Wind Loads on Architectural Attachments

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Introduction

Wind loading affects every element of a building, and wind loading analysis helps in determining the final structural design of the building. From low-rise structures to high-rise structures, wind effects are apparent in both structural and non-structural components. This paper will address the non-structural components as architectural attachments, where those attachments compose a façade of a building to add complexity and also appease the viewers. Some architectural attachments also provide wind mitigation to a structure and some transfer wind loading to the structure. Examples of these architectural attachments include railings, fences, curtain walls, columns, awnings, artwork, stained glass windows, and canopies. Most of these architectural attachments do not provide any wind load mitigation or transfer any loading, but they are installed to either provide comfort or safety for the users.

This paper will first focus on the theoretical side of wind loads and what types of winds are known that could cause major discomfort and damage to both structural and non-structural components. These types of winds vary from primary to secondary winds, where the most prominent in South Florida are hurricanes. Then, architectural attachments will be defined and how wind loading impacts them. ASCE 7 will also be discussed, most specifically, its application when designing architectural attachments and when analyzing wind effects in the southeast region of the United States. Ways to mitigate wind loading will be elaborated through specification of materials or structural components that can be used to reduce wind effects. Finally, two different applications where architectural attachments were utilized and how wind loading impacts them will be discussed. Both applications, the Royal Caribbean Cruise Terminal at the Port of Miami in Miami, Florida and the Student Academic Success Center (SASC) at Florida International University (FIU) at Miami, Florida, have architectural attachments on the buildings. Such attachments include curtain walls, railings, columns, and canopies.

Types of Winds

There are many types of winds that contribute to the wind loadings that engineers must design and consider. One type of wind to consider is local winds. Local winds are types of wind that are only prevalent in a specific area and specific to local geography. Local winds include events such as tornadoes and thunderstorms. These types of storms are prevalent to certain areas and are highly dependent on the local changes in temperature and pressure (Flexbook). Local winds are important factors to consider when designing, especially in areas that experience these events, such as South Florida. Thunderstorms are formed from the combination of isolated storms and advancing cold fronts resulting in severe winds (Holmes, 34). When moist and dry air is combined, convection occurs by letting cold air rise and warm air sink. This contributes to the formation of thunderstorms, where the cold air begins to condensate resulting in rain or hail (Holmes, 34).

Tornadoes are storms with the strongest convection cells. This is due to the longevity of their convection cells compared to the normal and ordinary convection cells (Holmes, 34). Tornadoes can cause severe damages due to the narrow path and strong intensity of the windstorms; this is due to the vertical funnel shaped clouds that are formed in thunderstorms. Additionally, tornadoes have short storm lives in which they are only able to travel up to 50 km before disappearing, thus making them local winds. Tornadoes are prevalent in selected areas but mostly in the midwest of North America. The winds produced by tornadoes are hard to be measured due to the severe wind speeds and short life, but the Fujita Scale of 1971 has been adopted to help classify these types of storms. The Fujita Scale classifies tornadoes based on wind speed ranges that is based on the observation of damages onto structures. Although the Fujita Scale is used to help identify the scale of tornadoes, it has experienced bias due to the lack of consideration of other factors such as contractibility of structures and the damage descriptions (Holmes, 34).

Another type of wind to consider are primary winds, also known as prevailing winds. Primary winds are permanent and exist throughout the world. They mainly blow over oceans and continents. Primary winds are also heavily dependent on the heating and cooling of land. This is because land can experience extreme weather conditions compared to the ocean, where the weather conditions occur gradually (Global Security, 3). Common examples of primary winds include the trade winds and easterlies, as shown in Figure 1.

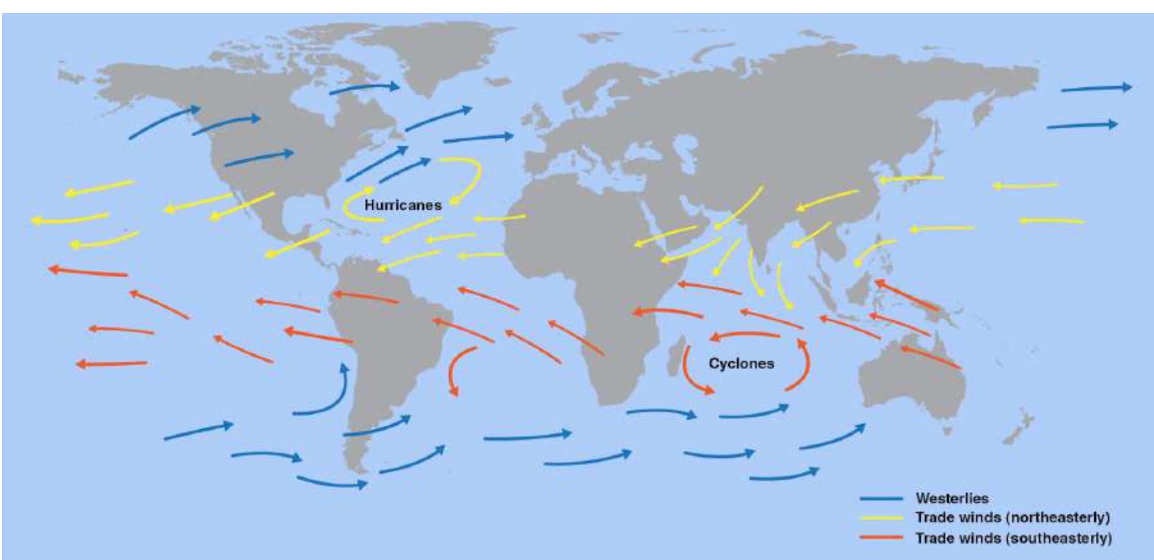

Figure 1. Types of Winds and Their Paths of Circulation (Source: NASA/JPL-Caltech)

The last type of wind to consider when designing are secondary winds. These winds include events such as hurricanes, which are prevalent in the Atlantic Ocean especially in areas such as the Caribbean and southeast United States. These wind developments are also referred to as cyclones in the Northern Indian Ocean and typhoons in the Western Pacific Ocean (NOAA). Hurricanes are storms that are formed when warm humid air and warm ocean water are prevalent. Hurricanes gain energy as access to warm ocean water and humid air becomes more available. Hurricanes are classified using the Saffir-Simpson Hurricane Wind Scale to help identify the severity of the storm (ASCE 7-16). The hurricane is then monitored and classified on a scale of 1 to 5 based on the sustained wind speeds (NOAA). This scale is also used to estimate the amount of property damage caused by the hurricane. According to the National Hurricane Center, winds exceeding 111 mph, category 3 or higher, are considered major storms that can result in significant damage and loss of life. While category 1 and 2 storms are dangerous but produce little to extensive damage (NOAA).

