An Examination of Wind-Related Design Criteria and their Applications in Hurricane Regions

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ABSTRACT

In the design of tall buildings, wind effects can significantly affect a number of aspects of design, but there is often little consideration of the type of wind climate in which the building is located. Wind climates governing the design of tall buildings are geographically dependent. In regions where hurricanes dominate the extreme wind climate, it needs to be recognised that these are unrelated to the parent wind climate. At latitudes beyond those where hurricanes occur, synoptic storms can dominate both the everyday and the extreme winds. It is for buildings in these areas, that many of the current criteria have been developed. Some of these assumptions, and the effects of their application to tall buildings in hurricane regions, are discussed in this paper. Issues relating to more appropriate design criteria for application in hurricane regions are also presented.

INTRODUCTION

Many of the wind engineering criteria used in the design of buildings are used universally, in spite of the different wind climates that exist in different regions. At the current stage of maturity of wind engineering, some differentiation in application of criteria is starting to occur in an almost organic or evolutionary way, but there has been little that has been codified or even published explicitly about the potentially different approaches that can be taken. This paper will discuss some of the considerations that can be taken into account in the design of tall buildings in hurricane-prone regions in order to increase building reliability and economy.

KEY CHARACTERISTICS OF A HURRICANE WIND CLIMATE

The first thing to note about hurricanes is that they are discrete events, and not part of the parent wind distribution at any location in the world. There are few major population centers in the world that will experience more than a few hurricanes (or tropical cyclones or typhoons depending on geography) each year. Of the hurricanes that might be experienced, some will be classified as mild events while some will be more extreme. The intensity that is experienced is a function not only of the strength of the hurricane, but also of the track of the hurricane in relation to the site location. In the outer bands of the hurricane, there is a fairly gradual change in wind speed and directionality. If, however, the eye of the hurricane passes over the site there are much more rapid changes in wind speed and directionality with a distinct lull in the wind speeds as the eye of the storm passes over the site.

Typically, a hurricane will affect an area for a period of 24-48 hours, but the most extreme wind speeds are only experienced close to the eye, and these will last for a few hours at most. With forecasting, the periods of the highest wind speeds during extreme hurricanes are well published and disseminated to the public well in advance of the event. This means that unlike, for example, extreme winds from thunderstorm events, safety measures can be taken to maximise life safety. In most urban locations when strong hurricanes are forecast, commercial activity ceases with publically broadcast warnings to the public to return to their residences, evacuate areas prone to storm surges, or otherwise take refuge in an alternative safe place.

ASSESSMENT OF HURRICANE WIND SPEEDS

Hurricanes are relatively rare events with, at most, a few each year affecting any given location. While there may be sufficient surface-level records in some regions to be able to statistically estimate extreme wind speeds, this is not the case for many places. There are never sufficient records to estimate directionality associated with these wind speeds. The reason for this hurricane directionality is the combination of rotational speed of the hurricane with the translational contribution from the hurricane path. To make up for this lack of data, it is standard practice to run Monte Carlo simulations of tens, or hundreds, of thousands of potential hurricanes to estimate both strength and directionality. This technique is the basis of the design wind speeds along the hurricane coast of the US presented in ASCE7.

At the beginning of wind engineering projects for tall buildings in hurricane regions it is normal to conduct a site-specific Monte Carlo simulation. This simulation will provide the most accurate estimate of directionality at the site. For inland sites this takes into account the changes in structure of the hurricane due to landfall. While for most projects the actual wind speeds are scaled to match local code requirements, it is still possible to make use of the hurricane directionality predicted by the simulation. The directionality of the hurricane events can be very different from the directionality of the parent wind climate. This is shown in Figure 1, which illustrates the directional wind speed ratios for 10-year return period winds from the surface level data and 100-year return period wind speeds from the Monte Carlo simulation for a site in New Jersey. It can be seen that these have fundamentally different directionalities, a design factor that will be discussed in following sections.

