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# DIAGNOSIS OF FATIGUE COLLAPSES OF SLENDER STRUCTURES DUE TO AERODYNAMIC WIND ACTIONS

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## 1 INTRODUCTION

Authors of the paper have recently proposed a complete procedure for wind-induced fatigue analysis of slender structures, which requires the evaluation of the wind loading effects and damage associated with all loading conditions [1, 2]. The application of the proposed method gives a picture of the evaluation of the stress state of the structure, furnishing useful information on the structural behavior and a key for the interpretation of collapses and damages causes. The paper illustrates the diagnosis of wind-induced collapses of two slender structures. Notwithstanding the simplicity of the structural scheme, the analysis shows some critical aspects of the aerodynamic behavior of the considered structures.

## 2 WIND-INDUCED RESPONSE AND FATIGUE ANALYSIS

The macro-meteorological wind state is dealt with as a 3-variate random vector whose components are the mean wind velocity $\bar{u}_r$ evaluated at height z=r, the wind direction $\varphi$ and the inverse of the Monin-Obukhov length (1/L) [2]. Time t is subdivided into successive $\Delta T$ intervals falling within the spectral gap, in which the three components are constant. When a time interval T greater than $\Delta T$ is taken into account, the wind loading effects induced in a structure are treated as a series of loading conditions, each corresponding to a $\Delta T$ step.

Let us introduce a series of velocity intervals $\Delta \bar{u}_i$ (i=1,2…), a series of directional sectors $\Delta\varphi_j$ (j=1,2, …, N) and a series of inverse Monin-Obukhov intervals $\Delta(1/L)_h$ (h=0,±1, ±2… ). A structure is said to undergo the ijh-th loading condition when $\bar{u}_r \in \Delta \bar{u}_i$, $\varphi \in \Delta\varphi_j$ and $(1/L) \in \Delta(1/L)_h$. Thus, the ijh-th loading condition is characterized by the probability $P_{ijh}=P[\bar{u}_r \in \Delta \bar{u}_i \cap \varphi \in \Delta\varphi_j \cap 1/L \in \Delta(1/L)_h]$. This quantity is linked with the territorial position, with the local site properties and with the thermal atmospheric stratification.

The damage induced by all the wind loading conditions is evaluated collecting the wind loading cycles into a discrete cycles histogram obtained applying a suitable cycle counting method [1, 2]. The mean damage induced by different cycles, the total mean damage and the mean fatigue can be evaluated adopting the Palmgren-Miner linear rule and assuming a suitable fatigue resistance curve for the critical structural detail.

The evaluation of the loading effects and damage associated with the loading conditions constitutes a fundamental step in fatigue evaluation; moreover, it furnishes useful information on the structural behavior and a key for the interpretation of collapses and damages causes.

## 3 CASE STUDY 1: ANEMOMETRIC POLE

The first examined structure is an anemometric pole, of total height h=10 m, composed by a steel shaft with octagonal section, which diameter varies linearly from 220 mm at bottom to 78 mm at top. The pole carries an anemometer at the top, a photovoltaic panel at z=9 m and a metallic box at z=2 m. This simple structure exhibited a premature collapse after one year from its installation, caused by a fatigue crack in the base welding joint (Fig. 1 a). During its life, the anemometer registered the ten-minutes mean wind velocity (Fig. 1 b).

Adopting the procedure previously explained, the evolution of the stress state and fatigue damage associated with the wind loading conditions is examined. The probability of occurrence of the loading conditions are obtained directly from the measured wind velocity time history (Fig. 1 c) .Fig. 1.d shows the mean value $\bar{s}$ and the standard deviations $\sigma_{sx}$ and $\sigma_{sy}$ of the nominal stress at the base of the structure. Fig. 1 e shows the mean fractions of damage induced by the loading conditions on varying the wind velocity values. Table 1 summarizes the maximum stress and the predicted fatigue life for alongwind, crosswind and mixed actions.

