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INFLUENCE OF k_4 AND OFFSHORE WIND VELOCITY FACTORS ON 40 M OPEN LATTICE TELECOMMUNICATION TOWER

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Abstract

To minimize the structural failures associated with high tropical cyclonic wind speeds, the IS 875 (Part 3): 2015 presents the k_4 factor to augment the quantification of design wind speed in coastal areas of India with different numerical values according to the importance of structures. This k_4 factor is presented both in static and dynamic methods of wind load computations. Besides the k_4 factor, the code specifies the offshore wind velocity multiplication factor. The open lattice steel (flat-sided) towers, which are vulnerable to cyclonic wind speeds, are modelled in SAP 2000 (4*i*) software to evaluate the effect of the two factors in both the methods. The results suggest that when the design wind speed increases by 30% for k_4 factor and 15% for offshore wind velocity factor, the top displacement increase by 36%, 50%, 62% and 91%; tilt increase by 33%, 41%, 55% and 78%; the reaction forces at the base of the tower increase by 43%, 66%, 74% and 117%; the axial forces for the (critical) bracing at the bottom panel increase by 60%, 95%, 105% and 164% for static, dynamic, offshore static and offshore dynamic analysis considerations respectively. The effectiveness of the above factors is reviewed with the cyclonic Gust factor values (Gc).

Keywords: IS 875 (Part 3): 2015, k_4 factor, Open lattice tower, SAP 2000 (4*i*) software, Tropical cyclone.

1. Introduction

The tropical cyclones, one among the others, are the alarming natural disasters in India and more numbers of cyclones are devastating the Indian east coastal region with the unpredictability of high gale speeds rendering huge property loss.

In view of better safety of structures, IS 875 (Part 3): 2015 code [1] recommends the cyclonic importance factor. This factor appears both in the static and dynamic analysis of wind load computations.

Post-hurricane investigations have frequently notified that wind and wind-driven rain have been the medium of scopious damage to building components and their premises. It is explained fact that many of the cyclonic wind speeds are many a time exceeded the basic wind speed during the cyclones [1]. In order to ensure safety and performance of the structures in the cyclone region, the IS 875 (Part 3): 2015 code [1] introduced the k_4 factor for enlarging the design wind speed computations for both static and dynamic wind load calculations. The k_4 factor has the different numerical values viz., 1.0, 1.15 and 1.30 for general structures, industrial structures and Post cyclone importance for emergency service structures respectively. Besides the k_4 factor, the code specified the offshore wind velocity factor with 1.15 value as an additional factor for a distance of up to 200 km from the nearest coast.

In the recent past, many free-standing lattice towers in and around the metropolitan cities of the coastal areas in the Indian subcontinent have been found due to active increase in the network of electronic communication systems. These are located either on the ground and/or roof-top according to the communication requirements. Very often, these structures have been subjected to strong winds and buffeting gusty winds during the cyclonic period in the coastal region of India.

In this paper, the effect of k_4 factor and offshore wind velocity factor on a 40 meter open-lattice- steel tower is analyzed in SAP 2000 (4*i*) software [2] to find the variation of internal forces such as top displacements, tilt, base reaction (axial stresses), axial forces in the bracing (critical) members of the bottom panel for both static and dynamic analysis in accordance with IS 875 (Part 3): 2015 code [1] provisions. The results are tabulated in comparison with the IS 875(Part 3) 1987 version guidelines [3]. The variations for a Gust factor and design wind pressure along the height of the tower are also presented. The effectiveness of k_4 and offshore wind velocity factors in terms of cyclonic gust factors (Gc) are reviewed.

2. Literature Review

The following sub-sections illustrate the process of introduction of cyclonic factor, the various other factors involved in the dynamic analysis, including Gust factors for computation of wind loads of tall structures.

2.1. Cyclones on East Coast of India and basic wind speed

Baswa et al. [4] reported that the severe tropical cyclones were predominated on the east coast region and scanty frequency on the west coast of India. They summarize that during the past couple of decades the most severe cyclones have become a common event of occurrence for every two to three years [5, 6].

Lakshmanan et al. [7] mentioned that the design wind speeds for 70 meteorological centres of India for a return period of the mean probable design life of 50 years have been evaluated based on the long-term data on hourly wind speed with a conclusion that the coastal zone wind speed is conservative.

