                               | 0.135 × L | 2.025                             |
| M-25      | 0.125 × L                         | 2.100     | M-26                               | 0.140 × L | 2.175                             |
| M-26      | 0.130 × L                         | 2.250     | M-27                               | 0.145 × L | 2.500                             |
| M-27      | 0.140 × L                         | 2.500     | M-28                               | 0.150 × L | 2.750                             |
| M-28      | 0.150 × L                         | 2.750     | M-29                               | 0.155 × L | 2.875                             |
| M-29      | 0.155 × L                         | 2.875     | M-30                               | 0.160 × L | 3.000                             |
| M-30      | 0.160 × L                         | 3.000     |                                    |           |                                   |

ETABS 16.0.0 software is used for modelling of the vertical irregular tall RC buildings with different cantilevered offset and plan size of the building. The grid system are used for the modelling. Figure 2 represents the typical plan and 3D–Render view of the models with the building data as shown in Table 1. The modal analysis and wind analysis is performed using ETABS software to study the dynamic characteristics of the building such as time period, frequency, displacements, drift and base shear for 3 regular and 27 vertical geometric irregular tall RC buildings.

Figure 2. Typical view of the Buildings

(a) Plan of bottom stories  
(b) Plan of stories from 18 to 21  
(c) Plan of stories from 22 to 25  
(d) 3D - Render view
The material properties and section properties considered for the study are shown in Table 3 and Table 4 respectively.

**Table 3. Materials data**

| Components       | Materials                                |
|------------------|------------------------------------------|
| Concrete         | M 40 (Beams & Columns)                   |
|                  | M 25 (Slabs)                             |
| Rebar’s          | HYS 500 (Longitudinal bars)              |
|                  | HYS 415 (Ties)                           |

**Table 4. Sectional properties of the buildings**

| Components                                   | Dimensions          |
|----------------------------------------------|---------------------|
| Columns                                      | 400 x 400 mm        |
| Floating Columns                             | 230 x 300 mm        |
| Beams                                        | 230 x 400 mm        |
| Periphery Beams in projection area           | 230 x 300 mm        |
| Shear wall Thickness                         | 300 mm              |
| Slab Thickness                               | 150 mm              |
| Slab Thickness in projected area             | 125 mm              |

Dead loads, super dead loads, live loads and wind loads are applied to the structure. The super dead loads as per IS 875 (Part 1): 1987, live loads as per IS 875 (Part 2): 1987 and wind load factors as per IS 875 (Part 3): 2015 are considered. The loads and wind load factors consider are shown in Table 5 and Table 6 respectively for the city Darbhanga. The p delta effect of the building is considered as per IS 16700: 2017.

**Table 5. Loads considered**

| Components      | Details       |
|-----------------|---------------|
| Live load       | 4 kN/m²       |
| Roof live load  | 1.5 kN/m²     |
| Super dead load | 1 kN/m²       |
| Glazing         | 1 kN/m        |

**Table 6. Wind load factors**

| Components               | Details |
|--------------------------|---------|
| Basic wind speed ($V_b$) | 55 m/s  |
| Terrain category         | 3       |
| Structural class         | C       |
| Risk coefficient factor ($K_1$) | 1.08   |
| Topography factor ($K_2$) | 1       |
5. Results and discussion

5.1. Modal analysis results – time period

Time period is an inherent property of the building which is controlled by its mass and stiffness. Safety of structure is governed by natural time period and amount of damping in each mode of vibration. Fundamental natural time period is an important parameter to understand the dynamic behaviour of building. Estimation of approximate translational natural time period is given in IS 1893 (Part 1): 2016, clause 7.6.2 which depends on base dimension, height of the building and type of the building. Time period is defined as the time taken by the building to complete one cycle of motion during vibration.

According to IS 16700: 2016 natural period of fundamental torsional mode of vibration shall not exceed 0.9 times the smaller of the natural period of the fundamental translation mode of vibration in each of the orthogonal directions in plan. As the modes increases the time period will get decreases. It is observed that in 12 modes of vibrations there will be a 9-translation mode of vibration and 3 torsional mode of vibration at mode 3, mode 6 and mode 10 for all type of models. Time period of torsional mode of vibration is less than 0.9 times of the smaller of the time period of translation mode of vibrations for all type of models. Total modal mass participation of the buildings in the considered modes are above 90 percent for all buildings. From the results it is observed that increase of time period with respect to increase of cantilevered offset is less in Type C buildings than Type B buildings than Type A buildings.

The time period increases with increasing the cantilevered offset from 0.99 m to 1.35 m. There is a 2.33% increase in the time period for increase of 4% cantilevered offset for 3 bays buildings. The time period for vertical irregular buildings are increases from 11.26% to 15.30% as compared to base model. The graphical representation of time period with respect to modes from modal analysis are as shown below in figure 3 for Type A models.

