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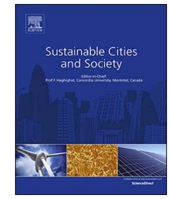

Retrofitting building roofs with aerodynamic features and solar panels to reduce hurricane damage and enhance eco-friendly energy production

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A B S T R A C T

Wind-induced negative pressure on roofs of low-rise buildings is a major source of losses and community disruption. Vortex suppression technologies may reduce wind loads on buildings; however, it is challenging to implement an effective strategy to reduce wind loads on roofs with minimal loads on the mitigation feature itself. In this paper, the performance of different aerodynamic mitigation features is investigated in a comparative study. The results show that solar panels are relatively effective in reducing wind-induced uplift forces on a flat roof. Compared with all mitigation features presented, the airfoil is the most effective in reducing uplift loads, with promises to proceeding research in this area. In addition, the study investigates wind impact on a gable roof building with different configurations of solar panels, to reduce wind-induced loads on the host building while maintaining a visually appealing installation to permit broad usage and application. Pressure coefficients on roofs and solar panels from both computational fluid dynamics (CFD) simulations and laboratory experiments are compared. The study shows that the optimal roof/solar panel combination reduces wind loads on low-rise buildings, i.e. improves the performance, in addition to providing ecofriendly energy especially when power outage is expected.

1. Introduction

1.1. Background

Wind-induced pressures on low-rise buildings may cause severe and/or sustained loads both of which are detrimental to the structure and put the inhabitants at risk. Windstorms vary from strong winds causing little to moderate damage to extreme winds from hurricanes, tornadoes, or heavy storms causing massive destruction. It is vital to build secure and more efficient infrastructure to balance safety issues with the reality of limited resources (resilience with sustainability). Wind-induced negative pressures develop due to flow separation when high velocity winds pass over the sharp corners of a building (Holmes, 2015). Negative pressures cause uplift effect that can detach panels, tiles, and/or membranes from roofs, like in the case of residential homes or industrial buildings. High suction is usually experienced at the corners of the windward edges (Lin, Surry, & Tieleman, 1995; Mehta, Levitan, Iverson, & McDonald, 1992; Stathopoulos, Baskdran, & Go, 1990; Tieleman, Surry, & Lin, 1994). Negative pressures that develop on roofs of low-rise buildings depend on the shape, among other factors, as a key parameter that affects the pattern and intensity of flow separation and hence wind-induced loads (Gerhardt & Kramer, 1992).

1.2. Aerodynamic mitigation

Wind loads on bluff bodies are dominantly governed by their shapes, among other factors (Davenport 1995). Accordingly, an aerodynamic mitigation approach should rely on shape modification as a technique by which aerodynamic loads can be greatly reduced. The shape of an airplane wing enables flight. It includes slats and flaps, as mechanisms that can be positioned to control aerodynamic forces developed on the plane, and are useful for landing and takeoff (Fig. 1). Turning the leading edge of the slat and the trailing edge of the flap downward increases the lift, while the large aft-projected area of the flap increases the drag, which slows the airplane down for landing. Similar to the way in which the airplane is manipulated for landing, an aerodynamic roof edge may be designed to reduce the total uplift loads on roofs of low-rise buildings. The main objective of a successful aerodynamic mitigation approach is to keep the roof permanently secured by minimizing uplift forces.

Secured roofs under wind loads may reduce windstorm-induced losses. Different roof mitigation strategies are suggested in literature (Banks, Sarkar, Wu, & Meroney, 2001; Bitsuamlak & Warsido, 2012; Blessing, Chowdhury, Lin, & Huang, 2009; Cochran & English, 1997; Kopp, Mans, & Surry, 2005; Lin, Montpellier, Tillman, Riker, & Gx,

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Fig. 1. Similar to an airplane landing and takeoff mechanism, aerodynamic features are inspired to reduce wind uplift loads: (a) slats (leading edge), and (b) flaps (trailing edge).

