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Non-Linear Dynamic Analysis of Guyed Towers to Wind Loading

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Abstract: *A nonlinear deterministic approach for predicting the wind response of guyed towers is described in this paper. The nature of wind, static and dynamic wind effect are defined. In the present approach, the time space history of wind is simulated and fed into the system's equations of motion. These are integrated in the time domain and the response of the guyed tower is obtained. Linear and non-linear response of a guyed tower are evaluated to simulated wind histories by a multi-regressive technique. In addition, comparative studies have been performed on the tower in order to check the effect of wind velocity and roughness length on their response. A comparison of mean and dynamic responses and a discussion of these results relative to the quasi static analysis are presented.*

Keywords*: Nonlinear analysis, guyed towers, wind loading, dynamic analysis..*

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I. Introduction

The Guyed towers are characterized by their lightweight, flexibility and often-large size. All these characteristics make them very sensitive to time dependent loading such as wind and earthquake loadings. These towers are usually designed using astatic gust approach (Davenport, 1967)[1] in order to take some account of the dynamic behavior of the wind. This approach is generally considered valid for buildings and other freestanding structures which tend to respond to gust loads in principally the fundamental mode of vibration. However, in the case of guyed towers, the higher modes of vibration can make a significant contribution to the total dynamic response (Vellozzi,1975)[2]. It seems likely that this over-simplified approach to include the dynamic properties of wind may be responsible for the relatively high failure rate among tall masts (Nakamoto and Chiu, 1985)[3]. Despite the above problems, the dynamic wind response of guyed towers has received limited attention (Vellozzi, 1975; Rothenthal and Skop, 1980[4]; Nakamoto and Chiu, 1985; Iannuzzi, 1987[5]) and therefore, there is need to do more work in this field.

The nonlinear spectral element method in order to analyze the nonlinear dynamic response of a guyed mast is used by Horr (2004)[6].

The dynamic response of guyed masts using different models for cables and evaluates the variation of the stiffness of the complete system using different levels of pre-stress on guys is compared by Preidikman et al (2006)[7]. Meshmesha et al. (2006)[8] introduce an equivalent beam-column analysis based on an equivalent thin plate approach for lattice structures, then evaluates the accuracy of the proposed method and classic methods to determine the equivalent beam proprieties (the unit load method and the energy approach) in determining the response of a guyed tower subjected to static and seismic loading. Shi (2007)[9] and de Oliveira et al (2007)[10] also used the finite elements approach

Lu et al. (2010)[11] introduce the principle of harmonic wave superimpose method for wind velocity simulation, as well as the improved method by introducing FFT in harmonic superimpose wave method. Wind velocity time series along the height of guyed-mast was simulated with the improved method. Matuszkiewicz (2011)[12] evaluates selected problems concerning designing of guyed masts with lattice shaft in accordance with the EN 1993-3-1: Design of steel structures. Part 3-1: Towers, masts and chimneys-Towers and masts" and discusses the method of application of the mast shaft geometrical imperfections in the calculation.

Ballaben et al (2017)[13], use simplified structural model consists of a beam-column accounting for the second order effect due to axial loads and one inclined guy which is represented by a nonlinear extensible cable. The governing system is discretized with finite elements and a reduced order model is afterwards constructed using a basis of vibration modes. Both, the load and the structural model are considered stochastic. The wind load is derived from a wind velocity field after the application of the Spectral Representation Method. Since nonlinear structures show special sensitivity to dynamic loads, the reference nominal, wind velocity (suggested by the codes) is also considered a random parameter.

In this paper, a nonlinear deterministic approach is presented to predict the response o guyed towers to turbulent wind. In the presented approach the time space history of wind speed is simulated, using a multi-regressive technique, and fed into the system's equations of motion. These are integrated in the time domain and the response of the guyed tower is obtained as a function of time. Nonlinear effects due to change of geometry, axial load in the mast and pretension in the cables are taken into account. Numerical studies of practical examples of guyed towers are presented to check the behavior of guyed towers when subjected when subjected wind loads. The validity of equivalent static approach presented by ECP 201-2012[14] is checked. The results are compared with nonlinear analysis of the towers under simulated wind time history.

