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Risk Analysis Procedure for Woodframe Roof Sheathing Panel Debris Impact to Windows in Hurricanes [1]

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Abstract

The assessment of losses during extreme events such as hurricanes is important for performance-based design of residential buildings. In this paper, a methodology for estimating the risk of debris impact, specifically roof sheathing panels, to windows as a result of hurricanes is introduced and applied to an illustrative example. The method is a combination of approaches on flat plate trajectories, numerical hurricane modeling, and statistical analysis of structural capacity. Within this methodology, one can estimate the risk of impact for one or more windows in a certain house group as a hurricane approaches and passes on a deterministic track as defined by the center of its eye. The impact risk is analyzed for the each hour making up the full hurricane duration rather than a single analysis using the blended (total) hurricane statistics. An illustration of the method is presented through a risk assessment of windborne debris impacts to windows in a house group located near the U.S. Gulf coast using a hurricane having the same track as hurricane Katrina in 2005. As a result, the probability of each window being hit by a

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roof sheathing panel (RSP) during each hour of the hurricane as well as during each hurricane is presented. The results quantify the risk from hour to hour during a hurricane and may serve to better orient houses in planned communities in hurricane prone regions as well as provide a better understanding of the interaction of hurricanes and structures.

Key Words: Light-frame wood; hurricane; wind force; fragility; windborne debris

Introduction

Over the last several years the development of performance-based design (PBD) has been a focus for the light-frame wood building research community, primarily in earthquake engineering, but is gaining popularity in wind engineering. Performance-based design is a design philosophy that provides a building owner additional design options in order to reduce losses during extreme loading events. Improving the performance of light-frame wood buildings is critical since over 80% of the total building stock in the United States and more than 90% of residential buildings in North America are light frame wood construction. A recent investigation (van de Lindt at el., 2007) showed that financial losses for residential wood construction during hurricane Katrina were not only significant from surge but also from wind and the resulting rainwater damage, thus improving the performance of residential buildings under hurricane winds would help mitigate these losses. Losses for residential wood construction during hurricanes occur for a variety of reasons. These include sources such as (1) water intrusion as a result of high uplift pressures on the roof system resulting in gaps but not loss of panels (Dao and van de Lindt, 2010); (2) water intrusion as a result of a loss of roof coverings and/or roof sheathing panels (Figure 1a and 1b); and (3) debris impact from a failed roof sheathing panel (Figure 1c). Heavy wind-driven rain which occurs during a hurricane can cause

rain-water intrusion through breaches leading to substantial financial losses as a result of both the structure and contents damage. This paper focuses on a fragility methodology and subsequent risk analysis of damage for residential windows during hurricanes due to impact loading from flat plate-like windborne debris, e.g. roof-sheathing panel failure resulting in flight and potentially impact.

To date, there has been limited research on windborne debris with studies focusing on either debris trajectory and/or risk assessment (Twisdale at el., 2006). Studies focusing on other aspects of wind loss modeling and related hazards have been somewhat prevalent (Kopp et al., 2008; Vickery at el., 2003; 2006; 2009; Henderson at el., 2009). Recently there was a special journal issue (*Wind and Structures*) that focused on windborne debris including a review of windborne debris models (Holmes, 2010; Lin and Vanmarcke, 2010; Lin at el, 2010). These existing models treat risk from windborne debris as occurring sometime during the hurricane, rather that discretizing the analysis in a deterministic fashion as in the present study. The discretized approach provides several advantages in that it allows consideration of nonlinear finite element models including damage accumulation during a hurricane.

Debris Flight

Based on the auto-rotating flat-plate theory proposed by Iversen (1977), Tachikawa (1983) developed a method to determine the trajectory of flat plates in uniform flow with application to windborne debris. This method was applied for 2-D flat plates flying in a uniform flow with aerodynamic drag, lift, and moment, expressed as:

$$
\begin{aligned}
D &= \frac{1}{2}\rho A\left[(U-\dot{x})^2+\dot{y}^2\right]C_D \\
L &= \frac{1}{2}\rho A\left[(U-\dot{x})^2+\dot{y}^2\right](C_L+C_{LA}) \\
M &= \frac{1}{2}\rho A l\left[(U-\dot{x})^2+\dot{y}^2\right](C_M+C_{MA})
\end{aligned}
\tag{1}
$$

where A is the area of the plate, ρ is the air density, l is the chord length, U is the wind velocity, x and y are the coordinates which indicate the location of the plate, and C_D, C_L, C_M are the aerodynamic drag, lift and moment coefficients, respectively, and C_{LA}, C_{MA} are autorotation lift coefficient and autorotation pitching moment coefficient, respectively. These coefficients must be determined experimentally using a wind tunnel. The plate trajectories are calculated by numerically integrating the equations of motions derived from forces acting on the plate (Tachikawa, 1983):

$$
\begin{aligned}
m\ddot{x} &= \frac{1}{2}\rho A\left[(U-\dot{x})^2+\dot{y}^2\right](C_D\cos\beta-(C_L+C_{LA})\sin\beta) \\
m\ddot{y} &= mg-\frac{1}{2}\rho A\left[(U-\dot{x})^2+\dot{y}^2\right](C_D\sin\beta+(C_L+C_{LA})\cos\beta) \\
I\ddot{\theta} &= \frac{1}{2}\rho A l\left[(U-\dot{x})^2+\dot{y}^2\right](C_M+C_{MA})
\end{aligned}
\tag{2}
$$

where g is the acceleration due to gravity, m is the mass, I is the moment of inertia, $\beta=\tan^{-1}\left(\frac{\dot{y}}{(U-\dot{x})}\right)$; and a dot denotes a derivative with respect to time t. The coordinates and forces acting on a plate are shown in Figure 2.

Based on the flat plate trajectory theory proposed by Tachikawa, Lin at el. (2006) investigated plate type windborne debris by performing wind tunnel experiments at full scale. Their study also investigated the aerodynamic characteristics of plate-type debris,

and two empirical equations were proposed for estimating velocity and position of the plate at a given flight time:

$$\bar{u} = 1 - e^{-\sqrt{1.8K.\bar{x}}} \tag{3}$$

$$K\bar{x} = 0.456\left(K\bar{t}\right)^2 - 0.148\left(K\bar{t}\right)^3 + 0.24\left(K\bar{t}\right)^4 - 0.0014\left(K\bar{t}\right)^5 \tag{4}$$

where $\bar{u}$ is the horizontal non-dimensional plate velocity, which is the ratio between the average velocity of the plate u_m and the wind velocity U; $\bar{x}$ is the dimensionless horizontal displacement of the plate; K is the Tachikawa number; $\bar{t}$ is non-dimensional time ($\bar{t} = \frac{gt}{U}$).

Visscher and Kopp (2007) also conducted a series of experiments in a wind tunnel for roof sheathing panel trajectories and showed that slight differences in the initial conditions at the time of roof sheathing panel failure resulted in very different observed trajectories. This is again an argument for use of a discretized risk model since the initial consitions of the plate can change during the hurricane. In the present study, the initial angle of a roof sheathing panel is calculated based on wind direction and the roof slope for each house. It is assumed that the roof sheathing panel is at rest on the roof when it fails from wind loading.

From experimental data, Holmes at el. (2006) estimated the aerodynamic coefficients used in the plate equations of motion for numerical use in computing plate trajectories. The results were then compared with Tachikawa's experiments and their wind tunnel test for plate trajectories. The comparison indicated generally good to excellent agreement. Lin at el. (2007) also developed empirical equations to estimate horizontal displacements

and velocities for different types of windborne debris: a compact object, a sheet and a rod. With these empirical equations, Lin and Vanmarcke (2008) developed an approach for windborne debris risk assessment. Their study focused on risk assessment based on the landing location of debris during hurricanes (horizontal displacement only). This is reasonable for risk assessment of building coverings, in general. For risk assessment of window impact from windborne debris, the vertical displacement of windborne debris must also be considered.

In the present study, estimation of the plate trajectories are made in order to check if a plate impacts a downstream target, therefore both the horizontal and vertical position of the plates versus time need to be identified. For this reason, the original form of the equations of motion for the plate will be used to determine the plate trajectory in the present study. Building on the work of Holmes at el. (2006) and Lin at el. (2007), Baker (2007) summarized and proposed the debris flight equations for a plate, which are presented in their most general form and includes wind velocity fluctuation and assumed aerodynamic coefficients using continuous functions based on the angle of wind attack, β, on the plate:

$$
\begin{aligned}
C_D &= 0.75\left(1+0.65\sin\left(2\beta-\frac{\pi}{2}\right)\right)\\
C_L &= 1.2\sin(2\beta)\\
C_{LA} &= K_{LA}\frac{\overline{\omega}}{\overline{\omega}_m}\\
C_M &= 0.2\cos(\beta)\left(C_D\sin(\beta)+C_L\cos\left(\beta^{-}\right)\right)\\
C_{MA} &= K_{MA}\left(1-\frac{\overline{\omega}}{\overline{\omega}_m}\right)\frac{\overline{\omega}}{\overline{\omega}_m}
\end{aligned}
\qquad (5)
$$

where $\overline{\omega}_m$ is maximum numerical value of $\overline{\omega} = \frac{\dot{\theta}.l}{U}$, and $\overline{\omega}_m$ is taken to be 0.64; K_{LA} and K_{MA} are constants and taken as 0.4 and 0.12, respectively.

