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Aeroelastic effects on a high-rise rectangular section building

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ABSTRACT

High-rise buildings can experience large across-wind response due to the vortex excitation generated by the detached flow around the bluff-body. The capability to predict this motion is fundamental for design purpose and occupancy comfort evaluation. Once the wind loads are known, for instance by wind tunnel tests on rigid models, the tower response can be numerically evaluated. Nevertheless, when the tower, during the oscillations, experiences motion-dependent forces the predicted response can be significantly different from the real one if aeroelastic effects are not evaluated. The paper investigates this problem by wind tunnel tests on non-moving and moving model of a rectangular section prism, having the wind force simultaneously measured together with the tower displacement. The across wind aeroelastic effects both in smooth and turbulent flow are investigated.

1. INTRODUCTION

Wind forces on high-rise buildings are usually defined by wind tunnel tests on scaled models: such tests can provide data on the overall and local loads both in mean and time-varying components and, in some cases, the wind response of the building can be directly measured if aeroelastic models are considered (ASCE, 1987).
Nevertheless more often the wind tunnel tests are carried out on rigid models, i.e. static models with geometrically scaled external features. In order to get reliable results also the simulation of the natural wind is important as happens in atmospheric boundary layer wind tunnels: mean vertical wind profile, turbulence intensity, integral length scales and wind spectrum should be reproduced correctly scaled.
In those tests different techniques are used to measure the wind force: overall wind loads are directly measured with base force balances that can give information on both mean and fluctuating loads providing that the structural frequency of the model and balance system is higher than the maximum frequency of interest. The surface pressure measurement technique allows for a deeper understanding of the

aerodynamic properties of the building because local data on the wind loads are available.
Once the wind loads are known, the wind induced response of the structure can be numerically evaluated providing estimations on full scale accelerations and displacements. The calculation of the response can be carried out both in time domain using the time histories of the loads or in frequency domain using power spectral densities of the modal wind loads (ASCE, 1987). Moreover, starting from surface pressures, through the modal approach, it is possible to evaluate not only the dynamic response, but also the inertial loads and, as a consequence, also the vertical distributions of shears, bending moments and torque (Rosa, 2008; Rosa, 2008b; Simiu, 2008; Rosa, 2012).
The main limitation of this procedure is that the forces used for the computation are measured on a rigid static model while the tower will experience motion as a consequence of those loads (Dyrbye, 1999). It is well known that the motion of the body can modify the aerodynamic forces so that the structure is subjected to aeroelastic effects (Vickery, 1993; Gu, 2004; Quan, 2005). These effects are important for slender and flexible structures and wind tunnel tests on aeroelastic models are needed to investigate those phenomena. In these tests the wind response of the building is directly measured and it is inclusive of the motion-dependent forces.
A research is going on at the Politecnico di Milano with the aim to investigate the aeroelastic effects on a rectangular section 200m height building. In particular the changes in the aerodynamic forces due to the building motion are studied. The wind tunnel model is a simplified aeroelastic model with two degrees of freedom that simulate the two orthogonal fundamental sway modes of vibration. The model set-up allows the simultaneous measurement of both the surface pressure and the body motion (Diana, 2009).
The comparison between wind loads measured on rigid and moving model allows to evaluate the effects of the body motion on the surface pressures. Moreover, numerical simulations through modal approach have been carried out starting from pressures measured on both moving and non-moving model. Thanks to these simulations, how the aeroelastic effects modify the tower displacement have also be studied. The wind tunnel tests are carried out both in smooth and turbulent flow to evaluate the effects of the turbulence intensity that was found to be very important for the possibility of instability phenomena (Zasso, 2007).

2. WIND TUNNEL TESTS SET-UP

The studied tower has a shape very close to a rectangular prism as visible in Figure 1. The wind tunnel tests are carried out both on a rigid model of the tower and a simplified 2DOF aeroelastic one. Atmospheric boundary layer turbulent flow and smooth flow test conditions are investigated.

2.1. Model set-up

The model is designed to allow tests both in moving (aeroelastic) and non-moving (rigid) conditions with the simultaneous measurement of the wind force and the tower response.