II. Wind Loads On Guyed Towers

The accuracy of results of structural analysis of any structure, including guyed towers, depends on how the loads on structure are assessed. The loads on the guyed tower include: wind loads, self weight and initial tension from guy cables. Since guyed towers are tall structures, the wind has considered effect on the mast and guy cables. It is well established that the wind speed varies with tower height and site conditions commonly represented by a wind profile coefficient (Simiue, 1974)[15]. The force due to wind acting on a tower is give by:

$$P(t) = \frac{1}{2}\,\rho C_d A(U + u(t) - x(t))^2$$

Where $\rho =$ specific density of air, $C_d =$ drag coefficient, $A =$ area exposed to wind, $U =$ mean wind velocity, $u(t) =$ fluctuated velocity component of wind, $x(t) =$ velocity of the body in the direction of wind. Thus, the analysis of the response of special structures such as guyed towers, to natural wind requires an efficient model for simulating the fluctuating velocity component of wind. A multi-regressive technique is used in this paper to generate a set of partially correlated wind histories ($u(t)$). The basic equation in the present technique is (Iwatani. 1982)[16]:

$$u(t) = \sum_{k=1}^{p} [\emptyset]_k\ [u(t - k\Delta t)] + N(t)$$

Where $N(t) =$ Random shocks having appropriate cross correlation $[\emptyset]_k$ =autoregressive coefficients matrix of order [MxM], $k =$ number of maximum lag of auto- and cross correlation, M= sets of wind fluctuations, $p =$ the order of multi-regressive model, $\Delta t =$ time increment.

III. Time Domain Nonlinear Dynamic Analysis

A nonlinear deterministic approach is presented to predict the response of guyed towers to turbulent wind. Three dimensional truss elements arid three dimensional beam column elements are used to idealize the guy cable and mast respectively (Shantaram and Murty, 1987)[17]. Nonlinear effects due to change of geometry, axial load in the mast and pretension in the cables ae taken into account. To evaluate the dynamic ·response of guyed tower to natural wind the equations of motion have to be solved using the step - by - step integration methods (Donea, 1980)[18]. In these methods, the response is evaluated at increments of time. At the, beginning of each interval, the condition of dynamic equilibrium is established. Then the response for a time increment. Δt is evaluated.

To account for the nonlinear effects, the stiffness matrix has to be recalculated according to the current deformed geometry and the instability effects caused by axial forces. Thus, at the end of each time increment, a check is made between the externally applied forces and the internal forces in elements. The residual dynamic out of balance force is calculated and reapplied to the structure to get a correction to the incremental displacement. Iterations are carried out using the Newton Raphson method until convergence of solution is satisfied, then, another time step is taken.Then, the dynamic linear and nonlinear analysis of three-dimensional guyed towers were studied.