2.2. Cyclonic importance factor -various suggestions

Baswa et al. [4, 8] outlined the historical development of introduction to k_4 factor in India. The impact of k_4 factor on A-type and Lean-to roof trusses for static analysis was examined. It was concluded that there was an appreciable increase in internal forces when the k_4 factor was 1.30 only.

2.3. Dynamic analysis (gust factor method)

Even though the wind force is dynamic in nature, it is treated as an equivalent static force for simplicity in analysis and design of wind-sensitive structures such as freestanding lattice towers, tall buildings etc.

The dynamic response becomes paramount either the natural frequency of towers in the first mode is below 1.00 Hz or the ratio of height to lateral dimension is more than 5 [1, 2, 9].

For calculating the buffeting/along wind load effect of the flexible/ tall structures, the design hourly wind velocity is multiplied by the Gust factor (G). This factor consists peak factor for upwind velocity fluctuation otherwise known as a background factor of approaching wind) (g_v) and peak factor for resonance (g_R) of the structure. These factors are introduced in IS 875 (Part 3): 2015 code [1] only. However, a single peak factor (g_f) provision was presented in IS 875 (Part 3): 1987 version [3].

Abraham et al. [10] suggested failure analysis of 101 m and 91 m microwave lattice towers for cyclonic wind speeds with gust loading factor method suggested that the conservation in design using a G (Gust factor) may not be guaranteed in cyclonic region because of possible deviation in the parameters used in the design code IS 875 (Part 3): 1987 [3], instead the cyclonic Gust factor (Gc).

The findings of Shanmugasundaram et al. [11] on the full-scale field experiment of 52 m tall steel lattice tower during the cyclones suggested that wind, terrain and structural characteristics showed the significant variation during tropical cyclone wind periods.

Kareem [12] suggested that since wind and the structure interaction is complicated by structural geometry, complex flow around them, complexity and uncertainty of the flow in the atmospheric boundary layer, the probabilistic effect of the wind loads on structures. On the other hand, Venkateswarulu et al. [13] conceived that gust response factor computed by the codes were higher than the values obtained by the spectral method.

All major international codes adopted the gust loading factor/gust response factor (GLF/GRF) approach to estimate the maximum wind load effects for along wind direction in the dynamic analysis of structures. However, each authority employs unique definitions of wind field characteristics, such as mean wind-velocity profile, turbulence length scale and intensity profile and wind spectrum. Carril Jr. et al. [14] described that slight differences in these characteristics have derived in discrepancies in GLF estimates and in the mean wind loads, which appropriately lead to dominant variation in the estimate of the wind-induced load effects.

2.4. Research objectives

This section explains the basic wind speed provision in the cyclone-prone areas and also describes the provisions of k_4 factor and offshore wind speed factors for both static and dynamic analysis and also elucidate why the dynamic analysis is performed for the computed frequencies of the tower are more than 1 Hz.

2.4.1. Static analysis

Even though, the revised IS 875 (Part 3): 2015 [1] code defined the same basic wind speed (with a return period of 50 years) of IS 875 (Part 3): 1987 [3], to ensure the safeguard of structures, the design wind speed in the cyclonic region is modified by the wind speed multiplication factor as a k_4 factor. This k_4 factor with 1.15 value for industrial structures and maximum of 1.30 for structures of post-cyclone importance emergency service structures.

2.4.2. Dynamic analysis

In the dynamic analysis, nonetheless, IS 875 (Part 3): 2015 [1] code specifies the respective gust factors for background and resonance conditions cannot guarantee in the design of the towers in cyclonic prone areas. The code preferred the k_4 factor as an extra margin of safety against the unprecedented high cyclonic wind speeds. The codes [1, 2] also specified the offshore wind velocity factor besides the k_4 factor to compute the wind speed calculation in the cyclone-prone region.

In spite of the computed tower fundamental frequencies, 1.147 to 1.55 Hz are more than 1 Hz, the tower needed to be appraised as dynamically sensitive in the code provisions (IS 875: 2015) [1] and IS 800: 2007 [9] since their aspect ratio is more than 5.

