

# EVALUATION OF THE STABILITY AND DYNAMIC CHARACTERISTICS OF FREE-STANDING COMMUNICATION MASTS SUBJECTED TO SELF AND ENVIRONMENTAL LOADINGS

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## ABSTRACT

*In a quest to improve the resilience of free-standing steel towers to wind-induced failures, static and dynamic characteristics of the widely used 30 m, 3-leg-telecommunication lattice mast of varying bracing types under turbulent wind action were evaluated. The mast structures were modelled using the Staad. Pro stiffness-matrix based software employing the 3-D beam elements for both the mast legs and bracings. Wind actions as the primary live load on the structure alongside self-weight of the structure and a surcharge load to simulate the communication gadgets on them were considered for the analyses. Basic wind speed of 35 m/s and turbulence effects for critical ground condition were employed to generate the vertical gradient of the wind action. The patch loading approach for open mast structure was employed. Thereafter the static as well as modal dynamic analyses were carried out. Findings from the study show that the mast base width of  $1/13^{\text{th}}$  of the 30 m height is stable for all bracing types considered in the study. The Z bracings masts are identified as the most cost effective in construction/erection compared to the other bracing types with cost savings of about 14%, 42.9% and 7.97% when compared to the K, diagonal and the X bracings respectively. Further findings show that the K bracing masts is more resilient to the loadings employed with maximum displacement up to 23% lower than all other bracing types considered. Maximum combined stresses are also lower in the K bracings compared with the other bracing types considered in a similar proportion. Results from the modal dynamic analyses however show that the K bracings masts are more susceptible dynamic response with the least natural frequency of 0.755Hz and the Z bracing more stable dynamically with a fundamental frequency of 0.89 Hz. It is recommended that the K bracings may be employed for 3-leg telecommunication mast up to 30 m high but with additional features to enhance its dynamic response. The findings in this paper are useful for planning and design of telecommunication masts and other similar structural systems.*

**Keywords:** Telecommunication Masts, Lattice Towers, Fundamental Frequency, Modal Analyses, Wind Loading

## 1 INTRODUCTION

**T**elecommunication masts are cantilever-like structures that serve as platforms on which electronic gadgets such as receivers and transmitters are placed for wireless-type communication of mobile and internet networking, television and radio broadcasting as well as integration of radar systems. Because of this essential function of the mast structure, structural stability of the structure against self and environmental load effects is a mandatory check often carried out at the design and construction stages to ensure that the huge investments, normally associated with the masts erections as well as the electronic equipment on them, are not lost to either total collapse or some form of serviceability failures that could

impede on normal telecommunication services. In spite of the traditional approaches employed in the masts tower designs and erections, concerns over serviceability failure and ultimate collapse are still on the rise owing to the increase reports of mast failures in the recent past, chiefly due to the environmental loadings of wind actions [1, 2, 3]. The wind action via its velocity, is an erratically fluctuating quantity with no regular periodicity but which may be considered to contain a large number of single frequency components that are spread over a wide frequency range and which when close to the masts natural frequency may respond dynamically to it and or collapse it as shown in Figure1 [4]. Lattice towers are reported to be sensitive to the dynamic environmental load of wind as well as random loadings from earthquake, blast or impact loadings and are largely so when the natural frequency of the structure is less than 1 Hz [5]. Thus to improve on the resistance of the mast structure to these loadings, studies carried out, though, largely on guyed masts and transmission towers covering analysis approaches/methods that best simulates the masts response [6, 7, 8] and effects of bracing configurations [3, 9] results in some promising outcomes. Other consideration to enhance stability and dynamic response of masts looks at the wind load which is an unsteady phenomenon due to its natural turbulence and gusting and its application either as static load or time history / varying load that accurately models the wind action on the masts structure [10, 11, 12, 13]. It is noted however, that though the wind load is highly fluctuating, its load value, when averaged over a long-time duration may be modeled as a static load [14]. The quasi-static wind load application has been used to accurately assess failure states of tower members and critical wind speed for the structure. Angle members often used for the structure are loaded eccentrically through the structure's legs subjected to primary tension or compression forces as well as secondary bending moments [15]. It is also on this premise that varied codes and standards provide simple approximation models for the application of wind loadings on structure. While the studies above are valid for the guyed masts, that rely on guyed cables for their lateral stability, same cannot be said of tower or free-standing masts whose response mechanism to loadings are different (Figure 1). In this regard thus, investigations into the bracing configuration types, masts topology and static as well as dynamic characteristics of the free-standing mast structure, which are practical issues that may affect the cost and weight of the structure, remains a gap in this area and hence this study.