All these types of winds can have an impact on low-rise and high-rise structures. It is important to be able to identify all the types of possible weather events that can impact a structure's integrity based on the loading that it will sustain. Being able to identify specific winds that would impact a structure could also help engineers design for extreme weather events such as 50-year and 100-year events.

Wind Impacts

Wind Uplift

There are many different factors that should be considered when designing a structure. These factors are the different types of winds and their impacts on the building. Wind effects that can be seen on a structure are lateral loading, shear loading, and wind uplift as well. When considering these loadings, specifically on elements of architectural attachments, they ultimately have an impact on the design of a structure.

According to ASCE-17, wind uplift is a design parameter that considers factors of safety to reduce the peak pressure within a structure (ASCE-17). Wind uplift can be detrimental to a structure considering severe wind loads and pressure that can act upon it. When designing a structure for wind uplift, the aspect of a structure that must be considered is the roof since it is most susceptible to uplift. Components to consider when trying to reduce the uplift experienced by a structure include, but are not limited to, roof shape, roof slope, material used, framing connections, the continuous load path, roof sheathing, framing, load path for shear transfer, and eccentricities. Although these aspects are general, they are essential to reducing the risk of uplift which is influenced by architectural attachments chosen for a project.

When considering uplift, the shape of a building is an important contribution toward the mitigation of wind pressure along the roof and walls that maintain the structural integrity of the building. According to FEMA in “Making Critical Facilities Safe from High Wind,” building aerodynamics is a large contributing factor to prevent wind uplift. In addition, the location of the building is crucial during the design stage of the building. Design aids that are used to help design these buildings to sustain a certain amount of wind include figures from ASCE 7-16: Wind Load Provisions. Figure 2 illustrates the sustained wind loads that should be considered based on a region within the United States.

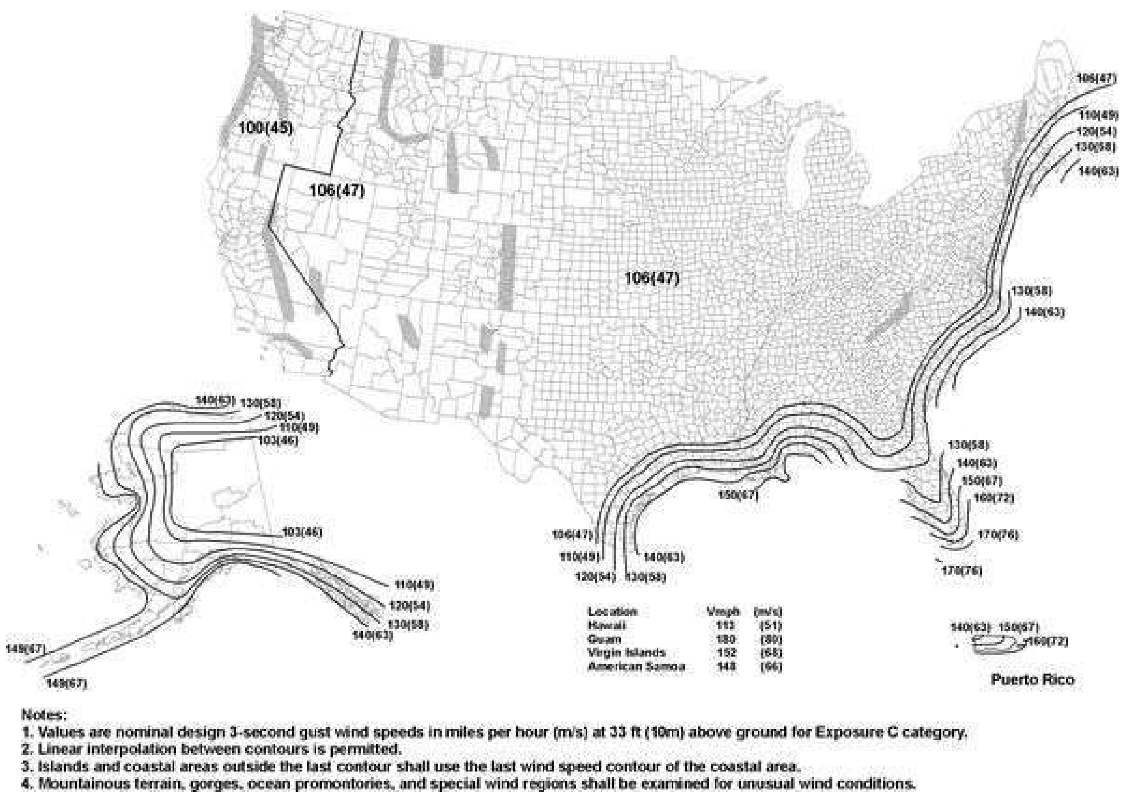

Figure 2: Wind Speed Map (Source: Vickery, Peter J. ASCE Library)

While architectural attachments improve the aesthetics of a building, some attachments can help mitigate loads caused by different types of loadings. According to the article “New Design Procedure for Wind Uplifting Resistance of Architectural Metal Roof” published in the Journal of Architectural Engineering, it is important to design while considering an architectural metal roof on a wooden deck system, where metal is a material chosen that would prevent the roof from uplifting. This material helps in the reduction of the leakage ratio, which would allow less winds to creep through the seams of the roof. The study evaluated the different types of leakage ratios on the same metal architectural roofs in Canada. In this study, design parameters were simulated based on weather experienced in the region. In concluding the study, it was determined that air permeability of the structural deck is another contributing factor when designing architectural metal roofs for buildings (Baskaran, et.al, 11).

Lateral Winds

Another aspect that should be considered in design is lateral wind loading on architectural attachments and on structures. When designing with lateral winds, maximum wind gusts are crucial to help analyze the loading a structure will experience (Brownjohn, et.al, ASCE). This can be very hard to calculate considering a structure does not have a traditional shape, or if winds cannot exit easily from structures, one example being parking garages. Although simulations and calculations can be done to help determine the lateral loading on a structure, it allows space for uncertainty when quantifying these parameters.

A study featuring an analysis of a full-scale dynamic response of a slender, high-rise building located in Singapore was conducted. The final response of the structure shows that the building experiences wind and lateral loading based on collected local wind characteristics. When considering these lateral wind loads, some characteristics that were considered were the natural wind frequencies relative to the region, mode shapes, longitudinal response, wind angles, torsional frequency, and damping ratios (Brownjohn, et.al., ASCE).

Wind Shear

Wind shear is defined as the change of wind speeds and/or direction over a short distance (FAASAFETY). Wind shear can occur laterally or longitudinally in many different weather events. In addition to wind shear, other components that should be considered is torsion. All types of structures from low-rise to high-rise buildings cannot avoid wind shear and are designed appropriately to help reduce the effects felt by the structure. The amount of wind shear a structure experiences depends on the frequency and strength of winds relative to the area. Therefore, the analysis and design process for structures depends on the conditions prevalent in the area in which the structure will stand. To ensure safety, a multitude of factors are considered when designing, and these include, but are not limited to, the shape of the structure, local wind gradients, topography, and dynamic properties. With the use of ASCE 7-16, established parameters contribute to the safety factor when considering the multitude of variables to consider in the design of a structure.

Many studies on the shear wind load effects on buildings have been conducted to help other engineers understand the relationship and effects of these loads on structures with varying heights. In the article “Experimental study of wind-induced shear, bending, and torsional loads on rectangular buildings'.” tall rectangular buildings of different elevations were tested within wind tunnels to help analyze the effects of wind flow prevalent in the area while featuring surrounding topography and other obstacles such as other structures (Guzman-Solis, et al). This study was spearheaded by the National Autonomous University of Mexico in their wind tunnel laboratory. The study considered 19 different wind patterns and 2 terrain categories within Mexico. Ultimately, the wind tunnel determined the different coefficients for shear, bending, and torque. This study helped develop maximum shear and bending coefficients for the models that were tested based on the parameters relative to the region.

Architectural Attachments

What They Are and Common Examples

Architectural attachments are elements that are typically installed on the exterior walls or roof of the structure, or they can be installed on the ground outside within the property of the structure. Architectural attachments are incorporated into the design of buildings and structures to provide visual enhancement. They may be used for aesthetic purposes, structural support, and/or mitigation of wind loads. Some examples of architectural attachments are railings, fences, gates, curtain walls, columns, spires, gazebos, sunshades, awnings, parapets, trellises, canopies, artwork, and more. An example of a railing, a trellise, sunshades, and artistic attachments are shown in Figures 3, 4, 5, and 6, respectively. Figure 6 depicts the Miami Museum Garage, which is an extraordinary structure in Miami composed of various, unique façade elements throughout the exterior of the structure.

Figure 3: Example of a Railing (Source: Decks.com)

Figure 4: Trellise On a Building (Source: Gardeners.com)

Figure 5: Architectural Sun Control (Sunshades) (Source: Hendrick Architectural)

Figure 6: Miami Museum Garage (Source: Diamond, R. Miami Design District)

Architectural attachments must be strong and secure to be able to resist strong local and hurricane wind forces. Wind loads are a critical aspect to consider when designing a structure, especially in South Florida where high wind speeds and hurricane events occur.

<u>Measurement of Wind Loads</u>

Wind is an important factor that must be considered in the design of structures. Wind is a strong force of nature that affects all structures and its components. Wind forces acted upon structures exert pressures on the surface. The wind pressures acted upon a structure depend on the shape, size, and orientation of the structure and its components and openings (e.g. attachments, windows, and doors), the speed and direction of the wind, the height of the wind loading in reference to the ground level, and the location of the structure and its surroundings (Dryden, Hill, 699). The distribution of wind pressures over a structure depends on the interaction between the structure and the wind flow (Dalgliesh, W.A., MIT). When wind loads are applied to a structure, the wind separates and passes around the structure. Figure 7 illustrates how streamlines pass a building. These wind loads can produce high suction pressures. Architectural attachments can unexpectedly experience suction pressures higher than its surroundings and cause large effects on the wind pressure distribution (Dalgliesh, W.A., MIT). To assess these effects, engineers and researchers test a model of the structure in a wind tunnel laboratory.

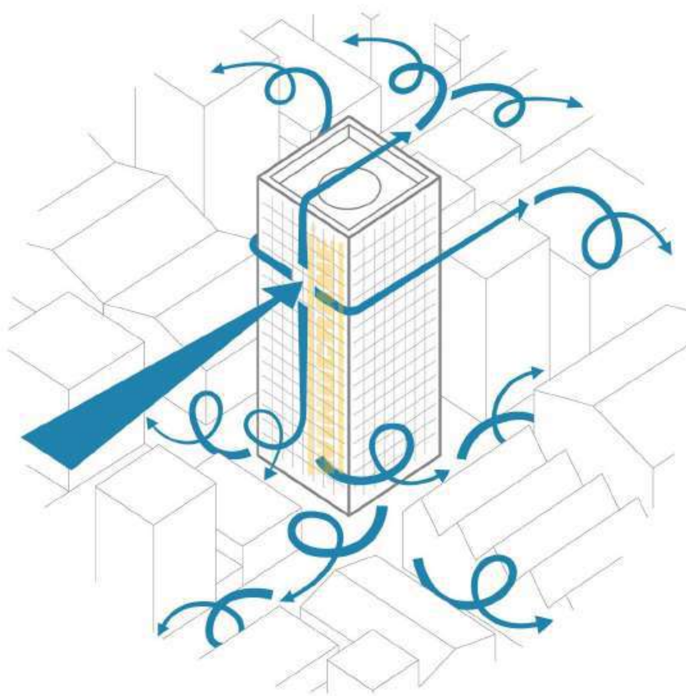

Figure 7: The Effect of Wind Flow On a Building Located in A City (Source: WindCrane)

Wind tunnel laboratory tests are the most common method used to measure wind loads and analyze its effects on structures (Mans, Kopp, Surry). In a wind tunnel study, a model of a structure of interest is subjected to wind forces designed to simulate the existing wind conditions within the geographic location of the structure. In some wind tunnel tests, the model is instrumented with pressure taps to determine the static pressures exerted on the structure by wind loads (Wind Tunnel Testing, NASA).