![Figure 3: Mode Vs Time period – Type A](image)

The time period increases with increasing the cantilevered offset from 1.32 m to 1.8 m. There is a 2.47% increase in the time period for increase of 4% cantilevered offset for 4 bays buildings. The time period for vertical irregular buildings are increases from 11.95% to 14.72% as compared to base model.
to base model. The graphical representation of time period with respect to modes from modal analysis are as shown below in figure 4 for Type B models.

Figure 4. Mode Vs Time period – Type B

The time period increases with increasing the cantilevered offset from 1.65 m to 2.25 m. There is a 2.28% increase in the time period for increase of 4% cantilevered offset for 5 bays buildings. The time period for vertical irregular buildings are increases from 10.24% to 12.75% as compared to base model. The graphical representation of time period with respect to modes from modal analysis are as shown below in figure 5 for Type C models.

Figure 5. Mode Vs Time period – Type C

5.2. Modal analysis results – Frequency
It is the number of times the building sways and comes to its original position in one second after its excitation. It also depends on the mass and stiffness of the building. It is the inverse of the time period of the building. From the results it is observed that decrease of frequency with respect to
increase of cantilevered offset is less in Type C buildings, Type A and Type B buildings frequency are almost equally decreased.

The frequency decreases with increasing the cantilevered offset from 0.99 m to 1.35 m. There is a 2.34% decrease in the frequency for increase of 4% cantilevered offset for 3 bays buildings. The frequency for vertical irregular buildings decreased from 11.4% to 13.47% as compared to base model. The graphical representation of frequency with respect to modes from modal analysis are as shown below in figure 6 for Type A models.

![Figure 6. Mode Vs Frequency – Type A](image)

The frequency decreases with increasing the cantilevered offset from 1.32 m to 1.8 m. There is a 2.33% decrease in the frequency for increase of 4% cantilevered offset for 4 bays buildings. The frequency for vertical irregular buildings decreased from 10.68% to 12.76% as compared to base model. The graphical representation of frequency with respect to modes from modal analysis are as shown below in figure 7 for Type B models.

![Figure 7. Mode Vs Frequency – Type B](image)
The frequency decreases with increasing the cantilevered offset from 1.65 m to 2.25m. There is a 2.06 % decrease in the frequency for increase of 4 % cantilevered offset for 5 bays buildings. The frequency for vertical irregular buildings decreased from 9.33 % to 11.20 % as compared to base model. The graphical representation of frequency with respect to modes from modal analysis are as shown below in figure 8 for Type C models.

![Figure 8. Mode Vs Frequency – Type C](image)

5.3. Wind analysis results – Storey Displacement

Wind force acting on a building will cause displacement of the building. Storey displacement is defined as displacement of a storey with respect to base of the structure. The tall buildings and buildings which are located in the cities where wind speed is high are more affected by the wind force. From the results it is observed that increase of displacement with respect to increase of cantilevered offset is more in Type A buildings than Type B buildings than Type C buildings.

The storey displacement increases with increasing the cantilevered offset from 0.99 m to 1.35 m. There is a 3.61% increase in the displacement for increase of 4% cantilevered offset for 3 bays buildings. The maximum storey displacements for vertical irregular buildings are increases from 10.9% to 14.9% as compared to base model. The graphical representation of displacement with respect to stories from wind analysis are as shown below in figure 9 for Type A models.

![Figure 9. Storey Vs Displacement – Type A](image)
The storey displacement increases with increasing the cantilevered offset from 1.32 m to 1.8 m. There is a 3.58 % increase in the displacement for increase of 4% cantilevered offset for 4 bays buildings. The maximum storey displacements for vertical irregular buildings are increases from 10.76% to 14.72% as compared to base model. The graphical representation of displacement with respect to stories from wind analysis are as shown below in figure 10 for Type B models.

![Figure 10.Storey Vs Displacement – Type B](image)

The storey displacement increases with increasing the cantilevered offset from 1.65 m to 2.25 m. There is a 3.50% increase in the displacement for increase of 4% cantilevered offset for 5 bays buildings. The maximum storey displacements for vertical irregular buildings are increases from 10.78% to 14.65% as compared to base model. The graphical representation of displacement with respect to stories from wind analysis are as shown below in figure 11 for Type C models.

![Figure 11.Storey Vs Displacement – Type C](image)

5.4. Wind analysis results – Storey Drift
Under the actions of lateral force induced due to wind action, building tends to displace which affects the lateral stability of the structure. Therefore, storey drift is one of the important factors to check the lateral stability of the structure which is defined as difference of displacements between two consecutive stories of the building. According to IS 16700: 2017 lateral drift ratio should be
limited to $H/500$ for the wind loads where $H$ is total height of the building. Since all the models are having the same height 75 m, lateral drift ratio is limited to 0.15, so the maximum allowable storey drift for the present study is 11.25 mm. The storey drift and storey levels at which there will be maximum storey drift was observed to be decreasing as the plan of the building increases for vertical geometric irregular tall RC buildings.

