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Construction quality issues in performance-based wind engineering: effect of missing fasteners

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Abstract. In light-frame wood construction, missing roof-sheathing fasteners can be a relatively common occurrence. This type of construction makes up the vast majority of the residential building stock in North America and thus their performance in high winds, including hurricanes, is of concern due to their sheer number. Construction quality issues are common in these types of structures primarily because the majority are conventionally constructed and unlike steel and reinforced concrete structures, inspection is minimal except in certain areas of the country. The concept of performance-based wind engineering (PBWE), a relatively new paradigm, relies on the assumption that building performance under wind loads can be accurately modeled. However, the discrepancy between what is designed (and modeled) and what is built (the as-built) may make application of PBWE to light-frame wood buildings quite difficult. It can be concluded from this study that construction quality must be controlled for realistic application of PBWE to light-frame wood buildings.

Keywords: performance-based design; light-frame wood buildings; sheathing fastener; wind engineering.

1. Introduction

Light-frame wood structures are the most numerous building type in North America but are also among the most susceptible to high wind hazard. In fact, the majority of damage and property losses during hurricanes are due to the failure of the building envelope beginning with coverings such as roofing materials and siding. Once roof coverings are lost significant water intrusion is possible. Although water intrusion is often possible when no sheathing panels are lost due to construction tolerances, and temperature and humidity levels, this is not a focus of the current effort but should eventually be examined in more detail. Recently, several studies focused on the assessment of the performance of light-frame wood buildings under extreme wind events through the introduction of fragility curves. Ellingwood, *et al.* (2004) applied fragility modeling to evaluate the structural risk to both earthquake and wind hazards. The risk was defined through the expression of the following limit state function

$$P[G(X) < 0] = \sum_{y} P[G(X) < 0 | D = y] P[D = y] \tag{1}$$

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where D is the random variable representing the demand on the system (e.g., 3-sec gust wind speed) and $P[D=y]$ is the natural hazard probability, $P[G(X)<0|D=y]$ is the conditional limit state probability, and denotes the so-called fragility. In that study fragility models for hurricane winds were developed for roof panel loss and roof-to-wall connection failures.

Lee and Rosowsky (2005) also performed a fragility assessment for roof-sheathing failure in high wind regions. The fragility curves were built by basing the roof sheathing capacity on sheathing panel test data, i.e., whole panel tests. Wind loads were calculated following the ASCE-7 standard and the roof-sheathing fragility curves were then constructed based on these roof-sheathing capacities and wind load distributions.

These two studies provided a method for generating fragility curves for roof-sheathing and roof-to-wall connections but did not go so far as to explain the application of wind fragilities in design. Although the panel-test approach is relatively accurate regarding the statistical distribution of the panel capacity, it does not necessarily allow one to investigate performance not associated with a capacity failure. In addition, the exact configuration being modeled must be tested at the panel level which is not practical for the large range of custom building roofs, geometries and wood/nail combinations in modern residential structures. Due to these drawbacks of the empirical method, Dao and van de Lindt (2008) introduced a new non-linear nail model that can easily be integrated into a finite element framework for roof-sheathing modeling under wind loading. This not only allows one the ability to calculate the roof-sheathing capacity under wind loading for any variable geometry, but also allows one to determine the roof sheathing behavior before capacity failure, thus allowing one to consider other levels of performance expectation such as excessive edge deformation. Combining this nail model with fragility concepts, van de Lindt and Dao (2008) furthered the concept of performance-based wind engineering for wood frame buildings.

In performance-based wind engineering (PBWE), the design criteria are based on the performance expectations of a structure subjected to a prescribed level of wind loading. The performance of a structure under this wind loading can be described consequently through performance expectations outlined in van de Lindt and Dao (2008) as follows: At the *occupant comfort* level, little or no reduction in living/inhabitant comfort following the wind event, and the structure should have no damage with water entry limited to moisture. In the *continued occupancy* expectation, electrical, plumbing and egress should still be present following the event, some moderate reduction in comfort may occur such as water intrusion, but there should be no threat to safety or likelihood of injury either during or after the event. An example of exceeding the continued occupancy limit state would be when loss of the first gable or roof sheathing panel occurs. For the *life safety* expectation, significant risk of serious injury might be expected to occur if someone was present during the event, and it is apparent that the safety normally provided by the structure to its occupants is no longer present either during or after the event. An example of a residential structure not meeting its life safety expectation would be when the roof-to-wall connection fails or one of the overhang support columns fail causing instability because it is likely framed back into the roof trusses. This may not strictly indicate a life or death situation necessarily but is representative of a performance-based limit state that one would target. For example, life safety in seismic design is indicated by 2% inter-story drift in several recent studies, but no real light-frame wood building will probably cause fatalities at these drifts. The intent is that it is a simple damage descriptor that correlates with other much more complex values, that often can't be easily computed within a model. The *structural integrity* performance expectation would be exceeded when the structure suffers visible signs of distress, such as excessive permanent lateral deformation, and subsequently the structure is not safe enough to be inhabited or even entered. It is important to note that while the performance expectation was presented in an approximate order of severity, the expectation levels are not necessarily mutually exclusive. Perhaps the most complex performance expectation, which is in a way a combination of much of the above, is *manageable loss*, which can be described as the cost to repair a structure not exceeding some prescribed percentage of construction/replacement cost. This is, of course, dependent on numerous factors, and is often the result of rainwater intrusion. The estimation of manageable loss can be accomplished by applying assembly-based vulnerability (Porter, *et al*. 2001, Pei and van de Lindt 2009) which essentially assembles all damageable components within the building. To date, this has not been performed for rainwater intrusion.

