Journal of the National Academy of Forensic Engineers®

NATIONAL ACADEMY OF FORENSIC ENGINEERS

http://www.nafe.org

ISSN: 2379-3252

DOI: 10.51501/jotnafe.v42i2

Vol. 42 No. 2 December 2025

Discerning Wind-Related Damage to Residential Roofs

By Ziad Azzi, PhD, PE, DFE (NAFE #1343M), Krishna Sai Vutukuru, PhD, PE, and Manuel Matus, PhD

Abstract

Hurricane season brings a significant rise in wind-related insurance claims, as powerful storms lead to property damage (particularly to roofs). Distinguishing between wind- and nonwind-related damage, as well as pre-existing issues with roofing components, is critical to ensuring fair, efficient, and timely resolutions. This study presents an in-depth analysis of wind-related damage to two common roof covering materials: asphalt composition shingles and clay/concrete tiles. A series of detailed studies coupled with data from field inspections is utilized to differentiate wind-induced damage to roofs from issues stemming from wear and tear, material aging, installation deficiencies, and simulated wind damage (among other environmental and mechanical factors). Damage patterns, damage location, and material behavior from field observations coupled with wind flow around bluff-bodies (such as residential structures) are examined to highlight how the unique properties of each roof (including its location, height, shape, and slope) influence its response to wind-induced pressures during extreme wind events. These insights enhance damage identification, including cause, origin, and duration of roof covering failures, as well as support informed decision-making for roof inspectors.

Keywords

Hurricane season, insurance claims, inspections, tile roofs, shingle roofs, wind damage, forensic engineering, residential roofs, weather-related roof damage

Introduction

Within the discipline of forensic engineering, civil and structural engineers are routinely engaged to perform evaluations of roofing systems in relation to alleged storm-related damage. Their objective and technically substantiated assessments are frequently integral to resolving matters that involve insurance disputes and legal proceedings. The expertise of these professionals is typically grounded in a combination of formal education, practical experience, and specialized training, qualifying them as expert witnesses in this domain.

Accurately distinguishing wind damage from other causes of damage on the roofs is essential for streamlining the insurance claims procedure and improving efficiency. Misclassification and improper damage attribution often lead to delays, disputes, and litigation, making the whole process expensive to both insurers and the insureds.

Advanced assessment methods, such as those discussed, help streamline the process, ensuring that the claims with actual wind damage are handled promptly. Enhanced damage identification, including cause, origin, and duration of roof covering failures, supports informed decision-making for roof inspectors.

The objective of this manuscript is fourfold: (1) to provide foundational background on roofing systems, with emphasis on the most commonly utilized roof covering materials; (2) to examine typical wind-induced damage patterns through the lens of fundamental wind science and wind engineering principles, highlighting how such damage is largely dependent on roof geometry, building height, configuration, and site exposure (among others); (3) to present illustrative case studies from field inspections conducted after major storm events, distinguishing between wind-related and nonwind-related damage to shingles and tiles; and (4) to summarize key guidelines for the assessment of wind damage in residential roofing systems by roof inspectors.

Ziad Azzi, PhD, PE, 5335 NW 87 Ave., Ste. 109, #381, Doral, FL 33178, (305) 874-7399, ziad@ddaforensics.com

Background Information

A tropical cyclone is a rotating system of low atmospheric pressure characterized by organized thunderstorm activity and the absence of frontal boundaries, which typically separate air masses of different densities. When the system's maximum sustained wind speeds are below 39 miles per hour (mph), it is classified as a tropical depression. Once these sustained winds increase to at least 39 mph, the system becomes a tropical storm[1,2]. If the storm intensifies further — and wind speeds reach or exceed 74 mph — it is designated as a hurricane.

Hurricanes are categorized using the Saffir-Simpson Hurricane Wind Scale, which ranks storms from Category 1 to Category 5 based on their maximum sustained wind speed (higher categories indicate a greater threat of structural and environmental damage). These powerful storms generally develop in the Atlantic basin, encompassing the Atlantic Ocean, Caribbean Sea, and Gulf of Mexico as well as in the eastern, and, less commonly, central regions of the North Pacific Ocean[1,2]. Note that the Saffir–Simpson Hurricane Wind Scale classifies hurricanes according to their maximum sustained wind speeds, measured over a one-minute period at a height of 33 feet (or 10 meters) above open water (or unobstructed terrain).

Over the past half-century, windstorms have accounted for roughly 70% of all insured losses attributed to natural disasters[3]. Nearly 39% of the U.S. population resides in coastal counties vulnerable to hurricanes and severe thunderstorms, and data show that this number is growing[4,5]. Although advancements in building codes have significantly improved structural resilience against wind forces in recent decades, substantial damage continues to occur primarily to the external building envelope[6], particularly roofing components such as roof sheathing, tiles, shingles, and metal roofs on residential structures, among other components[7,8,9,10].

In residential houses in the United States, two commonly used roof coverings are asphalt composition shingles and clay or concrete tiles.

Typically, asphalt shingles are favored for their affordability and variety of design choices[11,12]. These systems are made up of overlapping strips composed of asphalt-saturated organic or fiberglass mats, which act as a protective, water-repellent layer over the structural roof deck. Most asphalt shingles have been manufactured with a heat-activated sealant strip (typically asphalt-based) located on either the top or underside of each shingle. When the roof warms above the sealant's softening temperature, the adhesive bonds the shingles in place, helping to prevent uplift at the edges during high winds and allowing wind pressure to be distributed down to the underlying shingle layer[13,14].

On the other hand, clay and concrete tiles are commonly selected in roofing applications due to their strength, long service life, and aesthetic nature. Tiles are particularly valued for their ability to endure extreme weather, including strong winds, intense rainfall, and fire exposure. Such roofing components are most commonly installed using mechanical fasteners (such as screws or nails), mortar- or cement-set, or adhered to the roof deck using a foam application. It is worthwhile to note that in certain locations across the United States, the installation details of roofing components may be governed by the local jurisdiction of that geographical area. This manuscript will only tackle the most common roof covering components, including shingles and tiles.

During severe wind events, damage is typically caused by intense wind-induced uplift or suction forces concentrated at roof corners, edges, and ridge lines, also referred to as high suction pressure zones[15,16]. Elevated suction pressures develop at the roof corners of low-rise buildings due to conical vortex formation[17,18,19]. Consequently, roofing elements like tiles or pavers and rooftop equipment may become detached, transforming into hazardous windborne debris. Additionally, the detachment of roofing materials and rooftop appurtenances exposes structures to rainwater penetration and consequent interior damage[16,20,21,22,23,24,25,26]. Moreover, past research in wind engineering has clearly demonstrated that the aerodynamic behavior and overall wind performance of low-rise buildings are heavily influenced by roof design, roof shape, and roof pitch, among other characteristics[27,28,29].

Typical Wind Damage Patterns

Wind-related damage to residential roofs is largely influenced by wind speed, wind duration, wind direction, and the amount of turbulence inherent in the oncoming wind. The most common damage patterns include wind-induced uplift, windborne debris impact, and progressive failure. The damage caused by wind-induced uplift is classified under direct wind effects, and the damage caused by windborne debris is classified under indirect wind effects. Uplift (or suction) occurs when the wind pressure on the roof covering exceeds the wind resistance of the roof covering, leading to detachment of shingles or tiles. Debris impact can cause punctures or fractures. Progressive failure refers to the cascading effect — where initial damage weakens the roof covering and exposes the underlayment, making it more susceptible to further wind forces from one particular windstorm event and subsequent moisture intrusion.

Studies have shown that asphalt composition shingle roofs are particularly vulnerable to wind-induced damage due to their layered structure[30]. This structure consists of individual overlapping shingles that are installed in successive courses, where each course partially covers the one beneath it. While this arrangement facilitates water shedding and is effective for waterproofing under normal conditions, it also creates multiple points of uplift vulnerability. Wind forces can exploit the edges and gaps between these layers, particularly at the leading edges of the shingles, initiating progressive detachment or lifting and exposing underlying layers to moisture intrusion. Additionally, once one shingle is displaced, it can compromise the sealing of adjacent shingles, leading to a cascading failure across the roof surface[12,13].

While heavier and more resistant to uplift, concrete and clay tile roofs can suffer from breakage due to windborne debris. The American Society of Civil Engineering (ASCE) building code, *Minimum Design Loads and Associated Criteria for Buildings and Other Structures* (ASCE 7-22)[31], provides updated design guidelines for wind load calculations on buildings and structures. One of the key aspects of ASCE 7-22 is the identification of high-pressure zones, particularly at roof edges, corners, and ridges. These areas experience intensified wind forces due to flow separation and vortex formation leading to turbulence.

Figure 1 shows the peak pressure distributions (or contour plots) for three roof configurations: gable, hip, and flat as well as the locations of the high-pressure zones for each configuration, courtesy of Tokyo Polytechnic University (TPU)[32,33]. Note that the peak pressure coefficients (which are directly proportional to the peak pressures) are negative, indicating the wind forces are pulling away from the surface of the roof (or exerting uplift or suction pressures).

This graphic demonstrates that a typical wind damage pattern is generally located near the roof edges, corners, and ridges (or hip lines in case of hip roof configuration) before the wind can cause uplift to other areas, such as the field of the roof. While this is true for shingle and tile roofs, flat or low-slope roofs are typically covered with membranes, which may call for stricter guidelines or attachment methods for membranes located in zones of high-suction pressures. Additionally, during a high wind event, severe winds are typically recorded from a particular direction. Although the predominant wind direction might sometimes shift during rotational storms such as hurricanes, the roof inspector should first consider the predominant windward slope direction for wind damage assessment. As such, the above criteria can help the inspectors understand and segregate wind-related damage from other types of damage noted on the roofs.

On the other hand, wind flow characteristics around a building are significantly affected by terrain exposure and

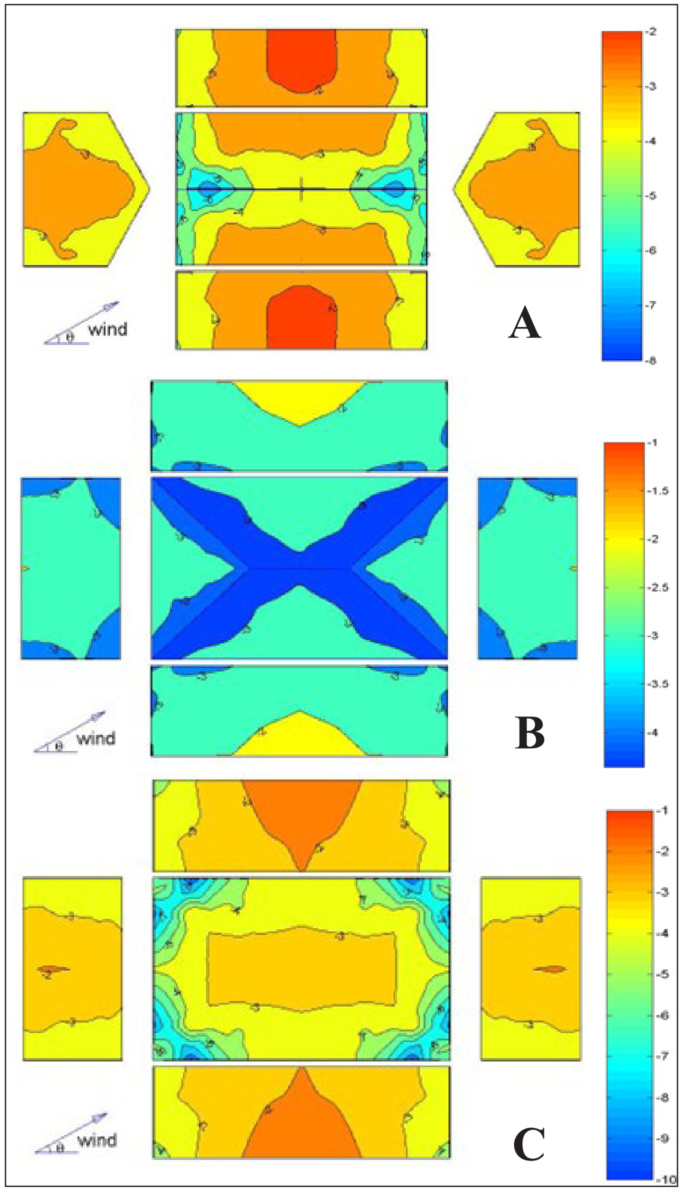

Figure 1
Contour plots of critical peak pressure coefficients for:
a) gable roof, b) hip roof, and c) flat roof.
Courtesy of Tokyo Polytechnic University (TPU)[32,33]

building height. ASCE 7-22 classifies terrain into three exposures — mainly B, C, and D — where:

- Exposure B represents urban or suburban areas with numerous obstructions.

- Exposure C includes open terrain with scattered obstructions.

- Exposure D pertains to coastal regions with unobstructed wind flow.

Buildings in Exposure D experience the highest wind loads due to minimal surface roughness (such as structures directly facing the ocean), and buildings in Exposure B experience the lowest wind loads due to numerous obstructions to the wind flow (such as structures located farther inland). Additionally, building height plays a crucial role in the distribution of wind pressure. Taller structures encounter increased wind speeds at higher elevations, necessitating stronger roof anchoring systems and stringent design. Hence, in general, a two-story residential building experiences higher wind forces than a one-story residential building in a similar location. Thus, in jurisdictions where no stricter attachment methods are enforced for roofing components located in high-suction pressure zones, it is highly unlikely that a lower roof gets damaged during a windstorm with no wind-related damage to the higher roof of the same structure.

The shape and configuration of a roof determine how wind interacts with its surface, as depicted in **Figure 1**. Gable roofs, for instance, create strong uplift forces at the ridges due to flow separation, making them more vulnerable to wind-induced damage. In contrast, hip roofs tend to distribute wind loads more evenly, reducing the likelihood of localized failure. Flat roofs, on the other hand, are particularly susceptible to vortex-induced suction, which can lead to the detachment of the roof covering at the corners. Roof slope is another critical factor influencing wind pressure distribution. Studies using computational fluid dynamics (CFD) simulations indicate that steeper slopes can reduce uplift forces, while flatter roofs experience higher suction forces[34]. Optimizing roof slope can significantly enhance wind resistance, particularly in hurricane-prone regions.

Aerodynamic mitigation strategies, such as parapets, roof overhangs, and curved roof designs, can significantly reduce wind-induced damage[35,36]. Parapets disrupt wind flow, reducing suction forces on flat roofs, while curved roofs help streamline airflow, minimizing turbulence. Overhangs, however, must be carefully designed, as excessive extension can amplify wind loads rather than mitigate them[18]. In addition, the presence of non-rectangular-shaped buildings also significantly affects the wind loads on the roof.

For instance, protruding sections of a structure may induce tunneling effects that could exacerbate the generation of wind-induced pressures on different roof sections. In addition, re-entrant flows shed from sections located upwind may introduce unconventional pressure distributions on areas of the roof that may deviate from typical wind-induced pressure distributions[37,38,39]. Furthermore, roof openings and ventilation systems can alter wind flow patterns.

Research indicates that buildings with strategically placed openings experience lower wind pressure coefficients than fully enclosed structures[40,41]. This highlights the importance of integrating ventilation designs that enhance wind resistance by reducing suction pressures on the roofs while maintaining structural stability. While the previous methods, strategies, or configurations are mostly related to enhancing the design and performance of roofing components during severe winds, the forensic engineer would greatly benefit from understanding how winds flow around bluff-bodies and irregularities in roof configurations to make an accurate determination in a roof damage case.

Asphalt Shingle Roofs

Asphalt shingles are a widely used roofing material in residential construction. They are made from a base mat that can be organic (such as cellulose fibers) or fiberglass, which is saturated and coated with asphalt to provide it with its waterproof capabilities. The top surface is then embedded with mineral granules, which provide color, protect against ultraviolet (UV) rays, and enhance fire resistance. Asphalt shingles come in a variety of styles, including 3-tab and architectural (dimensional) shingles, allowing homeowners to choose options that suit both aesthetic preferences as well as desired and/or required performance needs.

The history of asphalt shingles dates to 1901, when they were developed as a more affordable and practical alternative to wood shingles and slate tiles. They began to be mass-produced and marketed across the United States by 1911[42]. Initially, organic-based shingles dominated the market; however, by the 1960s, fiberglass-based shingles were introduced and quickly gained popularity due to their superior durability, lighter weight, and improved resistance to fire and weathering[43]. Throughout the decades, advancements in materials science and manufacturing techniques have significantly improved the performance of asphalt shingles. Modern shingles can feature algae resistance, enhanced wind ratings, and impact-resistant designs. Asphalt shingles remain one of the most popular roofing materials in North America due to their advantageous balance of durability, affordability, and aesthetic flexibility[11].

Although the design of asphalt shingles has improved over the past several decades, the susceptibility to wind-induced damage has not been fully mitigated. Therefore, problems such as design, manufacturing, installation, and durability of asphalt shingles continue to play a crucial role in their performance during extreme weather conditions. In fact, there are numerous research efforts aimed at better understanding the performance of asphalt shingles and their particular modes of failure[12,14,29,44,45].

Types of Shingles

Traditional Shingles

Traditional shingles, commonly referred to as 3-tab asphalt shingles, are composed of a single fiberglass mat layer embedded in asphalt and topped with mineral granules for UV protection. From a materials engineering perspective, their uniform geometry and minimal thickness contribute to their lighter dead load on structural systems (**Figure 2**). However, due to their lower tensile strength and limited dimensional stability, they exhibit reduced resistance to uplift forces, making them more vulnerable in high-wind zones.

In forensic evaluations, traditional shingles are frequently associated with failure modes, such as edge lifting, granular loss, and tab separation, particularly in aging systems or after moderate wind events. Their service life typically ranges from 15 to 20 years, contingent on environmental exposure and installation quality (according to the International Association of Certified Home Inspectors or InterNACHI).

Architectural Shingles

Architectural, or dimensional, shingles consist of multiple laminated layers of asphalt-saturated fiberglass mats, providing increased mass and enhanced mechanical interlock. This multi-layered configuration improves their modulus of elasticity and resistance to wind uplift forces. The irregular geometry and increased thickness contribute to better impact resistance. From a structural engineering standpoint, the higher unit weight imposes a slightly greater dead load but offers improved inertia against fluttering and delamination. These shingles generally exhibit a service life of 25 to 30 years (when adequately maintained). They are better suited for regions with moderate to high wind loads, offering enhanced aesthetic and functional performance (according to the International Association of Certified Home Inspectors or InterNACHI), as shown in **Figure 2**.

