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Aerodynamic analysis of a photovoltaic solar tracker

S. Hernández, J. Méndez, F. Nieto and J.Á. Jurado
School of Civil Engineering University of Coruña, La Coruña, Spain
hernandez@udc.es; fnieto@udc.es; jjurado@udc.es
ETS de Ingenieros de Caminos, Canales y Puertos; Campus de Elviña; 15071 La Coruña, Spain

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ABSTRACT

The new generation of photovoltaic solar farms are composed of solar panels mounted over mobile structures that rotate tracking sun trajectory in the sky with the aim of being always oriented perpendicular to the sun and consequently gaining efficiency and producing more electric energy. In this paper an aerodynamics study of this kind of solar tracker is presented. First, the wind speed required for the design was identified by comparing the requirements established in the Spanish code of practice with an extremal analysis of the wind at the farm site by using wind speed data recorded for a quite large period of time from two weather stations located not far from the solar farm.

Then, a finite element model was created for different inclination angle of the solar tracker and for each of them a proper structural analysis was carried out for several load combinations and configurations of the panel. Up to three different limit states were taken in account to validate the performance of the design. Numerical results demonstrated that the prototype was unable to undergo the full amount of wind pressure for each of the limit state required. As a consequence an inverse problem finding out the maximum allowable wind speed for each limit state was worked out.

Contact person: S. Hernández. School of Civil Engineering University of Coruña, Campus de Elviña, 15071 A Coruña Tf.: 34 981167000; Fax: 34 981167170, E-mail hernandez@udc.es

1. INTRODUCTION

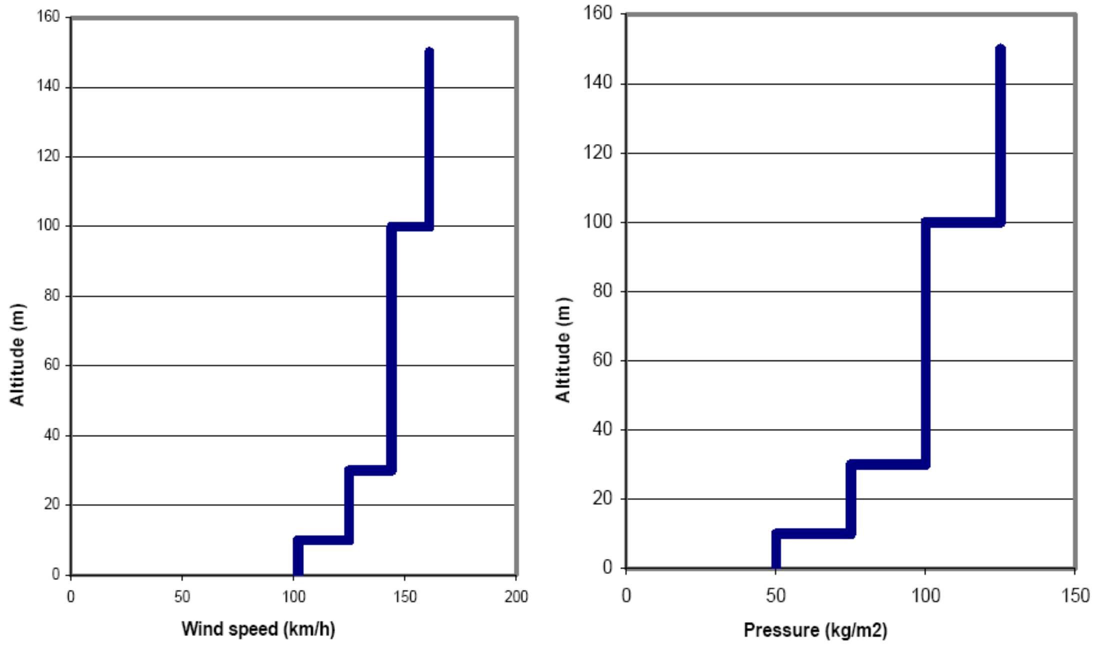
Electrical energy obtained by photovoltaic panels is increasingly used in many countries. To improve the efficiency of the system usually photovoltaic panels are mounted on mobile structures that rotate with respect to vertical and horizontal axes for tracking the sun trajectory in the sky. Commonly the surface exposed to wing pressure is very large and for the product to be competitive the structure must be designed to resist wind loads but with the strictly necessary amount of material. The authors have carried out a study for a prototype of this kind of photovoltaic solar tracker trying to identify its performance under the required set of loads for the Spanish code of practice. The methodology consisted in the following steps:

a) Identification of wind speed at the site
b) Evaluation of wind loads
c) Generation of structural model
d) Identification of ultimate limit state
e) Calculation of critical wind speed.

