Risk assessment of low-rise educational buildings with wooden roof structures against severe wind loadings

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ABSTRACT
This paper investigates the prominent failure modes of educational facilities by using field observations. Specifically, damage to the roof covering, roof structure and exterior windows were quantified. An archetype of these structures is modeled in a Monte Carlo Simulation wherein the probabilistic resistance capacities of the building envelope components are compared to their corresponding probabilistic wind loads. The probability of exceedance is then evaluated at three levels of damage state per 3-s gust wind speeds. For the vulnerability curve, the results were fitted into a cumulative probability density function with a mean of 4.7314 and a standard deviation of 0.4061. The results of the model are then evaluated through a case study of Typhoon Nina 2016. The model generally underpredicts the mean damage ratio per municipality by about 13.17% for wind speeds of 40.225 m/s and by about 3–6% for wind speeds between 49 m/s to 71 m/s. The reported damage by the respective government authorities was aggregated on a municipality level and compared to the performance of the model. A statistical analysis between the reported and mean predicted damage was also done by using the Spearman rank correlation coefficient. The results yielded a positive correlation of 0.856.

RISK ASSESSMENT OF LOW-RISE SCHOOL BUILDINGS WITH WOODEN ROOF STRUCTURES IN THE PHILIPPINES AGAINST WIND LOADINGS

1. Introduction

In the recent decade, the Philippines Area of Responsibility has been visited by a significant number of tropical cyclones. The recent decade recorded a total of 410 tropical depressions, 251 tropical storms, 123 typhoons and 50 super typhoons that have entered the Philippines’ Area of Responsibility. It was also in the recent decade that the Philippines experienced the second deadliest typhoon, Haiyan which made landfall on November 7–8, 2013. Aside from this, several super typhoons such as typhoon Pablo (2012), typhoon Mangkhut (2018), typhoon Ompong (2018), typhoon Kammuri (2019), typhoon Tisoy (2019) etc. have caused significant damage to infrastructure and agricultural land. For the decade, a total of 144,204.9 USD billion worth of damage and 18,372 deaths have been reported.

With regards to the resilience of the country against typhoon hazards, educational facilities are often designated as emergency shelters by respective disaster risk reduction management (DRRM) authorities. Countries such as Bangladesh, India, Philippines, Japan, and the

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US are currently using educational facilities as short-term evacuation centers for sheltering in response to tropical cyclone hazards (Shaw 2012, Takeuchi, and Fernandez 2016). In Japan, about 49.5% of their schools can provide post haven during natural hazards (Japan Times 2020). In the Philippines, according to DepEd DRRMS, a total of 713 schools or 2,513 classrooms across the 11 regions of the Philippines were used as evacuation centers (DEPED 2019) in the aftermath of typhoon Ompg. In the consolidated Rapid Assessment of Damages Report (RADaR) for typhoon Nina (2016), 948 schools or 3,984 classrooms were reportedly used as evacuation centers across 5 regions of the Philippines.

In 2019, the Department of Education’s Disaster Risk Reduction and Management office produced guidelines on evacuation center coordination and management of public-school buildings. Many global efforts such as the “Disaster and Emergency Preparedness: Guidance for Schools” published by the International Finance Corporation (IFC) have pushed for the Comprehensive School Safety (CSS) framework wherein the risk assessment and mitigation of existing school buildings are important in the sustainable development and resilience of a community (Ellena 2010).

Although the United Nations Office for Disaster Risk Reduction has made many efforts in the development of risk assessment tools for school buildings, the use of local wood as a construction material and construction practices vary significantly between different countries (UNDRR 2013). Structural fragility-based assessments of school buildings in Pakistan, Turkey, Istanbul, Sri Lanka against seismic activity have been done in the recent decade. The methodologies accounted for the uncertainties of parameters such as the material properties, geometrical characteristics, and direction of ground motion excitation (Abeysiriwardena, Buddika, and Wijesundara 2013; Bilgin 2013; Hancilar et al. 2014; Zain et al. 2019). The four levels of damage state defined by HAZUS are usually used to depict the performance level of a structure to a certain hazard. Aside from seismic assessments, fragility and risk assessments have been done for masonry school buildings for tornado hazards in the United States (Masoomi and Van De Lindt 2016).

