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Wind Vulnerability Assessment of Light-Frame Wood Structures in the Philippines using Component-Based Reliability Model considering Progressive Damage Analysis

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ABSTRACT

The vulnerability of light-frame wood structures is assessed by developing computational vulnerability curves using a Component-Based approach with consideration of progressive damage in the failure analysis. Wind loads were determined from a computational fluid dynamics (CFD) simulation and internal forces at the critical building components were obtained from structural analysis. Failure is defined when the resistance capacity is exceeded by the computed load at a critical building component. Progressive damage analysis was done by considering the change in the wind pressure distribution on the building envelope due to damaged roof and wall panels in the preceding runs of failure simulation. Results showed that the weakest connection is at the foundation supports and a maximum increase of 17% in building damage at 70 m/s wind speed was observed when compared to onset damage analysis.

1. Introduction

Light-frame wood structures are the type of residential structures most vulnerable to severe winds during typhoons. Observed severe wind damages in Leyte and Samar due to Typhoon Yolanda in 2013 show that timber structures are most devastated and were extensively damaged or collapsed as compared to concrete structures where only roof failure mostly happens and the rest of the (concrete) main structure is still intact (Aquino, 2014).

Figure 1. Extensive Damage on Light Frame Wood Structures vs Roof Damage on Concrete Structures

The distribution of light-frame wood structures across the Philippines using the Philippine Statistics Authority (PSA) database is shown in Figure 2. From this graph, it can be observed that light-frame wood structures are prominent in the Eastern and Western Visayas regions, areas that are most frequently impacted by strong typhoons.

