CTBUH Research Report

Cyclone-Resistant Façades

Best Practices in Australia, Hong Kong, Japan, and the Philippines

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Council on Tall Buildings and Urban Habitat

kuraray

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- TRABUCCO, D., MEJORIN, A., MIRANDA, W., NAKADA, R., TROSKA, C., STELZER, I. (2017). "Cyclone-Resistant Glazing Solutions in the Asia-Pacific Region: A Growing Market to Meet Present and Future Challenges." *Glass Performance Days 2017 Proceedings,* Tampere, Finland, June 28–30, 2017: 64–9.

This study provides a worldwide overview on the current best practices regarding cyclone-resistant glazing solutions for building envelopes located in cyclone/hurricane/typhoon-prone areas. Building case studies present technical solutions that have been adopted within four specific regions in the Asia-Pacific region. Furthermore, references for the current design requirements and mandatory testing procedures for 12 jurisdictions in Asia and Oceania are presented. The ongoing research activities being undertaken by the government, façade industry, and academic institutions on this specific topic are briefly discussed, and the possible future steps are highlighted in this research report.

Contents

Preface

Due to climate change, the number and the strength of strong wind-related events are increasing worldwide (Prevention Web 2018). There have been several initiatives undertaken by individual countries and global organizations to establish rules with the aim of containing climate change (IPCC 2018) and, subsequently, the growth of such disaster events.

In 2018 alone, numerous tropical cyclones have been recorded. Based on recorded data, the Asia-Pacific region is the most prone to these events (World Bank Group 2017). Depending on the location in which they occur, these cyclones could be also referred to as "typhoons" or "hurricanes". They can cause considerable loss in terms of injury to people, as well as building and property damage (CNN 2018). They are presented here in order of occurrence.

Typhoon Jebi hit the Asia-Pacific region in late August and early September 2018, starting in Taiwan, where it caused large waves that resulted in six fatalities in the Yilan County. It was the most intense storm to pass through Japan in the past 25 years (CNN 2018), breaking the historical records of 10-minute maximum sustained winds. Jebi reached Japan on September 4, causing 11 deaths and more than 600 injuries in the Kensai region. Also, facilities such as the Kansai International Airport and Kyoto Station had to be shut down. The post-disaster event assessment estimated US$5.5 billion in damages (Insurance Journal 2018).

Later in September 2018, a Category 5 super-typhoon was recorded, with ten-minute sustained winds at 215 km/h, referred to as Mangkhut by the Japan Meteorological Agency (JMA) and Ompong by the Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA). It formed near the Marshall Islands on September 7, before moving to the North of the Philippines, where it made landfall on September 14, and then crossed the South China Sea towards Hong Kong, not losing its energy until reaching the mainland of China on September 17. Mangkhut caused 134 fatalities: 127 in the Philippines, six in mainland China, and one in Taiwan. It was the strongest typhoon to hit Hong Kong in the past 50 years and many design considerations have had to be made since this Category 5 super-typhoon affected the city (Mühr et al. 2018).

Typhoon Trami, a Category 5 super-typhoon, made landfall in the Japanese Wakayama Prefecture on September 30, where it fortunately decreased to a Category 2 typhoon.

In late September 2018, in the waters near Pohnpei Island in the Federated States of Micronesia, a tropical disturbance formed and, in the next days, it exponentially grew as it moved westward. It continued becoming stronger and, on October 2, a Category 5 super-typhoon (with 10-minute sustained winds at 195 km/h), which came to be known as Kong-rey, was recorded by the JMA. The first damages were reported in the South Korean city of Tongyeong, in the South Gyeongsang Province, making landfall on October 6. During the same day, Kong-rey turned into an extra-tropical cyclone while transitioning, and made landfall on the southern part of the Hokkaido Island in Japan. As a result of Kong-rey's outer rain bands, four people were killed, and more than 12,000 homes in Nagasaki were left without electricity.

This data only refers to the Category 5 super-typhoons that began in September 2018 in the Asia-Pacific region. The historic wind-speed records were broken for two of the most densely populated jurisdictions in the world (Hong Kong and Kansai). The number of people who were affected — and continue to suffer from the damage — is huge, and it is these jurisdictions' responsibility to ensure safety and reduce damage as much as possible.

The envelope is the primary barrier to protect a tall building and its occupants from these external threats, in addition to controlling a building's internal climate and lighting. The failure of glazed enclosures, caused primarily by flying debris during a typhoon, represents a potential threat for occupants and is a significant contributor to the post-event recovery costs (South China Morning Post 2018b).

Even if there are no objects in the urban environment that could potentially fly during a strong wind event, urban trees and plants could fall or distintegrate, impacting the façades. In Hong Kong, after Typhoon Mangkhut, 46,000 felled trees were collected (South China Morning Post 2018a). This statistic highlights the rationale for glazing systems that are proven to be effective, and that could be certified as "cyclone-resistant," according to specific standard test procedures. This research investigates the current best practices and glazing technologies, worldwide, that have been adopted for a building envelope to withstand the impact caused by windborne debris during a strong wind event, such as a typhoon.

1.0 Research Objectives, Methodology, and Steps

1.1 Introduction

Highly-populated areas in Southeast Asia, including the Philippines, South and East China, Korea, and Japan, have been affected by typhoons, which are of such magnitude that they threaten the economic stability and growth of these regions. Additionally, the megacities that are forming in these areas demand additional residential and office space, which calls for the construction of high-rise buildings (Mejorin et al. 2018).

Over the past decade, the Asia-Pacific region has seen unprecedented growth in terms of its economy and its urban population. As growth in this area occurs, the demand for additional high-density residential and office space has also increased, resulting in record numbers of high-rise buildings being constructed, concentrated primarily in urban areas (CTBUH 2016). The urban growth in this region has largely occurred in coastal areas, which unfortunately are becoming increasingly vulnerable to typhoons.

This research report presents the norms and standards of the major tall building markets in 12 jurisdictions within the Asia-Pacific regions (including Australia and New Zealand), for the impact of flying debris on curtain walls during strong wind events in the urban environment.

This study looked for international codes and standards, and sought to examine how their adoption in different jurisdictions has spread, in order to highlight the effectiveness of existing solutions for the specific issue of flying debris resistance during major wind events (ASCE 2018). After Hurricane Andrew occurred in the United States in 1992, the Florida Building Code developed curtain wall provisions, so as to limit damage caused by high-velocity winds (ICC 2014a). This code still represents the most demanding building standard in the United States when it comes to impact-resistant façade systems.

The local requirements for protecting façades from flying debris, both in the Asia-Pacific region and worldwide, are compared in this document, and the main differences between existing standards on this specific theme are discussed.

Moreover, four Asia-Pacific jurisdictions are discussed, in order to further delve into specific problems for new curtain walls: the façade design, realization and testing processes for Australia, Hong Kong, Japan, and the Philippines are presented. The roles of the various government institutions were examined, both in their definition of the required façade performance and the subsequent approval process for curtain walls. The information presented here is intended to provide understanding of the local markets, and the respective hierarchies of the various professionals involved in façade design and realization.

Many regions evaluate the amount of damage that has occurred due to a cyclone in terms of deaths; the amount of buildings and infrastructure to be repaired; the total economic impact; and the possible mitigation actions to be undertaken (Ginger et al. 2010; Boonyapinyo 2010; Duy et al. 2007; Yimin et al. 2012). Videos and photos depicting the impact of strong winds on our cities and countries are now frequently appearing on television and news outlets (see Figure 1.1) (Nikkei 2018, BBC 2018, The Irish Times 2018, NBC News 2018, Miami Herald 2018).

The bond between the modern, conventional skyscraper and glazing is evident; the typical tall building design seeks to deploy as much glass as possible (Mori 2015). Although the building's design aims to achieve a transparent and lightweight image, it still must adhere to safety regulations and guarantee resiliency against the effects of natural events.

A comparison between the number of tall buildings in a cyclone-prone area, the number of tall buildings hit by past cyclone events, the number of tall buildings that are currently "at risk," and the total number of tall buildings of a certain height range within these regions is provided (World Bank Group 2017).

Curtain wall systems are not simply used to define a building's appearance; they form the true skin of the building. Like the skin on a living body, a building's curtain wall is the barrier between the indoor environment and the exterior. A building's façade is designed to control the indoor climate, allow natural light in, and to some extent, allow the building to take advantage of natural ventilation. However, in many circumstances, the curtain wall becomes a barrier (Taywade 2015), protecting the building and its occupants from external threats, such as rough climates, violent attacks (Clift 2006), and windborne objects (Shah 2009).

Building solutions have already been found, and façade technologies developed, to reduce building damage caused by the impact of flying debris. The effectiveness of cyclone-resistant façades against past cyclone events is proven (Miami-Dade County Building Code Compliance Office 2006), and evidence to support the goal of further advancing cyclone-resistant façades is presented in this document.

This technical publication is intended to be used as a reference document for industries and professionals in the design and renovation of curtain walls, and as a means of presenting tangible examples of the existing best practices in the Asia-Pacific region to developers and building owners.

Figure 1.1. Damage to Two Harbourfront office tower in Hong Kong, after Typhoon Mangkhut, 2018.
© Wpcpey (cc by-sa)

1.2 Research Objectives

The ultimate objective of this research is to provide a tool for professionals operating in the façade engineering discipline, when considering buildings located in cyclone-prone areas of the Asia-Pacific region.

This report aims to serve as a reference document to compare international and Asia-Pacific local codes and standard procedures on the topic of flying debris resistance. The differences in roles and responsibilities of various experts involved in the façade definition are described, highlighting the dissimilarities between the selected Asia-Pacific local markets.

Furthermore, the preponderance of tall buildings in cyclone-prone locations in the Asia-Pacific region is such that an examination of the destructive potential of such events and the state-of-the-art techniques underscores the scale of the global risk and range of responses. The research project primarily seeks to answer the questions:

- What buildings are generally protected against typhoons?
- Also, which are the best practices adopted for the most recent building façades in Australia, Hong Kong, Japan, and the Philippines?

The main risks of these construction types are highlighted, as well as the most suitable technical solutions to prevent façade failure in case of a cyclone event. By avoiding glass breakage and flying debris penetration into the building, the property losses stemming from these events can be minimized. Likewise, rain penetration and mold formation can also be avoided.

To conclude the discussion, existing building case studies serve as reference examples to share the current best practices within the selected Asia-Pacific jurisdictions, which exceed the minimum design requirements widely followed in these regions.

1.3 Research Methodology

The basis for the presented research derives from the analysis of books, post-cyclone event assessments, and technical papers on cyclone-glazing technology, cyclone/typhoon/hurricane wind loads, flying debris resistance, typhoon shelter systems, water-tightness in dynamic pressure conditions, and other relevant themes.

The international and Asia-Pacific codes and industrial standards were taken as the primary reference documents for the investigation of local requirements relating to the safeguarding of building construction and internal property. These requirements were compared with, and contrasted against, the US standards, which have been identified as the best available practices worldwide, for the certification of a building envelope's ability withstand a cyclone event. The main differences in the available codes and standards are highlighted and discussed; these constitute one of the main outputs of the research.

Finally, a primary source of information in this research derived from an interdisciplinary group of professional contributors within the façade industry, including experts from academia, code boards, and insurance companies. These experts were interviewed at regular intervals, and their feedback on the research activities — as well as their ongoing professional work in façade design — was fundamental to producing the materials in this research output. Thanks to the contributions from international experts and the collection of information on existing building case studies within the Asia-Pacific region, it was possible to present a comprehensive overview of the current best practices within four selected cyclone-prone jurisdictions. Moreover, possible improvements to the existing requirements for curtain walls prone to strong-wind events are discussed in the conclusion.

> “By avoiding glass breakage and flying debris penetration into the building, the property losses stemming from cyclone events can be minimized.”

1.4 Research Steps

The research project presented in this report took place over the period from January to October 2018, and can be divided into five main steps, each building off the last:

Identification of the Size of the Problem

The first part of the research gave a scale to the problem of building risk related to disaster events, and particularly with typhoon events. Geographic analyses of past typhoon events and the location of tall buildings were compared with Geographic Information System (GIS) mapping. The team used historic typhoon data produced by the United Nations Environmental Program, along with The Skyscraper Center, CTBUH's extensive database of tall building information. The concentration of tall buildings, the number of buildings that have previously been affected by storm events, and those buildings that are currently in threatened areas were identified for a select 12 jurisdictions within or near the Asia-Pacific region: Australia, Bangladesh, mainland China, Hong Kong, India, Japan, New Zealand, the Philippines (see Figure 1.2), South Korea, Taiwan, Thailand, and Vietnam.

Utilizing the GIS modeling of past typhoon events and tall building locations, the following information was extracted for the selected analyzed Asia-Pacific jurisdictions:

- Number of tall buildings affected by typhoon events in the past
- Number of tall buildings in prone areas that are currently at risk
- Number of tall buildings in prone areas that could be affected in the near future

Identification and Analysis of the Existing Codes

The next stage of the research analyzed existing typhoon/hurricane/cyclone-resistant curtain wall codes and standards in the 12 Asia-Pacific jurisdictions, with a view to developing a matrix, examining similarities and differences between these current requirements, and comparing these against the US code. The Florida Building Code has been identified as the current benchmark for best practice worldwide.

The team identified and briefly analyzed 138 documents. Of those documents, 19 were selected for an in-depth review, in which a number of topics were examined, including, but not limited to, identifying the availability of information relating to specific requirements and tests, and the particular strengths and limitations of each document. This analytical process served as the basis of comparison. This information was shared with technicians operating in the curtain wall industry, who helped identify the gaps in international and local requirements for typhoon-resistant façades.

Each document has been analyzed and summarized with the following contents:

- Identification of the document (author, title, year of publication)
- Identification of the availability of information regarding the following topics:
  1. Testing apparatus
  2. Wind loads
  3. Windborne-debris impact testing
  4. Pressure cycling testing
  5. Testing procedures
  6. Technical reports
  7. Wind speed maps

The selected documents were compared for the following topics related to flying-debris and strong-wind resistance:

- Small-missile impact testing
- Large-missile impact testing
- Pressure cycling testing
- Façade acceptance criteria procedure

Facade Professional and Government Institution Interviews

Research trips were organized to visit four selected Asia-Pacific jurisdictions, in order to meet local professionals who are involved in façade design. They were determined for their differences in the current requirements for flying-debris-resistant façades, which were highlighted during the previous stage of this research. Australia, Hong Kong, Japan, and the Philippines were chosen, and building case studies were collected.

Through these visits and subsequent interviews with experts operating in the selected countries, the duties and responsibilities of the following professionals are presented:

- Developers
- Designers
- Façade consultants
- Façade suppliers
- Façade test labs
- Government institutions

Figure 1.2. Zuellig Building podium, Makati, damaged by Typhoon Glenda, 2016. © Joe Khoury / ALT Cladding)

Figure 1.3. Typhoon York's winds shattered the curtain walls of several buildings in Wan Chai, Hong Kong, September 1999. © Joe Khoury / ALT Cladding

State-of-the-Art Definition and Case Study Collection

Information on buildings that incorporate strong wind-resistant technologies has been collected, in order to identify the best building solutions being used to meet local standard requirements in Australia, Hong Kong, Japan, and in the Philippines. The objective is to present current standards in curtain wall design and testing procedures, and the most innovative materials that are being utilized at this time. Through interviews with experts, this research identified solutions compliant with local requirements. These are easily comparable to conventional solutions, in order to understand and identify exactly where major technical advancements have occurred, when it comes to façades resistant to the effects of strong winds.

Peer Review Phase

The final phase involved sending all materials of the research to an international panel of experts for peer review. This critical analysis served as the final opportunity for the various professionals in the façade industry to provide input into this research. The panel of experts is an interdisciplinary group of professionals comprised of designers in major engineering and architectural companies, professors from leading universities, members of the primary building departments, and experts at research centers where strong-wind-resistant construction is studied.

1.5 Asia-Pacific Jurisdictions Selected for In-Depth Investigation

During the first year of this research project, "Cyclone-Glazing and Façade Resilience for the Asia-Pacific Region," the local statutory requirements for flying debris resistance of 12 Asia-Pacific jurisdictions were investigated and reported.

It was concluded that, in most of the Asia-Pacific areas that CTBUH investigated, there are no requirements regarding resistance to flying debris, but rather, just a few industry standards that try to address the safety concerns and potential damage caused by typhoons. It should be noted that the Asia-Pacific region is the most-prone region in the world to these strong wind events, both in terms of frequency and intensity (see Figure 1.3).

In the second year of the research project, specific regulations concerning resistance of curtain walls to typhoons used in four Asia-Pacific jurisdictions were examined.

The four jurisdictions were selected after examining the various standards and building regulations that exist throughout the region. The selected countries have the current best practices regarding façade design for resisting strong wind events. When referencing the GDP per capita (World Bank Group 2017), it can be seen that the selected jurisdictions cover a range of economies: Japan and Hong Kong (highly wealthy), Australia (wealthy), and the Philippines (developing) (see Figures 1.4–1.7).

These jurisdictions have been selected to identify the current best practices when it comes to façades that are threatened by strong wind events in the Asia-Pacific region. Specific building case studies are presented, and the best practices for typhoon resilience are provided by research contributors. These provide a snapshot of the local design and testing procedures. Furthermore, the roles and responsibilities of the professionals involved in façade design in the four jurisdictions are discussed.

The objective is to present an overview on the duties of the professionals involved in the design, realization, and testing procedures for façades in these four jurisdictions. In each location, different approaches exist when considering the local statutory requirements, professional responsibilities, and any third-party involvement that may be requested from clients.

Finally, the study aims to synthesize the best practices from selected Asia-Pacific glazed envelopes. This is because currently, especially in office and high-rise hotel spaces, a high premium is placed on outward views. Unsurprisingly, the selected building case studies all demonstrate a high ratio of glass-to-surface-area. Given this, it was unrealistic to consider reducing the amount of glass in order to reduce the risk of glass failure potentially caused by windborne debris in typhoon events.

The four jurisdictions discussed in the next sections are:

Figure 1.4. Osaka, Japan, 2015. © Ug (cc by-sa)

Figure 1.5. Hong Kong, China, 2018. © Milkomède (cc by-sa)

Figure 1.6 Darwin, Australia, 2015. © Jeremy De Guzman (cc by-sa)

Figure 1.7. Makati, Philippines, 2018. © Patrick Roque (cc by-sa)

Australia

This country was the world's first developer of standards and building technologies to specify cyclone-resistant façades capable of withstanding the impact of flying objects in strong wind conditions. The current Australian requirements for cyclone-resistant façade certification has changed recently. These are now stricter than related standards in the United States when it comes to impact-testing missile speed, but the testing procedures can be perceived as ambiguous. This has had a negative impact on the basic adoption of cyclone-resistant glazing systems. CTBUH wishes to highlight that, even though the projectile velocities in Australia are significantly higher than those in the US, unlike the US, there is no requirement to check the adequacy of the glazing to resist wind pressure after the impact.

Hong Kong

Hong Kong is one of the Special Administrative Regions (SARs) in China. It has very clear requirements regarding the design criteria and statutory approval process. This is due to the common occurrence of strong wind events. The safety factors for the design calculation take into account the location of buildings in Hong Kong that are often exposed to high winds. The *2018 Hong Kong Code of Practice for Structural Use of Glass* requires the use of laminated glass solutions for exterior building tempered-glass façades, when the size of the glass pane exceeds 2.5 square meters, and when any point of the glass pane is at a height five meters or more above the finished floor level of the accessible areas on either side of the pane. This document does not refer to any requirement for windborne-debris resistance, but it is just the first edition, and the Hong Kong Buildings Department (HKBD) has released many requirements based on the ASTM standard procedures. The next revisions may introduce references to flying-debris resistance for typhoon-prone regions. The HKBD is continually working on issues related to the safety performance of buildings, and a dialogue on the issues related to flying debris had already begun when CTBUH met the HKBD in June 2018.

Japan

In Japan, the testing requirements related to the resilience of glazing against the effects of typhoons underwent changes while this research project was being conducted, in the second half of 2018. The Japanese Industrial Standard (JIS) introduced glass performance specifications related to the resilience to windborne debris with different levels of impact resistance. The JIS R 3109:2018 standard was developed by the Disaster Prevention Research Institute of Kyoto University, and references International Organization for Standardization (ISO) 16932. Typical flying debris found during typhoons (e.g., Japanese roof tiles) have been analyzed, in order to verify that the energy to be absorbed by the glazing system in the tests is adequate and realistic. This JIS standard also introduces the definition of windstorm-resistant security glazing.