Aside from school buildings, various vulnerability & fragility models have been developed for varied structure types in the past two decades. Earlier models done by Foschi (1977), Kennedy et al. (1984), Bulleit et al. (2005) made use of classical methods of system reliability in the analysis of wood structural systems. Pinelli et al. (2004) incorporated a component-based approach using a Monte Carlo simulation engine. Lee and Rosowsky (2005) developed roof sheathing fragility curves for low rise wood frame structures built in high wind regions. Li (2005) showed that the height of a wood frame structure has little effect on the fragility but is greatly affected by the roof fasteners and roof-to-wall connection detail. Gleason (2009) investigated the reliability of the roof system due to the influence of the stiffness in the roof-to-wall connection using a specific analytical model for the connection. It was concluded that the variability of the connection stiffness had little effect on the system reliability. The fragility of building envelope components subject to windborne debris impacts was also investigated by Herbin and Barbato (2012). Their model consisted of a combination of a Monte Carlo Simulation with a Finite Element method to include the propagation of uncertainties from modeling parameters. Amini and Kasal (2010) also incorporated a FE model for a reliability assessment of roof sheathing performance of light wood structures. The wind loads were patterned after hurricane Andrew that occurred in Florida. Although their study shows that their model produced lower probability of failures than the reported values, they accounted this to higher wind loads that occurred during hurricane Andrew.

2. Development of archetype

Table 1 In this study, a field survey was done to investigate the actual damage responses of school buildings due to Typhoon Nina (Nock-ten) 2016. As shown in Figure 2, a total of 139 school buildings were surveyed across the provinces of Bicol (Region V) in the Philippines. The mean wind speed per municipality was derived from the wind speed map data provided by the Humanitarian Data Exchange (HDX 2017), which is an open platform for data exchange between different organizations. This platform is managed by the United Nations Office for the Coordination of Humanitarian Affairs (OCHA)’s center for humanitarian data.

Based on the Philippine’s Department of Education national school building inventory, school buildings can be categorized according to structure/construction material and according to design. There are four categories of school buildings according to construction material and there are 25 categories according to design. Most of the samples from the field survey comprise of RP-US (52.17%), DECS Standard (16.67%) and BLSB I (31.16%) designs are categorized as Type III or permanent structures. It should also be noted that based on the field surveys, about 73.6% of the schools were structures with wooden roof systems. These samples would also be the basis for the geometry and building envelope components of the archetype that would be used in the simulation engine. The dimensions of the archetype are shown in Figure 1.

Suppasri et al. (2015) were able to observe the damage of 166 school buildings due to Typhoon Yolanda (2013) in Tacloban, Palo and Tanuan. The
The mean wind speed was estimated to be about 110 USD/m². Most of the observed damage were in the roofing, roof frame, ceiling, wall, window, and doors. They attributed this to the fact that most of the structures were 1-storey buildings using timber or weak materials.

For the field survey of the damage due to Typhoon Nina (2016) in this study, the mean damage ratio is defined as the ratio of the cost of repair over the total construction costs of a school building. The damage of each component was quantified and aggregated into one building damage ratio by means of a cost component factor. The cost component factor being the percent contribution of one component to the total construction cost of the school building. The aggregated

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**Figure 1.** Rear elevation view (top) and right-side elevation view of 1-storey (DepEd, 2012).

**Figure 2.** Location of surveyed school buildings plotted over the mean wind speed per municipality of Region V, Philippines.
average mean damage ratio for all the surveyed school buildings was estimated at 7.4%

