An Historical Perspective on the Wind Resistance of Clay and Concrete Roofing Tiles

By Daniel J. Smith, PhD; Forrest J. Masters, PhD, PE; and Kurtis R. Gurley, PhD

INTRODUCTION
Tiles are one of the oldest forms of roof covering, with usage dating back more than 5,000 years. This article presents an historical overview of roofing tiles in four parts, spanning from early development to the last 40 years of advancements in research and design related to wind load resistance. Code provisions and testing standards are addressed throughout, with emphasis on provisions in the state of Florida. This article also provides a description of ongoing research at the University of Florida to investigate the wind resistance of clay and concrete roofing tile systems.

EARLY DEVELOPMENT (3000 BC-1970)
Tile roof covering has become increasingly popular over the last century, largely due to its durability, fire resistance, and insulating behavior. These favorable qualities are not a recent discovery. Evidence suggests use by the Chinese and Greeks up to 5,000 years ago (Figure 1). The Romans were responsible for bringing clay tile to England. Prior to this, English roofing materials included stone and slate. Straw, reed, and timber were also used for short-term coverage.

Use of roofing tiles in the U.S. began during the colonial period. In the mid-1800s, devastating fires prompted the establishment of building and fire codes in New York, Boston, and other major cities. These codes encouraged the use of clay roofing tiles because of the fire resistance of the system. During the same time period, commercial production of concrete tiles using natural cement began in Bavaria. Soon after, concrete tiles were introduced in England, Holland, and other European countries. Common practice soon included the addition of coloring pigment to the mix in order to imitate traditional clay roofing tiles. As the demand for concrete tile increased, so did the need for large-scale production.

Figure 1 – Earliest roofing tiles found in Greece circa 3000 BC (source: Wikipedia).
The earliest concrete roofing tiles were made using hand- or semi-hand-operated machines. The first power-driven tile-making machine, known as the Ringsted, was developed in Denmark in the early 1900s. A U.S. patent was filed for the Ringsted in 1912 (Figure 2). Once this machine was introduced in England, engineering led to improved designs and higher efficiency, causing rapid development of the roofing tile industry. By 1961, concrete tile comprised an estimated 82% of all domestic roof coverings in Great Britain. Today, estimates suggest that concrete tile accounts for 90% of all steep-slope roof coverings in Europe and the South Pacific basin, while Japan, China, and the U.S. are rapidly increasing use, as well.

EARLY DEVELOPMENT OF WIND RESISTANCE RESEARCH AND GUIDELINES (1971-1991)

The first published research to investigate wind load interactions for roofing tiles was conducted in the late 1970s and early 1980s (Figure 3). Supported by Redland Technology, R.A. Hazelwood in 1980 identified two modes of wind-induced loading on roofing tiles: 1) pressure differential created between the volume of air immediately above the tiles (i.e., external pressure) and the volume of air immediately below the tiles (i.e., internal cavity pressure) and 2) local pressures on the tile surfaces due to near-roof surface flows. While both conditions may cause uplift, the latter was thought to be the more dominant effect.

In order to relate external building pressures (provided by design standards, e.g., ASCE 7) to near-roof flow velocities, Hazelwood suggested using Bernoulli's equation, while noting, "It should be possible to avoid this rather unsatisfactory approximation when measured values of surface air flow become available." Hazelwood's work would set the precedent for present-day wind load models for roofing tiles.

The asphalt shingle industry also recognized the need for understanding of near-roof surface flow. Peterka et al. used an experimentally derived relationship between approach (upwind of the structure) flow and near-roof surface flow to derive the asphalt shingle wind uplift load model used today. To date, the authors are unaware of published data that relates approach flows to near-roof surface flows over roofing tiles.

During the construction boom of the 1970s, the state of Florida mandated that all municipalities and counties must adopt one of the four state-recognized model building codes. In 1987, the Roof Tile Committee

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of the National Tile Roofing Manufacturers Association (NTRMA—now known as the Tile Roofing Institute, or TRI) was commissioned to develop consensus guidelines for the installation of concrete and clay roofing tiles. The consensus document process would include meetings over a period of 18 years, made up of roofing contractors, manufacturers, suppliers, academics, roof consultants, and engineers.

