Engineering Structures 139 (2017) 153–169

Contents lists available at ScienceDirect

Engineering Structures

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

Design pressure coefficients for circular and elliptical plan structures with hyperbolic paraboloid roof

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ARTICLE INFO

Article history:
Received 24 July 2016
Revised 6 December 2016
Accepted 13 February 2017

Keywords:
Tensile structures
Hyperbolic paraboloid roofs
Wind tunnel testing
Pressure coefficients
Codes of practice

ABSTRACT

Hyperbolic paraboloid shapes are often used for tensile roofing systems, as they allow covering large spans with a very low self weight. In addition, they can be used in combination with a variety of plan shapes. The aerodynamics, and thus the wind loading of buildings provided with an hyperbolic paraboloid roof is different from that of the same building provided with a different roof shape; previous studies have made this aspect evident for square and rectangular plan buildings, and the differences prove to be even larger in the case of circular and elliptical plans. This paper is focused on the latter two geometries. In particular, two different curvatures of the roof and two different heights of the buildings were tested in the wind tunnel. Envelopes of the experimental pressure coefficients have been obtained, giving rise to simplified load maps for use in design and possible Code implementation. Pressure coefficients on the lateral surfaces have also been measured, and are compared with reference values available for the same plan shape, but different roof geometry.

1. Introduction

The need for large covered spaces is often satisfied using tensile structures, whose flexibility and lightness are the main reasons of their success.

Different types of tensile roofing systems exist, having different types of aerodynamic behaviour and therefore experiencing different wind loads. For example, Kawai and Yoshie [23], Letchford and Killen [25] and Letchford et al. [26] considered equivalent static wind loads and the wind-induced response of cantilevered tensile roofs. Kimoto and Kawamura [19], Kimoto and Kawamura [20] investigated the aerodynamics of hanging tensile roofs, whereas Kawakita et al. [22] presented the results of wind tunnel tests on an aeroelastic model of a suspended cable roof. Zhang and Tamura [43] and Li et al. [29] report results of wind tunnel tests on cable domes of the Geiger Type. Killen and Letchford [24] performed a parametric study of the wind loads on grandstand roofs. Finally, the air supported roofs have recently received attention in several Countries, e.g. Japan, Canada and Switzerland, and in Kassem and Novak [21] results concerning the wind-Induced response of hemispherical air-supported structures can be found.

Recently, tensile roofs have become an architectural feature, not only for temporary structures (e.g. Expo 2015 in Milan or 2014 FIFA World Championship in Brazil), but also for permanent buildings, as an example Zaha Hadid's Serpentine Gallery in Kensington Gardens, London, 2003.

On the other hand it is noticed that in Design Codes there is a weak coverage of tensile structures, from both the structural design and the wind loading points of view.

As to the general problem of the wind loading of non-conventional building geometries, examples can be found in the literature of studies carried out on particular structures, as part of their design process; yet a generalization of the results, allowing application to similar structures is difficult to find. As an example, Irwin and Wardlaw [18] present the results of the wind tunnel tests carried out on the retractable fabric roof of the 1980 Olympic Stadium in Montreal. Sykes [36] presents results regarding the wind loading of two temporary tensile structures designed for the 1992 Seville Expo. In Biagini et al. [5] a study of wind loads on different stadium roof geometries is presented. More generally, in Elashkar and Novak [14] similarity requirements for static and dynamic wind tunnel testing of cable roofs are discussed, and in Daw and Davenport [11] the aeroelastic behaviour of semi-circular roofs is studied, and aerodynamic damping and stiffness are quantified. In William and Knudson [38] analysis procedures

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http://dx.doi.org/10.1016/j.engstruct.2017.02.035
0141-0296/

of flexible structures are reviewed, for both static and dynamic analyses.

Purpose of this paper is to attempt a generalization of the results obtained from wind tunnel pressure measurements on a number of hyperbolic paraboloid roofs, and on the lateral surface of circular and elliptical plan buildings.

An experimental campaign was carried out in the CRIACIV boundary layer wind tunnel, in which pressure coefficients on the roofs and lateral surfaces of a variety of buildings with hyperbolic paraboloid roof were measured. The models had different plan shapes (square, rectangular, circular and elliptical), different building height, and different roof curvatures. In Rizzo et al. [31] and Rizzo and Sepe [34] preliminary results concerning the pressure coefficients on square, rectangular and circular plan roofs are presented. In Rizzo et al. [32], limited to the square and rectangular plans, pressure coefficient maps are presented for design application and possible Code implementation. For elliptical plan buildings, preliminary results are presented in Rizzo [33], regarding both the roof and the lateral surface. In the present paper, following a similar procedure to that of Rizzo et al. [32], a characterization of pressure coefficients of hyperbolic paraboloid roofs and of the lateral surface of circular and elliptical plan building, is proposed.