Moreover, Australian Standard: AS 3995-1994 [15] favoured adopting both static and dynamic methods for the towers whose first mode of natural frequency is more than 1 Hz. Along with these guidelines, this paper adopts both the methods of analyses of the tower.

From the above literature, it is found that, for static and dynamic analysis, the basic wind speed in the cyclonic prone region cannot exceed 50 m/s. However, there have been no studies found pertaining to the effect of incorporation of a k_4 factor and offshore wind velocity factor for the design of lattice tower structures in coastal areas. Hence, this paper elucidates the influence of the k_4 factor and offshore wind velocity factor for a 4-legged open Lattice steel angular 40-meter tower in the cyclonic area.

3. Methods

To ascertain the influence of the factors, the two types of analyses are performed. The geometry of a 40 m steel tower is fully described in the following section.

3.1. Tower geometry

The 40-meter open-lattice steel tower with a square cross-section in the plan is selected. The tower is classified as convergent and parallel leg sections. The primary part of the tower up to 30th m forms a pyramid frustum of convergence section and the top 10 m section is defined as a parallel leg section. The centerline dimension is 5.60 at its base and 1.46 m at the top. The topmost part of the tower is parallelepiped of a height equal to 10.00 m with the square cross-section. A geometric division of tower sections and their heights, *X* bracings and *K* bracings and the layout of all elements of the tower are shown in Fig. 1. Self-supporting towers are typically preferred since they require less base area and are more suitable for heavier lateral loading. The most prominent dimension of a tower is the height and the tapered part is regarding the bracing, as it reduces design forces.

The 4-legged open-lattice steel tower angular tower has been modelled as a 3D space frame using SAP 2000 (4*i*) software [2] with *K* and *X* type bracings.

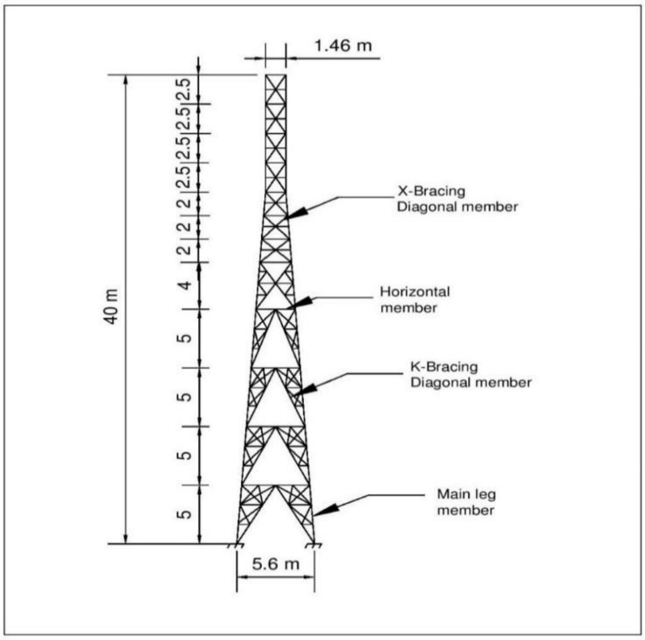

Fig. 1. Lattice tower.

3.2. Wind load calculations

Since the above factors affect the outcome of results both in the static and dynamic analysis of tower design, hence, both the methods are presented and comparisons have been made from the static analysis results.

3.2.1. Static analysis

The design wind speed (*Vz*) and design wind pressure (*Pz*) for the lattice tower have been computed with the Eqs. (1) and (2) respectively. India is segmented into six different wind zones and each zone is expressed as specific basic wind speed (V_b).

The design wind speed depends on the design life of the structure (k_1 factor), the risk factor 1.08 is adopted for 100 years design life of towers; the terrain and the height of the structure (k_2 factor), the topography of the location (k_3 factor) and also on the k_4 factor. In this way, along wind load for any panel of the tower is computed with the Eq. (3).

$$V_z = V_b \times k_1 \times k_2 \times k_3 \times k_4 \tag{1}$$

$$P_z = 0.6 V_z^2 \tag{2}$$

$$F_z = C_f A_e P_z \tag{3}$$

3.2.2. Dynamic analysis (gust factor)

The dynamic analysis of towers may be governed in the frequency domain based on the characteristic that depends upon the frequencies of both the approaching upwind action and the structural properties of the structure. This analysis addresses only on the wind action and structural elements of lattice tower, however, does not consider any exposed areas related to non-structural elements such as ladders, feeders, platforms or antennas. Zhou et al. [16] narrated that it is an accepted approach to consider the wind forces on antennas and the effect on the computation of the wind forces, however, the IS 875 (Part 3: 1987 and 2015) Indian code versions [1, 3] do not cover the force (drag) coefficient for the ancillaries such as antennae, etc. [13].