It is made in carbon fiber for stiffness and lightness purposes and it has a geometric length scale equal to 1/100. The main dimensions are 2.09 m height with a section B x D equal to 0.576 x 0.225m, resulting in an aspect ratio B/D equal to 2.56 and an elongation H/B equal to 3.62 (Figure 2a). The wind load is evaluated through the measurement of the surface pressure in 240 points using multi-channel pressure scanners (PSI System 8400 with ESP scanners). The scanners are placed inside the model to allow for short pneumatic connections. The sample-rate is 100 Hz for a duration of 100s. The overall base loads are evaluated by the integration of the surface pressures over tributary areas.
The model is elastically connected to the ground in a way to reproduce the oscillations in both the x and y directions. In particular, as represented in Figure 2b, the model is suspended through four harmonic steel bars; in order to adjust the damping factor, the model is equipped also by four pneumatic damping elements. These dampers are set between the model and the ground, in correspondence of the edges of a square, centered on the geometrical centre of the tower, in a way that the damping effect on the two modes is the same. The inertial properties of the model, the stiffness and the damping of the connection elements are correctly scaled using an aeroelastic similitude with respect to the prototype. In order to measure on the aeroelastic model the same accelerations having on the full-scale tower (acceleration scale factor $\lambda_a = 1$), the generalized masses associated to the first two flectional modes in x and in y direction, are reproduced on the model opportunely scaled (Table 1): steel bars are added within the model to match the desired generalized mass value. As a consequence of the design the mode shape are linear and the top displacement is normalized to 1.
The tests in rigid model set-up are achieved by fixing the model base avoiding any oscillation.
In this paper only two exposures are investigated: wind perpendicular to the short side (exposure 0deg) and to the long side (exposure 90deg), as visible in Figure 2a.

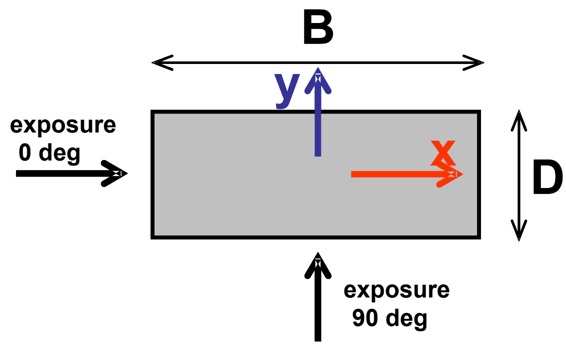
Fig 1 Building wind tunnel model. The elastic suspension system is under the false floor and allows for model oscillations

2.1. Incoming flow characteristics

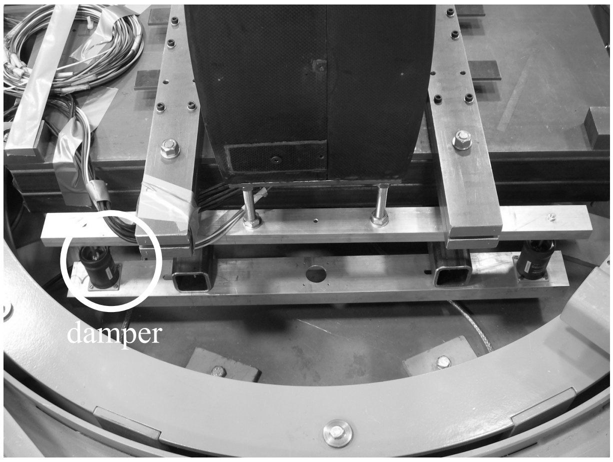
The wind tunnel tests are carried out in two different flow conditions. The first one is the simulation of the full scale atmospheric boundary layer for an urban area configuration, hereafter named TF (turbulent flow). The natural wind is reproduced by the technique of the passive turbulence generation by spires and roughness elements: in Figure 3 are the mean wind velocity vertical profile and the along-wind turbulence intensity profile. The power law index, evaluated through a curve fitting of the velocity profile is equal to 0.32 and the turbulence intensity level at top of the building is equal to 15%.

The second flow configuration is obtained without any turbulence generator, it has a low level of turbulence intensity, 2% and a uniform (block) vertical wind profile; in the paper this set-up is named Smooth Flow, SF and it is compared with the previous one in Figure 3.

As will be highlighted in the next section in this flow condition the aeroelastic effects in the wind response will be more clear because the perturbation on the tower displacement due to the buffeting turbulence effects are reduced.



(a)

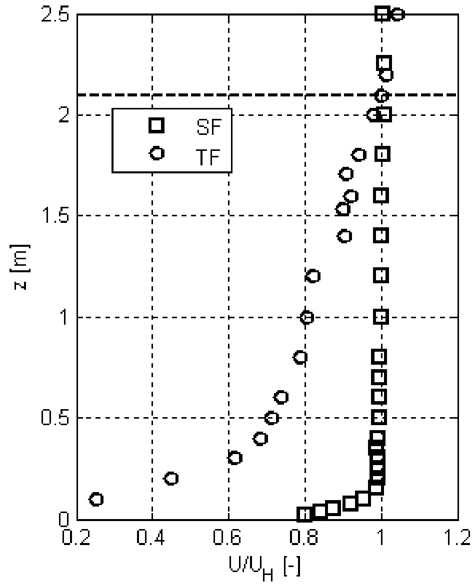


(b)

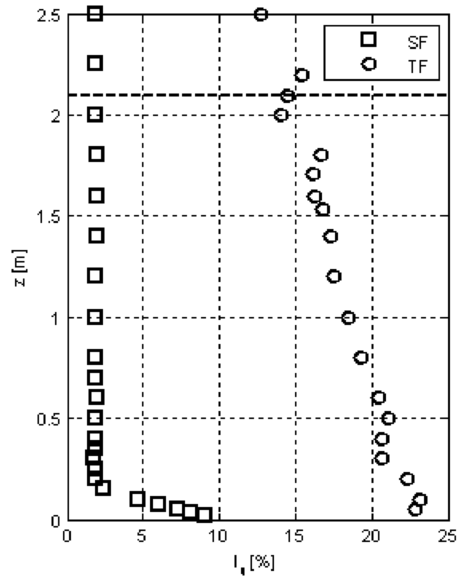
Fig. 2 Reference frame system and wind exposures (a). Detail of the suspension device. It is possible to see the elastic elements and the dampers (b)

mode	*x direction*	*y direction*
frequency [Hz]	1.23	1.367
generalized mass [kg]	29.73	28.7
damping [%]	0.5% and 1%	0.5% and 1%

Table 1 Main structural parameters of the scale model.



(a)



(b)

Fig. 3 Incoming wind characteristics for smooth flow and turbulent flow tests. (a) mean wind velocity vertical profile and (b) along-wind turbulence intensity vertical profile

3. RESULTS

3.1. Power spectral density of the wind force

The base moments of the model, evaluated by the integration of the surface pressures over tributary areas, are expressed in terms of moment coefficients as follows (see also Figure 2a):

$$C_{Mx} = \frac{M_x}{\frac{1}{2}\rho U_H^2 BH^2}$$
$$C_{My} = \frac{M_y}{\frac{1}{2}\rho U_H^2 BH^2} \qquad (1)$$

where the coefficients are referred to the flow velocity at the top of the building U_H.
Figure 4 shows the normalized power spectral density for the across-wind overturning moments in the two different flow conditions. The measures refer to tests on the non-moving model. When the wind is perpendicular to the long side of the building (Fig. 4b), a well defined Strouhal frequency is visible in smooth flow tests: the corresponding Strouhal Number is equal to 0.115, assuming as reference dimension the breadth B. In turbulent flow, as expected, the frequency content of the wind load is higher. There is always a peak corresponding to a vortex shedding phenomenon at a slightly lower value of reduced frequency, equal to 0.1.
In the other exposure investigated (Fig. 4a) the vortex shedding is still present: smooth flow tests highlight a Strouhal Number equal to 0.045 (assuming the short side D as reference dimension). It is interesting to note that a second peak is present at a higher reduced frequency of about 0.16 that would give a lower critical velocity. Nevertheless,

as it will be shown in the next section, tests on the moving model shows an appreciable effect in the response due to this second peak only at very low structural damping: this behavior is probably due to the too low energy introduced by the pressure field at this velocity. In turbulent flow tests the vortex shedding is less visible and the spectrum shows a broad-band response.

As known, the vortex shedding phenomenon can be dangerous for the structures when the Strouhal frequency is close to the structural frequency of the tower because resonance occurs and there is the possibility of lock-in phenomenon that can cause high oscillation amplitudes. In the tests on the moving model the flow velocity is varied over a wide range including the critical value. The critical reduced velocity, i.e. when the vortex shedding frequency is equal to the structural frequency, can be evaluated as the reciprocal of the Strouhal Number.

