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Wind loading on ridge, hip and perimeter roof tiles: A full-scale experimental study

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ABSTRACT

Full-scale experiments were conducted to investigate wind loading on roof tiles in hip, ridge, and perimeter locations, identified from past storms as main points of damage initiation. The objectives were to: (i) provide test-based data on wind-induced loads for tiles, and (ii) evaluate characteristics of near-surface flows to assess tile loading models. The experiments included pressure measurements on the external surface and in the cavity underneath the tiles, and wind speed measurements near tile surfaces. The highest net uplift pressure (computed as external pressure minus the cavity pressure) was observed on the gable end ridge tiles. Except for a few non-critical cases, due to effects of pressure equalization net uplift was lower than external surface uplift. Mean wind speeds at tile surfaces were recorded that were up to 55% higher than the mean wind speed at mid-roof height in the approach flow. Two alternative models that use wind speeds near the tile surface to determine net design wind loads on tiles were investigated. The results showed that the models can underestimate wind loading. However, when used with appropriate parameters, the models can produce results comparable to those obtained using ASCE's external pressure coefficients in conjunction with pressure adjustment factors.

1. Introduction

Damage to roof covering is historically recognized as a leading building performance problem during high wind events. In hurricanes, rainwater entering a building through damaged roofs can cause major damage to interior finishes and contents (Baheru et al., 2014a; FEMA, 2009). Permeable roof coverings are mostly made of roofing elements attached to an underlying support system and overlapping each other with interlocking patterns. The interlocking between individual roofing elements is important for load sharing, that is, for better distributing extreme loading. The interlocking enhances roof uplift resistance, but can at the same time increase susceptibility to progressive failure. When a single tile flies off, it not only exposes the roof deck to wind loads while initiating progressive failure; it can also become a flying debris impacting other structures downwind. The term “permeable” refers herein to permeability to wind flow.

Post-storm reports have indicated that ridges, hips, and roof edges on tiled roofs are frequently where tile damage and progressive failure is initiated, especially when the tiles lack efficient mechanical anchors (FEMA, 2005d; Meloy et al., 2007; RICOWI, 2006). Such failure has been observed even in hurricanes with speeds well below the design wind speed (FEMA, 2009; Baheru et al., 2014b), and might be attributed not only to poor construction practices but also to the inadequacy of code and standard provisions on design wind loads for hip, ridge and eave regions and/or on tile attachment methods for these roof regions.

This paper presents results of experimental investigations performed to understand and quantify the characteristics of wind loading on roof tiles in regions of damage initiation (i.e. on hip, ridge, and eave/perimeter tiles). Tests on a low-rise small building model fitted with full-scale roof tiles were performed in the Wall of Wind (WOW) open jet facility at Florida International University (FIU). Full-scale testing is needed to: (i) better replicate the details of roofing systems, (ii) perform tests under high wind speeds to observe potential failure; (iii) and avoid effects of Reynolds number violation that occur in scaled model testing. Such effects include the weakening of local vorticity at

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edges and corners, resulting in typically weaker local pressures than those at full scale (Simiu, 2011), and the distortion of mechanisms of pressure equalization due to wind flow through the very small openings between the roofing tiles. Moreover, full-scale testing captures the response of roofing systems to realistic wind loading, which is not the case for conventional product evaluation testing that uses uniform static pressures. Habte et al. (2015) showed that full-scale testing can capture wind-induced vibration effects that can lead to different types of failure modes than those typically observed in static pressure testing. Limitations and disadvantages of full-scale testing are: (1) higher costs, (2) blockage constraints that can limit test models sizes, and (3) the difficulty of applying flow measurement devices such as Particle Image Velocimetry (PIV) due the open-jet nature and large test section size of the facility.

Details and backgrounds of the specific objectives of this experimental investigation are provided in the following subsections. Although vibration effects on roof tiles are not within the scope of this study, it is noted that the vibration of roof tiles for prolonged periods of time can make them loose and undermine their anchorage strength, particularly in the case of mechanically attached roof tiles (Baheru et al., 2014b).

1.1. Evaluation of wind loading on hip, ridge and perimeter tiles

Although many experimental results on wind pressure coefficients and the failure mechanisms of roof tiles are available in literature, most of them are focused on field tiles (Geurts, 2000; Hazelwood, 1981; Huang et al., 2009; Kramer and Gerhardt, 1983; Okada et al., 2009; Robertson et al., 2007). The availability of test-based data on roof tiles including eave, ridge, and hip roof regions is very limited. Hip, ridge and perimeter tiles are more prone to wind damage because they experience high wind loads as they lie in wind flow separation and conical vortex regions that create highly negative, localized external pressures (i.e., uplift pressures or suctions). Field tiles may also be affected by conical vortices; however, in general the strength of those vortices, and thus the magnitude of negative pressure induced by them, decreases away from the roof corners and edges. Kawair and Nishimura (2003) carried out field measurements to assess the uplift forces on hip roof tiles in natural wind and observed that net uplift pressures depended on whether the under-tile cavity spaces were ventilated. Moreover, perimeter tiles often overlap the edge of the roof substructure and are thus not protected against positive pressurization of their under-tile cavity spaces (Hazelwood, 1980), which could result in increased net pressures on those tiles. Full scale tests have been performed to study the effect of roof pitch and tile profiles on the distribution of pressure coefficients on external and underneath surfaces of ridge and field tiles on a gable roof; their results showed that considerably higher pressures occurred on the gable-end ridge and corner tiles, and that the use of high profile field tiles increases the net pressures on ridge tiles (Tecle et al., 2013). Using a multi-scale experimental study, Li et al. (2014) compared wind uplift on bare roof decks to roofs with high-profile tiles, and observed significant differences. Li et al. (2014) also conducted a vulnerability study which showed that using net wind uplift loading on tiles, rather than external surface pressures only (i.e. assuming tile underneath cavity pressure to be zero), may significantly affect the estimated probability of roof tile damage. Detailed information on typical loading patterns experienced by gable and hip roofs can be found in much previous research (e.g., Meecham et al., 1991, Holmes, 1994 and Ahmad et al., 2002).

Wind loading on roofs with permeable roof cover elements (such as tiles and shingles) depends on several factors, including external roof profile, roof covering elements' geometric details, and roof porosity. Some codes and standards address the design of such systems by applying pressure equalization factors (e.g., the Netherland code, NEN EN (1991)-1–4/NA (1991) and Australian Standard for wind loads, AS1170.2 (2011)), or by using data from experiments on roofs with permeable covers (for example German wind code, DEUTSCHE NORM (2002)). However, in the American Society of Civil Engineer's Minimum Design Load for Buildings and Other Structures (ASCE 7, 2010) there are no provisions on the effects of pressure equalization on wind pressures experienced by air permeable roofing elements (see Chapter 30, Section 30.1.5 of the ASCE 7–10). Hence, the primary objective of this paper was to provide data on net wind-induced loading for hip, ridge, and eave/perimeter tiles. Such data can be used to improve aerodynamic load provisions in building codes and standards, and to validate wind load models.

1.2. Evaluation of near-surface local flows for hip, ridge and perimeter tiles

Wind loading on permeable roof coverings is influenced by the characteristics of the wind flow near the roof surface (Peterka et al., 1997). Besides affecting wind loading, other important aspects of surface flow velocity are its influence on rain penetration or snow accumulation, and on ventilation and the dispersion of fumes from heating systems (Barnard and Driviere, 1994).

The net wind pressure acting on a roof tile element is the algebraic sum of the external pressure on the tile's top surface and the internal pressure in the underneath cavity of the tile. If a tile element is situated in an entirely separated flow region, the external pressure depends mainly on the building flow field, but if the tile element is located in an attached flow region, the external pressure is also influenced by the tile elements' local flow field. For brevity, the wind flow approaching the building (undisturbed by the building) and the wind flow near the tile surface are henceforth referred to as "approach flow" and "surface flow" respectively. The under-tile internal pressure is determined by the external pressure, the space between the roof deck and tile, and roof permeability (Kramer and Gerhardt, 1983; Robertson et al., 2007).

In the absence of comprehensive net wind loading data on roof tiles, loading models which make use of surface flow wind speeds to estimate net wind loading on porous roofing elements have been in use. Hence, another objective of the current experimental investigation was to measure local surface flow wind speeds at selected hip, ridge and perimeter tiles in an effort to (i) investigate the characteristics of near tile surface flows in relation to the approaching wind flow, and (ii) analyze roof surface flow-based alternatives for estimating net design pressures on hip, ridge and roof perimeter tiles. This will assist in developing new wind loading models or calibrating existing models which use surface flow wind speed to estimate net wind loading data on roof tiles.

2. Experimental setup and testing protocol

A two-phase full-scale experimental investigation was conducted using the 12-fan Wall of Wind (WOW) facility at FIU. In the first phase, aerodynamic wind pressure measurement tests were performed on selected hip, ridge, and eave/perimeter tiles for different wind directions. In the second phase, local roof surface wind speed measurement tests were conducted. Pressure and wind speed measurement tests were conducted separately in order to avoid any effects the wind speed measurement equipment might impose on the wind pressure experienced by the roof tiles.

2.1. Roof models for testing

The roof models had the shape of a half-cut hip roof (with a pitch of 4:12 or 18.4 degrees) to represent edges and corners of both hip and gable roofs (Fig. 1). The plan dimensions of the roof models were 4 m x 3 m with 0.30 m overhang on the gable-end side and 0.60 m overhang on the remaining three sides. The model represented a portion of a low-rise residential roof, and was placed on a wood frame base with height of 2 m. The experiments were conducted on only one model; however,