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RELIABILITY ASSESSMENT OF WOODEN TRUSSES OF A HISTORICAL SCHOOL

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ABSTRACT: Records show that the National Structural Code of the Philippines (NSCP) wind load requirement increases over time. Increase wind velocity from stronger typhoon events translates to additional wind pressure. These changes pose a threat to existing historical structures such as Gabaldon schools which were designed and constructed more than a hundred years ago. The Department of Education (DepEd) continues its efforts in its conservation. Reliability assessment of wooden trusses is necessary to check if there is a need to retrofit to maintain its function and preserve its significance in the country's history. In the analysis of the roof trusses affected directly by wind load, all loads are considered as constant except for the uniformly distributed wind load. These constant loads serve as the initial stresses acting within the truss members. Uniformly distributed wind load produces additional stress on top of the initial stress. Any changes in the amount of wind load constitute proportionally to changes in the stresses of truss members. A commercially available software makes it easier to identify corresponding stresses for several amounts of wind load. Using a spreadsheet, a simple graphical model and equation are generated expressing the relationship between wind velocities against axial force, shear force and bending moment. Mechanical properties of wood establish the limits of its strength in terms of wind velocity using the graphical model and equation obtained. The result reveals the limitation of each truss member in terms of wind velocity that even ordinary people can now easily perceived and understood.

Keywords: Retrofit, Proportional changes, Simple graphical model, Mechanical properties

1. INTRODUCTION

The Philippines is located along a typhoon belt and the so-called Ring of Fire, a vast Pacific Ocean region where many of Earth's typhoon, earthquakes, and volcanic eruptions occur.

According to state weather bureau Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA), the Philippines is visited by at least 20 tropical cyclones every year with 5 having the potential to be destructive ones as shown in Figure 1.

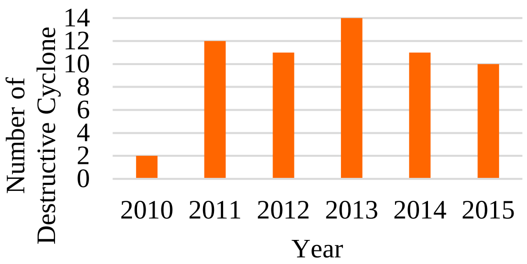
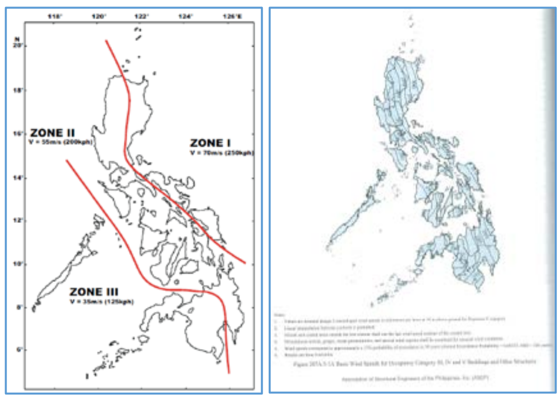


Fig. 1 Number of destructive tropical cyclones that entered the Philippines (2010 – 2015). Source: NDRRMC

According to the 3rd edition of National Structural Code of the Philippines (NSCP) that was released on 2001, the basic wind speed requirement was 200*km/h* for Zone 2 whereas the current 7th edition of NSCP that was released on 2015, the basic wind speed requirement was 255*km/h* for the same location. This only proves that the wind load requirement for a given building increases from time to time.



NSCP 2001 NSCP2015

Fig. 2 Wind velocity requirement difference between NSCP 2001 and NSCP 2015

This increase in basic wind speed pose hazard to existing structures. Historic structures such as Gabaldon schools are not exempted from this hazard for they were built during the American Regime. The

Department of Education (DepEd), recognizing its significant part in the history of Philippine education, continues its efforts in the conservation of the Gabaldon and heritage school buildings.

According to PAGASA, there is already a storm categorized as signal#5 with very strong winds of more than 220 kph. Super typhoon Yolanda (Haiyan) hit land with sustained winds of 196mph and even stronger gusts which ripped off roofs, collapsed buildings, shattered windows and inundated coastal regions with an incredible storm surge that left the majority of homes either completely destroyed or uninhabitable. Typhoon Lawin tears through the Philippines leaving homes damaged, roofs ripped off school buildings and trees uprooted. Lawin, a category 5 entered the Philippines with winds gusting up to 315kph but weakened to category 4 just before making landfall.