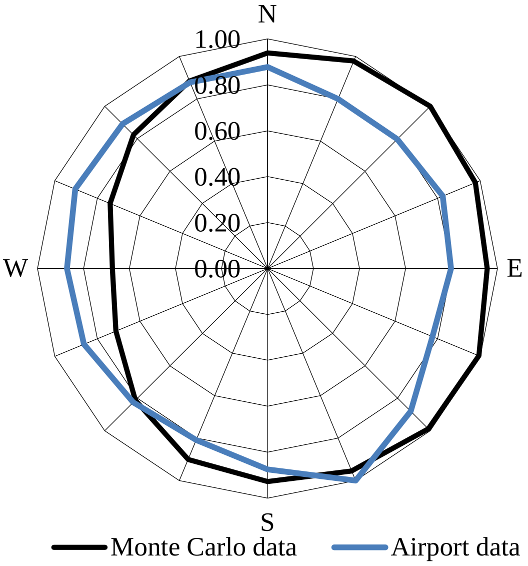

Figure 1: Directionality of 100-year hurricane wind speeds and 10-year non-hurricane wind speeds for a site in New Jersey.

DESIGN STRUCTURAL LOADS

The first part of determining the significance of hurricanes, in the determination of design structural wind loads, is the assessment of their significance relative to the parent wind climate in the extreme wind speeds. Figure 2 shows a graph for Galveston, Texas of wind speed versus return period for the parent wind climate and for hurricanes. It can be seen that the hurricane wind speeds start to exceed the parent wind climate wind speed at a return period of around ten years. This cross-over point changes depending on geographic location and wind direction. It can also be seen that the wind speed increases at a greater rate with return period, in this example, for the hurricane winds than the parent wind climate. The effect of this is that the classic approach used in many parts of the world of predicting ultimate design loads by multiplying a 50-yr or 100-yr load by a load factor can lead to very different levels of reliability. This was tackled in previous versions of ASCE7 by the wind speeds along the hurricane coast having a longer return period that those further from the coast. The wind speeds were based on a 720 year return wind speed divided by the square root of the standard load factor on wind loads of 1.5. In ASCE7-10, the design methodology has moved to an ultimate limit state approach using wind speeds with a return period of 1700 years. This approach has been used overseas in other wind loading standards, such as AS/NZS 1170.2 for a number of years, with the difference that a higher inherent structural damping ratio has been assumed. This can become increasingly important for tall buildings with a significant resonant response, often in the cross-wind direction.