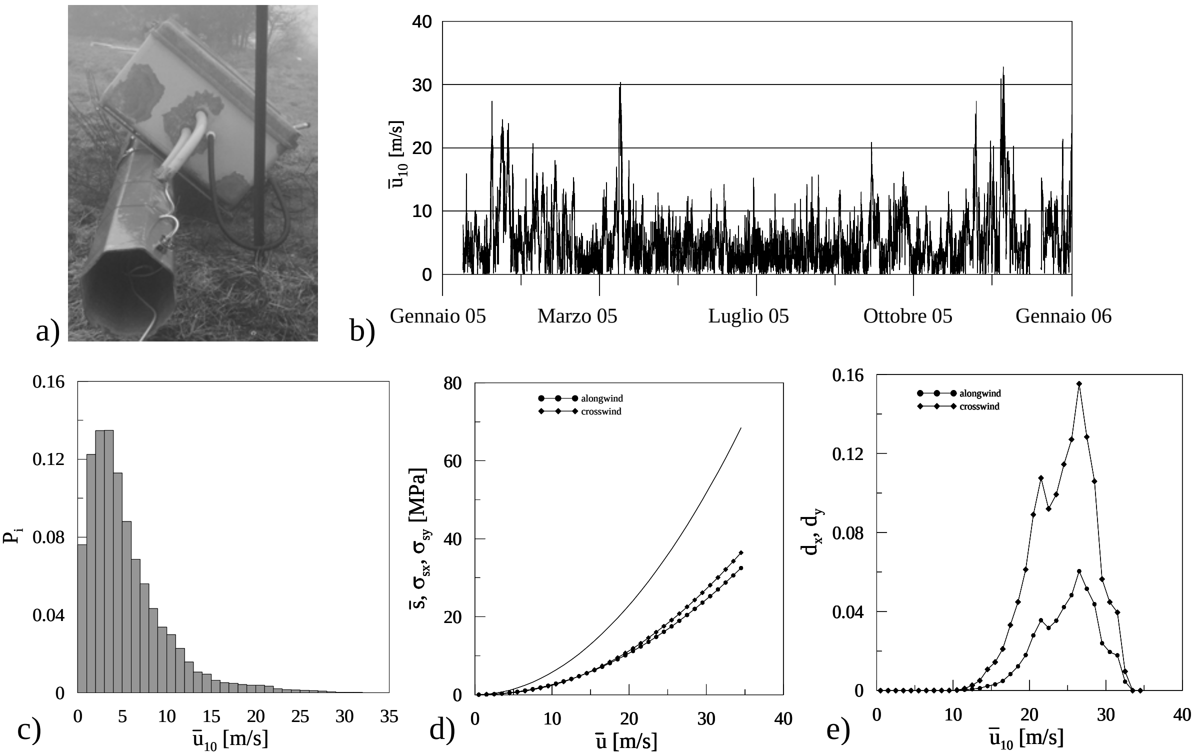


Figure 1: a) picture of the collapsed pole; b) measured wind velocity time history; c) wind velocity probability of occurrence; d) mean and standard deviation of stress; e) mean fractions of damage.

The analysis puts in evidence some points:

- the alongwind and crosswind responses are mainly due to turbulence and grows with the mean wind velocity (Fig. 1 d);
- the alongwind action produces the stress value $s_{max}$=170 MPa, at the maximum registered wind velocity $\bar{u}_{10}$ = 32.5 m/s, below the yield limit of the material $f_y$=355 MPa (Table 1);
- the alongwind and crosswind fatigue damages are concentrated in the range of high wind velocities, between 20 and 30 m/s (Fig. 1 e). This is a consequence of a parent distribution of wind velocity in the site shifted towards high wind velocities (Fig. 1 c);

- the crosswind action produces the maximum fatigue damage and the minimum fatigue life (Table 1). As the standard deviations of alongwind and crosswind fluctuating stresses are similar (Fig. 1 d), the difference is linked with the expected frequencies of the processes;
- the predicted fatigue life linked with alongwind, crosswind and mixed responses disregard directional effects, however the obtained values are very similar to the exhibited fatigue life (Table 1).

It can be concluded that the collapse is linked with a particular windy condition of the site. The safety factor adopted in structural design covers this anomalous situation from ULS point of view, it is completely inadequate from fatigue point of view.

| | alongwind | crosswind | along+cross |
|---|---|---|---|
| $s_{max}$ [MPa] | 170 | 125 | 160 |
| $T_F$ [days] | 740 | 270 | 374 |

Table 1: maximum stresses and predicted fatigue life.

## 4 CASE STUDY 2: ANTENNAS TOWER

The second examined structure is an antennas tower, of total height h=30 m, composed by a steel shaft with polygonal section, 24 meters high, which diameter varies linearly from 1100 mm at bottom to 550 mm at top, connected to a steel pole with circular section, 6 meters high, of constant diameter of 119 mm. The pole at the top can carry different configurations of telecommunication antennas, moreover it can be covered by a cover cylinder of diameter of 1500 mm, with aesthetic function. The configuration with the cover cylinder exhibited large fatigue damages and a premature collapse, caused by a fatigue crack at the shaft- pole conjunction.

Adopting the procedure previously explained, the evolution of the stress state and fatigue damage of the tower with the cover cylinder (C 1) (Fig. 3 a) and without the cover cylinder (C2 ) (Fig. 4 a) is examined. Figs. 2 b and 3 b show the mean value $\overline{s}$ and the standard deviations $\sigma_{sx}$ and $\sigma_{sy}$ of the nominal stress at the critical section. The probability of occurrence of the loading conditions are obtained assuming a conventional site category. Figs. 2 c and 3 c show the mean fractions of damage induced by the loading conditions on varying the wind velocity values. Table 2 summarizes the maximum stress and the predicted fatigue life for alongwind and crosswind actions for the two configurations.