In order to implement performance-based wind engineering concepts and satisfy the pre-selected performance expectations that are selected solely based on design and not construction quality, understanding the effect that construction quality plays on the fragilities and their application in PBWE is critical to its eventual implementation (Rosowsky and Kim 2004). Kim and Rosowsky (2005) investigated the effect of construction quality on fragilities for seismic design of wood shear walls and concluded that it was critical to consider this issue in performance-based seismic design as well. The quality of light-frame wood varies even further because residential light-frame construction is not inspected as rigorously as heavier commercial construction. For example, different nail capacities and nail spacings obviously lead to very different roof sheathing uplift capacities during wind storms or hurricanes. In the present study, the focus is on the assessment of the effect of missing fasteners or fastener groups on roof sheathing fragilities and subsequently their effect on selection of a nail pattern to provide the desired performance level within PBWE.

2. Numerical approach: fragility curves and PBD approach

In order to develop fragility curves which would be utilized for design selection during a performance-based design (PBD), one needs to determine the roof sheathing capacity statistics either by experimental or numerical methods. In the numerical roof-sheathing modeling used in this study the sheathing panels are modeled as eight-node finite elements (FE) and truss members are modeled as beam elements. A new non-linear nail model (Dao and van de Lindt 2008) was used in the FE model for the fasteners connecting the roof panels to the truss members. Within this new nail model, both axial and bending displacements are considered and the effect of eccentricity on rotational stiffness is accounted for in the development of the nail element stiffness matrix. To do this, a series of tests on both withdrawal and bending components on nails was conducted and the data was then used to calibrate an FE program to determine roof-sheathing capacity statistics. This new nail model is capable of accurately modeling the effect of load eccentricity and estimating roof-sheathing capacity. Fig. 1 shows the 3-D displaced mesh of a roof-panel at uplift pressure of 0.72 KPa (15 psf) resulting from an FE analysis using this new non-linear nail model. In the interest of brevity, the interested reader is referred to Dao and van de Lindt (2008) for numerical modeling details.

2.1. Fragility curve development

The assessment of structural performance can be evaluated by applying fragility analysis as a

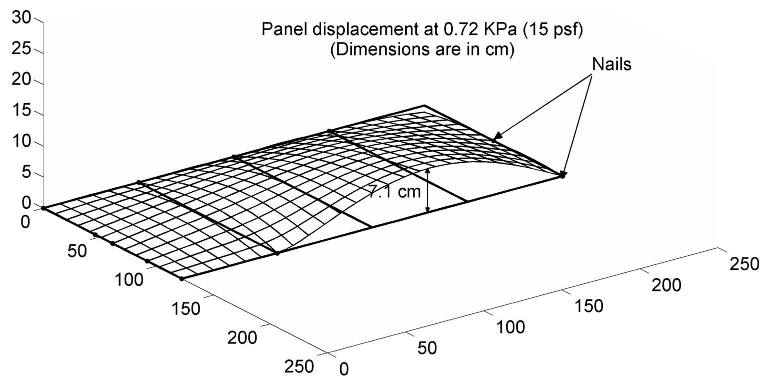


Fig. 1 FE analysis using new nail model (van de Lindt and Dao 2008)

function of the design wind speed. This design wind speed is defined herein using the ASCE-7 Standard (American Society of Civil Engineers 2005) as the 50-year 3-second gust wind speed. The fragility is essentially a damage state probability for a structural component or system conditioned on a demand variable such as wind speed. The probability of failure can be expressed as

$$P[G(\mathbf{X}) < 0] = \sum_{V} P[G(\mathbf{X}) < 0 | V_w = V] \times P(V_w = V) \tag{2}$$

in which the $P[G(\mathbf{X}) < 0]$ is the probability of roof sheathing failure, $P(V_w = V)$ is the probability of the basic wind speed being equal to V; $P[G(\mathbf{X}) < 0 | V_w = V]$ is the probability that roof-sheathing fails at wind speed V, and is termed the roof-sheathing fragility; $G(\mathbf{X})$ is the limit state function. In this study, the limit state function of roof-sheathing failure can be expressed simply as

$$G(\mathbf{X}) = C - (W - D) \tag{3}$$

where C is a random variable representing uplift capacity; W is a random variable of the wind pressure apply to the roof-sheathing at basic wind speed V; and D is random variable accounting for the dead load statistics of the roof-sheathing and covering.

As can be seen from Eq. (2), the structural fragility is a probabilistic function of structural capacity, dead load and basic wind speed. The structural capacity depends on construction quality which is a function of both manufacturing quality and personnel skill. Manufacturing quality is intended to mean the manufactured product(s) that are used in the system whereas personnel skill is intended to mean the construction errors themselves such as missing fasteners or the absence of hardware. In the numerical analysis for roof-sheathing capacity, the material properties are considered deterministic as are personnel skill, i.e., the missing nails within the nail patterns. The mean and coefficient of variation (COV) of the dead load considered in this study was taken as 168 N/m^2 (3.5 psf) and 0.10, respectively (Lee and Rosowsky 2005) and is assumed to remain constant during the analysis.

