Mitigation of extreme wind effects on low-rise structures in coastal zones.

Review

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Abstract—

Every year, hurricanes hit different regions of the world, causing significant economic and human losses. Climate change also has a great influence on these natural phenomena, which are becoming more frequent and intense. The large wind gusts that accompany this natural phenomenon are damaging to all types of areas, especially low-rise structures such as residential, commercial and industrial buildings. As a response, researchers and government agencies around the world have taken the lead in developing strategies to understand and improve the stability of structures in the presence of extreme winds. This article reviews the most recent work on various strategies for mitigating wind loads produced by hurricanes. Mitigation strategies in the coastal zone of the Mexican Republic are discussed in this study as well as the different methodologies used to better understand the effects caused by extreme winds (wind tunnel, full-scale experiments and computational fluid dynamics).

Keywords— hurricanes; mitigation strategies; wind tunnel test; computational fluid dynamics.

I. INTRODUCTION

The wind is unpredictable and threatens the safety of structures. During periods of strong winds, currents can change direction without warning, exerting pressure on the surface of the structure and can topple it, overturn it, or raise its foundation [1]. The maximum wind speeds occur regularly when a hurricane, typhoon or tropical cyclone occurs [2]. A hurricane is an atmospheric disturbance in the warm waters of the tropics during the summer and fall with winds sometimes reaching speeds of up to 300 km/h [3]. Its magnitude can be determined based on speed with the Saffir-Simpson scale being category 5 the deadliest.

Mexico, due to its geographical location, is vulnerable to hurricanes in practically the entire coastal zone of the country (Fig.1). According to the last report presented by CENAPRED (Mexico's National Center for Prevention of Disasters), between 2000 and 2021 alone, the costs for natural disasters exceeded 645,000 million pesos, with hurricanes being the natural phenomenon that caused the most expenses during this period. Deaths related to this type of event represent about 30% of deaths caused by natural and anthropogenic disasters [4].

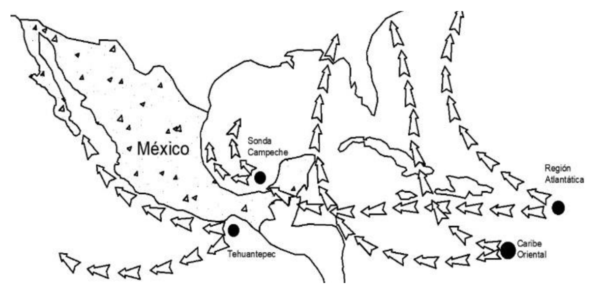

Fig. 1. Trajectory of hurricanes that can hit the Mexican Republic.

Global climate change and warmer ocean temperatures result in hurricanes occurring more frequently and being more intense [5] [6]. Hurricanes spread a series of dangers such as: large gusts of wind accompanied by debris and torrential rains. For this reason, the construction of structures with wind resistant design is gaining great importance considering economic and human losses. The study presented in this article is in accordance with the framework mentioned in the Agenda 2030, whose policies focus on the generation of strategies for the prevention, mitigation and strengthening of the most vulnerable population sector in the presence of natural phenomena.

This study, which is the first part of a scientific investigation, presents what has been done and what is being done to solve complex structural problems in the presence of extreme winds using different methodologies such as: scaled-down and full-scale wind tunnel experiments and the use of Computational Fluid Dynamics (CFD). The most common problems will be addressed in the first part of this paper. Then, the methodologies used by the scientific community to develop research in this area. The different techniques developed to dissipate the effects of wind are then explored: edge modifications, roof geometries, parapets, and house elevations. Finally, discussion and conclusions are presented.

II. PROBLEMS AND SOLUTIONS

A. Wind damage to low-rise structures

Wind loads on residential roofs are characterized by a significant spatial and temporal gradient caused by turbulence in the perimeter boundary layer generated by the structure [7]. The pressures exerted on the roofs of the houses cause suctions which in turn generate the partial or total detachment of the latter, however, some construction components such as coatings, doors and windows are also sensitive to these effects [8].