You can identify dimensional shingles by their unique look. Unlike 3-tab shingles, these shingles are not cut into identical shapes. Instead, each shingle is manufactured with alternating areas or tabs of single and double layers. This pattern is often referred to as “dragon’s teeth.” Some manufacturers also add a shadow line to some products,

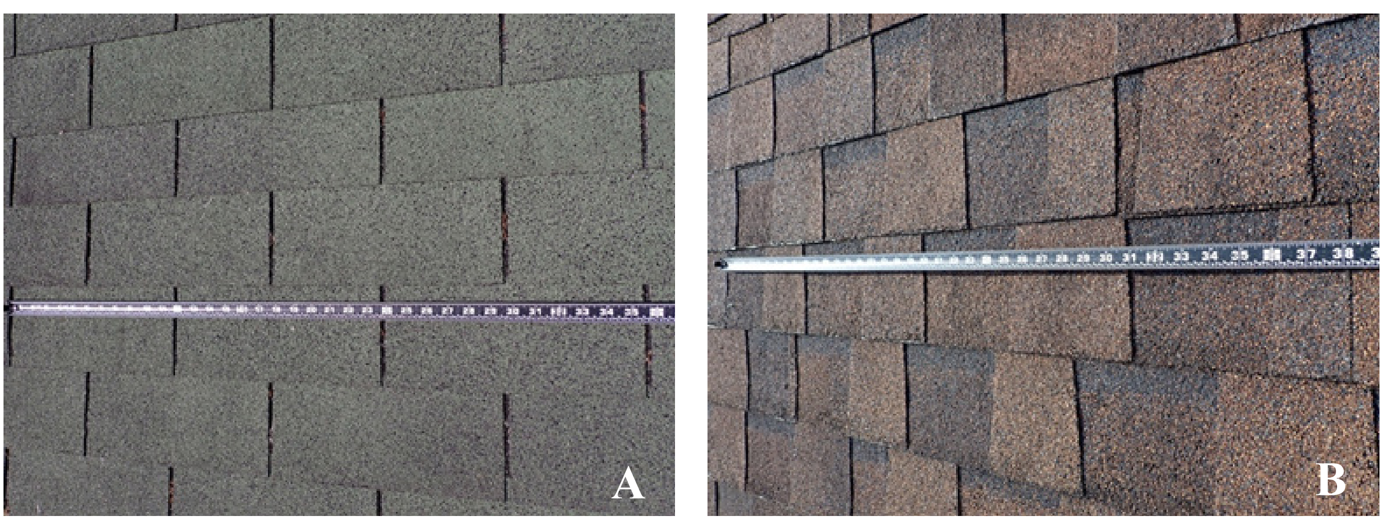

Figure 2
Types of shingles: a) 3-tab, b) architectural.

which is a band of darker granules. The intermittent double-layer tabs, in conjunction with the intermittent shadow band on the single-layer areas, add dimension to the roof — intended to enhance the home's look and style. It is important to note that, from a forensic engineering standpoint, the loss or debonding of the architectural tabs reduces the overall performance of this shingle type.

There are other types of shingles available in the market, such as premium shingles and "hip and ridge shingles." This paper will be limited to field observations gathered from inspections of 3-tab, architectural, and ridge or hip shingles.

Wind-Related Damage

Asphalt shingles are susceptible to damage resulting from a combination of intrinsic material characteristics and extrinsic environmental and structural influences. Intrinsic factors include the physical and mechanical properties of the shingle itself, such as the shingle mat (whether organic or fiberglass-based) chemical composition and aging resistance of the asphalt binder as well as the mineralogical composition and adhesion of surface granules. These elements collectively determine the shingles' resistance to thermal degradation, moisture infiltration, and UV-induced brittleness.

Extrinsic factors, such as improper installation techniques, insufficient sealing, or curing time, and the influence of structural aerodynamics (e.g., uplift pressures from turbulent flow separation at roof edges), significantly impact the shingles' performance under wind-induced loading conditions. While the mechanics of asphalt shingles' damage under high-wind scenarios have been extensively documented[11,12,14,24,29,43,44,45], distinguishing genuine wind-induced failures from damage due to aging, manufacturing defects, or mechanical impacts remains a critical challenge in forensic engineering investigations. Misattribution of wind damage to shingles can lead to incorrect failure diagnoses or disputes in insurance and legal contexts. Therefore, it is essential to understand damage attributable to excessive wind-induced pressures and how it manifests on roof sections.

A previous study was able to identify four primary modes of asphalt shingle failures, which were obtained from field observations performed after Hurricane Frances in 2004[45]. According to the study, the four identified wind-induced damage modes are: 1) creasing (**Figure 3a**); 2) flipping/flapping (**Figure 3b**); 3) tearing/removal (**Figure 3c, Figure 3d** and **Figure 3e**); and 4) abrading from flying or falling debris (**Figure 3f**)[45]. In addition, the study identified factors that can lead to asphalt shingle failure during windstorms, such as degree of weathering, design, quality of manufacture, and quality of installation.

The resistance of asphalt shingles against wind-induced uplift forces is primarily dependent on the sealant strip, which is a strip comprised of bituminous material that acts as a "Velcro" type of attachment between the top and bottom shingle tabs. However, the integrity of the sealant strip is susceptible to age-related deterioration due to exposure to environmental weather conditions (e.g., temperature swings, rain, ice, among others), causing reduction of the bonding capacity between the two asphalt shingle layers, which can lead to complete debonding of the layers. To assess wind-induced damage on asphalt shingles, the material transfer will differentiate between age-related deterioration of the bonding material — where the observations of material transfer between the two asphalt shingle layers would indicate external forces with magnitudes greater than those provided by the bonding force of the sealant strip[12].

Creasing

Shingle creasing refers to the visible lines or ridges often generated because of wind damage. When strong winds lift and flap shingles, they can bend and develop creases, which not only affect the roof's appearance but also indicate potential structural issues of the shingle's internal components (e.g., mat integrity). Creased shingles may lose granules, making them more vulnerable to sun damage, water leaks, and microbial growth.

The creasing of shingles occurs due to excessive wind suction pressures, which generate a lifting force that overcomes the predominant hold-down force provided by the shingle tab sealant plus the shingle self-weight. In a structure under the influence of hurricane wind forces, the highest suction pressures develop on the windward-facing roof slopes and in the roof critical zones identified as roof edges as well as ridges (see **Figure 1** for exact locations of critical zones)[31]. Thus, the creasing of shingles will first develop in windward-facing roof edges/eaves, rakes and hip/ridge lines and then in the roof field. The lack of creased shingles in the most susceptible areas of the windward roof sections, while finding creased shingles in areas less susceptible (e.g., field and leeward roof sections), may indicate that the creasing was caused by external forces unrelated to wind. Note that this statement typically applies when the attachment method of the shingles is uniform across the entire roof area[12,14,45,46].

It must be noted that the capacity of asphalt shingles to counteract the suction pressures induced by wind loading is achieved by the shingles' sealant strip, which bonds the upper layer shingle (bottom edge) with the lower layer shingle (upper edge). The sealant strip is made out of bituminous material, which ages with time, causing a reduction in the wind resistance[44] and making the roof prone to premature wind-induced damage such as creasing.

Figure 3
Wind-related damage: a) creasing, b) flipping/flapping, c) tearing of hip shingles, d) tearing of ridge shingles, e) removal, and f) windborne debris impact (linear pattern).

Flipping/Flapping

Shingle flipping/flapping is a failure mechanism observed in asphalt shingles, characterized by the uplift and permanent deformation of individual shingles due to aerodynamic loading. This phenomenon initiates when the shingle is detached from its asphalt sealant strip, typically as a result of wind-induced pressures exceeding the adhesive bond strength. Once unsealed, the leading edge of the shingle is susceptible to uplift and rotation.

If the imposed deformation exceeds the elastic limit of the shingle assembly (comprising the asphalt coating and the fiberglass or organic mat), the material undergoes localized creasing. This creasing represents a plastic deformation process in which the mat's flexural stiffness is irreversibly compromised, and the asphalt matrix may exhibit both macro and micro fracturing or cohesive failure. The result is a permanent loss of structural and elastic recovery capacity. Once this threshold is exceeded, the shingle is unable to return to its original installed position, thereby losing its functional performance in terms of wind resistance, water shedding, and overall system integrity. Similar to the shingle creasing phenomenon, shingle flipping/flapping will develop in the roof slopes facing the predominant wind direction and should first appear in roof edges/eaves, rakes and hip/ridge lines, before manifesting in the roof field[12,14,45,46].

Tearing/Removal

Wind-induced forces pose a significant challenge to the integrity of roof shingles, often leading to tearing or complete removal of roof covering sections. High wind speeds generate dynamic pressures and suction forces across the roof surface, particularly at edges and corners where airflow separation creates localized low-pressure zones. These forces exert uplift and shear stresses on shingles, exceeding their adhesive and mechanical fastening capacities.

Factors such as material properties, installation quality, and roof geometry further influence susceptibility to damage. Prolonged exposure to cyclic wind loading can weaken adhesive bonds and fatigue shingle tabs, initiating cracks or tears that propagate under subsequent wind events. In extreme wind events, such as hurricanes, intense uplift forces can dislodge entire shingle sections that compromise the roof's protective barrier, especially in the most susceptible areas of the roof, and expose the underlayment to environmental and wind damage. Understanding these mechanisms is critical for developing wind-resistant roofing systems and improving building codes in high-wind regions[12,14,45,46].

Windborne Debris Impact to Shingle Roofs

As defined by ASCE 7-22[31], the *2023 Florida Building Code* (FBC)[47] and the *2024 International Building Code* (IBC)[48], windborne debris refers to objects propelled by high winds during extreme weather events, posing a risk to the building envelope, particularly glazed openings.