2. IDENTIFICATION OF WIND SPEED

The solar farm was to be set up in the Spanish region of Extremadura, close to Portugal. In order to identify the wind speed to be considered in the design two alternatives were considered in the design. One was to apply the indications given in the Spanish code of practice. The second one was to carry out a study of maximum wind speed to be expected in the site of the solar farm.

Regulations provided by Spanish code of practice are described in Figure 1, that shows the vertical distribution of wind speed with regards to construction height, and the dynamic pressure associated.

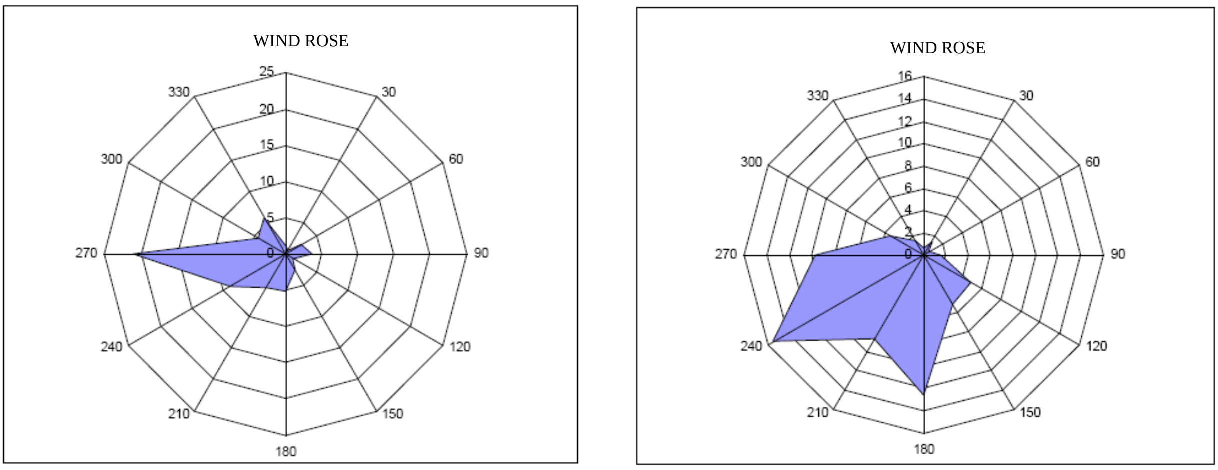


a) Wind speed b) Dynamic pressure

Figure 1: Vertical profile of wind speed in Spanish code of practice

The latter option requires actual data from weather station located in the neighbourhood of the site. In that regards quantitative information for the period of 1971- 2000 years could be found for two different facilities located in Badajoz and Caceres.

Actual data were maximum monthly wind speed and its spatial distribution as given in Figure 2.



a) Badajoz site b) Caceres site

Figure 2: Wind rose at weather stations selected

Using information of maximum monthly wind speed an extremal analysis was carried out in order to adjust an analytical expression to the actual data collected. Three possible extreme distributions were considered.

a) Gumbel curve

$$F_V(V) = e^{-e^{\frac{V-a}{b}}}$$

b) Frechet curve

$$F_V(V) = e^{-\left[\frac{b}{V-a}\right]^c} \qquad V > a \qquad c > a$$

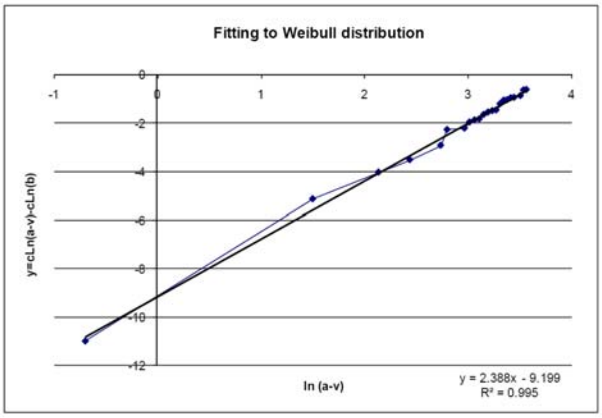
c) Weibull curve

$$F_V(V) = e^{-\left[\frac{a-V}{b}\right]^c} \qquad a > V \qquad c > 0$$

In those expressions *a, b, c* are parameters to be identified and $F_V(V)$ the cummulative distribution of wind speed *V*.