The wind force is modeled based on Ellingwood (1999), as

$$\bar{w} = 0.8 w_n \tag{4}$$

$$\sigma_w = 0.35 \bar{w} \tag{5}$$

Table 1 Load statistics (van de Lindt and Dao 2008)

Load Type	Mean	Coefficient of variation	Distribution Type	Source
Dead load	168 N/m^2 (3.5 psf)	0.10	Normal	Lee and Rosowsky (2005)
Wind load	$0.8W_n$[1]	0.35	Extreme Type I	Ellingwood (1999)

[1] W_n = nominal wind load computer per ASCE 7-05 (American Society of Civil Engineers 2005)

where $\bar{w}$ is the mean of the wind force, w_n is nominal the wind force and σ_w is the standard deviation of the wind force. Nominal wind forces acting on the structure and components are calculated using ASCE 7-05 (American Society of Civil Engineers 2005) wind pressures. In this study the coefficient of variation of 0.35 in Eq. (5) was assumed to include the uncertainties related to the wind pressure based on a given basic wind speed. Studies have considered each of these pressure and site coefficients as random variables (e.g., Ellingwood, *et al.* 2004), but in the present study the focus is intended to be on effects of construction quality on structural performance and not ASCE 7 and uncertainties associated with it, thus Eqs. (4) and (5) were felt to be adequate for comparative purposes. The resulting load statistics are shown in Table 1. The fragility of the performance descriptor versus wind speed can then be constructed by its definition as

$$Fr = P[G(\mathbf{X}) < 0 | V_w = V] \tag{6}$$

where Fr is the fragility of the performance descriptor versus wind speed, $G(X)$ is the limit state function using the random variable form of Eq. (3).

2.2. Performance-based design approach for wind

Recall that there were five performance expectations introduced by van de Lindt and Dao (2008). In order to examine the effect of missing roof sheathing fasteners on performance-based wind engineering this study focuses on two performance expectations, namely *occupant comfort* and *continued occupancy.* These two performance expectations are selected because they represent the most commonly experienced situations for occupants of residential building following hurricanes. Consider the arbitrary fragility curves (for purposes of discussion) shown in Fig. 2(a) which are for three different structures and might, for example, have three different nail patterns. It is assumed in this illustrative example that one was attempting to design for and satisfy the *occupant comfort* expectation, and this was defined as an edge opening exceeding 5 mm (0.2 in) which would then allow attic insulation to become wet. Of course, fragilities are by their very definition probabilistic, so it is proposed for illustrative purposes here to work with the 50% exceedance value fragility which is, of course, the median. For a homeowner wishing to be provided more confidence in the design they may choose another percentile such as the 84th or even the 99th. However, as the percentile increases so does the material and labor costs for the design and this must be accounted for in the decision-making process. In Fig. 2(a), one can see that at a wind speed of 144 kph (90 mph), structure A has a probability of exceedance of what appears to be 100%, and for structure B this is 88%, both of which do not satisfy the requirement, e.g., the exceedance probability must not exceed 50% for the wind speed and performance expectation combination under consideration. However, the fragility curve for structure C shows that this requirement is satisfied with an exceedance probability of only 8%, far below the median value requirement of 50%. While it is