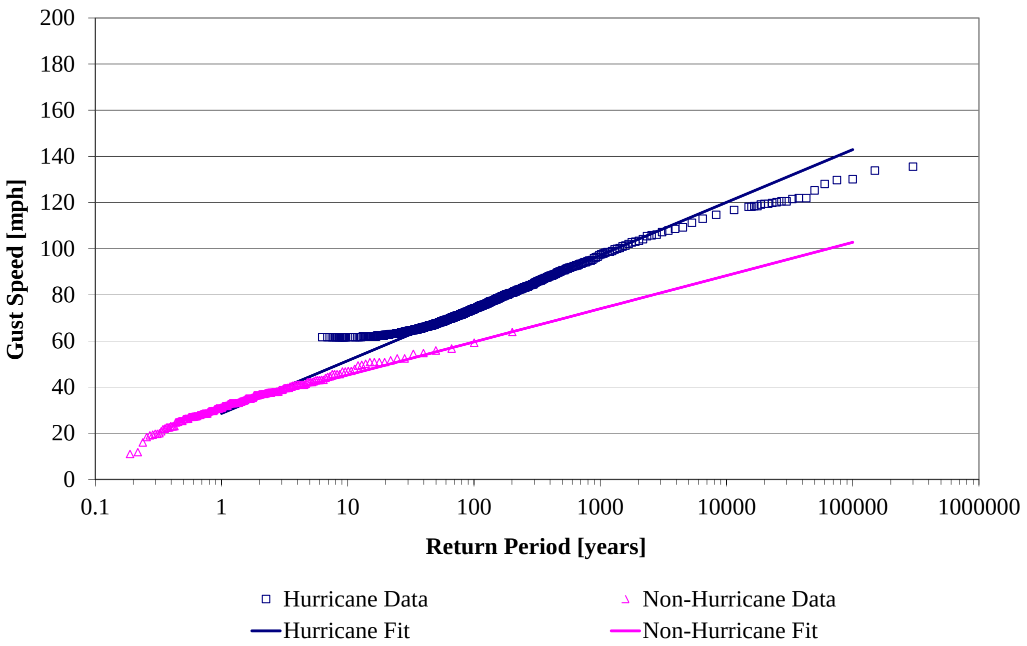

Figure 2: Predicted wind speeds for hurricane and non-hurricane wind speed in Galveston, Texas.

As the hurricane coast in the US experiences the highest design wind speeds, the move to a wind speed with an extremely long return period adds an additional factor, the possibilities that the peak loads on a tall, slender building may occur at a lower wind speed or the rate of change of response can vary dramatically between different wind speeds. This can occur due to cross-wind response where the peak responses due to vortex-shedding excitation occur at a critical reduced velocity which is a function of the natural frequency of vibration, the cross-wind width of the building, and the shape. An example of this is shown below in Figure 3. For the example in Figure 3, as the wind speed approach the critical reduced velocity, the loads on the building were increasing with the wind speed to the power of greater than 3.5. The effect of this is that traditional load factors do not accurately reflect the difference in loads between 50-yr and ultimate limit state wind speeds for tall buildings undergoing cross-wind response and it is important to ensure that neither under-design nor over-design results.

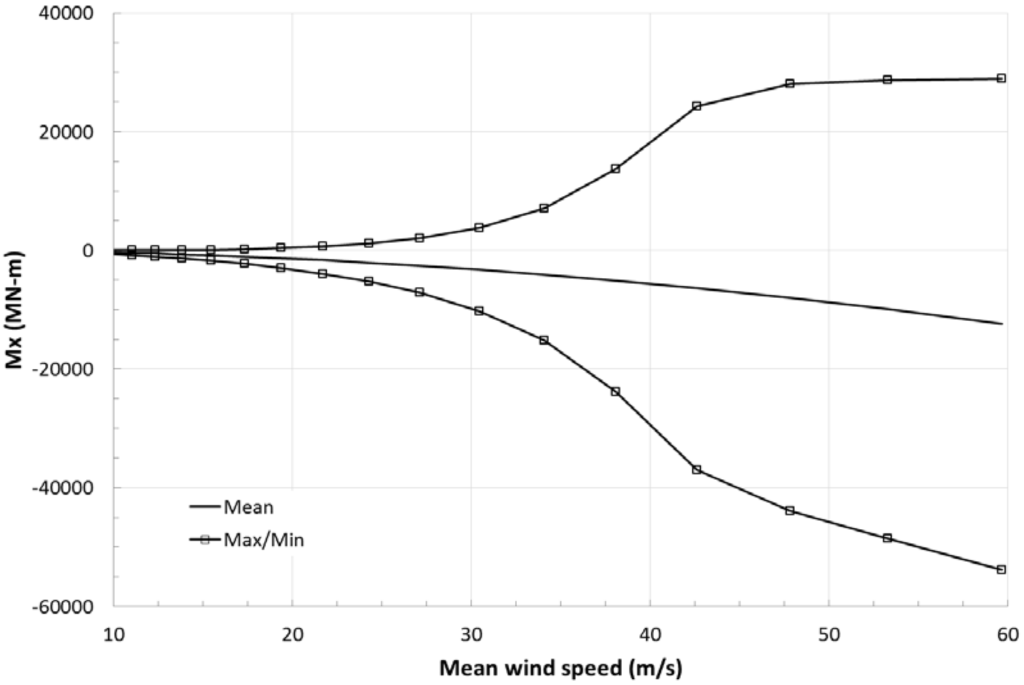

Figure 3: Example of the variation of base moment response with wind speed of a supertall building.