Other common problems due to the incidence of wind in low-rise structures are: (1) the absence of qualified control which will not allow to take into account that the pressures exerted perpendicularly to the plane in which they act will have a variable impact on the load capacity of the material; (2) the self-construction: widely used process characterized by omitting important construction details in the presence of lateral forces; (3) the use of unconfined masonry, since it has no tensile strength; (4) the use of materials with inappropriate structural capacities; (5) the situations that are not properly considered in national and international construction standards as elevated low-rise structures.

The damages caused by hurricanes in Mexico and other parts of the world is proof of this (Table 1). These events caused millions in losses and took the lives of thousands of people. This has raised the interest of the worldwide scientific community, which uses different techniques to understand the behavior and consequences of the fluid-structure interaction (FSI).

B. Methodologies used

The way to study the effects of wind on low-rise structures through the scientific research sector is practically based on the following methodologies: (1) the use of wind tunnel or large-scale experimentation; (2) the use of CFD simulations. Both methodologies arose as devices to address the need to understand and predict flow-related phenomena, resulting in a large number of multidisciplinary applications.

To better understand what each methodology consists of, a brief description is given. The wind tunnel consists of an installation in which an air flow with controlled characteristics is obtained in a test chamber. In this way the effects of wind on objects or scale models can be determined (Fig. 2). On the other hand, laboratories that allow for full-scale testing have more extensive features. For example, wind speeds are similar to those of a major hurricane, as are the effects of rain and debris (Fig. 3). Finally, CFD simulation can be considered as an analysis of systems involving fluid flow, heat transfer and associated phenomena such as chemical reactions by means of computational simulation [9] (Fig. 4). Navier Stokes equations are usually solved in CFD with the Finite Volume Method (FVM). The Navier Stokes equations describe the physical characteristics of the flow, including a system of five partial differential equations, starting from a fluid in a steady, Newtonian, incompressible and isothermal state, they are simplified in the form of continuity and momentum equations [12]:

$$\frac{\partial u_i}{\partial x_i} = 0 \qquad (1)$$

$$u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + v\frac{\delta^2 u_i}{\delta x_j \delta x_j} \qquad (2)$$

Where v is the kinematic viscosity, defined as viscosity (μ), divided by the density (ρ). There are also a wide variety of numerical solutions that help to determine parameters that the user wants to find ([10] [11]).

Table 1. Examples of destructive hurricanes.

Year	Wind Velocity (km/h)	Hurricane	Countries affected
1955	280	Janet	Mexico
1974	175	Tracy	Australia
1988	298	Gilbert	Caribbean, Mexico, USA
1992	280	Andrew	USA
1998	290	Mitch	Central America
2005	295	Wilma	Mexico and USA
2014	220	Odile	Mexico

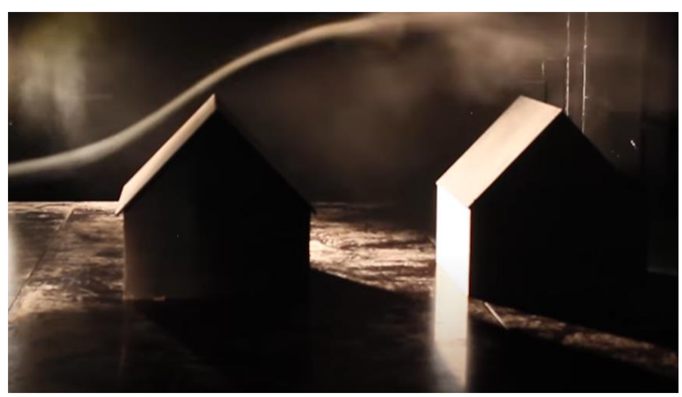

Fig. 2 Test houses in a wind tunnel (Source: https://www.youtube.com/watch?v=UEgk2Bgz16s)

Fig. 3 Full scale wind test in WOW laboratory (Source: https://www.youtube.com/watch?v=kkI0UjmFFDs)