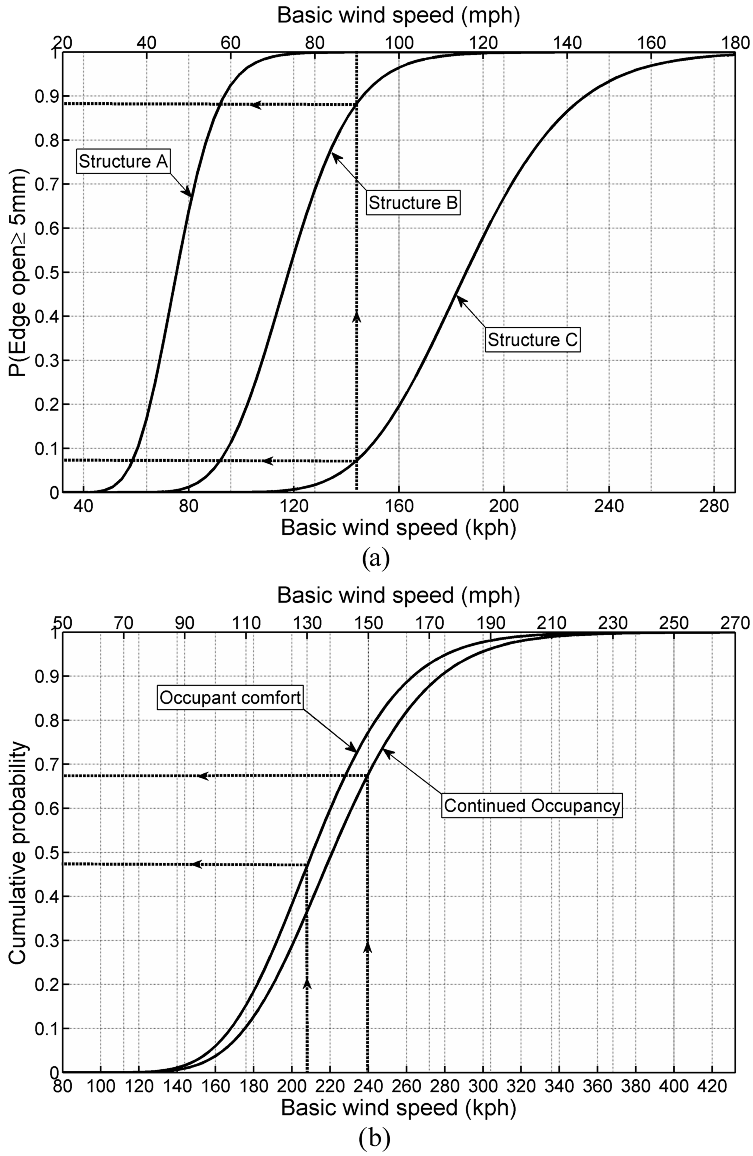


Fig. 2 Fragility curves for illustration (a) performance expectation *occupant comfort* for different nail patterns and (b) different performance expectations of the same structure (van de Lindt and Dao 2008)

obvious that the optimized nail pattern in the present illustrative example lies somewhere between structure B and structure C, one would select structure C in this case.

Another interesting circumstance can also arise in PBWE, namely, one must determine if a particular design satisfies the performance expectations for both *occupant comfort* and *continued occupancy* at the two corresponding predetermined wind speeds. In other words, in this study, one has to check if a roof sheathing nail pattern satisfies both of these performance expectations (each performance expectation is separately analyzed). So, consider Fig. 2(b), where the 208 kph (130 mph) and 240 kph (150 mph) are the design wind speeds for *occupant comfort* and *continued* *occupancy*, respectively. From Fig. 2(b), the *occupant comfort* and *continued occupancy* the probabilities of exceedance are 47% and 68% at those wind speeds, respectively. Thus, one would surmise that at the basic wind speed of 208 kph (130 mph), the structure satisfies the *occupant comfort* performance expectation. However, at 240 kph (150 mph) the *continued occupancy* performance expectation is not satisfied because there is a 68% probability of exceedance. This means that the nail pattern would be unacceptable for this performance-based design because the design must satisfy both of these requirements with these target objectives.

3. Effect of missing fasteners on performance-based design

3.1. Panel capacity

In light-frame wood structures, the quality of construction varies significantly because residential light-frame construction is not inspected the same way commercial construction is inspected. This is particularly true for details like roof-sheathing fasteners or connections between roof and wall or columns. In theory, they are supposed to be checked but in practice this is not always the case due to the volume of these types of buildings, particularly in North America. Fig. 3 shows a roof panel that was lost during hurricane Katrina. In that picture, it can be seen that not only the field nails are missing, but also one corner nail and several edge nails were not installed during construction (the circles indicate where the nails were installed). This picture is not as much of an exception as it should be, thus underscoring the fact that construction quality is a real issue in light-frame wood, but is not typically considered in design/detailing. The capacity and fragility of this roof-panel was computed in order to compare with an array of panel cases for missing fasteners, and are presented below.

In order to have a clear assessment of the effect of construction quality on the performance of residential structures and thus its effect on PBWE, consider the arbitrary simple rectangular building

Fig. 3 Loss of roof panel picture from hurricane Katrina (van de Lindt and Dao 2008)

shown in Fig. 4. The structure is 12.2 m (40 ft) wide, 18.3 m (60 ft) long and 3.7 m (12 ft) high. The roof slope is 1:3 and the roof is sheathed with 12 mm (15/32") thick Oriented Strand Board (OSB). The walls and truss members are made of 3.6 cm × 8.4 cm (2 × 4) Spruce-Pine-Fir (SPF) placed 61 cm (24") on-center. It is assumed that the house is constructed in the exposure B category (ASCE-7, American Society of Civil Engineers 2005). The structural dimensions and given exposure allow the calculation of the wind load, and by Eqs. (4) and (5), wind load statistics can be determined, assuming the angle of attack is known (In the present study, the angle of wind attack is assumed to be perpendicular to the longer side of the house. This assumption is made for fragility comparison to assess the effects of missing fasteners on roof sheathing panels thus ensuring that loading variable uncertainty does not enter the comparison.). Initially, the roof-sheathing capacities are estimated for different nail patterns. The wind load capacities for each type of failure, i.e., edge gap, are computed from the finite element model described earlier. In the present study, it is assumed that the *occupant comfort* performance expectation is somewhere between a roof sheathing edge opening of 5 mm (0.2 in) and 10 mm (0.4 in), which are denoted as case A and case B in Table 2, respectively. Case C is considered to be when the first field nail in the roof panel fails, which is the beginning of panel loss since the panel typically arches up and begins prying out the