A Pearson’s correlation was used to statistically evaluate the association of the damage ratios between different parameters as the basis for the archetype. Figure 1 and Figure 3 shows the correlation matrix between five parameters, specifically the damage ratio of the roof covering (RC DR), the damage ratio of the roof structure (RS DR), the damage ratio of the Exterior Windows (EW DR), the aggregated building damage ratio of the school building (BDR) and the number of classrooms per school building surveyed (CL No). The results show a moderate positive degree of correlation (0.43–0.51) between the damage ratios between the roof covering, roof structure and exterior windows. The highest degree of correlation (0.90) in the datasets is observed to be between the damage ratio and building damage ratio. This implies for these kinds of school buildings; the failure of the roof-to-column connections has the biggest effect on the total repair cost. The exterior walls, which are made from concrete masonry units (concrete hollow blocks), were observed to have little to no damage in response to typhoon Nina. A low correlation is also observed. Another observation is that as the number of classrooms per school building increases, the aggregated building damage ratio decreases as depicted by a low negative correlation of −0.20. The average floor area of one classroom is estimated at 51.2 m².

Another observation in the field surveys is that the fastener spacing for the roof covering, which were commonly corrugated galvanized roof sheets gauge 26, varied from school buildings and between different roof fastening zones. This difference in fastener spacing along the purlins affects the tributary area receiving wind pressures. Mizzell 1994 discussed that the effective tributary area can be used to derive the tributary load acting on the roof fastener. In the surveys, the fastener spacing varied from 75 mm to 375 mm, showing a mean of 219.75 mm spacing and coefficient of variance of 0.327. The data was fitted into a normal density function to account for the uncertainty of fastener spacings in this paper’s analysis. The prevalent failure mode for the roof fasteners was observed to be pull-out failure. It should be noted that the pull-out capacity is significantly affected by the lumber density. Nishijima and Espina 2015 were able to conduct multiple experimental tests to determine the lognormal distribution parameters for the cumulative density function.

For the anchorage of the trusses, there were two types of specifications observed in the field. The first specification is the use of 2–16 mm diameter anchor bolts which were in accordance to the structural drawings. These specifications were observed in school buildings over 30 years of age. Masoomi and Van De Lindt 2016 modeled the anchorage by the concrete breakout capacity of the anchor bolts in concrete masonry units. However, field observations show that the uplift of roof trusses is caused by the bending of a 100 mm x 300 mm by 10 mm thick ASTM A36 steel plate holding the trusses down rather than the concrete break out of the 16 mm anchors. The flexural strength was analyzed by calculating the
corresponding maximum concentrated load on a simple span beam given the probabilistic distribution parameters for the yield stress of ASTM A36 steel (Chen and Shen 1992). Aside from anchor rods, the use of dowels (12 mm rebars) that protrude from the masonry was used to tie down the trusses to the masonry wall. Doguiles 2015; Hokia 2019 were able to investigate the wind uplift capacity of commonly used roof-to-wall connections, wherein a uniaxial test was done to quantify the unbending strength of these kinds of connections.

The material of the exterior windows was also made from wooden panels. These wooden panels were found to be very resilient against wind pressures. As shown in Figure 4, the observed component failure was not due to the breakage of the panels but due to anchorage failure of the jalousie for the whole window unit. The observed damage ratio was then plotted against the wind speed and fitted into a cumulative lognormal density function using an SSE regression analysis to determine the probabilistic window capacity.

This paper then investigates the fragility of the structure based on the roof covering (fastener and corrugated roofing sheets), roof structure and exterior windows.

3. Fragility model

In determining the response of building components to severe wind loadings, the variability of many factors leads to a great deal of uncertainty. The turbulent nature of wind loadings on different topographic terrains produces fluctuating aerodynamic forces on the different parts of a building. Aside from this, the resistance of the building components itself varies due to its innate material properties and construction. To account for these, fragility analysis is used to quantify the probability of a certain damage state that a structure will experience, as a function of demand, given a set of parameters (Lee, Ham, and Kim 2013). The demand may be in terms of 3 s gust wind speed, spectral acceleration or depth of inundation depending on the hazard of interest. This damage state (DS) probability, \( P(DS) \), is defined as the following equation: (Li 2005)

\[
P_r(DS) = \int_{-\infty}^{X} f_R(r) dr = F_R(X) \tag{1}
\]

This equation is then numerically evaluated using a Monte Carlo simulation wherein the resistances are generated randomly from their respective probability distributions and compared to statistical code-based wind loads. The Monte Carlo simulation procedure is shown in Figure 6. A log-normal cumulative distribution function is then used to model the structural fragility.

\[
F_r(x) = \Phi\left[\ln(y) - m_R \right] = \frac{1}{\zeta_R}
\tag{2}
\]

Where \( \Phi \) is the standard normal probability integral, \( m_R \) is the median capacity and \( \zeta_R \) is the standard deviation of \( ln(R) \).