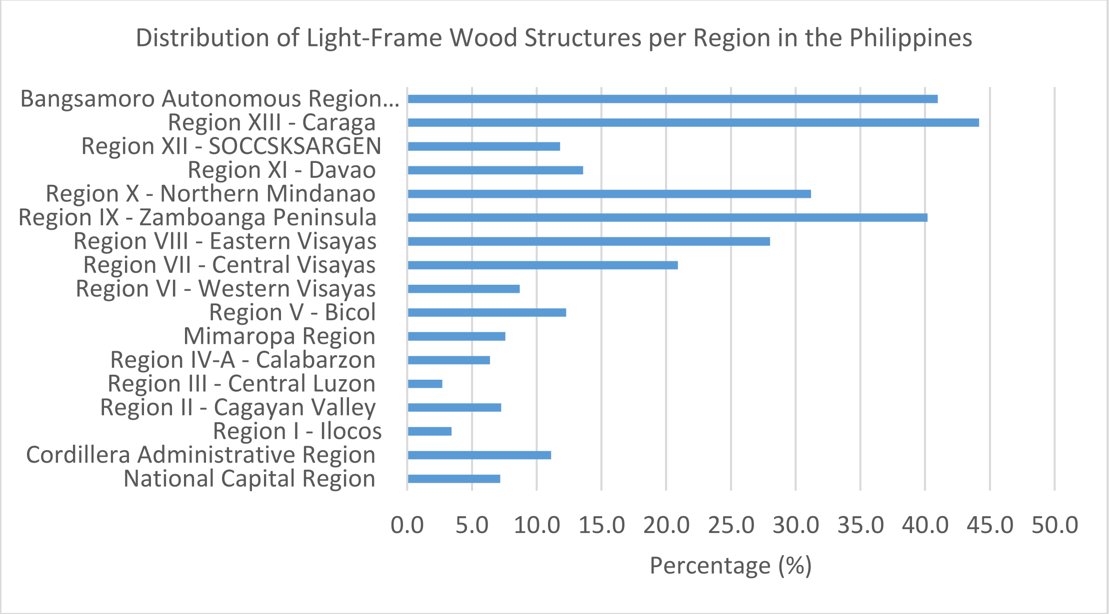


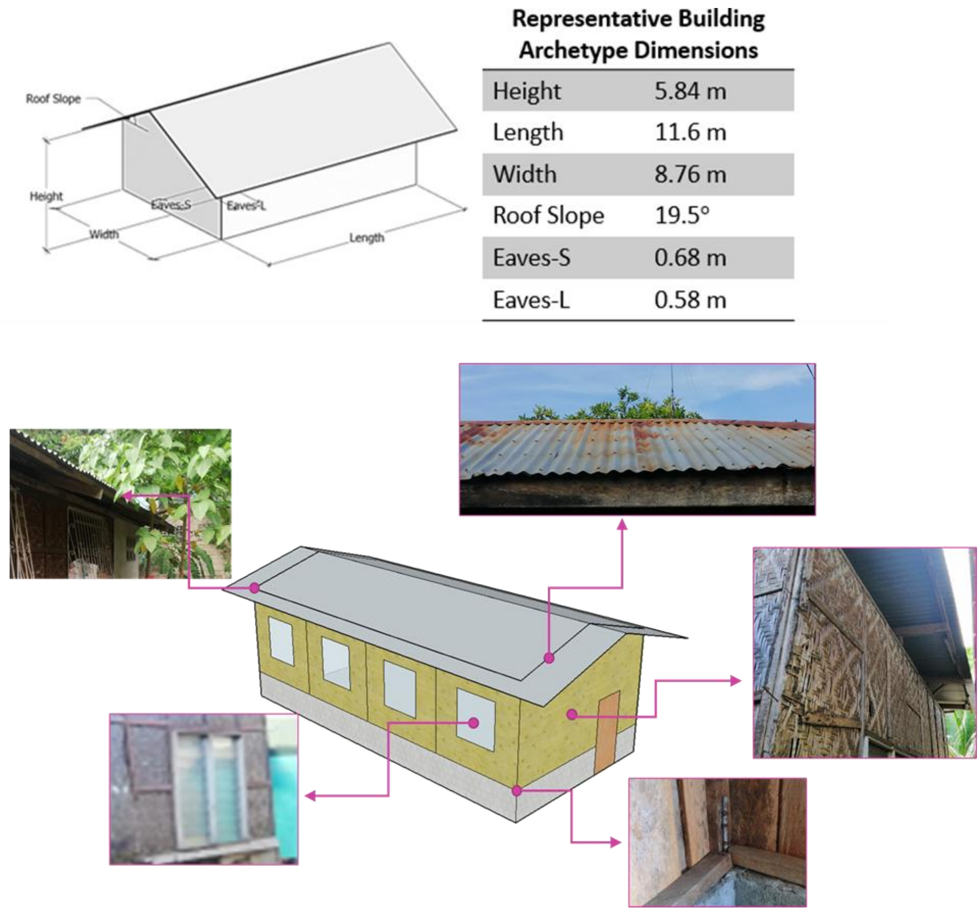
Figure 2. Distribution of Light-Frame Wood Structures per Region in the Philippines

Due to the exposure of light-frame residential wood structures to severe winds, this study aims to quantify the vulnerability of such structures against severe winds by developing computational vulnerability curves. This research will adopt the Component-Based approach in vulnerability modeling and will consider the effects of progressive damage to account for further damages in the structure when a breach in the building envelope occurs.

2. Materials and Methods

2.1 Research Methodology

The following flowchart presents the methodological framework of the study. A representative building archetype was developed for light-frame wood structures based on field surveys done in Cebu and Bicol regions that will serve as the building models for Computational Fluid Dynamics (CFD) simulation and structural analysis. A steady state (RANS) simulation was used to determine wind pressure forces which are then loaded to the building frame model to obtain the response of the structure translated to internal forces and moments at the connections and critical members. Resistance capacities of connections and critical members were determined from experimental testing and were used to assess the failure of the connections and critical members. Failure assessment using Monte Carlo simulation was done for varying wind speeds and wind directions. The wind speeds used in this study start from 10 m/s up to 100 m/s with 10 m/s increments and the wind directions considered are 0°, 30°, 60 °, and 90°.



Representative Building Archetype Dimensions

Height	5.84 m
Length	11.6 m
Width	8.76 m
Roof Slope	19.5°
Eaves-S	0.68 m
Eaves-L	0.58 m

Figure 3. Representative Building Archetype and Critical Building Components

Onset failure was checked on critical building components which include the following: wood to CHB wall connection, roof structure and wall/window panels. After determining onset failure, critical building components that were affected by the onset failure were removed and a new building model is created. This new building model is based on the representative building archetypes but with removed critical building components such as removed roof panels, wall or window panels, and connections. The criterion for removing critical building components is when it has at least 50% probability of failure. This new building model is then subjected to CFD simulation and structural analysis to determine the change in wind pressure distribution and the redistribution of loads on the building frame. The new building model then undergoes failure simulation, and this will account for the quantification of the further damage incurred in the building after onset failure which will constitute the progressive damage failure. The check for progressive damage failure is repeated until no critical building component is removed.

