Engineering Structures 83 (2015) 17–29

Contents lists available at ScienceDirect

Engineering Structures

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

Wind force coefficients on hexagonal free form shell

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ARTICLE INFO

Article history:
Received 4 November 2013
Revised 1 July 2014
Accepted 20 October 2014
Available online 21 November 2014

Keywords:
Wind pressure on shells
Wind force coefficients
Free form shells
Curved roof structures
Non-conventional structures

ABSTRACT

This paper presents the wind force coefficients on non-conventional building of the free form shell structure generated by the simulation of a membrane initially in the horizontal plane surface with hexagonal plant, under the action of self-weight and supported on six corners. Initially is presented the computational model for free form shells generation, the model generated and the correspondent construction of the hexagonal free form shell scale model in fiberglass by a CAD/CAM system. Following is presented the wind tunnel of atmospheric boundary layer and the scale model used to perform the tests to obtain the wind force coefficients. Finally are presented the numerical analysis of the scale model of free form shell structure by the computational fluid dynamics software ANSYS-CFX. The wind force coefficients for the free form shell obtained by the wind tunnel tests and ANSYS-CFX software are compared. The results demonstrates the possibilities to apply the computational fluid dynamic analysis for future applications to analyze other free form shells in order to obtain wind force coefficients.

1. Introduction

For shell structures, the geometric shapes are important to obtaining the most efficient structural behaviors. The stress state that occurs in a shell depends directly on its three-dimensional shape, active loads and boundary conditions. The optimal stress state for these structures is the pure compression according to the membrane theory [1].

Scale physical models to design free form shells were widely used by Heinz Isler since 1954 [2–8]. He developed models to design several free form concrete shells derived from experimental membrane scale model exposed to a variety of forces and by laboratory experimental techniques. Those shapes were obtained essentially from hanging free membrane method, inflatable membranes under pressure and by extrusion of viscous material. Isler designed hundreds of free form concrete shells with several horizontal projections in the last half century.

Afterwards became possible to simulate physical processes with the advances of computational models for the generation and optimization of free form shells. Advances to generate shapes of shell structures are very important because these methods have provided the possibility of many innovations for new projects. Several researchers have contributed to the advancement of computational models as can be seen, for example, in Smith and Wilson [9], Ramm and Mehlhorn [10], Bletzinger and Ramm [11], Maurin and Motro [12], Bletzinger et al. [13], and Block and Ochsendorf [14].

A computational model to generating free form shells for roof structures was developed by the author [15] inspired by the physical laws of nature, in particular by the methods of Heinz Isler for designing shell structures using physical models in the laboratory. The applications of this computational model to generate free form shell structures and the possibilities for applications to project conceptions in the areas of Architecture and Civil Engineering [16].

Several researchers have been contributed for the advance in the experimental investigations on structures under the action of wind, including structural roofs most commonly used. Results of these researches can be seen, for example, in Blessmann [17], Newman et al. [18], Taylor [19], Melbourne [20], Cheng and Fu [21] and Melbourne and Cheung [22–24], and have been included in most of the regulations and codes to wind actions used for design of structures in many countries.

However, it is difficult to analyze the behavior of structures such as roofs of unconventional and more complex shapes when subjected to wind loads. Therefore, the distribution of wind pressures on these structures can be determined by experiments of scale models in a wind tunnel and, nowadays, by means of computational simulations. Free form shell structures for roofing are related to better structural functionality and can have aerodynamic behavior more efficient and effective than other structures.

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http://dx.doi.org/10.1016/j.engstruct.2014.10.038
0141-0296/

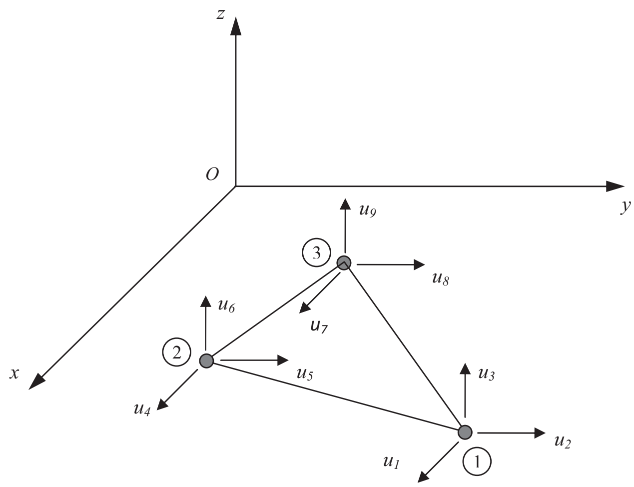

Fig. 1. Modified finite element CST (Constant Strain Triangle).

Table 1
Constants c_{ij} ($i = 1, 2, 3$; $j = 1, 2, 3$).