As discussed above, hurricanes have statistically significant directionality associate with them. For slender tall buildings where the characteristics are such that winds cause the lateral loading to be governed by wind, these directional characteristics can be employed to assist the architect with aerodynamic design modifications that can help in reducing loads and responses. In one example, on which the authors worked, the entire tower was rotated in order to decouple the strongest wind direction from alignment with the aerodynamically most-sensitive wind directions. This led to a reduction in loading of over ten percent.

In summary, when designing tall building to resist wind loads in hurricane regions, particular care needs to be taken to ensure adequate reliability. The standard load factor approach taken for pressures and along-wind loads of less dynamically sensitive structures is unlikely to give the same level of reliability when applied to a given return wind speed. If load factors from codes developed in countries without hurricanes are used, the level of reliability in the design is likely to be less than that in the region for which the code was intended. However, the move to ultimate limit state design does not overcome this entirely. For tall buildings, the use of higher design wind speeds can mean that it is more likely that cross-wind (rather than along-wind) loads will govern. ASCE7 does not contain methods for estimating cross-wind loads and the only way to accurately determine cross-wind loads and responses is through wind tunnel testing. Given the ultimate limit state approach, care needs to be taken to ensure that this still results in the correct level of reliability for tall, slender buildings.

SERVICEABILITY ASPECTS OF STRUCTURAL DESIGN IN HURRICANE WIND CLIMATES

One of the more keenly debated areas of tall building design is that of serviceability accelerations and their acceptability to building occupants. This is the subject of a soon to be published monograph by the Tall Buildings Committee of ASCE-SEI. As discussed in this section, the considerations on acceptability can be different in hurricane regions than for areas where the parent wind event causes the largest accelerations.

It is important to understand that there are two factors about perceptible wind-induced motion in tall buildings that need to be accounted for in setting criteria: fear and alarm from extreme event, and annoyance from regular occurrences of perceptible motion. In a hurricane region, the accelerations that are large enough to cause fear and alarm are most likely to occur during hurricane events, while the hurricanes will have no effect on the parent wind distribution-induced regularly occurring accelerations.

The fear and alarm component is generated by occupants being concerned about the structural integrity of the building, and this has life safety implications as it has been known for occupants to evacuate buildings as a result of these concerns. Clearly, if this was to occur during a hurricane the building occupants could then be placing themselves in a situation with significant risks. Figures 4 and 5 show the predicted acceleration responses of a tall slender building with hurricanes excluded in Figure 4 and included in Figure 5. These figures also show the NBCC guidelines (NBCC 2005) for a 10-year return period event. More recently, ISO10137 (2007) and the Architectural Institute of Japan have adopted a one year return period for assessment. There are advantages and disadvantages to each return period, but as can be seen in Figures 4 and 5, the 1-year return period accelerations can be relatively unaffected by hurricane events, while these events may be reflected very strongly in the predicted 10-year return period accelerations.

There should not be a single criterion that is applied to all buildings, but buildings should be considered individually and a consensus agreed upon between the building designers and owner/developer on acceptable acceleration levels. Some of the elements that should be considered are discussed in the following paragraphs.

Fear and alarm that would lead to an occupied building being voluntarily evacuated by residents is not acceptable, even for longer return periods. This type of response to perceptible wind-induced motion is more common among occupants who have no previous experience of this type of occurrence and education can be used to reduce this factor (Denoon and Kwok, 2011). Thus, longer return period accelerations should not be summarily dismissed but should be examined in the context of the likely knowledge of occupants about wind-induced motion. For the first tall building in an area, there is likely to be very little knowledge whereas in hurricane-prone areas with high densities of tall slender buildings wind-induced building motion during hurricanes may be a well-known phenomenon.

