A novel Fluid-Structure Interaction modelling and optimisation of roofing designs of buildings for typhoon resilience

Conrad Allan Jay Pantua1,2, John Kaiser Calautit1 and Yupeng Wu1
1Department of Architecture and Built Environment, University of Nottingham, Nottingham, UK
2Mechanical Engineering Department, De La Salle University, Manila, Philippines
E-mail: conrad.pantua@nottingham.ac.uk

Abstract. Stronger typhoons have been more frequent in the Western Pacific region. Typhoon Haiyan caused widespread loss of life and destruction to properties when it made landfall in the Philippines in 2013. An estimated 1.1 million homes were damaged or destroyed in the aftermath. Damage surveys show extensive roofing damage evident in most detached structures attributed to strong winds. Clearly, there is a need to evaluate the current roofing designs and its structural integrity for it to properly respond to extreme environmental events in the future. Using a novel Fluid Structure Interaction (FSI) approach, this study evaluated a single detached gabled building made of timber which is common in the Philippines. The building was subjected to typhoon strength winds in an urban environment using Computational Fluid Dynamics (CFD) analysis. Atmospheric Boundary Layer (ABL) flow simulation was conducted to predict the pressure distribution around the structure. A structural model of the roofing support was then developed, and the structural analysis performed using FSI to predict failure in the sheathing and the supports. The results of the study show the structural weaknesses in the current design considering the wind angle, structural frame and materials.

Keywords: Typhoon; Computational fluid dynamics; Finite element analysis; Fluid structure interaction; Urban environment, Buildings

1. Introduction

The western pacific region has been experiencing a lot of relatively stronger typhoons (tropical cyclones) in the past years. The Philippines a nation with a 100 million people [1] is visited by an average of 19 to 20 tropical cyclones every year [2]. The 2015 World Risk report ranked the country as the third most risk prone country in terms of natural disasters in the world [3]. Last 2013, the Philippines made headlines as it was hit by Typhoon Haiyan which was the strongest storm ever recorded at landfall. The super typhoon had sustained wind speeds up to 315 kilometres per hour (195 mph) and gustiness up to 380 kilometres per hour (235 mph) [4]. The damage to infrastructure and casualties were staggering. A total of 6,300 people died in the aftermath with 28,000 injuries [5]. Around 1.1 million homes were damaged or destroyed with an economic impact of 12.9 billion USD [6]. Visual evaluation and survey of the damage along Typhoon Haiyan’s path showed that majority of low rise detached buildings suffered roof damage caused by strong winds [7]. Immediately after the disaster there was interest and clamour for better typhoon resilient building in the country. Unfortunately, very few researches were conducted on typhoon resilient infrastructure in the Philippines. Most of the studies were concentrated on the effect of hurricanes to low rise structures in
the United States. There is a clear need to evaluate current roofing designs and infrastructure support to minimise the damage in future climatic events.

Numerous studies on wood frame low rise building performance under hurricane wind loads have been conducted in the past. The studies are usually categorised into hurricane hazard modelling, wind structure interactions, building representation and performance assessment [8]. Majority of wind structure interactions were conducted using wind tunnel tests and have been the basis of the design codes. The problem with wind tunnel tests is that it is highly dependent on the availability of high quality experimental facilities which is almost non-existent in a country like the Philippines. Costs are also prohibitive especially with the use of full scale models combined with the actual cost of wind tunnel facilities. The use of Computational Fluid dynamics (CFD) in the built environment to accurately predict aerodynamic behaviour in different Atmospheric boundary layer conditions (ABL) has been emerging lately [8-11]. The preference for CFD over wind tunnel tests is due to its practicality, shorter development time and lower costs compared to a full-scale prototype. Despite of its many advantages compared to wind tunnel tests [12-15], CFD cannot predict the structural response of the model which is only possible through actual wind tunnel tests or the use of Finite element analysis (FEA). The FEA method has been utilised in the assessment of light-framed wood roof structures to wind loads as seen in numerous studies [16-18]. However, the pressure loads required as boundary conditions are still obtained from wind tunnel tests. An alternative is to combine CFD and FEA into a fluid-structure interaction (FSI) analysis. This method was already performed successfully by Lee et al. [19] in the analysis of a phase VI wind turbine.

In the FSI analysis, the surface pressure results computed from the CFD analysis is transferred to the structural surface pressure loading and then a linear or non-linear finite element analysis is performed using the FEA module. The structural response of the model such as forces, stresses and displacements are calculated from the structural analysis. This paper utilises the FSI method to analyse the structural response of a low rise gabled timber building under typhoon strength wind conditions. The wind speed conditions and geometry of the building were patterned after He et al. [16] for experimental validation. The CFD and linear static analysis for the gabled building was performed using a commercial program ANSYS.

2. Methodology
2.1 FSI framework
FSI generally uses 1-way or 2-way modelling approach. In the 1-way approach, a converged solution is obtained for one field then used as a boundary condition for the second field. On the other hand, the 2-way approach solves fluid and solid equations separately and iterates within each time step to obtain an implicit solution. Implicit means the dependencies between the fluid and solid fields are converged within a time step. Unsteady transient turbulence models are more suitable for 2-way FSI analysis while steady Reynolds-averaged Navier-stokes equations (RANS) models use a 1-way FSI approach. 1-way FSI might be easier to implement compared to 2-way FSI due to uncertainties of obtaining convergence and the potential of having numerical singularities during the simulation in the interface and fluid domain [19]. Applications with weak physical coupling wherein the primary objective is to obtain maximum structural stresses and with strains not significant enough to affect the CFD results are most suitable for a 1-way FSI. Tominaga et al. [20] compared and validated the different RANS turbulence models and concluded that the RNG $k$-$\varepsilon$ exhibited the best performance compared to the standard $k$-$\varepsilon$ and $k$-$\omega$ SST. The modelling approach used in this paper is a 1-way FSI analysis utilising an RNG $k$-$\varepsilon$ turbulence model. The 1-way FSI methodology flowchart used in this study is described in Fig 1.
2.2 Flow field

The building model used in the simulation is a gabled-roof building with a roof pitch of 16.7 °. This gabled roof design is typical in the Philippines \[21\]. The size of the computational domain which is \(84 \times 46 \times 32.76\) m as described in Figure 2 complies with the guidelines recommended by Blocken \[22\] for directional blockage ratio. The size of the building \(3.57 \times 2.29 \times 0.91\) m is the same one used by He et al. \[16\] in their study. The velocity used is \(40.68\) m/s (\(147\) kph) with mean wind speed profile of \(\alpha = 0.15\) (power law). This wind speed is categorised to a Typhoon category 3 in the Philippines four cyclone warning categories.

2.3 Structural Members

The structure is composed of frames and sheathing panels made from 7/16 in Oriented Strand Board (OSB) which the material properties derived from literature are incorporated in the FEA model. The frame design and wind angle definitions are shown in Figure 3.
3. Results

3.1 Model Validation

The model was subjected to a constant wind speed at different angles from 0 to 180° at a 15° interval. The displacement at various locations were compared with the wind tunnel displacement results of the study conducted by He et al. [16]. The displacement results taken at two different sides in the model for the simulation and experimental runs are shown in Figure 4.
Both simulation charts followed the experimental trend with a little bit of overestimation for P4. The trend in the leeward side at P3 is much more better than at P4 except for some noticeable differences at the 120° and 150° wind angles. This may be attributed to the imported pressure data which is derived from the CFD results. The FSI analysis is highly sensitive to the CFD results which may result into some errors in the structural simulation. Another possible cause of error is that the structural model is assumed to be linear wherein the actual scenario follows a non-linear behaviour. Nevertheless, the differences in the displacement magnitudes of the simulation and experimental data are less than a mm.

3.2 FSI structural analysis

The equivalent von mises stresses and total displacements were obtained for wind angles cases. The maximum stress and displacements in the roof occurred in the 90° wind angle which was 38.288 MPa and 122 mm respectively. The imported pressure, stress and displacement plots are shown in Figure 5.

![Figure 5](image_url)

Figure 5. a.) Imported pressure results b.) Maximum and minimum equivalent stresses in the frame c.) Maximum and minimum displacements in the sheathing

Upon further observation, the maximum stress occurred in the frame of the roof near P5 and the maximum deflection occurred in the roof sheathing at area R4. Although the highest stresses are experienced at the structural frame, the highest deformation occurs at the roof section which can cause ripping. The pressure along the roof surface is highest at the windward (front) and lowest at the leeward side (back). The minimum deformation scenario in the roof occurred at the 0° angle which was around 0.65 mm maximum at the windward side. A relatively high stress of 44.65 MPa was experienced in the frame wall but it resulted into a small deformation of about 0.95 mm.

4. Conclusions

The study has successfully demonstrated the capability of FSI analysis in low rise building performance under typhoon winds. The model was validated and matched the response of the wind
tunnel results from a previous study. Based from the results, the area of the highest roof uplift can be properly estimated based on a worse case wind angle scenario. The highest stress concentration on the roofing frame can be properly determined as well. Both occurrences (highest stress and deflection) happened in the windward side. The importance of the wind angle can play the importance role in the orientation of houses. Urban planners can properly plan the orientation of houses in the known path of the typhoon to minimise destruction. Future directions of this study can include the evaluation of different roofing designs such as gabled with eaves overhang, mono-sloped, domed and hip. Optimisation of the pitch, height and length together with the structural parameters such as frame reinforcement and proper material selection are also essential for this FSI framework to be applicable in the real setting.

References

[1] World Bank. World Development Indicators 2017. Washington, DC: World Bank; 2017.
[2] Craig A, Cinco T, Monteverde C, Hilario F, Celebre C, Tudao A, et al. Tropical Cyclone Severe Wind Risk Modelling in GMMA. 2013 APEC Typhoon Symposium; NTU GIS convention center, Taipei: APEC Research Center for Typhoon and Society (ACTS) 2013.
[3] Garschagen, M, Hagenlocher M, Kloos J, Pardoe J, Lanzendörfer M, et al. World Risk Report 2015. Berlin, Germany: Alliance Development Works; 2015.
[4] Evans A. Annual Tropical Cyclone Report 2013. Pearl Harbor, Hawaii: Joint Typhoon Warning Center; 2014.
[5] National Disaster Risk Reduction and Management Council. Final Report Effects of Typhoon “Yolanda” (Haiyan). National Disaster Risk Reduction and Management Council. Quezon City, Philippines 2014.
[6] National Economic and Development Authority. Reconstruction Assistance for Yolanda. National Economic and Development Authority. Pasig City, Philippines 2013.
[7] Chen SE, Leeman ME, English BJ, Kennedy AB, Masters FJ, Pinelli JP, et al. Basic Structure System Rating of Post-Super Typhoon Haiyan Structures in Tacloban and East Guianan, Philippines. Journal of Performance of Constructed Facilities. 2016;30(5):11.
[8] He J, Pan F, Cai CS. A review of wood-frame low-rise building performance study under hurricane winds. Engineering Structures. 2017;141:512-29.
[9] Enteria N. CFD Evaluation of Philippine Detached Structure with Different Roofing Designs. Infrastructures. 2016;1(1):3.
[10] Hughes BR, Calautit JK and Ghani SA. The Development of Commercial Wind Towers for Natural Ventilation: a review. Applied Energy. 2012;92:606-27
[11] Hosseini SH, Shokry E, Hosseini AJ, Ahmadi G and Calautit JK. Evaluation of airflow and thermal comfort in buildings ventilated with wind catchers: Simulation of conditions in Yazd City, Iran, Energy for Sustainable Development. 2016;35:7-24
[12] Calautit JK and Hughes BR. Measurement and prediction of the indoor airflow in a room ventilated with a commercial wind tower. Energy and Buildings. 2014;84:367-377
[13] Calautit JK and Hughes BR. Wind tunnel and CFD study of the natural ventilation performance of a commercial multi-directional wind tower. Building and Environment. 2014;80:71-83
[14] O’Connor D, Calautit JK and Hughes BR. A study of passive ventilation integrated with heat recovery. Energy and Buildings. 2014;82:799-811
[15] Calautit JK, Chaudhry HN, Hughes BR and Sim LF. 2014, A validated design methodology for a closed-loop subsonic wind tunnel. Journal of Wind Engineering and Industrial Aerodynamics;125:180-94
[16] He J, Pan F, Cai CS, Habte F, Chowdhury A. Finite-element modeling framework for predicting realistic responses of light-frame low-rise buildings under wind loads. Engineering Structures. 2018;164:53-69.
[17] Jacklin RB, El Damatty AA, Dessouki AA. Finite-element modeling of a light-framed wood roof structure. Wind and Structures. 2014;19(6):603-21.


[18] Satheeskumar N, Henderson DJ, Ginger JD, Wang CH. Three-Dimensional Finite-Element Modeling and Validation of a Timber-Framed House to Wind Loading. *Journal of Structural Engineering*. 2017;143(9):11.

[19] Lee K, Huque Z, Kommalapati R, Han SE. Fluid-structure interaction analysis of NREL phase VI wind turbine: Aerodynamic force evaluation and structural analysis using FSI analysis. *Renewable Energy*. 2017;113:512-31.

[20] Tominaga Y, Akabayashi S, Kitahara T, Arinami Y. Air flow around isolated gable-roof buildings with different roof pitches: Wind tunnel experiments and CFD simulations. *Building and Environment*. 2015;84:204-13.

[21] Enteria N, Awbi H, Yoshino H. Application of renewable energy sources and new building technologies for the Philippine single family detached house. *International Journal of Energy and Environmental Engineering*. 2015;6(3):267-94.

[22] Blocken B. Computational Fluid Dynamics for urban physics: Importance, scales, possibilities, limitations and ten tips and tricks towards accurate and reliable simulations. *Building and Environment*. 2015;91:219-45.