The computations for the code-based wind load forces of the model made use of the local provisions of the National Structural Code of the Philippines.
Table 1. List of symbols and notations.

| Symbol | Description |
|--------|-------------|
| $F_z(x)$ | Probability of exceedance for specified damage state |
| $q_z$ | Velocity pressure at height $z$ from the ground |
| $K_v$ | Velocity pressure exposure coefficient |
| $K_{zt}$ | Topographic factor |
| $K_d$ | Directionality Factor |
| $V$ | Basic wind speed at 10 m height |
| $G$ | Gust effect factor |
| $C_p$ | External pressure coefficient |
| $C_{pi}$ | Internal pressure coefficient |
| $CCF$ | Cost component factor |
| $CDR$ | Component damage ratio |
| $BCC$ | Total building cost |
| $DR$ | Total damage ratio of a building |

(NSCP) 2015 7th Edition (Association of Structural Engineers of the Philippines, Inc. 2015) wherein the velocity pressure is as follows:

$$q_z = 0.613K_vK_{zt}K_dV^2 \text{ (N/m}^2\text{)}$$

(3)

For the computation of the wind loads on the trusses and exterior windows, the wind pressure for the main wind force resisting system (MWFRS) procedure was used.

$$p = qGC_p - q_p(GC_p) \text{ (N/m}^2\text{)}$$

(4)

For the computation of the wind loads on the roof covering, the components and claddings (C&C) procedure was used.

$$p = qGC_p - q_p(GC_p) \text{ (N/m}^2\text{)}$$

(5)

where $q_n$ = velocity pressure evaluated at mean roof height (h), $G$ = gust factor, $C_p$ = external pressure coefficient and $C_{pi}$ = internal pressure coefficient.

For the wind load statistics, Ellingwood and Tekie 1999 used a Delphi methodology to determine the basis for the uncertainty of the relevant wind parameters of the code-based wind loads of ASCE 7. These parameters were also used by Lee, Ham, and Kim 2013, Ellingwood et al. 2004 for the fragility assessments of different structures against extreme wind. Table 3 shows the wind load statistics used in this paper. The velocity pressure exposure coefficient for Exposure B (Urban and Suburban areas) and D (flat, unobstructed areas) due to the applicability of the terrain for Region V of the Philippines.

The different damage states definitions were patterned after the HAZUS-MH hurricane model (Ulmi 2014; Vickery et al. 2006). In this study, the parameters for consideration were only limited to their components mentioned in the previous paragraphs and only four damage states were defined. The summary of the parameters used for modelling the components can be shown in Table 2.

Figure 5. Pressure distribution on Structural model for 1-storey 2 classroom school building at $V = 100$ m/s.
Once the wind pressures were determined, the dead and wind loads were applied in a finite element structural model to determine the corresponding reaction forces for the truss-to-wall connections. A linear elastic model was used with the trusses modeled as line elements and the truss-to-wall connections modeled as pin supports. As shown in Figure 5, the pressures were applied on the roof covers and were distributed to the top chords of the trusses using a tributary method. It should be noted that the analysis was only done until the onset failure of each component per wind speed was achieved. The roof panel was discretized according to the different pressure regions of the NSCP 2015 and was discretized according to the tributary area contribution of each roof structure connection. Once the damage for each component was determined. The damage was aggregated together using cost component factors (CCF). The factors were derived from the Department of Education’s program of works for the original material specification (OMS) for RPUS, BLSS, and DECS standard school buildings. A cost component factor of 8.86%,
Figure 8. Fragility curves for case 2.

Figure 9. Fragility curves for case 3.