There should be a clear demarcation in assessment between buildings that will be occupied during hurricanes, and those that will be evacuated. For residential buildings on a hurricane coast that may be evacuated due to potential storm surge, then it could be argued that the criterion for building motion becomes a performance-based on where the limits are driven by ensuring no damage to building finishes and components as a result of the motion. For commercial buildings, that are generally evacuated in the case of an approaching hurricane, a similar argument could apply.

Other sociological factors should also be considered in the assessment of acceptability of wind-induced building motion. In high-rise, high density public housing, for example, complaint rates are likely to be lower than in buildings where individual residences are owned by high net-worth individuals, particularly in more litigious societies. In this latter case, it may be prudent to design the building for almost no perceptible motion at any time. Hotels are another interesting case. For hotels, it is possible to educate the (generally naive) occupants about the potential for motion and mitigate the fear and alarm in this way. For most hotels, it may be only the fear and alarm component that needs to be designed for as most do not have long-term residents who would be aware of regularly occurring motions.

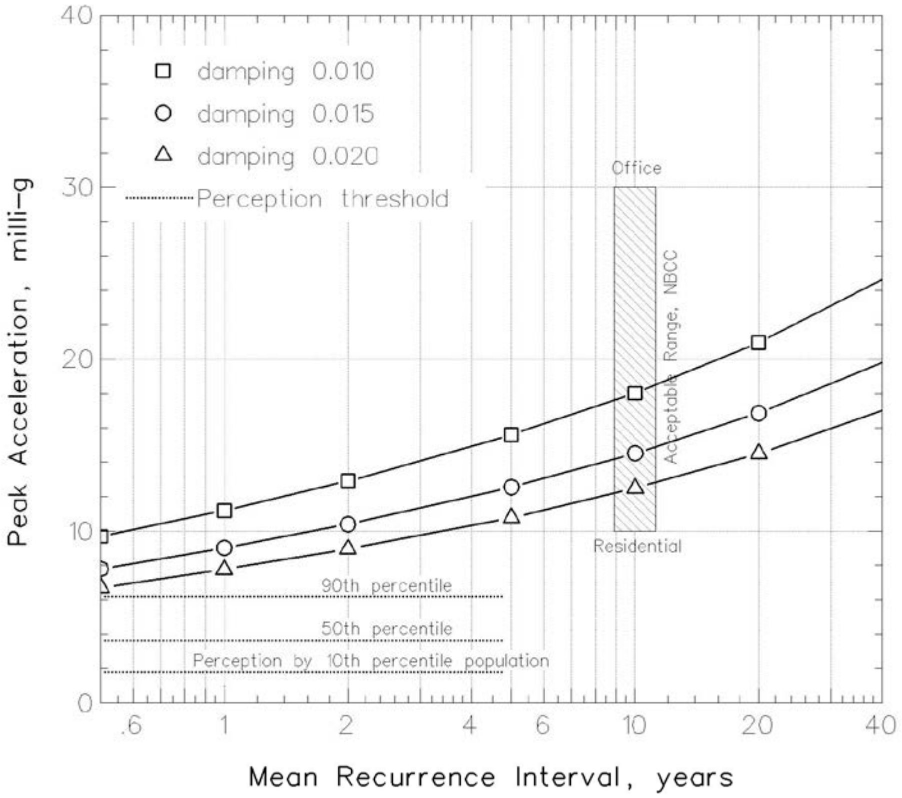

Figure 4: Acceleration response of a tall residential building under non-hurricane winds.