2008; Lin, Montpellier, & Tillman, 2011; Suaris & Irwin, 2010). Six different mitigation devices were tested in (Chowdhury & Blessing, 2007) and the Flat Roof Aero Edge Guard yielded significant decrease in localized negative pressures near roof corners. Experiments on a 1:100 scale Texas Tech University (TTU) test buildings were conducted under multiple flow conditions (Mahmood, Srinivas, & Budair, 2008), showing that rounding the edges of the building may decrease negative pressures. In addition, research carried out by Pindado Carrion et al. (2009) shows that cantilever parapets may reduce uplift forces as they disturb the formation of conical vortices (Banks & Meroney, 2001; Franchini, Pindado, Meseguer, & Sanz-Andrés, 2005; Pindado Carrion, Meseguer Ruiz, Franchini, & Barrero Gil, 2009). Also, screens were employed to suppress the conical roof vortices (Cochran & English, 1997). Additional aerodynamic edges and devices were studied (Banks et al., 2001; Blessing et al., 2009; Suaris & Irwin, 2010). However, a challenge with common architectural features (ex., screens and aerodynamic edges) is that the device may be vulnerable due to exposure to extreme drag and/or lift forces leading to failure with a potential of becoming a wind-borne debris, leaving the roof unprotected. The mitigation features should be further investigated to ensure that the loads and stresses developed on the mitigation features themselves are within the reasonable and allowable limits. The challenge is on exploring mitigation features that can reduce wind loads, not only at the corners, but also on the entire roof, and create minimal loads on the feature itself. Aerodynamic features with relatively high lift and drag forces may increase the overall wind loads on the main structure, which is not an economic solution. In the current paper, different aerodynamic mitigation techniques and devices were tested computationally in a comparative study to know the best approach for maximum roof protection with minimal loads introduced on the feature. This is an important consideration for the design of the main force resisting system of a low-rise building. In addition, an ideal mitigation feature should be attractive to building owners to permit widespread usage and applicability, which makes the investigations of the potential use of architectural features, such as solar panels, an important consideration.

1.3. Renowned interest in solar energy

The importance of solar energy as a source of eco-friendly energy was documented early in 1911 (Shuman, 1911). With worldwide concerns regarding the impact that combustible fuels have on the increase in greenhouse gas emissions and climate change, sustainable development policies supporting the integration of renewable energies have been implemented. Photovoltaic (PV) solar panels are common devices used for harvesting energy (Singh, 2013), and perhaps technology will lead to '*Covering the Planet with Solar Panels*' (Webb, 2007).

The popularity of the solar panel technology is increasing and spreading across the world and it is especially convenient on buildings as there is no need for power transmission over a long distance (compared to the case of solar farms). The technology provides various advantages such as reducing pollution, acting as a roof heat shield, increasing green energy production, and reducing electrical cost.

However, the wind flow and the aerodynamics of low-rise buildings are quite complicated due to flow separation around the building and other fluid dynamic mechanisms. Therefore, wind-induced loads govern the design and installation of solar panels. Installing solar panels on a building's roof may increase the uplift forces and the over estimation of these forces can significantly increase the construction cost. The design of solar panels on roofs of buildings requires accurate information and the present structural design codes still need more information to be directly applicable to the structural solar systems (Schellenberg, Maffei, Telleen, & Ward, 2013). In addition, there is a limited number of studies that attempt to look at the overall wind loads brought to a building after the solar panels are installed (Kopp, Farquhar, & Morrison, 2012; Stenabaugh, Iida, Kopp, & Karava, 2015). Most of available studies are focused on the estimation of the wind loads on the panels themselves. There is little attention to the overall loads on the host roof after installation.

1.4. CFD as a tool for wind load estimation

Considering the high demand for solar power and the variations among the solar technologies available, several wind tunnel and Computational Fluid Dynamics (CFD) studies exist on the subject of solar panel aerodynamics. CFD is a powerful tool that has been used to carry out and verify research in various engineering fields, especially wind engineering. CFD has plenty of advantages such as the potential to collect continuous flow data and study cases that are challenging to be investigated experimentally (for example, full-scale testing of large structures). In CFD, there is no interference effects of sensors on the aerodynamic loads, which can be an issue in laboratory experiments. In wind tunnel experiments, correct scaling of the flow and the test objects may lead to small models, to obtain similar physics as the case in full-scale. The smaller the model, the fewer measurement sensors can be installed (Aly, 2016; Aly & Bitsuamlak, 2013). These issues and restrictions do not exist in CFD.

CFD has been successfully used for wind load estimation on bluff bodies, for instance, it was employed to achieve optimal tall buildings design (Kareem, Spence, Bernardini, Bobby, & Wei, 2013). Aerodynaic shape optimization was studied by a CFD-enabled Kriging-based approach (Bernardini, Spence, Wei, & Kareem, 2015). Also, aerodynamic shape optimization for corners of tall buildings using CFD was invistigated in detail (Elshaer, Bitsuamlak, & El Damatty, 2015). Iaccarino, Ooi, Durbin, and Behnia, (2003) performed a computational experiment by using the Reynolds Stress Model (RSM) to test a cube in a wind field (Iaccarino et al., 2003). They proved that modelling the flow with the unsteady Reynolds-averaged Navier–Stokes (RANS) equations provides good quantitative and qualitative agreement with experimental data when the flow is not statistically stationary. In contrast, RANS repeatedly produced errors since the method neglects the average