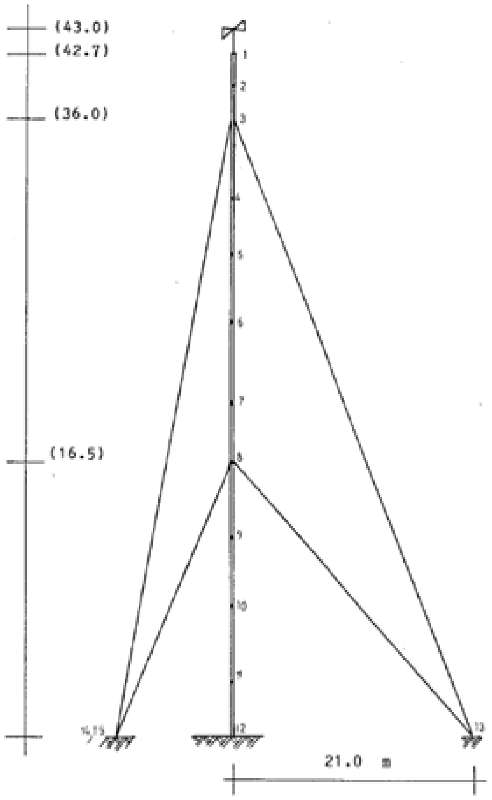
IV. Application To Guyed Towers

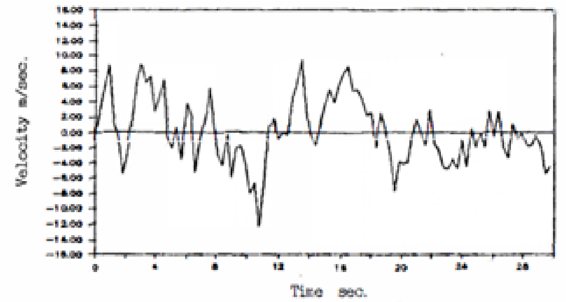
Example 1: two level guyed tower

The structure analyzed in this example is a 40m tall guyed tower (Iannuzzi. 1987). Specification for the mast and the guys are given in table 1 and Fig.1. Wind is assumed to blow along the X-positive direction. The averaged mean wind speed at 10m elevation was assumed 18.0 m/sec. A roughness length of 0.8m was taken. The drag coefficient C_d was taken as 2.33 and 1.2 for the mast and the guysrespectively.The response of guyed tower to natural wind have been evaluated through linear and nonlinear dynamic analysis using simulated wind time history. Three series of wind time histories have generated at three different elevation, which are: Un-correlated wind histories, partially correlated wind histories, and fully correlated wind histories. The results of analysis for the previous three sets of wind histories are summarized in table 2. In this table the maximum displacement along the mast and tension forces in the cable are given.

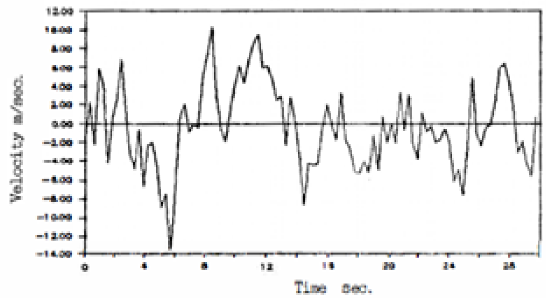
Table 1 Specification for Ex. 1

Cross- sectional area	A_c	$18.93x10^{-4}$	m^2
Moment of inertia	I_x	$1.1905x10^{-4}$	m^4
Moment of inertia	I_y	$1.1905x10^{-4}$	m^4
Moment of inertia	L_z	$2.2610x10^{-4}$	m^4
Young's Modulus	E	$2.1\ x10^{11}$	N/m^2
Drag coefficient	C_d	2.3	
Weight per unit length	W	348.07	N/m
Area exposed to wind	A	0.1869	m^2/m
cross sectional area	$A_{c'}$	$9.025x10^{-5}$	m^2
Initial tension	T_o	18150	N

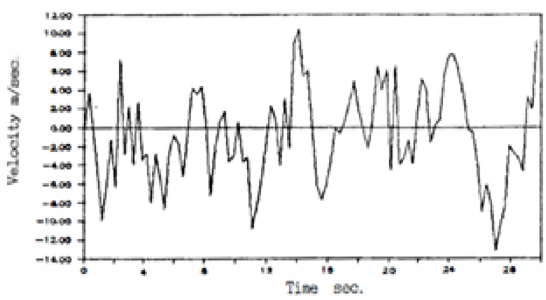




(a) At Joint 1



(b) At Joint 3



(c) At Joint 8

Fig. 1 Mathematical model and simulated wind histories (Ex. 1)

Following the equivalent static approach given by ECP 201-2012, the wind forces are calculated. The maximum lateral deformation of this guyed tower obtained by using equivalent static approach is given in table 3.

Also, the comparison between nonlinear static-dynamic analysis for the above sets of wind histories and equivalent static method are illustrated in table 3.