Lattice Towers, which are wind sensitive structures, shall be designed for dynamic wind loads with hourly mean wind speed is a reference wind speed [1, 3]. For computations of along-wind loads and response viz., bending moments, shear forces or top deflections in the dynamic method, the Gust factor method is used by IS 875 (Part 3): 2015 code [1]. Along wind load on a structure at a height "z" is computed by Eq. (4).

$$F_z = C_f z A_e P_z G \tag{4}$$

Equation (5) depicts to find the (G) Gust value for computation of along-wind loads at different heights of a tower. The components of S, E, Bs, β, g_v are specified in clause10.2 of IS 875 (Part 3): 2015 code [1].

$$G = 1 + \left(r \sqrt{g_v{}^2 B_s \left(\left(1 + \varphi \right)^2 \right) + \left(\frac{H_s g_R{}^2 SE}{\beta} \right)} \right) \tag{5}$$

4. Results and Discussion

The 40 m steel flat-sided open lattice tower was simulated in the SAP 2000 (4*i*) software [2] with IS 875 (Part 3): 1987 wind code provisions [3]. The same model was simulated with the k_4 factor and offshore wind velocity factor provisions for computation of the variation of internal forces such as top deflection, tilt, base reaction forces and axial forces for critical bracing in static and dynamic methods. Variation of Gust factor (G), along with the height of a tower in the dynamic analysis is also presented in Tables 1 and 2. The tower model in SAP 2000 (4*i*) software is depicted in Fig. 2. The relevant results have been computed and depicted in Figs. 3 to 9.

Figures 3 to 5 depict the percentage variation of wind pressure at 5, 20 and 40 m height of the tower with IS 875 (Part 3) code [1, 3] provisions for static, dynamic, offshore static and offshore dynamic considerations respectively.

Figures 6 to 9 show the variation in the displacements, reaction forces at the base of the tower, variation in the critical bracing member forces and variation in the tilt of IS 875 (Part 3) [1, 3] provisions for static, dynamic, offshore static and offshore dynamic considerations respectively.

Table 1. Variation of gust factor (with offshore wind velocity factor).

Height (meters)	IS 875:1987	IS 875:2015 ($k_4 = 1$)	IS 875:2015 ($k_4 = 1.15$)	IS 875:2015 ($k_4 = 1.30$)
40	2.54	2.45	2.54	2.63
37.5	2.52	2.48	2.58	2.67
35	2.49	2.53	2.63	2.72
32.5	2.48	2.59	2.70	2.80
30	2.42	2.66	2.77	2.87
28	2.41	2.71	2.83	2.94
26	2.40	2.76	2.88	2.99
24	2.39	2.82	2.94	3.06
20	2.36	2.90	3.03	3.15
15	2.35	3.01	3.15	3.28
10	2.33	3.15	3.29	3.43
5	2.33	3.37	3.51	3.65
Average	**2.42**	**2.79**	**2.90**	**3.02**

Table 2. Variation of gust factor.

Height (meters)	IS 875:1987	IS 875:2015 ($k_4 = 1$)	IS 875:2015 ($k_4 = 1.15$)	IS 875:2015 ($k_4 = 1.30$)
40	2.54	2.37	2.45	2.53
37.5	2.52	2.40	2.48	2.57
35	2.52	2.45	2.53	2.62
32.5	2.49	2.50	2.59	2.68
30	2.49	2.56	2.66	2.76
28	2.46	2.61	2.71	2.81
26	2.45	2.65	2.76	2.86
24	2.42	2.71	2.82	2.92
20	2.38	2.79	2.90	3.01
15	2.28	2.89	3.01	3.13
10	2.26	3.03	3.15	3.27
5	2.26	3.25	3.37	3.49
Average	**2.42**	**2.68**	**2.79**	**2.89**