Numerical hurricane model

The simple numerical hurricane model used in this study considers the location of a community, or subdivision, of houses in proximity to a hurricane path and the subsequent wind field model. In order to estimate the trajectories of windborne debris, the wind velocity and wind direction for each hour at the location of the house group being considered needs to be determined. This can be accomplished by applying the Rankine vortex model (Liu, 1991) as follows:

$$V_\theta = \frac{V_R r}{R} \text{ for } r < R; \text{ and } V_\theta = \frac{V_R R}{r} \text{ for } r \geq R \tag{6}$$

where V_θ is the tangential (circumferential) component of the wind velocity in a hurricane to the hurricane eye center ***O***, R is the radius to maximum velocity V_R; and r is the distance between the hurricane eye and the location the velocity, V_θ, being computed. In this case V_θ and V_R refer to the upper-level (gradient height) wind velocity or wind velocity at the same height and in the same terrain category, e.g. equation (6) is used to convert wind velocity between locations during a hurricane but not between different heights or different terrain categories. The direction of V_θ is calculated based on the relative location of the house group being considered with respect to the hurricane eye:

$$\vec{\mathbf{e}}_\theta = \vec{\mathbf{e}}_\mathbf{r} \times \vec{\mathbf{e}}_\mathbf{z} \tag{7}$$

where $\vec{\mathbf{e}}_\theta$ is unit vector in the direction of the wind velocity V_θ, $\vec{\mathbf{e}}_\mathbf{r}$ is the radial unit vector, and $\vec{\mathbf{e}}_\mathbf{z}$ is the unit vector for the Z axis all of which is described graphically in Figure 3. The direction and value of wind velocity V is then calculated by adding the two velocity components:

$$\vec{V} = \vec{V}_\theta + \vec{V}_O \tag{8}$$

where $\vec{V}_O$ is the velocity of the hurricane eye. A power law or log law should be used to determine the wind velocity, U, at mean-roof-height level before substituting into equation (2) to estimate the trajectory of the windborne debris.

The track of the hurricane and the location of the house group are shown in Figure 4. For each hour of the hurricane, the location and distance of the hurricane with respect to the house group, r, is calculated. Then the wind velocity and wind direction at the house group location are determined using equations (6) and (7), and the trajectories of the windborne debris are determined using equation (2).

Wind load and dead load modeling

To estimate the probability of a window in a certain house group being impacted by a panel lost from another house, the probability of a panel failure must first be determined. The limit state describing roof panel uplift failure involves wind load and dead load and can be expressed as (Ellingwood at el., 2004):

$$G(R,W,D) = R - (W - D) \tag{9}$$

where R is the resistance of the roof panel to uplift, W is the uplift wind load and D is the dead load on the panel. The un-factored wind load applied on low-rise building components and cladding can be computed as:

$$W = q_h \left[GC_p - GC_{pi} \right] \tag{10}$$

where q_h is velocity pressure evaluated at mean roof height, G is gust factor, C_p is external pressure coefficient and C_{pi} is internal pressure coefficient. The velocity pressure is calculated following ASCE-7 (2005) as:

$$q_h = 0.00256 \, K_h K_{zt} K_d V^2 \tag{11}$$

where K_h is the exposure factor, K_{zt} is the topographic factor (taken equal to unity so as not to make the results dependent on local topography surrounding the building); and K_d is the directional factor (in this study, because the wind direction is determined from equation (7) and (8) and therefore not considered as a random variable, K_d is set to unity); and V is wind velocity, i.e. 3-s gust wind speed. The specifics of these random variables will be expanded on in the fragility section of this paper. The statistics for dead load and wind load coefficients and factors are listed in Table 1.

In this study, because the pressure coefficients were taken from existing wind tunnel test data with different wind directions, thus the mean value of K_h was taken as 1 (already accounting for the exposure factor); and the mean values of GC_p were selected from the peak values of pressure coefficient time series from wind tunnel test data. Both GC_p and GC_{pi} values in Table 1 are converted for use to 3-s gust wind speed, and will be described in more detail in the illustrative example section of this paper. The coefficient of

variation for each random variable listed in Table 1 is based on the work of Ellingwood at el. (2004).

Construction of Fragilities

The objective here is to construct a fragility for a window in a certain house group being hit by a roof sheathing panel (RSP) that is lost from the roof of another house during a hurricane. In general, the fragility for a certain limit state can be described by G(**X**)<0, where **X** is a vector of basic random variables that describes the limit state condition, and is defined through the expression of the probability of that limit state as (Ellingwood at el., 2004):

$$P[G(\mathbf{X}) < 0] = \sum_{y} P[G(\mathbf{X}) < 0 | D = y] P[D = y] \tag{12}$$

in which D is random variable describing the intensity of the demand on the system. The term $P[D = y]$ defines the natural hazard probabilistically. $P[G(\mathbf{X}) < 0 | D = y]$ is the conditional limit state probability given that $D = y$, and is defined as the fragility.

In this study, the limit state is defined as a window being impacted by an RSP during a hurricane. It is assumed that the target window will be broken when hit by any RSP during the hurricane. Further study is needed to include a glass failure, i.e. capacity model, and impact loading model. Obviously if the window is protected by shutters (plywood, oriented strand board (OSB), or metal), the assumed breakage is not an accurate model. The conditional random variables are the maximum 3-s gust wind speed occurring during that hurricane and the velocity of the hurricane eye. The fragility is now described as:

$$F_f = P\left[Window_hit \middle| \mathbf{V_H} = \mathbf{v_H}\right] \tag{13}$$

where $\mathbf{V_H} = \left[V_R \; V_O\right]^T$ is the vector of random variables representing the maximum tangential wind velocity in the hurricane and hurricane eye velocity, respectively, which are described in equations (6) and (8), respectively. The probability of a target window (in a certain house group) being hit by a RSP during a hurricane depends on the arrangement of that house group, the design of each house in that group (e.g. nail patterns on each RSP which relates to failure probability of RSP or number of RSP failures during hurricane, roof geometry, etc.), the size and location of the target window, and the characteristics of the hurricane which are described numerically by equations (6) to (8).

In this study, it is assumed that the track of the hurricane and the distance R between the hurricane eye and the location where V_R occurs are known and are deterministic. When the hurricane moves on its track, the wind velocity and wind direction at the location of the house group change gradually (due to the change in relative position between the house location and hurricane eye, see equation (6) through (8)), therefore the RSPs will have different trajectories if they fail at a different point in time during the hurricane. In previous models this can only be accounted for statistically over the entire hurricane as a single value. In the present study this was accounted for by discretizing the hurricane into one hour segments to better account for this effect. Thus, it is easier to first estimate the probability of the target window being hit by the RSPs for each hurricane hour, then compute the probability of the target window being hit during the hurricane as:

$$F_f = \sum_{i=1}^{h} P_i\left[Window_hit \middle| \mathbf{V_H} = \mathbf{v_H}\right] \tag{14}$$

where h is the duration of the hurricane in hours, $P_i\left[Window_hit \middle| \mathbf{V_H} = \mathbf{v_H}\right]$ is the probability of the target window being hit during the i^{th} hour of the hurricane.

Probability of the target window being hit during each hurricane hour

It is assumed that in the i^{th} hour of the hurricane, the probability of j^{th} RSP in the house group hitting the target window is P_{ij}^{RSP}. Then, the probability of that panel not hitting the target window during the i^{th} hour of the hurricane is, of course, $1-P_{ij}^{RSP}$. The probability that none of the RSPs in the house group hit the target window will then be:

$$\overline{P}_i = \prod_{j=1}^{n}\left(1-P_{ij}^{RSP}\right) \tag{15}$$

where n is the number of RSPs that have trajectories during the i^{th} hurricane hour that hit the target window. The probability of the target window being hit by at least one RSP during the i^{th} hurricane hour is then:

$$P_i\left[Window_hit \middle| \mathbf{V_H} = \mathbf{v_H}\right] = 1-\overline{P}_i \tag{16}$$

***Probability of an RSP hitting the target window during the i^{th} hurricane hour*, P_{ij}^{RSP}**

In order to estimate the probability that a RSP hits the target window, the wind velocity and wind direction for each hour at the location of the house group must first be determined using equations (6) to (8). Then the trajectories of that RSP are determined using the method proposed by Tachikawa (1983) and the aerodynamics summarized by

Baker (2007). It should be noted that the P_{ij}^{RSP} is calculated for each hurricane hour, and it is not known at what moment during the hour the panel will fail. The trajectory of the RSP is a function of when it fails during the hurricane (due to the change in the wind direction and wind velocity). Therefore the trajectories are calculated for discrete points in time during each hurricane hour. From the calculated trajectories of that RSP during each hour of the hurricane model, the portion of the time during hurricane hour *i* that the RSP can hit the target window denoted as P_{ij}^{t} and can be calculated as

$$P_{ij}^{t} = \frac{\alpha_i^{hit}}{\alpha_i} \tag{17}$$

where α_i^{hit} is the initial angle between two roof-sheathing panel trajectories that bound the geometry of the target window, where α_i is the initial angle between roof-sheathing panel trajectories at the beginning and at the end of a hurricane hour (see Figure 5).