Table 2 Maximum response characteristics obtained for different wind histories (Ex. 1)

	Fully Correlated	Partially Correlated	Un-correlated
Max. along-wind displ. J_l, cm	6.975	6.775	6.713
Max. along-wind displ. J_3,cm	4.816	4.740	4.674
Max. along-wind displ. J_5,cm	3.807	3.700	3.693
Max. along-wind displ. J_8,cm	1.406	1.220	1.123
Max. tension in upper level, N	21300	20968	20628
Max. tension in lower level, N	19650	19283	18976

Table 3 Maximum response characteristics obtained for Ex. 1

	Linear analysis			Nonlinear analysis			Equivalent static
	Mean	Fluct.	Total	Mean	Fluct.	Total	
Max. along- wind displ . Jl, cm	2.916	3.859	6.775	2.940	4.077	7.017	7.430
Max. along-wind displ . J3, cm	2.188	2.552	4.740	2.230	2.237	4.467	5.181
Max. along-wind displ. J5, cm	1.774	1.926	3.700	1.800	1.832	3.632	3.693
Max .along-wind displ. J8, cm	0.507	0.693	1.200	0.487	0.636	1.123	1.170

The effect of wind velocity and the roughness length on the response of the guyed tower to natural wind are considered. The response of guyed tower model has been evaluated by using a roughness length of 0.8 with wind velocity of 18.0, 30.0, 36.0 m/sec. In addition, using wind velocity of 36.0 m/sec with roughness length of 0.1, 0.3, 0.5, and 0.8 wind velocity are studied. In table 4 and 5 and figs, 2 and 3 the obtained response through equivalent static and time history analysis for the tower are compared to check if the equivalent static analysis is satisfactory for this tower (with height 40m which less than limit presented in ECP 201-2012) or not.

Table 4 Ratio between linear time history analysis and equivalent static analysisFor different wind velocities (roughness length 0.80m)

Joint no.	18.0 m/sec. $\left(\frac{Linear\ T.H - Eq.Static}{Linear\ T.H}\right)$ % x-direction	30.0 m/sec. $\left(\frac{Linear\ T.H - Eq.Static}{Linear\ T.H}\right)$ % x-direction	36.0m/sec. $\left(\frac{Linear\ T.H - Eq.Static}{Linear\ T.H}\right)$ % x-direction
1	-9.67 %	2.11%	3.95 %
3	-9.30 %	3.45 %	7.59 %
5	-2.51 %	-10.89 %	-9.84 %
8	4.10 %	-13.45 %	-12.53 %

Table 5 Ratio between linear time history analysis and equivalent static analysisFor different roughness length (wind velocity 36.0 m/sec.)

Joint no.	0.10 $\left(\frac{Linear\ T.H - Eq.Static}{Linear\ T.H}\right)$ % x-direction	0.30 $\left(\frac{Linear\ T.H - Eq.Static}{Linear\ T.H}\right)$ % x-direction	0.80 $\left(\frac{Linear\ T.H - Eq.Static}{Linear\ T.H}\right)$ % x-direction
1	-10.79 %	-4.03 %	3.95 %
3	0.72 %	-3.61 %	7.59 %
5	-22.68 %	-16.88 %	-9.84 %
8	-25.82 %	-23.94 %	-12.53 %