Philippines

The Philippines is currently undergoing rapid economic growth in many sectors, which has led to an increase in demand for high-rise commercial buildings. It is also the country most prone to typhoons in the Asia-Pacific Region. In the 2010 edition of the National Structural Code of the Philippines (NSCP), there are clear references to the ASTM E1886 and ASTM E1996 standard procedures for flying-debris impact testing to be carried out on façades. The 2015 edition of the NSCP specifies the requirements, but there are no regulations for developers to produce test certificates to local government building officials to prove that the façade is fit for purpose. This lack of regulatory enforcement, and developers' demand for low-cost façades, mean that the requirements set out in the NSCP are not being effectively followed.

1.6 Selection of Building Case Studies

The research activities were conducted in collaboration with professionals operating in the four Asia-Pacific jurisdictions: Australia, Hong Kong, Japan, and the Philippines. Many of these experts contributed necessary information for the research project, and also identified existing buildings and past disaster events for further study.

A summary of the previously mentioned design regulations and guidelines is presented in each regional section. Also described are the roles and responsibilities of the professionals involved, which vary depending on the jurisdiction. This section gives a brief overview of the different Asia-Pacific markets, as well as explains the rules that the various professionals involved in the design, installation, and approval of the curtain walls must follow and how they interact. Furthermore, building case studies for each of the four regions identifies and presents existing built solutions.

The selection of the building case studies was made based on several parameters:

- *Location:*
  All the buildings that have been selected are in typhoon-prone locations and could experience a typhoon in the near future.
- *Year of construction:*
  Only building envelopes built between 2008 and 2018 have been examined.
- *Typology:*
  Buildings of significant size or importance, with highly public functions (e.g., universities, hospitals, etc.) were selected.
- *Building Envelope:*
  Buildings with predominantly glazed façades and curtain wall construction were chosen.

Professionals involved in the development, design, testing, and management of buildings were consulted to obtain the following data on each project:

1. General project data
2. Architectural features of the building
3. Building design requirements
4. Façade design
5. Façade typology
6. Lessons learned and recommendations

2.0 Threats to the Asia-Pacific Region

2.1 Tropical Cyclones

Tropical cyclones are rapidly rotating storm systems that produce strong winds and heavy rain. They originate almost exclusively over tropical seas. Viewed from overhead, a clear "eye" of the storm can be identified as the center of the spiral arrangement of wind, blowing counterclockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere. They grow over large bodies of relatively warm water through water evaporation from the ocean surface, which condenses into clouds and rain. This occurs when air moisture rises and saturates.

Cyclones have different names depending on the geographical area in which they occur. They are called "hurricanes" in the Atlantic Ocean, Caribbean Sea, Gulf of Mexico and east of the International Date Line; "cyclones" in the Southwest Pacific Ocean; and "typhoons" west of the International Date Line in the Pacific Ocean (see Figure 2.1 and Table 2.1). These events threaten the safety of one billion people every year, through the effects of violent precipitation and devastating wind (World Bank Group 2017). The resulting windborne debris can be source of façade damage during these events (see Figure 2.2).

These disaster events differ from typical European storms due to their diameter, which can range between 100 and 2,000 kilometers wide. The rotating winds conserve their angular momentum while flowing, traveling large distances without losing any energy (Montgomery & Farrell 1993). The period of the year in which they normally occur is the late summer, when the difference between the temperature of the air and the sea surface is higher.

The geographic area most affected by these events is the Asia-Pacific region. The World Bank Group, in its October

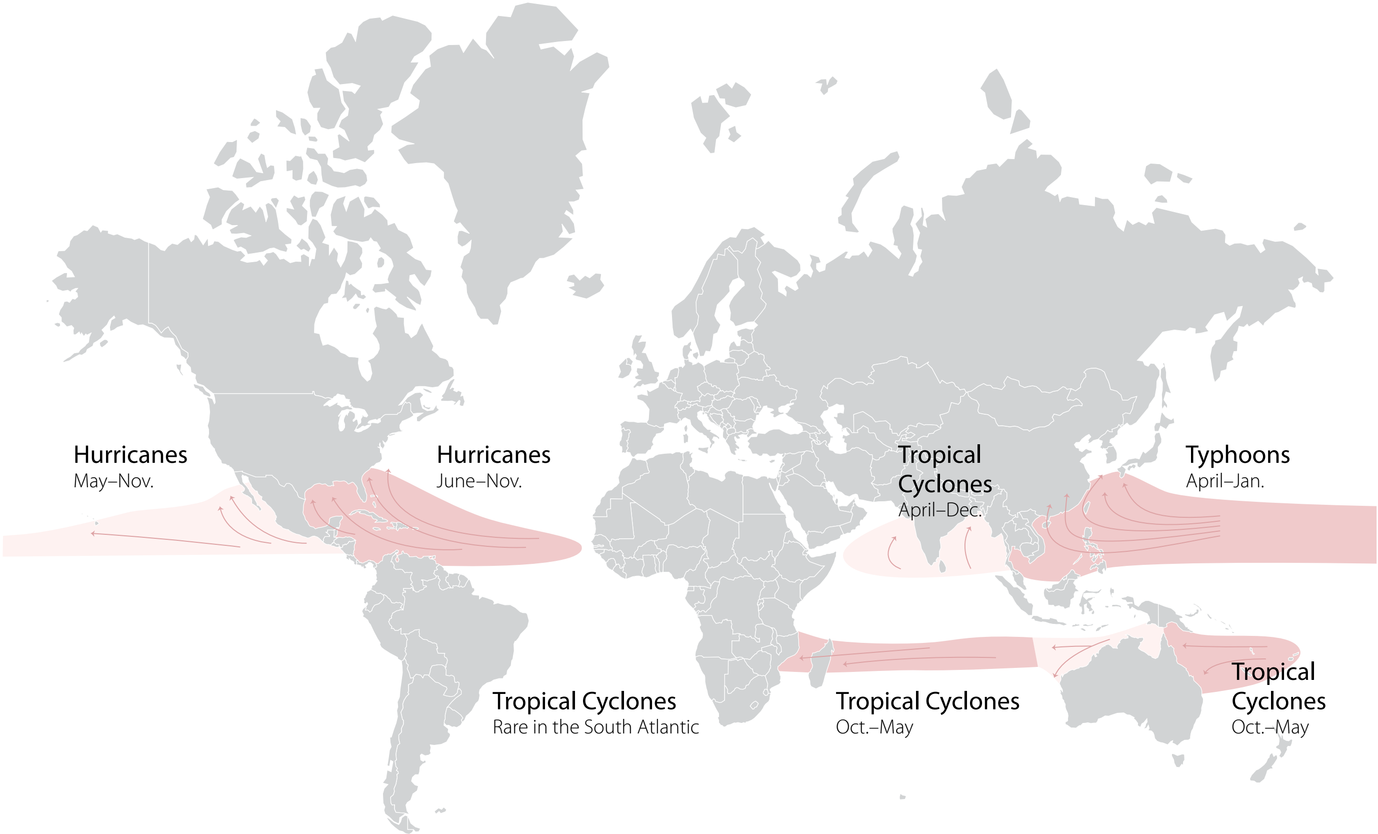

Figure 2.1. Typical seasons for tropical cyclones, hurricanes and typhoons. © National Weather Service Online Weather School JetStream

TROPICAL CYCLONE CLASSIFICATION

Beaufort Scale	1-minute sustained winds	10-minute sustained winds	NE Pacific & N Atlantic	NW Pacific		N Indian Ocean	SW Indian Ocean	Australia & S Pacific
			National Hurricane Center (NHC)/ Central Pacific Hurricane Center (CPHC)	Joint Typhoon Warning Center (JTWC)	Japan Meteorological Agency (JMA)	India Meteorological Department (IMD)	Meteo France's La Reunion Tropical Cyclone Centre	Australian Bureau of Meteorology / Fiji Meteorological Service
0–7	<32 knots (37 mph; 59 km/h)	<28 knots (32 mph; 52 km/h)	Tropical Depression	Tropical Depression	Tropical Depression	Depression	Zone of Disturbed Weather	Tropical Disturbance
7	33 knots (38 mph; 61 km/h)	28–29 knots (32–33 mph; 52–54 km/h)				Deep Depression	Tropical Disturbance	Tropical Depression
8	34–37 knots (39–43 mph; 63–69 km/h)	30–33 knots (35–38 mph; 56–61 km/h)	Tropical Storm	Tropical Storm			Tropical Depression	Tropical Low
9–10	38–54 knots (44–62 mph; 70–100 km/h)	34–47 knots (39–54 mph; 63–87 km/h)			Tropical Storm	Cyclonic Storm	Moderate Tropical Storm	Category 1 Tropical Cyclone
11	55–63 knots (63–72 mph; 102–117 km/h)	48–55 knots (55–63 mph; 89–102 km/h)			Severe Tropical Storm	Severe Cyclonic Storm	Severe Tropical Storm	Category 2 Tropical Cyclone
12+	64–71 knots (74–82 mph; 119–131 km/h)	56–63 knots (64–72 mph; 104–117 km/h)	Category 1 Hurricane	Typhoon				
	72–82 knots (83–94 mph; 133–152 km/h)	64–72 knots (74–83 mph; 119–133 km/h)			Typhoon	Very Severe Cyclonic Storm	Tropical Cyclone	Category 3 Severe Tropical Cyclone
	83–95 knots (96–109 mph; 154–176 km/h)	73–83 knots (84–96 mph; 135–154 km/h)	Category 2 Hurricane					
	96–97 knots (110–112 mph; 178–180 km/h)	84–85 knots (97–98 mph; 156–157 km/h)	Category 3 Major Hurricane					
	98–112 knots (113–129 mph; 181–207 km/h)	86–98 knots (99–113 mph; 159–181 km/h)				Extremely Severe Cyclonic Storm	Intense Tropical Cyclone	Category 4 Severe Tropical Cyclone
	113–122 knots (130–140 mph; 209–226 km/h)	99–107 knots (114–123 mph; 183–198 km/h)	Category 4 Major Hurricane					
	123–129 knots (142–148 mph; 228–239 km/h)	108–113 knots (124–130 mph; 200–209 km/h)						Category 5 Severe Tropical Cyclone
	130–136 knots (150–157 mph; 241–252 km/h)	114–119 knots (131–137 mph; 211–220 km/h)		Super Typhoon		Super Cyclonic Storm	Very Intense Tropical Cyclone	
	>137 knots (158 mph; 254 km/h)	>120 knots (140 mph; 220 km/h)	Category 5 Major Hurricane					

Table 2.1. Tropical cyclone classifications, used by the official warning centers worldwide. NHC, CPHC, and JTWC use one-minute sustained wind, the IMD uses three-minute sustained wind (not shown in the table), while all other warning centers use 10-minute sustained winds. The regional differences in classifications are shown.
Source: Wikipedia (2019)

Figure 2.2. Plywood repair panels were visible on the Colonial Bank building, Miami, after Hurricane Wilma, 2005.
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> “Since 1980, in the East Asia-Pacific region, more than 3.5 billion people have been affected by natural disasters, and the region has sustained some US$525 billion in losses.”

2016 *Reducing Vulnerabilities: East Asia and Pacific Economic Update* (World Bank Group 2016b), has shown that both the frequency and severity of disasters in East Asia-Pacific (EAP) region have been rising since 1980. Over this period, more than 3.5 billion people have been affected by natural disasters, and the region has sustained some US$525 billion in losses (nearly a quarter of total global losses from natural disasters). Although the number of fatalities has not followed a linear trend, the total number of disasters and the amount of people affected in the EAP region between 1980 and 2015 have been constantly rising.

The World Risk Report has created a World Risk Index, which characterizes the disaster risk for 173 jurisdictions. The risk index takes into account natural hazards and the social sphere. This is calculated on:

- The exposure to natural hazards
- Susceptibility: likelihood of suffering harm
- Coping capacities: the capacity for a jurisdiction to reduce negative consequences
- Adaptive capacities: the capacity for a jurisdiction to develop long-term strategies for societal change

Currently, seven of the 10 most at-risk jurisdictions in the world are located in the Asia-Pacific region; 11 Asia-Pacific jurisdictions are in the top 20 (Bündnis Entwicklung Hilft and UNU-EHS 2016) (see Figures 2.3 and 2.4).

Furthermore, the *Sustaining Resilience: East Asia and Pacific Economic Update* of April 2017 (World Bank Group 2017) indicates that most of the small Pacific Island Countries are experiencing moderate to strong growth, but at the same time, are vulnerable to natural disasters and climate change, with these jurisdictions experiencing, on average, one major natural disaster annually. In the "Pacific Possible" program (World Bank Group 2017), which examined long-term economic opportunities of these areas, the vulnerability still remained high, even with an increase in policy focused on disaster risk management. This high level of vulnerability could undermine the development of these jurisdictions.

2.2 Economy and Population

From 1990 to 2017, the gross domestic product (GDP) of the Asia-Pacific region has experienced an incredible increase, and now the Hong Kong region, Australia, Japan, New Zealand, and South Korea are standing out in the world ranking as the jurisdictions that have the highest GDP PPP (GDP based on purchasing power parity), globally (see Table 2.2).

Alongside the economy, the Asia-Pacific region has also seen unprecedented growth in population, specifically urban population. As the growth in urban areas occurs, the demand for additional high-density residential and office space has also increased, resulting in record numbers of high-rise buildings being constructed (World Bank Group 2018) (see Table 2.3).

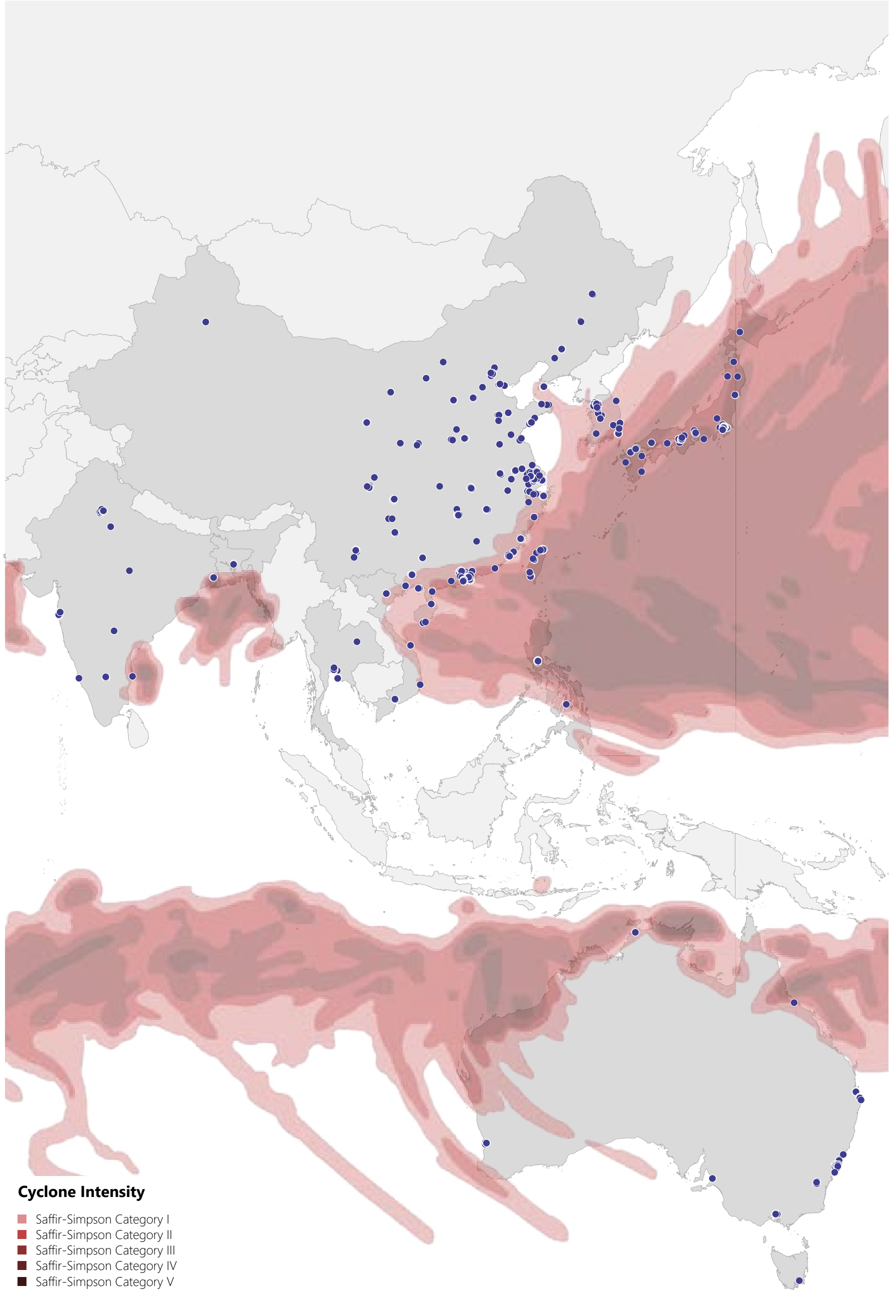

Figure 2.3. Cyclone intensities in the Asia-Pacific Region, based on the Saffir-Simpson scale, 2017.
Sources: Prevention Web, UNEP/UNISDR, and CTBUH.

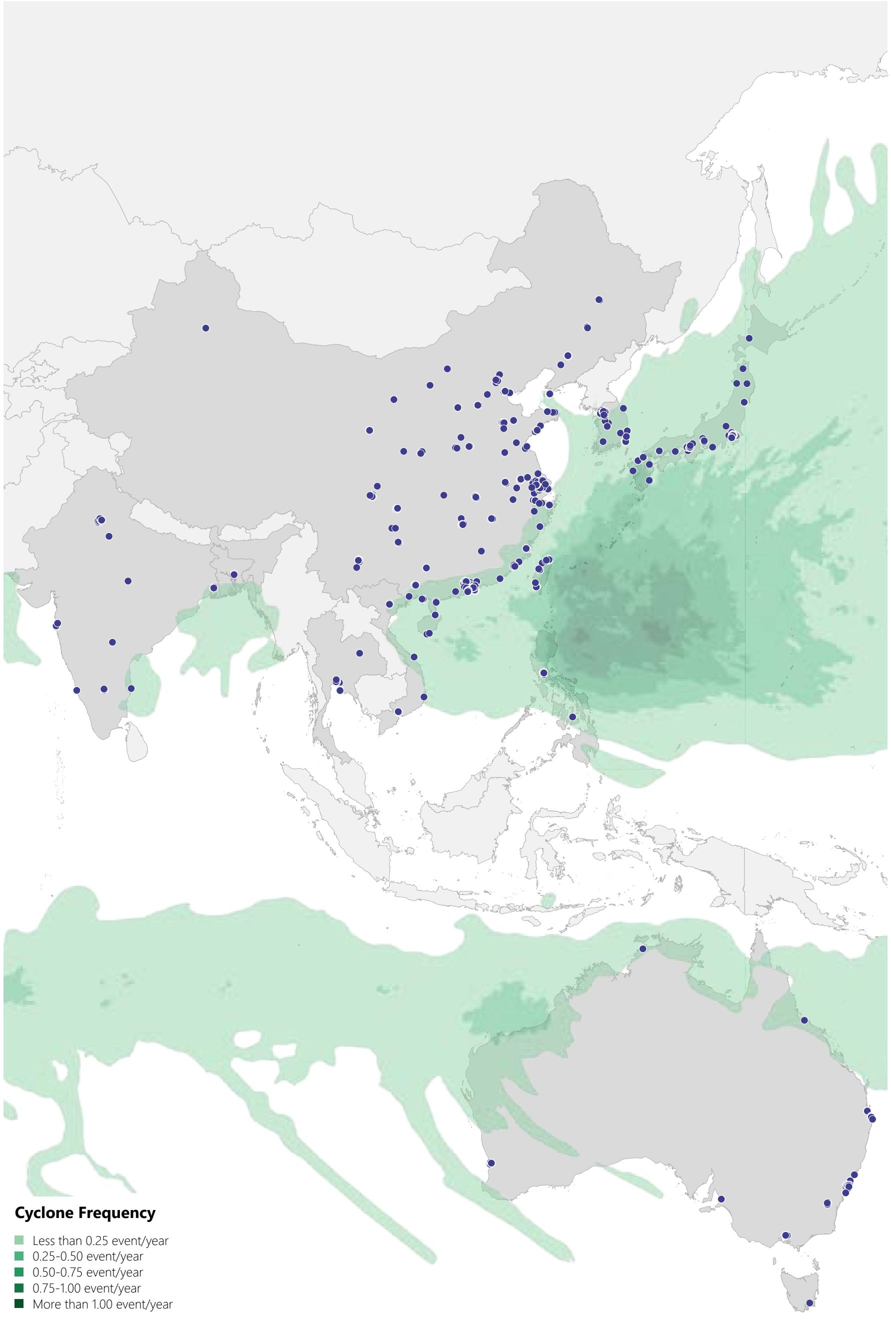

Figure 2.4. Cyclone frequencies in the Asia-Pacific Region, 2017. Sources: Prevention Web, UNEP/UNISDR, and CTBUH.

The Asia-Pacific region has recently seen the emergence of a new urban typology, the megacity, defined as an urban agglomeration with a total population of 10 million people or greater, consisting of a continuous built-up area that encompasses one or more city centers and suburban areas, economically and functionally linked to those centers. (Safarik, Ursini & Wood 2016). These primarily coastal urban agglomerations are threatened by major storm events, and without appropriate standards and testing requirements for curtain wall resilience, this could present a major threat to the prosperity that has recently taken hold in these areas.

From 1960 to 2017, there was a significant increase in urban population and GDP of the jurisdictions analyzed in this research. Peaks are recorded in South Korea, China, Bangladesh, and Thailand, where the average increase of the urban population from 1960 to 2017 is 53.79 percent, 41.76 percent, 30.72 percent, and 29.53 percent, respectively (World Bank Group 2018) (see Tables 2.3 and 2.4).

2.3 Tall Buildings

In order to determine the exact extent to which skyscrapers within these jurisdictions have been and still are being affected, data from the CTBUH Skyscraper Center, the premier source for accurate, reliable information on tall buildings around the world, and the collection of historic cyclone data, produced by the United Nations

Environmental Programme (UNEP), within its Global Resource Information Database (GRID) network, were compared (Mejorin et al. 2018). With the geographic and time data for the buildings and cyclones, not only can the number of tall buildings that have suffered a cyclone event in the past be determined, but also, recently developed buildings that are located in an areas that have previously been struck by a cyclone can be identified. As major storm events are now occurring more regularly than ever before, it is safe to assume that areas having experienced major events in the past will experience one in the near future.

Through geographic analysis, it was determined that 1,778 buildings within the 12 select developing jurisdictions have experienced at least one cyclone event. Many of these building have experienced multiple events, resulting in at least 14,617 total instances, in which buildings have been affected by 240 unique cyclones in the past 45 years, with 293 of the 1,778 buildings having experienced a severe cyclone event with wind speeds greater than 150 km/h. The impact of the typhoon events on tall building construction does not follow a precise pattern; damage occurred in the urban environment depending on several variables, such as the presence of temporary structures, and construction sites close to the affected building (ASCE 2018).

	GDP 2017 (million current US$)	GDP per capita 1990 (US$)	GDP per capita 2017 (US$)	GDP, PPP per capita 2017 (US$)	GDP, PPP per capita, 2017 world ranking (US$)
Australia	1,323,421	18,215	53,800	48,460	22
Bangladesh	249,724	298	1,517	3,869	185
China	12,237,700	318	8,827	16,807	96
Hong Kong	341,449	13,486	46,194	61,540	11
India	2,597,491	364	1,940	7,056	155
Japan	4,872,137	25,359	38,428	43,279	31
New Zealand	205,853	13,670	42,941	41,109	36
Philippines	313,595	715	2,989	8,343	147
South Korea	1,530,751	6,516	29,743	38,335	39
Thailand	455,221	1,508	6,594	17,871	87
Vietnam	223,864	95	2,343	6,776	159

Table 2.2. The GDP of the Asia-Pacific jurisdictions in this study (Taiwan data not available). Source: World Bank.

	Total Population (1960)	Total Population (2017)	Urban Population (1960)	Urban Population (2017)	Increase of urban population (1960–2017)	Average of increase of urban population (1960–2017)
Australia	10,276,477	24,598,933	8,378,309	21,131,467	12,753,158	4.37%
Bangladesh	48,199,747	164,669,751	2,475,057	59,047,279	56,572,222	30.72%
China	667,070,000	1,386,395,000	108,085,352	803,554,542	695,469,190	41.76%
Hong Kong	3,075,605	7,391,700	2,620,415	7,391,700	4,771,285	14.80%
India	449,480,608	1,339,180,130	80,564,904	449,964,523	369,399,619	15.68%
Japan	92,500,572	126,785,797	58,526,962	116,053,379	57,526,417	28.26%
New Zealand	2,371,800	4,793,900	1,802,521	4,145,094	2,342,573	10.47%
Philippines	26,273,025	104,918,090	7,959,938	48,977,863	41,017,925	16.39%
South Korea	25,012,374	51,466,201	6,930,929	41,946,498	35,015,569	53.79%
Thailand	27,397,175	69,037,513	5,389,572	33,966,456	28,576,884	29.53%
Vietnam	32,670,629	95,540,800	4,802,582	33,642,782	28,840,200	20.51%

Table 2.3. Total and urban population data for Asia-Pacific jurisdictions in this study (Taiwan data not available). Comparison 1960 – 2017. Source: World Bank.

Rank by population	Megacity	Country	Combined Population	Area (sq. km)	Density (ppl/sq. km)	# of Buildings h ≥ 200 m	Cities & administrative areas within
1	Pearl River Delta	China	64,899,778	56,217	1,154	220	Dongguan, Foshan, Guangzhou, Hong Kong, Huizhou, Jiangmen, Macau, Shenzhen, Zhaoqing, Zhongshan, and Zuhai
2	Shanghai – Changzhou	China	50,302,212	28,010	1,796	90	Changzhou, Jiaxing, Shanghai, Suzhou, and Wuxi
3	Tokyo (Kanto Region)	Japan	42,797,000	32,424	1,320	29	Prefectures of Chiba, Gunma, Ibaraki, Kanagawa, Saitama, Tochigi, and Tokyo
4	Beijing-Tianjin	China	40,594,839	34,588	1,174	50	Beijing, Langfang, and Tianjin
5	Delhi	India	34,397,873	15,562	2,210	3	Delhi, Nodia, Gurgaon, Ghaziabad, Rohtak, and Meerut
6	New York – Philadelphia	United States	30,907,175	54,880	563	96	Atlantic City, Jersey City, New Haven, New York, Philadelphia, Trenton, and Wilmington
7	Chongqing	China	30,165,500	82,403	366	46	Chongqing Province
8	São Paulo	Brazil	29,740,692	23,556	1,263	0	Baixada Santista, Campinas, Santos, São José dos Campos, São Paulo, and Sorocaba
9	Jakarta	Indonesia	28,424,717	6,438	4,415	46	Bekasi, Bogor, Depok, Jakarta, and Tangerang
10	Mumbai	India	26,136,721	17,313	1,510	38	Districts of Mumbai, Mumbai suburban, Palghar & Raigad, Thane
11	Seoul - Incheon	South Korea	25,524,572	11,807	2,162	39	Gyeonggi Province, Incheon, and Seoul
12	Manila	Philippines	25,169,197	8,113	3,102	30	Provinces of Bulacan, Cavite, Leguna, Rizal, and the National Capitol Region
13	Dhaka	Bangladesh	24,952,038	9,353	2,668	0	Districts of Dhaka, Gazipur, Munshiganj, Mymensingh, and Narayanganj within Dhaka Division.
14	Karachi	Pakistan	23,500,000	3,527	6,663	1	Karachi Administrative District
15	Mexico City	Mexico	23,492,352	11,317	2,076	6	Metropolitan areas of Mexico City, Tianguistenco, Toluca, Tula, and the municipality of Tepeji del Río de Ocampo
16	Cairo	Egypt	21,455,656	6,649	3,227	0	Al Qalyubia, Cairo, and Giza Governorate
17	Hangzhou – Ningbo	China	21,218,301	34,936	607	24	Hangzhou, Ningbo, and Shaoxing
18	Osaka	Japan	20,750,000	27,351	759	6	Prefectures of Hyōgo, Kyoto, Osaka, Nara, Shiga, and Wakayama; including the cities of Himeji, Izumisano, and Kobe
19	Kolkata	India	20,608,327	18,885	1,091	1	Districts of Hooghly, Howrah, Kolkata, North 24 Parganas, and South 24 Parganas
20	Lahore	Pakistan	20,530,000	12,631	1,625	0	Districts of Gujranwala, Kasur, Lahore, and Sheikhupura
21	Moscow	Russia	19,002,220	33,262	571	19	Moscow City and the more urbanized portions of the Moscow Oblast
22	Los Angeles	United States	18,679,763	87,944	212	13	Long Beach, Los Angeles, Oxnard, and Riverside
23	Ho Chi Minh	Vietnam	18,051,200	23,724	761	7	Ho Chi Minh City and Provinces of Bà Rịa-Vũng Tàu, Bình Dương, Đồng Nai, Long An, Tây Ninh, and Tiền Giang
24	Bangkok	Thailand	17,718,258	21,028	843	20	Provinces of Bangkok, Chachoengsao, Chon Buri, Nakhon Pathom, Nonthaburi, Pathum Thani, Rayong, Samut Prakan, and Samut Sakhon
25	Chengdu	China	17,663,383	18,115	975	24	Chengdu and Deyang
26	Xiamen	China	16,469,863	25,792	639	20	Quanzhou, Xiamen, and Zhangzhou
27	Istanbul	Turkey	16,437,489	8,808	1,866	7	Istanbul and Kocaeli provinces, including the districts of Gebze and İzmit
28	Tehran	Iran	15,450,000	18,814	821	0	Provinces of Alborz and Tehran, including the cities of Eslamshahr, Karaj, and Varamin
29	Buenos Aires	Argentina	15,333,035	11,134	1,377	1	Greater Buenos Aires and La Plata Metropolitan Areas
30	London	United Kingdom	14,031,830	12,091	1,161	8	London and the districts of Essex, Hertfordshire, Kent, and Surrey
31	Shantou	China	13,943,141	10,660	1,308	0	Chaozhou, Jieyang, and Shantou
32	Johannesburg – Pretoria	South Africa	13,937,500	22,017	633	1	Gauteng Province (including Johannesburg, Midrand, and Pretoria), and the municipality of Madibeng
33	Bangalore	India	13,093,168	13,139	1,297	0	Districts of Bangalore, Krishnagiri Districts, and Ramanagara
34	Kinshasa – Brazzaville	Democratic Republic of Congo	13,271,392	10,229	997	0	Brazzaville and Kinshasa
35	Rhine – Ruhr	Germany	12,695,656	14,160	640	0	Bonn, Cologne, Duisburg, Düsseldorf, Essen, Mönchengladbach, and Wuppertal
36	Chicago – Milwaukee	United States	11,970,050	37,324	1,154	31	Chicago, Kankakee, Michigan City, Milwaukee, Naperville, and Schaumburg
37	Lagos	Nigeria	12,864,745	20,107	1,749	0	Lagos State, Ogun State
38	Rio de Janeiro	Brazil	12,678,779	7,249	1,537	0	Belford Roxo, Dudue de Caxias, Nova Iguaçu, Rio de Janeiro, and São Gonçalo
39	Chennai	India	12,373,088	8,052	705	0	Districts of Chennai, Kancheepuram Districts, and Thiruvallur
40	Hyderabad	India	12,273,352	17409	1,005	0	Districts of Hyderabad, Medak, and Ranga Reddy
41	Paris	France	12,073,914	12,011	321	2	Departments of Essonne, Paris, Seine-Saint-Denis, Seine-et-Marne, Val-de-Marne, Val-d'Oise, and Yvelines
42	Nagoya	Japan	11,321,000	21,567	525	4	Prefectures of Aichi, Gifu, Mie; including the cities of Nagoya, Toyohashi, and Tsu
43	Wuhan	China	10,834,056	10,088	1,074	29	Ezhou and Wuhan
44	Taipei	Taiwan	10,280,569	5,209	1,974	6	Hsinchu, Keelung, New Taipei City, Taipei, and Taoyuan
45	Shenyang	China	10,244,261	24,132	425	41	Fushun and Shenyang

Table 2.4. World megacities, with jurisdictions included in this study highlighted. More than 500 million people currently live in these megacities, and there are more than 600 buildings 200 meters and taller located in these megacities. Source: Safarik, Ursini & Wood, 2016.

	Average annual number of natural disaster events, 2005–2014 (typhoons' proportion of disasters)	Tall buildings affected by typhoon event before 2016	Tall buildings in typhoon prone area – existing, December 2017	Tall buildings in typhoon prone area – under construction, December 2017
Australia	4 (43.5%)	68	170	27
Bangladesh	6 (52.8%)	1	5	4
China	29 (33.2%)	300	1,675	387
Hong Kong, China	1 (78.3%)	575	819	12
India	16 (22.7%)	6	25	5
Japan	6 (55.4%)	470	564	10
New Zealand	1 (32.3%)	5	10	0
Philippines	18 (51.3%)	74	144	47
South Korea	2 (51.6%)	192	371	21
Taiwan, China	3 (81.3%)	78	102	12
Thailand	4 (25.7%)	0	0	0
Vietnam	7 (48.7%)	9	102	57
Total number	**–**	**1,778**	**3,987**	**582**

Table 2.5. Asia-Pacific jurisdictions' tall building development and average typhoon occurrences. Total number of tall buildings in the 12 Asia-Pacific jurisdictions is 7,086 as of December 2017. Sources: Prevention Web, UNEP/UNISDR, and CTBUH.

Currently, more than double the amount of historically affected buildings (3,987) have now been built in these same areas that have experienced a cyclone event in the past, with a further 582 currently under construction. In this analysis, 7,086 buildings, complete or under-construction were examined. More than half of those (4,569) are located in typhoon-prone areas (see Table 2.5 and Figure 2.5).

One might draw confidence from the fact that in Thailand, no complete or under-construction tall buildings experienced a typhoon event in the past 45 years, but this would be unwise. Considering the increase in severity and frequency of major cyclone events, it is more than likely that the past events do not fully represent the geographic scope that the storms will reach in the near future. Consequently, buildings in areas that have not experienced past events could very well experience a typhoon in the future.

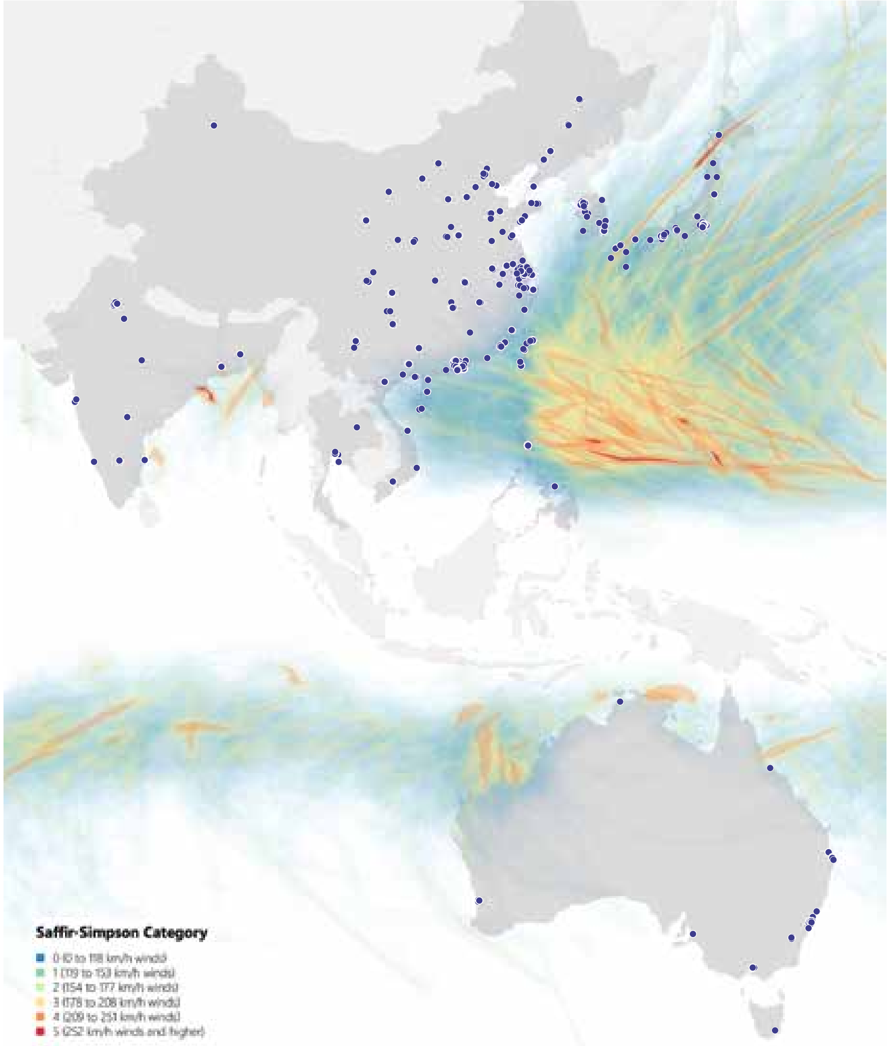

Figure 2.5. Cities in the Asia-Pacific region with at least one 150-meter-or-taller building, cross-referenced with historical average of cyclone wind speeds, based on the Saffir-Simpson scale, 2017.
Sources: Prevention Web, UNEP/UNISDR, and CTBUH.

3.0 Development of Cyclone-Resistant Façade Standards

3.1 First Steps: Australian Standards

Since the mid-1960s, there has been an attempt to codify the impacts of strong winds on structures, with the determination of return periods based on limited data of wind gusts in tropical regions of Australia (Holmes, Kwok & Ginger 2012). Previous to this, in 1952, the Standards Association of Australia (SAA) published the *Int. 350 Minimum Design Loads on Structures* (SAA 1952). This document started the practice of "referenced documents" in building regulations, and it was in effect until there was a change in designation to AS 1170 (SAA 1971), which is still in place today (Pham 2007). The Int. 350 is the first Australian national loading specification issued in the absence of any national building regulation.

In the early morning of Christmas Day, December 1974, the city of Darwin, in the Northern Territory, was hit by Tropical Cyclone Tracy and suffered massive damage and loss of life (Walker 2010) (see Figure 3.1). The anemometer at Darwin Airport recorded a gust of 217 km/h before the recording failed. Estimates based on previous readings suggest that peak gusts associated with Tracy were most likely in the range of 217 to 240 km/h, corresponding to maximum mean winds (10-minute average) of 140 to 150 km/h. This was among the most destructive storms ever recorded in Australia, after Severe Tropical Cyclone Althea, which hit Townsville, Queensland in 1971 (see Figure 3.2). This was not the first time Darwin had been severely damaged by a cyclone: it was also hit in January 1897 and March 1937.

In the aftermath of Cyclone Tracy, The Darwin Reconstruction Commission (CA 2276) was established through the Darwin Reconstruction Act of 1975, which mandated the city's rebuilding. There was also a report commissioned by the Australian Department of Housing, which found that a major factor in the extreme damage to housing appeared to be the loss of roof cladding, which led to significant loss of strength in many structures, which led to their structural collapse. The production of a large amount of wind-blown debris became a major agent in the further damage to buildings, thereby creating a chain-reaction effect. Over 90 percent of all houses in Darwin had significant loss of roofing, as did approximately 70 percent of all other structures. The means of attachment of all types of roof cladding proved inadequate, and it appeared that a reduction in strength due to fatigue under repeated loads played a significant part in this.

As a result, more focus was placed on improving the performance and integrity of structures in areas subject to extreme winds in cyclonic areas (Mason & Haynes 2010b) because it was evident that the damage to glazing systems, caused by windborne debris, represented a serious threat to the safety of building occupants during storms, and could contribute significantly to post-event recovery costs (Murphy 1984).

With the establishment of the Commission, the *Darwin Area Building Manual* of 1975 introduced the general requirement to test any material used or proposed to be used in construction

Figure 3.1. Darwin, after Cyclone Tracy, 1974. © Bill Bradley (cc by-sa)

of a building, and potentially prohibit the use of materials not compliant with the requirements of the manual or found to be unsuitable or unfit for the purpose. It is also stated under the manual's structural provisions that, where a material or form of construction is not covered by an Australian Standard, test evidence carried out by a laboratory registered by National Association of Testing Authorities may be accepted. This influenced Australia to develop a technically upgraded solution to protect windows from flying debris in strong-wind conditions.

With particular focus on doors, windows and cladding, the manual stated that the protection of openings is considered adequate if it has demonstrated the capability to resist a 4-kilogram mass having a 50-by-100-millimeter impacting cross section striking at any angle, at a velocity of 20 m/s, without affecting internal design pressure. When subjected to a test, the glazing could be fractured, but had to withstand the impact, which represents an energy of 800 Joules without penetration. The cracked glass was then subjected to the full design wind pressure applicable to the cyclonic region. The cracked glass should be able to resist the pressure without any air leakage, provided the edges of the glass were properly held to the frame using an adhesive glazing compound. That is, the critical part of the design was not only the glass being adequate, but also the cracked glass needed to adhere to the frames to prevent the entire glass panel being forced out of the supporting frame. This can be considered the first "cyclone-resistant glazing".

Figure 3.2. Damage to a hotel in Townsville, Queensland, after Cyclone Althea, 1971.
© City Libraries Townsville (cc by-sa)

Innovative testing of glass was developed in a laboratory in Pilkington, Australia in 1975. This testing procedure became the basis in the development of modern standards to address impact resistance from windborne debris loading. Subsequently, in 1977, the Australia Bureau of Meteorology, Department of Sciences, published the *Report on Cyclone Tracy, December 1974* (ABM 1977).

The guidelines defined within the Darwin Area Building Manual were not mandatory for all the Australian cyclone-prone regions and, as a consequence, these were not widely adopted, because the designers felt them too conservative for lower-risk areas (Walker & Reardon 1987).

In 1978, the Experimental Building Station, Department of Construction published *Technical Record (TR) 440, Guidelines for the Testing and Evaluation of Products for Cyclone-Prone Areas* (EBS 1978). It was issued as an outcome of a workshop, where the subject of discussion was the weak adoption of the standard testing procedures set forth by the Darwin Area Building Manual. The TR 440 focused on two main areas: "the nature of winds and the response of buildings and building components to them; and the development of valid methods of performance testing" (EBS 1978). The aim of these modifications to the impact speed was to ensure the implementation of the minimum level of performance in terms of flying debris resistance for all cyclone-prone areas in Australia.

TR 440 generally agreed with the recommendations of the Darwin Area Building Manual with regards to debris impact criteria and internal pressurization. TR 440 specified that the approved level of debris protection should be reduced from a 20 m/s projectile to 15 m/s, using the same 50-by-100-millimeter timber. This reduction in projectile velocity was a result of research conducted after Cyclone Tracy (EBS 1978).

TR 440 also differed from the Darwin Area Building Manual with respect to serviceability design pressures. These were based on a 25-year return period, and the assumption was that no dominant openings were present. Therefore, windows and doors were assumed to fail under winds near to the ultimate design wind (Williams & Redgen 2012), where the high internal pressures were prescribed (EBS 1978).

In 1987, it was highlighted that TR 440 aimed to provide a standard performance level for reducing windborne debris damage to windows and doors, and consequential damages to the structure, which was permitted to be designed without considering dominant openings on the building envelope, if the windows were tested according to TR 440. Also, in TR 440, the requirement for metal roof cladding in cyclone-prone regions to withstand dynamic wind loading effects was agreed, but there was not any requirement of pressure cycling for windows. The discussion focused on the necessity of improving the façade performance testing, beyond the study of impacts, to the effect of continual wind loads, representative of the post-impact conditions in a cyclone event (Walker & Reardon 1987). After 1987, the need for the implementation of a testing procedure for cyclone-resistant façades became increasingly clear.

TR 440 was not a regulatory document, but immediately after its publication, it was taken as a reference standard for cyclone-prone Australian regions, such as the State of Queensland.

The events following Cyclone Tracy resulted in a national Australian standard, the 1989 version of AS 1170.2 (SA 1989). The same testing procedure defined by TR 440 was required within this standard. It also attempted to provide an alternative, simpler approach for smaller low-rise buildings, and to provide a more accurate determination of wind loads for tall structures with a significant dynamic response. A new feature of the AS 1170.2-1989 was the specification of high-return-period design wind speeds (i.e., 1,000 years) for ultimate limit-state design. This concept has since been adopted in the United States.

The 1989 Standard also contained numerous other changes, with revisions to shape factors for multi-span buildings, free-standing walls and roofs, and building frames, reflecting the extensive research carried out in the 1970s and 1980s. The cross-wind response of tall buildings was also incorporated in detail (for the first time anywhere in the world).

AS/NZS 1170.2:2002 (SA/SNZ 2002a) was the first combined Australian/New Zealand wind-action standard and was also a major revision in format compared to AS 1170.2-1989. Major changes in the AS/NZS 1170.2:2002 include:

- Variable annual probability of exceedance adopted for wind speeds, which replaced importance multipliers used in AS 1170.2-1989.
- The separate “simplified procedure”, and “detailed procedure: dynamic analysis”, used in AS 1170.2-1989 were removed, and a single design method based on a gust wind speed was adopted.
- Direction multipliers for wind speeds for all non-cyclonic regions were introduced, replacing directional wind speeds for capital cities only in AS 1170.2-1989.
- Methods based on mathematical formulae were introduced for calculation of hill shape (topographic) multipliers and for cross-wind dynamic response of tall buildings.
- The methods for dynamic response used for along- and cross-wind dynamic response in AS 1170.2-1989 were replaced with approaches based on a peak gust wind speed, consistent with the rest of the Standard.

In addition, numerous smaller changes, additions and adjustments to the tables of shape factors were incorporated. For the first time in its history, the 2002 edition of the Standard was later supplemented by the user-friendly Guide to *AS/NZS 1170.2:2002 Structural Design Actions – Wind Actions* (Holmes & King 2005), containing nine detailed examples of application of the Standard to various types of structure.

The 2011 revision of AS/NZS 1170.2 had a number of significant changes, and additional clauses have been incorporated. The principal changes are as follows:

- Windborne debris impact loading criteria were added.
- A torsional loading requirement in the form of an eccentricity of 20 percent of the breadth, b, applied to the along-wind loading. This was only prescribed for tall buildings greater than 70 meters in height.
- New wording required designers to treat closed doors and windows, particularly roller doors, as potentially dominant openings, unless it could be demonstrated that they are structurally capable of resisting the design wind loads.
- A new requirement on consideration of wind loads on internal walls and ceilings.
- Some changes on local pressure factors.

The 2011 revision of AS/NZS 1170.2 was based on recent research on the wind profiles in tropical cyclones and hurricanes in the United States. These regard the strong relationship between horizontal missile speed and distance traveled (Holmes, Kwok & Ginger 2012). The same criteria were considered in 2006 for the debris loading in *Design Guidelines for Queensland Public Cyclone Shelters* (Queensland Government 2006).

The basis of the required performances of windows and façades are based on the research "Trajectories of Windborne Debris in Horizontal Winds and Applications to Impact Testing" (Lin, Holmes & Letchford 2007). The research establishes ratios for missile speed in terms of wind gust speeds (ASCE 2018). The Texas Tech University wind tunnel was used, together with full-scale simulation using an aircraft (to produce strong winds) for this research release. The 0.4 x $V_{10,000}$ ratio for horizontal trajectories used in the Design Guidelines for Queensland Public Cyclone Shelters represents horizontal distance traveled, according to the plots by Lin et al., published in 2007.

For the 50-by-100-millimeter missile the quotient of 0.4 represents a horizontal distance traveled of about 3–5 meters; for the steel ball, the same proportion represents about 25–30 meters traveled. This percentage is appropriate for a timber missile for with spacing between houses of 7–8 meters, which would give a ratio of about 0.5 (according to the Lin et al. plots). Moreover, the ratio for the steel ball likewise appears reasonable, given that roof gravel flight is likely to be initiated at higher levels, and hence can travel farther (Williams & Redgen 2012).

> "The 1989 Australian cyclone-damage protection standard was the world's first to incorporate detailed research into tall buildings' cross-wind responses."

AS/NZS 1170.2:2011

Clause 5.3.2 – Openings
In Regions C and D, internal pressure resulting from the dominant opening shall be applied, unless the building envelope (windows, doors, and cladding at heights up to 25 meters) can be shown to be capable of resisting impact loading from windborne debris determined in accordance with Clause 2.5.7.

Clause 2.5.7 – Impact loading from windborne debris
Where windborne debris loading is specified, the debris impact shall be equivalent to:

a. *Timber member of 4-kilogram mass with a nominal cross-section of 50 by 100 millimeters, impacting on-end at 0.4 V_R for horizontal trajectories, and 0.1 V_R for vertical trajectories.*
b. *Spherical steel ball 8-millimeter diameter (approximately 2 grams mass) impacting at 0.4 V_R for horizontal trajectories, and 0.3 V_R for vertical trajectories.*

There is no provision for cyclic load testing post-debris impact for glass façades and debris screens in AS/NZS 1170.2:2011, and the building envelope components are required to be flying-debris-resistant for a height of only 25 meters from the ground level. The last requirement is based on research that states that the upper limit for flight initiation is 20 meters (Moghim & Caracoglia 2012). Whereas, the small projectile (2-gram steel ball) has been chosen, because it is representative of roof gravel, thus it could be higher than 25 meters.

3.2 US Standards

Eighteen years after the Darwin incident, in mid-August 1992, Hurricane Andrew hit the coasts of Florida, the Bahamas and Louisiana. This was the most destructive and costliest disaster event at the time, and maintained that title until Hurricane Katrina occurred in 2005. The highest winds were recorded in Miami-Dade County, Florida, between August 23 and 24, 1992, reaching 270 km/h. Hurricane Andrew was a Category 4 Hurricane on the Saffir-Simpson Scale, and caused US$25 billion in damage to local buildings, especially to their envelopes. It caused 44 fatalities in Florida alone (see Figure 3.3).

The South Florida landscape changed completely. Some 250,000 people were left homeless, and communication and transportation infrastructure were significantly impaired; there was tremendous loss of water, power and utilities (Cochran & Levitan 1994). At least 1.4 million people were left without power, and residential buildings remained "dark" for up to six months after Andrew occurred.

Andrew was the most powerful hurricane to hit South Florida in almost 30 years; there was a significant segment of the local population that had never experienced a hurricane. For these residents, the psychological impact was shocking. Many people decided to move to other cities and states, instead of repairing their homes and businesses. For people who decided to rebuild, the reconstruction process took years to complete.

Post-disaster event assessments highlighted various issues related to strong wind occurrences (FEMA 1993; Powell & Huston 1996). Similar to Australia, in years following the disaster event, the Florida Building Code developed curtain-wall provisions, which include strengthening building openings and glass surfaces to limit damage caused by high-velocity windborne debris (ICC 2014a). These codes, and the revisions introduced since, still represent the most stringent in the United States when it comes to impact-resistant façade systems (Marshall, Gilvary & Kestner 2012).

The Australian TR 440 (1978) was the basis for the introduction of impact test requirements for building façades and windows. The Florida impact test procedure improved upon Australia's; it differed from the Australian document because of well-identified points in which the missile had to impact the glazing building component, and the request for the specimen to withstand a cycling of positive and negative pressure after the impact test.

Another test procedure was used as the basis for the development of the Florida Building Code requirement: the non-mandatory reference standard *SBBCI Test Standards for Determining Impact Resistance from Windborne Debris* by the Alabama-based Southern Building Code Congress International (Shah 2009). This document was edited with the purpose of strengthening window glazing, in order to facilitate the glazing withstanding windborne debris, which can act as missiles that penetrate a building during a hurricane, and the push/pull force of the eye of a

Figure 3.3. South Florida landscape after Hurricane Andrew, 1992. © Bob Epstein/FEMA News Photo

hurricane. For the glazing system building component to pass the test for the voluntary product approval process, it has to withstand both the missile impact and, next, the pressure cycling.

The Florida Building Code was the toughest in the United States, and it was the first building code in which windborne debris requirements were introduced, in order to improve the impact resistance of façade systems to cyclone events. In 1994, the Florida Building Code began to introduce façade performance requirements, and the Florida Building Commission, regulating the High-Velocity Hurricane Zone (Wind Zone 4) introduced the Testing Application Standard (TAS) procedures (TAS 201-94, TAS 202-94, TAS 203-94 specified in the Florida Building Code).

Since 1996, the Miami-Dade County best practice includes the product approval program with the Notice of Acceptance (NOA). These are set forth by Miami-Dade County for all construction trades; Florida Product Approval organizes the owner's product acceptance.

The design of a cyclone-resistant façade to withstand the requested test for the product approval process does not consist solely of the changing of the glazing system. It is a complex process, in which many factors have to work together in order to reach the resilience needed by the window system. All the elements have to cooperate to resist first the impact test, then the cycling

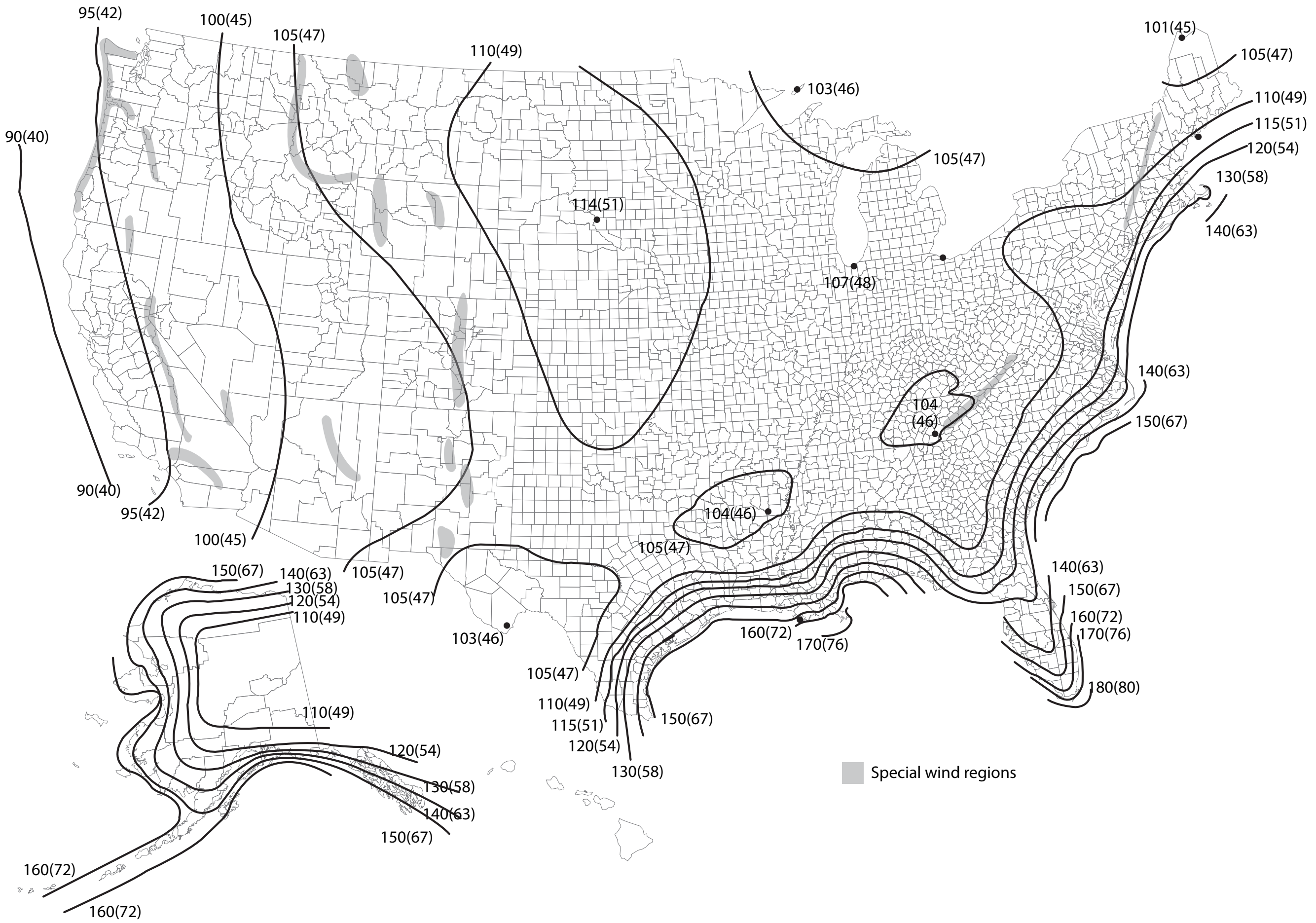

Figure 3.4. **ASCE 7-16 Risk Category II Basic Wind Speed Map.** © ASCE. Source: ASCE 7-16.

pressure test, which are associated with flying windborne debris and extreme winds, respectively. The design choice of the glass characteristics, the interlayer for glass lamination, and the fastening method all affect the performance of the building glazing system. By focusing on the window or façade's size, geometry, and design pressure, it is possible to proceed with the design of glass thickness and strength characteristics, and the interlayer material properties and thickness specifications.

Looking at extreme wind events, different kinds of damage on the glazing systems and building components have been observed. On the basis of this damage, the test requirements for cyclone-resistant façades and windows have been improved. In the contemporary tests, a large wooden missile is quite representative of tree branches, garbage cans, and other objects that typically impact buildings close to the ground level. These objects, during a cyclone event, normally build up enough energy to break windows and penetrate inside the building. Also, it has been noted that all building elevations could be impacted by small windborne debris during a cyclone event, where small debris could reach high velocity and break the glass of the façade.

From these realizations, testing procedures for small and large missile impact tests were developed. Then, the investigation pointed out that, during a cyclone event, alternating positive and negative pressure acts on the building envelope, and positive internal pressure develops if the envelope of the building is broken due to the impact of windborne debris.

The aim of impact-resistant building codes is to guarantee that new building constructions preserve their integrity without breaking during a cyclone event. US standards provide the most stringent testing requirements on the research topic. The Florida Building Code requirements were the first in the United States for building protection from windborne debris. These were the more stringent testing requirements since ASTM standards were developed, and are the most representative of a real storm event, as agreed by the scientific community. Hurricane-resistant building components have thus begun to follow a strict product approval process, which includes withstanding impact and pressure-cycling testing.

In the ASCE 7-16 (ASCE 2016), the main US Building Code, the wind zone map (see Figure 3.4) is shown to identify the windborne debris regions and the boundary for hurricane-prone regions. ASTM E1886 and ASTM E1996 requirements, or local standards requirements, whichever is more stringent, must be followed by buildings constructed in United States areas affected by hurricanes. Two ASTM standards dictate the glass composition for the building envelope, as well as the air infiltration control during a disaster event:

- ASTM E1996 Standard Specification of Exterior Windows, Curtain Walls, Doors, and Impact Protective Systems Impacted by Windborne Debris in Hurricanes
- ASTM E1886 Standard Test Method for Performance of Exterior Windows, Curtain Walls, Doors and Impact Protective Systems Impacted by Missile(s) and Exposed to Cyclic Pressure Differentials

The ASTM E1996 standard defines the parameters of the small and the large missile impact tests, and the pressure-cycling phase of the testing procedure. It introduces other parameters for testing, not mentioned in the AS 201-94, TAS 202-94, or TAS 203-94 (ICC 2014a), such as test temperatures. This is a very important parameter to control, as it often causes the failure of the test. This standard specifies "protection zones" and additional missile types for users. Furthermore, the ASTM E1996 identifies the testing performance requirements for vertical glazing and skylights based on Wind Zone as determined in ASCE 7. The design wind speed has to be taken into account, together with the risk category of the building; "enhanced protection," for example, refers to essential facilities such as fire rescue stations, emergency centers, and hospitals (see Table 3.1).

The ASTM E1996 identifies the number of specimens required for testing, both for large and small missile impact tests. Moreover, the location and number of missile impacts to be carried out on the façade are dictated. For large-missile impact resistance, impact locations are typically the center and corners of the glass panel. For test specimens with fixed and operable panels, operable panels have to be tested, with the corner impact near the locking device. For specimens with bracing, the impact should not be near the bracing. Finally, the ASTM E1996 determines pass/fail criteria for all impacts and cyclical testing.

Buildings designated as essential facilities require "enhanced protection." These include: hospital and health care facilities, police stations, fire rescue stations, emergency shelters,

Level	Description
1	Level 1 is advised for unprotected buildings and other structures, which are expected to have low hazard to human life in a cyclone or other severe storm. Buildings in this level may include, but are not restricted to, agricultural houses, temporary facilities, and storage facilities.
2	Level 2 is advised for protection of buildings and other structures which are expected to present a moderate hazard to human life in cyclones and other severe storms. Buildings in this level may include, but are not restricted to, houses, commercial, and industrial buildings.
3	Level 3 is advised for protection of buildings and other structures which are expected to present a substantial hazard to human life in cyclones and other severe storms. Buildings in this level may include, but are not limited to, major office buildings, schools, shopping centers, hotels, and other buildings and structures where a significant number of people congregate in one area.
4	Level 4 is advised for enhanced protection of essential facilities. Buildings in this level may include, but are not limited to, hospitals and other health care facilities, fire, rescue, ambulance, and police stations, and buildings and other structures having critical national defense functions or designated as storm shelters during a severe storm.

Table 3.1. Levels of Protection of Buildings, ISO 16932, 2016. Source: International Standards Organization (ISO).

> “The increase in code-specified missile speed resistance requirements has greatly increased glass and framing costs, resulting in buildings without cyclone-resistant glazing.”

communication shelters, jails and detention centers, and buildings that are critical to the national defense. The enhanced protection, compared to the basic protection of buildings in hurricane-prone areas, is consistently more demanding in terms of the mass of the missile for the impact test on the building envelope that has to be certified. The testing missile weights and speeds vary also, depending on the wind zone location of the building (ranging from Wind Zone 1, the least wind-prone, to Wind Zone 4, the most wind-prone).

The pressure cycling to conduct on the façade after the impact tests pass is based on the design wind pressure (inward and outward) from the building code, based on an unbreached building envelope. A total of 4,500 positive and 4,500 negative pressure cycles have to be conducted, and the duration of each cycle is 1–3 seconds.

The ASTM E1886 standard test method has been developed through a consensus process with the participation of manufacturers, consultants, building code officials, and other experts. The testing procedures and conditions have been clearly identified, and the allowable tolerances for testing standards for debris missile impacts and the cyclic program have been established.

There are some differences between the wind zone map represented in ASCE 7-05 and in ASCE 7-16. The wind maps are used to determine the wind zone and performance level needed for a building depending on its location. In ASCE 7-05, the wind speed is lower than that shown in the ASCE 7-16. This reflects the definition of a safer wind speed map based on climate change, but in the last edition of ASCE 7-16, the wind speed maps represent reduced wind speeds for much of the jurisdiction and clarify special wind study zones (including new maps for Hawaii).

3.3 International Standards

Internationally, areas in 209 km/h wind zones and higher, which are identified as windborne debris regions, are regulated by the International Code Council (ICC) (ICC 2014b), and the required debris missile resistance is defined. The International Building Code (IBC) (ICC 2015), developed by the ICC, as well as the International Organization for Standardization (ISO) 16932 (ISO 2016) which defines destructive windstorm-resistant glazing requirements, references the standards set in place by ASTM E1886 and ASTM E1996.

The main difference between the ISO and the ASTM testing procedure is in the testing of the glazing, or of the entire system constituting the building envelope. The ISO standard takes into account the glass installed in a standard metallic frame, whereas the ASTM tests the actual installation that will be used on-site.

3.4 Asia-Pacific Local Requirements

The Asia-Pacific Region is the most prone area to natural disasters (World

Bank Group 2017). This vulnerability partially relates to the lack of infrastructure in place for most Asia-Pacific jurisdictions to suddenly react in the case of a catastrophic event.

Typhoons in this region represent an inestimable danger in terms of interruption of public services and essential activities (see Figure 3.5). These are the territories where a large number of high-rises have been built in recent years, clad with curtain walls. But there are just a few jurisdictions that have introduced requirements for typhoon-resistant construction, and where glazed system components must be tested to withstand the impact, and then pressure-cycling testing of wind and debris.

Australia and New Zealand have their own rules for typhoon-resistant glazing building components. Australia was the very first developer of such kinds of requirements for buildings, in order to safeguard the structural integrity and protect the safety of occupants and property from devastating events. Even still, a precise standard testing procedure is not currently required by the actual codes and standards in these countries.

Thus, in order to take into account the goals of other relevant product-approval processes that had been tested under natural conditions (Miami-Dade County Compliance Office 2006), a discussion to define a general guideline could begin in the near future.

The 2011 edition of AS/NZS 1170.2 Structural Design Actions – Wind Actions included significant increases to speeds for the large missile tests, which are now higher than those specified in the United States. The speed of the 4-kilogram timber missile was increased from 15 m/s to 0.4 of the Regional Velocity (V_R). The value of V_R depends on factors including building importance (ABCB 1996a), and can be as high as 34 m/s in Queensland, and even higher in Western Australia. The basis for this increase was a conclusion from wind studies conducted in the United States, which determined that the 4-kilogram timber missile picked up by a 69 m/s wind gust would accelerate from 0 to 15 m/s in less than two meters (Lin et al. 2007). Previously, it had been concluded (in the JDH 99/1 report on *Debris Damage for Cyclone Shelter Buildings in Queensland*) that the 4-kilogram missile would have traveled almost a kilometer before reaching a speed of 20 m/s, and that this "is clearly an extreme event."

The increase in missile speed in AS/NZS 1170.2:2011 has greatly increased the cost of glass and framing that can meet the new requirements. As a result, buildings are being built without cyclone-resistant glazing.

Figure 3.5. Debris in Osaka after Typhoon 21 Higobashi, which hit Japan in September 2018. © Totti (cc by-sa)

Furthermore, Note 5 in Clause 2.5.8 of AS/NZS 1170.2:2011 Amendment 4 (August 2016) states:

> *This Standard does not specify a test method or acceptance criteria. Acceptance criteria may vary according to the purpose of the test. An appropriate test method and acceptance criteria for debris tests are given in Technical Note No. 4: Simulated Windborne Debris Impact Testing of Building Envelope Components, Cyclone Testing Station at James Cook University.*

This is an "Advisory Note." Standards Australia Standardization Guide 009 *Preparation of Standards for Legislative Adoption* states that Advisory Notes "shall not suggest a higher level of conformity than required, nor provide alternatives to, or allow exemptions from, the normative content (of the standard)."

Cyclone Testing Station (CTS) *Technical Note No. 4: Simulated Windborne Debris Impact Testing of Building Envelope Components* still does not include the cyclic pressure testing required by the Building Code Board of Australia for metal roofs in cyclonic areas. This test is included for cyclone-resistant windows in the Florida and ASTM hurricane testing protocols, because the resistance of windows containing laminated glass to cyclic pressure such as that encountered in cyclones is representative of the natural phenomena. This is the reason for the common adoption of an ionoplast interlayer for the 4-kilogram missile impact test in the United States.

In a public lecture in November 2017, Dr. Geoff Boughton of the Cyclone Testing Station at James Cook University strongly emphasized that currently no debris impact test method exists in Australia. Furthermore, in this occasion he said that "the industry is getting together and putting together a test standard. We are hoping it will be out in the next couple of years."

Page 20 of the *Wind Loading Handbook for Australia and New Zealand -* Background to AS/NZS 1170.2:2011 Wind Actions revealed the source for the decision to increase the missile speed in the impact test from 15 m/s to 27.6 m/s for Region C (Queensland): "The research by Lin et al. (2007) clearly indicates that a missile speed of 15 m/s in a windstorm producing 69 m/s gusts will be attained in a very short distance of travel – less than 2 meters in fact."

AS/NZS 1170.2:2011 has resulted in continuing confusion in the Australasian market, as evidenced by the fact that:

- Despite Note 5 of Amendment 4 and Dr. Boughton's lecture, a glass company in New Zealand claims its cyclone-resistant glass "is certified to AS.NZS 1170.2:2011".
- Azuma Design has a "Debris Testing Facility for building products, compliance to AS 1170" and issues letters of compliance.
- The Cyclone Testing Station at James Cook University also offers testing of cyclone-resistant glazing.

In other Asia-Pacific jurisdictions, different approaches have been identified for building codes and standard minimum design requirements.

Looking at the 12 jurisdictions analyzed in this research, only three outside of Australia and New Zealand have introduced standard testing procedures for typhoon-resistant glazing systems: Japan, Bangladesh, and the Philippines. The relevant standards are *JIS R 3109:2018 Glass In Building – Destructive-Windstorm-Resistant Security Glazing – Test Method,* established July 20, 2018; Housing and Building Research Institute, 2004, Bangladesh National Building Code; and Association of Structural Engineers of the Philippines, 2015, C101-15, NSCP (National Structural Code of the Philippines). These standards also reference the ASTM standards, despite their geographic location being closer to Australia.

In the following sections of this publication, the approaches to cyclone-resistant glazing of four jurisdictions are presented, with building case studies and detail, explaining the roles and responsibilities of various professionals involved in façade design.

The Philippines and Bangladesh directly refer in their building code requirements to the ASTM standards for flying-debris impact resistance. However, Japan, in its JIS R 3109:2018 (established July 20, 2018, investigated by the Japanese Industrial Standard Committee, and published by Japanese Standards Associations), requires performance against the effects of the windborne debris, according to *ISO 16932 Glass In Building – Destructive-Windstorm-Resistant Security Glazing – Test And Classification* (ISO 2016).

ISO 16932 doesn't take into account the entire façade system, only the glass and its impact resistance to standardized projectiles. The result is that the façade still doesn't have to be certified as a technological system; the certification applies only to the glass provided by the glass supplier.

Recently in Japan, several research activities were conducted by the Building Research Institute (BRI) in collaboration with the Disaster Prevention Research Institute (DPRI) of Kyoto University (Maruyama 2014). These institutes studied all the available standards and performances to be stipulated for typhoon-resistant building envelopes. They noticed that typical building components (such as roof tiles) would affect the impact in case of strong wind conditions. The ASTM E1886 and E1996 standards were shown as inadequate for their standardized impact requirement, when contextualized to the Japanese urban environment.

Safety coefficients were developed by the DPRI in collaboration with the BRI, simulating the flight of various objects of different shape and materiality (e.g., steel pipe sections, Japanese roof tiles, etc.). Kyoto University, and in particular Prof. Maruyama, also conducted physical tests with specialized missiles that hadn't been tested in the United States. This research involved firing traditional Japanese roof tiles from an air cannon. The output of the software simulation, where various different object trajectories had been modeled, showed that the projectile weight and speed both have to be increased in order to show the window/façade systems absorbing realistically high levels of energy carried by projectiles under strong wind conditions.

Jurisdiction	Code/Standard Requirements
Australia	AS/NZS 1170.2:2011
Bangladesh	ASTM E1886, ASTM E1996
China	None
Hong Kong, China	None
India	None
Japan	JIS R 3109:2018
New Zealand	AS/NZS 1170.2:2011
Philippines	ASTM E1886, ASTM E1996
South Korea	None
Taiwan, China	None
Thailand	None
Vietnam	None

Table 3.2. Asian jurisdictions' cyclone-glazing test requirements.

The above-mentioned jurisdictions are the only ones in the Asia-Pacific region that have typhoon-resistant curtain wall requirements. Although jurisdictions like China, Taiwan, Hong Kong, and India have been, and continue to be affected by typhoons, they are not introducing any kind of requirements to ensure buildings and people are safeguarded.

From the various parties consulted by CTBUH, it is evident that a major problem faced by contractors operating in the Asia-Pacific region is that bids for new projects can be over-exhaustive and contain a generic list of codes. It is often up to the contractor to decide which one to comply with. Many international codes are frequently mentioned but, in most cases, no façade testing reports are required by the building authorities (see Table 3.2).

4.0 Cyclone-Resistant Façade Technologies

4.1 Façades in Cyclone-Prone Areas – Main Threat: Flying Debris

The major threat to façades in severe storms is represented by the windborne debris that could potentially impact the glazing system and create an opening in the building envelope. This failure would increase internal pressurization and, in this way, the other outer walls could potentially collapse if the structure is not designed to sustain the high wind pressure of a typhoon event. Furthermore, when the building envelope breaks, a typical follow-on event is the detachment of the roof. Another consequential effect is damage from wind-driven rain penetrating the building's interior.

The volume and effect of windborne debris, according to the current best practices in terms of code and standard testing, varies based on the building location, maximum wind speed, and height. It is evident that the potential debris sources are also related to surrounding constructions and vegetation (plants, trees, etc.), and other sources of debris, such as trash bins, signs, and so on.

Several international studies have been conducted that aim to understand the effects of various debris sources (Maruyama et al. 2013). Furthermore, calculating the risk from flying debris in typhoon events is very complex (ASCE 2018). Data variables in that risk calculation include: the ability of a structure to absorb flying debris impact; the impact energy; and the trajectory of the debris flight. These factors also vary depending on the intensity of the typhoon event.

The unpredictable occurrence of these disaster events does not allow for precise estimation of the possible loss, and it presents an obstacle for developers and building owners to calculate the return on their investments in typhoon-resistant façade solutions.

The typical debris in a typhoon include missiles (tree branches, fences, etc.), roof gravel, roof tiles, signage, portions of other damaged structures carried on the wind, and metal sheets. The impact energy has to be absorbed by the façade system if building failure is to be prevented. The flying debris does not have to penetrate the façade to cause building failure, therefore, "in windborne-debris regions, door and window assemblies must be specified to resist test missile loads specified in ASTM E1996-14a (ASTM 2014)" (ASCE 2018).

4.2 Cyclone-Resistant Façades – Main Characteristics

Façade resilience is needed to provide adequate safety during a typhoon event. This characteristic aims primarily to avoid broken glass. When breakage occurs, the glass could injure people and, in order to avoid this, requirements for tempered glass should be introduced. Further, the whole façade system needs to be designed properly. During a wet disaster event such as a typhoon, if the glass breaks, inevitably the internal property loss could carry a significant recovery cost in terms of furniture, electronic devices and documents. The framing system design and the installation of the glass in the framing system are two important components that need to be analyzed and properly designed.

The frame is commonly designed to avoid the glass being ejected from this retaining system when subjected to high wind pressure. In this perspective, the curtain wall frame is stronger, compared to a façade not exposed to typhoon winds. Furthermore, the glass bite is normally deeper, in order to let the façade system work as a unit (consisting of glass, sealant, and frame) with the aim to protect interiors from atmospheric threats.

If the aim is that a glazing system be effective in mitigating damage from windborne debris, the entire system needs to be designed properly to resist the storm event. All the window and curtain wall components (the framing system and the glass installation within that system) must be designed to perform during a cyclone event. When designing glazing systems, it is important to understand what kind of wind loads the building will experience. The impact test requirement will be determined by building location and wind zone. The pressure cycling required will be determined not only by the wind zone region, but also by the shape, height, and location of the building, both in relation to other buildings and the size of the window itself. This becomes more important in urban settings, where the wind loads can increase due to the surrounding buildings, resulting in a wind-tunneling effect.

Laminated glass could be defined as "cyclone glass" when it guarantees a precise level of performance. The composition used in typhoon-resistant glass must resist both the wind load and the missile impact specified by codes. The thickness of the glass lites in the laminated glass is determined by the wind load and the interlayer type. However, resistance to penetration by missile impact is determined by the interlayer type and the thickness of the interlayer. The interlayer thickness relates to missile impact speed, not to design wind load. It works by coupling two or more lites of glass with one or more interlayer elements (see Figure 4.1). This guarantees glass retention if breakage occurs. The main interlayer types are polyvinyl butyral (PVB) and ionoplast.

Both PVB and ionoplast interlayers have been used successfully in laminated glass for hurricane glazing systems. PVB is a soft interlayer and works well when the design pressure is lower and the missile size is smaller. Because of the low stiffness, laminates using PVB tend to not perform well when the design pressure is high. The high wind pressures can cause the laminate to pull out of the frame during the cycling portion of the test, and therefore typically will need better frame design or a thicker interlayer and/or glass. The laminate is at risk of becoming detached with high wind pressures during the final pressure cycling testing (ASTM 1996).

Ionoplast was introduced in 1998 in South Florida; it can meet the highest performance criteria required for impact resistance (large missiles D and E from ASTM E1886 and ASTM E1996). Being a stiff interlayer, it provides added strength and rigidity, and remains intact after the pressure cycling test. This could potentially allow a lower grade of glass to be used, saving costs. Another advantage of the ionoplast interlayer is the possibility it gives to the glazing system to be dry-glazed, reducing installation costs and time, as compared to the traditional wet-glaze system installation. It is not possible to design a dry-glaze system with laminated glass that uses PVB interlayers, because the resulting product will be too flexible. Table 4.1 illustrates the differences between the three kinds of window assemblies. See Figure 4.2 for an example of an ionoplast installation.

However, in the testing for the product approval process, the aim is not just to test the components, but the whole system. In this way, the glass can be pre-dimensioned based on the size of the specimen and the impact velocity of the missile, but it is necessary to

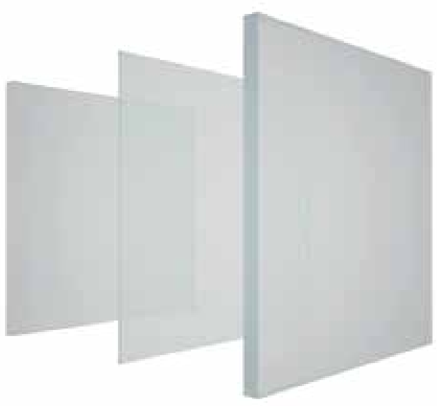

Figure 4.1. Laminated glass: two glass lites and one interlayer. © Michele Bettineschi

Type of Assembly	Description
Typical Construction	• 6-mm heat-strengthened (HS) glass + 2.28-mm interlayer + 6-mm HS glass for large missile impact • 6-mm HS glass + 1.52-mm or 0.89-mm interlayer + 6-mm HS glass for small missile impact
Polyvinyl Butyral (PVB)	• Typically used in 2.28 mm thickness for relatively small glass panel sizes and low pressures in large missile-impact resistance applications • Small missile-impact resistance typically uses a 1.52 mm thickness • Available in clear or colored tint • UV-filtering
Ionoplast	• Typically used for high design pressures, large windows, and large missile impacts • Can be used in dry-glaze systems - lower cost and easier installation • High-modulus interlayer used to bond two lites of glass together • 100x stiffer than PVB, 5x more tear-resistant • Thicknesses include 0.89 mm, 1.52 mm, 2.28 mm • UV-filtering • UV-transparency available • Available in clear or translucent white • Less sensitive to moisture intrusion at the laminate edge than PVB

Table 4.1. Typical window assembly descriptions and cyclone-resilience capabilities.

Figure 4.2. Porsche Design Tower, Miami (2017) extensively uses ionoplast interlayers in its façade. © Angela Mejorin

verify that the system can withstand testing requirements. Impact testing and subsequent application of pressure cycles and depression must present positive results for approval of the window to be used.

Wet- and dry-glazed systems are both logical options for flying-debris-resistant façade solutions.

The wet-glazed systems are often used for shop-glazed fenestration products, and they are commonly used in high-velocity hurricane zones (Wind Zone 4). PVB-based interlayers in large-missile impact applications must be wet-glazed to pass the required cycling test.

Dry-glazed systems are especially suitable for glazed fenestration systems that need to be assembled on the job site. These systems eliminate the use of wet sealants and more closely replicate the "as-tested" conditions. The large-missile impact systems have been certified up to ±6.2 kPa. The dry-glazed systems represent a cost savings in terms of labor and materials, and further potential savings from replacing broken glass (such as after a hurricane event).

4.3 Hurricane Events Tested the Resilience of US Buildings

In the United States, building codes and standards are in place to regulate glazing in windborne-debris regions. The testing requirements vary according to the location of the glazing within the building, according to the importance level of the building and the wind zone location of the building.

In 2005, Florida was hit by Hurricane Wilma. It represented the first incident that could be used to understand if typhoon-prone buildings regulated by the Florida building code (TAS 201-94 Impact Test Procedures and TAS 203-94 Criteria for Testing Products Subject to Cyclic Wind Pressure Loading) worked appropriately (ICC 2014a). Two significant reports enumerated some of the key post-event observations:

Post-Hurricane Wilma Progress Assessment, Miami-Dade County Building Code Compliance Office, April 2006

Glass and glazing:

- High-rise buildings in isolated areas of the county were affected

- Loss of glazing in balcony railings, sliding glass doors, curtain walls and windows did occur
- None of the damage was observed in buildings constructed under the most recent building code
- In those isolated cases where the building envelope was breached, interior damage due to water intrusion and internal pressurization occurred, causing collateral damage

Building construction elements: effectiveness confirmed

- Window, curtain wall and sliding-glass-door frames tested under the current impact tests (TAS 201-94)
- Glass tested under the current impact tests (TAS 201-94)

Performance of Laminated Glass During Hurricane Wilma in South Florida, Glazing Consultants International LLC, September 2006

- Survey buildings utilizing laminated glass with SentryGlas® or Butacite® PVB interlayer that were in the path of Hurricane Wilma in South Florida and to report the findings
- Eighty-two properties in the path of Hurricane Wilma were built with these interlayer products and were surveyed: 71 percent had no damage; 18 percent had broken glass but no glazed system failure; 11 percent of the interviews had no answer or vague responses.
- Differences can be observed between the building glazing systems that had been installed under the most-updated building code and those which had not, which were heavily damaged by Hurricane Wilma (see Figure 4.3).

In 2017 and 2018, the period during which this research project was carried out, further disaster events occurred in the United States. Hurricane Michael, a Category 4 hurricane that hit the Florida Panhandle in October 2018, with sustained winds of 250 km/h, is significant to understanding the importance of the very strict requirements that the Florida Code has in its general application (see Figure 4.4). In Florida, there are two different reference codes for building construction: they are the Florida Residential Code (FRC) (ICC 2017b) and

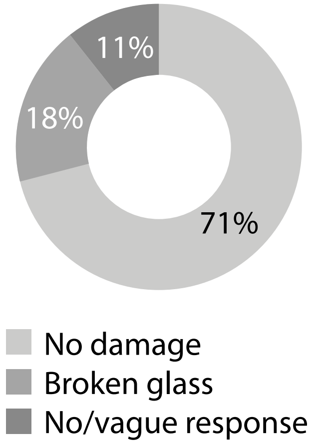

Figure 4.3. Results of a survey of buildings with interlayers, asking about the level of damage incurred during Hurricane Wilma, 2005.

Figure 4.4. The damage to Florida's Panhandle by Hurricane Michael, 2018, was significant. © Jeff Gammons.

> “When Hurricane Wilma hit Florida in 2005, none of the high-rise buildings constructed to the current code at the time sustained damage to their glass or glazing assemblies.”

the Florida Building Code (FBC) (ICC 2017a). The FRC provides rules and guidance for the construction of one- and two-family dwellings, whereas the FBC addresses all other buildings and structures. The 2010 Florida Building Code was based on the effective IBC 2009, and this reference document did not incorporate the specifications of ASCE 7-10. With the 2012 and subsequent revisions, ASCE 7-10 served as the foundation of the Florida Building Code.

In 2000 the State of Florida released its first statewide building code, which was published incorporating a “Panhandle Exemption”. It stated the non-mandatory application of the more stringent requirements regarding wind design, but only for buildings more than 1.6 kilometers inland. Hurricane Michael provided an occasion to observe the existing differences that were noticeable even within the same US state during the same event. It confirmed the effectiveness of the testing procedures adopted in hurricane-prone regions in order to prevent any significant damage to the building envelopes and property. After Hurricane Ivan occurred in 2006, the exemption for the Florida Panhandle was repealed under Legislation HB 7A – Building Code Hurricane Preparedness (Florida Senate 2007). Hurricane Michael’s effects highlighted that the past decision not to include the stricter requirements related to windborne-debris resistance of building envelopes was compromising the resistance of the urban environments to these strong wind-related events (StEER 2018).

4.4 Australian Resilience Tested

In the aftermath of Cyclone Debbie in April 2017, window systems were realized in accordance with Australian code requirements for protection from flying debris. Australian experts highlighted that problems related to penetration nevertheless occurred in recent cyclone events. Many occupants of newer buildings reported significant damage from wind-driven rain entering through windows and doors or under flashings, even though there was no structural damage to the building. Many people reported mopping up water in front of windward window-walls during periods of maximum winds, which exposed them to risk of injury. Further research is required to improve performance of building elements that leak during high wind events (CTS 2017b).

Australia’s lack of pressure-cycling testing for wind-driven rain performance represents a gap, causing cyclone conditions to have a negative effect on the safety of internal property.

Section 4.9.3 on “Glass failure” begins with the statement: “Many newer doors that broke during the cyclone had toughened glass that fractured into small pieces, or laminated glass that remained substantially intact."

The report contains numerous photos of broken toughened glass in doors, balustrades and pool-fence applications. However, it fails to recommend the use of laminated glass for these applications.

There is a weakness in the Australian National Construction Code (NCC), such that windows in housing are only required to be tested for water-penetration resistance against a static pressure, which does not reflect the real-life wind gust conditions that occur in a storm. However, changes to the existing glazing products used in housing to achieve higher water penetration resistance may detrimentally affect the affordability of housing. A lifecycle cost-benefit evaluation, including initial cost increase vs. long-term insurance premiums, rectification costs and public risk, should be undertaken in order to have a better understanding of the return on investment of changes made in observance of cyclic-pressure requirements.

4.5 Shutters: The Alternative Solution for Flying Debris Protection

Beyond laminated glass, there are different existing shuttering solutions for windows on the market, such as storm panels, perforated hurricane barriers, and accordion-, roll-down-, "Bahama"- and colonial-type shutters. When the hurricane/cyclone/typhoon alarm is given, private residences still typically adopt self-installed plywood shutters for hurricane protection.

This section of the publication aims to show the main advantages and applications of various commercial shuttering products. Shutters do provide protection under strong winds but it should be noted that, when these systems are deployed, it is not possible to see outside. Consequently, if the electricity is shut off or disrupted, as often happens during a storm, users are left without light. This information must be considered by designers when choosing the appropriate protection against windborne debris. See Table 4.2 for a description of shutter types and applicability.

Shutter Type	Advantages and Applicability
Roll-down	• Permanently installed and housed in a box above each opening; rolls down along a set of tracks on either side and locks at the bottom. • Manual or motorized; requires more maintenance than other shutter types. • Easiest and quickest preparation; each opening can be closed in minutes.
Accordion	• Permanently installed and housed in a box at the side of the opening; deployed by manually pulling out of enclosure. • Moves horizontally between upper and lower tracks. • Manual; quick and easy to operate. • Ideal for curves and for large openings. • Each opening can be closed in minutes.
Perforated barrier	• Permanently attached. • Allows high levels of light transmittance; view from inside the building is not disrupted.
Bahama	• Permanently installed; hinged at the top of the opening. • No maintenance required. • Quick and easy to operate; no tools required to close. • Preparation time is 5 to 10 minutes per opening.
Colonial	• Permanently installed; hinged on the side and open to the outside of the opening. • No maintenance required. • Easy to close and lock for storm protection. • Preparation time is 5 to 10 minutes per opening.
Storm panels	• Least expensive after plywood; easy storage. • Removable panels. • Can be installed with or without tracks. • Preparation time is as much as 30 minutes per opening.
Plywood shutter	• Least expensive; installation may be difficult due to weight. • Bulky to store; can rot and warp. • Takes only minutes to mount per window.

Table 4.2. Advantages and applications of various shuttering products. Source: Haroon et al. 2006

5.0 Australia

Australia was the world's first developer of standards and building technologies, which facilitated the realization of cyclone-resistant façades capable of withstanding the impact of flying objects in strong wind conditions. The current Australian requirements for cyclone-resistant façade certification has changed recently. These are now stricter than related standards in the United States when it comes to impact-testing missile speed, but the testing procedures can be perceived as ambiguous. This has had a negative impact on the basic adoption of cyclone-resistant glazing systems. CTBUH wishes to highlight that, even though the projectile velocities in Australia are significantly higher than those in the United States, unlike the US, there is no requirement to check the adequacy of the glazing to resist wind pressure after the impact.

5.1 Principal Design Rules

Current Australian building codes do not require the external building fabric to be resistant to windborne debris, unless the building internal pressure is to be reduced in accordance with AS/NZS 1170.2:2011, Clause 5.3.2, i.e., ignoring the possibility of a dominant opening.

Australia has introduced some requirements for the design of curtain walls, which must guarantee performance against the effects of strong wind on a building. The first building code for protection from windborne debris in cyclones was put in place shortly after Cyclone Tracy devastated the city of Darwin on Christmas Eve, 1974 (Darwin Reconstruction Commission 1975). The approved strategy to protect against debris was defined as the ability to prevent a 100- by 50-millimeter, 4-kilogram timber missile traveling at 20 m/s from causing a significant opening. Although the Pilkington ACI Company launched "Triplex" 13.8-millimeters cyclone-resistant glass in January 1977, this product was aimed at preventing failure of roofs experiencing cyclic pressures, and was not focused on the design of cyclone-resistant glazing systems. For cyclone-prone areas outside of Darwin, design guidelines were developed at a workshop, organized by the Commonwealth Department of Construction, and published in TR 440 in July 1977. This document recommended an impact speed of 15 m/s for the 4-kilogram timber missile. This debris impact requirement was adopted in the 1989 revision of the *AS 1170.2-1989 SAA Loading Code*.

Since the development of the first drafts of requirements in Australia, various studies have been conducted, and standards for hurricane protection were developed in the United States. In Australia, there is one fundamental requirement that is still referenced, which aims at reproducing the effects of flying debris during tropical cyclone events that could potentially impact a building envelope. This is the loading requirement presented in the *AS/NZS 1170.2:2011 Structural Design Actions – Wind Actions,* which takes into account the location of the building and the related regional velocity of the wind, the level of importance for the building, and the level of protection. Cyclic pressure testing following missile impact was omitted.

Based on this data, the weight and the velocity of the projectile for the impact test simulations were defined. In 2011, a change was made to AS/NZS 1170.2 to increase the projectile speed from 15 m/s to 0.4 of the regional velocity (see page 49). The basis for this increase was derived from conclusions obtained during wind studies in the United States where a 4-kilogram timber missile picked up by a 69 m/s wind gust could accelerate from 0 to 15 m/s in less than 2 meters (Lin et al. 2007).

The increase in missile speed in AS/NZS 1170.2:2011 has greatly increased the cost of glass and framing in order to meet the new requirements. As a result, buildings are being built without the use of impact glazing, and windows that fail can allow rain, wind, and debris to enter the interior, causing significant damage to buildings and their contents, and potentially cause injury or death to occupants.

Depending on the building location, the façade is always tested to guarantee many other performance specifications, not just flying-debris resistance. However, one issue that was highlighted in the most recent post-cyclone reports is that the current systems allow water penetration during strong wind conditions (CTS 2017). In Australia, the results of the cladding tests do not have to be presented to any government institution in most cases. As a result, glazing protection (laminated glass or well-designed and thoroughly-tested shutters) is still falling short of what is needed in tropical regions of Australia.

Rise in Stories	Class of Building	
	2, 3, 9	5, 6, 7, 8
4 OR MORE	A	A
3	A	B
2	B	C
1	C	C
Note: Type A construction is the most fire-resistant and Type C the least fire-resistant type of construction		

Table 5.1. Minimum type of fire-restricting construction required in Australia. Source: National Construction Code (NCC) 2016, Vol. 1.

Class of buildings		Description
1	1A	A single dwelling being a detached house, or one or more attached dwellings, each being a building, separated by a fire-resisting wall, including a row house, terrace house, town house, or villa unit.
	1B	A boarding house, guest house, hostel or the like with a total area of all floors not exceeding 300 m^2, and where not more than 12 reside, and is not located above or below another dwelling or another Class of building other than a private garage.
2		A building containing 2 or more sole-occupancy units each being a separate dwelling.
3		A residential building, other than a Class 1 or 2 building, which is a common place of long term or transient living for a number of unrelated persons. Example: boarding-house, hostel, backpackers' accommodation or residential part of a hotel, motel, school or detention center.
4		A dwelling in a building that is Class 5, 6, 7, 8, or 9 if it is the only dwelling in the building.
5		An office building used for professional or commercial purposes, excluding buildings of Class 6, 7, 8, or 9.
6		A shop or other building for the sale of goods by retail or the supply of services direct to the public. Example: café, restaurant, kiosk, hairdressers, showroom, or service station.
7	7A	A building which is a car park.
	7B	A building which is for storage or display of goods or produce for sale by wholesale.
8		A laboratory, or a building in which a handicraft or process for the production, assembling, altering, repairing, packing, finishing or cleaning of goods or produce is carried on for trade, sale, or gain.
9		A building of a public nature.
	9A	A health care building, including those parts of the building set aside as a laboratory.
	9B	An assembly building, including a trade workshop, laboratory, or the like, in a primary or secondary school, but excluding any other parts of the building that are of another class.
	9C	An aged care building.
10		A non-habitable building or structure
	10A	A private garage, carport, shed, or the like.
	10B	A structure being a fence, mast, antenna, retaining or freestanding wall, swimming pool, or the like.
	10C	A private bushfire shelter.

Table 5.2. Building classifications in Australia. Source: National Construction Code (NCC) 2016, Vol. 1.5

There are other conditions in which the requirement is different. The debris impact-resistant façades in the Northern Territory and the state of Queensland often require a registered engineer's certificate confirming the façade meets the debris-impact test requirements. The client, client's certifier, or client's representing consultant typically requires a debris-impact test report to be presented.

The reference requirements can be found in the following local standards (see Tables 5.1 & 5.2). Technical Note No. 4 could be chosen as a standard testing procedure (CTS 2017).

5.2 Professional Roles and Responsibilities

Developers

Australian developers have to deal with the local rules in cyclone-prone regions C and D (see Figure 5.1). The AS/NZS 1170.2:2011 Structural Design Actions – Wind Actions has indicated the appropriate impact resistance for the building envelope, depending on the precise location of the building and the regional velocity of the wind. Developers rely on advice from consultants hired on the projects during design documentation, and ultimately the façade contractors, who are providing the design and construction (D & C) service. Specialist façade contractors are also required to certify the design/engineering, fabrication and installation of façade products. Façade solutions/shutter systems are certified to guarantee precise levels of performance in case of a cyclone event. Moreover, the importance of these building technologies, and their ability to protect the private/public property in case of a cyclone event is highlighted by the reports issued by government authorities.

Developers and building owners are also the professionals that deal with the

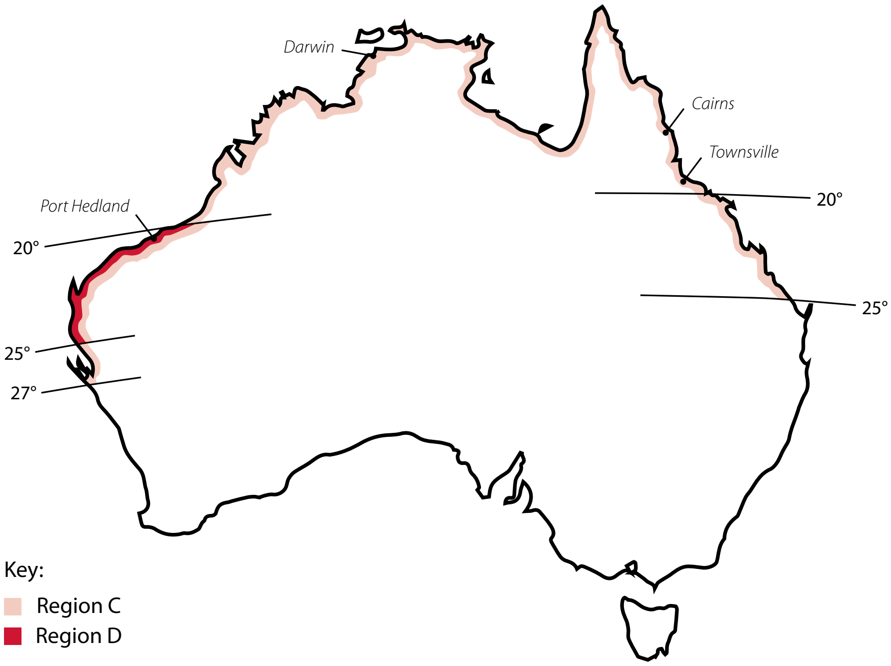

Figure 5.1. Australian Wind Regions. Region C and D are identified as cyclone-prone areas. © 2016 Commonwealth of Australia and States and Territories of Australia. Source: National Construction Code (NCC) 2016, Vol. 2.

insurance companies. The basis for the insurance premium derives from the various characteristics of the building and the certified level of performance for the façade solutions.

The 2016 changes presented in Amendment No. 4 to the AS/NZS 1170.2:2011, in which the velocity of the missile for the impact test simulating the flying debris in a cyclone event increased significantly, are causing changes in the Australian façade market. The increase in projectile velocities from 15 m/s to $0.4V_R$ occurred in the original issue of AS/ZS1170.2:2011. Amendment 4 in 2016 clarified and explained this but did not increase the projectile velocity. Note 5 to Clause 2.5.8 of this amendment recommends the use of CTS Technical Note No. 4 for the pass/fail criteria. This is a positive step towards removing the ambiguity of the test method, but a "Note" to an Australian Standard is only "informative", not "normative". Therefore, it is unfortunately only a recommendation, not a requirement.

Developers must ensure guarantees for higher levels of performance of the glazed system, and this can considerably increase building costs. Shutter systems are significantly cheaper, when compared to the new requirements for glazed building envelopes, and that is the reason why many projects are abandoning cyclone-resistant glazing solutions.

However, there are projects where the adoption of shutters is not permitted, due to the function and design choices of the building. In these cyclone-prone areas, the current requirements for the product approval process of windborne-debris-resistant façades ask for an improved design, if compared with the existing solutions built before 2016.

Designers

Australian architects and structural engineers operating in cyclone regions C and D in Australia have to take into consideration three options for the building design. Each of these options would inevitably have a consequence on the façade final solution, with the aim of preventing building failure in case of a tropical cyclone event occurrence:

- shutters
- debris-impact-resistant façades
- high internal wind pressures

Australia conducted the first testing and presented the first design solutions for window systems that are capable of withstanding the impact of flying debris during cyclone events.

The design choices have to follow the current requirements presented in AS/NZS 1170.2:2011, where the cyclone-prone locations within the country are identified (Cyclone Regions C and D). Currently, a loading standard is specified, and it must be verified by the designer of the project, but this is still not a testing standard. The responsibility of the designer, in terms of façade performance, is strictly confined to ensuring the local qualifications are met.

AS/NZS 1170.2:2011, incorporating Amendment No. 4, 2016

Clause 2.5.8
Where windborne debris loading is required for impact resistance testing, the debris impact loading shall be:

a. a timber test member of 4 kg mass, of a density of at least 600 kg/m^3, with a nominal cross-section of 100 mm × 50 mm impacting end on at 0.4 V_R for the horizontal component of the trajectory, and 0.1 V_R for the vertical component of the trajectory;

and

b. a spherical steel ball 8 mm in diameter (approximately 2 gr mass) impacting at 0.4 V_R for the horizontal component of the trajectory, and 0.3 V_R for the vertical component of the trajectory, where V_R is the regional wind speed given in Clause 3.2.

Notes:

1. *Examples of the use of this Clause would be for the evaluation of internal pressure, or the demonstration of resistance to penetration of the building envelope enclosing a shelter room.*
2. *The two test debris items are representative of a large range of windborne debris of varying masses and sizes that can be generated in severe wind storms.*
3. *The spherical ball missile is representative of small missiles, which could penetrate protective screens with large mesh sizes.*
4. *These impact loadings should be applied independently in time and location.*
5. *This Standard does not specify a test method or acceptance criteria. Acceptance criteria may vary according to the purpose of the test. An appropriate test method and acceptance criteria for debris tests are given in Technical Note No. 4: Simulated Windborne-Debris-Impact Testing of Building Envelope Components.*

A glazed windborne-debris-resistant envelope and a shuttered envelope both would have to be capable of resisting the impact of flying debris in strong wind conditions. If the glazed façade/window solution is not designed to withstand the impact of flying debris in case of strong wind conditions, then the whole building (including the façade) needs to be designed to resist high internal wind pressures. The final decision on whether to install a transparent system or an enclosed one, from the Australian façade market's perspective, is generally influenced by the main contractor (the "builder").

In Australia, it is very common that a façade consultant is designated in major projects to define the various façade performance criteria, including resilience to cyclones. In this case, the designer works very closely with the façade consultant in order to achieve the desired characteristics, in terms of aesthetic appearance, technical properties, compliance with local regulations, and achieving the client's expectations.

It is a common practice, especially for northern Australian projects (in cities such as Darwin, Cairns, etc.), to get the wind-tunnel consultant involved in the design of major buildings. In this way, the ultimate limit-state peak design pressures for the building-specific, site-specific project that can be identified represent the best opportunity for the designers to study alternative façade solutions. These could consistently cut down the cost of the project, justifying design choices that otherwise, following only the AS/NZS 1170.2:2011, could not be accepted.

Façade Consultants

Façade consultants operating in the Australian cyclone-prone regions are required to refer to the local code requirements. Curtain walls and windows have to follow the required performance levels for flying debris resistance. The glazed building envelope systems produced in other countries also have to be tested according to the load specifications dictated by the AS/NZS 1170.2:2011.

The façade consultant takes care of the design choices, safeguarding all the aspects related to the final solutions for the façade, from the structural, thermal and fire performance, to the aesthetic qualities, the maintenance strategies, budget, etc. From façade design to realization, the professional is responsible for checking the shop drawings of the supplier, visiting the manufacturing plants as necessary, and attending the performance mock-up tests. They deal directly with the client, the architect, the façade manufacturer, and the testing lab. The façade consultant then guarantees the effectiveness of the performance targets, from the genesis of the façade design to the façade installation, and also establish the service required for the system's future, by laying out a maintenance process.

In the Australian market, it is very common to have an additional specialist attending the façade performance mock-up tests, such as an interlayer specialist or glass manufacturer. These consultants attend the tests in order to check the testing parameters, and to verify possible issues related with the product they supplied or recommended as the most adequate solution for the identified parameters. The role of the façade consultant, however, varies depending on many factors: type of project, budget, developer, architect, engineering firm, etc. In any case, the consultant's goal is ultimately to optimize the performance, cost, and durability of the façade.

Façade Suppliers
Façade suppliers operating in the Australian market can be found locally and globally. When they are local, it is typical that they also provide and test cyclone-resistant solutions for cyclone-prone regions within the country. In both cases, the façades must be tested before the entire production process can take place, in order to verify the final solution complies with the façade requirements, in terms of performance.

The Australian Window Association (AWA) coordinates with nearly 600 window manufacturers and industry suppliers throughout the country. Their products are tested according to the *AS 2047-2014 Window and External Glazed Doors in Buildings,* and the AWA members produce products that conform to the Australian requirements. AWA members are expected to: provide products and services that comply with the performance requirements of relevant Australian standards and the Building Code of Australia; adhere to the AWA third-party National Association of Testing Authorities (NATA), Australia accreditation program; and submit inspections by accredited auditors.

Currently, the lack of a formal debris-impact-testing standard, and the prevailing Technical Note No. 4 contained in the normative section of AS/NZS1170.2:2011, has led to a high degree of ambiguity in the definition of a "conforming product," and a wide variance in what is being supplied and installed as "conforming" tested products. Many products are being installed and certified as "debris-impact-resistant," but have only been tested for the less-onerous center impact, not the more-stringent corner impact.

Façade Test Labs
The Australian façade test labs are largely located within the territory they service. They usually test glazed building envelope solutions according to both AS/NZS and international standards. Australia has several standards regarding façade/glazed system assembly.

For the whole façade system:

- AS/NZS 4284:2008 Testing of Building Façades

For windows, sliding doors and the like:

- AS/NZS 2047:2014 Windows and External Glazed Doors in Buildings
- AS/NZS 4420.1:2016 Windows, External Glazed, Timber and Composite Doors – Methods of Test Sequence, Sampling and Test Methods

When it comes to resistance to flying debris, for façades that are to be installed within Australian cyclone-prone locations, the reference requirement is the AS/NZS 1170.2:2011. This is not a testing standard, but rather, a loading standard. Precise impact locations are not identified, and the same is true for other parameters, such as the specimen testing temperature, projectile characteristics (other than the weight and the section), etc.

The industry is currently putting together a test standard for windborne-debris simulation, in which these missing requirements will be indicated. These in-progress testing methods would aim to define a procedure that is completely repeatable, based on well-identified details of typical debris, including the density of the item, the radius of the curve on the end of the item, its rigidity, etc.

Of all the testing centers, the Cyclone Testing Station (CTS) at the James Cook University (Townsville) is particularly significant. It was established in the mid-1970s, after Cyclone Tracy hit Darwin, and its primary mission is to conduct research on the topic of collateral effects from cyclonic winds on buildings. The station is guided by a management committee composed of a mix of industry, government, and research professionals from around Australia. Technical Note No. 4 issued by

CTS, represents the only official testing standard related to flying-debris-resistance for façades, presented in AS/NZS 1170.2:2011.

Government Institutes

The AS/NZS 1170.2:2011 is the reference loading standard in Australia for the performance that a façade has to guarantee when located in tropical cyclone-prone regions C and D. This document is issued by Standards Australia (SA), the country's leading independent, non-governmental, not-for-profit standards organization. Furthermore, although the Australian Government is a member of the International Organization for Standardization (ISO), SAA is Australia's representative to the ISO.

Additionally, the government institution Geoscience Australia (GA) publishes the biannual National Tropical Cyclone Hazard Assessment (TCHA). It aims to ensure the safety of Australia's communities by studying potential disaster-event scenarios, in order to apply appropriate requests for urban environmental resilience. The mitigation of the impacts of natural hazards and disasters is contingent upon the availability of information on incidents and the review of specific hazards. That is why GA releases hazard assessments such as the TCHA. Thanks to the Bureau of Meteorology, the tropical cyclones are monitored, and warnings are issued to Australian citizens. Moreover, post-cyclone technical reports are delivered.

The CTS in Townsville also releases specific technical reports such as *Technical Report No. 63 – Tropical Cyclone Debbie – Damage to Buildings in the Whitsunday Region* (CTS 2017b). In these reports, the main building components, such as the façade systems, are analyzed in detail in order to highlight the primary building damage caused by tropical cyclones. The latest research shows that Australian building regulations, in terms of the structural objectives, generally guarantee that cyclone-resistant glazed solutions withstand the wind loads and flying debris impacts during a strong-wind event. A main problem identified concerns water penetration of the façade due to wind-driven rain, as this is a major factor in insurance claims.

The Bushfire and Natural Hazard Cooperative Research Centre receives funds from both the Australian government and from local governmental organizations, research institutions, and NGOs. It coordinates a national research effort in hazards, including cyclones, and organizes specific events related to risk reduction, such as the International Day for Disaster Reduction and the Australasian Natural Hazards Management Conference. Research partners include the Bureau of Meteorology and GA, universities (including James Cook University), and several international research organizations.

Furthermore, national and state governments and the insurance companies actively provide education to the public through television advertisements, and public education to inform of the need to secure large projectiles (chairs, tables, trampolines, etc.), not only in the forewarned event of a cyclone, but also in the event of an afternoon storm. This education is probably the most practical way to minimize large debris impact.

5.3 Tall Buildings in Cyclone-Prone Areas of Australia

The December 2017 count of buildings 150 meters and taller are presented in Table 5.3. Furthermore, CTBUH conducted a GIS analysis in order to highlight how many of these buildings experienced a cyclone event, and how many were in cyclone regions C and D in December 2017.

Buildings 150 m or taller in 1995	34
Buildings 150 m or taller in 2005	55
Buildings 150 m or taller in 2017	99
Buildings 150 m or taller in cyclone-prone areas (2017)	12
Buildings 150 m or taller affected by cyclones (2017)	1

Table 5.3. Tall buildings in cyclone-prone areas of Australia, December 2017.
Sources: Prevention Web, UNEP/UNISDR, and CTBUH.

Figure 5.2. Integrated Marine Operations Centre (IMOC) tower, Port Hedland. © Pindan / JML-Craft.

Project Data

- **Official Name:** Integrated Marine Operations Centre (IMOC)
- **Location:** Port Hedland, Australia
- **Developer:** Pilbara Ports Authority
- **Architect:** Pindan
- **Structural Engineer:** Pindan
- **Façade Consultant:** Inhabit Group
- **Façade Contractor:** JML-Craft
- **Façade Testing Lab:** Azuma Design

5.4 Case Study

Integrated Marine Operations Centre (IMOC)

Port Hedland, Australia

Architectural Features of the Building

The Integrated Marine Operations Centre (IMOC) tower (see Figure 5.2) replaced the outdated control tower in Port Hedland, Western Australia. It consists of a tower and a two-story podium.

The L-shaped podium comprises approximately 1,500 square meters of area and is 15 meters tall, and will fulfill various functions: reception, operations, offices, temporary accommodation, and public and common facilities. The majority of the podium is enclosed within an external perforated screen, with the glass curtain wall offset about one meter behind the screen.

The control tower area is approximately 240 square meters, and rotated slightly from the podium. It includes the Facility Plant rooms, the Incident Control Room (ICR) on Level 5, and the Vessel Traffic Services System (VTS) on Level 6. At Level 5, the ICR utilizes the same full-height window glazing system as the podium, while the glazing at Level 6 is on a 67.5° slope, and supported at the top and bottom, starting 600 millimeters above finished floor level. Additionally, an external balcony circumnavigates the ICR and VTS (see Figure 5.3).

Port Hedland is located in the northwest section of Western Australia, an area with flat terrain and few high-rises. According to AS/NZS 1170.2:2011, Port Hedland falls in Region D, Australia's worst cyclonic region. Also, the structural, electrical, communications and HVAC designs of the building are classed as Importance Level 4 (for Post-Disaster Functionality).

In the event of a cyclone, IMOC has to be evacuated and unoccupied, as it cannot be considered a suitable cyclone shelter; however, it can be operational and occupied immediately following a cyclone event. In typical weather, the VTS is to be fully operational, 24 hours a day, seven days a week, while the offices are to be operational from 7:00 a.m. to 6:00 p.m., five days per week, as well as on-call outside of standard operational hours.

Building Design Requirements

The following standards and guidelines, among others, form the basis of the building design:

- AS/NZS 1170.1:2002 Structural Design Actions – Permanent, Imposed and Other Actions
- AS/NZS 1170.2:2011 Structural Design Action – Wind Actions
- AS/NZS 1644.1 Aluminum Structures – Limit State Design
- AS 1288-2006 Glass in Buildings – Selection and Installation
- AS 4100 -1998 Steel Structures
- Technical Note No. 4: Simulated Windborne Debris Impact Testing of Building Envelope Components,.

In addition to typical wind load considerations in Australia, due to its location, cyclonic considerations, as per AS/NZS 1170.2:2011, were also required. Wind tunnel tests have not been used to predict unusual wind effects around the construction.

Façade Design

Code and Guidelines

In cyclonic regions, the AS/NZS 1170.2:2011, Clause 5.3.2, indicates that

> *"internal pressure resulting from the dominant opening shall be applied, unless the building envelope (windows, doors, and cladding at heights up to 25 meters) can be shown to be capable of resisting impact loading from windborne debris determined in accordance with Clause 2.5.7."*

For the IMOC project, impact loading considerations were required for the podium-level glazing, whereas the external screens were not considered for impact loading. Clause 2.5.7 provides limited guidance on the impact testing procedure, so the design team adapted the testing procedure issued by the Cyclone Testing Station (CTS) at James Cook University, Technical Note No. 4: Simulated Windborne Debris Impact Testing of Building Envelope

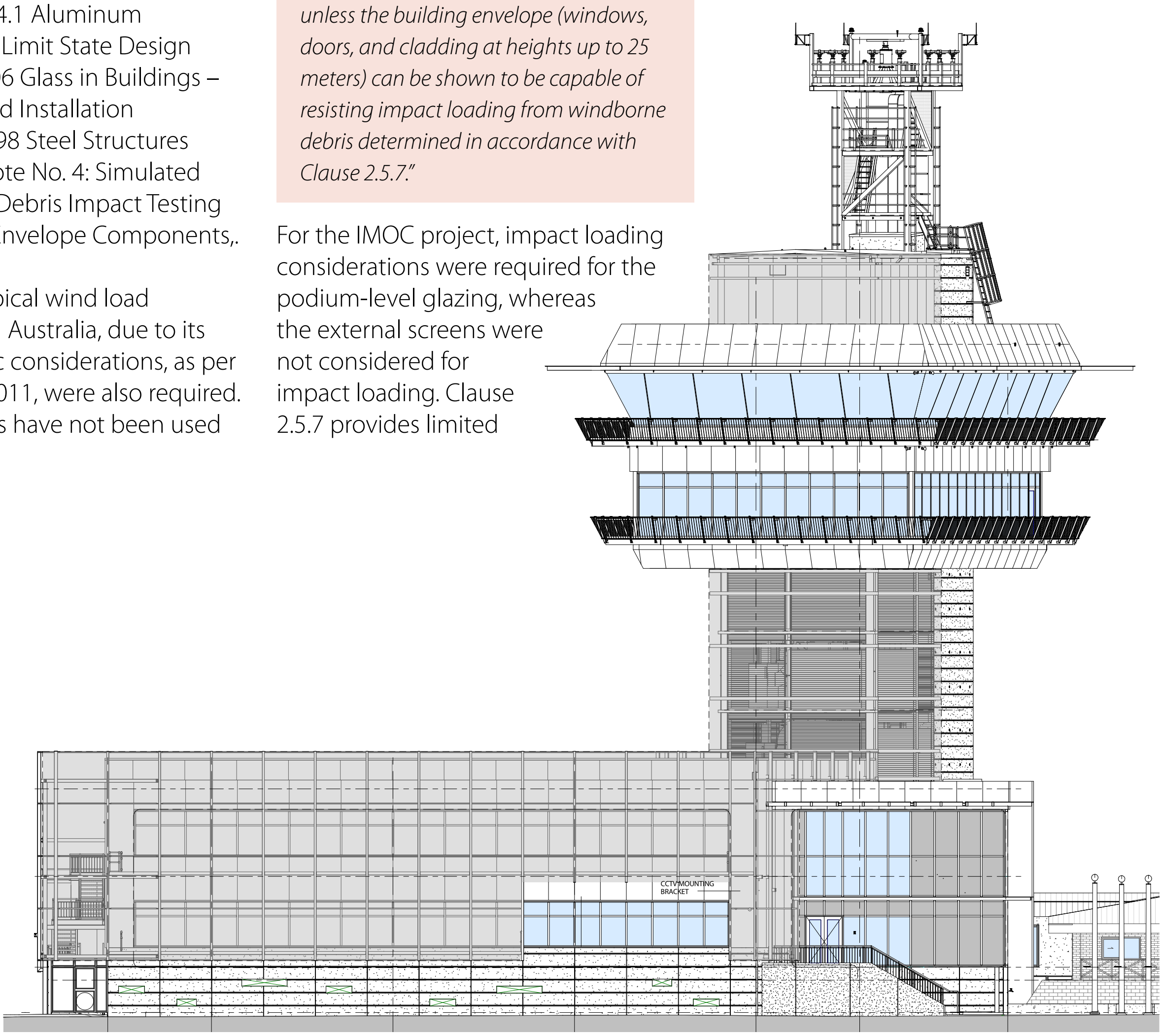

Figure 5.3. IMOC – southwest elevation. © Pindan / JML-Craft

Component. An extract of AS/NZS 1170.2:2011 Clause 2.5.7 is provided as follows:

> *Where windborne debris loading is specified, the debris impact shall be equivalent to:*
>
> *a. timber member of 4 kg mass with a nominal cross-section of 50 by 100 mm impacting end on at 0.4 V_R for the horizontal component of the trajectories;*
>
> *and*
>
> *b. spherical steel ball 8 mm in diameter (approximately 2 grams mass) impacting at 0.4 V_R for the horizontal trajectories and 0.3 V_R for the vertical trajectories*
>
> *where V_R is the regional wind speed given in Clause 3.2.*
>
> *Notes:*
>
> - *Examples of the use of this clause would be the application of Clause 5.3.2 or the building envelope enclosing a shelter room.*
> - *These impact loadings should be applied independently in time and location.*

For IMOC, the 0.4 V_R was calculated to be 39.6 m/s. When comparing this to ASTM E1996 Table 2, the required speed seems excessive (see Table 5.4).

The US testing looks at the cyclic loading of glazing, however, this is not required in Australian Standards, and thus, not tested.

Missile Level	Missile	Impact Speed (m/s)
A	2 g ± 5% steel ball	39.62
B	2,050 g ± 100 g, 5 x 10 cm, 1.4 m ± 100 mm lumber	12.19
C	4,100 g ± 100 g, 5 x 10 cm, 2.4 m ± 100 mm lumber	15.25
D	4,100 g ± 100 g, 2 x 4 in. 2.4 m ± 100 mm lumber	24.38

Table 5.4. Missiles applied to test façade resilience of IMOC. Source: ASTM E1996: Performance of Exterior Windows, Glazed Curtain Walls, Doors and Storm Shutters Impacted by Windborne Debris in Hurricanes, Table 2. © JML-Craft

Design Principles

The curtain wall system of IMOC (see Figure 5.4) focuses on the following aspects: safety, maintenance, water-tightness, aesthetics, buildability, sustainability, durability, acoustical control, and fire safety. After a cyclone occurs, the building has to be immediately operable.

The considered material properties for the IMOC project:

- *Glass Properties:*
  Elastic Modulus, $E = 70$ GPa
  Poisson's Ratio, $\nu = 0.22$
  Coefficient of Thermal Expansion, $\alpha = 8.5 \times 10^{-10}$
  Density $\rho = 2{,}500\ \mathrm{kg/m^3}$

- *Mild Steel Properties:*
  Elastic Modulus, $E = 200$ GPa
  Grade = C300
  Yield Stress, $f_y = 300$ MPa

The considered loads for the IMOC project:

- *Wind Loads.* Design pressures for limit state correspond to 3-second gusts of a 2,000-year return period.
- *Load Factor.* For serviceability wind loads, a factor of $(53/90)^2 = 0.35$ is used.

Analysis Modeling and Software

The methods of analysis for the structural members (e.g., glass, aluminum, etc.) are based mainly on formulas in design standards.

Design Phase Considerations

Preliminary design

The main two different façade typologies identified are control tower and podium offices. The wind loads used in the engineering calculations were taken from the Inhabit testing report. The applicable loads for Level 6 Upper (VTS) are summarized in Table 5.5.

The two parts of the complex took into account differential loads. The curtain wall definition derives from the desired aesthetic appearance of the building envelope and the required performance and structural efficiency. Based on these design parameters, possible curtain wall solutions are considered, in order to find the most suitable one that meets all technical specifications and achieves the design intent.

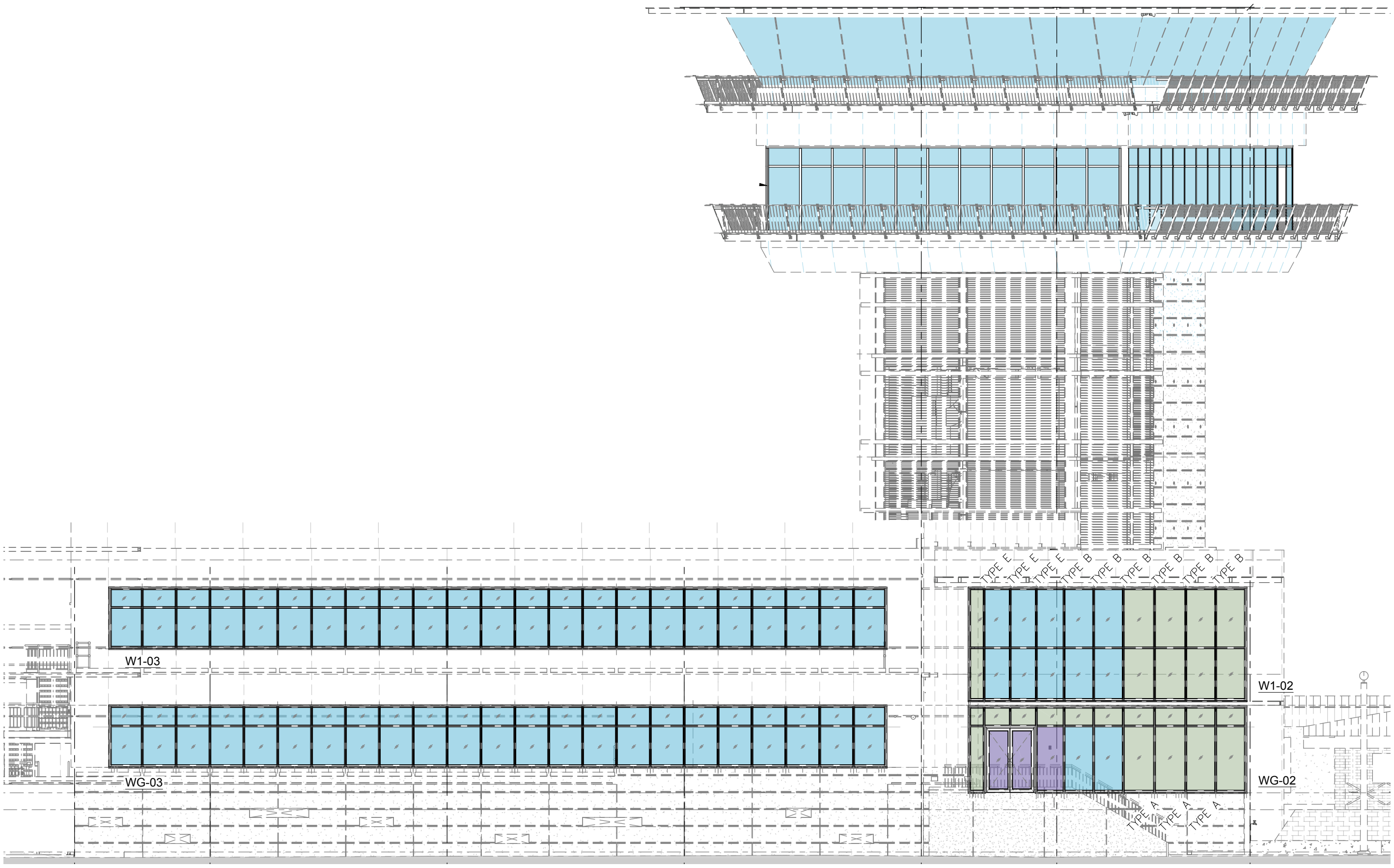

Figure 5.4. IMOC – Ground and first floors façade glazing, western elevation. © Pindan/JML-Craft

	Loads Tower		Loads Podium	
	ULS Load (kPa)	SLS Load (kPa)	ULS Load (kPa)	SLS Load (kPa)
Positive Pressure	+11.4	+3.3	+9.6	+2.7
Suction SA5 (within 2 m of corner)	-15.8	-4.4	-8.9	-2.6
Suction SA4 (next 2 m from corner)	-10.6	-3.1	-6.7	-1.9
Suction SA3 (typical)	-7.9	-2.3	-4.5	-1.3

Table 5.5. Calculated ultimate limit state (ULS) and service limit state (SLS) wind loads for tower and podium of IMOC facility. © JML-Craft

Design development

The IMOC is to be designed as a facility with Importance Level 4 (Post-Disaster Functionality). The post-disaster functionality specifications are applied to the structural, electrical, communications, HVAC designs, and other services as required by the National Construction Code (NCC). The building will not be used as a cyclone shelter and, during cyclone events, all port operations are suspended and staff are not permitted on-site.

The NCC classification of the IMOC is expected to be Class 5 office. The contractor verifies the building classification during the design stage.

Product Approval Process Requirements

In Australia, there is not a strict procedure to follow for obtaining façade acceptance by building authorities.

This differs from the Florida Building Commission requirements for the cyclone-glazing solutions certification process, where there is an established product approval system. All window and door systems have to be tested and approved for use in Florida, and from the moment that the specific flying debris simulation test method is determined, the glazing system must

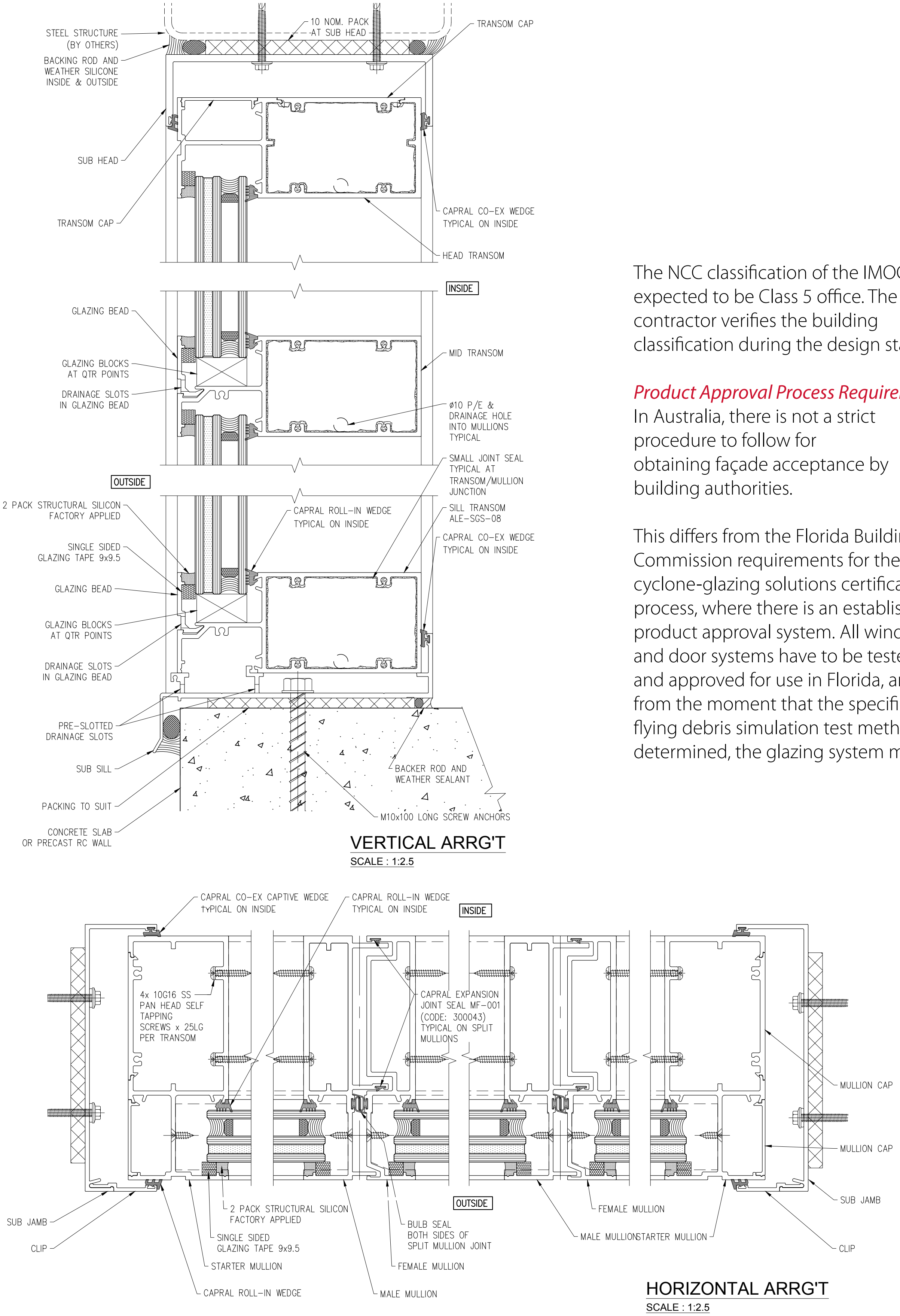

Figure 5.5. Aluminum extrusion shop front glazing suite arrangements for the podium curtain wall. © JML-Craft

be approved by Miami-Dade County and receive a "Notice of Acceptance" (Miami-Dade County 2012).

Façade Typologies: Podium Offices

Support

In the podium, the façade support is represented by an aluminum captive glazed system (see Figure 5.5).

Mullions/Frame

At the podium office level, steel stiffeners were used in many mullions. The façade designer had proposed intermediate restraints; however, the architect and sub-contractors preferred to have mullions that spanned top to bottom.

Glass

Specific glass makeup solutions have been developed to meet the various levels of curtain wall performance specification, based both on differential pressure loads and resistance to impacts on the building envelope (see Table 5.6). A 6.08-millimeter polyvinyl butyral (PVB) layer was required to pass the impact test on the podium level, which uses a projector to simulate windborne debris during a cyclone event. Timber missile testing using a 4.1-kilogram projectile at 40 m/s showed that the flexibility of the PVB allowed for plastic deformation and prevented the missile from passing through the laminated glass. Insulated glass units (IGUs) required an argon-filled cavity, opposed to just a typical air gap, in order to pass thermal targets.

Location	Glass makeup
Podium Offices	TYPICAL 6-mm heat-strengthened (HS) + 6.08-mm PVB + 6-mm HS + 12 mm air + 6-mm HS
	SIDE LITES 6-mm HS + interlayer + 6-mm HS + 12 mm air + 6-mm toughened
	Debris impact testing is required.

Table 5.6. Composition of glass at the podium office level of IMOC. © JML-Craft

Experimental Tests

Australian Standard references are:

- AS/NZS 1170.2:2011 Clause 2.5.7, Clause 3.4, and Clause 5.3.2
- NCC

These codes provide minimal guidance for the testing procedure and the acceptance criteria. There is also limited information on the required testing velocities for the varied importance levels. In general, each test consists of two parts, using speeds that are specified in Clause 2.5.1:

- Timber missile test – a 4-kilogram timber missile, with a cross section of 50 by 100 millimeter.
- Steel ball bearing test – a 2-gram ball bearing, 8 millimeters in diameter, is shot at the passed glass specimen.

Guidance for the criteria that must be met for curtain wall acceptance is provided in Technical Note No. 4. This was adopted in the testing of SY-6168 IMOC, Port Hedland (see Figures 5.6–5.11). An extract of Section 5.2 is outlined as follows:

Inspect test specimen:

a. If timber debris item did not penetrate and no obvious aperture is present → ***Pass***
b. If test specimen stops timber debris item but is left with an aperture smaller than 5,000 mm → ***Pass***
c. If test specimen stops timber debris item but is left with an aperture greater than 5,000 mm → ***Fail***
d. If test specimen stops timber debris item but timber debris item is visible from the inside (i.e., protruding through test specimen) → ***Fail***

The typical podium window wall modulations were tested at Azuma Design Lab according to Technical Note No. 4. According to this standard, for the IMOC project, only the center of the façade panel was tested and passed the requested impact of a 4-kilogram timber projectile at 40 m/s (see Figures 5.12 and 5.13).

- Neither timber nor steel ball bearings penetrated the panel.
- The back pane of heat-strengthened glass shattered.

Figure 5.6. IMOC Windborne Debris Testing Procedure. (Left:) The testing specimen should arrive at the laboratory as it would be delivered on site. This will account for effects due to the degree of rigidity between the glass and its frame. (Right:) For four-sided fully-framed glass, the frame was clamped to vertical posts on either side of the mullion. © JML-Craft

Figure 5.7. IMOC Windborne Debris Testing Procedure. The air cannon is placed 2 meters away from the testing specimen and the nozzle is approximately 1.2 meters from the ground. The cannon is only able to achieve velocities to the nearest whole number, as read on a gauge. Once the desired velocity is reached, the missile is released from the cannon. © JML-Craft

Figure 5.8. IMOC Windborne Debris Testing Procedure. AZ/NZS 1170.2 specifies a 100-by-50-mm, 4-kg timber missile for Part 1 of the test, but does not specify a required length. Hence the testing facility generally takes a one-meter length, and fits steel blocks to the inside to achieve the required mass (left). Note that during the firing, witnesses stand behind a transparent safety barrier a few meters away (right). © JML-Craft

Figure 5.9. IMOC Windborne Debris Testing Procedure. The nozzle is then fitted with a steel ball bearing adapter. The steel ball bearing can be fired at the same specimen of glass if it passed the timber missile test. Five steel ball bearings are fired in five different locations. In general, the effect of the ball bearing on laminated glass is minimal. From discussion with the testing facility, the ball bearing has the greatest effect on monolithic glass. © JML-Craft

Figure 5.10. IMOC Windborne Debris Testing Procedure. A 4-kg timber missile is fired 40 m/s at a glass panel. Glass panel makeup: 6-mm HS + 6.08-mm PVB + 6-mm HS + 12 mm air + 6-mm HS. © JML-Craft

Figure 5.11. IMOC Windborne Debris Testing Procedure. While missiles were fired at the center of the glass, on the last test for SY-6168 IMOC, Port Hedland, the timber missile was fired at the corner at 40 m/s for comprehensiveness. Because of the equipment limitations, the missile had to be fired at the top corners. A forklift was used to achieve the required altitude. © JML-Craft

Figure 5.12. IMOC Windborne Debris Testing Procedure. The glass panel impacted by 4-kg timber missile at 40 m/s. Both lites of the outer pane shattered, however the PVB was not penetrated, and the timber missile landed in front of the panel. The back pane shattered. The edges of the imprint were deeper than the center. The missile front surface was flat. © JML-Craft

Figure 5.13. IMOC Windborne Debris Testing Procedure. The back pane completely shattered, but there was no penetration or dominant opening in the outer pane. © JML-Craft

- At the area impact, glass shards fell, but the shards around the edges remained in place.

AZ/NZS 1170.2:2011 specifies that a 50-by-100-millimeter, 4-kilogram timber missile be used for Part 1 of the test, but does not specify a required length. The Azuma Design Lab generally uses a 1-meter-length timber piece and embeds steel blocks within the projectile to achieve the required mass. During the testing, witnesses stand behind a nearby transparent safety barrier.

Although not required by the standards, the experts attending the test at Azuma Design Lab decided to collect further information by firing a timber missile at the corner of a compromised (but approved) glass panel. In this test, the glass deformed out of its frame, and due to its cavity size, would be considered a failure. As mentioned above, cyclic loading was not tested, but if it had been, the inward/outward motion could cause the edge of the glass to tear from the structural sealant anyway, the same result as the additional impact test at the corner of the glass panel.

A façade capable of resisting a 4-kilogram timber missile at 40 m/s was the minimum performance requested for the façade of the podium sections.

The total time for a test procedure (set-up + timber missile + five steel ball bearings) takes approximately one hour. The missile testing area had barriers around its perimeter and the witnesses are required to stand behind an additional barrier, two meters away, as there is a high chance that steel ball bearings will bounce off the glass panels in all directions.

Also, the testing showed that, upon timber missile impact, the plastic deformation of the front pane would hit the back monolithic pane, causing the back pane to fracture. The fracture would occur regardless of the heat treatment of the inner pane. Fracture of the inner pane is not considered as a failure of the system for cyclone testing as:

- The timber test was only to determine if missiles would penetrate the panel, leaving an aperture greater than 5,000 square millimeters.
- The building is to be evacuated and unoccupied in the event of a cyclone, thus there is minimal threat to occupant safety.

Façade Typologies: Tower

Support

The control tower will include a Vessel Traffic Service (VTS) system on Level 6, and an Incident Control Room (ICR) on Level 5. The podium and Level 5 ICR use an aluminum captive glazed system (see Figure 5.14).

Mullions/Frame

All Level 5 ICR mullions required steel stiffening.

Glass

Specific glass formulations have been developed to respect the various levels of performance of the curtain wall solution, based on differential pressure on the tower section of the analyzed complex (see Table 5.7).

Experimental Tests

Levels 5 and 6 of the tower were tested for their ability to adequately perform and withstand the allowable limits and imposed loads: Deflection $\Delta_{limit} = 14$ mm (glazing bar governed by BS 5516-2:2004).

Lessons Learned and Recommendations

Difficulties in the Design

Podium offices façade solution:

- Steel ball bearings have minimal impact on laminated glass, like that of a fly on a windshield. They are more frequently used to test monolithic glass. Laminates are expected to hold shattered glass.
- In the tested laminated specimen, it was common for remnants of the ball bearing to be lodged into the glass. It was also common for the ball bearing to bounce off the specimen and hit the witnesses' protective barrier.
- For information only, the timber missile was shot at the "passed" panel to assess failure modes. Because of the way the frame supports the glass, and even though the glass system is approved for the project, there is a chance that the glass edge could disengage from the frame.

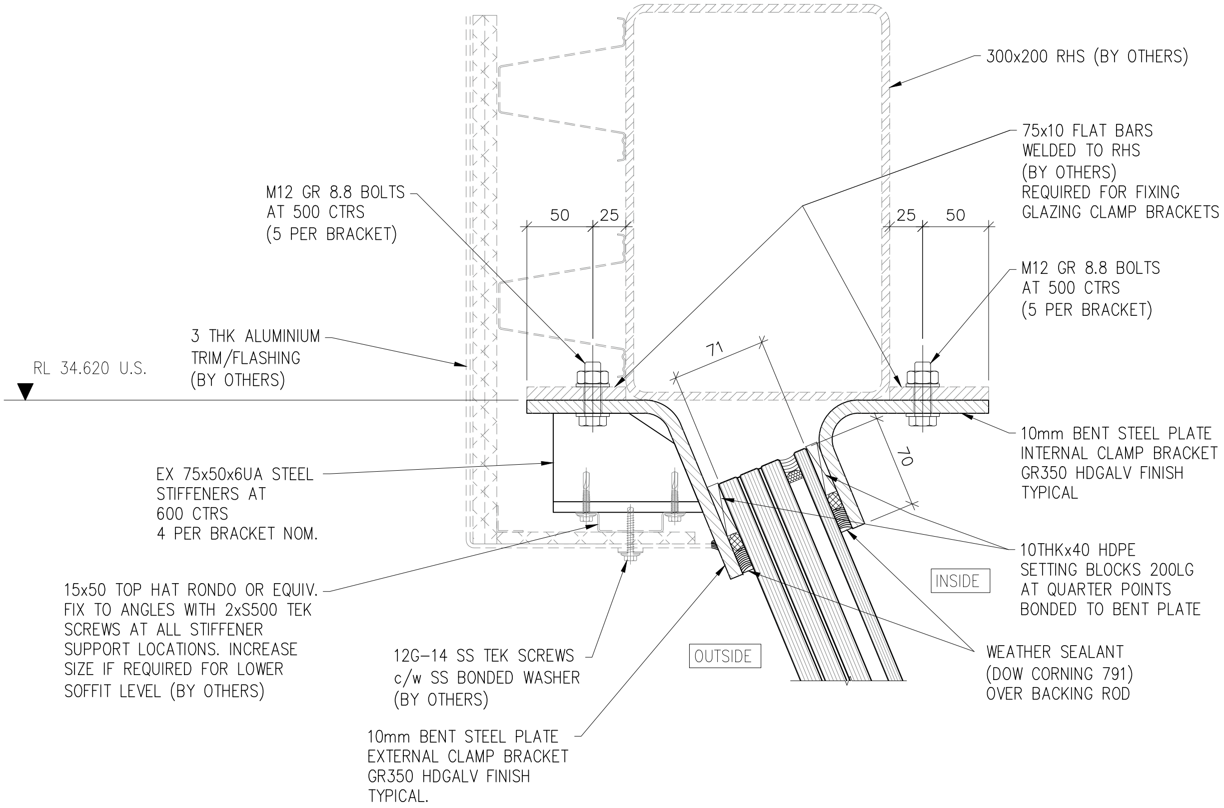

Figure 5.14. IMOC Tower Level 6 VTS façade detail. © JML-Craft

Design Innovative Solutions

The glass composition of 6-mm heat-strengthened (HS) + 6.08-mm PVB + 6-mm HS + 12 mm air + 6-mm HS was considered adequate to pass the required cyclone impact testing from windborne debris, as outlined in AS/NZS 1170.2:2011 (timber projectile impact at 40 m/s). It can also be concluded that the inner pane of glass will shatter under testing missile impact, regardless of whether heat treatment had been applied or not.

Location	Glass Makeup
Level 6 VTS	15-mm toughened + 2.28-mm SG5000 interlayer + 15-mm toughened + 2.28-mm SG5000 interlayer + 15-mm toughened + 12 mm air + 10-mm monolithic HS
	Windborne impact testing not required
Silicone	100-mm bite
Setting Block	Standard 10-mm-thick HDPE setting block on profiled aluminum block. Both to be minimum 200 mm long, at quarter-points of glazing panel. Profiled aluminum block to be anchored to steel substrate (by others) with 2x12 g S500 TEK screws (non-structural). Profiled aluminum block to be full bearing onto steel substrate and back folded steel plate. Ensure bi-metallic separation between dissimilar metals.

Table 5.7. Glass formulations and testing requirements for IMOC Level 6. © JML-Craft

Figure 5.15. Australian Institute of Tropical Health and Medicine, Townsville. © AITHM

Project Data

- **Official Name:** Australian Institute of Tropical Health and Medicine
- **Location:** James Cook University, Douglas Campus, Townsville, Australia
- **Architect:** Jackson Architecture
- **Structural Engineer:** Opus
- **Façade Contractor:** G.James Glass & