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TECHNICAL PAPER

Structural behavior of guyed mast with asymmetrical anchors

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Abstract This paper discusses the influence of asymmetrical anchors on guyed mast behavior under wind loads. Anchor asymmetry is due to variations on anchor levels in guyed mast placed at the top of hills. Six FEM models were developed with different guy anchor asymmetries. The mast was modeled as a three dimensional structure formed by pinned members (braced and horizontal members) and continuous members (columns). Cables were modeled with catenary formulation. Non-linear analysis under extreme wind loads was performed to calculate internal force on the guyed mast components. Comparison between members force on each model was made to assess structural behavior. Relative increments in internal forces in asymmetric models in relation to symmetric models were observed in all members. Results of this investigation show that asymmetry on anchor levels of guyed mast can produce a significant increase in internal forces of masts members, hence disregard of anchors asymmetry at guyed mast design can conduce to important errors.

Keywords Guyed towers · Structural failure · Structural behavior · Anchors asymmetry

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1 Introduction

Guyed masts are common structures to support telecommunication devices used worldwide. They are slender and light structures frequently exposed to high winds which are determinant loads in their structural design. Research on latticed towers and masts [1, 5, 6] indicates that guyed masts are structures with a high level of failure compared with other structures. Most of failures have occurred under severe conditions due to wind and ice loads.

Cuba, located in the Caribbean and exposed to hurricanes every year, has reported the failure of 30 communication structures in the last 10 years [2]. Wind velocities reported at the closest meteorological stations were not above the design wind load recommended by the Cuban code of wind load [7]. A preliminary analysis of failures indicated that 70 % of failed towers were of the guyed type. Due to characteristics of the Cuban topography, it is very common to place guyed masts near the summit of the hills, where the wind is accelerated. This location generates an asymmetry in the anchorage of guys due to different vertical levels of hill slope. Anchorages are commonly placed trying to maintain the symmetry in the horizontal plane regardless of the vertical symmetry. These variations on vertical levels of anchorage involve different cable lengths and different angles of cables with the mast that can produce a variation in the structural behavior of the mast under severe wind conditions. These conditions have not been properly considered in the design of the masts, so the purpose of this paper is to investigate the influence of the anchorage asymmetry on the structural response by means of changes in the axial forces of the members of the mast, cables and reaction of the structure.

Information about guyed mast failures in the Cuban countryside [3] was compiled and processed to define the characteristics of the structural models for the study. Member sections, guy's diameter, number of guy levels, number of anchors by lane and anchorage asymmetry were computed. Geographic and topographic characteristics of guyed mast locations were studied, as well as wind climatic conditions of sites. Observation of specific anchorage positions determined that variations in anchor levels could produce a different kind of asymmetry. Similar conclusions were obtained with the study of cable topology; small variations in number and position of cables could produce large changes in structural response. The number of independent variables and the lack of previous studies on this topic led to a numerical experiment to evaluate general structural behavior, as shown as in Fig. 1. Two variables with two levels were defined for the experiment to identify the weight of each variable in the total response of the structure.