Figure 1. Typical failure modes due to wind gust and dynamic excitation

This paper thus, assesses different bracing configuration types and topology for free-standing masts/tower under quasi-static wind loadings in addition to the gusting and turbulence effect for evaluation of the structure's response under varied wind loading with height for resilient design against failure. In the following Sections the methodology covering geometry of the masts considered, modelling, materials and support conditions are presented in Section 2. Section 3 reports on the loading, detailing wind actions and section 4 presents the analysis and structural modeling employed. Section 5 presents the finding from the study and finally the conclusions and recommendations are presented.

## 2 METHODOLOGY

### 2.1 Description of the model considered

The study considers the widely deployed 3-leg free-standing towers of 30 metres tip height. The masts are of 1 m bay intervals tapering from the base to the tip level as shown in Figure 2. The tip transverse elements were kept constant at 1m length while the tower mast base widths are taken as 1/3 of the mast height consistent with the submission by [3]. The bracing types also considered, include the diagonal bracing, Z and inverted K-bracings and the X (scissors) bracings as widely used in Nigeria and other part of the world.

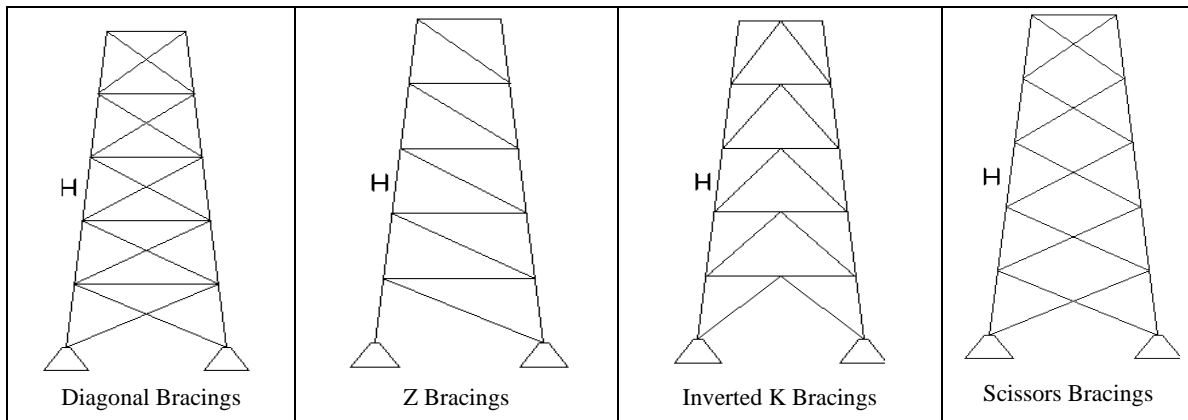


Figure 2. Typical Bracing Types considered in the study

### 2.2 Modelling

The mast towers were modeled using the Staad. Pro commercial stiffness matrix-based software using the 3-D beam elements for the tower legs and bracings. All joints were modelled as rigid connections.

### 2.3 Materials

Structural steel of grade S355 was utilized. Basic material properties of the steels are presented in Table 1. Equal angle steel profile of 80 x 80 x 8 kg/m is utilized for the analyses.

Table 1. Basic Material Properties of the structural steel employed

S/N	Material Property	Value	Unit
1	Density	7850	Kg/m <sup>3</sup>
2	Young's Modulus	205	GPa
3	Poisson's ratio	0.3	-
4	Tensile Strength	5.0	GPa
5	Yield Strength	3.55	GPa
6	Damping ratio	0.03	-

### 2.4 Supports

All supports for the 3-legs masts were encastre / fixed with moment carrying capacity. Typical 3-leg mast model of the diagonal bracing type structure is presented in Figure 3. Similar models were employed for other bracing types considered in the study.

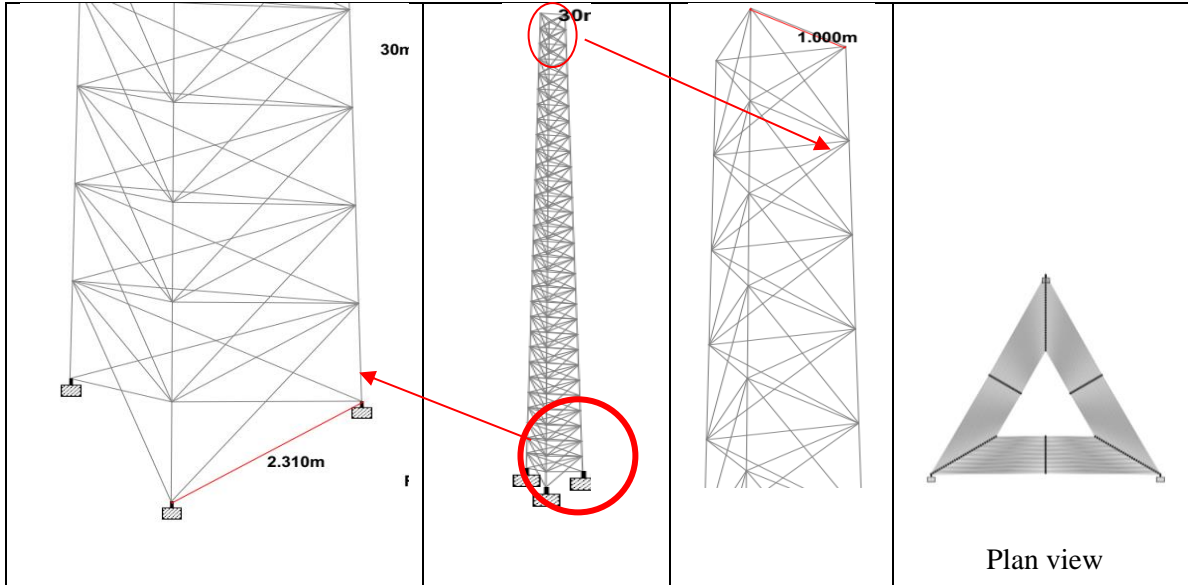


Figure 3. Typical Structural model of the 3-leg diagonal bracing mast structure

### 3 LOADINGS

The loadings considered are the masts self-weight computed based on the element's density and cross-sectional dimensions as well as a load surcharge of 1kN to simulate the telecommunication gadgets. The surcharge loads are applied to members at the tip level -3 m from that level consistent with the practice. The wind loadings imposed on the structure considers both static wind actions due to its mean velocity, gusting and the turbulence wind velocity. Fundamental value of the basic wind speeds of 45 m/s was considered for the study, assuming terrain category II as described in the [16]. The basic wind velocity is obtained from Eq. (1).

$$v_b = c_{dir} \times c_{season} \times v_{b0} \quad (1)$$

Where:  $v_b$  is the basic wind velocity, defined as a function of wind direction and time of year, at 10m above ground of terrain category II of BS EN 1991-1-4.  $v_{b,0}$  is the fundamental value of the basic wind velocity from the 10 minutes mean value.  $c_{dir}$  is the directional factor, taken as 1.0.  $c_{season}$  is the season factor, taken as 1.0. Variation of the wind speed with height was computed using the relation in Eq. (2).

$$v_m(z) = c_r(z) \times c_0(z) \times v_{b0} \quad (2)$$

Where  $c_r(z)$  is the roughness factor, determined using the relation in Eq. (4).  $c_0(z)$  is the orography factor, taken as 1.0. Terrain roughness factor was determined using the recommended roughness length in BS EN 1991-1-4 (2010) based on the relation in Eqs. (3) and (4).

$$k_r = 0.19 \times \left(\frac{z_0}{z_{011}}\right)^{0.07} \quad (3)$$

Where  $k_r$  is the terrain factor,  $z$  is the reference height,  $c_r$  terrain roughness.

$$c_r = k_r \times \ln\left(\frac{z}{z_0}\right) \quad (4)$$

The wind speed value for the fundamental basic wind speed stated earlier with heights, as a function of the roughness factor were evaluated using Equations (2 to 4) and typical form of the design windspeed for the basic wind speed of 45 m/s is presented in Figure 4.

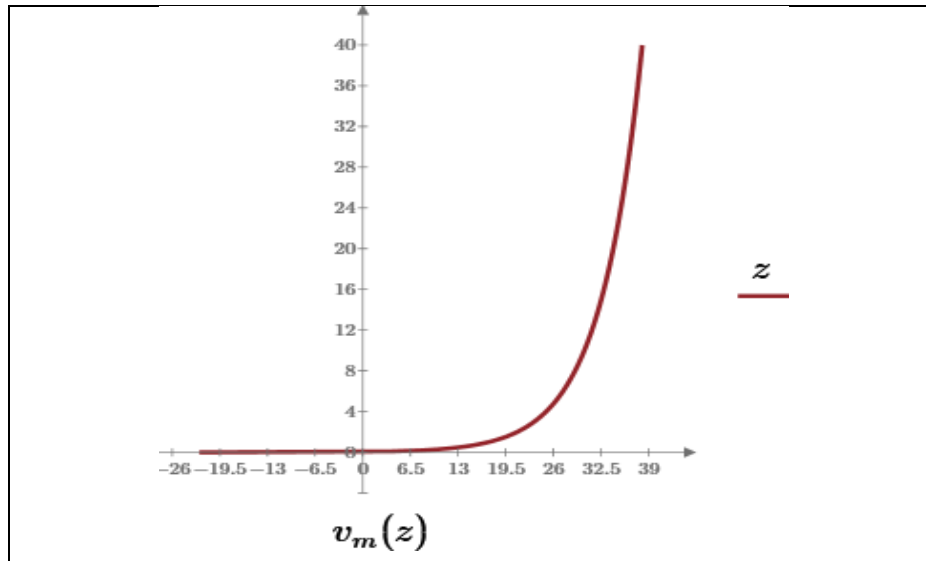


Figure 4. Typical variation of the basic wind speed as a function of the terrain roughness

To account for the wind turbulence factor, the wind turbulence intensity was determined based on the relation in Eq. (5).

$$I_v(z) = \frac{\sigma_v}{v_m(z)} = \frac{k_1}{c_0(z) \times \ln\left(\frac{z}{z_0}\right)} \quad (5)$$

Where  $k_1$  is the turbulence factor taken as 1. And finally, the Peak velocity pressure is computed using Eq. (6).

$$q_p(z) = (1 + 7 \times L_v(z)) \times \frac{1}{2} \times \rho \times v_m(z)^2 \quad (6)$$

Where  $\rho$  is the air density and is taken as  $1.25 \text{ kg/m}^3$ ,  $q_p(z)$  is the design wind pressure as a function of the turbulence factor. Typical values of the evaluated design wind pressure employed for basic wind speed of  $45 \text{ m/s}$  is presented in Figure 5.

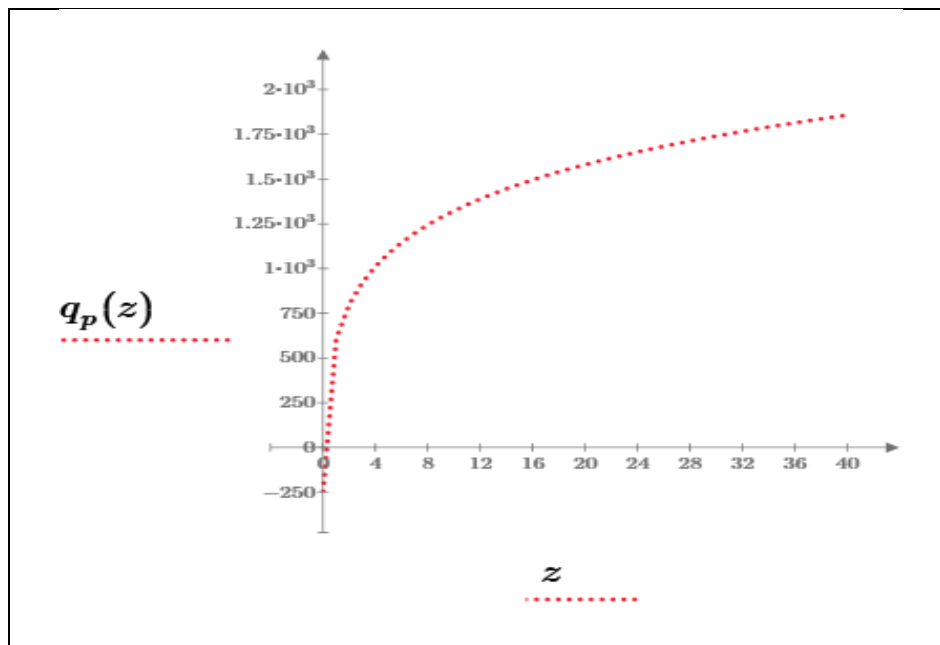


Figure 5. Typical variation of the design wind pressure loading with height of the mast structure

These wind pressures were applied on the windward direction of the mast using the patch loading method for open structure. Typical wind action (loading) on the mast is shown in Figure 6.