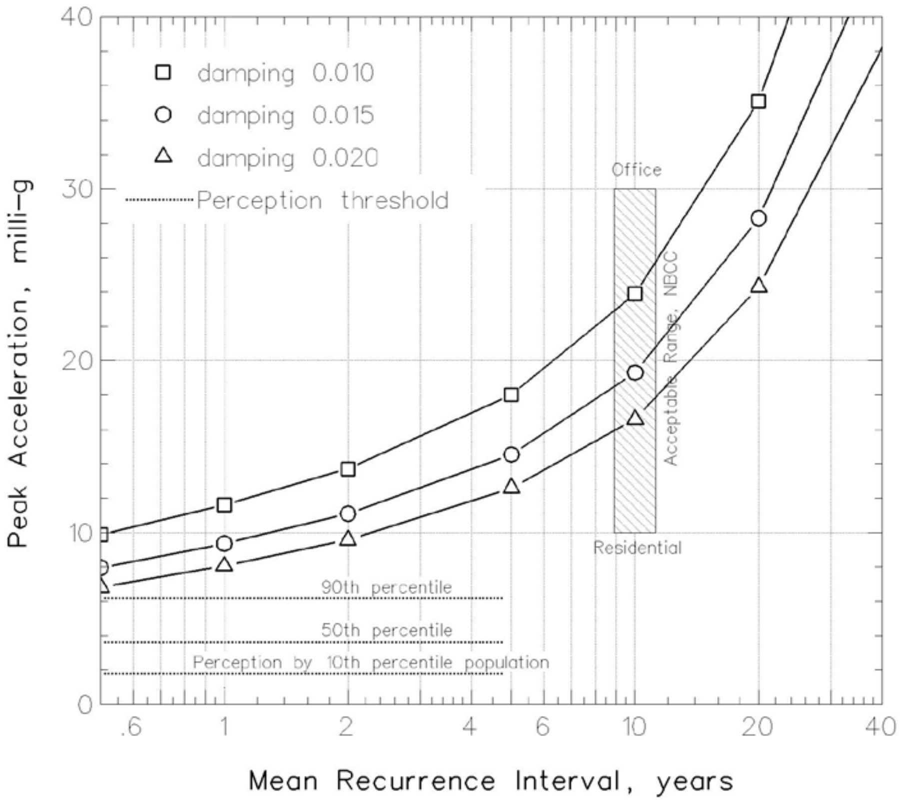

Figure 5: Acceleration response of a tall residential building under all winds, including hurricanes.

DESIGN CLADDING LOADS

Cladding loads for tall buildings in hurricane regions are, for the most part, predicted in the same manner as buildings in any other type of climate. There are two differences that should, however, be accounted for. The first is that in some parts of the world impact resistance to flying debris is taken into account in design. The second factor is the consideration of internal pressures.

Design cladding loads are a combination of the external pressure on a building and an assumed internal pressure. Internal pressures result from a combination of factors including infiltration through leakage in the façade. However, any openings in the façade will tend to dominate the internal pressures. Openings can occur due to operable windows or doors being left open, or breakage of façade elements. The design team or developer has the option of specifying how to treat the internal pressures, with three options being provided in the ASCE7 for a nominally sealed building, a building with distributed openings, or a dominant opening.

For buildings with operable facades, buildings in hurricane regions can be treated rather differently from those in areas where, say, thunderstorms cause the extreme winds. In thunderstorm regions, it is possible for storms to develop very quickly in which case it is likely that some windows will be open. In hurricane regions, however, the advance knowledge of the approach of the hurricane, combined with the rain bands in advance of the peak wind speeds, mean that it is unlikely that windows will have been intentionally left open. Building management can also play a role in ensuring that all operable sections of the façade are sealed. One area where this can be difficult to achieve is in lobbies and entrance areas to buildings. At hurricane design wind speeds it can be difficult to both open doors and to keep them closed. In occupied buildings it is often not an option to lock doors and prevent their use. As some of the most sensitive glazing and cladding can be located at ground level, this is something that needs to be carefully considered during design.

In some regions, there are requirements to ensure impact resistance of facades in hurricane regions. This is sometimes achieved by shuttering. On residential buildings where shutters are installed around the perimeters of balconies, the shutters can alter the aerodynamics of the building. Depending on the configuration of the shuttered balconies and the aerodynamic characteristics of the building, shutters can work to either increase or decrease the overall loads and responses of the building.

ENVIRONMENTAL WIND SPEEDS

Environmental wind speeds are normally considered in the context of ensuring pedestrian comfort around buildings. During severe hurricanes, it is normal to expect that reasonable people will not be walking around the exterior of the building, and it is not therefore necessary to consider pedestrian comfort or safety during these conditions. There are, however, other areas where extreme wind speeds around the envelope of a building need to be considered during hurricanes. For example, it is necessary as part of building management to ensure that there are no potential projectiles on the outside of the building, such as balcony furniture, that could be blown from the building and cause damage elsewhere on the building or on neighboring buildings.

While issues like external furniture can be dealt with by building management, the architectural design team is playing an increasingly responsible role in ensuring that there are no sources of potential debris on the outside of the building. While Hurricane Andrew, amongst others, taught designers much about the importance of detailing the exterior features of buildings and avoiding items such as roof gravel that can be scoured and then impact adjacent buildings, it appears that the passage of time has caused some of these memories to dim. Increasingly, roof gardens and external foliage are being proposed as part of demonstrating the sustainable credentials of tall buildings. Anyone who has ever walked the streets following a severe hurricane will know that there is a great deal of damage to trees and soft landscaping. Figure 6 shows an immature tree at the base of 2IFC in Hong Kong following a typhoon. In this case, the tree was only kept upright by the paver system restraining the root ball. If this tree had been at elevation on a building, clearly it would be important to ensure (a) that it was sufficiently wind resistant not to shed branches; and (b) that it was suitably restrained and would not become detached from the building. This is an area where additional care needs to be taken on the part of the design team to ensure that design features do not pose additional risks to the environment.

Figure 6: Tree at base of 2IFC in Hong Kong following Typhoon Dujuan.

FIELD EXPERIENCE OF TYPHOON EVENTS

The first author had the benefit of living in Hong Kong, where typhoons occur on an annual basis, for a number of years; something that has informed his outlook on some of these issues, Hong Kong also having one of the highest densities of tall buildings in the world. There are a few observations that are relevant to the design and construction community, and other anecdotal behavioral observations.

During Typhoon Dujuan, the source of the tree damage shown in Figure 6, the author and a colleague spent the night on the top (soon to be) occupied floor of 2IFC. This period spanned the peak winds of the storm and measurements were made of the dynamic response of the tower to the typhoon event. Typhoon Dujuan was severe enough for the Typhoon Signal No. 9 to be raised (the second highest rating) by the Hong Kong Observatory, although this was later downgraded to Typhoon Signal No. 8. In these conditions, businesses are closed and public transport suspended. Despite this, there were a number of taxis available on an un-metered basis at negotiable, but much higher than normal, fares. While the building performed in a manner consistent with design predictions, it was interesting to observe the amount of wind-borne debris that was visible from the windows at nearly 400 m above street level. As the building was nearing completion at the time, the author did visit the rooftop areas to ensure that no construction materials, such as bamboo scaffold poles, remained as potential missiles.

In the morning, following the passage of the storm, the author travelled extensively around the central business district looking for any wind-related storm damage. There was extensive damage to trees and a great deal of debris on the streets. The majority of non-vegetative debris was from ground-level construction works. The author found only one damaged façade element, which was a glass door on a boutique belonging to a manufacturer and retailer of high-end fashion accessories. It later transpired that this damage had not occurred as a result of wind damage, but from a criminal enterprise taking advantage of the deserted streets to conduct a ram raid style robbery.

CONCLUSIONS

Hurricane wind climates pose a unique set of challenges to tall building designers and some of the basic assumptions that are commonly used in design need to be evaluated more carefully in order to create serviceable, economical buildings that satisfy the requirements of maintaining life safety and not posing any threat to their surrounding environment. As discussed above, this needs to be done on the basis of consideration of geography, sociology, and building-specific characteristics.

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