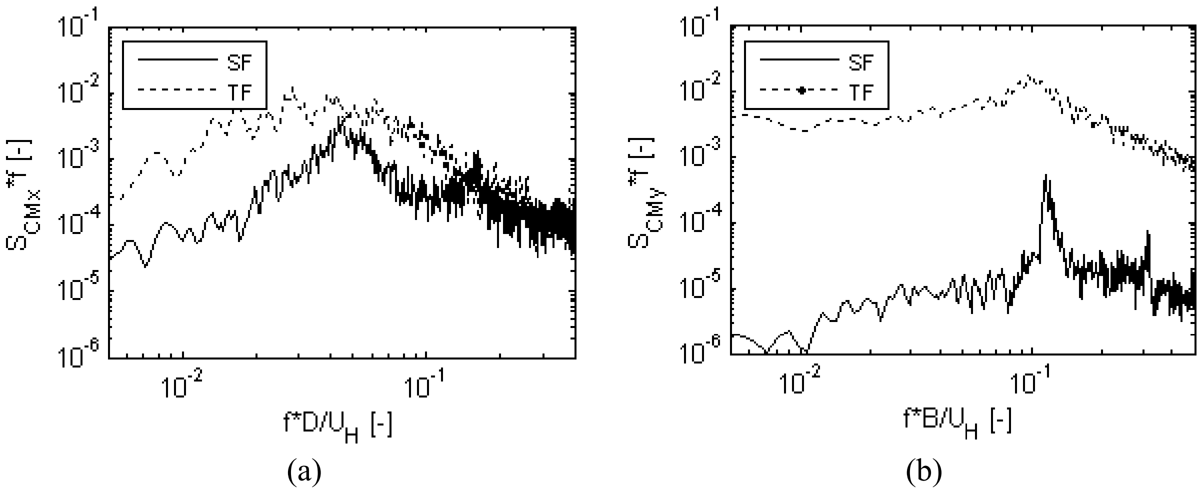


Fig. 4 Normalized power spectral density of the across wind base moment. (a) exposure 0deg, CMx and (b) exposure 90deg, CMy

3.2. Aeroelastic response

We want to focus our attention on the cross-wind aeroelastic response for the wind exposure 0 deg, wind perpendicular to the short building side. In this case the building could be sensitive both to vortex induced oscillation, and also to galloping instability (Dyrbye, 1999). These two phenomena are typical problems related to high rise buildings and chimneys (Steckely, 1989).

The galloping instability is caused by a negative aerodynamic damping and it is related to the derivative of the lift force coefficient. Figure 5b shows the building lift force coefficient: it is possible to see that in smooth flow the derivative is negative while in turbulent flow it is positive (Zasso, 2007). The flow turbulence can strongly modify the rectangular section aerodynamic properties (Larose, 2006). The model aeroelastic response is showed in Figure 5a: smooth flow data at the lower damping level (h=0.5%) present a vortex shedding response with the lock-in phenomenon at a reduced velocity of about 6.3 that is related to the second Strouhal number identified in the previous section. Then, increasing the wind velocity the building response increases, with an important growth at reduced velocities higher than 20 that is indicative of a possible galloping instability. On the contrary, the amplification in correspondece of the first identified Strouhal number, expected at the critical velocity of 22.2, is not visible. Increasing the structural damping (h=1%), the vortex shedding response disappear: the higher Scruton number of the building is sufficient to avoid vortex induced oscillations. At higher wind velocity it is still appreciable a growth in the response that is related to galloping excitation: the phenomenon happens at higher wind velocities since the structural damping is higher. In atmospheric boundary layer incoming flow (turbulent flow) the response is higher than in smooth flow tests at the same reduced velocity: this is related to the buffeting response that increases as the turbulence increases. Unfortunately turbulent flow data available cover only a smaller range of reduced velocities so that it is not possible to investigate the behavior in the high reduced velocity region.