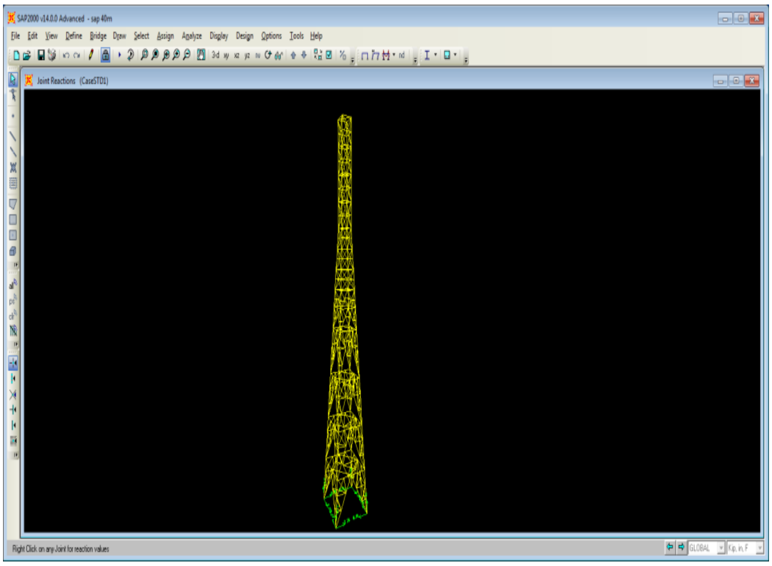

Fig. 2. Tower modelled in SAP.

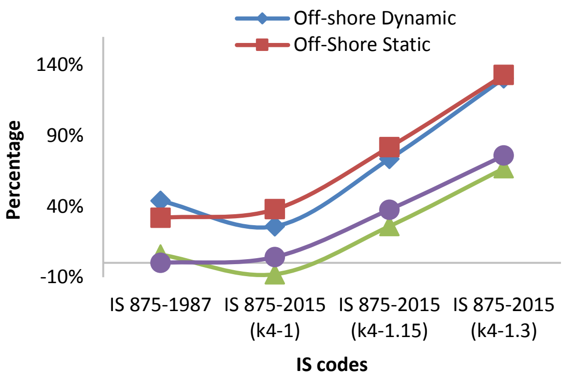

Fig. 3. Variation of wind pressure at 5 m height.

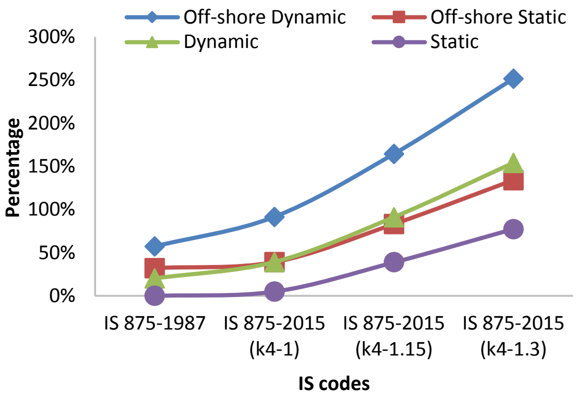

Fig. 4. Variation of wind pressure at 20 m height.

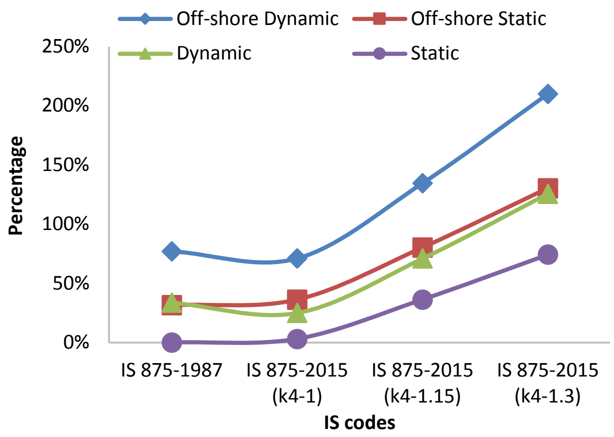

Fig. 5. Variation of wind pressure at 40 m height.