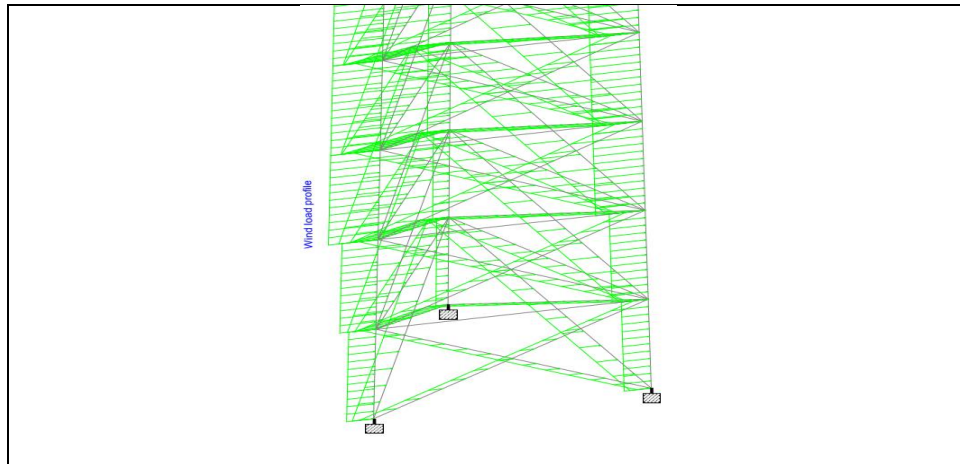


Figure 6. Typical wind action on mast members

## 4 RESULTS AND DISCUSSION

### 4.1 Mast geometry and topology

Table 2 presents structural material requirement and net weight of the structure for different bracing types of the mast structure. The Z bracing has the least total length of structural members of 413.98 m with a corresponding weight of 39.12kN. This is about 14% less than the K bracing and 42.9% less than the diagonal bracings. Thus, showing a direct cost reduction erection and materials procurement by the same percentages.

Table 2. Erection Material Requirement for different Mast tower types

S/N	Mast Type	Materials Requirement (Total Length) (m)	Weight (kN)
1	3-Legs Diagonal Bracings	586.90	55.455
2	3-Legs-K Bracings	473.35	44.726
3	3-Legs-Z Bracings	413.98	39.116
4	3-Legs-Diagonal with no lateral bars	446.99	42.334

### 4.2 Displacements

The displacement of the mast structure is generally maximum at the tip end of the structure with a displacement value of 608.43 mm for the diagonal bracings which drops exponentially to 6.28 mm and then zero at the base owing to the support system employed. Similar trends were recorded for the K bracings with tip displacement of 662.46 mm. mid span and at 2 m from the base as 218 mm and 7.7mm were recorded respectively, consistent with other findings in the literature[3, 7, 9, 17]. The Z bracings on the other hand results in a tip displacement of 552.438 mm which is less than the displacement values recorded for both the diagonal and the K bracings. Displacement profile for the bracing types considered are presented in Figures 7 and 8. The maximum displacements values for all the bracing types considered are higher than those reported for the guyed mast under a wind action of 30 m/s [17]. This is expected given the lower wind action considered in the study and the primarily guyed effect of limiting tip displacements. Meshmesha et al. [9] however reported higher tip displacements of up to 8 m at guyed tower height of 45 m for a pinned ended guyed mast. The displacements so reported can be considered too high for communication masts but may be employed for other functions if they mast is to be 45 m or higher.