However, it is difficult to accurately measure and analyze the wind loads that act upon architectural attachments due to the small size of architectural attachments compared to the dimensions of the larger structure to which it is attached to. Due to this constraint, it is not common to directly test wind loads on architectural attachments in wind tunnel studies. However, the wind pressures exerted on the nearby building surface can provide useful information about the wind loading on the architectural attachments (Mans, Kopp, Surry).

For architectural attachments located on the face of the building that experiences the least local winds, the wind pressures exerted on the attachment can be assumed to be equivalent to the wind pressures of the nearby building surface (Mans, Kopp, Surry). On the contrary, in areas of strong local winds, the wind pressures exerted on the structure and its architectural attachments vary significantly. The wind pressures on the architectural attachments cannot be assumed to be equivalent to those of the nearby building surface, and they cannot be directly measured using pressure taps in a wind tunnel laboratory. These pressures are required to accurately calculate the wind loading on the attachments, thus, alternative techniques must be used.

Two alternative techniques to measure wind loads on architectural attachments are smoke visualization and direct measurement of wind flows through hot-wire anemometry. Hot-wire anemometry involves placing hot-wire anemometers on the model in the proximity of the existing architectural attachment without the attachment included in the model to measure and record the peak wind pressures. Then, the wind loads acting on the architectural attachments are estimated using existing aerodynamic coefficients obtained from literature (Mans, Kopp, Surry). Another technique used in the field by engineers and researchers is smoke visualization. Smoke visualization involves injecting smoke in a wind tunnel to visualize how wind moves across the surface of the model. Smoke visualization is an old technique used in wind tunnel studies to detect vortices and regions of separated flow (Smoke and Tufts, NASA).

In summary, hot-wire anemometry and smoke visualization techniques can be used to accurately measure wind loads on architectural attachments that cannot be evaluated using traditional pressure tap instruments in a wind tunnel laboratory or estimated using the pressure measurements of the nearby building surface. In the following three sections, three types of architectural attachments and their details in which they are designed and constructed against wind loads will be discussed.

Curtain Walls

A curtain wall is a non-loading, bearing cladding system anchored to the exterior of a structure (Wheaton, AISC). Unlike a typical window system, curtain walls are installed on the exterior of a structure rather than fitted into the structure. The One World Trade Center, shown in Figure 8, is an excellent example of a well known curtain wall system. Curtain walls can be made of any combination of glass, panel, or stone, and they are supported by aluminum or steel structural framing members called mullions. Horizontal and vertical mullions join the glass panes of the curtain wall together and act as structural members that transfer wind and gravity forces to the perimeter of the structure. The forces imposed by these wind and dead loads vary greatly depending on many factors, including the type of system and materials used and the wind pressures and loads exerted on the building. Dead loads and anchors of glass curtain walls typically provide 1,000 to 1,500 pounds of force, and wind loads can range between 2,000 to 6,000 pounds (Wheaton, AISC). These estimated dead loads are based on the normal weight of curtain walls, which is about 8 to 10 lb/ft^2 (Wheaton, AISC).

Figure 8: Example of a Curtain Wall System (Source: Shapiro, G. Architect Magazine)

Furthermore, full-scale models of curtain wall systems are required to be tested against hurricane forces prior to installation to verify the performance of the system. The system must pass the impact test as established by ASTM E 1886 and E 1996 (Stuart, PDH Online). This test simulates hurricane wind speeds and pressures, debris impact, and water infiltration. Curtain walls are constantly exposed to the atmosphere and wind forces, so they must be properly designed, installed, and maintained to improve the durability of the structure and elongate its service life.

Moreover, glass, as likely inferred, is the weakest component of the curtain wall system. The impact strength and load resistance of the glass panes can be increased by selecting laminated glass materials containing structural PVB interlayers or multi-ply polycarbonate plies (Stuart, PDH Online). Laminated glass containing multi-ply polycarbonate plies are more suitable for higher wind loads. Another option to increase the durability of the glass panes is to select a thicker glass material, or increase the width of the mullions. In addition, specific resistant levels (low, medium, or high) of mullions and glazing materials can be selected to improve the load resistance of the curtain wall system (Stuart, PDH Online).

Stained Glass

An architectural attachment that is typically used in churches are stained glass windows, an example of them shown in Figure 9. These architectural attachments are windows in art form. Typically, stained glass windows do not provide the structure in which they are attached to any type of support and are mainly for aesthetics. Stained glass windows are designed with a standard wind speed of 90 mph, but can be engineered and manufactured to withstand wind loads from 110 mph to 150 mph (eganchurchfurnishings).

Stained-glass windows have their own reinforcement to hold the different pieces of glass together. Older generations of stained-glass windows have utilized wood as support. Nowadays, typical stained-glass windows use steel reinforcement bars and copper ties for the frame of the window. When designing these elements, it is crucial that every reinforcement bar, copper tie, and glass are attached properly or the integrity of the window will fail. The purpose of the internal structural system of these glass windows is to help transfer the weight of the glass of the upper panels towards the bottom without causing the whole system to collapse (NPS). In addition, the incorporation of steel reinforcement bars allows for flexibility to avoid any type of damage in occurring on the frame of the window caused by the expansion and contraction due to weather events.