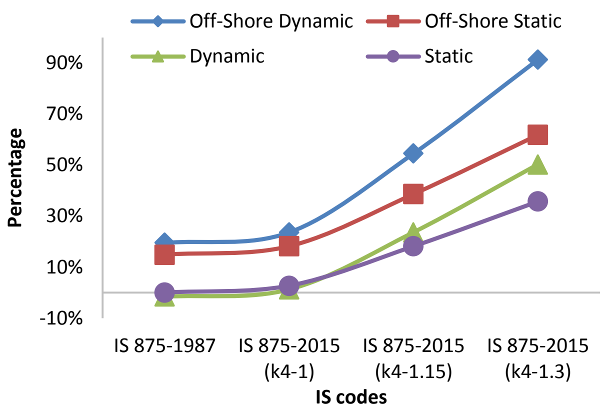

Fig. 6. Variation of displacements.

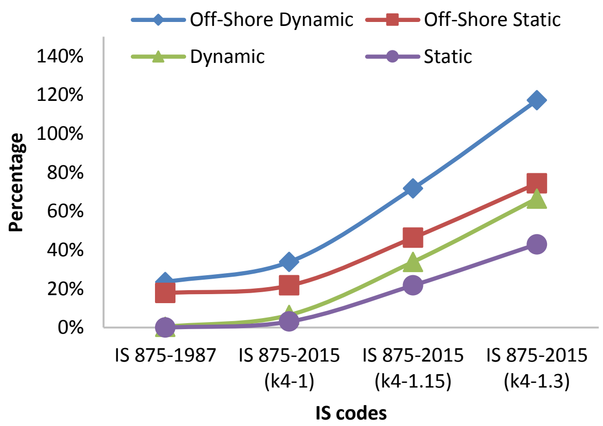

Fig. 7. Variation in reaction forces.

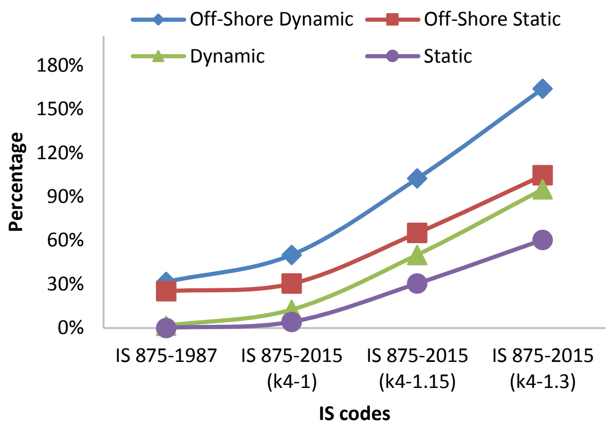

Fig. 8. Variation in bracing member forces.

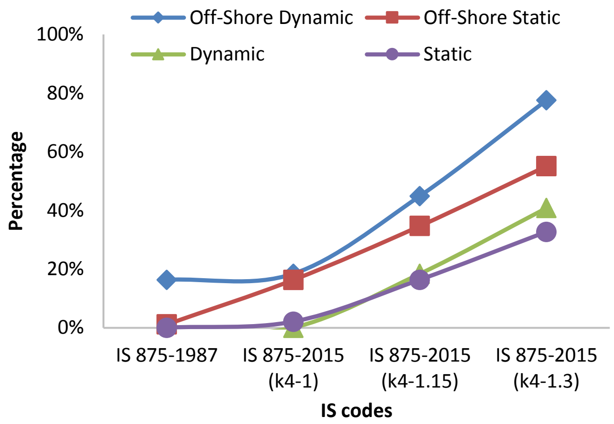

Fig. 9. Variation of tilt angle.

Discussion

The open lattice 4-legged 40 m square, steel tower has been modelled and simulated to find the wind forces with respective to IS 875 (Part 3): 1987 code provisions [3]. However, IS 875 (Part 3): 2015 [1] revised version specified the k_4 factor for both static and dynamic analysis methods of computation of wind loads. Hence, the above-mentioned model with the k_4 factor and offshore wind velocity factors has been simulated. The results obtained for the recommendations of IS 875 (Part 3): 1987 [3] and 2015 [1] have been compared and presented in Figs. 4 to 9. The variations of wind velocity for each height of the tower viz; 5, 20 and 40 meters are approximately 33% and the pressure variation is 76%. The following observations can be drawn for the analysis of tower design. The results pertain to terrain category 2 only.