The top storey drift is increasing for every 1.5 % increase in the cantilevered offset. The storey drift increases with increasing the cantilevered offset from 0.99 m to 1.35 m and maximum drift was observed to be in storey 11 for each model including the base model. The maximum storey drift observed in Type A models is 8.9 mm which is less than the maximum allowable storey drift 11.25 mm. The graphical representation of lateral drift with respect to stories from wind analysis are as shown below in figure 12 for Type A models.

![Figure 12. Storey Vs Drift – Type A](image)

The storey drift obtained from the wind analysis for critical stories of Type B models are shown below in the Table 4.11. The storey drift increases with increasing the cantilevered offset from 1.32 m to 1.8 m and maximum drift was observed to be in storey 9 and 10 for each model including the base model. The maximum storey drift observed in Type B models is 7.9 mm which is less than the maximum allowable storey drift 11.25 mm. The graphical representation of lateral drift with respect to stories from wind analysis are as shown below in figure 13 for Type B models.

![Figure 13. Storey Vs Drift – Type B](image)
The storey drift obtained from the wind analysis for critical stories of Type C models are shown below in the Table 4.12. The storey drift increases with increasing the cantilevered offset from 1.65 m to 2.25 m and maximum drift was observed to be in storey 8 and 9 for each model including the base model. The maximum storey drift observed in Type C models is 7 mm which is less than the maximum allowable storey drift 11.25 mm. The graphical representation of lateral drift with respect to stories from wind analysis are as shown below in figure 14 for Type C models.

![Figure 14. Storey Vs Drift – Type C](image)

5.5. **Wind analysis results – Base Shear**

Base shear is termed as estimation of maximum expected lateral force on the base of the structure. According to IS 1893 (Part 1): 2016 design base shear is calculated for the complete building as a whole. The design base shear is distributed to the complete building at a various floor levels at the respective centre of the mass. Base shear of all the models from wind analysis are determined. The graphical representation of base shear with respect to models for wind analysis are as shown below in figure 15. It is observed that there is an equal increase of 2% base shear as the cantilevered offset is increased from 11% to 15% for all type of buildings.

![Figure 15. Models Vs Base Shear](image)
5.6. Correlation for responses

In this section a correlation for responses are presented in order to find the response characteristics of building for different overall dimension and cantilevered offset. This correlation is well suited for the symmetric buildings having plan dimension between 9 m × 9 m to 15 m × 15 m and cantilevered offset up to 15% of the building lateral dimension.

Multiple linear regression analysis is carried out to formulate an equation to find the maximum displacement and base shear of the building caused by wind load and time period from modal analysis. Cantilevered offset in terms of percentage of the building lateral dimension and building lateral dimension is taken as the two independent variable and the responses are taken as one dependent variable. The correlation developed for the responses from this study are shown below in Table 7.

Table 7. Correlation for Responses

| Responses               | Correlation                      | $R^2$ |
|-------------------------|----------------------------------|-------|
| Time Period             | $y = 0.0253A + 0.0033L + 2.5898$ | 0.980 |
| Maximum Displacement    | $y = 1.337A - 7.768L + 228.977$ | 0.992 |
| Base Shear              | $y = 11.914A + 200.566L - 139.842$ | 0.999 |

Where, $y$ = Responses, $A$ = Cantilevered offset in terms of percentage of the building lateral dimension

$L$ = Building lateral dimension at bottom

The coefficient of determination $R^2$ is a statistical measure that measures the proportion of variance in the dependent variable (responses) that is predictable from independent variables (% of cantilevered offset and horizontal length of building). $R^2$ value will tell how well the regression prediction approximate the real data points. The range of $R^2$ in the multiple linear regression is 0 to 1. Residual is the difference between the actual values and the values obtained from the equation (predicted values). Residual represent how much the predicted value is deviated from the actual value. The positive residual represent that the predicted value is less than the actual value and negative residual represent that the predicted value is more than the actual value. The graphical representation of residual Vs predicted values from the formulated equations are shown below in figure 16 to figure 18.

Figure 16. Time Period Predicted Vs Residuals
6. Conclusions

The analytical study on vertical geometric irregular tall structural system was carried out in this study. From the results and comparative study, following conclusions are drawn:

- From the modal analysis it can be concluded that, the increase of time period with respect to increase of cantilevered offset is less in buildings having larger plan dimension. Time period of torsional mode of vibration is less than 0.9 times of the smaller of the time period of translation mode of vibrations for all type of buildings as per IS 16700: 2017.
- The increase of lateral displacement of the buildings with increasing the cantilevered offset is more for buildings having smaller plan dimension for the action of wind load.
- The storey drift and storey levels at which there will be maximum storey drift was found to be decreasing as the plan of the building increases for vertical geometric irregular tall RC
buildings. The storey drifts are within the limits provided by the IS 16700: 2017.

- There is an equal increase of 2% base shear as the cantilevered offset is increased from 11% to 15% for all type of buildings.

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