For the Badajoz weather station data fitted better to a Weibull curve. By taking logarithms twice in the expression of $F_V(V)$ a linear regression could be carried out with the values of recorded wind speed and therefore identifying values of *ln (a-V).*

In the case of the Caceres site a Frechet curve was more appropriate and again the proper values of parameters *a, b, c* were adjusted by linear regression. Figure 3 shows the accuracy of both curve fitting.



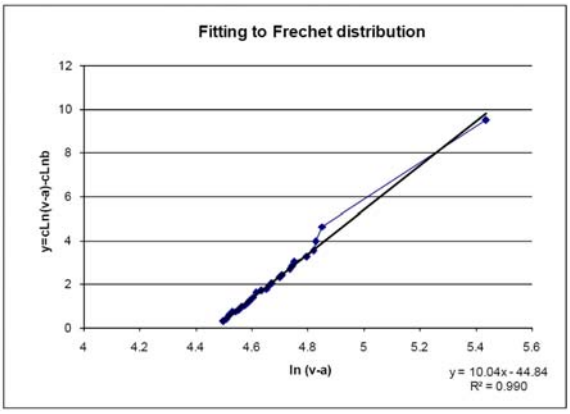


Figure 3: Fitting of monthly wind speed

After finding out expressions for $F_V(V)$ at each weather stations the wind speed for a return period of 25 years, that was the expected service life of solar farm, was evaluated the following values were found out:

Badajoz site: V_{max}: 97.14 Km/h
Caceres site: V_{max}: 111.11 Km/h

Measurement of wind speed was done at altitudes of 17 m and 10 m respectively. In Badajoz an Caceres observatories. Thus the next step was to establish the vertical distribution of wind speed according with the logarithmic law

$$V(z) = \frac{1}{k} V_* \ln \frac{z}{z_0}$$

Where z_0 is the roughness length, k_0=0.4 is the Von Karman constant and V_* is the shear velocity of wind flow. Values of z_0 depend on terrain types as indicated in Table 1 and in this case the mown grass type of terrain was selected as more appropriate.

Type of surface	**z_0 (cm)**
Sand	0.01 – 0.1
Snow surface	0.1 – 0.6
Mown grass (-0.01m)	0.1-1
Low grass, steppe	1-4
Fallow field	2-3
Hight grass	4-10
Palmetto	10-30
Pine forest (mean height of trees: 15 m; one tree Per 10 m$^{2:}$; $z_4 \simeq 12m$)	90-100
Sparsely built – up suburbs	20-40
Densely built – up suburbs	80-120
Centers of large cities	200-300

Table 1: Values of z_0 for various terrains types

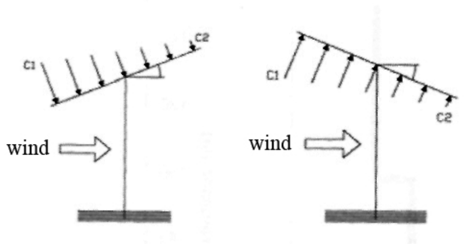
Using this logarithmic law and substituting z =17 m, and z =10 m for the Badajoz and Caceres sites, respectively, the wind speed at the altitude of z = 6 m, corresponding to the top of the solar tracker could be evaluated producing the following values:

Using Badajoz site data: V = 86.53 Km/h.
Using Caceres site data: V = 98.97 Km/h.

It turned out that both values were lower that the ones required by the Spanish code of practice, shown in Figure 2 with a value of V = 102 Km/h for $0 \le z \le 10m$ .Therefore the results of wind speed obtained from the extremal wind analysis were left aside and the Spanish regulation was used afterwards in the study.

3. EVALUATION OF WIND LOAD

The solar tracker studied is presented in Figure 4 that includes a 3D-view and a lateral elevation. The main surface is due to the panel containing the photovoltaic elements. They all are in a plane having varying orientation as it searchs for the sun in the sky. Therefore after having obtained the design wind speed the dynamic pressure on the panel with inclined geometry was calculated using the expression $p = c_i V^2/16$ were c_i $(i = 1, 2)$ depends on the inclination angle of the panel as mentioned in Table 2.