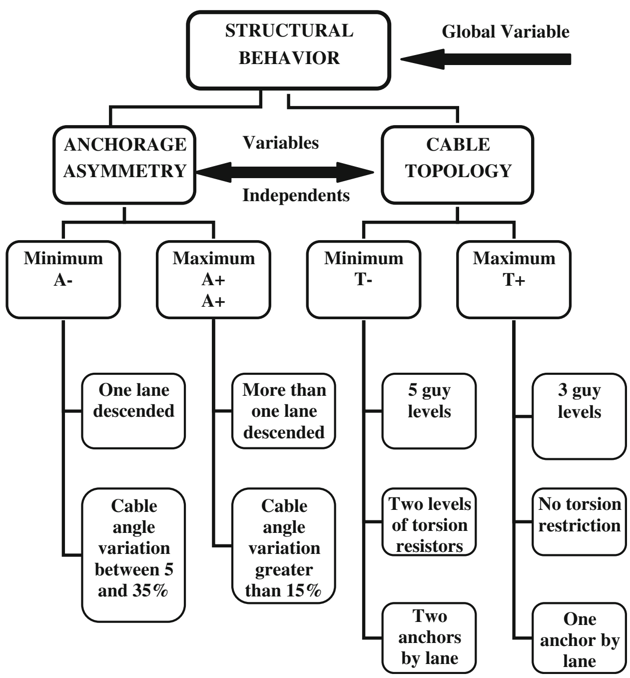


Fig. 1 Schematic representation of experimental study of structural behavior

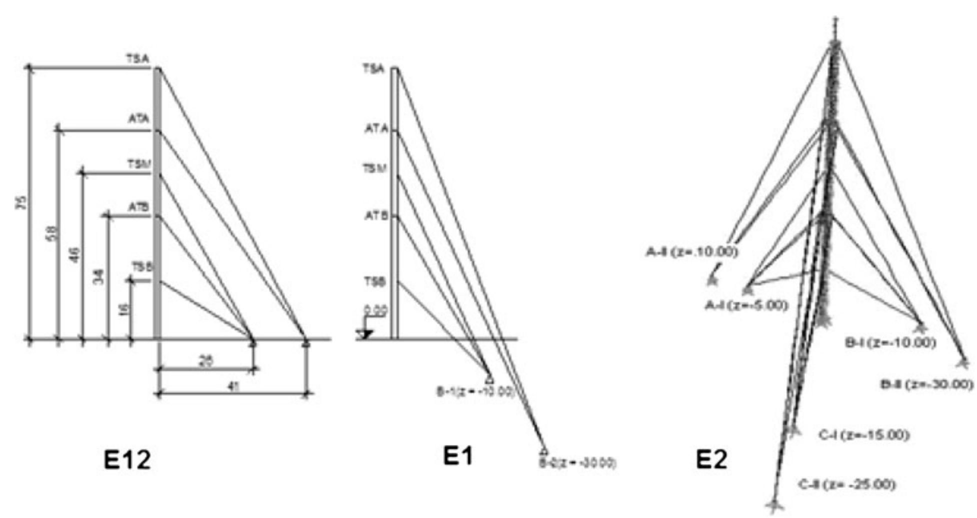
2 Description of structural models of guyed mast

The design of the experiment resulted in four asymmetric guyed mast models formed with different variations on cable topology and anchor asymmetry, which are shown on Figs. 2, 3 and 4. Models E1 and E2 are both of the same cable topology: five guy levels and different anchor asymmetry; the corresponding symmetric model is E12 with all six anchors at level 0.00 with respect to mast base. E1 model has only one lane of the anchors descended and model E2 has three lane anchors at different ground levels. Models E3 an E4 are of the same cable topology: three guy levels with only one anchor and different asymmetry; the corresponding symmetric model is E34 with all anchors at level 0.00 with respect to mast base. E3 model has only one lane of anchors descended and model E4 has all lane anchors at different ground levels. Detailed anchor levels on each model are shown in Tables 1 and 2.

3 Modeling considerations

Many researchers on guyed mast [4, 8] have used the beam equivalent model to represent real 3D truss. This is a valid approximation when there is no asymmetry on the mast. According to asymmetry considerations of this study, the mast was modeled as a 3D spatial structure with pinned braced members and continuous column members. The union between mast and foundation was considered as three pinned joints at the bottom of the column. Anchors were

Fig. 2 Models E12, E1 y E2 selected for the comparative study



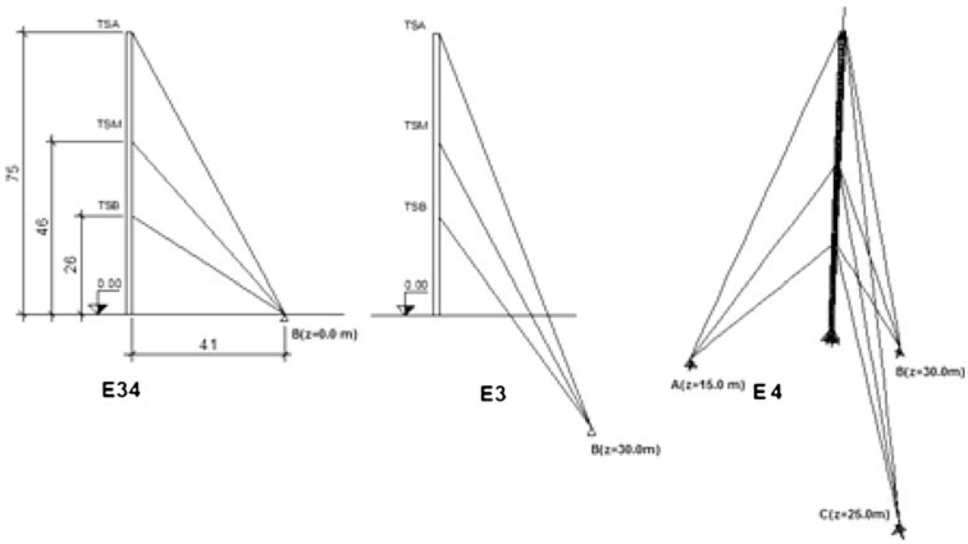


Fig. 3 Models E34, E3 y E4 selected for the comparative study

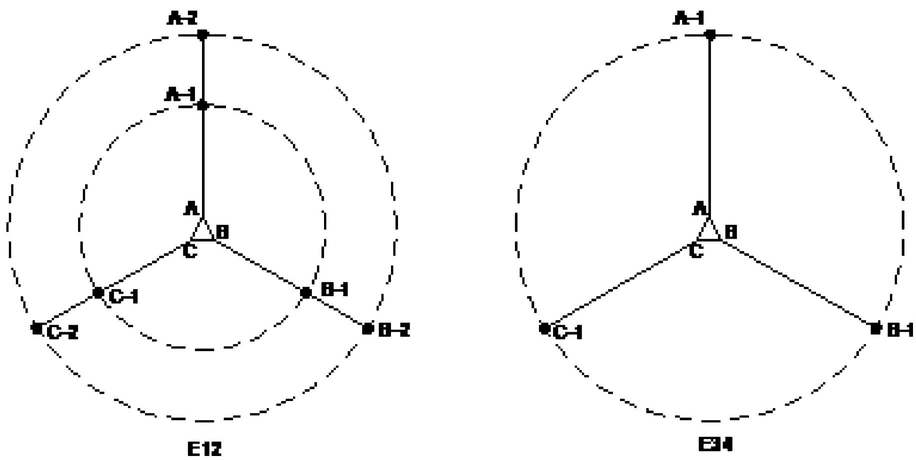


Fig. 4 Plane view of guyed mast with anchors distribution

Table 1 Anchor's ground levels E1 Y E2

Anchor lane	Anchor	Horizontal distance from mast to anchor (m)	Anchor vertical level with respect to mast base (m)	
			E1	E2
A	A-1	26	0.00	−5.00
	A-2	41	0.00	−15.00
B	B-1	26	−10.00	−10.00
	B-2	41	−30.00	−30.00
C	C-1	26	0.00	−10.00
	C-2	41	0.00	−25.00

Table 2 Anchor's ground levels E3 Y E4

Anchor lane	Anchor	Horizontal distance from mast to anchor (m)	Anchor vertical level with respect to mast base	
			E3	E4
A	A-2	41	0.00	−15.00
B	B-2	41	−30.00	−30.00
C	C-2	41	0.00	−25.00

considered as spatial pinned joints fixed on the ground. Material of members was steel with 280 MPa minimum yield stress and 2×105 MPa modulus of elasticity working on the elastic and linear range. Cable mechanical properties were considered to be minimum yield stress of 1,600 MPa and a modulus of elasticity of $E = 2 \times 105$ MPa.

4 Load considerations

Permanent load due to weight of members and accessories was taken into account for the analysis of the guyed mast. Wind load on mast and cables was determined according to the Cuban Standard for wind action on structures [7] with a basic wind velocity of 45 m/s (10 min on average). For dynamic analysis, equivalent static method Patch Load was applied to the mast. To calculate wind load on the mast, it was divided into 6 m lengths. Wind pressures were applied as concentrated forces acting on mast joints. Wind on cable elements was considered as distributed and in the direction of the wind force vector. Pre-tension loadings in the catenary cables were considered in a geometric non-linear static analysis. Pre-tension loading on cables was modeled as target force applied on cables end near the anchor. Values of initial cable tension were assumed between 8 and 15 % of the specified breaking load, and they were applied in an iterative form on cables to achieve equilibrium and vertical position of the mast before wind force action on the structure. Wind load was considered on 12 different directions on the mast to obtain the worst condition of mast member and cable stresses.

5 Analysis considerations

Non-linear geometric analysis was performed to obtain internal forces on members and joint reactions. Two non-linear load cases were defined: initial loading case and final loading case. The initial loading case (ILC) was defined as the equilibrium achieved under permanent load and initial tension of cables while the final loading case (FLC) is the equilibrium reached under wind loads acting on the mast and cables considering the deformational and tensional state of the initial load case.