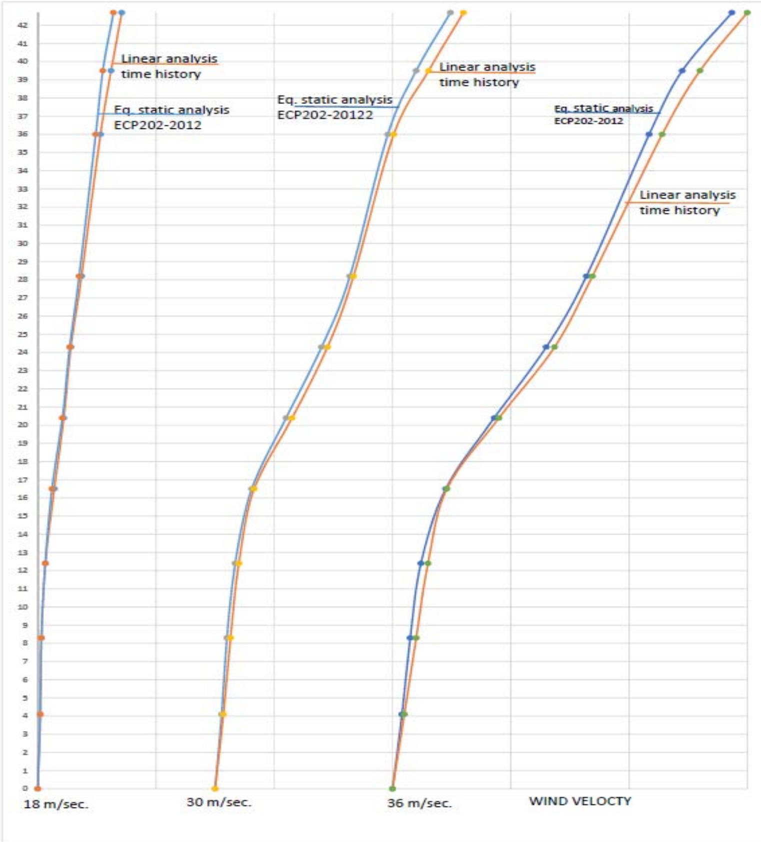


Fig. 2 Tower displacement under variable wind speed with roughness length 0.80

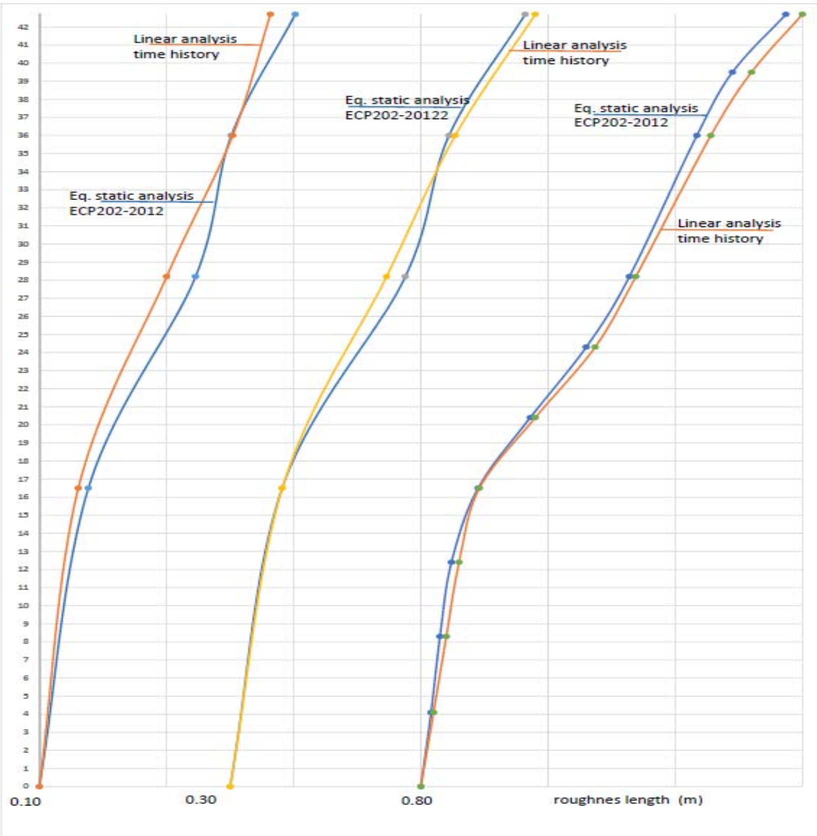


Fig. 3 Tower displacement under variable roughness length with wind speed 36.0m/sec.

Example 2 : Multi-level guyed tower

The structure analyzed in this example, Fig.4 is a 295.0 m tall-guyed tower. Geometric and structural properties of this tower are summarized in Fig.4 and in tables 6 and 7. Wind is assumed to blow along the x-positive direction. The averaged wind speed at 10m elevation was assumed to be 33.5 m/sec. with roughness length of 0.1m. The drag coefficient C_d was taken as 1.1, 0.32 and 1.1 for the antenna, mast body and the guys respectively. The response of the guyed tower is calculated using 3-sec. gust loading. Table 8 illustrates the distribution of maximum lateral deflection.

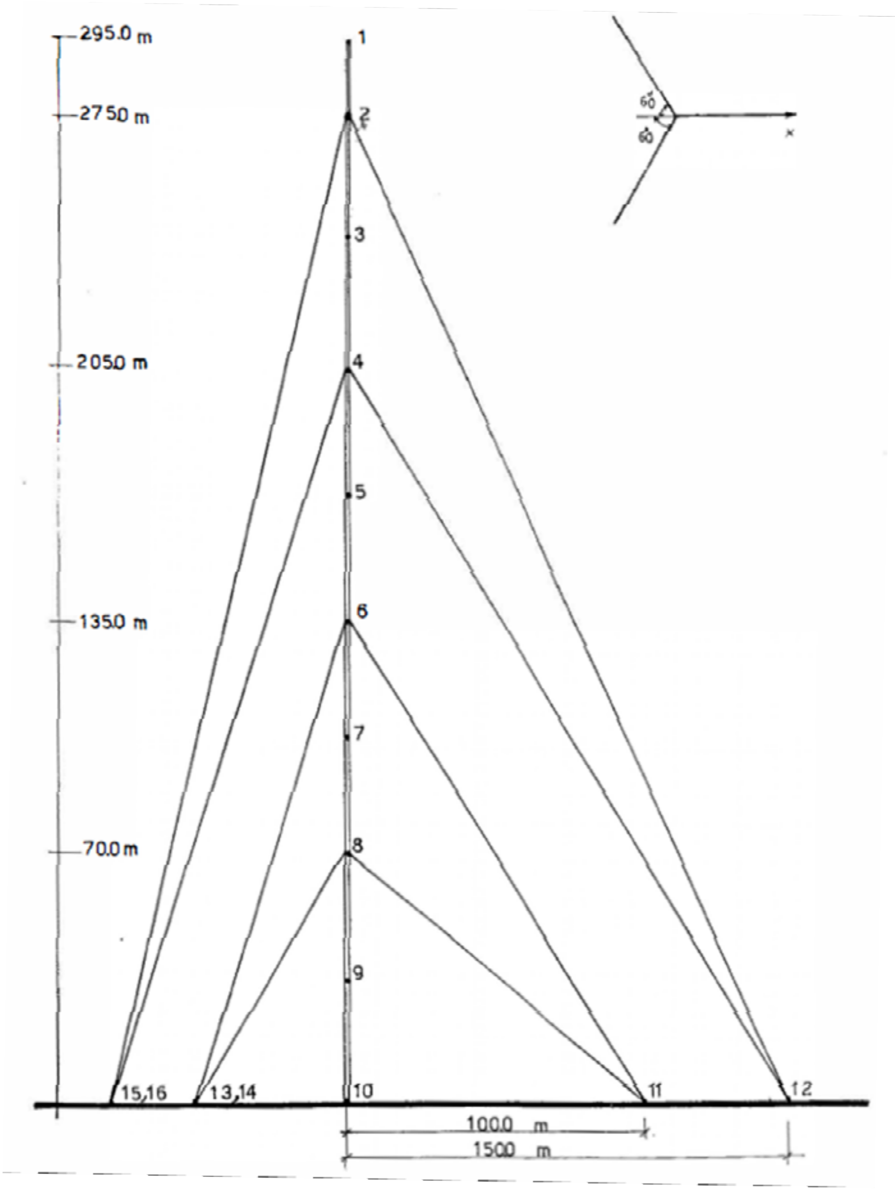


Fig. 5 Mathematical model and simulated wind histories (Ex. 2)