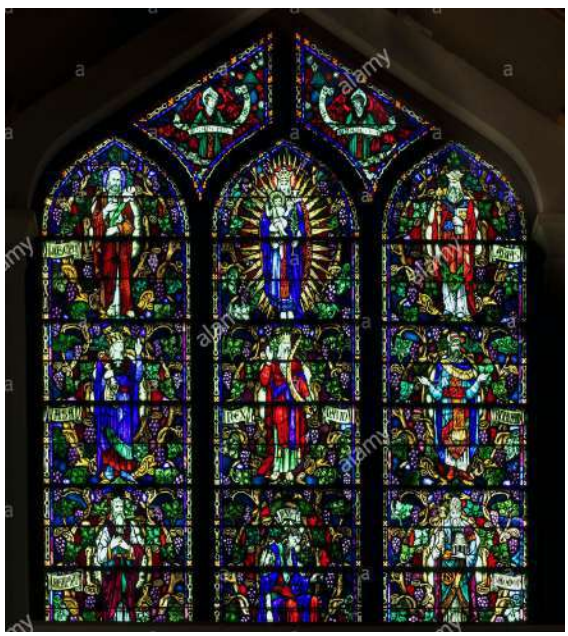

Figure 9: Stained Glass in a Church (Source: Key West, St. Pauls Episcopal)

One viable solution to protect the windows from wind pressure is protective glazing. Protective glazing is used to protect the architectural attachment by reducing the amount of maintenance, reducing the amount of energy the structure will use, and protecting against harmful lighting such as Ultraviolet Light (NPS). The disadvantages of using protective glazing is that when installed improperly, the service life of the window is significantly decreased due to the reaction of the glaze. In addition, when installing protective glazing on the architectural attachments, proper ventilation is also required.

This will help extend the service life of the stained-glass window without destroying its aesthetic appeal (NPS).

Another viable solution to protect windows from wind is installing vented protective coverings. According to Egan's Church Furnishing and Restorations, a contractor that specializes in stained-glass window manufacturing, installation, and restoration suggests that a ventilated protective covering installed over stained-glass windows can reduce the amount of moisture the window may be exposed to. Thus, it extends the service life of the architectural attachment by protecting it from rotting (eganchurchfurnishings).

Canopies

Canopies are considered an architectural attachment that could be either a free-standing element or be attached to a building structure. Canopies are usually added to a building for aesthetic purposes, but they can also protect an entrance of a building or a specific area from rain, dust, and wind. There is not much information regarding canopies in codes for structural design, but they are still considered as "Components and Cladding" in ASCE 7-16 for design purposes (Reddy, Medapati). ASCE 7-16 provides guidelines for canopy design for buildings with an overall height less than 60 feet, so high-rise structures are not considered. Although, when engineers design a canopy that does not satisfy this requirement, wind loads are overestimated (Reddy, Medapati). Most importantly, for canopies satisfying this requirement, an upper surface pressure and a lower surface pressure on the canopies are accounted for, and the two loads are used to obtain a net pressure (Reddy, Medapati).

The location of the canopies on the building and the shape of the buildings are aspects that should be considered when designing to avoid any damage on the architectural attachment after wind loading is applied. The height of the canopy and the height of the face of the building where the canopy is attached are factors towards the final downward pressure that acts on the canopy. When wind hits the face of the building where the canopy is attached, a downward force is applied to the top of the canopy and an upper surface pressure results. Uplift forces acting on the canopy are caused by an upward force, which results in a lower surface pressure. When both loads act simultaneously, a net pressure results, as previously stated. All cases are stated as shown in Figure 10.

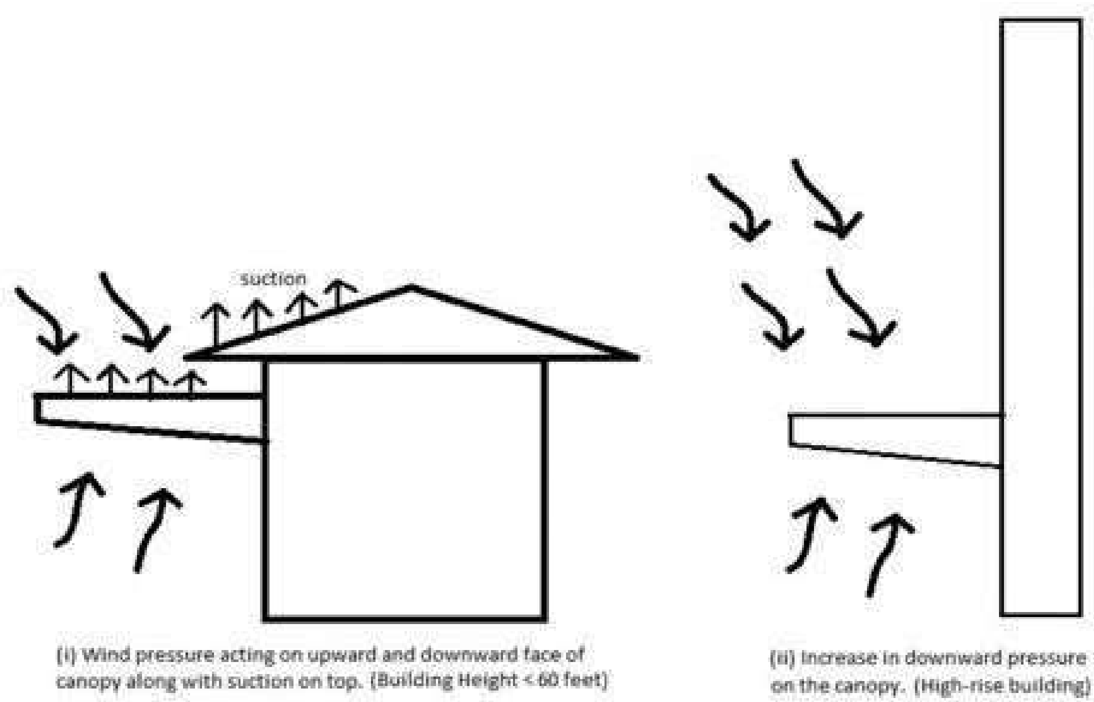

Figure 10: Wind Impacts on Canopies (Source: Reddy, Medapati)

ASCE 7

General Introduction

ASCE 7, a standard that provides criteria for the design of structural and non-structural components, states all the general requirements for the analysis of different types of loading and other provisions considered to design strong and durable structures (ASCE 7-16). The standard is a necessary tool that helps in determining the impacts of wind loading on components for low-rise buildings, mid-rise buildings, high-rise buildings, and on architectural attachments. This standard also provides wind hazard maps, also known as wind speed maps, to assist engineers in evaluating risk categories that vary with the consequences of failure of a structure, as stated in Figure 11 (ASCE 7-16). The figure specifies the annual probability of failure that depends on the risk category, where failure for structural components is usually sudden and causes widespread damage, for example (ASCE 7-16). If the structure falls under a certain risk category, then the annual probability can be deduced. Risk category II, in specific, is used as a basis with a 50-year reference period obtained from ASCE 7-16. Another criteria that is found in ASCE 7-16, and one that engineers use, is the design strength and how one can calculate it. Both Allowable Stress Design (ASD) and Load and Resistance Factor Design (LRFD) are specified (ASCE 7-16). With ASD, the engineer should design just so the service load applied to the structure does not exceed the allowable stress. The method to deal with uncertainty in this type of design is utilizing a factor of safety, typically 0.6 (ASCE 7-16). With LRFD, load factors are utilized to find the required strength of a structure, and resistance factors are used to approach uncertainties in variable loads applied to the structure. Nominal capacities are used to deal with uncertainties in material properties and construction tolerances (ASCE 7-16).