6 Comparative analysis

Internal forces on members of the mast: columns, braces, horizontal members, guys and anchors were obtained from the analysis under 12 different directions of the wind load. Members with maximum stress for each asymmetric model, in any wind direction, were selected to compare the members with maximum stress of the symmetric guyed mast model. Relative increments of the members' forces were calculated as percentage of the symmetric members' forces by Eq. (1):

$$\Delta = \frac{\left(F_{\text{asymmetric}} - F_{\text{symmetric}}\right)}{F_{\text{symmetric}}} \times 100 \qquad (1)$$

The analysis of the six models demonstrates that zero wind direction was, in all cases, the worst condition for column members. Maximum compression forces were developed on the leeward column A (Fig. 5).

7 Columns and braced members

Maximum forces were obtained at bottom of the mast, in column A. At medium and high levels of the mast, axial forces are of similar magnitude on symmetric and asymmetric models, as shown in Fig. 6. Forces on columns B and C are also incremented in relation with the symmetric model, although magnitudes of force are smaller than forces in column A.

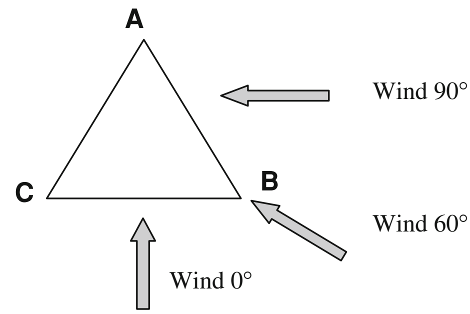


Fig. 5 Wind direction on mast section

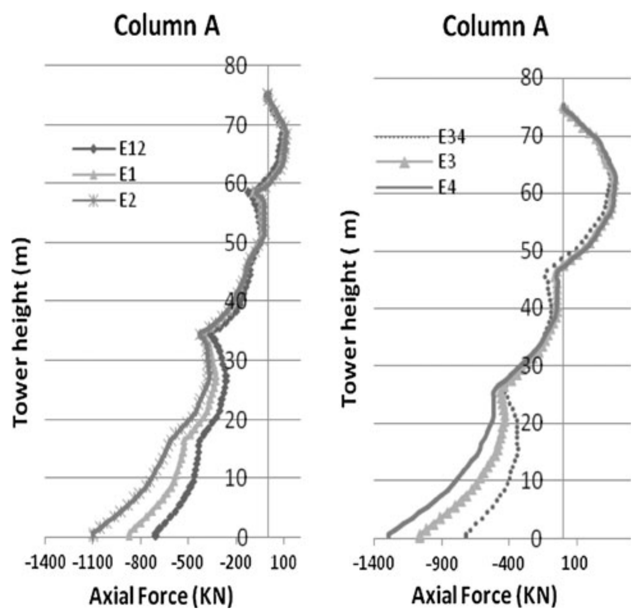


Fig. 6 Axial force on columns A of six models of mast

Relative increments in compression forces on the columns for asymmetric models in final load state have been calculated and represented in Fig. 7. It was found that maximum increment is in model E4 with an increment of 80 % in relation to symmetric E34. The minimum increment was found in model E1 with 24 % less than symmetric model E12.

In braced members, internal forces are greater at the vicinity of guy union with the mast. Asymmetric models have revealed an increase of maximum forces, either tension or compression force. Braced members of face AB and AC of the mast have to resist compression forces all along the mast; however, at guy union with mast tension forces reach considerable values. As the critical condition for steel members of the mast is the compression force, increments have been calculated with maximum

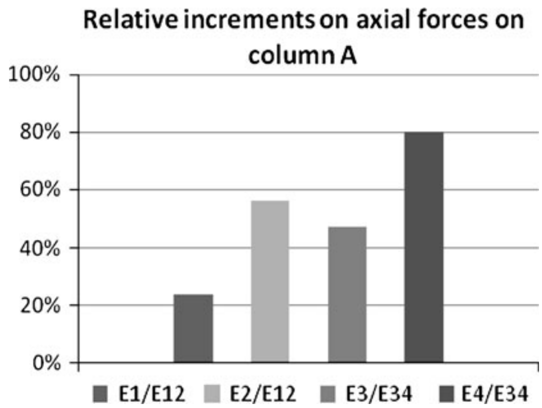


Fig. 7 Relative increments of maximum axial force in column A in asymmetric models