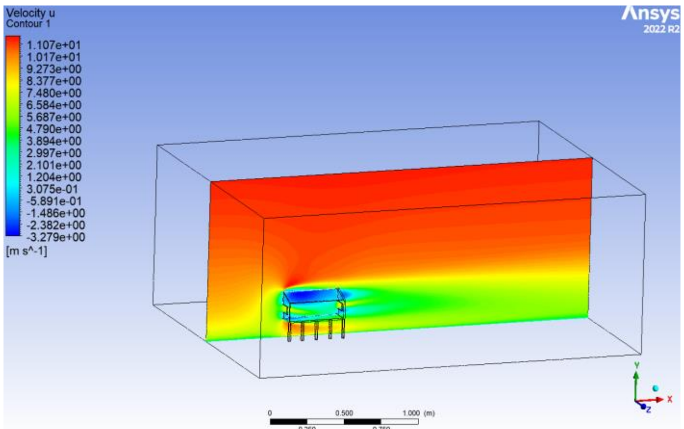

Fig. 4. CFD simulation in ANSYS FLUENT software

III. BACKGROUNDS

As mentioned above Mexico, Central America and the Caribbean are vulnerable to the presence of hurricanes. During these events, valuable field information has been collected to determine common characteristics and problems in the event of large gusts of wind. Hurricanes Gilbert 1988 and Odile 2014 hit the Mexican Republic, leaving great economic and human losses as a result of inappropriate construction regulations and low-performance construction materials. The site investigations carried out by [3] and [13] present a report detailing these events, highlighting the lack of studies to reduce the damage caused. The need for more robust measures against the problems generated by extreme winds in the aforementioned countries is discussed in the reports of [2] and [14] as well as in the work of [15]. To date, it is known which parts of a house are the most vulnerable to extreme winds. In the search for a solution to prevent the collapse of lightweight fiber cement roofs, common in the Caribbean region, [16] presented an investigation to determine the mechanical capacities of the material used through the use of finite method modeling, demonstrating its insufficiency to withstand category 5 hurricanes. This study also provides a simple alternative to stabilize roofs against extreme winds through the use of load slings.

The United States has taken stricter measures in the search for solutions to reduce the damage caused by hurricanes on its coasts, investing in million-dollar projects to carry out cutting-edge research that allows generating mitigation strategies against hurricane risk, with the following objectives: improve construction manuals and standards, development of construction materials and learning of students and researchers in the area. Laboratories such as Wall of The Wind (WOW) and Three Little Pigs were created for this purpose in the investigations of [17] and [18] provides more details about these laboratories. One of the advantages offered by these projects is being able to represent a house with real measurements and typical geometric characteristics and materials used in the analysis region. In [19] improvements for regulations, product safety standards and loss models were proposed.

Other countries have also addressed the issue due to the damage generated by extreme winds: Australia, Japan, India among others, have presented their proposals and initiatives to mitigate the effects caused to low-rise structures. The following sections present the alternatives used in different parts of the structures to reduce wind pressures.

A. Edge variation

Another widely used solution to mitigate the effects of wind is to modify the corners of the structures. Indeed, sharp corners can lead to a separation of the wind flow, which generates high loads induced by the interaction between the wind and the structure. The replacement of 90° corners by aerodynamic shapes had a positive response in high-rise buildings. For example, the Taipei 101 skyscraper (Taiwan) and Mitsubishi Heavy Industries Yokohama (Japan) buildings. Sometimes the modifications do not necessarily have to be complicated because the fact of varying the typical rectangular or square shape by rounded, chamfered, beveled corners, among others (Fig. 5), is a minor strategy that has been used to improve wind performance of tall buildings [20] [21]. On the other hand, there are also more sophisticated or complex ways to make structures more aerodynamic with major structural and architectural modifications. For example, the variation in building form and setbacks along the height, tapering, inclusion of openings in the upper part and twisting of the building, among others (Fig 6). The famous Burj Khalifa skyscraper is an example of the aforementioned method. These types of strategies have been transferred to lower height structures, using the same principle. In [22], different configurations with various edges were explored, highlighting the proposal of an aerodynamic edge inspired by airplane wings to help reduce wind loads. This also helps to interrupt vortex formation and divert the flow from the clearance zone on the roof edge away from weak elements. In [23], a combination of various edges and the implementation of a solar panel as a structural element of the house were implemented, presenting an environmentally friendly mitigation technique.