This study is an initial effort to address deficiencies and inefficiencies such as additional loadings which are not included in the original design and in past construction practices of structural engineering concepts through a comprehensive design evaluation approach that draws on existing and innovative engineering technologies in a practical manner. The desired effect to continuously improve the value of historical structure of Gabaldon School in San Rafael, Bulacan in terms of economy and structural performance can be started through the reliability assessment of wooden truss which is directly affected by wind. But why Gabaldon school when such structure is a symbol of oppression, subjugation, and injustice? Fr. Ted Milan Torralba's paper "Making Cultural Heritage Alive in Contemporary Philippine Culture" pointed out that principle of identity that constitutes an extension of who we are and that every heritage is a knowledge resource.

Numerous studies are being done to know and address the effects of wind load on structures. Numerical Assessment of Roof Panel Uplift Capacity under Wind Load written by Weixian He (2010, October), highlights the impact of construction error in terms of missing nail effects. Analysis indicates that missing a single nail could reduce the mean of the panel uplift capacity by 10%, and missing two nails could reduce the mean of R by as much as about 23%.

Gavansk et al (2014) in their paper entitled "Reliability Analysis of Roof Sheathing Panels on Wood-Frame Houses Under Wind Loads in Canadian Cities" found that relatively small differences in fastener size result in large differences in roof sheathing performance. Kyung Ho Lee and David V. Rosowsky. (2004, December) in their paper "Fragility Assessment For Roof Sheathing Failure In High Wind Regions" developed complementary fragilities in the form of lognormal cumulative distribution. A study in "In Situ Nail Withdrawal Strengths in Wood Roof" by Prevatt, David O., et al. (2014, May) indicates that premature failure of wood roof sheathing under wind loading has been primarily blamed on poor nail installation resulting in reduced nail withdrawal strengths.

Garciano et al., (2013) in their study developed a vulnerability assessment of low-cost housing in Malate, Metro Manila. The results obtained show that pullout failure is the main mode of failure attaining a maximum of 27.2% for a 150-year wind return period (200 km/h wind speed). Finally, the study follows the same objective of the study "The reliability assessment of wooden roof trusses of historical churches in Laguna" written by Dr. Garciano (2017) which generally studied the reliability of historic churches that lead to a conclusion of considering a restoration and retrofitting of the church structures in the future.

2. STUDY DETAILS

Gabaldon schools are under the supervision of DepEd and National Historical Commission of the Philippines. Presently, part of Gabaldon School in San Rafael, Bulacan, functions as classrooms for students and part functions as an activity hall for general assembly. Roof trusses of the school are typically designed. It consists of 19 trusses having the same specifications and dimensions as shown in Figure 3.

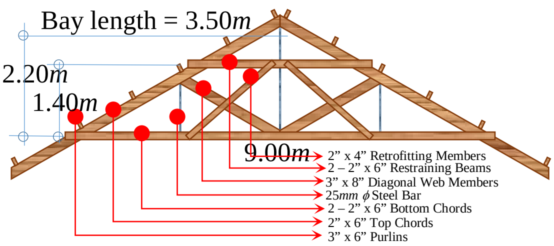


Fig. 3 Typical detail of truss

The original timber truss is made of Yakal wood and the reinforcement is made of Apitong wood having the mechanical properties as shown in Table 1.

Table 1 Graded wood characteristic of Yakal and Apitong

80% Stress Grade	Strength	
	Yakal	Apitong
Bending/ Tension Parallel to Grain, *MPa*	24.5	16.5
Modulus of Elasticity in Bending, *MPa*	$9.78 x 10^3$	$7.31 x 10^3$
Compression Parallel to Grain, *MPa*	15.8	9.56
Compression Perp. to Grain, *MPa*	6.27	2.2
Shear Parallel to Grain, *MPa*	2.49	1.73

The roof panel is made up of Ga. 20 Corrugated GI sheet. GI plates equally spaced at 0.25m on center are riveted to the roof panel which is anchored by 2 screws on wood purlins as shown in Figure 4.

Fig. 4 Actual connection detail of roof panel and purlins

Data from the nearest Agromet station were incomplete which led to the use of estimated wind requirement of 255*kph* based from NSCP2015 as shown in Figure 5.

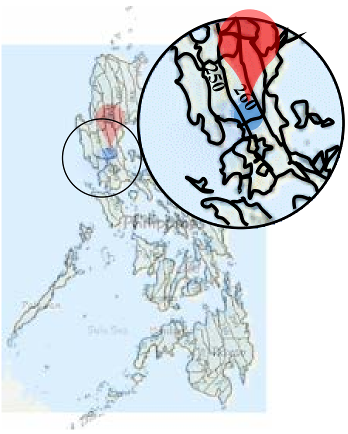


Fig. 5 Superimposed map on NSCP 2015 basic wind speed requirement

3. MATHEMATICAL FORMULATION

3.1 Maximum Allowable Strength

Three equations were used to determine the allowable strength of the truss members.