In 1989, the Florida Roofing, Sheet Metal and Air Conditioning Contractors Association Inc. (FRSA) and the Florida chapter of NTRMA issued a joint guide for mortar-set roof tiling. This guide served as the basis for additions to the Standard Building Code (SBC) in 1991 and was the forerunner to the TRI/FRSA Concrete and Clay Roof Tile Installation Manual in use today.

In 1991, the Southern Building Code Congress International (SBCCI) commissioned Redland Technology to continue Hazelwood’s work by developing the first wind load model for roof tiling (Figure 4). Findings were reported in the document Fixing Studies for MRTI Normal Weight Tiles – SBCCI Submission. The document summarized tests performed to study the fixings required for standard-weight tiles to withstand extreme wind loads and presented a design methodology for code provisions in the United States.

**THE REDLAND STUDY**

Redland Technology developed its design method using two experiments:

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 the tile located in a sample tile array.
2. Constant displacement (i.e., static) uplift tests quantified the uplift resistance of roofing tiles with various attachment configurations.

**Equation 1**

\[
C_p = \frac{p - p_s}{q_r}
\]

Where:
- \(p\) = Local static pressure (at tap locations)
- \(p_s\) = Reference static pressure at 100 mm above the deck
- \(q_r\) = Reference velocity pressure at 100 mm above the deck

In the first experiment, wind-induced surface pressures were measured on four tile configurations: 1) medium-profile tile without battens, 2) medium-profile tile with battens, 3) medium-profile tile without battens with a 50.8-mm (2-in.) tail lift, and 4) high-profile tile without battens.

Tile arrays were oriented with the leading edge of each tile perpendicular to the wind flow. For each array, one tile located 2.5 m (8.2 ft.) from the windward edge and in the center of the array was used for top- and bottom-surface pressure measurements at 20 locations along the centerline of the tile, parallel to the direction of wind flow. Pressure was measured at each location through a tap, which consists of a small hole in the tile connected to a length of vinyl tubing whose far end was connected to a pressure measurement device.

Wind was blown across the deck in a 4.5-m/s (10-mph) “step-and-hold-for-60-seconds” pattern starting at 31 m/s (70 mph) and ending at 56 m/s (125 mph). Turbulence characteristics in the approach wind and the vertical profile upwind from the tile array were not reported. Mean wind velocity and static pressure in the free