Constants c_{ij} for the expressions α_k, β_k and γ_k		
$c_{11} = (y_2 - y_3)/\delta$	$c_{12} = (y_3 - y_1)/\delta$	$c_{13} = (y_1 - y_2)/\delta$
$c_{21} = (x_3 - x_2)/\delta$	$c_{22} = (x_1 - x_3)/\delta$	$c_{23} = (x_2 - x_1)/\delta$
$c_{31} = (x_2\, y_3 - x_3\, y_2)/\delta$	$c_{32} = (x_3\, y_1 - x_1\, y_3)/\delta$	$c_{33} = (x_1\, y_2 - x_2\, y_1)/\delta$
$\delta = [(x_1\, y_2 + x_2\, y_3 + x_3\, y_1) - (x_1\, y_3 + x_2\, y_1 + x_3\, y_2)]$		

Researchers have been worked with wind actions on structures by using computational simulations and comparing the numerical results with the wind tunnel tests for scale models. As example, Meroney et al. [25] presented a numerical model of a spherical dome subjected to wind forces considering the aerodynamic parameters. The data were obtained for three different wind directions with different values of turbulence and Reynolds number. Afterward the results were compared with the experimental values obtained by Taylor [19], showing values with good approximation.

Gomes et al. [26] presented the paper with results for both the wind tunnel and numerical models for pressure distributions experiments on irregular-plan shapes. The same tests were carried out on a cube-shaped model as an experimental validation. The experimental data for the irregular-plan models showed different wall pressure distributions from those expected for single rectangular blocks. Furthermore, a computational fluid dynamics (CFD) code was used to illustrate some particular cases and to provide a better understanding of the flow patterns around these irregular-plan models and the pressure distributions induced on their faces. The computational results for pressure coefficients have also been compared with wind tunnel results for normal and oblique wind incidence.

Faghih and Bahadori [27] presented a paper where the aim of the study was to determine the air pressure distribution over domed roofs, employing a numerical method. A three-dimensional model and a laminar inlet air flow were considered. The κ–ε RNG method was employed for the turbulent flow simulation method. Simulation was run under three conditions of windows and a hole on top of the dome being open, or closed. The computational results were compared with those obtained in the experimental investigation of the same domed-roof model.

Tavakol and Yaghoubi [28] presented the numerical and experimental analysis considering the flow of air around a dome, varying the Reynolds number and considering several wind velocities. The results contributed to modeling and visualizing the vortex air and recirculation zones around the dome.

Alireza and Mohammad [29] presented a numerical modeling for a dome by using the ANSYS software to simulate the effect of wind action compared to uniformly applied loads and analyzing the results obtained from different trials.

Accurate determination of the pressure forces are the most difficult task when the geometry of the buildings are not directly covered by the most common geometrical shapes tabulated by the different codes or standards. Cornejo and Mato [30] presents a paper which focuses on study case of a complex building with unusual geometry. The article presents three different methods to obtain the force coefficients applying the simplified parameters tabulated in the standards, with a scale-model wind tunnel test, and with wind action computer modeling based on particle models.

Thus, a series of wind tunnel tests and computational simulations were carried out in order to obtain the wind force coefficients on hexagonal free form shell, considering both the laminar and turbulent flow, with measurements of wind force coefficients in both the internal and external points of this non-conventional building.

2. Computational model for free form shells generation

The method for shape generation developed by Vizotto [16] was used to obtain the hexagonal free form shell. A relatively simple method is presented to generating free form shells by means of mathematical programming combined with the finite element technique.

The computational model automatically simulates a flexible isotropic membrane, initially in the horizontal plane surface, with any shape and boundary conditions in order to generate shell structures in accordance with the structural membrane theory.

The hypothesis adopted for the material is a linear stress–strain relationship and the constitutive relationship is given by Eq. (1):

$$\sigma = D\varepsilon \tag{1}$$

with σ and ε vectors and D matrix for the plane state of stress given respectively by Eqs. (2)–(4):

$$\sigma^t = [\,\sigma_{xx} \quad \sigma_{yy} \quad \sigma_{xy}\,] \tag{2}$$

$$\varepsilon^t = [\,\varepsilon_{xx} \quad \varepsilon_{yy} \quad \varepsilon_{xy}\,] \tag{3}$$

$$D = \frac{E}{(1-\nu^2)}\begin{bmatrix} 1 & \nu & 0 \\ \nu & 1 & 0 \\ 0 & 0 & (1-\nu) \end{bmatrix} \tag{4}$$

with Young's modulus E and Poisson's ratio ν.

The finite element adopted was the CST (Constant Strain Triangle), in which the hypothesis of strain and the stress constant are considered. The finite element was modified to enable displacements orthogonal to its plane, resulting in an element with nine degrees of freedom, three displacements by nodal point at the vertices of the triangle.

The initial configuration of the element is represented in the xy plane of the tri-orthogonal system of reference adopted. After deformation, the element occupies a final equilibrium position in the $Oxyz$ system. The nodal variables are the displacements of translation u_k ($k = 1,\ldots,9$) in x, y, and z directions, as shown in Fig. 1.

The interpolating functions given by Eq. (5) with the coordinates x and y for the displacement field on the domain of the element are: