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Aerodynamic mitigation of wind-induced uplift forces on low-rise buildings: A comparative study

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ABSTRACT

Negative pressures on roofs of low-rise buildings are a major source of losses and community disruption during windstorms. The main driver for negative pressures is the fact that buildings are bluff bodies that cause flow separtion, compared to streamline objects such as an airplane wing. Consequently, the separated flow may create conical vortices that can significantly increase wind-induced uplift loads on roofs. Although vortex suppression technologies play a role in reducing wind loads on buildings, the challenge is related to exploring techniques that can reduce loads on roofs and the mitigation features themselves. In this paper, several aerodynamic mitigation techniques/features are proposed and tested by computational fluid dynamics (CFD) simulations, in a comparative study to permit selection among different potential solutions. Modifications to eliminate the sharp corners that cause flow separation and uplift forces are carried out. Different aerodynamic mitigation features including barriers, circular edges, inclined edges and airfoil edges are investigated. The study explores mitigation devices that not only can reduce wind-induced uplift loads on roofs, but also have minimum drag and lift forces. The results show that the slope-in features, representatives of solar panels for green energy production, are effective in reducing wind-induced uplift forces. In fact, having solar panels on buildings can be a feasible solution, especially when there is a potential for power outage due to windstorms. Such features, among other devices, can potentially protect roofs under windstorms, creating economic and green buildings. In addition, compared to all mitigation features presented in the current study, the airfoil produced the minimum uplift loads, with promises to proceeding research in this area.

1. Introduction

1.1. Background

According to a report published by the NOAA's National Climatic Data Center [42], in the year 2012 weather and climate disaster events caused losses exceeding $110 billion in damages and 377 deaths across the United States. This makes the year 2012 the second costliest on record, after the year 2005 which witnessed $160 billion of losses due to hurricanes, including hurricane Katrina. The major driver of damage costs in 2012 was hurricane Sandy at approximately $65 billion. During the 1980-2005 period, the U.S. sustained over $500 billion in overall inflation adjusted costs due to extreme climate events [38]. However, there is a significant increasing trend in billion-dollar disasters [41,47]. Although advanced forecasts and warnings and more effective emergency responses can help reduce mortality, the economic impact of hurricanes is huge and there is a need for a comprehensive research program to improve the resiliency and sustainability of buildings under extreme windstorms [54,55]. Wind impact on low-rise buildings can cause severe and/or sustained loads, both of which can be detrimental to the structure and human occupants. Windstorms can range from moderate winds, causing little to no damage, to extreme winds from hurricanes, tornadoes, or heavy storms, causing massive destruction.

1.2. Wind effects on low-rise buildings

When wind passes over a roof of a low-rise building, flow separation occurs [22]. As a result, negative pressures form on the roof, producing uplift forces that can initiate damage (residential homes and industrial buildings). Negative pressures are usually experienced at the corners of the windward edges [35,50,52]. Banks et al. [7] attempted to better understand the flow mechanism (conical vortices), which produces significant negative pressures, by studying low-rise buildings in a wind tunnel. It was found that the greatest uplift forces occurred directly beneath the moving vortex core, but there was no relationship between vortex

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Fig. 1. Similar to an airplane landing mechanism, aerodynamic features are inspired to reduce wind loads on buildings: (a) slats; and (b) flaps.

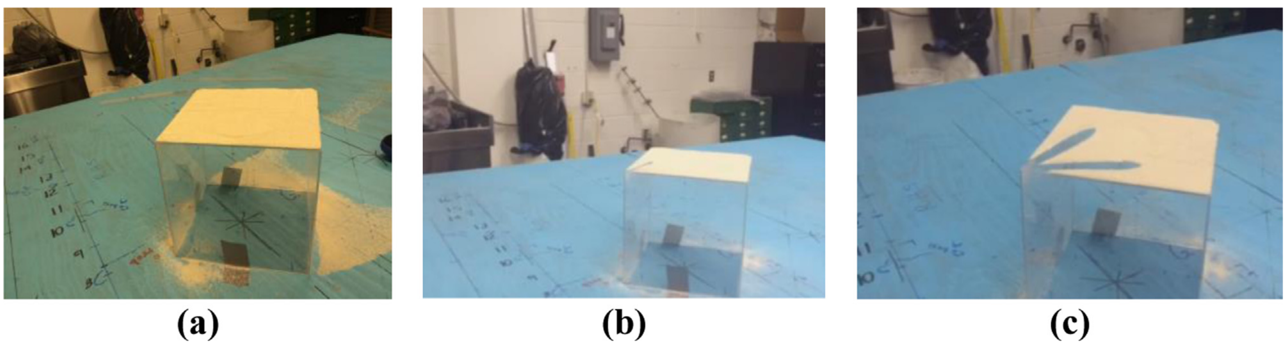

Fig. 2. Formation of conical vortices on a roof under a wind direction angle of 45°: (a) no wind, (b) flow at a medium speed, and (c) flow at a relatively high speed. This visualization experiment was carried out at the LSU open-jet simulator.

size and negative pressures. Tieleman [53] did a review of wind loads on low-rise structures tested in wind tunnels, which show that peak negative pressures on prisms are inherently associated with vortex generation under separated shear layers and peaks are observed under the corner vortices. Conical vortices formed on roofs are a major source of negative pressures. Fig. 2 presents photographs showing the formation of conical vortices on a flat roof under a wind direction angle of 45 deg. These photographs were taken in a flow visualization experiment carried out at the Louisiana State University (LSU) newly built open-jet hurricane simulator [1]. The wind direction, speed, and duration are significant parameters that govern the size of conical vortices.

Banks and Meroney [6] studied rooftop surface pressures produced by conical vortices. They looked at the relationship between negative pressures and upstream flow. The study shows that the speed of the vortex spin is determined by the flow velocity component normal to the roof edge. Regardless of the wind direction angle, the pressure above the vortex will be controlled by the speed of gusts passing over the roof corner. Negative pressures developed on low-rise buildings depend basically on the shape of the roof, among other factors. The roof's geometry is a key parameter that affects wind-induced loads on a building [19].

Wind affects buildings by pressures causing significant loads that can lead to damage. Windstorms cause significant negative pressures on roofs of domestic homes and industrial/commercial buildings that can initiate failure [13,28,49,8]. Once part of the roof failed, the building becomes vulnerable and may be subject to cascade failure of the whole envelope [14]. The Institute for Business and Home Safety (IBHS) showed in its hurricanes Ike and Charley reports that roofs had the highest failure rate out of all building components [21].

Wind flow can create negative pressures on roofs far from their corners, and hence an increase in the overall uplift forces on the entire roof. This is an important consideration for the design of the main force resisting system of a building. Wind loads on bluff bodies are dominantly governed by their shapes, among other factors. Accordingly, an aerodynamic mitigation approach should rely on the shape modification as a way by which aerodynamic loads can be greatly reduced. The shape of an airplane wing enables flight, at the same time slats and flaps form a mechanism for landing (Fig. 1). Dynamic and passive control surfaces have been introduced to reduce wind loads on tall buildings, bridges, and roofs of low-rise buildings. Similar to the way in which the airplane is manipulated for takeoff and landing (Fig. 1), an aerodynamic roof edge can be designed to reduce the total uplift loads on roofs (roofs should be landed all times). An important design consideration, however, is to reduce wind-induced loads that may damage the roof partially or totally and cause it to become windborne debris, including the aerodynamic features themselves. To improve the resiliency of our communities to natural disasters, new design techniques should be implemented. Promising solutions like aerodynamic optimization and mitigation are therefore needed to balance safety issues with the reality of limited resources (sustainability constraints).

1.3. Aerodynamic mitigation

The mitigation of the roofs under wind loads can reduce hurricane related losses. Different roof mitigation strategies are suggested in the literature [10,11,14,2,29,36,37,48,9]. Many researchers have attempted to develop ways to prevent or reduce uplift forces. Prasad et al. [46] tested low-rise building models with flat, gabled and hip roof configurations in a boundary layer wind tunnel and found that negative pressures were significantly influenced by the roof configuration. There was a 91% reduction in peak localized negative pressures by using a gabled roof as