Damage aggregation and quantification is in terms of building damage ratio. The percent damage of each critical building component is translated in terms of building cost hence, the use of component cost factor (CCF). The component cost factor was determined by computing the repair cost of the building component over the total construction cost. The repair costs for building components and total construction costs were based on Bill of Materials (BOM) of projects available to the researcher or were obtained by construction estimates.

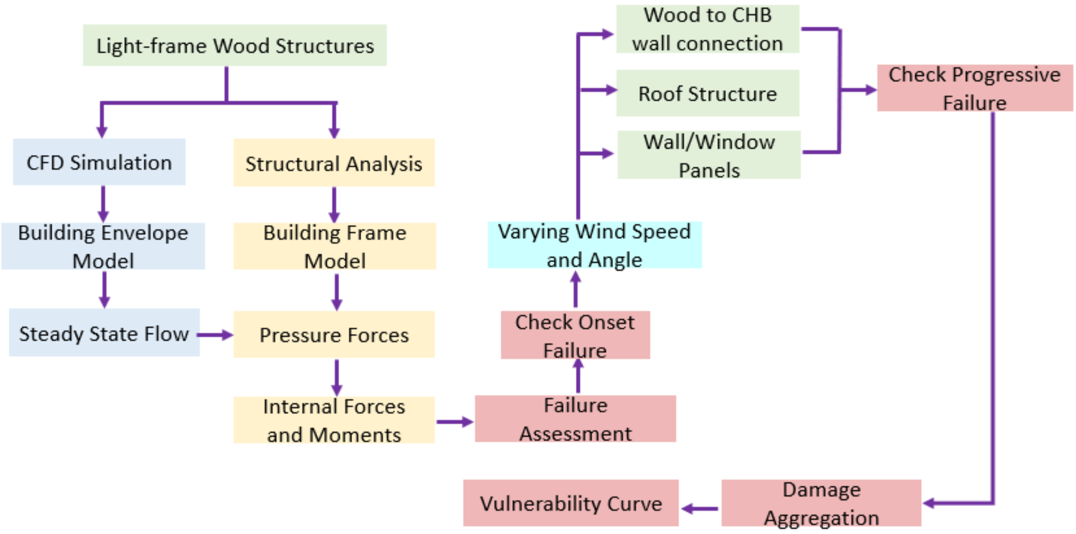


Figure 3. Research Methodology

Table 1. Critical Building Component Resistance Capacities and Probability Distribution

Building Component	**Type**	**Mean**	**Std Dev**	**Distribution**
Roof Fastener	Wood Nail	647.692 N	150 N	Lognormal
Purlin Connection	Wood Nail	4035 N	416 N	Normal
Purlin Section	Cocolumber	61.7 MPa	6.17 MPa	Normal
Roof to Column Connection	3" Angled Wood Nail	13,010 N	740 N	Normal
Wood Wall to CHB Wall Foundation Connection	Bent Nails around Rebars	7777.10 N	801.77 N	Normal
Wall Panels	Sawali, Plywood	4270 Pa, 4330 Pa	610 Pa, 680 Pa	Lognormal
Window Panels	Glass Jalousie	4218 Pa	970 Pa	Lognormal

2.2 CFD Simulation

To develop a set of simulation parameters to be used for wind simulation, this study replicated the results of the experimental wind test done by Tan (2017) for school buildings and one of the experimental wind tests done by Tokyo Polytechnic University (TPU) for gable structures found in their database using an open-source software for CFD simulation, OpenFOAM. In order to replicate the results of these experimental tests, the following simulation parameters were varied: nut, RAS turbulence solver, meshing parameters and numerical schemes.

