J. Wind Eng. Ind. Aerodyn. 155 (2016) 47–59

Contents lists available at ScienceDirect

Journal of Wind Engineering and Industrial Aerodynamics

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

Investigating a wind tunnel method for determining wind-induced loads on roofing tiles

Daniel J. Smith [a,b,*], Forrest J. Masters [a], Arindam G. Chowdhury [c]

[a] Department of Civil and Coastal Engineering, University of Florida, 365 Weil Hall, Gainesville, FL 32611, USA
[b] College of Science, Technology, and Engineering, Cyclone Testing Station, James Cook University, Townsville, QLD 4811, Australia
[c] Department of Civil and Environmental Engineering and International Hurricane Research Center, Florida International University, 10555 W. Flagler St. Miami, FL 33174, USA

ARTICLE INFO

Article history:
Received 28 April 2015
Received in revised form
16 May 2016
Accepted 16 May 2016

Keywords:
Roofing tiles
Roof damage
Florida Building Code
International Building Code
Residential buildings
Surface pressure measurements
Wind loading

ABSTRACT

Current design loads for roofing tile systems in the U.S. are determined based on a standardized wind tunnel testing method developed in the 1990s to examine wind-induced pressures on the upper and lower surfaces of the tile. The method neglects several key parameters that are well known to affect wind loading (e.g. wind angle, specimen shape, etc.). The research objective of this study is to investigate this method by [1] characterizing wind-induced surface pressure distributions on field tiles for varying wind angles of attack and [2] measuring load path intensity through mechanically fastened tile attachments. Surface pressure distributions were measured on three full-size, rapid prototyped roofing tile models with 256 pressure taps immersed in wind flows. The models are geometrically identical to low-, medium- and high-profile concrete roofing tiles that are widely used in high wind areas. Additionally, their real counterparts were instrumented with load cells to measure reaction forces at mechanical fasteners. The results highlight areas of the method that are lacking in specificity and shows that low-resolution pressure measurement may yield conservative parameters for low- and medium-profile tiles but is potentially not conservative for asymmetric (s-shaped) high-profile tiles.

1. Introduction

Annual hurricane-induced economic losses have increased steadily in the U.S. during the past 50 years, averaging $1.3 billion (in constant 2006 dollars) from 1949 to 1989, $10.1 billion from 1990 to 1995, and $35.8 billion from 2001 to 2006 (National Science Board, 2007). Wind related damage on the East and Gulf coasts of the U.S. alone averaged $5 billion in annual economic losses as of 1998 (Pielke and Landsea, 1998). Florida is a particularly strong contributor to annual losses, largely due to the high likelihood of hurricane landfall in the Southeast U.S. Insured losses related to roof cover damage (i.e. shingles, roofing tiles, metal) accounted for over 50% of insured losses in Florida during the 2004–2005 hurricane seasons (ARA, 2008). Although asphalt shingles are the most prevalent form of roof cover in Florida, roofing tile systems represent significant market share, particularly in the South Florida region due to their esthetic appeal, ventilating characteristics, and durability. As of 2011, tile roofing market share was 56%, 36%, and 24% for Broward, Palm Beach, and Lee Counties respectively (FPHLM, 2011). Insurance claim analysis post-2004 hurricane season in Florida suggested insured losses for tiled roofs were greater than asphalt shingles when wind speeds were greater than 54 m/s (120 mph). Replacement costs for roofing tiles are a key factor, exceeding those of asphalt shingles in some cases by 400% (ARA, 2008). Post-2004 hurricane damage assessments indicated that in several instances, tiles did not perform as predicted (i.e. failed at less than design level wind speeds) by the 2001 FBC and FRSA/TRI Concrete and Clay Tile Installation Manual (FEMA, 2005). In addition to cladding replacement costs, damage to any roof covering system during hurricane events increases likelihood of water ingress related damages, making roof cover loss a leading cause of building performance issues during hurricanes (FEMA, 2005).

Field tiles are those in the zone that generally make up the largest surface area of the roof (i.e. the "field" of the roof) and include all tiles not within edge/corner zones or along ridge, hip, and gable end lines. Several full-scale studies have examined wind loading on roofing field and ridge tiles (i.e. Robertson et al., 2007; Laboy-Rodriguez et al., 2013; Tecle et al., 2013a, 2013b; Li et al.,

* Corresponding author at: College of Science, Technology, and Engineering, Cyclone Testing Station, James Cook University, Townsville, QLD 4811, Australia. Tel.: +61 7 4781 5512.
E-mail addresses: daniel.smith8@jcu.edu.au (D.J. Smith), masters@ce.ufl.edu (F.J. Masters), chowhur@fiu.edu (A.G. Chowdhury).

http://dx.doi.org/10.1016/j.jweia.2016.05.006
0167-6105/

2014), but not directly examined the methodology employed by design standards.

Internationally, the majority of standards for wind resistance of roofing tiles systems were introduced or underwent significant development in the 1990s, including British Standard BS 5534 (BSI, 2015), Dutch Standard NEN 6707 (Netherlands Standardization Institute, 2011), European Standard EN 14437 (CEN, 2004), Australian Standard AS 2050 (Standards Australia, 2002), and the US-based standard SSTD-11 (SBCCI, 1999). The British and U.S. methods were both heavily influenced by research conducted in the UK in the late 1980s and early 1990s by Redland Technology. All of the standards are based on wind tunnel tests of some form, however, the U.S. standard is the only one to include a wind tunnel testing method for determining local wind-induced pressure distributions on roofing tiles. This paper briefly reviews a Redland Technology (1991) study, which serves as the basis for current roofing tile design provisions in the U.S.. The study was based on several of the first published works on wind loading mechanisms of roofing elements (i.e. Kramer et al., 1979; Hazelwood, 1980, 1981; Kramer and Gerhardt, 1983). A review of the current design provisions, including limitations, is also presented. Finally, the first two of four experiments recently conducted to investigate the wind resistance of roofing field tiles are discussed. Experimental findings are discussed in context of the 2014 Florida Building Code (FBC) and 2015 International Building Code (IBC) provisions for roofing tiles. The third and fourth experiments in the series are discussed in a separate companion paper.