Mechanical damage to asphalt shingles resulting from windborne debris is a significant failure mode observed in residential and light commercial roofing systems subjected to severe wind and storm events. This damage mechanism arises when solid objects entrained by high winds impact the shingle surface with sufficient kinetic energy to compromise its protective and structural function. Windborne debris, such as branches, loose construction materials, or gravel, can cause tearing, puncturing, edge lifting, or complete shingle detachment, especially in older or poorly fastened roofing systems. The nature and severity of the damage depend on various factors, including debris shape, mass, and velocity; impact angle; shingle composition; installation quality; and exposure age. Granular loss leaves the underlying bitumen layer exposed to UV radiation and moisture, initiating premature aging and leakage pathways[12,14,45,46].

The Federal Emergency Management Agency (FEMA) has extensively documented such damage patterns through post-disaster assessments, highlighting their widespread occurrence and role in initiating progressive roof system failures. For instance, the FEMA findings after Hurricane Charley in 2005[49] note that windborne debris and hail often work in tandem with uplift forces to weaken the roof covering, especially in cases where shingles are not rated for high-wind or impact resistance. FEMA's analysis emphasizes that improperly installed or inadequately secured shingles are particularly susceptible to damage, even under moderate impact loads. The report further recommends the use of asphalt shingles that meet or exceed Class 4 impact resistance standards as defined by UL 2218[50] and high-wind performance classifications under ASTM D7158[51], particularly in regions designated as high-wind or hail-prone zones[49].

Nonwind-Related Damage

Asphalt shingles are susceptible to a variety of nonwind-related damage mechanisms that compromise the roof system's integrity over time. From a forensic engineering perspective, several contributory factors must be considered in diagnosing shingle failure unrelated to wind uplift forces[46]. Improper installation practices, including misalignment, under-driven or over-driven fasteners, and inadequate surface preparation, can create stress concentrations and initiate premature distress[12,14,45,30]. Sealant strip failure (whether due to contamination, poor adhesion, insufficient activation, or age) can diminish inter-shingle bonding, making the system more vulnerable to moisture infiltration and material displacement.

Manufacturing inconsistencies, such as variable asphalt saturation, granule loss, or dimensional irregularities, further affect shingle performance and durability. Age-related material degradation, exacerbated by UV radiation and environmental exposure, leads to embrittlement and cracking. Thermal expansion and contraction cycles introduce fatigue stresses, often manifesting as buckling or splitting along the shingle body. Additionally, mechanical damage from foot traffic or tool impact, as well as external abrasions from overhanging vegetation or animal interference, contribute to localized wear and physical compromise. A comprehensive evaluation of these factors is essential in forensic assessments aimed at distinguishing between wind-induced and other failure modes in asphalt shingle roofing systems that are nonwind-related. The most common field observations of nonwind-related damage to asphalt shingles are presented in the following paragraphs.

Shingle Debonding

Shingle debonding, specifically the loss of adhesion along the sealant strip, is a critical issue in asphalt shingle roofing systems and has been widely documented across in-situ assessments and post-storm evaluations. The sealant strip, a thermally activated bitumen-based adhesive located along the leading edge of each shingle, is essential in transferring uplift forces through the roofing assembly[13].

Field investigations have shown that partial or full unsealing of shingles can occur as roofs age, independent of wind loading. A comprehensive survey in Florida revealed that up to 79% of shingle strips on roofs older than six years exhibited signs of unsealing, with the phenomenon notably absent in roofs younger than six years[12,14]. The primary mechanism behind field shingle debonding appears to be internal shear failure of the sealant strip, driven by long-term thermal cycling that imposes repetitive expansion and contraction stresses on the shingle system[45]. Unsealing patterns tend to follow the geometry of shingle installation — that is diagonal patterns for diagonally laid shingles and vertical patterns for vertically laid ones. Additionally, the unsealing patterns are often localized to the extreme end tabs of 3-tab shingles or along specific courses in laminate shingles[12,14] (**Figure 4**).

In contrast, debonding observed at hip and ridge caps frequently stems from either inadequate sealant application during installation or weak initial adhesive bonding, rather than aging-related mechanisms. Typically, field inspections of debonded shingles reveal improper nailing or nailing over the sealant strip, in which fasteners were driven over the sealant strip of the downslope shingles. This phenomenon results in a reduced uplift capacity of the shingles to resist wind forces.

Shingle Mechanical Damage

Mechanical damage to asphalt shingles encompasses a broad spectrum of nonwind-related physical impacts that compromise the integrity, performance, and longevity of roofing systems. As described in previous investigations/assessments[45,30], this type of damage often results from

Figure 4
Shingle diagonal debonding pattern.

incidental contact with overhanging tree limbs, animal activity, foot traffic, or even deliberate actions. Such impacts may lead to localized abrasions, granule displacement, tears, marring, or deformation of individual shingle elements.

Scuffing from foot traffic, displacement under pressure (especially on hot shingles) and flaking due to weak granule adhesion are examples of mechanically induced conditions that expose the asphalt-impregnated base mat, accelerating degradation through UV radiation.

Unlike wind-induced uplift damage, mechanical damage tends to appear in irregular patterns, typically concentrated in walkable areas away from zones of high suction pressures. Intentional or misattributed damage may also be identified by specific patterns, such as the removal of shingle corners rather than complete tab displacement. Marshall et al. (2010)[45] further noted that the presence of torn sealant remnants can indicate that shingles were originally well bonded, requiring significant force for separation (likely caused by forceful attempts to manually simulate wind damage), a key distinction in post-storm forensic evaluations (**Figure 5**). Given the potential for mechanical damage to reduce a roof's water-shedding capability or service life, accurately identifying its source may be valuable for an owner requesting insurance assessments and structural evaluations of roofing systems.

Shingle Cupping and Clawing

Cupping and clawing are deformation patterns in asphalt shingles that affect both the visual appearance and functional performance of steep-slope roofing systems, often leading to misidentification as wind damage. Cupping refers to the upward curling of the shingle corners or the butt edge, producing a concave distortion that can protrude up to 1 inch above the roof surface, while clawing is the downward curling of the shingle corners toward the roof deck[45,46]. These anomalies typically begin within the first few years of service (sometimes as early as 18 months after the shingles have been installed), and said damage is observed in both square-tab and traditional 3-tab fiberglass shingles. Such anomalies result from a combination of factors, including long-term material fatigue, aging of the asphalt binder, thermal cycling, and inadequate attic ventilation[44].

Cupping occurs when the top layers of the shingles shrink more than the lower layers, whereas clawing initiates at the exposed corners and progresses inward. The progression of both distortions is characterized by initial deformation on the shingle tabs edges (**Figure 6**). Although commonly dismissed as aesthetic issues, these forms of deformation may signal underlying structural degradation and increase susceptibility to cracking or wind uplift over time. Differentiating them from true wind-induced failures, such as creasing or tearing, is essential for accurate roofing evaluations and insurance assessments[45,46].

Shingle Blistering and Granular Loss

Blistering and granular loss are common asphalt shingle anomalies (both of which are nonwind-related), and can compromise the long-term performance of residential roofing systems.

Granular loss refers to the shedding of the protective granule layer from the shingle surface, which exposes the underlying asphalt-impregnated base mat to UV radiation and mechanical damage, thereby accelerating deterioration and potentially shortening the roof's service life[30]. While hail and windborne debris impacts can cause acute and localized granule displacement (meeting the definition of "damage" due to reduced water-shedding capability), granular loss can also result from non-impact-related mechanisms such as aging, scuffing from foot traffic, marring, flaking, and general mechanical abrasion[50].

Blistering, on the other hand, is a material defect caused by gas pockets within the base mat that rise to the surface and release, displacing granules in small, scattered patterns. This condition typically manifests in areas of poor ventilation of the attic below the damaged shingles and is distinguished from hail impact by the size and distribution of the affected areas. Unlike hail damage, which is round and localized, blistering produces smaller and more random granule loss that can be mistaken for impact damage (**Figure 5**). Differentiating between these forms of deterioration is crucial during forensic assessments to ensure accurate attribution of cause and to avoid misclassification in roofing evaluations[30].

Shingle Splitting

Shingle splitting is a failure mode that results from long-term thermal cycling and material fatigue, typically manifesting as cracks or splits in asphalt shingles. According to previous studies[12,14], splitting often occurs at the end joint of the shingle course below, with cracks emanating from this point due to internal tensile failures in the fiberglass reinforcement mat. This type of failure is exacerbated by the repeated expansion and contraction of the shingle material caused by fluctuating temperatures over its service life. Over time, the tensile strength of the reinforcement mat may degrade to the point where the mat can no longer withstand thermal stresses, leading to splitting.

Koonts (1990)[52] further attributes this failure to insufficient tensile strength of the mat, which, when combined with the shear forces acting on the sealant strip, results in

Figure 5
Nonwind-related damage: a) debonding, b) tree abrasion, c) animal activity, d) blistering, e) granular loss, and f) alligatoring.

cracking. These splits are typically observed more frequently in aged shingles, with studies showing that the likelihood of such failures increases as the roof ages, particularly after six years of service[12,14].

Shingle splitting can take several forms, including horizontal, vertical, random, and in-line cracking. Horizontal splitting occurs between the two lines of restraint, with one part of the shingle fastened to the roof deck and the other edge secured by the sealant strip. Vertical splitting typically occurs when the top shingles shrink over the butted joints of the underlying shingles, with splits extending vertically upslope in racked installations and in curved patterns in diagonally installed shingles[45]. A couple of examples of shingle thermal splitting are provided in **Figure 6**.