The nut quantity represents the near wall treatment function which is used to model shear stresses near walls. The wall function that gave the most accurate result was the nutUSpaldingWallFunction which gives constraints on nut based on velocity as dictated by Spalding's law. For RAS turbulence solver, the turbulence solver that gave the most accurate results was the kOmega model. As for the meshing parameters, the refinement of building surfaces and inflation parameters were varied. In the numerical schemes, the schemes were switched from a first-degree numerical scheme (Gauss upwind) to a second-degree numerical scheme (linear Upwind scheme, limited linear scheme) to have more accuracy. It was observed that first-degree numerical schemes converged easily and is stable however, they are too diffusive which underestimates the pressure coefficients. The following figures are sample results of pressure coefficients, Cp, that show the close approximation of the simulation results using the developed model parameters to the experimental results of Tan (2017) and TPU.

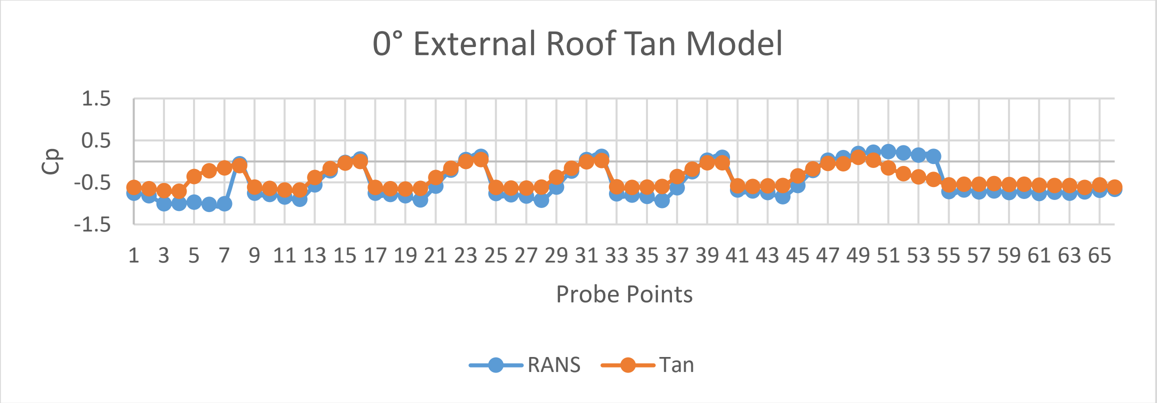


Figure 4. CFD Simulation vs Experimental Results using Tan's Model

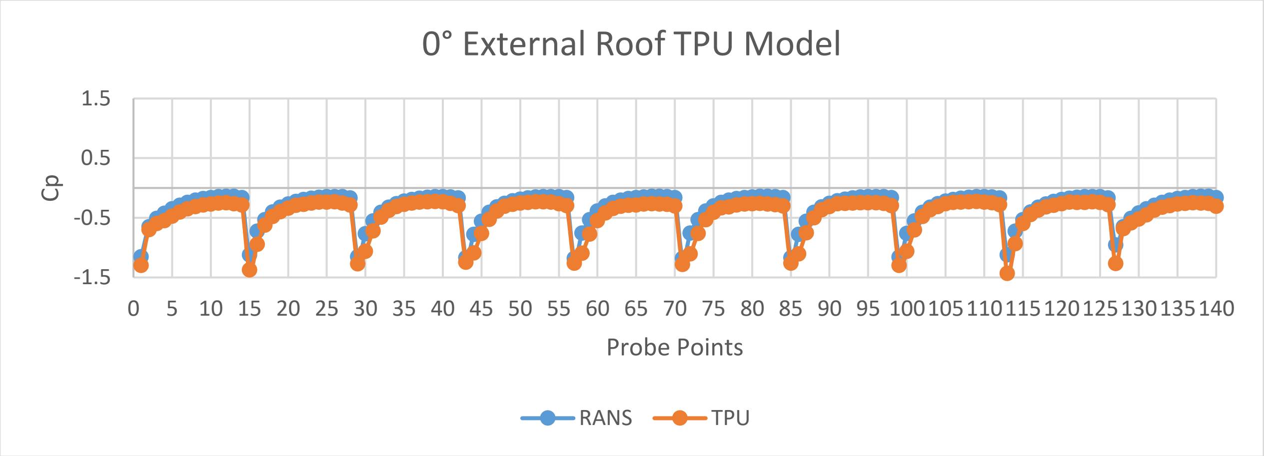


Figure 5. CFD Simulation vs Experimental Results using TPU's Model

3. Results and Discussion

The following graph shows the developed vulnerability curves considering onset and progressive failure analysis.

