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Research Paper

Design and analysis of the response of elastically supported wind-break panels of two different permeabilities under wind load

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The design and response of elastically supported short-length windbreak panels of different permeabilities under wind load is presented. The response of the panels was investigated through full-scale experiments and numerical simulation analysis. Two cladding materials were used: an impermeable film and a permeable net (62% porosity ratio). For the field experiments the elastic support of the panel was achieved by using extension springs which allowed it to pivot in response to wind loading through a hinge support at its base. The wind pressures developed on the panel for various equilibrium positions reached under different wind velocities were measured. The elastic support response resulted in a significant reduction of the wind pressures and the stress resultants on the windbreak for both cladding materials. A combined model coupling two-dimensional computational fluid dynamic simulation and non-linear structural analysis was used to analyse the behaviour of the elastically supported panel when interacting with the wind. The numerical results for the elastic support response under wind load, and the developed wind pressures, were found to agree with the full-scale experiments for both cladding cases. For the permeable cladding case, the wake flow of the elastically supported panel was shown to be free of large scale turbulent eddies when analysed by numerical simulations. The wake airflow for the impermeable panel case was found to be complex and extensive investigation is required.

1. Introduction

Vertical panels are widely used for protection against the wind in various applications such as pedestrian comfort, noise barriers, etc. An extensive overview of the aerodynamic behaviour of vertical panels and walls is presented in Giannoulis, Stathopoulos, Briassoulis, and Mistriotis (2012). Windbreaks are also frequently used in agricultural applications where they are easy to install, of low cost and in most cases very efficient (Castellano et al., 2008). They are used for crop protection and for the control of the microclimate by reducing wind velocity in the protected area. Windbreaks can be both permeable and impermeable depending on the application. The required permeability can be achieved by using permeable cladding materials such as plastic nets. The

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Nomenclature

Latin characters

A	sum of the projected area of the solid members of the cladding sample (i.e. the fibres of the nets), m^2
A_b	area of the panel supported by a single typical beam in the two dimensional model, m^2
A_c	total area of cladding sample, m^2
b	the ratio of wind speeds V and V_{10}
F	spring force, N
F_w	spring force, N
h	the panel height, m
h_{ref}	reference height of the panel defined based on Eurocode 1-1-4 CEN, 2005, m
i	the step of the iterative process
k	spring constant, N m^{-1}
l	distance between the springs connection to the panel frame and the hinge at the base of the corresponding beam. Also the distance between the foundation of the steel cable connecting the springs to the ground and the base of the panel, m.
$N(\theta)$	axial force, N
p	porosity ratio, %
P_{net}	average net wind pressure developed on the panel, Pa
$P_{windward}$	average wind pressure developed on the windward face of the panel, Pa
$P_{leeward}$	average wind pressure developed on the leeward face of the panel, Pa
V	windspeed at the panel reference height, m s^{-1}
V_{10}	reference wind speed measured at a level of 10 m above ground, far upstream (i.e. undisturbed flow), m s^{-1}
x	distance between the foundation of the steel cables connecting the springs to the ground and the springs connection to the panel frame, m

Greek characters

Δx	extension of the spring, m
θ	inclination angle of the panel (equal to zero at a vertical to the ground position), degrees
θ_{eq}	inclination angle of the panel at equilibrium position, degrees
ρ	density of air, kg m^{-3}

Abbreviations

CFD	computational fluid dynamics
RANS	Reynolds averaged Navier Stokes
URANS	unsteady Reynolds averaged Navier Stokes

continuously expanding use of permeable vertical panels against wind-induced forces is a proof of the significance of this type of structures (Castellano et al., 2008).

Agricultural windbreaks have been extensively investigated. Most studies concern the distribution of mean pressures or peak pressures along the windbreak (Letchford & Robertson, 1999; Robertson, Hoxey, Short, Ferguson, & Blackmore, 1998; Robertson, Hoxey, Short, Ferguson, & Osmond, 1996). Other works investigate the variation of pressure distribution along the windbreak when its geometrical characteristics change (Letchford & Holmes, 1994; Robertson, Hoxey, Short, Ferguson, & Blackmore, 1997). There are several research works on permeable windbreaks (Bradley & Mulhearn, 1983; Lee & Kim, 1999; Packwood, 2000; Ranga Raju, Garde, Singh, & Singh, 1988) focusing on their ability to suppress the development of turbulence phenomena due to their porosity.

Computational fluid dynamics (CFD) simulations have been successfully used to analyse the airflow and the wind forces in permeable and impermeable windbreaks (Robertson, Hoxey, & Richards, 1995; Robertson, Hoxey, Richards, & Ferguson, 1997). These studies investigated rigid wooden structures used as fences. Recently, permeable panels covered by a permeable membrane made from plastic nets have also been studied by both numerical and experimental methods (Briassoulis, Mistriotis, & Giannoulis, 2010; Giannoulis, Mistriotis, & Briassoulis, 2010). These studies showed that CFD simulations can be a reliable and inexpensive analytical and design tool for investigating the aerodynamic behaviour of permeable panels. Both numerical and experimental results have indicated that the use of plastic nets as a covering material of windbreaks suppresses the development of vortices at the leeward side of the panel and reduces the wind speed to make it more uniform. Moreover, the designer has the flexibility to adjust the structural design parameters of the supporting frame to the required shielding effect of the windbreak by selecting a net with the optimal aerodynamic resistance. In this way, lighter structures can be developed if lower levels of wind protection are satisfactory.

Flexible structures are not unusual in both urban and rural environments. They are constructed of light semi-rigid frames made of steel, polymer fibres, natural materials or other flexible materials. These frames are usually covered by a flexible membrane. The elastic behaviour of the flexible structures results into variable shapes (i.e. elastic deformations) due to the influence of external forces, such as wind. Since variable geometrical characteristics due to elastic deformations are linked to the aerodynamic behaviour of the flexible structure, the wind–structure interaction system becomes complex. In other words, as wind pressure elastically deforms the flexible structure, the corresponding wind pressure on the structure also changes. Analysis of this complex aerodynamic behaviour of flexible structures is interesting from the design point of view, since their wind induced elastic deformation results in reduced wind pressures. Therefore, flexibility alleviates wind forces on the structure, thus lighter designs can be developed.

CFD simulations can be used for modelling the air-structure coupling. Numerical studies concerning the dynamic response of various flexible bodies to the wind have been published. Structures such as shading constructions (Michalski et al., 2011), soft convertible car roofs (Knight, Lucey, & Shaw, 2010), membrane made liquid containers (Yuan, Puyong, & Xianlong, 2010), sails (Augier, Bot, Hauville, & Durand, 2012), have been investigated.