Figure 10. Fragility curves for case 4.
Table 4. Damage state definitions for School Buildings.

| Damage state   | Roof panel failure | Roof structure failure | Opening failure |
|----------------|--------------------|------------------------|-----------------|
| No Damage      | ≤ 2%               | None                   | ≤ 10%           |
| Slightly Damaged | > 2%              | > 2% or 1 connection failure | > 10% or 1 window |
| Moderately Damaged | > 15%           | > 20% or 2 connection failure | > 20% or 3 window failure |
| Severely Damaged | > 50%             | > 30% or more than 3 connection failure | > 50% |

Table 5. Fitted lognormal parameters for different combinations of building envelope components.

| Case | Exposure category | Damage state | Lognormal parameters |
|------|-------------------|--------------|----------------------|
| 1 D  | Slightly Damaged  | 3.438, 0.103 |                      |
|      | Moderately Damaged| 3.817, 0.083 |                      |
|      | Severely Damaged  | 4.160, 0.049 |                      |
| 2 D  | Slightly Damaged  | 3.436, 0.108 |                      |
|      | Moderately Damaged| 3.823, 0.078 |                      |
|      | Severely Damaged  | 4.132, 0.049 |                      |
| 3 B  | Slightly Damaged  | 3.614, 0.115 |                      |
|      | Moderately Damaged| 4.010, 0.082 |                      |
|      | Severely Damaged  | 4.318, 0.049 |                      |
| 4 B  | Slightly Damaged  | 3.618, 0.101 |                      |
|      | Moderately Damaged| 4.009, 0.076 |                      |
|      | Severely Damaged  | 4.283, 0.052 |                      |

20.30% and 10.14% was used for the roof panels, roof structure and exterior windows, respectively. The total damage ratio (DR) of the building was derived using the following equation:

$$ DR = \frac{\sum_{i=1}^{n} nCDR \times CCF}{BCC} $$  \hspace{1cm} (6)

Where CDR = damage ratio of each component, CCF = component cost factor, BCC = total building costs.

4. Performance of the model

In this paper, only the variation of the exposure category from B to D and the different roof-to-column connections were investigated. The damage state definitions used for the fragility models are shown in Table 4.

Table 5 presents the fragility curves of the different damage states for four different cases. For case 1 & 3, the building envelope components considered are wood nails, 100×300mm steel plate and wooden jalousies. For case 2 & 4, the wood nails and wooden jalousies were held constant but 12 mm dowels were used instead for the roof to column connections. The derived fragility curves are a function of 3 s gust wind speed at 10 m height. As shown in Figures 7–10, there is no significant difference between cases 1 & 2 and 3 & 4. By varying the roof-to-column connection in exposure category D, the results show that there is only a relative difference of 0.06% in the lognormal mean of slight damaged building. The relative difference in the lognormal mean can go up to 0.68% for severely damaged buildings. The same trend can also be observed even in exposure B wherein there is only a relative difference of 0.11% in the lognormal mean for slightly damaged buildings and 0.80% for severely damaged buildings. Unlike the roof-to-column connection, the exposure has a significant effect wherein relative differences up to 5.14% can be seen in lognormal mean for the fragility curves.

To validate the performance of the simulation model, the results of the model are compared to the actual damage data of schools recorded in the RADaR of DepEd.

In the RADaR report, the sum of the number of schools with reported infrastructure damage per municipality were recorded. This data set was compared to the fragility curve for the slightly damaged damage state. The fragility curves, mean wind speeds per municipality together with the exposure database of the Department of Education were used to simulate the average number of damaged schools per municipality. The following equation was used for the damage count per municipality:

$$ NOD = Fr(X) \times NB $$  \hspace{1cm} (7)

Where NOD = Number of Damaged Buildings per municipality for a certain damage state, Fr(X) = probability of exceedance of damage state, NB = number of buildings per municipality.

The analysis was applied to Region V for Typhoon Nina (2016) wherein 107 affected municipalities were investigated. As shown in Figure 11, the simulated damage data were then compared to the damage data reported by the Department of Education. It can be observed that the simulation results have a high Pearson correlation of 78.3% and a Spearman correlation of 85.6% with the actual reported data. With 95% confidence, there exists a very high positive monotonic relationship between the two data sets. With the given statistical results, the ranking and categorization of the predicted damage data may be used to assign priority indices to each municipality/city.