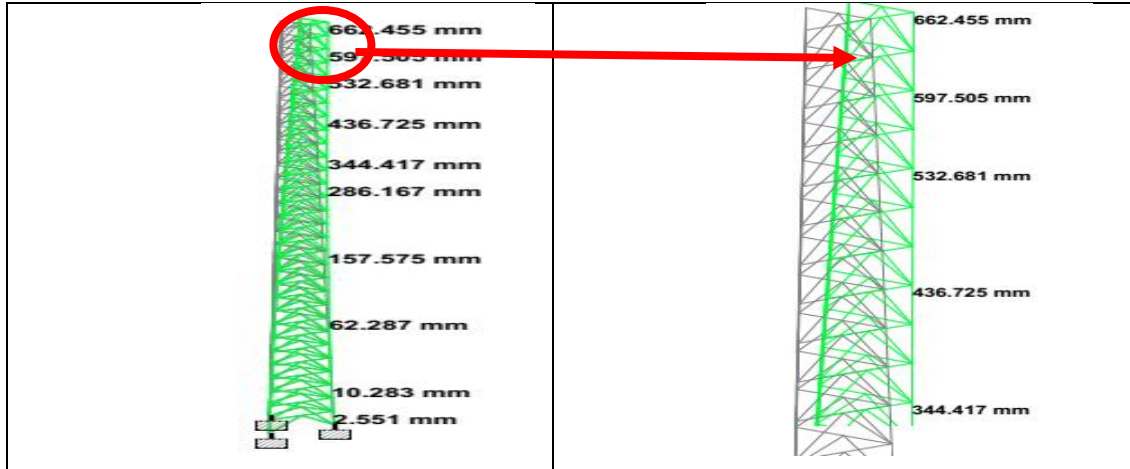


Figure 7. Typical displacement profile with height of the mast structure

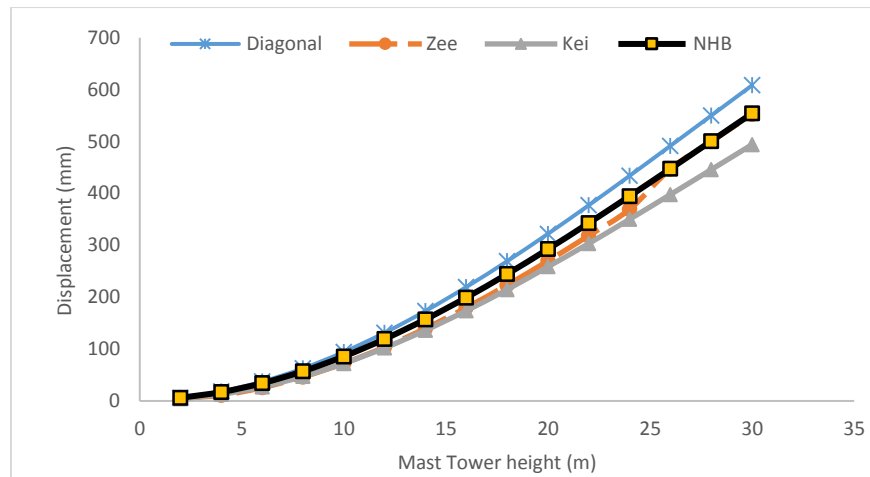


Figure 8. Typical Displacement with height of mast for varying mast bracing types considered

### 4.3 Combined Stresses in Mast Structures

Members stresses recorded for the mast structure indicate that the stresses are generally higher at about the base elements and decreases with height of the mast, consistent with other submissions [3], [9], [17]. Typical stress profile for the diagonal bracings is presented in Figure 9. Owing to the stress range in the mast, Figure 9c shows that mast legs generally fail in compression in the leeward side of the wind action and in tension in the wind ward direction. For the diagonal bracings, the failed elements in compression extends to about mid span of the 30 metres span mast tower (i.e 15 m) and up to 10 metres in tension elements. The Z bracing records up to 14 m and height of members that failed in compression and tension respectively. The X or scissors bracings extends up to 16 m and 8 m of the failed element in compression and tension respectively while the K bracings has more elements failing in tension (up to 12 m) but having span / height of the failed elements same as the diagonal bracings. Figure 10 shows the maximum combined stresses with height with the varying bracings types considered. The results show that the combined stresses are higher in the diagonal and X bracings of stress range of 500 to 250N/mm<sup>2</sup> at based of the mast to about mid span of the structure. The K bracings under similar loadings have less stresses in the elements compared to all bracing types considered. The stresses at the base of the K bracing typer mast is 25% less than that recorded for the diagonal bracings and about 24% at mid span of the structure. Base stresses in pinned-ended steel guyed masts are reported to be around 100 to 500 N/mm<sup>2</sup> for mast heights between 45 to 364m [9].This implies that smaller steel section may be employed in their erection as compared to the free-standing mast considered in this paper.

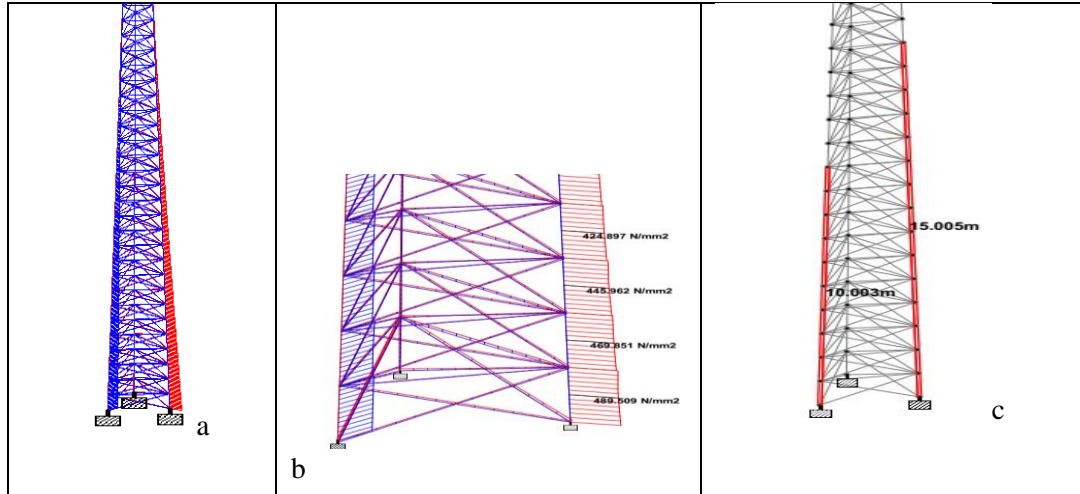


Figure 9. Typical Combined Stresses and highlight of Failed Elements in Mast

Plots of the stresses with height of mast for the different bracing type considered is presented in Figure 10.

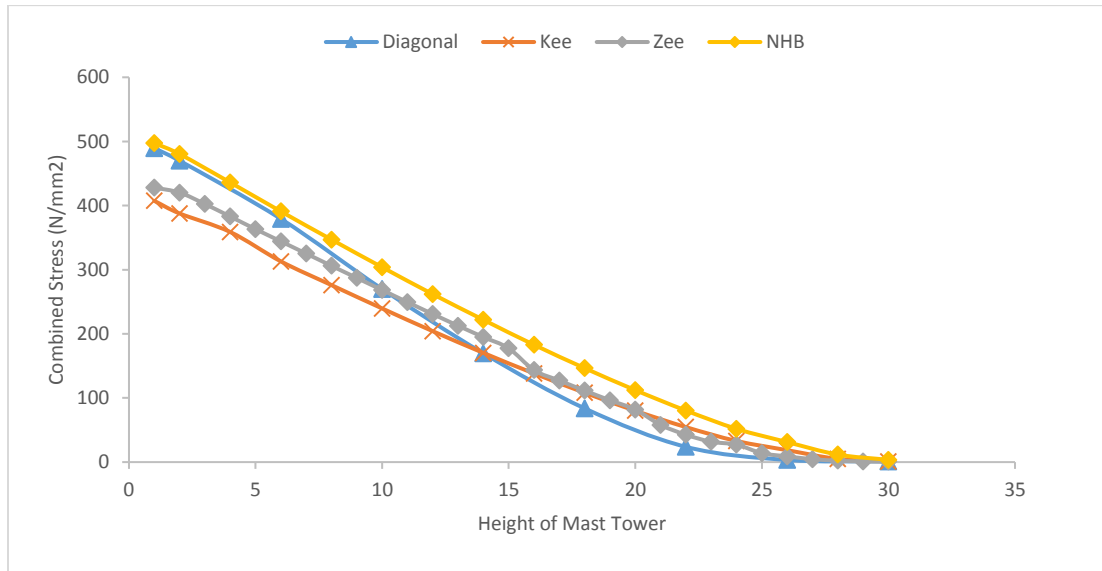


Figure 10. Combined stress distribution for the masts types considered with height

#### 4.4 Support Reactions

Typical reaction forces/moments recorded for the diagonal bracing is presented in Figure 11. This is similar to the results presented by Gambo et. al.,[3]. The support reactions recorded for the mast types and bracings considered, indicate that the normal forces in the X, Y and Z directions are much higher than the reaction bending moments in those directions. The maximum reaction moments for the diagonal bracing are 0.488 kNm, 0.30 kNm for the K bracings, 0.402 kNm for the Z bracings and 0.519 kNm for the X bracing type mast. The findings are consistent with those reported in [7] 18, 19]. Table 3 presents the vertical and horizontal reaction forces for the mast types considered. Maximum combined forces are observed in the diagonal and X bracings in tandem with the elements' combined stresses that are transferred to the mast support/foundations.