**Equation 2**

\[
C_L = \frac{\sum_i C_{pb_i} \delta_{bi}}{l \times b} - \frac{\sum_i C_{pt_i} \delta_{ti}}{l \times b}
\]
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pressures along the width of each tributary taps. Redland Technology assumed that the corresponding to the tile's width by one-half mm (4 in.) above the tile deck (Equation 1). Velocity pressure measurements made 100 centimeters (converted to dimensionless pressure coefficients) measured by the pitot-static tube. Mean static pressure of each tile tap, mean ing data were recorded for each hold period: upwind of the instrumented tile. The follow-
surface of the tile deck and 1.5 m (4.9 ft.) tube placed 100 mm (4 in.) above the
stream were measured using a pitot-static tube placed 100 mm (4 in.) above the surface of the tile deck and 1.5 m (4.9 ft.) upwind of the instrumented tile. The follow-
ing data were recorded for each hold period: mean static pressure of each tile tap, mean wind velocity, and mean static pressure measured by the pitot-static tube.
Pressure tap measurements were con-
verted to dimensionless pressure coefficients \(C_p\) referenced to the static and velocity pressure measurements made 100 mm (4 in.) above the tile deck (Equation 1).
Each tap was assigned a tributary area corre responding to the tile’s width by one-half the distance from each of the two adjacent taps. Redland Technology assumed that the pressures along the width of each tributary
strip were equivalent, despite the varying cross-section of the high- and medium-profile tiles (i.e., not a flat plate). A coefficient of lift \(C_L\) was then calculated using the pressure coefficients and corresponding tributary areas to represent the average pressure acting to lift the tile (Equation 2 and Figure 5). A coefficient of moment \(C_m\) was computed to represent the moment acting about the axis of rotation near the head of the tile (Equation 3).
The testing configuration was meant to simulate a tile roofing section subjected to wind flow moving parallel to the roof slope and near the roof surface. Consequently, the coefficients of lift and moment are referenced to the simulated near-roof velocity and static pressures. However, in order to incorporate the coefficients into code provisions, it was required that they be referenced to the approach velocity and static pressure. To accomplish this reference transformation, Redland Technology employed Bernoulli’s equation (using Hazelwood’s method), equating the total pressure in the approach flow to the total pressure in the near-roof flow using the static and velocity pressure for each flow location (Equation 4). The equation is valid for roof locations outside of flow-separated regions where the flow is inviscid and irrotational. Neither condition is valid for flow near the roof, but this approach does provide a reasonable first approximation to calculate the speed-
up of flow over the roof. The relationship is convenient because ASCE 7 external pressure coefficients for roof zones are referenced to approach wind flow. External pressure coefficients are employed in this calculation as proxy for the static pressure measured by the pitot-static tube in the wind tunnel tests of roofing tiles.
Expression of the external pressure coefficient \(C\) is shown in Equation 5. Equation 16-33 of the 2010 Florida Building Code (FBC) (Equation 6) is derived by rearranging Equation 4 and combining it with Equation 5.
The load model and testing procedures developed by Redland Technology were incorporated into the 1992/1993 SBC revisions as SSTD 11-93, SBCCI Test Standard for Determining the Wind Resistance of Concrete or Clay Roof Tiles. This stan-
dard described the process for calculating wind-generated uplift moment and wind uplift resistance for roofing tiles. The SBC wind load provisions for roofing tiles were later incorporated into the FBC and still govern design in the state of Florida today.

### MODERN BUILDING CODE ERA (1992-PRESENT)

Hurricane Andrew made landfall near Homestead, Florida, in 1992 with three-second peak gusts exceeding 65 m/s (145 mph). An estimated 90-95% of all homes in Dade County, Florida, suffered roof damage. Mortar-set roofing tile systems performed poorly. In response, Polyfoam Products, Inc. (now a 3M company) and Dow released two-component polyurethane adhesives for roofing tile attachment in the years following the storm. This product was produced largely in reaction to the performance of mortar-set attachments during Hurricane Andrew. Techniques for mechanical attachment were also developed at that time.

Widespread roof cover losses exposed the need to advance performance of these systems. T.L. Smith discussed clay and concrete tile failure modes, wind performance, and missile impact research, and provided recommendations for enhanced performance in hurricanes and other high-wind environments. Sparks et al. recommended that the building envelope and cladding systems be designed to the same probability of failure as the main structural system in light of exponential increases in insured losses when building envelopes are breached during high-wind events that include rain.

In 1997, the state of Florida admin-
istered the 1997 edition of the SBC (with Florida-specific amendments) and the South Florida Building Code. In 1998, the Florida legislature amended statutes to begin creation of a single statewide model code known as the Florida Building Code.

Because the SBC provisions for roofing tiles allowed a design load reduction due to air permeability, the question was raised as to whether adhered roofing tile systems being developed in the late 1990s (e.g., foam adhesive) had sufficient air permeability. As a result, Redland Technology developed a procedure to measure the air permeability of roofing tile systems that was added to the testing standard, SSTD 11-93. In 1999, an updated version of the standard, SSTD 11-99, was issued. This edition of the standard contained a new Section 900, entitled “Air Permeability Measurements.”

John Shepherd reports that at the time, roofing tile systems accounted for 80% of new residential construction in the Sunbelt regions of the U.S. In 2002, the FRSA and TRI produced the first edition of the Concrete and Clay Roof Tile Installation Manual. This document was the first stand-alone installation guide for roofing tile systems, although it was not adopted into the code at the time. In March of 2002, the 2001 FBC officially superseded all local Florida codes. This edition was modeled after the 1999 SBC and the South Florida Building Code and referenced ASCE 7-98.