Simple stress formula was used in determining the maximum capacity in terms of the compressive and tensile strength of truss members and was defined as

$$P = SA \tag{1}$$

where S denotes the maximum stress capacity of the truss members found in Table 1. and A is the cross section of the truss members.

Shear stress in the rectangular beam was used in determining the allowable shear and was represented by

$$S_s = \frac{3V}{2A};\ V = \frac{2AS_s}{3} \tag{2}$$

where S_s denotes the maximum stress capacity of truss members found in Table 1. and A is the cross section of the truss members.

Flexure formula was used in determining the bending moment capacity and was defined as

$$f_b = \frac{MC}{I} = \frac{6M}{bd^2};\ M = \frac{bd^2 f_b}{6} \tag{3}$$

where f_b denotes the maximum stress capacity by the truss members found in Table 1, b is the width of the beam and d is the height of the beam.

The calculation for the uplift load on purlins, wind pressure on the components and cladding and total uplift pressure was taken from NSCP2010/2015 as seen in the following equations below.

$$q_h = 47.3\times10^{-6} K_z K_{zt} K_d V^2 I_w \tag{4}$$

$$p = 0.80 q_h \left(GC_p - GC_{pi}\right) \tag{5}$$

$$S_p = T_A\left(DL + q_h\right) \tag{6}$$

The pull-over and pull-out resistance of the rivet and roof panel R_p were represented by the formula below.

$$R_p = 1.5 d_w F_u t \tag{7}$$

$$R_w = w \times p \tag{8}$$

where F_u is the tensile strength of the member in contact with rivet head, t is the thickness of material and d_o is the diameter of the rivet head.

The methodology is consist of six components:

1. Actual inspection of the truss to determine the wooden properties of truss members.
2. Analysis of truss members stresses using SAP2000 having zero wind load as the baseline information and different amount of wind load as samples both for transverse and longitudinal directions.
3. The results of the most critical element in each of the seven typical members were selected: purlins, top chord, a bottom chord, vertical web members, retrofitting members, straining beam and vertical web members.
4. Generation of the simple graphical model (SGM) and equation using Microsoft Excel, expressing the relationship between wind velocities against axial force, shear stress and bending moment.
5. Determination of allowable axial force, shear and moment using Eq. (1), Eq. (2) and Eq. (3) then substitute to the generated graphical model to determine the projected wind velocity that will cause damage or failure.

6. Determination of uplift load per purlin, S_p, pull-over resistance of the roof panel, R_p, and pull-out resistance of Rivet, R_w.

3.2 Simple Graphical Model

A simple graphical model was constructed by plotting the axial force, stress or moment on the *y*-axis versus the wind velocity on the *x*-axis as shown in Figure 6.

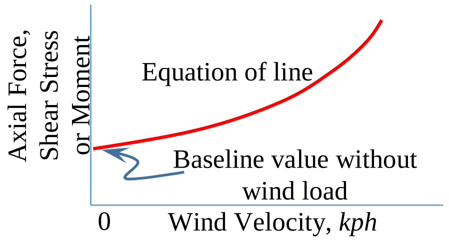


Fig. 6 Simple graphical model of wind velocity versus axial force, shear stress or bending moment.

The study requires graphical models for the three (3) mode of failure of truss members, namely: axial force, shear stress and bending moment.

4. DATA AND RESULTS

In this study, timber used in trusses were identified and proper mechanical properties were applied (see Table 1.)

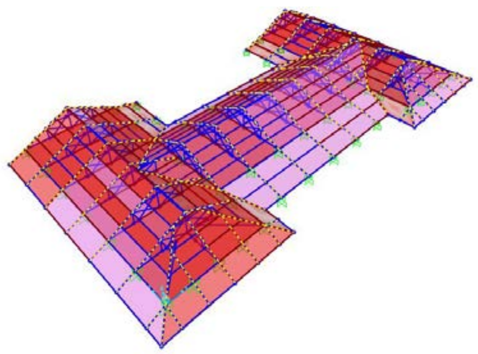


Fig. 7 3D Model of truss frame using SAP2000

Using SAP2000 for 3D modeling as shown in Figure 7, the results showing the relationship with wind velocity against, axial, shear force and moment were obtained for the seven subdivided members. Due to the huge data, only the most critical elements among the seven typical members were selected for the three modes of failure as shown in Table 2.

Table 2 Selected critical value from SAP2000 analysis

Wind Velocity	Max. Force	Max. Shear	Max. Moment
kph	*KN*	*KPa*	*KN.m*
0	84.538	18.260	4.0649
50	84.538	18.313	4.0649
100	85.104	18.472	4.0678
150	86.490	18.738	4.1189
200.6465	88.429	19.111	4.1903
255 (NSCP)	93.880	19.643	4.3542
300	98.817	20.686	4.5581
500	134.369		5.8640

Figure 7 shows the curve line that represents the relationship between axial force and wind velocity. Equations of the lines were generated by Excel software.