As to Codes of Practice, no provision is available regarding buildings with hyperbolic paraboloid roof. On the other hand, pressure coefficients are available for circular buildings with flat roof or dome roof. ISO 4354 [15] contains provisions only for the alongwind force coefficient of circular buildings, and no information is given regarding the pressure distribution on the lateral surface and on the roof. ASCE [3] gives pressure coefficients for circular dome roofs. The Commentary to National Building Code of Canada [6] gives provisions for the alongwind force coefficient and the pressure coefficient distribution on the lateral surface of circular plan buildings, together with the pressure coefficient distribution on circular dome roofs and on low-curvature circular tank roofs.

AIJ [1] gives pressure coefficients for circular dome roofs and alongwind force coefficients for circular buildings; SIA 261 [37] gives pressure coefficients for ground based circular domes and pressure coefficients for circular cylinders. AS/NZS [4] gives pressure coefficients for the lateral surfaces and for the dome roof of circular bins, silos and tanks. IS 875 Part 3 [17] gives pressure coefficients for circular cylinders an d force coefficients for clad buildings of uniform plan, in particular circular and elliptical. EN-1991 [7] gives pressure coefficients for the lateral surfaces and for dome roofs of circular buildings, and the same data are also reported in CNR-DT 207/2008.

In general, not much information is available concerning pressure coefficients of buildings with hyperbolic paraboloid roof. Forster [16] reports an historical survey on cable and membrane roofs. Lewis [27] and Majowiecki [30] give general information concerning tension structures. More specifically, aerodynamic data form wind tunnel tests on hyperbolic paraboloids are given by Shen and Yang [35], where the purpose is to describe an example of wind-resistant design of hyperbolic paraboloid cable net structures. Yang and Liu [41] provide a general discussion on the aerodynamic stability of membranes. Finally, insights on

Table 1
Model geometries.

Model	D_1 cm	D_2 cm	f_1 cm	f_2 cm	H cm	f_1/D_1	f_2/D_2	H/D_1	H/D_2	
p9	80	80	4.44	8.89	13.33	0.06	0.11	0.17	0.17	Circular
p10	80	80	4.44	8.89	26.66	0.06	0.11	0.33	0.33	
p11	80	80	2.67	5.33	13.33	0.03	0.07	0.17	0.17	
p12	80	80	2.67	5.33	26.66	0.03	0.07	0.33	0.33	
p14	40	80	2.67	5.33	13.33	0.07	0.07	0.33	0.17	Elliptical
p15	40	80	2.67	5.33	26.66	0.07	0.07	0.67	0.33	
p16	40	80	4.44	8.89	13.33	0.11	0.11	0.33	0.17	
p17	40	80	4.44	8.89	26.66	0.11	0.11	0.67	0.33	

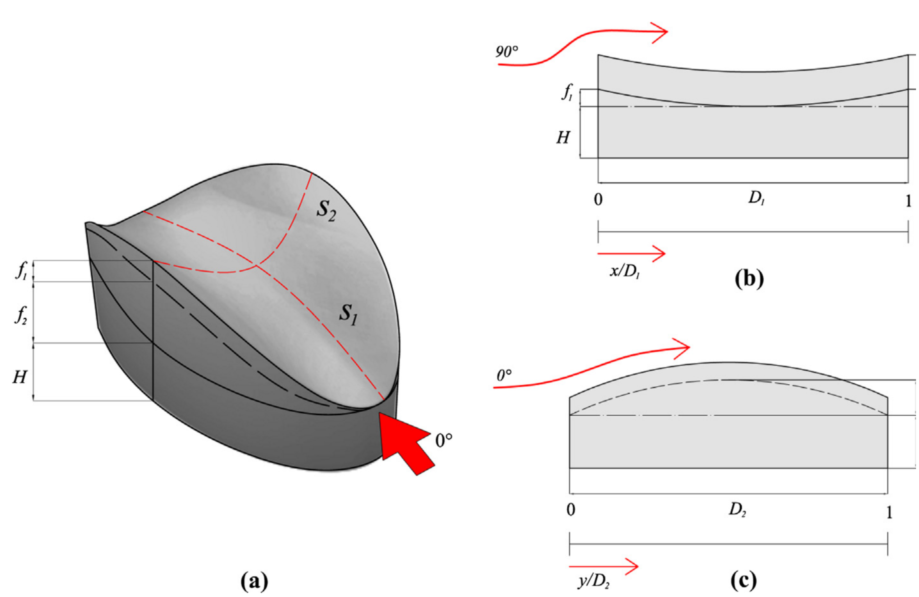

Fig. 1. Models geometry: 3-D view (a), x-z plane view (i.e. 0°) (b), y-z plane view (i.e. 90°) (c).