2. The “Redland” study

In 1991, the Southern Building Code Congress International (SBCCI) commissioned Redland Technology (a UK-based company) to investigate wind loads on roofing tile systems and develop a code consistent design methodology. Two experiments were performed by Redland to develop their design method: [1] wind loads were estimated from wind tunnel tests where surface pressures on medium and high profile roofing tiles were measured as wind was blown across a tile array and [2] wind uplift resistance was estimated from constant displacement rate uplift tests that quantified the uplift resistance of roofing tiles with various attachment methods. The resulting method was incorporated into the Standard Building Code (SBC), and later the Florida Building Code (FBC) and International Building Code as Equation 16–33 and Equation 16–34 respectively (see Eq. (1)), FBC Testing Application Standards (TAS) 101, 102, 102A, 108 (FBC, 2014a, 2014b, 2014c, 2014d, 2014e) and FBC Roofing Application Standard (RAS) 127 (FBC, 2014f). The study is also the basis for SBCCI 11-99 (SBCCI, 1999) and ASTM International standards C1568, C1569, and C1570 (ASTM, 2003a, 2003b, 2003c). A brief overview of these standards is provided in Table 1 (Note: Table 1 provides the first publication year while references throughout the paper provide the most current publication year). The focus of this paper is limited to the wind tunnel testing method described by TAS 108, C1569, and SSTD 11 (see Eqs. (2)–(4)). Key limitations of the Redland study include: [1] the approximated relationship between near-roof flow and approach flow conditions (originally proposed by Hazelwood, 1981), [2] limited wind angles of attack (perpendicular to the leading edge only), and [3] use of low-resolution surface pressure measurements to determine design parameters (e.g., lift coefficients) for roofing tiles. Since the study, progress has been made and it is known that the method was not fully representative of wind loading mechanisms for roofing tiles. While the mechanisms are briefly discussed by Smith et al. (2014), and are known to include cavity pressure effects and local effects on the external surface of tiles, a critical review of the mechanisms and the progression of related research to date is not yet available in the literature.

3. 2010 Florida Building Code

In 2002, the 2001 FBC officially superseded all local codes in the State of Florida. The design guidelines for roofing tiles were modeled after SBC provisions (based on Redland Technology work). The wind-load interaction for tiles is expressed in the 2010 FBC (Building) chapters (appears as Eqs. (16)–(33)) as an overturning moment:

$$M_a = q_h C_L b L L_a (1 - GC_p) \quad (1)$$

where, b is the exposed width of the roofing tile, C_L is the tile lift coefficient, GC_p is the roof pressure coefficient for each applicable roof zone determined by ASCE 7 (not adjusted for internal pressure), L is the length of the roofing tile, L_a is the moment arm from the axis of rotation to the point of uplift on the roofing tile, M_a is the aerodynamic uplift moment acting to raise the tile leading edge, and q_h is the wind velocity pressure determined from ASCE 7 (ASCE, 2010). Eq. (1) is also used as the design equation for roofing tiles in the 2012 IBC (appears as Eq. (16)–(34)). In design, the aerodynamic uplift moment is compared to the attachment resistance moment (M_f), determined via TAS 101/102/102A testing and included in product approval documentation for the tile. Eq. (1) may be used for design in areas outside of the HVHZ.

The lift coefficient (C_L) is determined by laboratory testing per TAS 108 (FBC) or SSTD-11 (IBC). The method of these standards is generally the same as both are derived from the work of Redland Technology. TAS 108 is the more detailed document and will be used for discussion in this paper. Tile specimens are fitted with pressure taps along the centerline and subjected to wind loading from the longitudinal direction (perpendicular to the leading

Table 1
Progression of standardized test methods for roofing tiles from the Redland Technology (1991) study to the present (Smith et al., 2014).

Designation	First Publication	Basis	Overview
SSTD 11	1993	Redland	Includes methods for determining uplift capacity of mechanical, mortar, and adhesive attachments. Air-permeability method added in 1999 revision.
FBC TAS 101	1995	Redland	Static uplift capacity of mortar or adhesive tile attachments.
FBC TAS 102	1995	Redland	Static uplift capacity of mechanical tile attachments.
FBC TAS 102A	1995	Redland	Static uplift capacity of mechanical tile attachments with clips.
FBC TAS 108	1995	Redland	Wind tunnel test for determining overturning moment coefficients and aerodynamic load multipliers for tiles.
FBC TAS 116	1995	BS5534/Redland	Procedure for determining air permeability of rigid, discontinuous, roofing systems.
ASTM C1568	2003	SSTD 11/Redland	Mechanical uplift resistance testing. Derived from SSTD 11, essentially a combination of TAS 101, 102, 102A.
ASTM C1569	2003	SSTD 11/Redland	Wind tunnel test for determining overturning moment coefficients. Derived from SSTD 11, similar to TAS 108.
ASTM C1570	2003	SSTD 11/Redland	Test for determining air permeability of a roofing tile system. Derived from SSTD 11–99 update, similar to TAS 116.