If $P_{ij}^{t} > 0$ (this means that a RSP can hit the target window during that hour, provided it fails structurally), the probability of that RSP failing during that hurricane hour is calculated and is termed P_{ij}. The probability that the RSP hits the target windows during the i^{th} hurricane hour is:

$$P_{ij}^{RSP} = P_{ij}^{t} P_{ij}^{F} \tag{18}$$

Probability of a RSP failing during the i^{th} hurricane hour, P_{ij}^{F}

From the limit state describing roof panel uplift failure, namely equation (9), one can determine the probability of a panel failing due to wind loading during the i^{th} hurricane hour as:

$$P_{ij}^{f} = P\left[G(\mathbf{X}) < 0 \middle| \mathbf{V_H} = \mathbf{v_H}\right] \tag{19}$$

Here the wind load statistics follow equation (10) and random variables are listed in Table 1. Recall that in Table 1, there are two different values of GC_{pi} which leads to two different RSP failure states. Equation (19) can be used to calculate the probability of failure of each RSP in the structure for closed and partially closed states, and are denoted as P_{ij}^{fC} and P_{ij}^{fPC} $(i = 1,2 \ldots H;\ j = 1,2,\ldots N)$ where H is number of hurricane hours and N is number of panels in the structure. It is assumed that if a RSP fails, it fails in either the closed state or partially closed state. Then, it follows logically that:

$$P_{ij}^{F} = P_{ij}^{FC} + P_{ij}^{FPC} \tag{20}$$

where F_{ij}^{FC} and F_{ij}^{FPC} are the probability of RSP fails in closed state and partially closed state, respectively. These probabilities can be estimated as:

$$F_{ij}^{FC} = P_{ij}^{Close} P_{(i-1)j}^{Survival} P_{ij}^{fC} \tag{21}$$

$$F_{ij}^{FPC} = P_{ij}^{PartClose} P_{(i-1)j}^{Survival} P_{ij}^{fPC} \tag{22}$$

where P_{ij}^{Close} is the probability of the building being in a closed state and $P_{ij}^{PartClose}$ is probability of the building being in a partially closed state. $P_{(i-1)j}^{Survival}$ is the probability of panel j surviving during the first (i -1) hurricane hours. P_{ij}^{Close} and $P_{ij}^{PartClose}$ are estimated from the probability that at least one window in windward wall was hit before the i^{th}

hurricane hour. It is assumed that if none of the windows in the windward wall are hit before the i^{th} hurricane hour, the house will be in a closed state; otherwise the house will be in a partially closed state. For the first hurricane hour, $P_{1j}^{Close}=1; P_{1j}^{PartClose}=0.$ After the first hurricane hour, P_{ij}^{Close} and $P_{ij}^{PartClose}$ are calculated as:

$$P_{ij}^{Close}=\prod_{q=1}^{W}\prod_{k=1}^{i-1}\left(1-P_{kq}\left(Window_hit\right)\right) \tag{23}$$

$$P_{ij}^{PartClose}=1-P_{ij}^{Close} \tag{24}$$

where $P_{kq}\left(Window_hit\right)$ is the probability of window q being hit during the k^{th} hurricane hour, W is the number of windows in windward walls considered during i^{th} hurricane hour. The probability $P_{(i-1)j}^{Survival}$ can be estimated by equation:

$$P_{(i-1)j}^{Survival}=P_{(i-1)j}^{SC}+P_{(i-1)j}^{SPC} \tag{25}$$

where $P_{(i-1)j}^{SC}$ is the probability that panel j survives in a closed building state during (i-1) hurricane hours and $P_{(i-1)j}^{SPC}$ is probability that panel j survives in a partially closed building state during (i-1) hurricane hours; which can be evaluated by equations:

$$P_{(i-1)j}^{SC}=P_{(i-1)j}^{Close}P_{(i-2)j}^{Survival}\left(1-P_{(i-1)j}^{fC}\right) \tag{26}$$

$$P_{(i-1)j}^{SPC}=P_{(i-1)j}^{PartClose}P_{(i-2)j}^{Survival}\left(1-P_{(i-1)j}^{fPC}\right) \tag{27}$$

Illustrative example and discussion

Now, consider an illustrative house group with its location shown on the map in Figure 4, which is assumed to be in a suburban terrain as defined by ASCE-7 (2005). For illustrative purposes, it is assumed that there are nine identical houses and there are four large windows in each house (one window on each side), making a total of thirty-six windows in the example house group. The house group layout is shown in Figure 6 with the houses numbered for later discussion. Each house is 18.2 m (60ft) by 9.1 m (30ft) in plan with a mean roof height of 4.4 m (14.3 ft) having a roof overhang of 0.3 m (one ft) beyond the wall.

For illustrative purposes, it is assumed that the hurricane follows the track taken by hurricane Katrina in 2005 which is shown in Figure 4, but it should be noted that the wind field of hurricane Katrina is not used, just the path. The hurricane eye velocity is assumed to be 22.4 kph (14 mph); the maximum wind velocity V_R during the hurricane occurs at R = 28.8 km (18 miles) from the hurricane eye (V_R is measured at the height of 33ft or 10m in open terrain). The analyses for different maximum wind velocities V_R were performed to observe the effects of hurricane category on window damage in the house group. The corresponding wind velocity, V_θ, in open terrain at the house group location is determined for each discretized hour of the hurricane using equation (6) in which the variable r depends on the location of the hurricane at the mean time within each hour. The total wind velocity at the house group location is calculated using equation (8), which is then converted into 3-s gust wind velocity at the mean roof height (4.4m or 14.3 ft) in suburban terrain using

$$V_{mrh,sub} = V_{10m,open} \frac{\ln\left(\frac{Z_{mrh}}{Z_{0,sub}}\right)}{\ln\left(\frac{10}{Z_{0,open}}\right)} \frac{\ln\left(\frac{Z_{g,open}}{Z_{0,open}}\right)}{\ln\left(\frac{Z_{g,sub}}{Z_{0,sub}}\right)} \tag{28}$$

where $V_{mrh,sub}$ is the 3-s gust wind velocity at mean roof height in suburban terrain (at the location of the house group), $V_{10m,open}$ is the total wind velocity at the height of $10m$ in open terrain determined by equation (8); $Z_{mrh} = 4.4m$; $Z_{0,sub} = 0.22m$ and $Z_{0,open} = 0.02m$; $Z_{g,open} = 274.43m$; $Z_{g,sub} = 365.76m$

With the wind velocity, $V_{mrh,sub}$, at the house group for each hurricane hour known, all RSP trajectories at discrete points in time are calculated, then each panel's trajectories are checked to determine if they would hit any target window for those points in time during that specific hurricane hour (recall from equation (17) that during that hurricane hour, one can see that there may be a portion of time that if the RSP fails, its trajectory will not hit the target window). If there is a hit, then the portion of time during that hurricane hour that the panel may hit the target window (if it is failed) is estimated (see Figure 5). The probability of each panel hitting a target window is then calculated using equation (18), and the probability of a target window being hit during each hurricane hour is then determined using equation (16). Figure 7 shows the trajectories of the RSPs that may hit the windows in the house group during a hurricane with V_R = 145 mph. In this figure, only the RSP trajectories that hit the windows in the house group are shown, i.e. there are many trajectories that fall short of the windows or hit elsewhere. From these RSP trajectories, the portion of time that the RSP may hit the windows is calculated for each hurricane hour (i.e. there is some portion of time during each hurricane hour that the RSP

may not hit the target window due to wind direction changes as the hurricane approaches on its track).