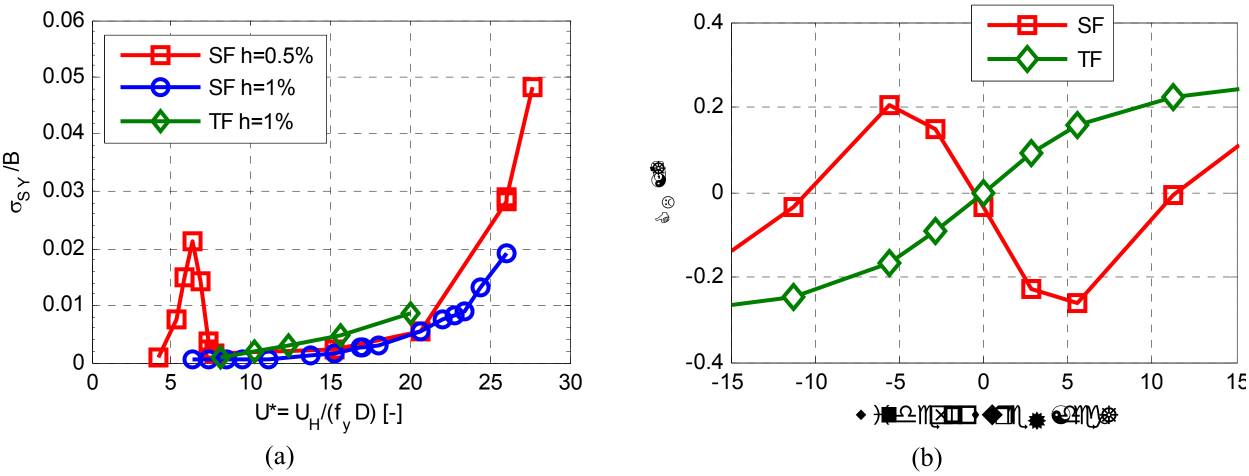


Fig. 5 (a) across wind response for the wind exposure 0 deg. (b) lift coefficient in smooth and turbulent flow

The dynamic response of the aeroelastic model has been simulated also by means of a numerical code based on modal approach which starts from the modal properties of the tower and from the pressures experimentally measured in the wind tunnel (Rosa et al., 2008). The modal approach allows to evaluate, known the modal information (frequencies, modal masses and modal shapes), the response of the tower caused by the turbulent wind. The analysis is carried out, in the time domain, by step by step numerical integration of the motion equations of the tower, known the pressure measurements in correspondence of the pressure taps.

Fig. 6 shows, for the same exposure of Fig. 5, the across wind response of the building in terms of comparison between numerical simulation (blu line) and experimental measurements (red line) for a structural damping of 1% in smooth flow. It is possible to see that, in the numerical response, the amplification associated to the first Strouhal number, highlighted in the power spectral density of the wind force, is visible in correspondence of the critical velocity of 22.2 while in the experimental response only the galopping instability is visible. This is due to the fact that the numerical model show the response to the vortex induced excitation that is identified in the force measured on the rigid model. On the contrary the aeroelastic model highlights the negative aerodynamic damping effects related to the negative lift derivative. The interaction

between galloping and vortex shedding can justify this behavior as reported in Steckley (1989).
The analysis in the time domain is shown in Fig.7a where the peak factor (Dyrbye, 1999; Steckley, 1989) of the dynamic response of the aeroelastic model is shown. This parameter is equal to about 3.5 when the response is due only to buffetting (random response) while it go down to 1.4 when the response is sincronised with the excitation due to vortex shedding or galopping (sinusoidal response). Only the peak factor measured in smooth flow conditions with the lower value of structural damping presents a drop in correspondence of the critical velocity equal to about 6.3 due to the vortex shedding phenomenon. On the contrary, the reduction of the peak factor increasing the velocity associated to the galopping is shown in both the damping levels of smooth flow tests.

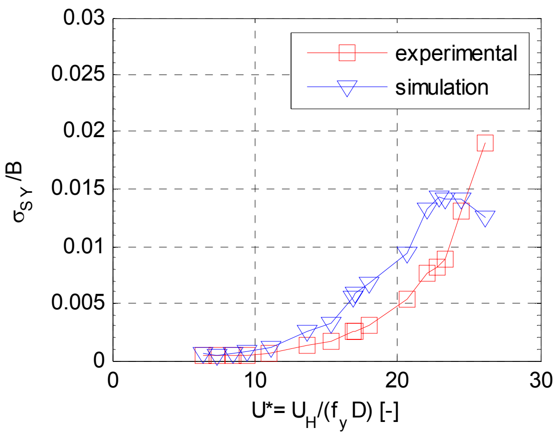


Fig. 6 comparison between the aeroelastic model response and the numerical simulations. Wind exposure 0deg, smooth flow condition and structural damping 1%.