The response of the guyed tower to natural wind is carried out using linear and nonlinear dynamic analysis under simulated wind time histories time domain. For this purpose, artificial wind histories were generated by multi regressive scheme using the logarithmic profile of wind speed and Kaimal's spectrum of turbulence (Simiue 1974). Wind loading was applied to all nodes of the mathematical model (Fig.4), but for convenience, only 5 wind histories were generated. Table 8, shows the results for the maximum static and dynamic response of the guyed tower under wind loading cases of the linear and nonlinear analysis. The maximum displacements, bending moment and normal forces, are given in table 9.

The effect of roughness length on the response of this guyed tower to natural wind is considered. The response analysis is carried out using equivalent static method and using simulated wind time histories. With mean wind velocity of 33.5 m/sec., three values of roughness length are chosen. These values are; 0.1m, 0.3m and 0.6m. Table 10 shows the response of the joints along the mast.

Table 6 Mast specification for Ex. 2

Mast members	Area (m^2)	Weight (kN/m')	I (m^4)	E (kN/m^2)	Drag coefficient C_d	Width (m)
Antenna	0.039	3.065	0.0004	$206.84x10^4$	1.10	0.300
1,2	0.0624	4.903	0.0248	$206.84x10^4$	0.32	2.286
3,4	0.0624	4.903	0.0298	$206.84x10^4$	0.32	2.286
5,6	0.0731	5.706	0.0363	$206.84x10^4$	0.32	2.286
7,8	0.0821	6.450	0.0457	$206.84x10^4$	0.32	2.286

Table 7 Guys specification for Ex. 2

Cable level	E (kN/cm^2)	Area (cm^2)	Weight (kN/m')	Tension kN	Drag coefficient C_d
1	16574	8.00	0.063	131.6	1.10
2	16574	13.61	0.107	213.5	1.10
3	16574	9.48	0.074	128.1	1.10
4	16574	7.25	0.057	91.6	1.10

Table 8 Maximum response characteristics obtained for Ex.2

	Linear analysis			Nonlinear analysis			Equivalent
	Mean	Fluct.	Total	Mean	Fluct.	Total	static
Max. along-wind displ . Jl, cm	107.1	31.25	138.4	110.0	28.24	138.2	132.8
Max. along-wind displ . J2, cm	66.02	10.86	76.88	67.40	10.93	78.33	81.48
Max. along-wind displ. J4, cm	41.00	9.29	50.29	41.40	6.45	47.85	50.84
Max .along-wind displ. J6, cm	26.15	3.77	29.92	26.50	4.09	30.59	32.43
Max .along-wind displ. J8, cm	10.73	1.71	12.44	10.70	2.17	12.87	13.31

Table 9 Response characteristics obtained for Ex.2

Joint No.	Displacement (X-direction)			Bending moment (kN.m)			Sec.	Normal force (kN)		
	Mean	Fluct.	Total	Mean	Fluct.	Total		Mean	Fluct.	Total
1	107.1	31.25	138.4	0.0	0.0	0.0	1-2	-30.0	-0.1	-30.1
2	66.02	10.86	76.88	230.0	180.0	410.0	2-3	-487.0	-0.3	-487.3
3	57.50	12.40	69.90	828.0	425.0	1253.0	3-4	-658.0	-0.2	-658.2
4	41.00	9.29	50.29	1075.0	180.0	1255.0	4-5	-1329.0	-0.2	-1329.2
5	34.93	6.40	41.40	587.0	174.0	761.0	5-6	-1501.0	-0.2	-1501.2
6	26.15	3.77	29.92	454.0	163.0	617.0	6-7	-1971.0	-0.1	-1971.1
7	19.85	2.80	22.60	540.0	163.0	703.0	7-8	-2156.0	-0.1	-2156.1
8	10.73	1.71	12.44	503.0	104.0	607.0	8-9	-2519.0	-0.1	-2519.1
9	4.12	0.20	4.30	87.0	120.0	207.0	9-10	-2745.0	-0.1	-2745.1

Table 10 Maximum displacement (X-direction) for different roughness length under wind velocity 33.5 m/sec.