	Risk Category			
Basis	I	II	III	IV
Failure that is not sudden and does not lead to widespread progression of damage	$P_F = 1.25 \times 10^{-4}$/yr $\beta = 2.5$	$P_F = 3.0 \times 10^{-5}$/yr $\beta = 3.0$	$P_F = 1.25 \times 10^{-5}$/yr $\beta = 3.25$	$P_F = 5.0 \times 10^{-6}$/yr $\beta = 3.5$
Failure that is either sudden or leads to widespread progression of damage	$P_F = 3.0 \times 10^{-5}$/yr $\beta = 3.0$	$P_F = 5.0 \times 10^{-6}$/yr $\beta = 3.5$	$P_F = 2.0 \times 10^{-6}$/yr $\beta = 3.75$	$P_F = 7.0 \times 10^{-7}$/yr $\beta = 4.0$
Failure that is sudden and results in widespread progression of damage	$P_F = 5.0 \times 10^{-6}$/yr $\beta = 3.5$	$P_F = 7.0 \times 10^{-7}$/yr $\beta = 4.0$	$P_F = 2.5 \times 10^{-7}$/yr $\beta = 4.25$	$P_F = 1.0 \times 10^{-7}$/yr $\beta = 4.5$

Figure 11: Annual Probabilities based on Risk Category and Type of Failure (Source: ASCE 7-16: Table 1.3-1)

<u>Non-Structural Components (Architectural Attachments)</u>

Several risk categories are used interchangeably when designing nonstructural components, otherwise known as architectural attachments. Risk category II and III are typically used in the design of architectural attachments, where these attachments have to undergo wind tunnel testing to evaluate their strength and how they act on a structure, and especially, design the attachments to remain essentially elastic (ASCE 7-16). The risk categories obtained from wind maps provide the type of wind loading the components will be subjected to, so this wind loading is used in determining how many tests and what types of tests should be performed in a wind tunnel study (ASCE 7-16). Different failure modes, the complexity of the architectural attachment's behavior, the consequences of this failure, and the behavior variability also help in determining how many tests and what types of tests should be performed in a wind tunnel study. Nevertheless, structural systems should be composed of attachments that have adequate strength, stiffness, and ruggedness after they are attached to the structure to ensure that these components don't fail under certain types of wind loading that vary in different regions, as shown in wind maps (ASCE 7-16).

Mitigation

Mitigation is defined to be the reduction in severity or seriousness of something (Merriam-Webster). When considering the event in which severe weather events occur, designing a structure to be able to withstand the elements may be difficult. The two main solutions to mitigating wind loads on tall structures are architectural and structural. Some options that have been considered to help mitigate wind loading a structure may experience is to consider the shape of the building, the use of plants, weight of the structure, and geometric modifications to increase the aesthetics of the building.

An architectural component that can help mitigate the wind loading on a structure is the use of landscaping. Landscaping within or around the structure provides a series of positive effects. A positive attribute with the incorporation of plants is the mitigation of wind breaks (WindTech Australia). Another positive result with the incorporation of plants is the reduction in energy the building needs.

Tall buildings that utilize landscaping to help mitigate wind loads are called vertical forests. This concept of structures is to increase the amount of structures in fast growing cities by making them more environmentally friendly. A journal article, written and performed by the Department of Civil and Environmental Engineering at Shantou University in China called “Mathematical Model Case and Study of Wind-Induced Responses for a Vertical Forest,” shows that the incorporation of trees into a structure helps reduce the vibration the structure absorbs under wind loads. This project tested two residential towers of different heights with the incorporation of approximately 900 trees and over 20,000 plants built in Milan, Italy in 2014 (Boeri). The second vertical forest that was inspected was built in Lausanne, Switzerland in 2016 with approximately 2,400 plants and 100 cedar trees (Boeri). The third vertical forest analyzed was two high-rises built in 2018 in Nanjing City, China with 1,100 trees and 2,500 plants (World Architects). The final vertical forest was the Toronto Tree Tower (Lynch). In this study, they concluded that tree covers reduced the acceleration of the winds depending on the wind direction, the ability for the trees to absorb vibrations depended on the direction in which the winds were coming from, and equivalent static wind loads were lower when analyzing the vibration absorption factors when tree cover was accounted for (Wang, et. al).

Micro- and macro-leveling are aerodynamic modifications that are precautionary ways to help mitigate wind loads on tall structures. This type of leveling can also mitigate the weight of the structure and cost of construction at the same time. Micro-leveling specifically modifies the architecture by rounding and cutting corners (Alaghmandan, et. al). While macro-leveling considers the whole structure and the geometric shape of it. By utilizing both micro- and macro-leveling, the aerodynamics of the building is also improved (Alaghmandan, et. al).

The structural method to mitigate wind loading is by evaluating the weight of the structure. The reduction in weight caused by the architectural elements helps toward the reduction of the weight of the structure (Longarini, et.al). Engineers will design to use the minimum amount of materials to be able to withstand certain parameters and conditions, but enough material that satisfies the required safety factors, and thus, reduce the overall dead load on the tall building. By analyzing the structure in its entirety, it provides the opportunity to design by optimizing the amount of materials, the shape of the structure, and the variables that guide the design such as damping.

Case Studies

To gain a better understanding of how wind loads affect architectural attachments, structures in the community of South Florida were picked as real-world applications of architectural attachments. We chose to study and investigate the Royal Caribbean Cruise Terminal at the Port of Miami in Miami, Florida and the Student Academic Success Center at Florida International University's (FIU) Modesto A. Maidique Campus in Miami, Florida. These structures were considered to be excellent examples to conduct research based on their various architectural attachments, including glass doors, guard rails, columns, canopies, and curtain walls. To learn more, engineers that played a major role in the engineering design and development of the Royal Caribbean Cruise Terminal and the Student Academic Success Center at FIU were contacted. In the following two sections, findings on these structures will be shared and their differences will be discussed.

Royal Caribbean Cruise Terminal

The first case study that was researched was the Royal Caribbean Cruise Terminal at the Port of Miami in Miami, Florida. A photograph of the Cruise Terminal is shown in Figure 12. This structure is an excellent example of a curtain wall system with the incorporation of unique inclined walls that imitate and resemble the shape of a giant glass crown. The authors of this report had the opportunity to learn more about the specific design and testing of the Cruise Terminal by speaking with Ms. Lianet Rodriguez from Eastern Engineering Group. Eastern Engineering Group is a civil and structural engineering consulting firm in Doral, Florida that provides high quality specialty engineering services of a variety of structural components, including gazebos, trellises, fences, stairs, railings, awnings, and other decorative façade elements. Ms. Lianet Rodriguez, who is a Project Engineer at Eastern Engineering Group, served as the Project Lead for the Royal Caribbean Cruise Terminal project and played a major role in the determination of the structural integrity and durability of the aluminum mullions on the West inclined curtain wall and the front side of the structure.

Figure 12: Royal Caribbean Cruise Terminal Located at the Port of Miami in Miami, Florida (Source: Royal Caribbean Blog)

The Royal Caribbean Cruise Terminal was designed and constructed with precast concrete elements that envelope the building as a skeleton. The structure mainly consists of a curtain wall system attached to the exterior of the structure. The Cruise Terminal is composed of double-insulating laminated glass panes, and the structure is supported by aluminum mullions connected to the structure by silicone joints. The mullions are connected every 16 feet in the horizontal direction and every 4 feet 6 inches in the vertical direction. Figure 13 depicts a project plan drawing prepared by Eastern Engineering Group of the West inclined curtain wall of the structure. The curtain wall system does not provide any support to the structure or mitigation of wind loads to the overall structure, and thus, it primarily accommodates the architectural intent and vision of resembling a giant glass crown. The curtain wall system carries its own weight and transfers gravity and lateral wind loads exerted upon the structure. These loads are transferred to the mullions, which are then transferred to the structure.

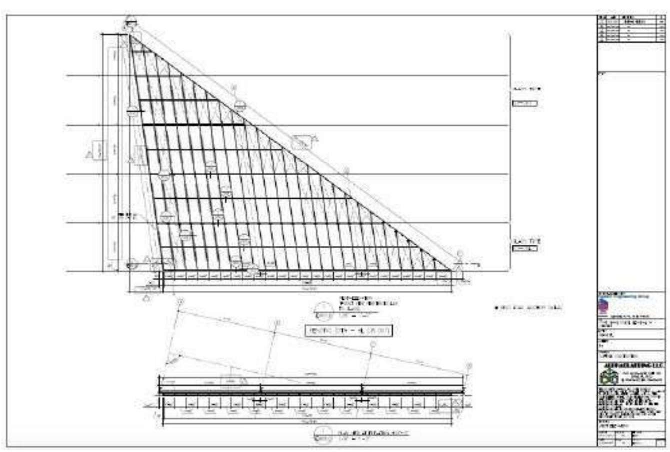

Figure 13: Project Plan Drawing of the West Inclined Curtain Wall of The Royal Caribbean Cruise Terminal (Source: Eastern Engineering Group)

The curtain wall system was designed in accordance with standards established by the Florida Building Code and ASCE 7. Two different safety factors were utilized based on the components, where the design of the skeleton used a Load and Resistance Factor Design (LRFD) safety factor of 1.0 and the curtain wall used an Allowable Stress Design (ASD) safety factor of 0.6. A safety of factor of 2 was also used in the design of the reaction forces because doubling the forces and stresses would also double the strength of the curtain walls and improve the safety and durability of the overall structure. The curtain walls were designed to withstand severe wind effects for up to 700 years with 175 mph winds and stronger.

The curtain wall design was selected from a Florida Approval Notice of Acceptance (NOA), which is a certificate issued and approved by the Miami-Dade County Regulatory and Economic Resources Product Control Section. An NOA certifies the structural integrity and extreme weather impact resistance of specific engineering products designed in accordance with rigorous rules and regulations (K Line Impact). However, the inclined curtain wall system on the West side of the structure did not use an NOA and, therefore, a wind tunnel test of this side of the structure was required to verify that the design meets the Florida Building Code standards and the design can perform successfully under hurricane wind forces.

The wind tunnel study, performed by RWDI Consulting Engineers, was conducted using a 1:300 scaled model of the structure in a 12 foot by 7 foot boundary layer wind tunnel. Figure 14 depicts the model of the Royal Caribbean Cruise Terminal in the boundary layer wind tunnel facility. The wind tunnel test procedures followed the requirements established in Section 31.2 of the ASCE 7-10 Standard. The model of the structure was analyzed under the exposure C category where open terrain was considered in accordance with the design wind load standard for High Velocity Hurricane Zones established by the Florida Building Code and ASCE 7. The Miami design wind speed was used at the ultimate design wind speed in this study, which is a 3-second gust wind speed of 175 mph at a height of 33 feet in an open-terrain environment. The model was instrumented with pressure taps and tested with a scaled model of the existing surroundings within a 1,200-ft radius. The model tested did not include any additional structures or objects, including docked cruise ships or shipping containers, as shown in Figure 14.

Figure 14: Model of the Royal Caribbean Cruise Terminal in the Boundary Layer Wind Tunnel (Source: RWDI Consulting Engineers)

Horizontal and inclined wind components were modeled, and each side of the structure was subjected to negative wind pressures ranging from -50 to -180 lb/ft^2 and positive pressures ranging from +50 to +110 lb/ft^2. Internal and external pressures were applied in the wind tunnel study to determine the net pressure applicable for the design of the structure. The terminal façades received an internal pressure of ± 20 lb/ft^2 and the roofs and soffits received an internal pressure of ± 11 lb/ft^2. The aluminum mullions were analyzed to evaluate the amount of wind loading the members could withstand.

The results of the wind tunnel study found that the wind pressures are not the same on each side of the building. The results indicated that the West inclined curtain wall is the most vulnerable side of the structure because it received the most loads of each load component, as compared to the vertically framed curtain walls. Since the design considered an open terrain environment, the structure was more susceptible to higher wind loads. The wind tunnel study also determined that the curtain wall system needed additional mullion reinforcement due to high wind pressures exerted upon the structure.

The design and testing of the curtain wall system and mullion reinforcement led by Eastern Engineering Group increased the strength and durability of the overall Royal Caribbean Cruise Terminal. The design and analysis performed by Eastern Engineering Group assisted the architect and Engineer of Record in further designing the remaining curtain walls for the structure.

<u>Student Academic Success Center</u>

There are many types of buildings that incorporate a multitude of architectural attachments to its structural design. One building that should be highlighted due to the incorporation of structural and architectural components is the Student Academic Success Center (SASC), as shown in Figure 15, located on the Modesto A. Maidique

Campus at Florida International University (FIU) in Miami, Florida. In order to determine specific details about this building, Scott Martin, who is the Principal at Walter P. Moore, was able to provide details regarding the structure. Walter P. Moore was the company hired for the structural engineering aspects of this project.

Figure 15: Main Entrance of the Student Academic Success Center (Source: Photographed by Ryan B. Ocampo)

Important design details about this project was that a wind tunnel study was not performed because the building was not big enough. Any findings discovered in a wind tunnel study would not result in significant cost reductions. The structure was also designed to have a service life of 50 to 75 years since there were no specifications made by the owner in terms of serviceability. Wind loading on the structure was a huge factor that had to be considered on multiple elements. Since the SASC was an educational facility with high occupancy spaces, building Risk Category III was chosen to pilot the wind load parameters. Engineers designed the building to sustain wind speeds up to 170 mph specified in the Florida Building Code. Fluid dynamics was utilized to analyze the wind effects on the building to determine how the building would respond to extreme wind speeds. This process allowed wind velocity profiles to be developed that helped conclude that the drag coefficients and wind pressures were at its greatest at the top of the building.

Important details provided were that the project was originally designed to have metal panels for walls, but ultimately, precast concrete elements were chosen instead. With precast elements, construction was faster but parameters regarding architecture had to be changed. Due to this change, the columns and beams utilized had to be stiffer to hold the precast concrete walls. This would influence the design parameters for architectural and structural components.

To highlight the different architectural attachments, some elements that can be noticed within this structure are the curtain walls, roof, railings, guard rails, columns, and canopy, where the latter is shown in Figure 16. The engineer specified that the architectural attachments did not provide any type of mitigation or support for the structure and were solely utilized for aesthetics. It was also noted that the railings and guardrails supported less wind load as per code. Nevertheless, the roof and curtain wall system were designed with a 50-year wind speed event.

Figure 16: Canopy at the Student Academic Success Center (Source: Photographed by Ryan B. Ocampo)

Specifically, the curtain wall system was a glass and aluminum system that is designed as part of the structure that spans from the floor to the roof system. In this glass system, cladding was used and required a specific contractor in order to be installed. Cladding is the process of placing one material over another to create this second layer, or what is also considered as a “skin.” The vertical mullions are clipped to the roof and floor, while the horizontal girts are attached to the columns. Mullions added resistance for the curtain wall against wind effects. While the horizontal components, called girts, collected the winds. Ultimately, both components acted as one system.

When discussing wind effects, an interesting feature about the Student Academic Success Center on campus is the overhang. The overhang and the wall near the overhang both received a negative pressure of -173.9 lb/ft^2 of wind loading that flows over the top of the building. While a positive pressure of +149.3 lb/ft^2 flowed under the overhang. These positive wind pressures directly affect the curtain wall and girts as they absorb loads that are transferred to the columns. Another interesting architectural attachment on this building are the side panels that absorb most of the wind loading on the building. While the canopies located at the top of the grass steps were designed to be able to withstand wind effects.

Conversely, the structural components mitigated the wind loading. In order to analyze the loads that each component would sustain, the skeleton of the structure needed to be designed. When designing, the wind loads were governed by ASCE 7 and the Florida Building Code. There were structural components that were specifically designed to combat uplift and shear loads. These components included the precast shear walls located on the north end of the building that take most of the wind loads and transfer them to the structure. While the precast soffits were designed against uplift.

Conclusion

In conclusion, architectural attachments are elements that are built on a structure to either aesthetically appeal viewers, provide wind load mitigation, or transfer wind loading to the structure. Architectural attachments are typically attached to the exterior walls, on the ground outside within the property of a structure, or roof of a structure. Previously mentioned examples of architectural attachments include railings, fences, curtain walls, stained glass, columns, and others that are not so significant. Wind loads are measured on the attachments based on the risk category obtained from wind maps from ASCE 7, which is a standard that states different load combinations, hazard levels, and load characteristics to help discover loading that will act on structures. Performance goals for structural components and nonstructural components are also stated. What is typically used to measure wind loads acting upon a structure are pressure taps. However, wind pressures exerted on the building where the architectural attachments are attached to are utilized as the basis to design the attachment.

Significant architectural attachments that can be seen in various structures are curtain walls, stained glass in churches, and canopies. These three attachments can be utilized to transfer wind loading or solely for aesthetic purposes. Most importantly, there are various types of winds that occur in certain regions in the country, with those winds varying from local winds to secondary winds. These winds make a significant impact on structures with the impacts depending on how loading is applied to the architectural attachments, the physical dimensions of the structure or attachment the wind is applied to, and the terrain where the structure is. Finally, both applications, the Royal Caribbean Cruise Terminal in Miami, Florida and Student Academic Success Center (SASC) at Florida International University (FIU) in Miami, Florida, are excellent examples with architectural attachments. The primary architectural attachment, curtain walls, were designed to transfer wind loading to the main building structure and also appeal to the viewers. The wind pressures applied to the curtain walls vary with the height of the curtain wall, but the curtain walls do not provide any structural support to the actual structure.

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