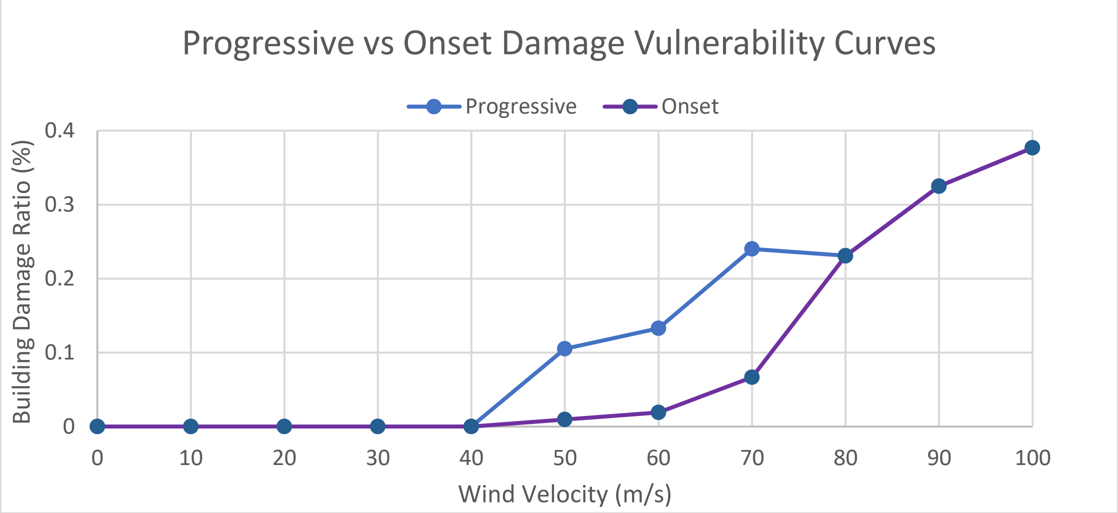


Figure 6. Progressive vs Onset Damage Curve for Light-Frame Wood Structures

Significant progressive damage was observed in wind speeds ranging from 50 m/s to 70 m/s. At wind speeds greater than 70 m/s, onset failure happens at roof-to-column connection and wood to CHB wall connection so that greater than 50% of the roof panels and wall panels are removed. For these cases, when greater than 50% of roof panels or wall panels are removed, the net pressure coefficients are greatly lessened such that no further damage is incurred in the structure so that the vulnerability curve considering progressive damage is coincident with that of the onset damage. In this scenarios, the air just freely flows in and out of the structure since there is enough openings in the structure for the air to just flow through.

The result of the progressive analysis shows that an onset partial roof damage (less than 50% of roof panels removed) increases the wind pressure loads that is carried by the wood to CHB wall connection which serves as the foundation of the structure. Hence, increasing the probability of failure of the wood to CHB wall connection and the possibility of collapse of the whole structure. This behavior accounts for the maximum increase of 17% between onset and progressive damage at 70 m/s. Since the foundation supports is sensitive to progressive damages and critical to the stability of the structure, strengthening this building component will help reduce severe wind damages from total building collapse to localized failures.

4. Conclusions

The vulnerability of light-frame wood structures against severe wind loading is assessed by developing computational vulnerability curves where the building damage is in terms of damage ratios defined as the repair costs of damaged building components over the total building cost. Damaged building components were determined through a failure simulation where wind loads on critical building components were compared to their resistance capacities. Progressive failure analysis was done to track how an onset damage in a roof fastener connection may possibly lead to a failure in roof to column connections and wood to CHB wall connection along with the associated building component damages. An onset damage in the roof fastener connections which causes the partial removal of roof panels resulted to a damage progression to the wood to CHB wall foundation connections. Specifically, a maximum increase of 17% at 70 m/s is observed when comparing the damages from onset to progressive failure analysis. This is mainly attributed on support connection damages making the wood to CHB wall connection, the most vulnerable critical building component and most viable candidate for strengthening measures.

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