The 2004 hurricane season was devastating for Florida. For the first time on record, four hurricanes made landfall in a single season. Hurricane Charley, a Category 4 storm, was the most destructive. On August 13, 2004, Hurricane Charley made landfall just southwest of Punta Gorda, Florida, as a design-level event from the point of landfall to approximately 120 miles inland. Measured three-second peak gusts were 50 m/s (112 mph) in Punta Gorda. Mortar-set systems underperformed in comparison to mechanical and foam adhesive attachment methods. In several instances, performance assessments indicated that the tiles did not withstand wind load as predicted by design provisions.

This marked the first time that a large number of adhesive-set roofing tile systems encountered high winds, providing an opportunity to analyze the performance of the relatively new attachment method. Adhesive attachments performed well when installed per manufacturers’ instructions. Failures were reported only when foam patties were too small or did not provide enough contact area.

In general, code adjustments made post-Hurricane Andrew were effective in reducing building damage. An analysis of insurance claims by the Institute for Business and Home Safety (IBHS) suggested that homes built after 1995 and the adoption of high-wind design provisions required nearly 44% fewer total roof covering replacements than those homes built before 1995.
Homes built after 1995 most often required partial roof covering replacements only.\textsuperscript{19} Also in 2004, Hurricane Ivan made landfall on September 16 near Gulf Shores, Alabama. Ivan was categorized as a Category 3 storm with estimated three-second peak gusts of 47-54 m/s (105-120 mph). However, "surface observation sites in the coastal region provided data indicating that most of the region impacted by the storm likely experienced Category 1-intensity winds with some areas near the Alabama-Florida border experiencing Category 2-intensity winds."\textsuperscript{20} Hurricane Ivan was not considered a design-level wind event with respect to the 2001 FBC or the 2000/2003 International Building Code (IBC) and International Residential Code (IRC). However, wind damage was extensive. Evidence suggested that homes built in accordance with the 2001 FBC or 2000/2003 IBC performed well with regard to structural issues.\textsuperscript{21} In response to unsatisfactory perfor-

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Table 1 – Progression of standardized test methods for roofing tiles from the Redland Technology (1991) study to the present.

Figure 6 – Medium-profile rapid prototype tile replica with 256 pressure taps.
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mance of roofing tile systems during the 2004 hurricane season, the Federal Emergency Management Agency (FEMA)22 recommended that installation be simplified for foam adhesive set tiles, installers be held to a higher standard of certification, and safety factors for design be re-evaluated. With insurance industry support, a ban on mortar attachment of tiles was proposed but was unsuccessful due to widespread opposition by roofing contractors. As a compromise, the tile roofing industry proposed a code-approved prebagged mortar mix. After weaknesses in mortar-set hip/ridge attachments were exposed again during Hurricane Charley, TRI and FRSA began producing new hip and ridge tile attachment guidelines. TRI/FRSA released the updated set of guidelines in the fourth edition of the Concrete and Clay Roof Tile Installation Manual. The guidelines addressed high-wind applications much more thor-

Figure 7 – Mock-up roofing tile section with replica tile for pressure measurement is loaded into the Dynamic Flow Simulator at UF.
oughly than previous editions and were adopted into the 2004 Florida Building Code, which officially went into effect October 1, 2005. The new guidelines required contractors to securely fasten hip and ridge tiles to a wood or metal structural support using screws, nails, or foam adhesive.

In an effort to educate builders and raise awareness of proper installation procedures, in 2006, TRI launched a nationwide training initiative for roofing tile contractors. The two-day program covered installation systems for the entire country, including high-wind areas, taking an important step towards educating contractors on proper installation procedures.

LOOKING FORWARD

Over the last 20 years, there has been an increased focus on mitigating wind damage, with particular emphasis on maintaining building integrity by improving the performance of roof covering systems. Post-storm damage assessments have provided valuable information regarding the adequacy of code standards and the frequency of adherence. In response, there has been a significant increase in research to improve the understanding of wind load mechanisms, attachment capacities, and frangibility of roofing tiles.  

Figure 8 – Mechanical uplift testing for roofing tiles using custom steel test frame and Instron Universal Testing Machine (UTM) at UF.
Several areas are in need of additional research. Topics include:
1. High-resolution measurement of wind-induced surface pressures
2. Direct measurement of wind-induced tile attachment reaction forces
3. Effects of oblique wind angles on surface pressures and attachment reaction forces
4. Enhancement of design provisions/standards based on current research
5. Probabilistic consideration of load and resistance in design

In July of 2011, the University of Florida (UF) commenced a four-phase research project to address these topics. This three-year project builds upon previous and concurrent research on discontinuous roof coverings with the goal of improving the wind performance of roofing tiles. Three replicas (low-, medium-, and high-profile) of typical Florida roofing tiles were manufactured using rapid prototyping. Each replica has 256 pressure taps distributed throughout the upper-, lower-, and leading-edge surfaces.

In the first phase of the project, the replicas are installed in a mock-up tile array section to measure wind-induced surface pressures at high resolution for a variety of approach wind angles (modified TAS 108).

In the second phase, six-axis load cells are affixed to the mechanical fastening locations of concrete tiles. The load cells are used to directly measure the wind-induced reaction forces to which typical fasteners are subjected. The instrumented mock-up roofing sections are subjected to wind loading inside the Dynamic Flow Simulator (DFS) at the UF.

Surface pressure measurements on the replica tile are used in combination with load cell measurements at the tile attachments to develop a comprehensive understanding of the wind-loading mechanism that causes tile uplift and failure. In the third phase, various tile attachment capacities are measured by mechanical uplift testing using a custom steel-framed rig designed at UF (modified TAS 101/102).

Measured attachment capacities from uplift testing are related to findings from Phases 1 and 2 (i.e., wind-induced load investigation) in order to develop a prob-
The outcomes of this project will be used to expand the current understanding of wind loading on discontinuous roofing systems and to supplement design provisions if needed. For more information on this project or other ongoing wind research projects at the University of Florida, please contact Daniel Smith at 07-4781-5512 or daniel.smith8@jcu.edu.au.

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Dr. Daniel J. Smith received an undergraduate degree in civil engineering in 2010 from the University of Florida. In 2011, Smith joined Dr. Masters’ wind engineering research group at UF as a research assistant. Smith’s work included investigations on the wind resistance of clay and concrete roofing tiles and asphalt shingles. After completing his doctoral studies, he accepted a position at James Cook University in Townsville, Australia, to continue researching the vulnerability of residential structures to high-wind events.

Dr. Forrest J. Masters, PhD, PE, is an associate professor of civil and coastal engineering at UF. His research focuses on improving the resistance of buildings to extreme winds and rain. Experiments are conducted with full-scale simulators and in hurricanes to study the behavior of surface wind and wind-driven rain. He has received more than 25 grants from state, federal, and private sources, including the NSF Faculty Early Career Development (CAREER) Program. Masters is a reviewer for five journals and a member of ASCE, RICOWI, and ASTM.

Dr. Kurtis R. Gurley is an associate professor at UF. His primary areas of research are wind effects on residential structures and stochastic modeling of extreme winds and structural resistance. The research output from Dr. Gurley and his colleagues contributes to a variety of hazard preparation and response initiatives. Dr. Gurley is an associate editor for ASCE Journal of Structural Engineering and a member of the Technical Advisory Committee for the Federal Alliance for Safe Homes.

WSRCA Holds “The Roofing Games”

The Western States Roofing Contractors Association (WSRCA) introduced The Roofing Games™ at its annual expo in June. Designed specifically for the roofing industry, The Roofing Games are the nation’s “first official set of competitions sanctioned by a roofing association.” Participants competed in a series of events that challenged their knowledge and skill set levels pertaining to equipment, materials, and processes used in the roofing industry. The inaugural year was launched with just one main event: the Nailing Competition, sponsored by Malarkey Roofing Products. Six contestants were randomly chosen in a drawing during a product demo. With two decks on the stage, contestants battled in a timed event, showcasing their asphalt-shingle nailing skills. They were judged on both time and accurate shingle installation. The first-place winner was Sean Johnson of Johnson Design & Construction of Camarillo, California. The WSRCA plans to expand The Roofing Games to include additional events for the Western Roofing Expo 2015, scheduled for Las Vegas, Nevada, on June 14-17, 2015.