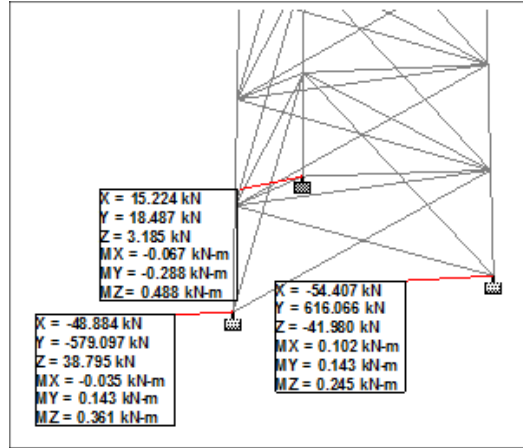


Figure 11. Typical Reaction Forces and Moments in Diagonal Bracings

Table 3. Maximum Vertical and Horizontal Forces

Mast Type	Maximum Horizontal Fx ( kN)	Maximum Vertical Fy (kN)
3-Legs Diagonal Bracings	54.41	616.07
3-Legs-K Bracings	32.925	514.579
3-Legs-Z Bracings	52.87	537.02
3-Legs-Diagonal with no lateral bars	41.108	619.696

#### 4.5 Dynamic Characteristics

The dynamic characteristics of the various mast considered were assessed and the findings indicate that the fundamental modes of vibrations of the mast structure are generally less than 1.0 Hz. Hence indicative of high susceptibility to dynamic response [5]. The Diagonal bracings is of natural frequency of 0.795 Hz, K bracing 0.755 Hz and Z bracings with a slightly higher fundamental frequency of 0.89Hz. Other frequencies at higher modes for the structure are presented in Table 4. The natural frequencies reported are generally consistent in trend with those reported in the literature [7, 8, 20, 21, 22]. They are however higher in the second (2<sup>nd</sup>) and higher vibrating modes of the guyed system.

Table 4. Fundamental and Higher Frequency for the various Mast Bracing Types Considered

Mast Type	Mode	Frequency (Hz)
Diagonal	1	0.795
	2	4.277
	3	10.419
K-bracing	1	0.755
	2	4.084
	3	10.086
Z-Bracing	1	0.829
	2	4.312
	3	6.180
NHB Bracing	1	0.828
	2	4.393
	3	7.974

## 5 CONCLUSIONS

In this study, 30 m, 3-leg telecommunication mast of diagonal, K, Z and X bracings were evaluated to establish their respective static and dynamic characteristics under environmental turbulent wind loading. From the analyses carried out, the following conclusions were drawn, that the: Mast base width of 1/13<sup>th</sup> of the 30 m height is stable for all bracing types considered in the study. Telecommunication mast structures of Z bracings are cost effective in construction/erection compared to the other bracing types considered. Cost savings by length of structural elements required are found to be about 14%. 42.9% and 7.97% for the K, diagonal and the X bracings respectively. Mast displacements under loading increases with increase in height of the mast and is maximum at the tip of the mast for all bracing types considered. Maximum displacement in the K-bracings is lower than all other bracing types considered. The displacement is 23% less than that of diagonal bracings and 12% less than the Z and the X bracing masts. Maximum combined stresses are also lower in the K bracings compared with the other bracing types considered. It is 22% less than the diagonal and X bracings but 5% less than the Z bracing mast. Reaction forces and Moments are generally higher on the leeward side support for all bracing's types considered and bending moments are generally of much lower (less than 1kNm) compared to the vertical and horizontal reactive forces in the mast support/foundation. Mast structures are generally of natural frequency less than 1 Hz with the Z bracings having the highest fundamental frequency of 0.89 Hz and the K having the least natural frequency of 0.755Hz.

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