Incidence angle of wind	Leading Edge C1	Trailing Edge C2
70º	1.2	1.2
60º	1.2	1.2
50º	1.4	1.0
40º	1.6	0.8
30º	1.6	0.8
20º	1.2	0.4
10º	0.8	0.0
0º	0	0

Table 2. Values of c_1 and c_2

Several inclination angles, namely, $\alpha = 10^o, 20^o, 30^o, 40^o, 50^o, 60^o$ and 70^o were considered in the study, because they were the set of possible configurations of the panel during the sun tracking process during daytime. Horizontal geometry was of no interest from the structural analysis point of view as no pressure is produced by the wind and thus the values of internal forces in the structural elements will be lower than in the inclined configurations. Also two different wind directions as presented in Figure 5 were taken in account, because the static equilibrium of the solar panel was different.

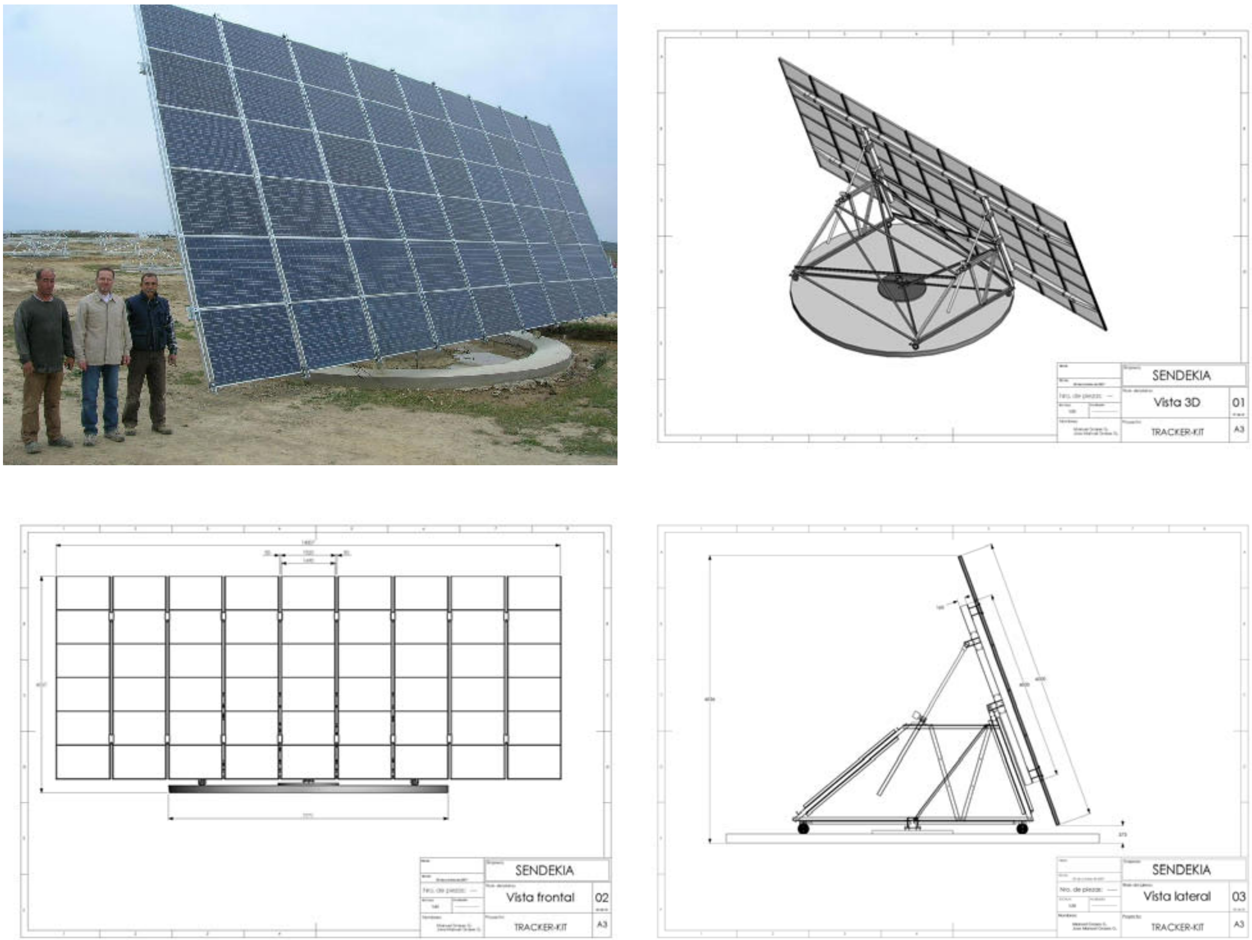
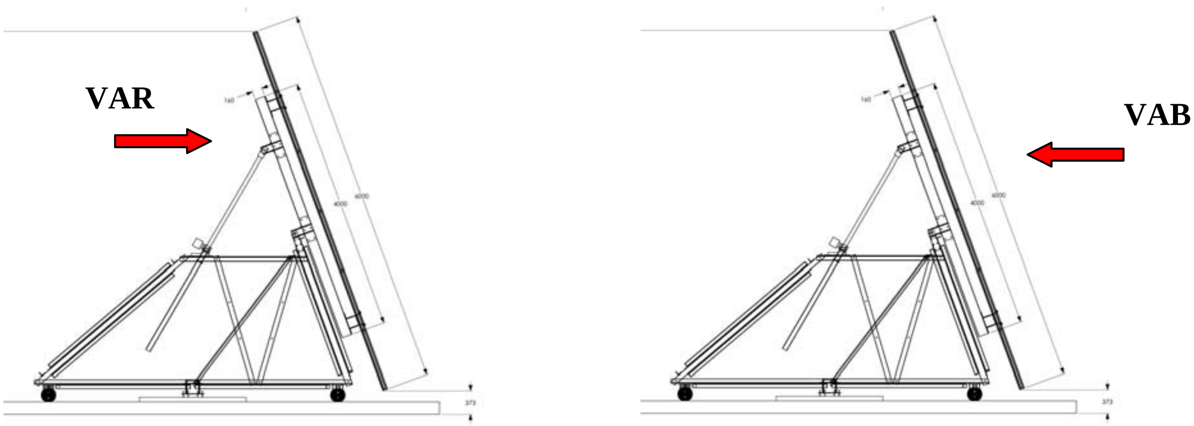


