A fluid-structure interaction modelling of roof mounted renewable energy installations in low rise buildings for extreme weather and typhoon resilience

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Abstract. Super typhoon Haiyan made landfall in the Philippines last 2013 where an estimated 1.1 million homes were damaged. There was massive roofing damage in the houses due to strong winds. With the increasing number of roof-mounted renewable energy installations, there is a clear need to review the current systems to respond to future climactic events. The current approach for building performance analysis under typhoon wind loads involves a lot of wind tunnel tests, full scale testing and finite element modelling which is heavily reliant on wind tunnel data which are costly and time consuming. Current renewable energy mounting technologies with its different installation methods, and mounting locations consequently affected by wind loads differently. Using the proposed framework, this study evaluated solar panels attached to the gabled roof of a single detached low-rise building. The stress and deformation of the structure and the panels was determined using the typhoon’s Atmospheric Boundary Layer flow simulation. Building energy simulation was used to determine the appropriate site orientation to maximise solar energy generation. Results show areas of high failure rate in the panels in the 0 degree wind angle direction and in the panels closer to the edge. Maximum solar energy generation was determined at the 90 degree site orientation.

Keywords: Typhoon, Building, Fluid Structure Interaction, Computational fluid dynamics, Solar Panel
1. Introduction
The Philippines was hit by super typhoon Haiyan with wind speeds up to 315 kilometres per hour (235 mph) last 2013 [1]. It was the strongest storm ever recorded at landfall at that time. There were around 6,300 casualties and 28,000 injuries related to the disaster across the country [2]. In the aftermath of the typhoon, 1.1 million homes were damaged or destroyed [3]. In the city of Tacloban and East Guian, infrastructure surveys showed that 53% of low-rise buildings suffered wind damage and the most critical damage is roof system failure which accounted for 21% of all damage [4]. On the other hand, current solar panel mounting technologies are also affected by wind loads. Solar panel installations may increase the uplift forces and over estimation of these forces can increase the cost of construction costs. The present structural codes require further information for it to be directly applicable to the solar systems. Lastly, limited studies were conducted to look at the overall wind loads brought to the building with solar panels installed [5]. Majority of the studies are on the estimation of the wind loads on the panels itself and not on the overall effect on the entire building after panel installation. This research proposes the use of fluid-structure interaction (FSI) method for the analysis of typhoon wind pressures on a low-rise timber building to assess the structural response of its components, sheathing panels and solar panel arrangements. Moreover, this research investigated the Solar PV generation potential for a year of the solar panels at different building orientations in the city of Tacloban in the Philippines.

2. Material and methods

2.1 Fluid structure interaction framework
The Fluid structure interaction (FSI) method in this study used a 1-way approach. This meant that a converged CFD solution is obtained for one field which is then transferred to the second field or the finite element analysis (FEA) as a boundary condition. The assumptions for the steady state simulation comprised a three-dimensional, fully-turbulent, and incompressible flow. The turbulent nature of the flow was modelled by the standard $k$–$\varepsilon$ model. The simulations were completed using parallel processing on a workstation with two Intel Xeon 2.0 GHz processor and 64GB Fully-buffered DDR2. The FSI analysis used in this study was performed using the commercial program ANSYS 18.1 which includes the CFD FLUENT, Structural Mechanical and System Coupling tools.

The CFD and FEA geometry which consists of the building model (frame and sheathing) and micro-climate computational domain were constructed using the commercial CAD software Solidworks. Solidworks allowed the different components of the building to be created and combined into a 3D assembly. The integration of Solidworks with ANSYS enabled a seamless and more efficient workflow preventing the creation of several different CAD model iterations within Solidworks when modifying dimensions and iterating through designs. The benchmark building model used in the simulation is an isolated building with a gable roof pitch of 14 degrees. The computational domain described in Figure 1.

![Figure 1. Computational domain and boundary conditions for the simulation of the low rise building](image-url)
1 is measured to be 57 m x 38 m x 27 m (L x W x H) which complies with the directional blockage ratio guidelines recommended by Blocken [7]. The dimension of the building is 11.78 m x 7.56 m x 3 m (L x W x H). The solar panels which has dimensions of 1.559 m x 1.046 m x 0.046 m (L x W x H) were modelled after a commercial Sunpower 310W solar panel which is constructed using an anodised aluminium 6063 frame and high transmission tempered glass. The approach profiles for the airflow velocity \( U \) and turbulent kinetic energy (TKE) are imposed at the inlet, with the stream-wise velocity of the incident airflow following a modified power law with an exponent equal to 0.077 (power law) which was generated by Song et al [8] specifically for typhoons. The velocities used were 40.68 m/s (147 kph) and 61 m/s (220 kph) at a height of 10 m. categories.

A grid sensitivity analysis was conducted to determine the most appropriate mesh design for computational efficiency. The process varied the elements between coarse to fine global mesh elements. The average value of the velocity in the windward side of the building starting from the roof eave was used as the error indicator. The average error between the fine and medium mesh was found to be 0.26% with the maximum error of 2.05%. The medium mesh was used in this study.

2.2 Structural model components

The building as shown in Figure 2 is modelled by using the ANSYS Mechanical tool, and the structure components are represented directly by the built-in elements in ANSYS. The building’s structure is composed of frame elements made from Spruce Pine form (SPF) and sheathing made from Oriented Strand Board (OSB) in [9]. Thirty six solar panels were installed to cover the entire roof area. These panels are evenly spaced apart with the minimum distance of 100 mm from the roof edges. The panels were modelled as an assembly composed of anodised aluminium 6063 and high transmission tempered glass (front glass) in which the material properties also obtained from literature. The other parts of the panel such as monocrystalline solar cells and junction box were not included to simplify the model and because they are not structurally integral parts.

![Figure 2. 3D model of frame and sheathing with 36 solar panels](image)

2.3 Structural model meshing and boundary conditions

The boundary conditions for the structural model are to be set independently from the CFD analysis. The CFD domain will be suppressed in the setup and the appropriate material to be assigned in the sheathing, frame, tempered glass and aluminium frame. Contact behaviour in this case is a no separation type of contact were assigned in the sheathing areas to the corresponding frame members which is enough already for this study. The tempered glass edges were bonded to the frame in which the frame was attached to the roof sheathing. There is also a potential towards the use of more modelling of connections particularly nail behaviour to further improve accuracy. A fixed support constraint was applied in the base of the frame and a standard earth gravity load was also added to correspond to the weight of the structure. The pressure data from the completed CFD analysis was added as an imported load. The process to interpolate the pressure data took 12 hours to finish. The FEA mesh which is separate from the CFD mesh generated an unstructured tetrahedron mesh with 1258135 elements. The body sizing method was applied for similar sizing with the CFD elements for the frame and the sheathing.
2.4 Solar energy PV generation
The solar energy PV generation potential was estimated for a year in the city of Tacloban as shown in Figure 4.B using the IES commercial program. The building’s orientation was altered from 0° to 360° at a 45° interval as shown in Figure 4.A with the north direction as the basis of the 0°. Typhoon Haiyan originated from the Pacific with its wind direction path flowing from east to west as in the situation in Tacloban city.

3. Results and discussion
Following the validated FSI methodology, building was subjected to wind speeds of $U_{10} = 40.68 \text{m/s}$ and $U_{11} = 61 \text{ m/s}$ at 0 degree and 90-degree wind angles at the same boundary conditions to investigate the air flow and pressure fields around building models. Furthermore, this will also test the structural performance of the solar panels and other building components. This will be compared to the Solar energy PV potential to check the optimal building orientation for solar energy generation potential and typhoon strength wind resilience. The succeeding sections describes the fluid dynamics results such as flow field velocity and surface pressure coefficient followed by structural response (equivalent stress, deflection) findings using FEA and lastly the solar energy PV generation results.

3.1 Flow velocity and pressure
Figure 5 a-b shows the velocity contours of a cross sectional plane at 90 degree wind direction angle subjected at both wind speeds while Figure 6 c-d shows the velocity contours at a 0 degree wind direction angle. As observed, there is a significant change in the flow fields between the 0 degree and 90 degrees wind angle direction. A weak velocity or recirculation region is observed on the roof on the 90 degrees wind angle direction due to flow separation while recirculation occurred at the 90 degree wind angle direction. The positive pressure in front of the building is greater in the 90 degree wind angle. A negative peak pressure can be observed for the windward corner ridges at both wind directions and minimal for the leeward ridge. Higher negative peak pressures are observed in the windward ridge of the 0 degree wind angle direction.

![Figure 3. a) Building orientation b) Tacloban city’s geographical location in the Philippine islands](image-url)
3.2 Panel equivalent stresses

The maximum stress induced in the panels are located on the edges of the tempered glass at the interface of the frame. This was observed in all cases. The panel will have a high deflection in the middle resulting into high stress concentration along its edges. This panel would most likely to fail or break in this area. Minimal stresses were also experienced by the frame. Figure 6 shows the equivalent stress distribution on both wind angle orientations at two different wind speeds. Per visual inspection of the results, higher stress is observed for panels located in the windward side of the roof. The stress is significantly higher at the 61 m/s wind speed and at the 0-degree wind angle direction which exhibited the highest equivalent stress experienced by a panel at 136 MPa. Panels which are further away from the windward edge experience less amount of stress compared to the panels closer to the edge. This is the same observation made in the displacement results since higher deflections would also yield higher stresses. It was also observed that panels located closer to the windward edge tend to have higher stresses compared to the panels that are further away from that edge.

![Figure 4. Velocity contours at 90° wind direction (a) U10 = 40.68 m/s and (b) U11 = 61 m/s and Velocity contours at 0° wind direction (c) U10 = 40.68 m/s and (d) U11 = 61 m/s](image)

![Figure 5. Equivalent stress at 90° wind direction (a) U10 = 40.68 m/s and (b) U11 = 61 m/s and at 0° wind direction (c) U10 = 40.68 m/s and (d) U11 = 61 m/s](image)

![Figure 6. PV generated electricity vs Building orientation angles](image)
3.3 Solar energy PV generation results

The annual PV generated electricity (MWh) at different building orientation angles is shown in Figure 7. The building orientation is based on the site as shown previously in Figure 4. The highest potential is found to be at the 90° building orientation with the second highest at 45°. The lowest potential is at the 225 and 270°.

4. Conclusion

The FSI methodology coupled with PV generation simulations has been implemented for the analysis of a low rise timber frame building with solar panel installations to evaluate the aerodynamic-structural performance and energy generation potential under typhoon winds. A three-dimensional structural model of the building with solar panel assembly mounted on the roof was developed. Structural analysis based from the CFD results successfully predicted displacement and stress of the solar panel frame and tempered glass. Based on the results, majority of the solar panels would fail at the worst case wind angle scenario at 0 degree. It was also determined that the solar panel’s tempered glass is significantly affected during a super typhoon. Panels should be located as far away as possible from the edge to minimise damage. For the solar energy PV generated for a year, the best setup is the 90 degree site orientation which delivers the highest electricity generation and minimum panel destruction under typhoon wind strength conditions.

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