Wind tunnel data for pressure coefficient on the roof

In order to estimate the probability of RSP failure for each hurricane hour, wind load statistics for each RSP for each hour within the hurricane are determined. As the hurricane approaches on its track, the wind direction at the house group location changes gradually and can be determined by equation (8). Therefore the wind directionality factor K_d in equation (11) was taken as unity and not considered to be a random variable. Wind tunnel test data from testing conducted at Clemson University (Datin and Prevatt 2009; Prevatt and Datin 2007) was used to estimate the mean value of the pressure coefficient on each RSP. In that study a residential building that was nominally identical to the building used in this example was modeled as a 1:50 scale rectangular, gable roof structure with 387 pressure taps installed on the roof. The dimensions and pressure-tap layout are shown in Figure 8. The pressure at each tap on the roof is recorded as a time series for five wind directions (0, 45, 90, 135 and 180), from which the pressure coefficient time history can be calculated as

$$C_p(t,\theta)_i = \frac{P_i(t,\theta)}{\overline{P}_{ref}(\theta)} \tag{29}$$

$$\overline{P}_{ref}(\theta) = \frac{1}{2}\rho\overline{V}_{mrh}^2 \tag{30}$$

where $P_i(t,\theta)$ is the pressure at tap i at time t for wind direction θ, $\overline{P}_{ref}$ is the reference pressure at the mean roof height, ρ is the density of air, and $\overline{V}_{mrh}$ is the mean velocity of

air at the mean roof height during the sample. This mean wind velocity, $\overline{V}_{mrh}$, is equivalent to the one-hour wind velocity averaging time in full scale.

The pressure tap locations and tributary area of each tap for each RSP can then be determined based on Figure 8. Based on the tributary area and the pressure over each tap, the time series for forces due to wind pressure are calculated at each pressure tap. Then the time series of the force acting on each panel is determined by summing all the forces at pressure taps on that RSP. The peak value of the time series force acting on each panel is selected to calculate wind pressure and then the wind pressure coefficient for that RSP. This pressure coefficient is then set as the mean value for the random variable, GC_p, in equation (10) when computing the probability of RSP failures for each hurricane hour. Note that the pressure coefficient for the overhang is different than the other roof portion which was included in the calculations. The pressure coefficients for the wind directions that were not tested by Datin and Prevatt (2009) were interpolated from the five wind directions that were tested.

Results and discussions

Because the house group in this example is quite small and only one type of windborne debris is considered, there are relatively low probabilities for the RSP's impacting windows. The discussion will focus more on the trend and the effect of wind velocity and wind direction change during a hurricane.

Figure 9 shows the probability that window #14(the south window of house #4) is hit for each hurricane hour and for two different RSP capacities (different nail patterns) if V_R =

145 mph. One can see that the probability of window #14 being hit is much higher with an RSP capacity of 33psf than with that of 69 psf, as would be expected. Here the RSP capacity of 33 psf represents a nail pattern of 6/24 (6 inches between edge nails and 24 inches between field nails) which is intended to be representative of poor construction, i.e. missing field nails. The 69 psf RSP capacity is representative of a nail pattern of 6/12, which is standard construction practice in coastal areas of the United States. These roof sheathing capacities were estimated using a finite element model with a non-linear nail model developed by Dao and van de Lindt (2008). It should be noted here that the highest probability of hitting window #14 is during the second hour of the hurricane, but this does not align with the highest wind velocity which occurs during the third hour of the hurricane. This is due to the change in wind direction as the hurricane approaches on its track. This is also the reason that the probability of windows being hit during the hurricane does not change gradually even though the wind velocity model of the hurricane at the house group location actually does change gradually. This example was analyzed for the five most susceptible hours of the hurricanes for illustrative purpose.

Figure 10 presents the probability of each window in the house group being hit during the hurricane with V_R = 145 mph. In Figure 10, the results for all thirty-six windows in the house group are presented. It should be noted that windows #1 to #4 (in the order: north, south, east, west for house #1 to #6 and in the order: west, east, north, south for the house #7 to #9) belong to house #1, windows #5 to #8 belongs to house #2 and so on (each house has four windows). From inspection of Figure 10, it can be seen from the results that the windows in houses #1 and #4 are the most susceptible to the RSP impact generated by the hurricane with V_R = 160 mph because these houses are in the downwind

region. Obviously, windows #1 and #13 have no risk of RSP impact during the hurricane (these windows are located along the leeward walls of the houses). Finally, houses #7, #8 and #9 are safer from RSP impact generated from this subgroup of houses during the hurricane because they are in an upwind area. It is clear from these results that the windows in the windward walls in downwind sides are most susceptible to an RSP hit, as one would expect.

In Figure 11, the probability of window #14 being hit during the hurricane is presented for different maximum wind velocities, V_R. It can be seen from the results that the highest probability of window #14 being hit during the hurricane is when the hurricane is modeled with a V_R = 145 mph for both RSP with nail pattern 6"/24" and nail pattern 6"/12". Interestingly, when the hurricane has a high V_R, the probability that window #14 is hit by RSPs is lower because the RSPs fly farther in the high velocity wind field and actually land outside of the house group. However, this does not necessarily mean that window #14 would always be safer with a stronger hurricane. Within a stronger hurricane, heavier types of debris (such as compact or bar objects) may be generated, and their trajectories may fall well within the house group area leading to higher risk of impact to the target windows. In addition, the illustrative house group is relatively small in this study. It can be seen from Figure 11 that the probability of window #14 being hit by a RSP has different trends with V_R between the two nail patterns. For the nail pattern 6"/24", because the RSP has a high failure probability at high wind and that probability does not change much with V_R greater than 145 mph. Therefore the probability of wind #14 being hit by a RSP depends significantly on the number of trajectories hitting it. While the nail pattern 6"/12", a RSP has higher capacity, therefore the probability of

window #14 being hit by a RSP depends on both the RSP failure probability and the number of RSPs able to hit the window with their trajectory.

From the probability of each window being hit during the hurricane, one can calculate the probability of at least one window, two windows, three windows, etc. being hit during the hurricane using a statistical combination. Figure 12 shows the probability that at least one window in the house group is hit during the hurricane. Again, the probability of at least one window in the house group being hit has different trends between the two nail patterns as discussed earlier.

Conclusions and recommendations

In this study, a methodology for estimating the probability that windborne roof sheathing panels impact windows in a house group during a hurricane was introduced. The method combined a recent study on windborne debris trajectory, numerical hurricane modeling, and nonlinear static analysis of roof sheathing capacity by finite elements as well as wind loading on the roof. The numerical hurricane model gives the wind velocity and wind direction at the house group location for each hour as the hurricane approaches on its track. From the wind velocity and wind direction estimated, the windborne debris trajectories are determined for each discretized hour of the hurricane. Based on the statistics of the roof sheathing panel as well as wind loading on the roof, a statistical method was presented to estimate the probability of a roof sheathing panel hitting a target window during each hour of the hurricane as well as during the entire hurricane. The results showed that the highest probability of hitting a window does not align with the highest wind velocity during a hurricane, mainly due to the change in wind direction as the hurricane approaches on its track. This is also the reason that the probability of

windows being hit during the hurricane does not change gradually even though the wind velocity model for the hurricane wind field at the house group location actually does change gradually. The most damaging wind velocity for a hurricane was also computed for a specific window, which is not necessarily caused by the hurricane wind field model with the highest wind velocity, because the RSPs typically fly further in higher winds and may land beyond the houses. However, even though the probability of a particular window in a house group being hit does not necessarily coincide with the strongest winds in a hurricane, the probability of at least one window being hit within the entire group of homes is highest at the maximum wind speed in the hurricane, again, as might be expected.

This methodology represents one major component within the broader framework of performance-based wind engineering for residential buildings.

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Re eren es

American Society of Civil Engineers (2005), *Minimum Design Loads for Buildings and Other Structures,* ASCE/SEI 7-05, ASCE, Reston, VA.

Baker, C. J. (2007). "The debris flight equations", *Journal of Wind Engineering and Industrial Aerodynamics*, 95 (2007), 329–353.

Dao, T.N. and van de Lindt, J. W. (2008). "New Roof Sheathing Nail Model for use in FE Applications." ASCE *Journal of Structural Engineering*, 134 (10) 1668-1674.

Dao, T. N. and van de Lindt, J. W. (2010). "Methodology for Wind-Driven Rain Water Intrusion Fragilities for Light-Frame Wood Roof Systems." ASCE *Journal of Structural Engineering*, in press.

Datin, P. L., and Prevatt, D. O. (2009). "Equivalent Roof Panel Wind Loading for Full-Scale Sheathing Testing." Link: "http://www.davidoprevatt.com/wp-content/uploads/2009/05/datin_david_equivalent_roof_panel1.pdf"

Ellingwood, B. R., Rosowsky, D. V., Yue Li, S., and Kim, J. H. (2004). "Fragility Assessment of Light-Frame Wood Construction Subjected to Wind and Earthquake Hazards", ASCE *Journal of Structural Engineering*, 130(12) 1921 - 1930.

Henderson, D.J., Ginger, J.D., Morrison, M.J., and Kopp, G.A. (2009). "Simulated tropical cyclonic winds for low cycle fatigue loading of steel roofing." *Wind and Structures*, 12(4), 383-400.

Holmes, J. D., Letchford, C.W., Lin, N. (2006). “Investigations of plate-type windborne debris – Part II: Computed trajectories”, *Journal of Wind Engineering and Industrial Aerodynamics*, 94 (2006), 21–39.

Holmes, J. D., (2010). “Windborne debris and damage risk models: a review”, *Wind and Structure*, 13(2), 2010.

Iversen, J. D. (1979). “Autorotating flat-plate wings: the effect of the moment of inertia, geometry and Reynolds number”, *J. Fluid Mech.*, Vol. 92, Part 2, 1979.

Kopp, G. A., Oh, J. H., and Inculet, D. R. (2008). "Wind-induced internal pressures in houses." *Journal of Structural Engineering*, 134(7), 1129-38.

Lin, N., Letchford, C., Holmes, J. (2006). “Investigation of plate-type windborne debris - Part I: Experiments in wind tunnel and full scale”, *Journal of Wind Engineering and Industrial Aerodynamics*, 94 (2006), 51–76.

Lin N., Holmes J. D., Letchford C. W. (2007). “Trajectories of windborne debris and applications to impact testing”, ASCE *Journal of Structural Engineering*, 133(2), 274–82.

Lin N., Vanmarcke E. (2008). “Windborne debris risk assessment”. *ELSEVIER Probabilistic Engineering Mechanics*, 23 (2008), 523 – 530.

Lin N., Vanmarcke E. (2010). “Windborne Debris Risk Analysis: Part I. Introduction and Methodology”. *Wind and Structures*, Vol. 13, No. 2 (special issue on windborne debris; invited), 191-206.

Lin N., Vanmarcke E. and Yau S.C. (2010). “Windborne Debris Risk Analysis: Part II. Application in Structural Vulnerability Modeling”. *Wind and Structures*, Vol. 13, No. 2 (special issue on windborne debris; invited), 207- 220.

Liu, H. (1991), “A Handbook for Structural Engineers”. Prentice Hall, Englewood Cliffs, New Jersey.

Prevatt, D. O., and Datin, P. L. (2007). "Wind Uplift Reactions at Roof-to-Wall Connections of Wood-Framed Gable Roof Assembly." *WLTF 01-07*, *submitted to South Carolina Sea Grant Consortium, Clemson, SC*.

Tachikawa, M. (1983). “Trajectories of flat plates in uniform flow with application to wind-generated missiles*”, Journal of Wind Engineering and Industrial Aerodynamics*, 14 (1983), 443 - 453.

Twisdale, L.A., Vickery, P.J. and Steckley, A.C. (1996), ``Analysis of hurricane windborne debris risk for residential structures", Technical report, Raleigh (NC): Applied Research Associates, Inc.

van de Lindt, J.W., A. Graettinger, R. Gupta, S. Pryor, T. Skaggs, and K. Fridley. (2005). “Damage Assessment of Residential Woodframe Structures in the Wake of Hurricane Katrina”, *Report to the National Science Foundation*.

Vickery, P. J., Lin, J. X., and Twisdale Jr, L. A. (2003). "Analysis of hurricane pressure cycling following missile impact for residential structures." *Journal of Wind Engineering and Industrial Aerodynamics*, 91(12-15), 1703-30.

Vickery, P. J., Lin, J., Skerlj, P. F., Twisdale Jr, L. A., and Huang, K. (2006). "HAZUS-MH hurricane model methodology. I: Hurricane hazard, terrain, and wind load modeling." *Natural Hazards Review,* 7(2), 82-93.

Vickery, P. J., Skerlj, P. F., Lin, J., Twisdale, L. A., Young, M. A., and Lavelle, F. M. (2006). "HAZUS-MH hurricane model methodology. II: Damage and loss estimation." *Natural Hazards Review*, 7(2), 94-103.

Vickery, P. J., Masters, F. J., Powell, M. D., and Wadhera, D. (2009). "Hurricane hazard modeling: The past, present, and future." *Journal of Wind Engineering and Industrial Aerodynamics*, 97(7-8), 392-405.

Visscher, B. T., and Kopp, G. A. (2007). "Trajectories of roof sheathing panels under high winds."*Journal of Wind Engineering and Industrial Aerodynamics*, 95(8), 697-713.

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Table 1: Wind load and dead load statistics

Variables	Mean	Coefficient of variation (COV)	Distribution
Dead Load D	1.6 psf (0.077 kPa)	0.10	Normal
K_h (exposure B)	1	0.21	Normal
GC_p (C&C)	Wind tunnel tests	0.12	Normal
GC_{pi}	0.15 (Closed)	0.05	Normal
	0.55 (Partially Closed)	0.05	Normal

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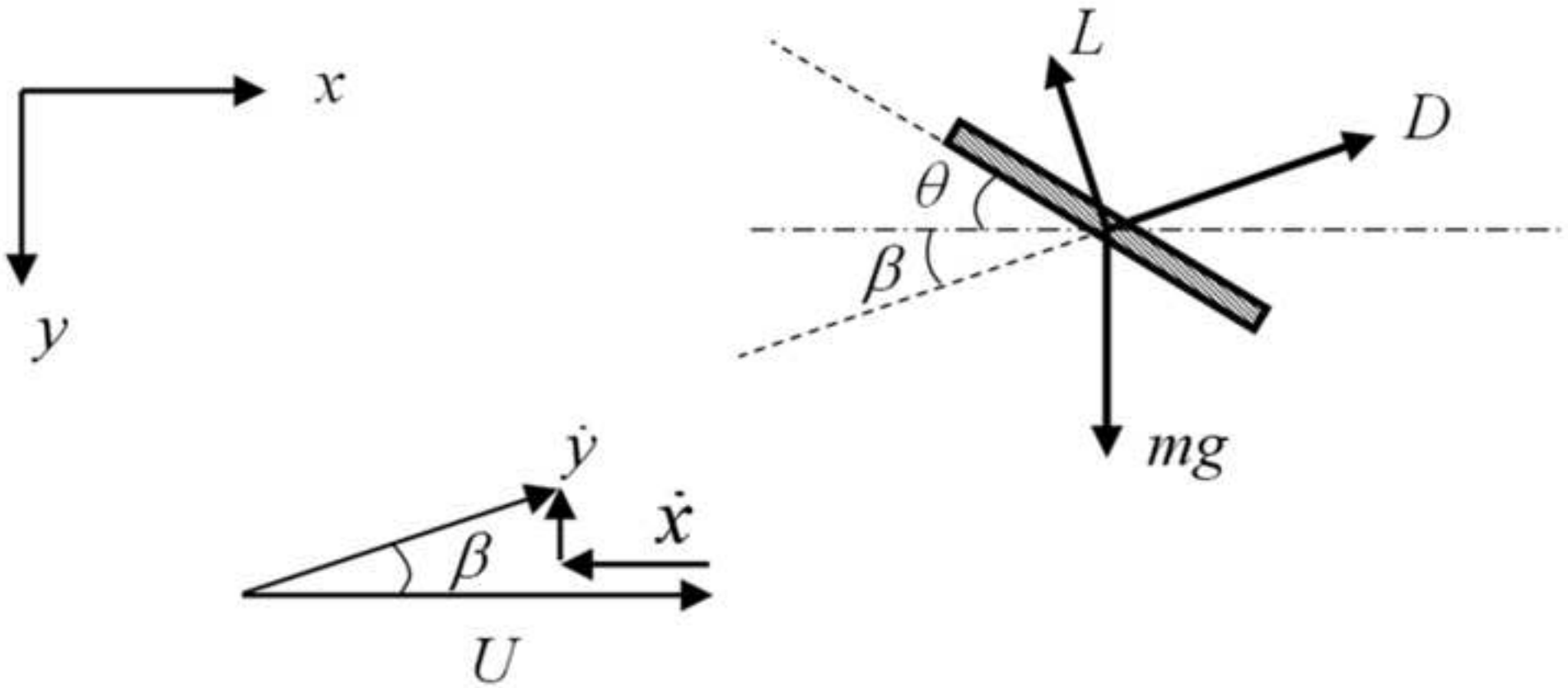

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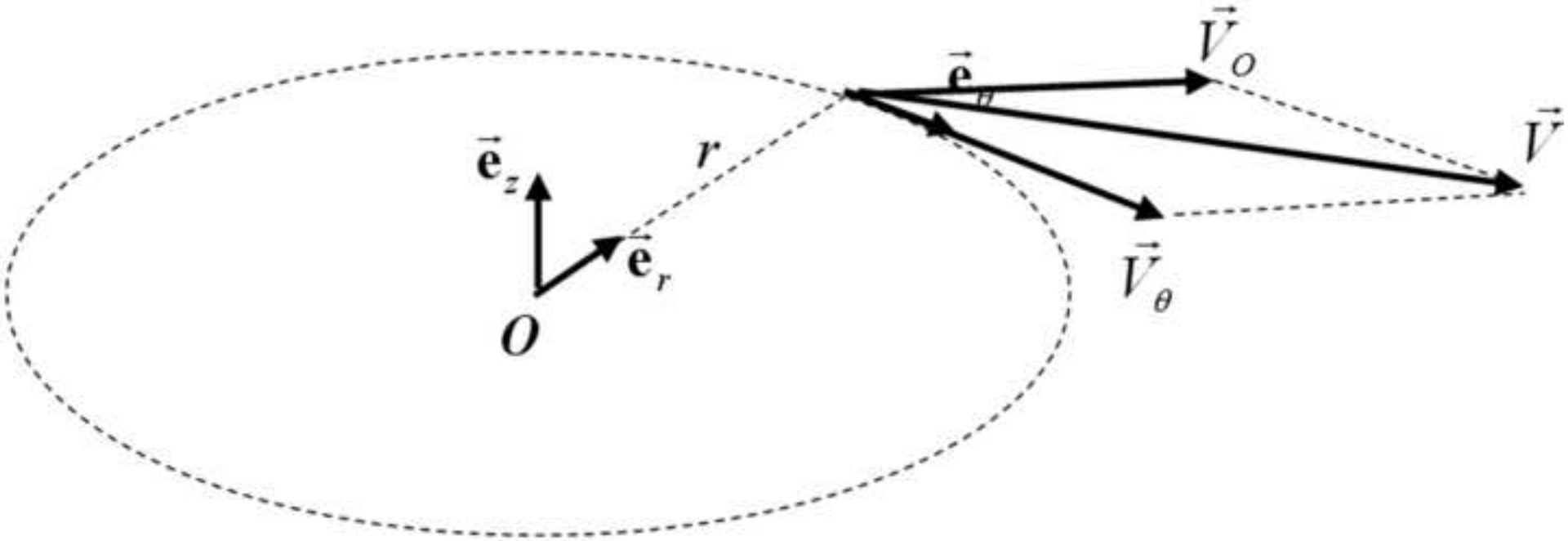

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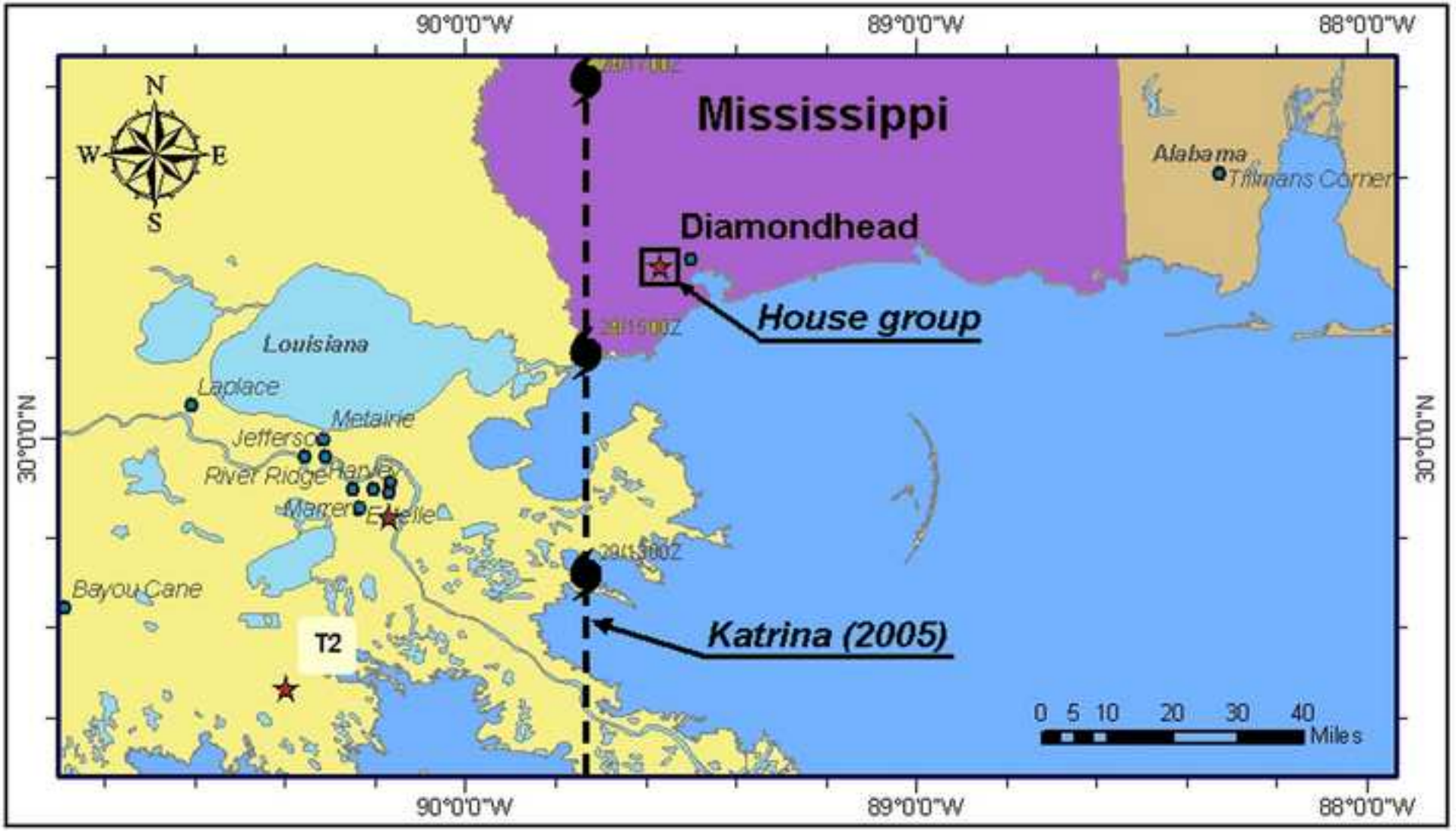

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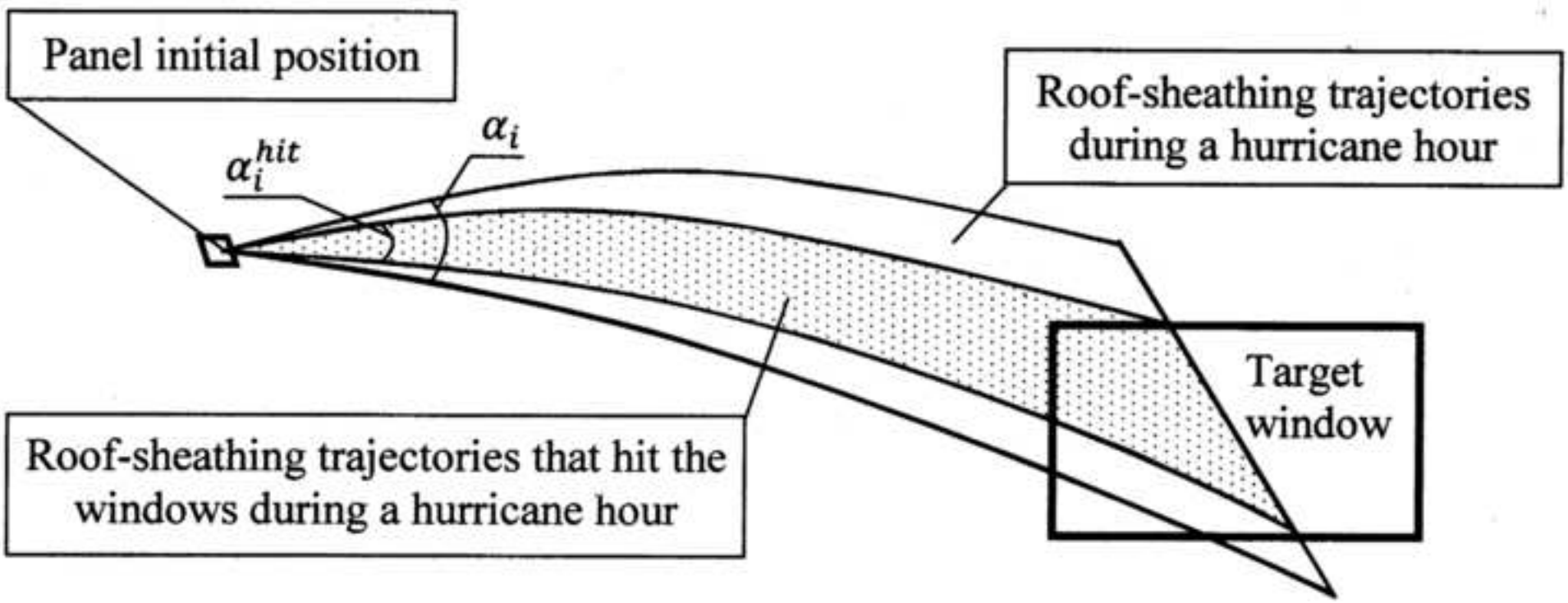