The analysis puts in evidence some complex aerodynamic phenomena and a very different behavior for the two configurations, summarized by the following points:

- The C 1 response is dominated by the crosswind actions, resonant on the first mode at $u_{cr}$= 6 m/s and on the second mode at $u_{cr}$= 18 m/s (Fig. 3 b). In particular, vortex shedding separated by the cover cylinder is characterized by very low Scruton number;
- the C 1 maximum stress value associated to the first critical velocity is $s_{max}$=220 MPa, below the yield limit of the material $f_y$=355 MPa (Table 2); the C 1 maximum stress associated to the second critical velocity is higher than the yield limit of the material, however it can be considered a rare event.
- the C 1 fatigue damage is mainly linked with the vortex shedding resonant with the first mode (Fig. 3 c). As the associated loading conditions are characterized by high probability of occurrence and high stress states, the resulting fatigue life is very low (Table 2).
- the C 2 response grows with the mean wind velocity and is associated with turbulence actions and with vortex shedding actions resonant to the first and second mode (Fig. 4 b). However, vortex shedding effects are drastically reduced by the cover cylinder remove.
- the C 2 alongwind action produces the stress value $s_{max}$=137 MPa, at the reference wind velocity $\overline{u}_{10}$ = 27 m/s, below the yield limit of the material $f_y$=355 MPa (Table 2);

- the C 2 alongwind and crosswind fatigue damages are concentrated in the range of moderate and frequent wind velocities, between 10 and 20 m/s (Fig. 4 c);
- the C 2 fatigue damage is mainly linked with the crosswind actions (Table 2). As the standard deviations of alongwind and crosswind fluctuating stresses are similar (Fig. 4 b), the difference is linked with the expected frequencies of the processes;

It can be concluded that fatigue damages observed in C 1 towers are linked with aerodynamic effects generated by the cover cylinder; however, the conjunction of two poles with very different stiffness gives rise to a critical section in the structure.

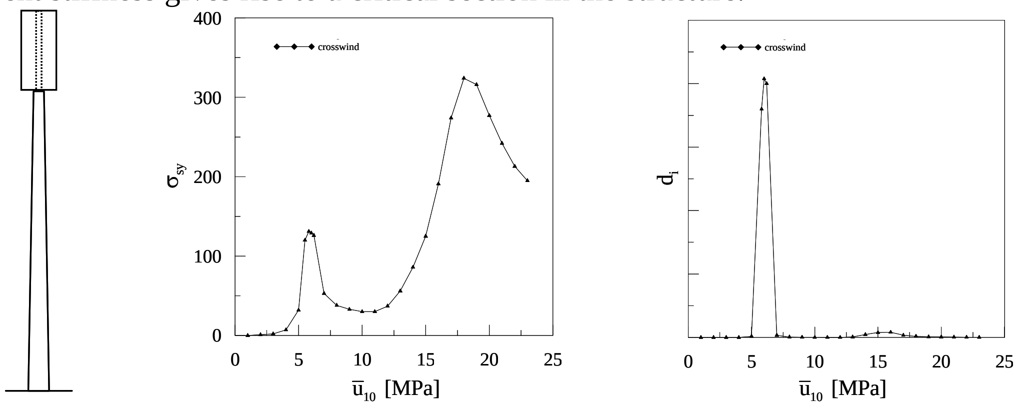


Figure 3: a) scheme of the antennas tower with the cylinder (C 1); b) standard deviation of crosswind stress; c) mean fractions of damage.

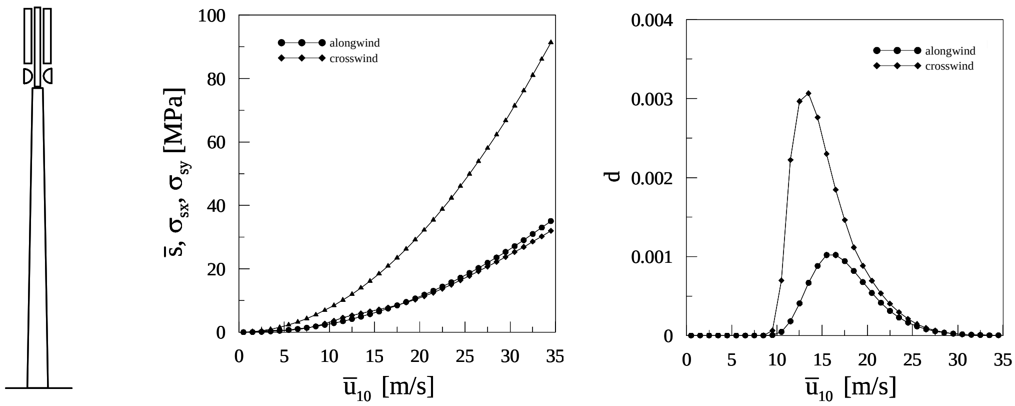


Figure 4: a) scheme of the antennas tower without the cylinder (C 2); b)mean and standard deviation of crosswind stress; c) mean fractions of damage.

| | C 1 crosswind | C 2 alongwind | C 2 crosswind |
|---|---|---|---|
| $s_{max}$ [MPa] | 220 (1 mode) | 137 | 80.5 |
| $T_F$ | < 1 year | 115 years | 45 years |

Table 2: maximum stresses and predicted fatigue life.

## REFERENCES

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