- The top displacement was increased by 36%, 62%, 50% and 91% for static, offshore static, dynamic and offshore dynamic factor conditions respectively.

- The tilt at the top of the tower was increased by 33%, 55%, 41% and 78% for static, offshore static, dynamic and offshore dynamic factor conditions respectively.
- The maximum reaction force at the base of the tower was increased by 43%, 74%, 66% and 117% for static, offshore static, dynamic and offshore dynamic factor conditions respectively.
- The bottom panel bracing (critical) member force was increased by 60%, 105%, 95% and 164% for static, offshore static, dynamic and offshore dynamic factor conditions respectively.
- The average variation of the Gust factor is 2.42 to 2.89 for k_4 factor and 2.42 to 3.02 with offshore wind velocity factor.
- The computed cyclonic gust factors are very close to the proposed Gust factor (Gc) values in the cyclonic region [10].

5. Conclusions

After simulating the 40 m open lattice tower in SAP 2000 (4*i*) software with provisions of 1987 code and provisions of 2015 code with k_4 factor and offshore wind velocity factor for both the methods of analyses and with thorough discussions above the following conclusions have been drawn.

- The maximum top displacement for offshore static and the offshore dynamic wind speed conditions was increased by 62% and 91% in comparison with the static load recommendations of IS 875 (Part 3): 1987
- The tilt at the top of the tower for offshore static and the offshore dynamic wind speed conditions was increased by 55% and 78% in comparison with the static load provisions of IS 875 (Part 3): 1987
- The maximum reaction forces at the ground level of the tower for offshore static and the offshore dynamic wind speed conditions was increased by 74% and 117% in comparison with the static load provisions of IS 875 (Part 3): 1987
- The maximum bottom panel (critical) bracing member forces for offshore static and the offshore dynamic wind speed conditions was increased by 105% and 164% in comparison with the static load provisions of IS 875 (Part 3): 1987
- The Gust factor (G) obtained as per provisions of 1987 code is directly proportional to the height of the tower, however, inversely proportional to the height of the tower as per recommendations of the 2015 code
- The Gust factor (G) was increased by 19% and 25% respectively (i) after incorporation of cyclonic wind speed and (ii) A cumulative effect after incorporation of both cyclonic importance structure factor 1.30 and offshore wind speed factor of 1.15.
- To ensure the validity and effectiveness of the k_4 factor and offshore wind velocity factor in the dynamic analysis for the cyclone-prone area, the computed gust factors are compared with the proposed cyclonic gust factors (Gc) values for coastal regions of India. It is concluded that the current results are closer to the proposed Gc values. Hence, the k_4 and offshore wind speed provisions together guarantee the minimum safety against the cyclonic failures.

Nomenclatures

A	Surface area of a structure, m^2
Ae	Effective area of panel, m^2
A_z	Effective frontal area of the structure at height z, m^2
B_s	Background factor
B_{sh}	Average width of structure between height h and s, m
C_f	Force coefficient/drag coefficient for structure
C_p	Pressure coefficient
E	Spectrum of turbulence in approaching wind stream
F	Force normal to surface, N
Fz	Design peak along wind load on the structure at a height z, N
fa	First mode natural frequency of structure along wind direction, Hz
G	Gust factor
Hs	Height factor for resonance response
h	Height of structure above the mean ground level, m
k_1	Probability factor (risk coefficient)
k_2	Terrain roughness and height factor
k_3	Topography factor
k_4	Importance factor for cyclonic region
N	Reduced frequency, Hz
P_d	Design wind pressure, N/m^2
P_z	Wind pressure at a height z, N/m^2
S	Size reduction factor
s	Level of a structure, m
V_b	Regional basic wind speed, m/s
V_z	Design wind velocity at height z, m/s

Greek Symbols

β	Damping coefficient of structure
ϕ	Second-degree order turbulence factor

Abbreviations

AS	Australian Standards
Gc	Gust factor for cyclonic wind characteristics
IS	Indian Standards

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