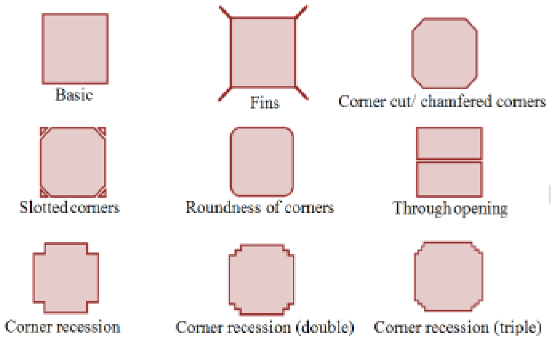

Fig. 5 Simple corner modifications to modify aerodynamics (Source: [21]).

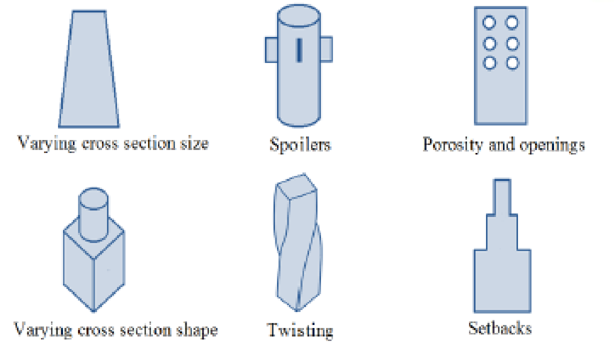

Fig. 6 More sophisticated modifications to improve aerodynamics (Source: [21]).

B. *Roof geometries*

Houses with wooden structures are common in many coastal regions of the world, exposing themselves to large wind loads. There is currently a wide variety of architectural forms for houses and, consequently, for roofs. Partial or total loss of roofs is a common problem in low-rise structures due to the vortices generated in this area. In addition to severely damaging the structure, it also causes water to enter the interior, increasing the costs incurred. This damage is caused by inadequate sheet metal thickness, insufficient fasteners, improper fastening devices and poorly executed construction processes [24]. It has been shown that the angle of inclination, the materials used, the shape of the roof and the angle of incidence of the wind are determining factors in the good behavior of it. The following research works have addressed the improvement of the stability of roof structures. For example, in [25] is mentioned that one of the most vulnerable areas is the roof-wall connection. Since this element is responsible for transmitting and distributing the generated loads, this study determined the possible causes of its failure and listed a series of recommendations for better performance. Nowadays there are many roof shapes, for example: gabled, hipped, pyramidal, flat, spherical, among others (Fig. 7). Their behavior has been explored to determine which factors and characteristics make them vulnerable [26] [27] [28]. It was found that the pyramidal roof presents a better aerodynamic behavior.

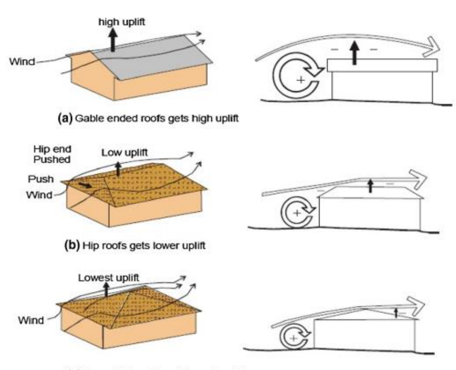

Fig .7 Example of roof geometries (Source: [24]).

C. *Parapets as a mitigation solution*

Parapets play an important role in dissipating the effects of flow during impact with the structure. A large number of studies have been carried out in this regard, exploring a wide range of designs and the use of materials to improve the behavior of this mitigation system. One of the first to carry out studies in this regard was [29], in more recent times the study of parapets has also continued with [30] [31] [32] [33]. Many configurations have been tested including: a) solid parapets; b) porous parapets; c) discontinuous parapets; d) partial parapets, e) perimeter spoiler; f) streamlined edges; among others (Fig. 8). It was found that partial parapets failed to reduce the negative pressures in the corners compared to the case without parapets. In contrast, continuous parapets were found to reduce the maximum pressure at the corners by up to 56% [33].