Severe splitting of aged shingles is typically referred to as "alligatoring," since the cracked and wrinkled appearance of the shingles surface resembles the hide of an alligator (**Figure 5**). Random cracking does not follow any distinct pattern, often starting as surface crazing and eventually leading to complete splits as the shingle ages, while in-line cracking occurs directly above joints in the sheathing panels, depending on the movement of the roof decking[46]. These cracks can significantly compromise the roof's structural integrity, increasing the risk of water infiltration and wind damage, making shingle splitting a critical concern for designers and contractors.

Concrete/Clay Tile Roofs

Globally recognized for its timeless design and resilience, tile roofing stands apart with a heritage unmatched by any other roofing material. Although tiles have played a vital role in architecture for thousands of years, the modern era has seen a remarkable surge in innovation and industry development[53,54]. As such, concrete and clay tiles are among the most prevalent types of roofing materials.

Concrete tiles are typically made from a blend of

Figure 6
Nonwind-related damage: a) clawing, b) cupping (or curling), c) random thermal splitting, and d) horizontal thermal splitting.

Portland cement, sand, and water in varying ratios. This mixture is then shaped under high pressure using individual molds. Often, the tile surface is treated with cement-based materials and enhanced with synthetic oxides to create a glossy finish, or colored by adding pigments directly to the mix. The final surface can be either smooth or textured. Once molded, the tiles are placed in controlled environments with regulated temperature and humidity to undergo hydration and achieve the necessary strength prior to distribution. Among concrete tiles, the most widely used designs in the roofing industry are the high-profile S-curved tiles and the flat-style varieties, both represented in **Figure 7**[55].

Conversely, clay tiles are derived from natural materials such as clay, shale, or similar earth-based substances. These tiles are shaped and then hardened through a high-temperature firing process. In the United States, S-shaped clay tiles are the most popular configuration, also illustrated in **Figure 7**[41]. Despite the aesthetic and historical appeal of clay tiles, concrete tiles are often favored due to their superior durability, strength, and resilience against long-term weathering effects[56].

Concrete tiles are produced in a range of sizes, profiles, and colors. They are generally thicker at the top and bottom, with strengthening ribs between those points. The upper part of the tile, which rests on a wooden batten, is known as the "head lug," while the "nose lug" refers to the section that overlaps with the course of tiles below it (**Figure 7**). Modern flat and curved tiles often feature interlocking systems with ribs and grooves along their edges. These interlocks enhance structural alignment, ensure consistent spacing and mitigate moisture intrusion beyond the tile. The interlocking strip is usually about 1 inch wide and half the tile's thickness on either side[55].

Wind-Related Damage

The impact of wind forces on roofs with permeable coverings, such as tiles, is influenced by several factors,

Figure 7
a) S-shaped concrete tile, b) flat concrete tile, c) S-shaped clay tile, d) head and nose lugs in flat tiles.

including the overall roof profile (e.g., configuration and slope), the design details of the roof covering elements, and the degree of roof porosity. Tile systems are generally known for their strong resistance to environmental stressors, yet extreme weather conditions can still affect them to varying extents. During high wind events, damage to tile roofs becomes clearly visible. Common signs include displaced tiles, tiles entirely blown off the roof (indicating direct wind damage), and fractured tiles caused by impact with windborne debris (signifying indirect wind damage). This section will focus on direct and indirect wind damage to tile roofs.

Tile Uplift

As previously noted in the discussion on common wind damage patterns, hip, ridge, and perimeter tiles are particularly vulnerable to wind-related damage. This increased susceptibility arises because these tiles are situated in regions (previously referred to as "high suction pressure zones") where wind flow separation and conical vortex formation generate intense, localized suction forces or uplift pressures. While field tiles may also experience the effects of these conical vortices, the strength of the vortices and the resulting negative pressures tend to diminish as wind moves away from the roof corners and edges[19,57,58,59,60,61,62].

Some roof manufacturers, especially in recent times, have included additional fasteners in these zones to increase wind resistance in these zones. Further studies have shown that most roof damage tends to occur on the windward side, where tiles are subjected to higher net uplift forces. This is because both external and internal pressures (with internal pressure forming in the gap between the tiles and the roof deck) align in the same direction, increasing the overall forces on these tiles. In contrast, tiles on the leeward side benefit from a reduction in stress, as the internal and external forces act in opposite directions, providing a degree of relief[63,64,65,66] (**Figure 8**).

According to the *2023 Florida Building Code* (FBC)[47], to dislodge a tile, the overturning moment produced by wind-induced suction must exceed the resisting moment, which is determined by factors such as the tile's weight, attachment method to the roof deck, tile size, tile profile, and other related parameters. As previously noted, clay and concrete tiles are typically secured to the roof with fasteners or adhesives such as foam or mortar in high wind zones such as coastal Florida. However, in certain regions as well as in the case of the hip and ridge zones, tiles are installed using mortar.

Field investigations and past reconnaissance have shown that mortar attachments are often inadequate to withstand the high uplift pressures experienced during hurricanes, particularly in storm-prone areas. This is mainly because mortar tends not to bond effectively with the tiles unless the tiles are pre-wetted — a practice indicative of less effective construction[53]. Consequently, when subjected to extreme wind forces, tiles either detach from the mortar or tear the underlayment, leading to significant roof damage[54] (**Figure 8**).

Windborne Debris Impact to Tile Roofs

Roof tiles are highly susceptible to damage from windborne debris during high-wind events such as hurricanes, where debris may originate from various sources, including broken tree limbs, dislodged rooftop equipment, cladding components, or even other roof coverings like tiles and pavers. As established by Kordi and Kopp[67], the likelihood of roof tiles becoming airborne and contributing to further damage is closely tied to their orientation relative to the oncoming wind.

When the angle of exposure aligns with favorable aerodynamic conditions, tiles can be uplifted and transformed into projectiles, traveling downwind and potentially compromising the roof coverings of both the originating structure and neighboring buildings. Their study[67] found that tile flight velocities typically range between 30% and 60% of the mean roof-height gust speed at the moment of failure. This underscores the significance of initial aerodynamic conditions in the behavior of roof-covering components as debris.

Beyond the hazards posed by flying tiles, the impact of such debris on intact roofing systems can be severe. According to a previous research investigation, projectile impacts on tiled roofs often result in localized cracking or shattering of the impacted tiles (**Figure 8**). However, the damage extends beyond the point of impact; loss of tiles due to projectile strikes can lead to breaches in the roof covering that promote wind infiltration beneath adjacent tiles, thereby escalating the overall damage through progressive failure[68]. Comparative testing between concrete and clay tiles revealed key performance differences: concrete tiles exhibited 39% greater resistance to impact forces than clay tiles[67]. Moreover, concrete tiles tended to break in larger, more localized pieces, particularly when bonded with mortar, absorbing the impact energy. In contrast, clay tiles tended to shatter extensively, creating larger areas of failure around the impact zone[68].

Figure 8

Wind-related damage: a) uplifting of hip cap tiles, b) uplifting of ridge cap tiles, c) impact with windborne debris, d) fractures from impact with windborne debris (black arrows indicate oncoming wind direction on the date of loss).

Damage to concrete roof tiles induced by windborne debris displays distinct failure mechanisms and fracture characteristics when compared to mechanical damage from nonwind-related sources. Windborne debris impacts are typically high-velocity and irregular, arising during extreme wind events such as hurricanes. These impacts frequently result in localized, brittle failures manifesting as transverse cracking, edge fragmentation, or surface spalling with the most damage observed on roof slopes oriented toward the prevailing wind direction (**Figure 8**).

Such damage can undermine the aerodynamic performance of the roof system, potentially triggering progressive dislodgement of adjacent tiles[68]. The severity and pattern of failure are influenced by multiple factors, including the tile's orientation relative to the wind, the quality of its underlying support, and the method of installation, among others.

Nonwind-Related Damage

While known for their aesthetic appeal and long-term durability, clay and concrete tile roofing systems are nonetheless susceptible to various nonwind-related degradation mechanisms that can compromise performance and reduce service life. From a forensic engineering perspective, identifying and differentiating these modes of failure from wind-induced damage is essential for accurate post-event assessments and insurance determinations[69.70.71]. The most common field observations of nonwind-related damage to the roofing tiles are presented below.

Improper Tile Installation

Tile roofs are particularly vulnerable to damage resulting from improper installation practices. Common errors include insufficient fastening (e.g., using incorrect nails or omitting required fasteners), poor alignment, and improper mortar bedding or foam adhesive application[72,73]. These deficiencies introduce localized stress concentrations, reduce mechanical interlock, and create voids or misalignments that may lead to premature tile cracking or slippage under normal thermal or mechanical loads[69] (**Figure 9**).