The Netherlands Red Cross (NLRC) proposed a method to identify high-priority areas for humanitarian response by using priority indices (PIs) that varied from five classifications. Class 5 being the most damaged areas and class 1 being the least damaged areas (Van Der Veen 2016). In this study, the municipalities were categorized into five damage categories to serve as priority indices. The ranges of the category varied from 1–6, 7–12,13–18,19,23 and 24–30 damaged schools per municipality for the damage categories 1,2,3,4 and 5, respectively. Comparing the predicted
priority indices with the actual priority indices results to a $R^2$ value of 0.948.

The Figures 12–13 show the mapped priority indices using the damage data from the reports of the department of education and the indices using the simulation methodology. This shows that the methodology in the paper is highly accurate and is helpful for local government units in disaster risk reduction strategies and post-disaster infrastructure reconstruction.

This paper also investigated the performance of the model in the prediction of the damage ratio of the schools with wooden roof systems. The simulated damage ratios per building envelope component were aggregated into one building damage ratio using the cost component factors. The simulation model considers an equal weight for all four simulation cases shown in Table 5. The results were plotted against their corresponding wind speeds to come up with vulnerability curves. Figure 14 shows the vulnerability curve using the simulated mean damage ratio having a lognormal mean of 4.7314 and standard deviation of 0.4061. The upper and lower bounds are also shown by the red and blue
markers, respectively. For wind speeds above 67 m/s, the damage ratios have standard deviations greater than 5% while wind speeds below 67 m/s have lower deviations.

As shown in Figure 14, the plot of the field survey damage ratios data due to Typhoon Nina 2016 was superimposed on the simulated vulnerability curves. It can be observed that simulated vulnerability curves generally underpredict the mean damage ratios at weaker wind speeds. A mean damage ratio difference of 13.17% can be observed for wind speeds of 40.225 m/s. This translates to an estimated repair cost difference of 48.40 USD/m². A lower mean damage ratio difference of around 3–6% ($11.03/m² – 22.06 USD/m²) can be observed for wind speeds between 49 m/s and 71 m/s.

Some factors that contribute to the underestimation of the simulated mean damage ratio is the inability to consider the effect of the age of the wooden roof systems and the presence of termites in actual field data for low wind speeds.

An analysis of the field data on the effect age show that roof systems using wooden roof nails
with more than 30 years of age have a 25.33% higher probability of being in a slightly damage state than wooden roof systems less than 10 years of age. For the moderately damage state, a wooden roof system of more than 30 years has a 30.66% higher probability than wooden roof systems of less than 10 years while for the severely damage state, roof systems with 30 years of age have a 16% higher probability than roof systems of less than 10 years of age.

5. Conclusions

The paper presents a risk assessment methodology for low-rise school buildings with wooden roof systems using wind fragility curves and priority indices in the Philippines. The model made use of the strength capacities derived for unique local construction practices which are common in the Philippines and other developing countries. The proposed risk assessment in this paper is an area-based analysis wherein the predicted number of schools damaged per area is a function of the mean wind speed of the area under investigation. Priority indices are then assigned to each of the areas under investigation. These indices are assigned from 1 to 5 based on dividing the maximum predicted number of damaged schools by five ranges.

Vulnerability curves were also derived by aggregating the simulated damage ratios per building envelope components into one building damage ratio. The results were fitted into a cumulative lognormal density function with the mean of 4.7314 and a standard deviation of 0.4061. The expected ranges of repair cost per unit area can be determined as a function of the wind speeds experienced by a school building. The current methodology underpredicts the repair cost per unit area by up to 13% depending on the wind speed experienced. Further research can be done when more post-disaster survey data are available. The effects of age and presence of termites should also be investigated.

The methodology gives a spearman correlation of 85.6% when comparing the simulated priority indices vs actual priority indices for areas damaged by typhoons. This shows that the current methodology can be used to assess the risk of low-rise public-school buildings in typhoon prone regions in the Philippines. The evaluation of the potential impact of typhoon prone areas can assist respective government authorities in disaster risk reduction strategies to be implemented.

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