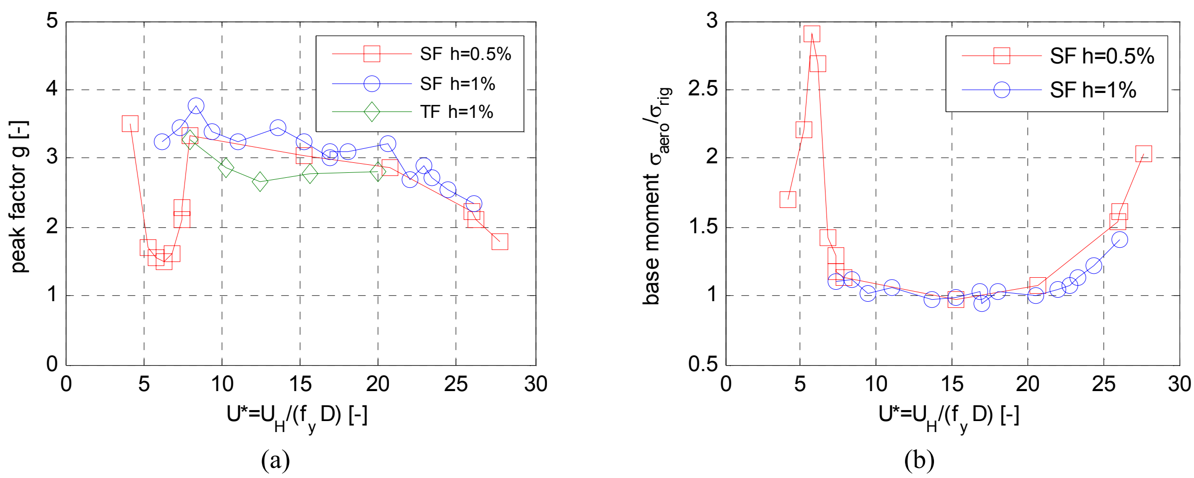


Fig. 7 Exposure 0 deg, across wind direction: (a) peak factor of the aeroelastic model response (b) standard deviation of the across wind base moment, ratio between aeroelastic and rigid model tests (b).

Similar conclusions can be drawn also by the analysis of Fig. 7b and Fig. 8a where the standard deviation of respectively the across wind base moment and of the acceleration, in terms of ratio between aeroelastic and rigid model, are shown. The data presented in Fig.7b are all experimentally measured while in Fig. 8a the response of the rigid model has been evaluated by means of the numerical model.
It is possible to see that these ratios reach values significantly higher than one for critical velocity equal to 6.3, in case of lower structural damping, due to the vortex shedding phenomenon, and for U* higher than 20, with both the considered dampings, due to the galopping instability.
Moreover, from Fig. 8a we can see that, for velocities ranged between 7 to 20, where the response is associated only to the buffeting, the aeroelastic model shows a damping effect with respect to the rigid model (ratio lower than one).
In conclusion, the total damping of the aeroelastic model is due to the sum of the structural damping (equal to that of rigid model) and of the 'equivalent aeroelastic damping' which is associated to the interaction tower-wind, when the tower is moving.
As a consequence, from Fig.8a it is possible to draw the following conclusions:

- in the intermediate region of velocity (buffeting), where the ratio between the response of the aeroelastic model and rigid model is lower than one, the 'equivalent aeroelastic damping' is positive, because the response of aeroelastic model is more damped with respect to that of rigid mode;
- in correspondence of the vortex shedding velocity and of the galopping instability, the 'equivalent aeroelastic damping' is negative, with an amplification of the response of the aeroelastic model with respect to the rigid one.

Similar behavior has been found also by other authors (Marukawa, 1996; Quan, 2005; Steckley, 1989).
Finally, the estimated equivalent aerodynamic damping is shown in Fig. 8b: its trend is in agreement with the conclusions drawn by Fig.8a also if some values, especially in the intermediate region, are clearly too high.