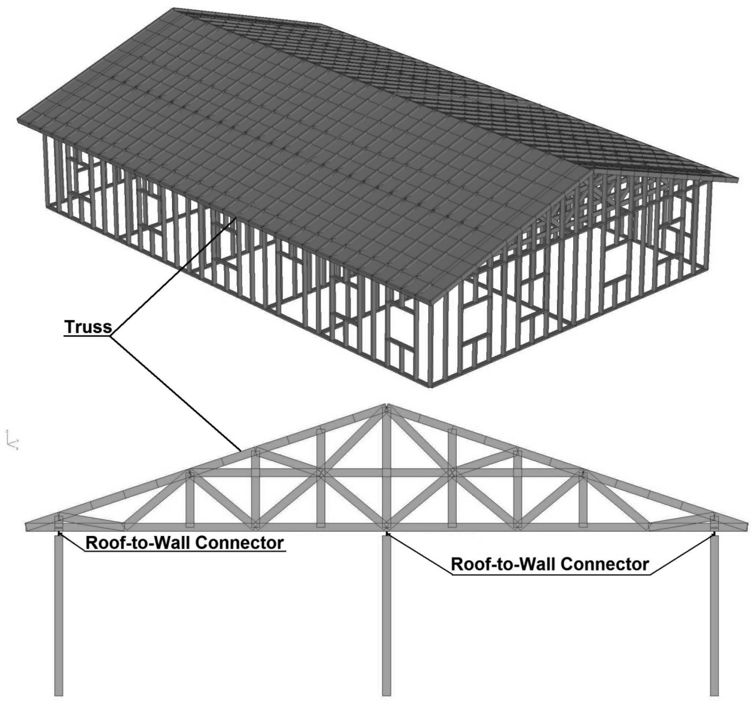


Fig. 4 Structure analyzed (van de Lindt and Dao 2008)

Table 2 Performance levels of interest (van de Lindt and Dao 2008)

Case A	Case B	Case C	Case D
Maximum roof panel edge opening is 5 mm (0.2 in)	Maximum roof panel edge opening is 10 mm (0.4 in)	The first field nail in the roof panel fails	The entire panel is lost

edge nails. This is felt to align well somewhere between the *occupant comfort* and *continued occupancy* performance expectations. Case D is when the roof sheathing panel is completely lost and is assumed herein to represent *continued occupancy*. The beginning of the *continued occupancy* performance expectation is assumed to be somewhere between case C and case D.

The capacity statistics are then fit to a lognormal distribution and identified in Table 3 by the column headings A, B, C and D as shown in Table 2. The new non-linear nail model was used to analyze the roof-sheathing capacities for each of the different nail patterns. The nail used in the FE model is an 8d box nail, which is 6 cm (2.4 in) long, 0.3 cm (0.113 in) in diameter. The up-lift

Table 3 Panel capacity statistics for the four performance levels (van de Lindt and Dao 2008)

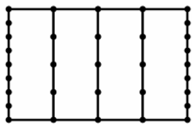
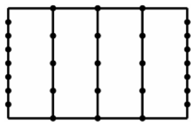
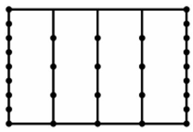
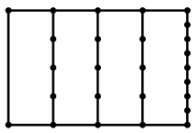
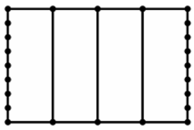
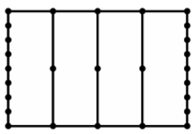
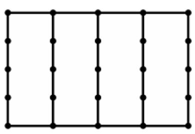
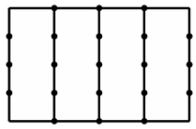
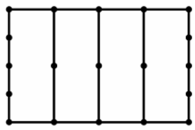
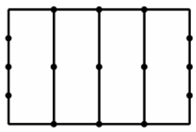
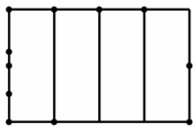
Panel No.	Description of construction defect	Nail pattern	Panel Capacity (lognormal distribution)							
			Case A		Case B		Case C		Case D	
			Mean Kpa psf	COV	Mean Kpa psf	COV	Mean Kpa psf	COV	Mean Kpa psf	COV
1	15cm/30cm (6”/12”) (Standard or Ideal)		3.95 82.60	0.10	4.66 97.38	0.15	3.34 69.85	0.24	4.79 101.0	0.14
2	15cm/30cm (6”/12”) (Miss corner nails)		3.63 75.86	0.09	4.34 90.61	0.12	3.40 71.10	0.24	4.57 95.36	0.17
3	15cm/30cm (6”/12”) (Miss long edge nails)		1.92 40.07	0.08	2.73 56.97	0.13	2.46 51.43	0.27	3.65 76.24	0.14
4	15cm/30cm (6”/12”) (Miss short edge nails)		NA	NA	NA	NA	2.48 51.88	0.24	4.30 89.75	0.16
5	15cm/30cm (6”/12”) (Miss all field nails)		1.87 39.15	0.12	2.11 44.02	0.15	NA	NA	2.18 45.55	0.15
6	15cm/61cm (6”/24”) (No missed nails)		2.50 52.19	0.10	2.68 55.97	0.10	1.62 33.79	0.29	2.80 58.40	0.13
7	30cm/30cm (12”/12”) (No missed nails)		3.72 77.76	0.10	4.34 90.70	0.12	3.41 71.12	0.25	4.57 95.36	0.17

Table 3 Continued

Panel No.	Description of construction defect	Nail pattern	Panel Capacity (lognormal distribution)							
			Case A		Case B		Case C		Case D	
			Mean Kpa psf	COV	Mean Kpa psf	COV	Mean Kpa psf	COV	Mean Kpa psf	COV
8	30cm/30cm (12”/12”) (Miss corner nails)		NA	NA	4.18 87.33	0.12	3.34 69.68	0.25	4.53 94.57	0.17
9	30cm/61cm (12”/24”) (No missed nails)		2.52 52.69	0.11	2.79 58.24	0.13	1.63 33.98	0.28	2.80 58.46	0.13
10	30cm/61cm (12”/24”) (Miss corner nails)		2.35 49.07	0.08	2.78 58.05	0.14	1.53 32.02	0.24	2.78 58.06	0.14
11	Real picture (From Katrina hurricane investigation)		NA	NA	NA	NA	NA	NA	1.06 22.10	0.10

*Note: Only strength cases are included for panel numbers 4, 8 and 11. This is because the material variability in the sheathing panel and studs are not included in the model.

pressure is divided into small steps so that the load-displacement curves in each nail can follow the experimental data smoothly since the nail model is empirical (see Dao and van de Lindt, 2008, for details). The displacements at each node were recorded for each load step. From the performance requirements, for example, the opening in the panel edge is 5 mm (0.2 in). The corresponding load is computed and taken as the panel capacity for that performance level. Of course, this is done numerous times based on the various nail test results which then allows generation of the statistics.

Panel No. 1 is considered to be of ideal construction quality for a panel whose distance between panel edge nails is 15.2 cm (6 in) and 10.5 cm (12 in) for the field nails, respectively. Each of the other illustrative examples investigates various patterns of missing nails which have either been seen in the field by the authors during post hurricane inspection or are felt to be reasonable for consideration based on common construction errors or omissions. Panel No. 11 shows the capacity results for the panel shown in the photo of Fig. 3 which was found during investigation after hurricane Katrina. One can see from Table 3 that, depending on the missing nail position, the effect on the performance of the roof-sheathing is quite different. Although this is expected there is no way to determine which nails are most often missed with perhaps the exception of field nails. Field nails are often put in place but miss the truss if chalk lines are not used during construction. The missing nails can have an effect on the load distribution in the remaining nails. For example, in panel No.2, four corner nails were missed and because the short edges are strong enough the load demand in the field nails is actually less than that of the field nails for panel No. 1. But this same load redistribution does not occur when comparing panel No. 7 and No. 8, or panel No. 9 and No. 10, because the short edges are not strong enough to redistribute the load.

3.2. Effect on fragilities

Fig. 5 shows the fragilities for panel No. 1, No. 5 and No. 11 at the upper limit of the *continued occupancy* performance expectation, assumed to be case D described earlier as loss of the first roof sheathing panel. Recall from above that an exceedance probability of less than 50% is sought. At a wind speed of only 140 kph (88 mph) one can see that panel No. 11 has a 50% exceedance probability. However, this wind speed is quite low and in fact during hurricane Katrina, gust wind speed in this area was estimated to be as high as 208 kph (130 mph) (Peterka 2007). Although circumstantial, at best, this evidence suggests that the numerical model and wind fragilities are a fair interpretation of the probability of exceeding a limit state for use in PBWE. Further, at a wind speed of 160 kph (100 mph) the probability of panel No. 11 being lost is 76%, panel No. 5 is only 13% and panel No. 1 is virtually 0%. One can say that panel No. 1 and No. 5 satisfy the performance-based design requirement, i.e., satisfy the performance expectation numerically, for the *continued occupancy* expectation if medians are considered as in our earlier discussion, but panel No. 11 clearly does not. It is critical here to observe that panels 1, 3, 5 and 11 would have all had the same nominal design and the only difference would be the construction quality. In other words, if a performance-based design called for the nail pattern of panel 1 and received the nail pattern of panel 11, the performance expectation is far from achieved.

Fig. 6 present fragilities for the 11 cases of missing fasteners considered herein. From those plots one can see that the general trend is that the field nails are critical in keeping the panel from being lost, i.e., the *continued occupancy* performance expectation, but the edge nails are critical to eliminate water intrusion, i.e., the *occupant comfort* performance expectation. This can

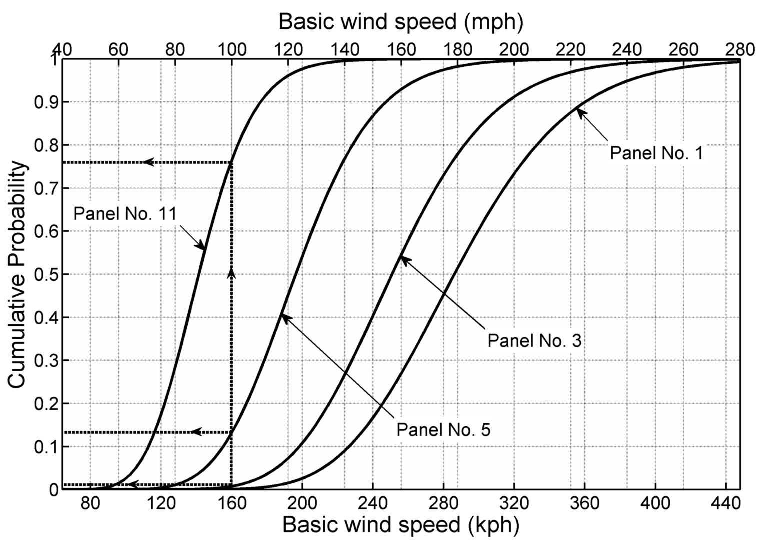


Fig. 5 Fragility and effects of missing fasteners (van de Lindt and Dao 2008)

be seen in the distance between the fragility curves for all cases in Fig. 6. Panel No. 11 is clearly the poorest performing panel for all performance expectations simply because so many fasteners are missing. From the fragility curves in Fig. 6, among 11 panels, one can see that sometimes the field nails fail before the edge opens 5 mm (0.2 in), and sometimes the field nails fail after the edge open 5 mm (0.2 in). This means that the *occupant comfort* and *continued occupancy* performance expectations have some level of overlap and as mentioned before are not mutually exclusive.

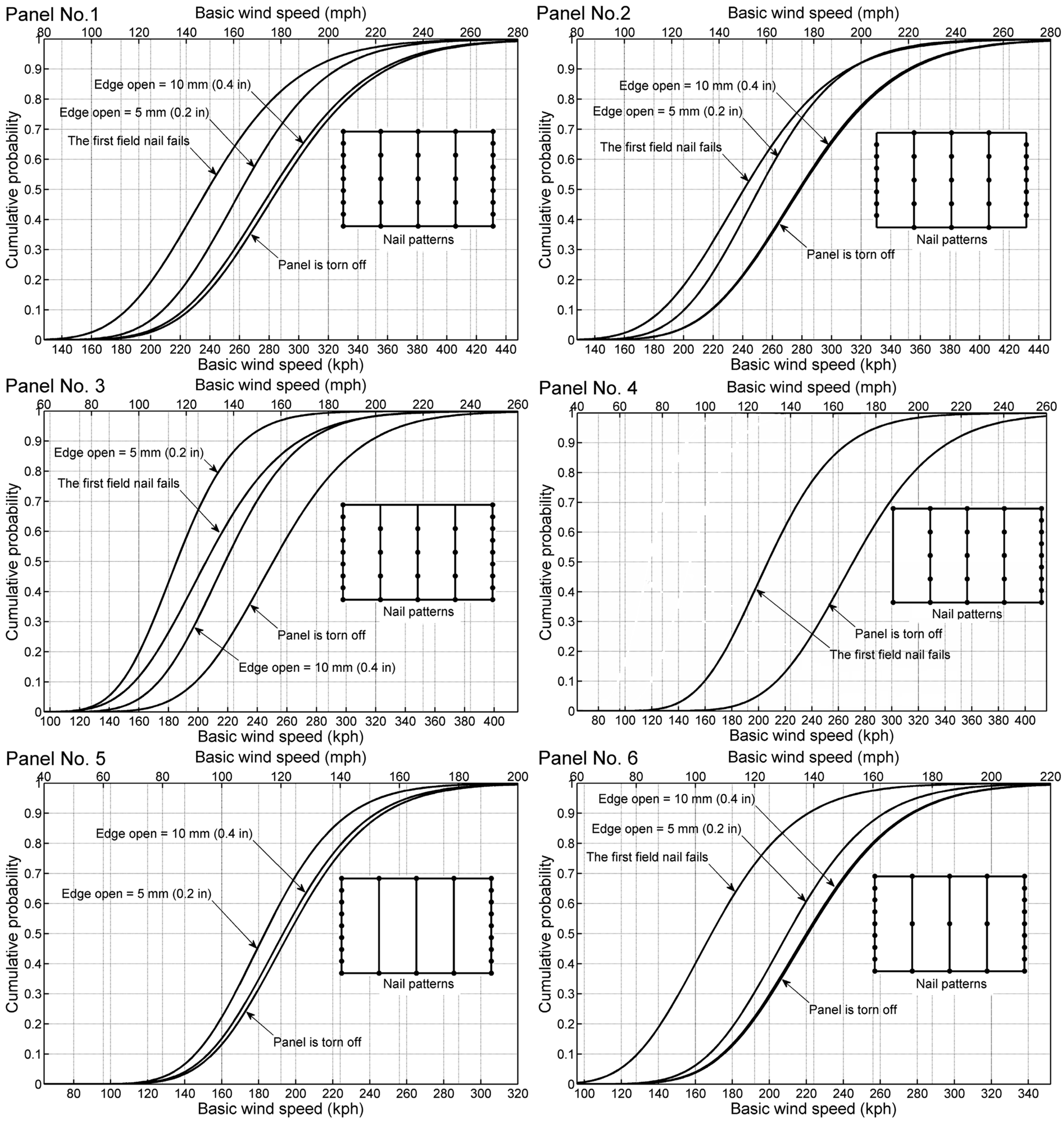


Fig. 6 Fragilities of different cases (van de Lindt and Dao 2008)