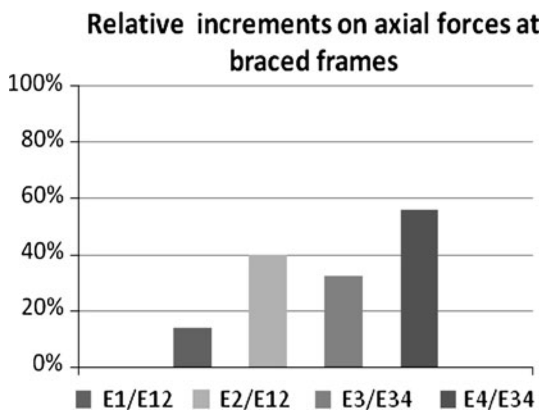


Fig. 8 Maximum relative increments of axial force in braced members in asymmetric models

compression forces. Tensions forces were disregarded on braced members in this analysis.

Relative increments of compression forces in braced members have been calculated for the asymmetric models in final load state. It has been found that maximum increment is in E4 model with a percentage of increment of 56 % in relation to symmetric E34. The minimum increment was found in E1 model with 16 % related to symmetric model E12, as can be seen in Fig. 8.

All horizontal members are tension-resisting elements. No significant increments were found in asymmetric models.

8 Guys

Maximum tension forces on cables are represented in Fig. 9 for models E1, E2, E3 and E4 in final loading state. These forces correspond to cables of lane B in all cases. Worst wind direction was found to be 90° to face BC, as seen in Fig. 5, where lane B is the lowest of the anchor's lanes. For symmetrical model E12, tension of the cables is between 40 and 78 % of breaking strength under design wind load, while asymmetric models E1 and E2 achieved up to 102 % of breaking strength load in the same loading condition. It was observed that asymmetric models E1 and E2 had an increment of cable tension on third and fifth-level guys. These guy levels are simple cables while in the second and forth guy levels, with torsion reducing systems, smaller increments were observed. Similar results were found in asymmetric models E3 and E4 with tension increment at all guy's levels. Major increments on guy's forces at wind direction of 90° are represented in Fig. 10, while Table 3 shows relative increments at 0° and 60° wind directions.

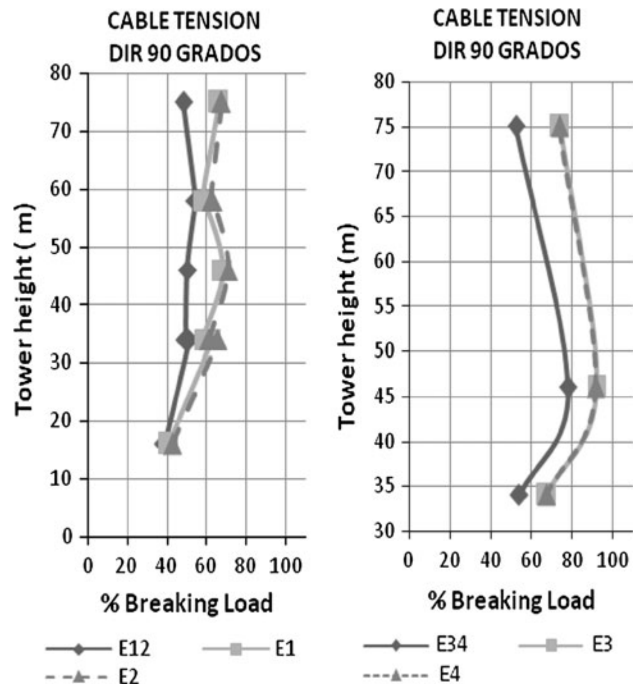


Fig. 9 Cable forces in percentage of breaking load in symmetric and asymmetric models

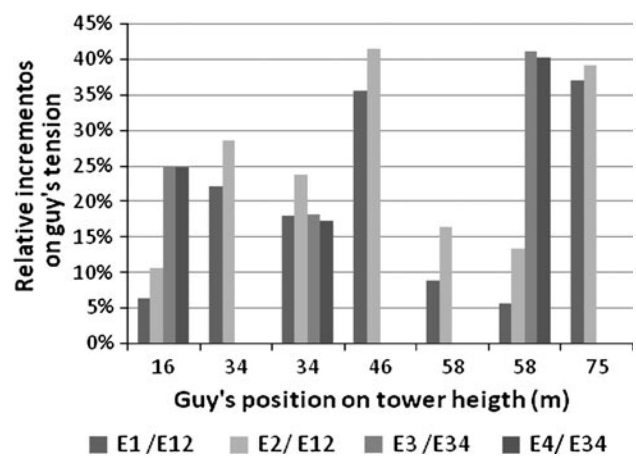


Fig. 10 Relative increments of cable tension at 90° wind direction for asymmetric models