Figure 4: Solar tracker

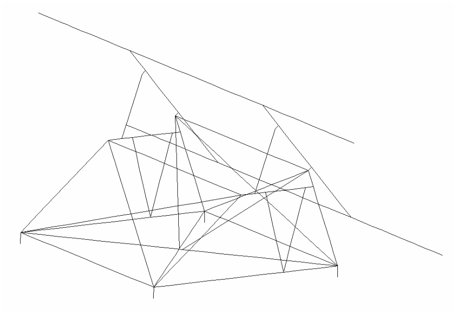


VAR VAB

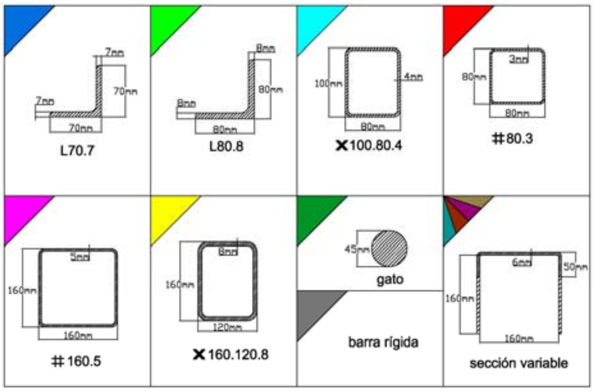
Figure 5: Wind directions studied

4. STRUCTURAL MODEL

A finite element model was developed considering bar elements. Figure 6 shows a view of the structural model and the set of cross section of bars. In overall the number of bar elements was 370 and the number of nodes 479. The material was steel S2755R with a yield stress value of 275MPa. It was considered linear and elastic with the following properties: E = $2.1 \cdot 10^5$ N/mm^2; $\nu = 0.3$ and density $\gamma = 7.85\,\mathrm{t/m^3}$



3D model



Set of cross sections

Figure 6: Structural model

As mentioned previously up to 7 different positions of the solar tracker were considered, therefore the structural model needed to be modified for each of this configurations. The set of loads included in the analysis were the structural weight (PP), an amount of snow load, required by the Sapnish code of practice, of PPN=600 N/m^2 and wind pressure. The following load combinations for SLS and ULS were considered:

For SLS (Service Limit State):

- PP + PPN + VAB
- PP + PPN + VAR

For ULS (Ultimate limit state):

- 1,35 PP + 1,35 PP + 1,5 VAB
- 1,35 PP + 1,35 PP + 1,5 VAR
- PP + PPN + 1,5 VAB
- PP + PPN + 1,5 VAR
-

The set of limit states were related with different constraints of the design:

- Maximum value of one degree of rotation (1º) at the lateral sides of the solar tracker.
- Maximum value of the Von Mises stress of the material.
- Non detachment of structural supports.