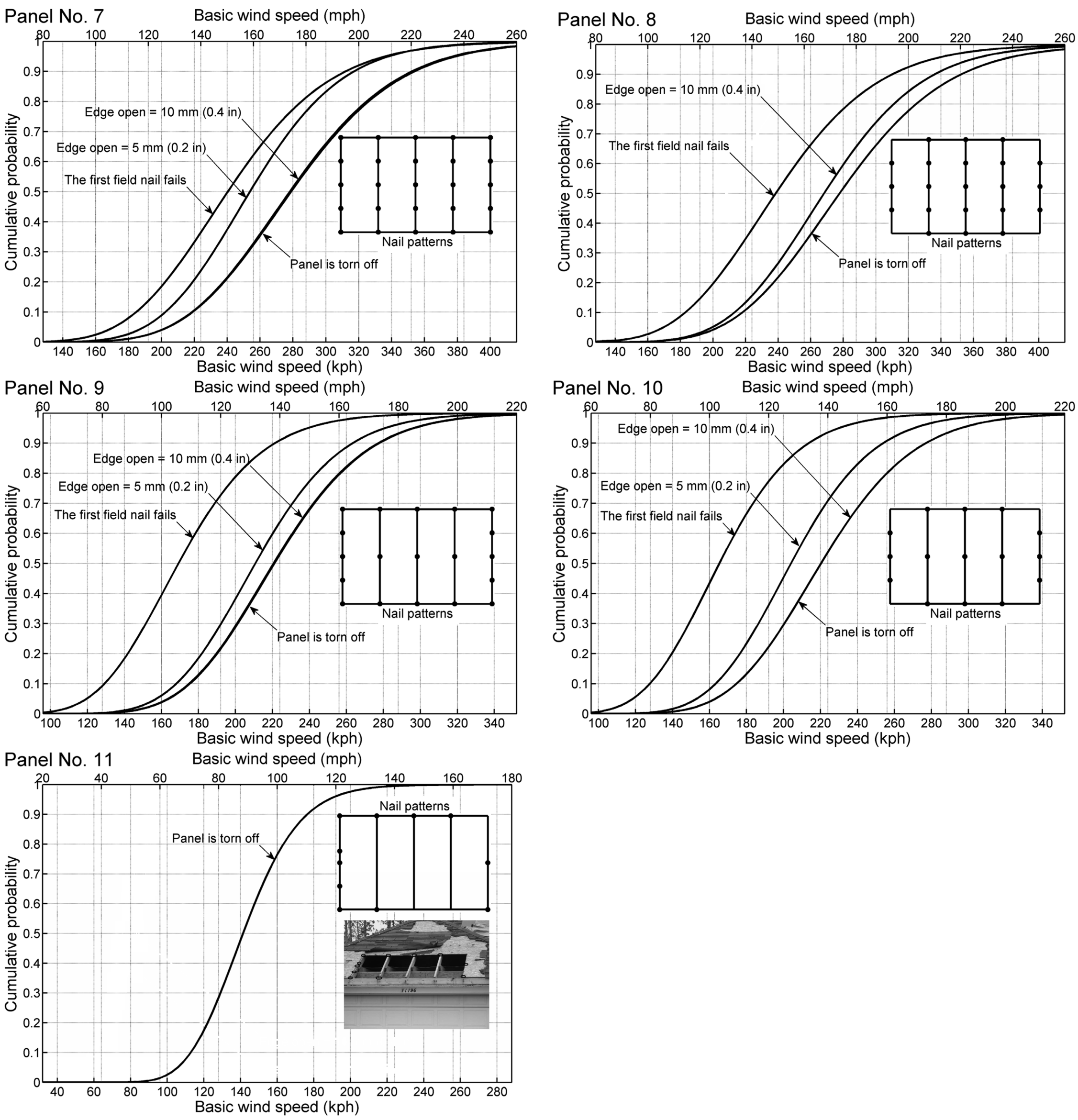


Fig. 6 Continued

4. Conclusions

In the present study, several performance expectations for performance-based design for wind were explained including *occupant comfort, continued occupancy, life safety, structural integrity* and *manageable loss.* Then, the effect of construction quality on the different performance expectations was investigated. Construction quality was limited in the present study to changes in the nail pattern, such as missing nails and nail lines, from the original design.

Different nail patterns representing various construction quality-related defects in residential roof construction were analyzed using a finite element model which adopted a new non-linear nail model developed previously by the authors. Then the roof-sheathing capacity statistics for different levels of performance expectation were determined. The wind statistics were applied from an existing model and fragility curves for different panels built for several different performance expectations. The results show that depending on the position of the missing nails, very different effects on roof-sheathing performance can be observed. It can be concluded that the edge nails are important in preventing water intrusion and are thus directly tied to the *occupant comfort* performance expectation, while the field nails are more directly tied to the roof-sheathing capacity and thus keeping the panel from being lost, i.e., the *continued occupancy* limit state. This means that if the risk of missing nails is not accounted for properly, the application of PBWE to residential structures can be negatively affected at different performance expectations. It can be concluded based on this limited study that construction quality should potentially be introduced as a random variable within performance-based wind engineering applications. Finally, proposed herein are performance descriptors that can be determined using engineering principles. For wind engineering to eventually accept and adopt performance-based design principles, these will need to be better defined and agreed upon.

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