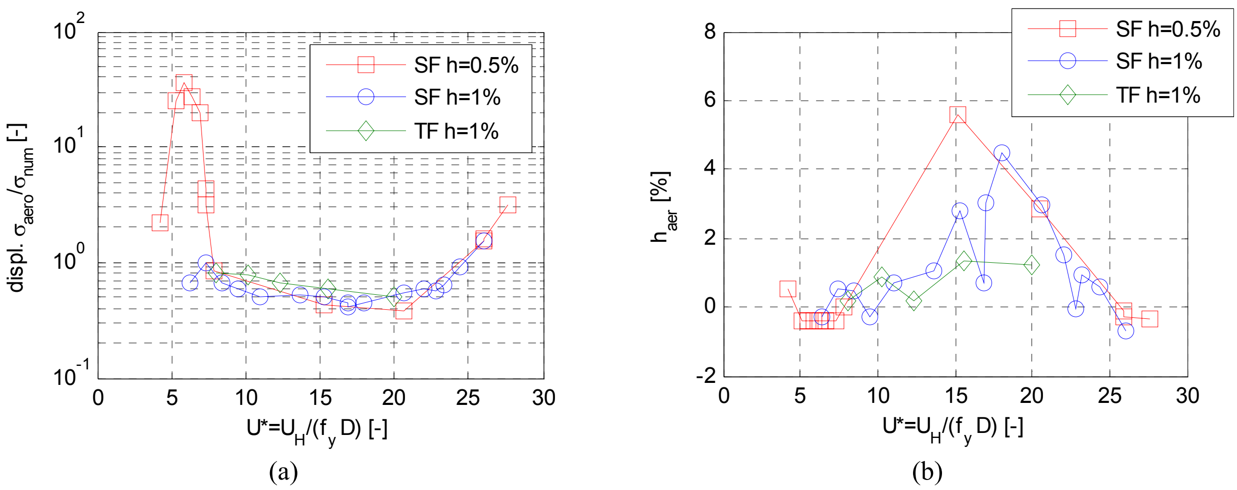


Fig. 8 Exposure 0 deg, across wind direction: (a) ratio between the standard deviation of the aeroelastic model response and numerical simulation results (b) aerodynamic damping in across wind direction.

The aerodynamic damping has been evaluated by means of the random decrement technique method (Ibrahim, 1977).
Unfortunately, probably due to the short length of the experimental time history, the estimation of the aerodynamic damping parameter is not completely satisfactory an reliable (in particular for the higher values of the positive aerodynamic damping). Nevertheless the decreasing trend is in agreement with the literature data. Finally it is to point out that the random decrement technique is not well suited for the analysis of the lock-in condition, since the vortex shedding excitation is not a random forcing.
In the next future, the application of other techniques for the evaluation of the aerodynamic damping will allow to improve also the quantitative estimation of this parameter.

CONCLUSION

The paper investigates the wind response of a high-rise building where there is vortex shedding excitation and galopping instability and so possible motion-dependent effects. Wind force measurements are carried out on both non-moving and moving model, being the latter inclusive of aeroelastic effects. Turbulent and smooth flow conditions are investigated to highlight the effects of the turbulence intensity. Than numerical simulations are performed using a modal approach to predict the dynamic behavior of the model using the pressures measured on the non-moving model.
From the analysis of the wind force in terms of power spectral density of the across wind overturning moment it is found that, when the wind is perpendicular to the short side of the tower (exposure 0deg), in smooth incoming flow, two peaks due to the vortex shedding are present: the first characterised by a Strouhal Number equal to 0.045; the second, at a reduced frequency of about 0.16, which corresponds to a lower critical velocity, equal to about 6.3.
From the analysis of the dynamic response of the numerical simulations and the aeroelastic model, it has been shown that the amplification in the response due to the second peak is appreciable only at the lower structural damping: this behavior is probably due to the too low energy introduced by the pressure field at this velocity. On the contrary, the amplification in correspondece of the first identified Strouhal number, expected at the critical velocity of 22.2, is not visible on the aeroelastic model. Increasing the wind velocity, the building response increases, with an important growth at reduced velocities higher than 20 that is indicative of a possible galloping instability. This instability is shown with both the structural damping analysed and both in smooth and turbulent flow conditions. In the intermediate range of velocities, where the response is associated only to the buffeting, the aeroelastic model shows a damping effect with respect to the rigid model.
Finally, the estimation of the equivalent aerodynamic damping has been performed: the trend found is in qualitative agreement with the dynamic behaviour measured for the moving model but the values estimated for this parameter, especially in the intermediate zone, are cleary not correct.
In the next steps of the work, the application of other tecniques for the evaluation of the aerodynamic damping will allow to improve also the quantitative estimation of this parameter.

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