Table 3 Relative increments of cable tension under different wind directions on asymmetric models

Nivel cable	Cota (m)	E1/E12			E2/E12			E3/E34			E4/E34		
		0° (%)	60° (%)	90° (%)	0° (%)	60° (%)	90° (%)	0° (%)	60° (%)	90° (%)	0° (%)	60° (%)	90° (%)
TSB	16	6	3	6	6	11	11	21	16	25	18	30	25
ATB	34	17	23	22	14	23	28						
ATB	34	21	20	18	23	26	24						
TSM	46	35	37	36	36	47	41	16	9	18	13	19	17
ATA	58	3	−5	9	8	7	16						
ATA	58	8	9	6	14	14	13						
TSA	75	35	46	37	31	47	39	32	18	41	34	30	40

9 Anchors

Larger reaction forces were observed on anchors on asymmetric models than on symmetric models. Anchors with higher variations from ground level were found to support larger forces. In models E1 and E2, with more than one anchor by lane, bigger forces are located at external anchor B2, which is lower than the mast base; however, larger increments of forces have been found at internal anchor B1 of the same lane, see Figs. 11 and 12. Cables of medium level with maximum forces correspond to this anchor.

Table 4 shows increments in force reaction of asymmetric models with respect to symmetric models. Values are represented for initial loading state and final loading state to discriminate increments due to dissimilar pre-tensioning of the cable.

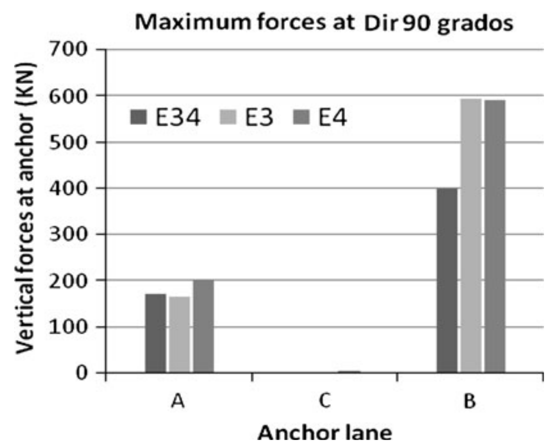


Fig. 12 Anchor reaction forces at 90° wind direction for E·34, E3 and E4

10 Conclusions

Results of this investigation show that asymmetry on anchors levels of guyed mast, under extreme wind loads, has a great influence on the magnitude of forces in all members; this condition, frequently disregarded in mast design, can produce a change in design section of members of the mast. Relative increments in internal forces in asymmetric models in relation to symmetric models were observed in all members; the percentage of these increments for studied models was: for cables, between 12 and 58 %; for anchors, between 33 and 45 %; for columns, between 12 and 80 %; and for braced frames, between 10 and 45 %.

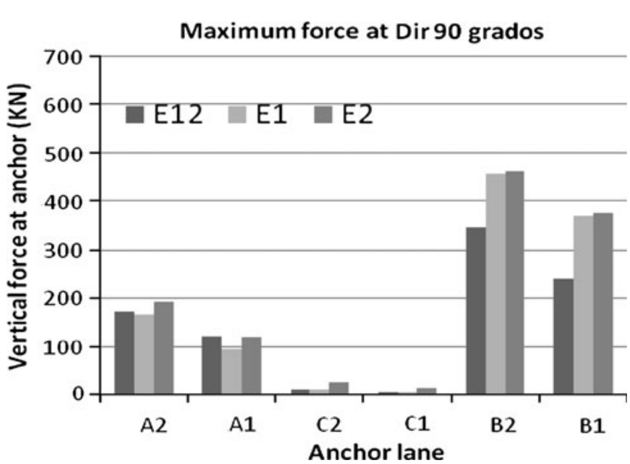


Fig. 11 Anchor reaction forces at 90° wind direction for E12, E1 and E2

Table 4 Increments in anchor vertical reactions

Models	Initial loading state (%)	Final loading state (%)
E1/E12	38	33
E2/E12	45	36
E3/E34	54	44
E4/E34	38	46

Both asymmetry and cable topology have a significant influence on internal forces in members of the mast under wind loading, but interaction between these factors was found to be not important when compared to their isolated effects on structural response.

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