Additionally, improper installation includes nail heads that are installed flush with the tile surface restraining the tiles from any movement. Such practices lead to premature linear cracking of the tiles at the nail penetration location. Improper installation also renders the tiles susceptible to flutter/chatter during repeated windstorm events, which loosens the fasteners further, abrade the underlayment and exposes the roof underlayment to moisture intrusion. The loosening of these fasteners aggravates the tile

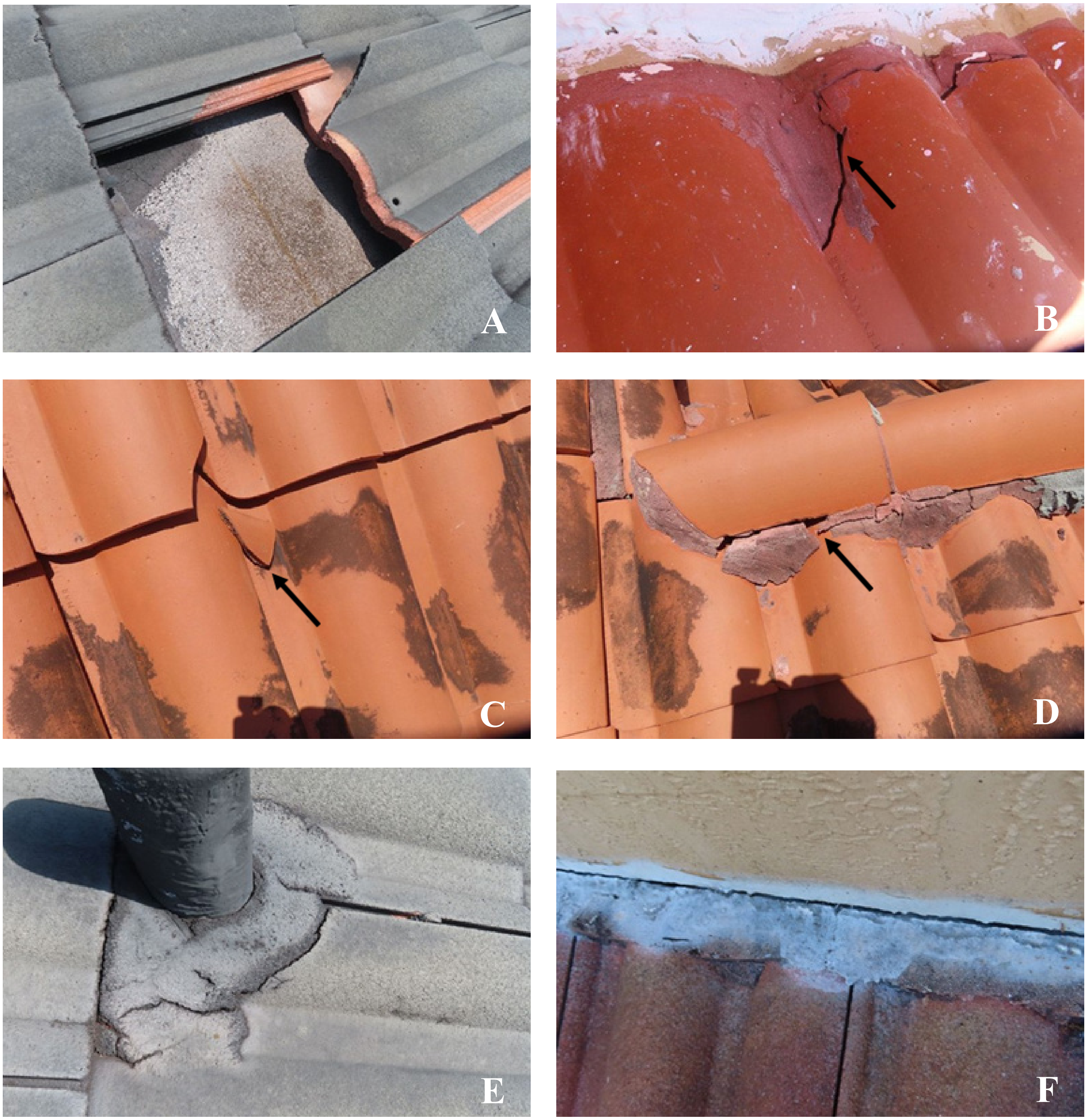

Figure 9

Nonwind-related damage: a) downward shifted tile due to missing fastener, b) improperly sized tile and poor alignment, c) corner chipped tile, d) premature cracking and chipping of mortar, e) cracked mortar around a plumbing vent, f) cracked mortar at roof-to-wall interface.

movement and furthers deterioration. It is important to note that the fluttering/chattering of tiles is commonly observed in steeper roofs and such tiles are recommended to be installed with wind clips along with a construction-grade sealant as a precaution to prevent instability and movement of the tiles from excessive pressures, especially in the high suction pressure zones[48].

Material Quality Control and Defects in Tiles

Tile manufacturing and material inconsistencies, such as a lack of quality control to ensure dimensional regularities, porosity, and proper mix proportions of mortar, can lead to premature deterioration and subsequent cracking. Concrete tiles with improper quality control are more susceptible to thermal degradation[74]. Clay tiles with dimensional variances are more susceptible to edge/corner chipping and fatigue cracking during the expected useful life of the roof[75]. The absence of gouges or holes at or near the intersection of the fractures may be a further indication that the cracking is not the result of impact with windborne debris. The brittleness of clay tiles and the shrinkage of cement in concrete tiles contribute to cracks or corner chips under cyclical loading[71]. The inadequate quality control of the mortar mix, insufficient curing time, or improper curing of the mix lead to premature cracking of the mortar (**Figure 9**).

Nonwind-Related Impact Damage to Tiles

Impact damage is a leading cause of nonwind-related failure in tiled roofing systems. This includes localized cracking from foot traffic, impacts from overhanging branches, and tool or ladder contact during maintenance activities. Such cracks are typically irregular and located in walkways, valley intersections, or under satellite dish mounts[69,76]. Concrete tiles, though more resilient than clay, are still susceptible to cracking or chipping at unsupported corners when subjected to concentrated loads emanating from foot traffic and mechanical impact[70] (**Figure 10**).

Footfall damage to roof tiles is typically evidenced by a linear nature of the cracks and lack of radial cracks emanating from point of impact to broken tile surfaces. Broken tile pieces typically remain in place or are slightly displaced downward, depending on the age of the fracture itself. As such, broken tile fragments that remained in place are evidence that the cracking was not caused by wind, as strong wind would have removed the cracked portion from its original position.

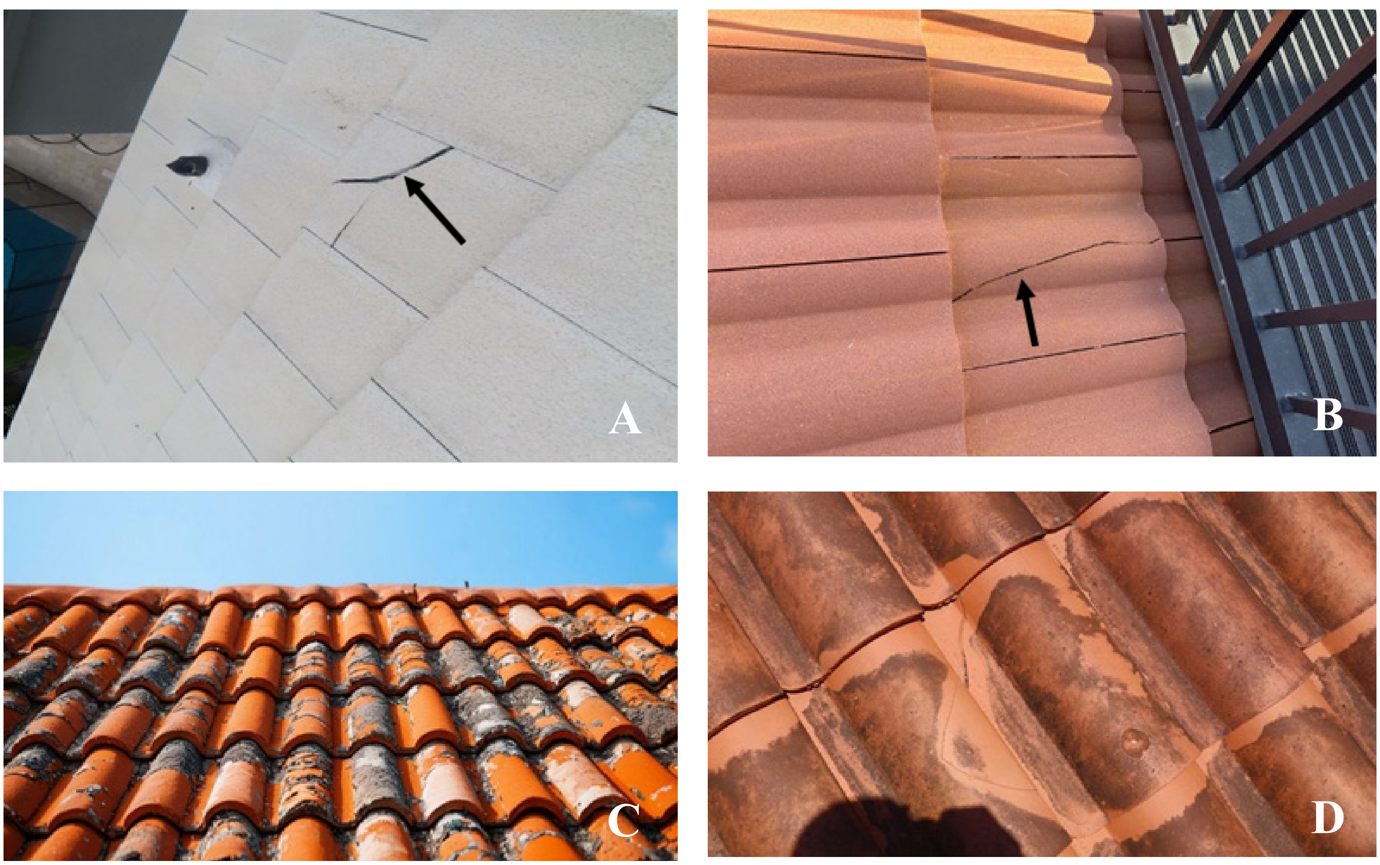

Figure 10
Nonwind-related damage: a) footfall damage, b) fractured tile due to foot traffic, c) algae accumulation, d) mildew growth.

Biological and Environmental Effects in Tiles

Moss, algae, and lichen growth can degrade both clay and concrete tile surfaces. These organisms retain moisture against the tile, encouraging efflorescence and biological etching over time. Root systems from lichens and mosses can expand existing microcracks and lead to mechanical tile displacement[77,78]. Furthermore, animal activity, such as droppings, often damages the surface of the tile, resulting in gradual deterioration and discoloration of tiles[71] (**Figure 10**).

Conclusion

Based on extensive experience evaluating hundreds of roofs for potential wind damage, and understanding of windstorm events, wind flow around structures, and bluff-bodies in the built environment, the following general guidelines are recommended for evaluating wind damage:

- A crucial first step involves reviewing wind speeds, including both sustained winds and gusts, during and around a particular storm event. This helps determine whether wind speeds were sufficient to cause uplift and failure of roofing components. This step also includes obtaining the duration for which the wind speed was sustained to determine the amount of time the structure was exposed to windstorms.

- Wind direction also plays a prominent role, as higher damage is typically observed on windward-facing roof slopes. Wind damage consistently occurs in high-pressure zones, as outlined in the ASCE 7-22 standard as previously discussed. Therefore, the initial indications of wind damage are often located at the edges, corners, ridge lines, and hip lines of a roof. For recent construction, a higher emphasis is placed on adding more fastening mechanisms in the high-suction pressure zones and hence, it is recommended to review the manufacturer specifications whenever applicable. For shingle roofs, this damage often manifests as compromised sealant strips, creasing, tearing, folding, or missing shingles. For tile roofs, typical damage includes broken, missing, uplifted or displaced tiles.

- Damage caused by windborne debris during storms can be classified based on the randomized nature of debris impacts, the damage patterns noted on the roof covering, and the location of these impacts. In cases of indirect wind damage caused by windborne debris, a thorough evaluation of collateral evidence (including oncoming wind direction on or around the date of loss) and a holistic understanding of potential damage to other vulnerable elements such as mechanical equipment, garage doors or roof top equipment are critical.

- Installation deficiencies, manufacturing imperfections, age-related deterioration, and nonwind-related damage patterns should be considered. Such deficiencies include debonding, splitting, cupping and clawing, granular loss, and mechanical damage to shingle roofs, footfall damage, biological growth, and thermal chipping and cracking to tile roofs among other forms of damage.

Forensic experts, equipped with insights into how roofing materials respond to impact forces and practical experience examining storm damage, are exceptionally positioned to evaluate storm-induced damage to residential roofing systems, including both shingle and tile roofs. The authors' forensic engineering experience indicates that engineers must adopt a holistic approach when evaluating a roof for wind damage. Each failure mechanism discussed in this paper must be considered in light of the roof's history and either included or excluded based on the observed physical evidence at the time of the inspection.

Acknowledgements

The authors greatly acknowledge the internal support provided by DDA Forensics and the engineering team. The contents of this paper reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein.

References

1. B. Norcross, Hurricane Almanac: The Essential Guide to Storms Past, Present, and Future, St. Martin's Press, 2007.

2. K. Emanuel, Divine Wind: The History and Science of Hurricanes, Oxford University Press, 2005.

3. J. Holmes, Wind Loading of Structures, 4th Ed., Taylor & Francis, 2021.

4. NOAA, "Population Trends from 1970 to 2020," National Oceanic and Atmospheric Administration, National Coastal Population Report, 2023.

5. Z. Azzi, H. Al Sayegh, O. Metwally and M. Eissa, “Review of Nondestructive Testing (NDT) Techniques for Timber Structures,” Infrastructures, vol. 10, no. 28, 2025.

6. K. Vutukuru, M. Moravej, A. Elawady and A. Chowdhury, “Holistic Testing to Determine Quantitative Wind-Driven Rain Intrusion for Shuttered and impact Resistant Windows,” Journal of Wind Engineering and Industrial Aerodynamics, vol. 206, 2020.

7. MDC-BCCO, “Post Hurricane Wilma Progress Assessment,” Miami-Dade County Building Code Compliance Office, Miami, FL, 2006.

8. W. Suaris and P. Irwin, “Effect of Roof-Edge Parapets on Mitigating Extreme Roof Suctions,” Journal of Wind Engineering and Industrial Aerodynamics, vol. 98, p. 483–491, 2010.

9. Z. Azzi, F. Habte, A. Elawady, A. Chowdhury and M. Moravej, “Aerodynamic Mitigation of Wind Uplift on Low-Rise Building Roof Using Large-Scale Testing,” Frontiers in Built Environment, vol. 5, no. 149, 2020.

10. G. Bitsuamlak, W. Warsido, E. Ledesma and A. Chowdhury, “Aerodynamic Mitigation of Roof and Wall Corner Suctions Using Simple Architectural Elements,” Journal of Engineering Mechanics, vol. 139, no. 3, pp. 396-408, 2013.

11. M. Noone and W. Blanchard, “Asphalt Shingles — a Century of Success and Improvement,” in Tenth Conference on Roofing Technology, Gaithersburg, Maryland, USA, 1993.

12. C. Dixon, F. Masters, D. Prevatt, K. Gurley, T. Brown, J. Peterka and M. Kubena, “The Influence of Unsealing on the Wind Resistance of Asphalt Shingles,” Journal of Wind Engineering and Industrial Aerodynamics, vol. 130, pp. 30-40, 2014.

13. J. Peterka, J. Cermak, L. Cochran, B. Cochran, N. Hosoya, R. Derickson, C. Harper, J. Jones and B. Metz, “Wind Uplift Model for Asphalt Shingles,” Journal of Architectural Engineering, vol. 3, no. 4.

14. C. Dixon, D. Prevatt, F. Masters and K. Gurley, “The Unsealing of Naturally Aged Asphalt Shingles: An In-Situ Survey,” in 1st Residential Building Design & Construction Conference, Bethlehem, PA, USA, 2013.

15. D. Banks, R. Meroney, P. Sarkar, Z. Zhao and F. Wu, “Flow Visualization of Conical Vortices on Flat Roofs with Simultaneous Surface Pressure Measurement,” Journal of Wind Engineering and Industrial Aerodynamics, vol. 84, p. 65–85, 2000.

16. B. Bienkiewicz and Y. Sun, “Wind Loading and Resistance of Loose-Laid Systems,” Journal of Wind Engineering and Industrial Aerodynamics, vol. 72, no. 1, pp. 401-410, 1997.

17. G. Kopp, C. Mans and D. Surry, “Wind Effects of Parapets on Low Buildings: Part 4. Mitigation of Corner Loads with Alternative Geometry,” Journal of Wind Engineering and Industrial Aerodynamics, vol. 93, pp. 873-888, 2005.

18. G. Kopp, D. Surry and C. Mans, “Wind Effects of Parapets on Low Buildings: Part 1. Basic Aerodynamics and Local Loads,” Journal of Wind Engineering and Industrial Aerodynamics, vol. 93, pp. 817-841, 2005.

19. R. Hazelwood, “The Interaction of the Two Principal Wind Forces on Roof Tiles,” Journal of Wind Engineering and Industrial Aerodynamics, vol. 8, pp. 39-48, 1981.

20. C. Feng, A. Chowdhury, A. Elawady, D. Chen, Z. Azzi and K. Vutukuru, “Experimental Assessment of Wind Loads on Roof-to-Wall Connections for Residential Buildings,” Frontiers in Built Environment, vol. 6, 2020.

21. K. Alawode, K. Vutukuru, A. Elawady and A. Chowdhury, “Review of Wind Loading on Roof to Wall Connections in Low-Rise Light Wood-Frame Residential Buildings,” Journal of Wind Engineering and Industrial Aerodynamics, vol. 236, 2023.

22. H. Kawai and H. Nishimura, "Field Measurement on Wind Force on Roof Tiles, Texas Tech University, Lubbock, Texas," in Proceedings of the 11th International Conference on Wind Engineering, Texas Tech University, Lubbock, Texas, USA, 2003.

23. A. Robertson, R. Hoxey, N. Rideout and P. Freathy, "Full-scale study of wind loads on roof tiles and felt underlay and comparisons with design data," Journal of Wind Engineering and Industrial Aerodynamics, vol. 10, no. 6, pp. 495-510, 2007.

24. B. Visscher and G. Kopp, "Trajectories of roof sheathing panels under high winds," Journal of Wind Engineering and Industrial Aerodynamics, vol. 95, pp. 697-713, 2007.

25. Z. Azzi, F. Habte, K. S. Vutukuru, A. G. Chowdhury and M. Moravej, "Effects of roof geometric details on aerodynamic performance of standing seam metal roofs," Engineering Structures, vol. 225, no. 111303, 2020.

26. H. Al Sayegh, A. Chowdhury, I. Zisis, A. Elawady, J. Estephan and A. Tolera, "Full-scale experimental investigation of wind loading on ballasted photovoltaic arrays mounted on flat roofs," Journal of Wind Engineering and Industrial Aerodynamics, vol. 256, 2025.

27. P. Krishna, "Wind loads on low rise buildings - A review," Journal of Wind Engineering and Industrial Aerodynamics, vol. 54/55, pp. 383-396, 1995.

28. T. Stathopoulos, "Wind loads on low-rise buildings: a review of the state of the art," Engineering Structures, vol. 6, no. 2, pp. 119-135, 1984.

29. A. Tolera, K. Mostafa, A. Chowdhury, I. Zisis and P. Irwin, "Study of wind loads on asphalt shingles using full-scale experimentation," Journal of Wind Engineering and Industrial Aerodynamics, vol. 225, 2022.

30. L. Sharara, J. Jordan and R. Kimble, "Residential Roofing Evaluation," in Fifth Forensic Engineering Congress, Washington, D.C., USA, 2009.

31. ASCE/SEI-7, Minimum Design Loads and Associated Criteria for Buildings and Other Structures, Reston, VA, USA: American Society of Civil Engineers (ASCE), 2022.

32. Y. Quan, Y. Tamura, M. Matsui, S. Cao and A. Yoshida, "TPU Aerodynamic database for low-rise buildings," in Proceedings of the 12th International Conference on Wind Engineering (ICWE12), Cairns, Australia, 2007.

33. Y. Tamura, "Wind and Tall Buildings," in Keynote Lecture: the 5th Europe-African Regional Conference on Wind Engineering (EACWE5), Florence, Italy, 2009.

34. D. Prasad, T. Uliate and M. Rafiuddin Ahmed, "Wind Loads on Low-Rise Building Models with Different Roof Configurations," International Journal of Fluid Mechanics Research, vol. 36, pp. 231-242, 2009.

35. T. Ho, D. Surry, D. Moorish and G. Kopp, "The UWO Contribution to the NIST Aerodynamic Database for Wind Loads on Low Buildings: Part 1. Archiving Format and Basic Aerodynamic Data," Journal of Wind Engineering and Industrial Aerodynamics, vol. 93, no. No.1, pp. 1-30, 2005.

36. S. Wagaman, K. Rainwater, K. Mehta and R. Ramsey, "Full-Scale Flow Visualization Over a Low-Rise Building," Journal of Wind Engineering and Industrial Aerodynamics, vol. 90, no. No.1, pp. 1-8, 2002.

37. D. Hrishikesh, I. Zisis and M. Matus, "Effects of Roof Shape on Wind Vulnerability of Roof Sheathing Panels," Journal of Structural Safety, vol. 100, 2023.

38. O. Metwally, H. Ibrahim, A. Elawady, I. Zisis and A. Chowdhury, "Wind Load Impact on Tall Building Facades: Damage Observations During Severe Wind Events and Wind Tunnel Testing," Frontiers in Built Environment, vol. 10, 2025.

39. M. Eissa, O. Metwally, K. Alawode, A. Elawady and G. Lori, "Performance of High-Rise Building Façades under Wind Loading: A State-of-the-Art Review," Journal of Building Engineering, vol. 113, 2025.

40. L. Marslan, K. Nguyen, Y. Zhang, Y. Huang, Y. Abu-Zidan, T. Gunawardena and P. Mendis, "Improving Aerodynamic Performance of Tall Buildings Using Façade Openings at Service Floors," Journal of Wind Engineering and Industrial Aerodynamics, vol. 225, 2022.

41. NIST, "Generic Clay Roofing Tile," National Institute of Standards and Technology, 2005.

42. H. Snoke, "Asphalt-Prepared Roll Roofings and Shingles," National Bureau of Standards, Report BMS70, 1941.

43. W. Cullen, "Research and Performance Experience of Asphalt Shingles," in 10th Conference on Roofing Technology, Gaithersburg, MD, USA, 1993.

44. F. Masters, "Phase II Report: Investigation of the Wind Resistance of Asphalt Shingle Roof Coverings," Oak Ridge National Library, 2013.

45. T. Marshall, S. Morrison, R. Herzog and J. Green, "Wind Effects on Asphalt Shingles," Haag Engineering Co., Irving, TX, USA, 2010.

46. R. Ribble, D. Summers, R. Olson and J. Goodman, "From Generation to Generation: Issues and Problems Facing the Steep Slope Roofing Industry," in 10th Conference on Roofing Technology, Gaithersburg, MD, USA, 1993.

47. FBC, Florida Building Code, 8th Edition, Florida Building Commission, International Code Council, Inc., 2023.

48. IBC, 2024 International Building Code, International Code Council, Inc., 2024.

49. FEMA, "Hurricane Charley in Florida - Observations, Recommendations, and Technical Guidance," Federal Emergency Management Agency, FEMA 488, 2005.

50. IIBHS, "Relative Impact Resistance of Asphalt Shingles," Insurance Institute for Business & Home Safety, 2014.

51. ASTM-D7158-20, "Standard Test Method for Wind Resistance of Asphalt Shingles (Uplift Force/Uplift Resistance Method)," American Society for Testing and Materials International, 2020.

52. J. Koontz, "Shingle Splitting Problem," Western Roofing Magazine, 1990.

53. R. Fulmer, "Tile Roof Systems: Analysis and Inspection Techniques for Roof Consultants," International Institute of Building Enclosure Consultants (IIBEC), 2006.

54. T. Marshall, "Roof Damage Issues in Hurricanes," Haag Engineering Company, 2004.

55. T. Marshall, "Curved Corner Fractures in Concrete Tile," Haag Engineering Company, 1990.

56. V. Durão, J. Silvestre, R. Mateus and J. de Brito, "Comparative Assessment of Roof Tiles' Environmental Performance from Cradle to Cradle," in World Sustainable Built Environment 2024, 2024.

57. C. Geurts, "Wind Loads on Permeable Roof Covering Products," in Fourth Colloquium on Bluff Body Aerodynamics and Applications, Bochum, Germany, 2000.

58. P. Huang, A. Mirmiran, A. Chowdhury, C. Abishdid and T. Wang, "Performance of Roof Tiles under Simulated Hurricane Impact," ASCE Journal of Architectural Engineering, vol. 15, no. 1, pp. 26-34, 2009.

59. C. Kramer and H. Gerhardt, "Wind Loads on Permeable Roofing Systems," Journal of Wind Engineering and Industrial Aerodynamics, vol. 13, no. 1, pp. 347-358, 1983.

60. H. Okada, J. Katagiri and T. Ohkuma, "Study on Method for Evaluating Wind Performance of Tiled Roof," in Proceedings of the 7th Asia-Pacific Conference on Wind Engineering, Taiwan, 2009.

61. A. Robertson, R. Hoxey, N. Rideout and P. Freathy, "Full-Scale Study of Wind Loads on Roof Tiles and Felt Underlay and Comparisons with Design Data," Wind and Structures, vol. 10, no. 6, pp. 495-510, 2007.

62. F. Habte, M. Mooneghi, T. Baheru, I. Zisis, A. Chowdhury, F. Masters and P. Irwin, "Wind Loading on Ridge, Hip and Perimeter Roof Tiles: A Full-Scale Experimental Study," Journal of Wind Engineering and Industrial Aerodynamics, vol. 166, pp. 90-105, 2017.

63. H. Kawai and H. Nishimura, "Field Measurement on Wind Force on Roof Tiles," in Proceedings of the 11th International Conference on Wind Engineering (ICWE11), Lubbock, Texas, USA, 2003.

64. R. Li, "Effects of Architectural Features of Air-Permeable Roof Cladding Materials on Wind-Induced Uplift Loading," ProQuest ETD Collection for FIU. AAI3541803., 2012.

65. A. Tecle, G. Bitsuamlak, N. Suskawang, A. Chowdhury and S. Fuez, "Ridge and Field Tile Aerodynamics for a Low-Rise Building: a Full-Scale Study," Wind and Structures, vol. 16, 2013.

66. T. Baheru, F. Habte, M. Moravej and A. Chowdhury, "Full-Scale Testing to Evaluate Wind Effects on Residential Tiled Roofs," in International Conference on Building Envelope Systems and Technologies (ICBEST), Aachen, Germany, 2014.

67. B. Kordi and G. Kopp, "Effects of Initial Conditions on the Flight of Windborne Plate Debris," Journal of Wind Engineering and Industrial Aerodynamics, vol. 99, no. 5, pp. 601-614, 2011.

68. A. Mirmiran, T. Wang, C. Abishdid, P. Huang, D. Jimenez and C. Younes, "Performance of Tile Roofs Under Hurricane Impact - Phase 2," International Hurricane Research Center (IHRC), 2007.

69. FEMA, "Mitigation Assessment Team Report - Hurricane Irma in Florida," Federal Emergency Management Agency (FEMA) P-2023, 2018.

70. C. Dunlop, Roofing Inspection, Home Reference Book, 2015.

71. S. Petty, Forensic Engineering: Damage Assessments for Residential and Commercial Structures (2nd ed.), CRC Press, 2021.

72. NRCA, Roofing Manual: Steep-Slope Roofing Systems, National Roofing Contractors Association, 2023.

73. FBC, Tile Roofing Installation Manual for Florida, Florida Building Commission (FBC), FRSA/TRI 7th Edition, 2023.

74. A. Neville, Properties of Concrete, 5th Edition, Pearson, 2011.

75. ASTM-C1167-22, Standard Specification for Clay Roof Tiles, ASTM International, 2022.

76. Haag-Engineering, Field Guide to Residential Roof Damage Assessment, Haag Engineering Company, 2020.

77. P. Berdahl, H. Akbari, R. Levinson and W. Miller, "Weathering of Roofing Materials – An Overview," Construction and Building Materials, vol. 22, no. 4, pp. 423-433, 2008.

78. E. Di Giuseppe, "Algal Growth on External Building Envelope," Nearly Zero Energy buildings and Proliferation of Microorganisms, Springer Nature, 2013.