Using Eq. (1), the maximum allowable *P* obtained was 177.75*KN* which was then substituted to the equation of the curve line on Figure 7 to get the projected wind velocity to cause damage or failure. The obtained value of wind velocity was 614.1529*kph* denoting it safe and adequate.

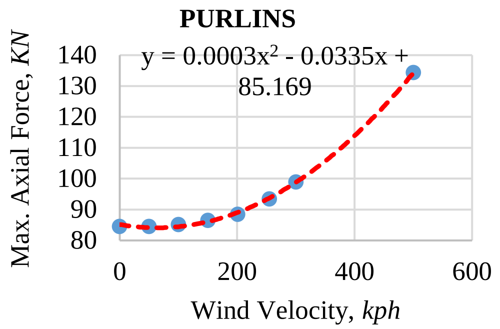


Fig. 7 Simple graph representing maximum axial force vs wind velocity from Table 2

Using Eq. (2), the maximum allowable *V* obtained was 1.722*KN* which was substituted to the equation of the curve line on Figure 8 to get the projected wind velocity to cause damage or failure. The obtained value of wind velocity was 514.3937*kph* denoting it safe and adequate.

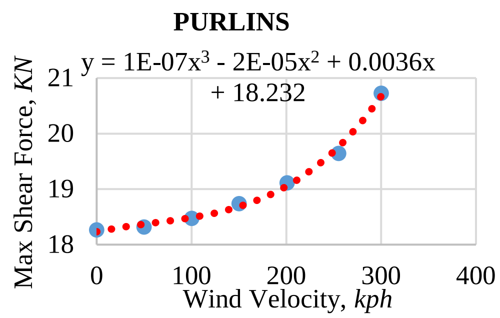


Fig. 8 Graph representing maximum Shear Force vs wind velocity from Table 2

Using Eq. (3), the maximum moment *M* obtained. was 12.25*KN.m*. The value was used to the equation of the curve line on Figure 9 to get the projected wind velocity to cause damage or failure. The obtained value was 975.9581*kph* denoting it safe and adequate.

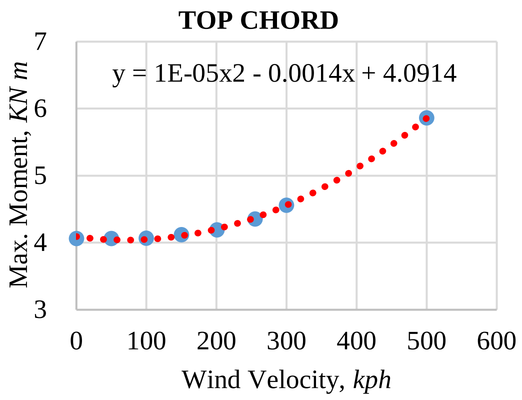


Fig. 9 Graph representing maximum moment vs wind velocity from Table 2

Due to limited and unavailability of other samples, roof panel was assumed to have a tensile strength of 311*MPa* for schedule 40 which are considered the weakest among the available roof panel in the market for safety purposes. Using Eq. (6), the value obtained for the uplift load on purlins is 15.8016*KN* which is less than 53703.293*KN* for pull-over resistance of roof panel obtained using Eq. (7). This indicates that it is still safe and adequate even for the worst case scenario. Another unavailable sample is the rivets which were assumed to be made of aluminum with the strength of 320*lb*. An assumption was done through the exposed head diameter and selecting the weakest material among available rivet in the market. Using Eq. (8), the total pull-out capacity of 14 rivets is 19.9766*KN* which is greater than the uplift force of 15.8016*KN* indicating safe and adequate.

5. CONCLUSIONS

Reliability assessment was done and indicates that the overall performance of the roof structure is still good and safe. The most critical of all elements was the purlins but still considered safe and adequate by having 259.3937*kph* wind velocity allowance before reaching failure. Previous NSCP wind speed requirements show that it would take decades for the wind velocity to increase by 100*kph*. With the result of the failure of truss in term of wind velocity, even ordinary people can now perceive and understand the limitation of structure because here in the Philippines typhoons are categorized based on their wind speed. Due to the unavailability of data and sample, some were assumed for the worst case scenario but still, the analysis indicates that truss members are still considered safe and adequate. A more detailed analysis including seismic analysis of the whole structure is encouraged in the future. It is also necessary for the immediate review of other existing structure.

6. ACKNOWLEDGMENTS

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