J. Wind Eng. Ind. Aerodyn. 137 (2015) 46–57

Contents lists available at ScienceDirect

Journal of Wind Engineering and Industrial Aerodynamics

journal homepage: www.elsevier.com/locate/jweia

Static loads to simulate dynamic effects of wind on hyperbolic paraboloid roofs with square plan

Fabio Rizzo [a,*], Vincenzo Sepe [b]

[a] CRIACIV, Inter-University Research Centre for Building Aerodynamics and Wind Engineering, Italy
[b] CRIACIV and Department of Engineering and Geology, University "G. D'Annunzio" of Chieti-Pescara, Italy

ARTICLE INFO

Article history:
Received 25 February 2014
Received in revised form
12 September 2014
Accepted 16 November 2014

Keywords:
Wind tunnel testing
Pressure coefficients
Hyperbolic paraboloid roofs
Equivalent static wind loads
Nonlinear dynamic analysis
Dynamic displacements field

ABSTRACT

The main international standards do not report any specific information (e.g. pressure coefficients) for wind-induced loads on tensile suspended roofs with hyperbolic paraboloid shape, that require therefore ad hoc wind tunnel tests or CFD analyses even in the preliminary design stage. This motivated a wide and parametric investigation aimed to explore the general trend of their aerodynamic behaviour, and experimental tests on in-scale models were performed in the CRIACIV boundary layer wind tunnel (see Rizzo, 2009; Rizzo et al., 2011, 2012), to measure pressure fields for several angles of attack of the incoming wind on different models of hyperbolic paraboloid roofs. On the base of experimental results and of finite element analyses for the sample case of square footprint, this paper explores the possibility of defining equivalent static pressure fields able to reproduce the envelope of dynamic displacements of the cables net.

1. Introduction

A typical structural solution to cover large spans consists of cables nets (Majowiecki 2004; Lewis 2004; Forster 1994). Roofs of this kind are currently used for sports arenas and indoor swimming pools, but could also be ideal for concert and conference spaces. This type of structure has in fact very high performance characteristics and, due to the low structural weight, they are particularly suited for buildings in seismic areas.

This research is motivated by the need to have reference predesign data for wind-induced loads on hyperbolic paraboloid roofs of this kind, while no parametric data about this type of geometric shape is found in national and international standards. On the other hand, the very complex and special configuration of these structures makes it impossible to use pressure coefficient data assigned in technical codes (ASCE, 1999; ASCE, 2005; Australian/New Zealand Standard 2002; Eurocode 1 CEN (Comité Européen de Normalization), 2005; Italian technical code NTC 2008; CNR-DT 207/2008 CNR (National Research Council of Italy), 2011) for flat, dome or inclined roofs, even for preliminary evaluation of the wind action. Such a deficiency is a source of difficulty for designers in the early design stage, when preliminary dimensions of structural elements have to be roughly assigned to compare alternative solutions (Elashkar and Novak, 1983; Shen and Yang, 1999). A research project on this subject has therefore been started since 2005; wind tunnel tests on hyperbolic paraboloid roofs have been performed using in-scale models of square, rectangular, circular and elliptical footprint shape (Rizzo et al., 2011; Rizzo et al., 2012; Rizzo, 2014). Parametric and simplified maps of extreme values (maximum and minimum) of wind-induced loads for hyperbolic paraboloid roofs, according to code of practice formulation, were derived in Rizzo et al. (2012) on the basis of pressure coefficients (c_p) maps for several wind-tunnel tests.

Although this approach allows to reproduce the peak expected local loads (maximum, i.e. pressure, or minimum, i.e. suction) for a given wind speed, that is useful for safety evaluations of single elements of the suspended structure, it cannot reproduce the global displacements and stresses in the main structure (i.e. cables net), that has instead to be evaluated by time-step analyses of FEM models.

Based on the available experimental results, this paper explores the possibility of defining equivalent static pressure fields able to reproduce the envelope of dynamic displacements of the suspended surface, for the sample case of hyperbolic paraboloid roofs with square footprint. A comparison is performed between structural response obtained by static and dynamic analyses in the time-domain, with reference to vertical displacements of the cables net.

In particular, equivalent pressure coefficients c_p^{eq} are evaluated to reproduce the envelope of dynamical vertical displacements of the cable net by means of conventional static analyses; to this respect, c_p^{eq} are expressed through correction factors ψ applied to the extreme experimental pressure coefficients c_p^{en} reported in (Rizzo et al., 2012),

---

[*] Corresponding author.
E-mail addresses: fabiorizzo79@libero.it (F. Rizzo), v.sepe@unich.it (V. Sepe).

http://dx.doi.org/10.1016/j.jweia.2014.11.012
0167-6105/© 2014 Elsevier Ltd. All rights reserved.

List of symbols

α, β	Rayleigh coefficients for modal damping
w	vertical displacement
w_d^t	vertical displacement downwards: peak value of dynamic analysis in the time-domain
w_u^t	vertical displacement upwards: peak value of dynamic analysis in the time-domain
w_d^{en}	vertical displacement downwards: static analysis with envelope pressure coefficients c_p^{en}
w_u^{en}	vertical displacement upwards: static analysis with envelope pressure coefficients c_p^{en}
w_d^{eq}	vertical displacement downwards: static analysis with equivalent pressure coefficients c_p^{eq}
w_u^{eq}	vertical displacement upwards: static analysis with equivalent pressure coefficients c_p^{eq}
c_p	pressure coefficient
c_p^{en}	envelope of experimental pressure coefficients (Rizzo et al. 2012)
c_p^{eq}	equivalent pressure coefficients to reproduce dynamic effects by means of conventional static analysis
ψ	correction factors applied to c_p^{en} in order to obtain equivalent pressure coefficients c_p^{eq} (i.e. $c_p^{eq} = \psi c_p^{en}$)
H	maximum height of the roof on the ground
h	minimum height of the roof on the ground
L	length of the plan side
f_1	sag of the load bearing cable
f_2	sag of the stabilising cable
i	distance between two cables (equal for load bearing and stabilizing cables)
$A_{c,s}$	stabilizing cable area
$A_{c,b}$	load bearing cable area
$\varepsilon_{c,s}$	stabilizing cable pre-stress deformation
$\varepsilon_{c,b}$	load bearing cable pre-stress deformation
M	distributed mass: dead, permanent and variable loads
$p(t)$	time-dependent pressure on the surface
p_0	static (i.e. atmospheric) pressure of undisturbed flow
q_m	mean value of the undisturbed flow kinetic pressure
V_m	mean value of undisturbed flow speed
V_{10}	average wind speed at 10 m height (real scale)
ρ	air density
λ_l	length scale
λ_v	speed scale
λ_t	time scale

and the variation of ψ is explored for two curvatures of the square roof that define a range including the more frequent shapes used in practice, for several angle of incidence of wind.

2. Wind tunnel tests on hyperbolic paraboloid roofs

2.1. Models characteristics

In order to generate a sufficiently representative sample of possible geometric shape combinations, in (Rizzo et al., 2011) a total of four shapes were considered, i.e. square, rectangular, circular and elliptical, with a total of 16 different geometrical configurations.

In this paper, only the experimental results for two different models of square plan roof (Fig. 1 and Table 1) are taken into account; namely, two different curvatures of the square roof are considered that define a range including the more frequent shapes used in practice; they correspond to the p.1 and p.7 models of the full experimental campaign reported in (Rizzo et al., 2011 and Rizzo 2012). The models dimensions are defined in Fig. 1 and reported in Tables 1; f_1 and f_2 denote the sag of the load bearing cable (upward curvature) and of the stabilising cable (downward curvature), respectively, H and h are the maximum and minimum height of the roof on the ground, respectively, L is the dimension of the plan sides, M is the distributed mass.

Each model was equipped with 183 pressure taps, distributed on the roof and on the sides and, according to the expected wind-pressure field variations, a higher "density" of pressure taps was used along the edges and the two centreline sections (longitudinal and transversal) of the roof; each pressure tap was linked to the pressure transducers with a pneumatic connection made of Teflon pipes with 1.3 mm internal diameters. Pneumatic connections have been optimized in order to get an as flat as possible frequency response in the range of interest (0–100 Hz); this target has been reached by inserting a restrictor (damper) along the tube at a certain distance from the transducers in order to minimize the frequency/phase distortions. The pressure tubes consists of two parts (33.5 cm plus 11.5 cm) connected by a damper, with another damper connecting the tube to the transducer. Due to the pneumatic optimization of the tubing system, neither digital nor numerical corrections have been utilized.

2.2. Wind-tunnel setup

As it is well known (Simiu and Scanlan, 1986) an effective evaluation of aerodynamic phenomena requires that flow characteristics be correctly simulated during wind tunnel tests. In particular, a special attention must be devoted to scaling of the Reynolds' number, whose effects are particularly significant in case of bluff bodies with curved surfaces, as the roof here considered. However, it is also well known that a strict matching of the Reynolds' number can never be obtained in wind tunnel tests with the scale factors usually introduced for the models; simulation with a model in scale 1:100 would require, for example, wind tunnel speeds one hundred times greater than those recorded in reality.

However, as the pressure distribution on the roofs considered in this paper is mainly due to the strong separation occurring at the leading edges, no particular Reynolds' effect has to be expected, so that no superficial roughness has been added on the model. On the other hand, the tests performed on circular roofs (Rizzo et al., 2011), more sensitive to the surface roughness, showed a relatively small c_p variation even in case of extreme roughness variation (smooth surface vs thick sand paper).

The aerodynamic tests (Rizzo, 2009, 2014) were carried out at CRIACIV's (Inter-University Research Center for Building Aerodynamics and Wind Engineering) wind tunnel in Prato (Fig. 2). This is an open circuit tunnel with suction propulsion and closed test section, equipped with an axial fan with adjustable pitch blades, which allows the flow speed to be continuously varied between 0 and 35 m/s; the main parts of the device are described in Fig. 2. A turbulent boundary layer is generated by means of roughness panels placed along the longitudinal surface of the wind tunnel. In the sample cases described here an average roughness was chosen (corresponding to a suburban context), obtained by adding $200 \times 80\ \text{cm}^2$ wooden panels equipped with wooden cubes. Grids and spires, set vertically, and horizontal barriers have also been introduced in the intake section of the tunnel to raise the boundary layer. With a total wind tunnel length of 22.09 m, the upwind distance between the model and the intake is equal to 8.8 m, about