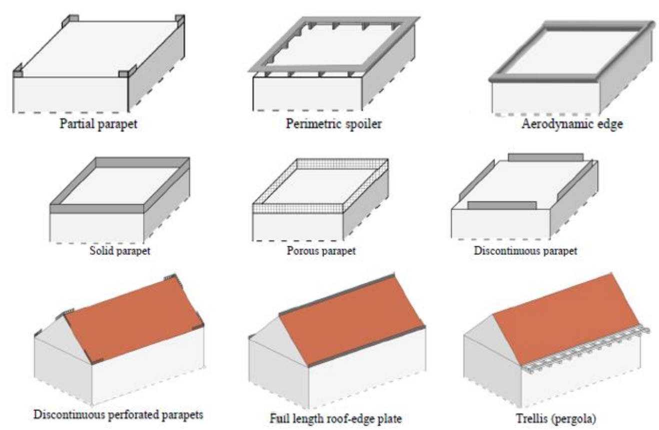

Fig .8 Example of diferent parapets types (Source: [21]).

D. *Elevated houses*

Elevated houses have emerged as an alternative to hurricane damage. They are placed on a pile-type foundations that allows them to rise above ground level. The main purpose of these constructions is to avoid damage caused by floods. The existing variety of this type of construction can be observed in different coastal areas of the world. However, building standards do not provide enough information on wind actions on this type of structure. Recent hurricanes have shown that elevated houses suffer severe structural damage from extreme winds. The most vulnerable parts are the roof and the lower part of the house, due to the significant negative pressures that cause the siding and roof to detach; in some cases, the foundation detaches from its location. For more information on this damage, see [12]. For this reason, several researchers have been working on the subject trying to make this strategy an option to combat the ravages of both flooding and extreme winds. In [34], tests were carried out in a wind tunnel with a scale model (1:100) of a common elevated house in the Australian coastal area, finding that raising the house increases the average pressure coefficient on the face surfaces by 30%. The proposal of an innovative technique in the design of a house at a ground level, with the ability to rise when exposed to flooding (Fig. 9) is presented by [6], also showing good behavior against the effects of wind. The study in [12] showed that different configurations provided a better understanding of the behavior of elevated houses, recommending the continuity of more variables and mitigation techniques to improve stability against wind pressures. In [35], different configurations with different elevations were presented to determine the effects in different parts of the house.

IV. Discussion and Conclusion

As it has been shown, there is a wide field of research regarding the different techniques that allow the dissipation of wind pressures on low-rise structures. All the techniques described above were carried out using methodologies such as: wind tunnel, laboratories that allow full-scale experimentation and CFD simulations. It should be noted that each of these techniques has its own advantages and disadvantages. However, recently, thanks to advances in computer science, CFD methodology has developed considerably, allowing the generation of reliable and accurate simulations. By obtaining results similar to experimental findings, this advantage has allowed for cost and time optimization, which are extremely valuable elements in research and industry.

Despite efforts by researchers to find mitigation strategies to improve structural stability, there is still a long way to go. Currently, more than 50% of the world population lives within 200 km of the coast [36]. In 1996, [35] estimated that by 2025 approximately 70% of the world's population will live within 200 km of the coastal zone. His research focus is extremely important for Mexico and the world. In Mexico, the problem of houses built with precarious materials is added to the problems posed, for example, by the issue of elevated houses or angles of wind incidence other than 0° or 90°, which are not covered by existing standards, as well as by the insufficient scientific research in this area.

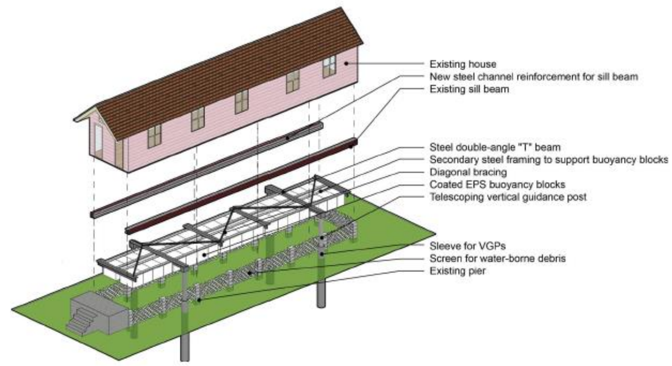

Fig .9 Amphibious house (Source: [6]).

Therefore, this work aims to: (1) arouse the interest of students and researchers in the field by showing some of the efforts of various authors to find a solution to a growing problem as well as the use of existing methodologies to address the issue; (2) establish the research baseline proposal for the coastal zone of the Mexican Republic using CFD that allows exploring new ways to optimize cost and computation time.

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