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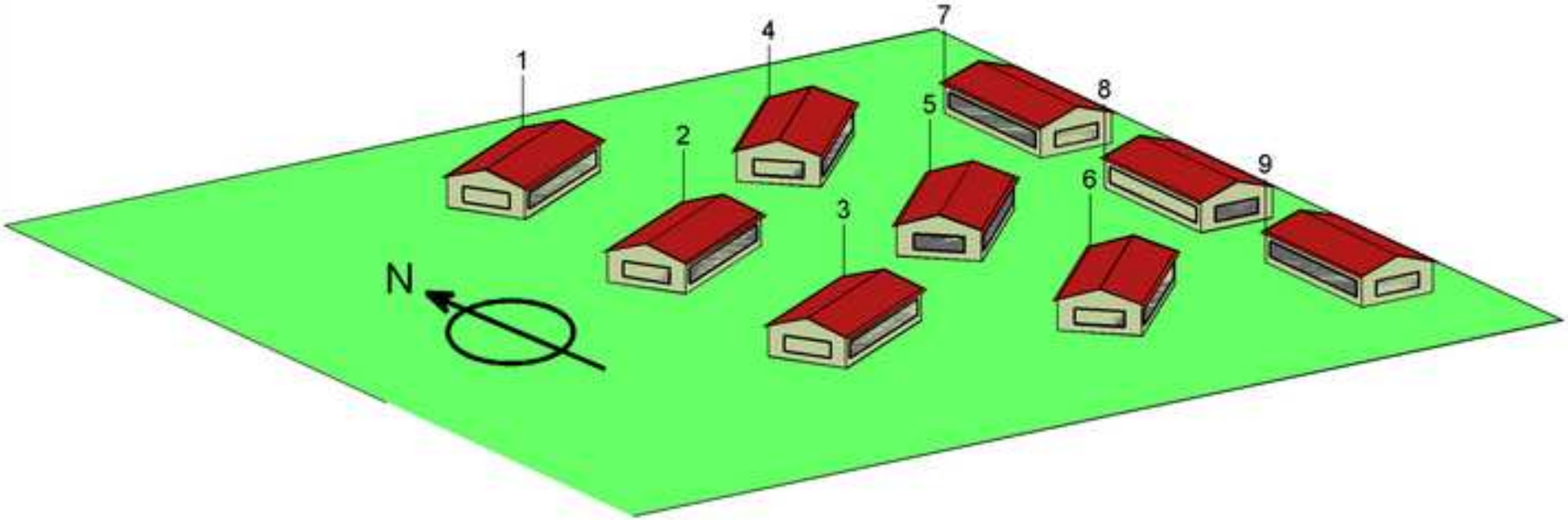

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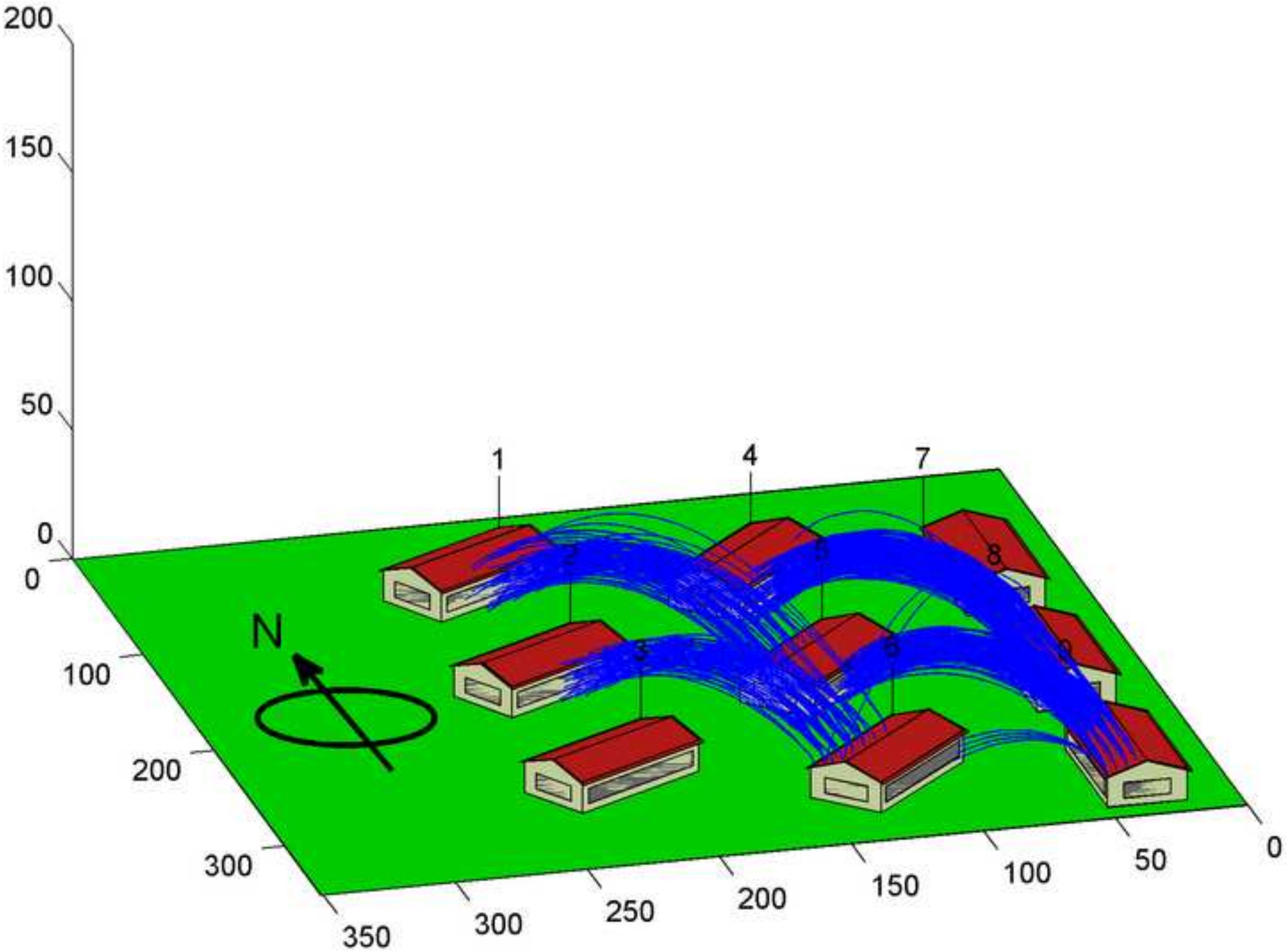

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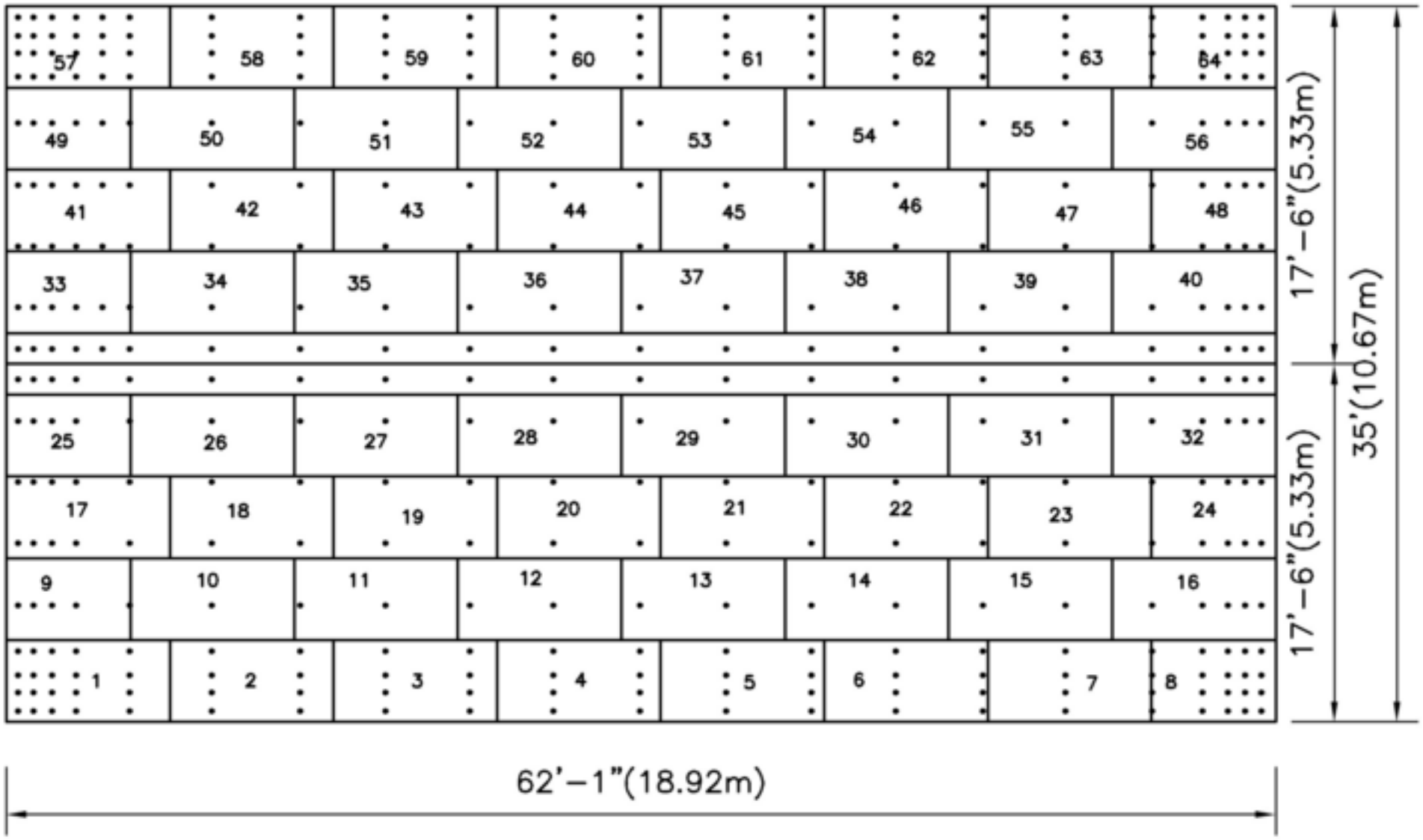