The following tables show the maximum values of the numerical results of the structural analysis for each solar tracker configuration angle, regarding to each limit state taken in account.

Angle of panel	Maximum slope (º)	Node	Maximum allowable slope (º)
0º	0.40	259	1
10º	0.937	259	1
20º	1.303	259	1
30º	1.665	259	1
40º	1.639	259	1
50º	1.515	259	1
60º	1.38	259	1
70º	1.317	259	1

Table 3: Slope on lateral sides

Angle of panel	Maximum stress (MPa)	Upper limit of stress (MPa)
0º	116.7	275
10º	183.1	275
20º	242.3	275
30º	307.4	275
40º	301.7	275
50º	275.8	275
60º	247.7	275
70º	240.5	275

Table 4: Maximum Von Mises stress

Angle of panel	Lower vertical force (N)	Node	Lower allowable force
0º	2415	262	0
10º	-2419 -1855	262 560	0
20º	-4718 -4155	560 262	0
30º	-8077 -6305	560 262	0
40º	-9019 -7277	560 262	0
50º	-7965 -5760	560 262	0
60º	-6807 -6687 -4010	560 563 262	0
70º	-11950 -8287 -6986	563 265 560	0

Table 5: Minimum vertical force at supports

Information on tables 3 to 5 shows the following:

1. Inclination angles greater than 10º produce unacceptable slope at the lateral sides of solar tracker.
2. Configurations with 30º to 50º of inclination create greater values of Von Mises stress than allowed.
3. Almost no configuration can be accepted because of negative forces appears at the supports and detachment from the foundation can be expected.

These discussions of the numerical results lead to the conclusion that the solar tracker designed could not undergo the full amount of load pressure of the Spanish code of practice. Therefore in order to avoid fatal failures, an inverse problem should be formulated being it to identify the value of wind speed acceptable for each limit state and configuration angle. This is the information provided in Figure 7.

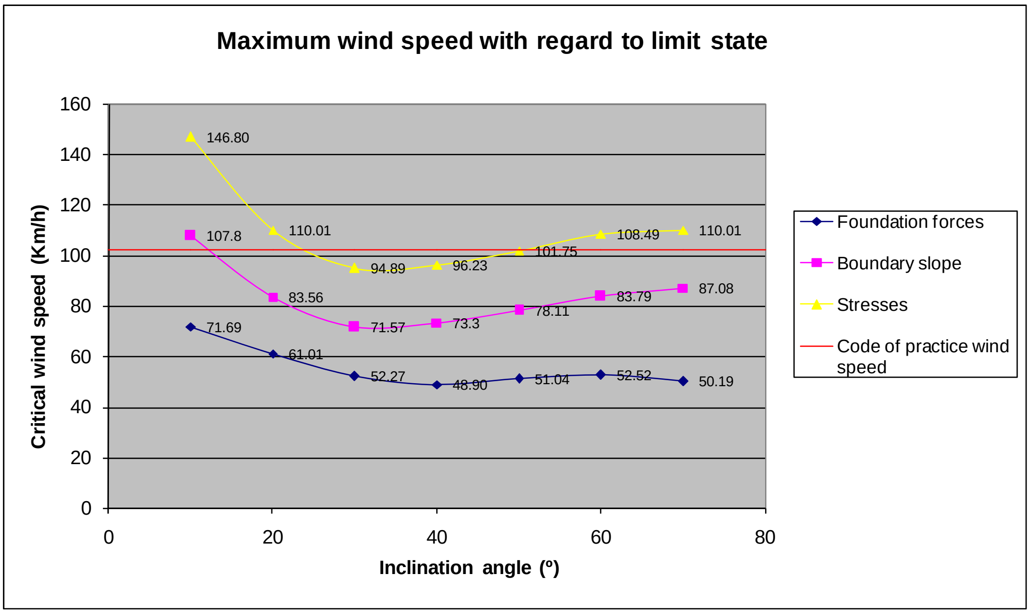


Figure 7: Maximum wind speed for each limit state and solar tracker configuration

5. CONCLUSIONS

The following conclusions can be extracted from this work:

1 A study of wind loads and effects on a prototype of a real solar tracker considering several configurations was carried out.

2 The numerical results coming from the structural analysis allowed to discover that several configurations of the solar tracker were unsafe with regards to the complete set of limit state taken in account.

3 An inverse study aimed to identify the maximum wind speed allowable for each solar tracker configuration was than performed.

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