Node No.	0.10 $Linear\ T.H$			$Eq.\ Static$	0.30 $Linear\ T.H$			$Eq.\ Static$	0.60 $Linear\ T.H$			$Eq.\ Static$
	Mean	Fluct.	Total		Mean	Fluct.	Total		Mean	Fluct.	Total	
1	107.1	31.3	138.4	132.	137.3	47.80	185.1	170	172.4	69.3	241.7	213
2	66.02	10.9	76.9	81.8	84.42	20.8	105.2	105	105.8	25.5	131.3	131
3	57.50	12.4	69.9	71.3	73.21	19.1	92.3	91	91.4	27.5	119.0	113
4	41.00	9.3	50.3	50.8	51.82	14.1	66.0	64	54.3	26.3	80.7	80
5	34.93	6.4	41.4	43.3	43.70	10.9	54.6	54	53.8	14.2	68.0	67
6	26.15	3.8	30.0	32.4	32.35	8.7	41.1	40	39.5	10.3	49.7	49
7	19.85	2.8	22.6	24.6	24.24	4.2	28.4	30	29.2	4.9	34.1	36
8	10.73	1.8	12.5	13.3	12.88	2.6	15.4	16	15.3	3.6	18.9	19
9	4.12	0.2	4.3	5.1	4.81	1.3	6.1	6.0	5.6	1.9	7.4	6.9

V. Discussion Of Results

For the two level guyed tower (Ex. 1), the different wind histories fully correlated, partially correlated, and un-correlated are used and presented in table 2. A comparison of the results reveals differences in the response depending on method used to generate the wind history. In case of fully correlated, the results indicate that the response of guyed tower is higher than the partially correlated and un-correlated histories. From table 4, 5 with figs. 3and 4, it is clear that the equivalent static analysis in center of cities (with high roughness length) may be not sufficient to evaluate the response of guyed towers to natural wind especially in case of high velocity.

For the multi-level guyed tower (Ex ; 2), the maximum lateral deflection calculated according to equivalent static analysis, table 8, is reasonably close to the corresponding values calculated using the linear and nonlinear dynamic analysis using simulated wind time history except for the points along cantilever. The difference is generally less than 8%. From table.10, it is obvious that the roughness values greatly affect the fluctuated response of the four levels guyed tower. The difference between the total deflection.in the cases of using linear and nonlinear dynamic analysis using simulated wind time history and equivalent static analysis are generally less than 12%.

By comparing the results in case of linear and nonlinear dynamic analysis for the two towers, tables 3 and 5 it can be concluded that the differences in deformation are about 1-8%.

VI. Conclusions

The conclusion obtained from the present research work can be summarized in the following concluded remarks:

1- The equivalent static analysis given by ECP 201-2012 is generally not sufficient to calculate the response of the cantilever top part of the guyed mast. So, in the equivalent static analysis additional load factor for the cantilever part may be estimated in accordance with the results illustrated in this study.

2- The assumption of fully correlated, partially correlated and un-correlated fluctuated wind histories leads to slightly significant variation in both the artificial wind and the corresponding guyed towers response.

3- The dynamic changes in guy tension are seen to be fairly small. and the effect on the axial forces in the shaft are entirely negligible and can be neglected.

4- The study of the nonlinear static and dynamic response of guyed tower to wind loads indicates that, the nonlinear effects are insignificant especially for low wind velocity.

Therefore, it is sufficient to use a conventional nonlinear analysis to determine static equilibrium position of guyed tower under mean wind loads. Next, a linear dynamic analysis is performed, but with a cautionary note with respect to the analysis of large masts and masts in which the tensions in the leeward guys become very small.

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