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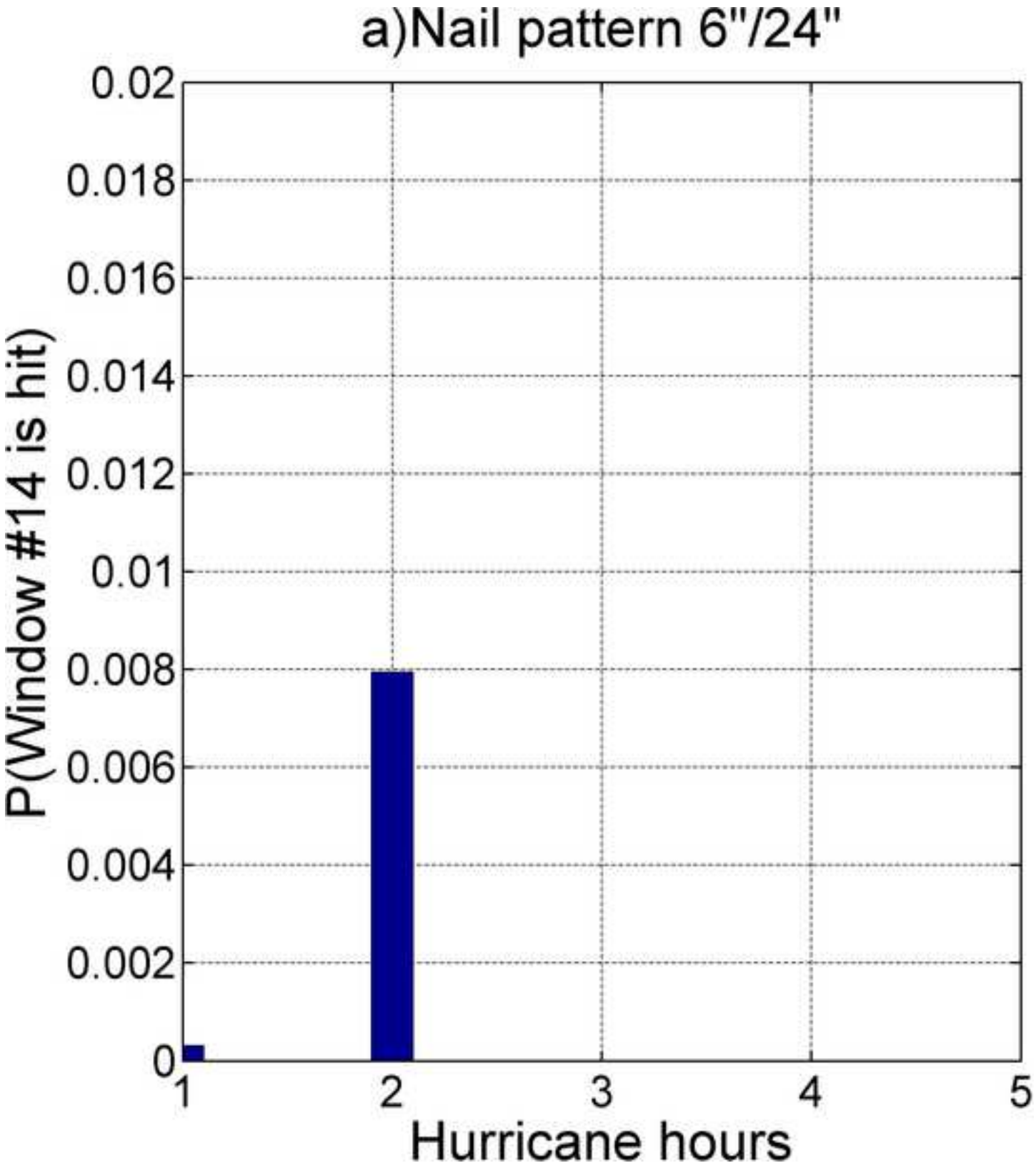
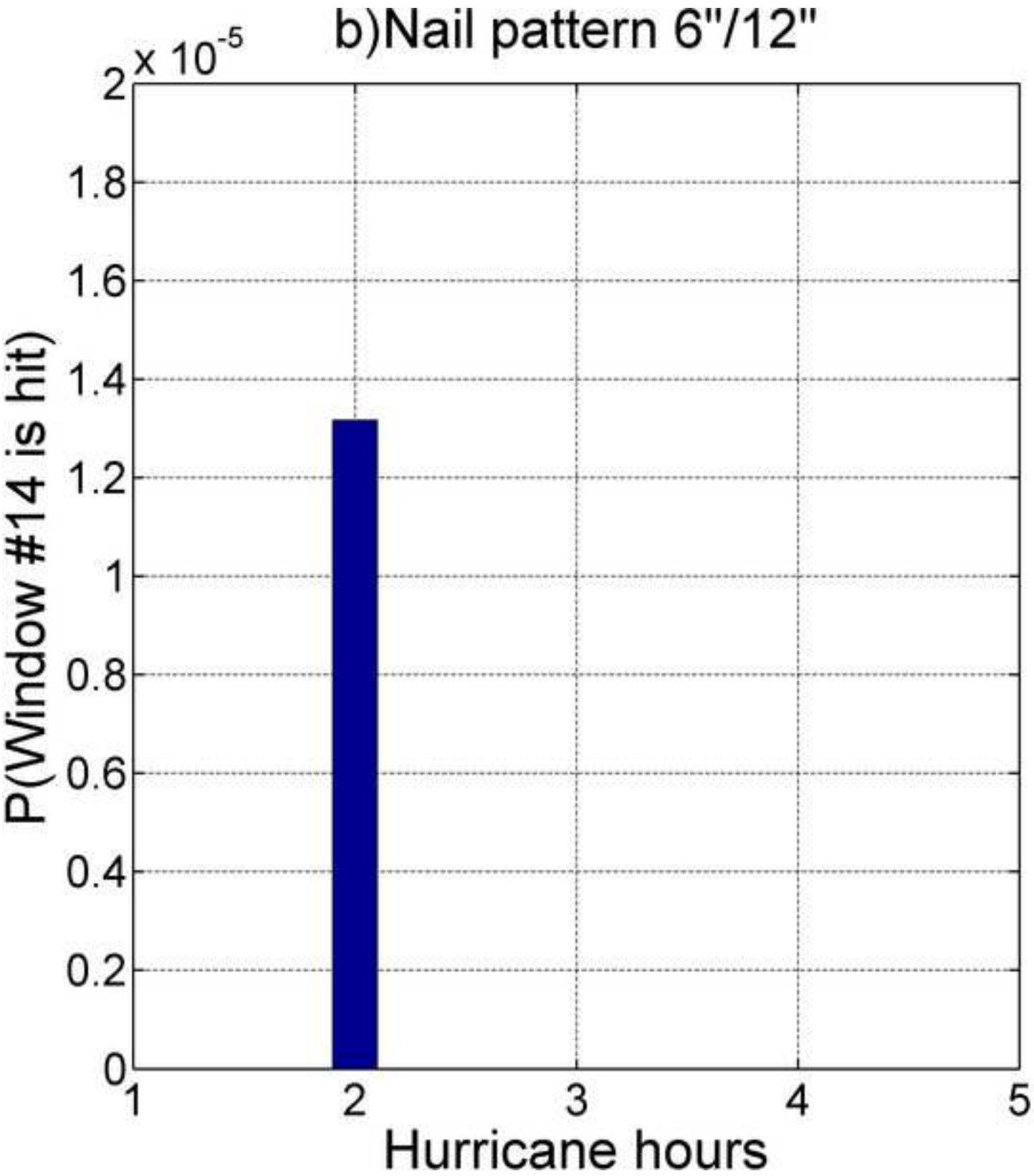
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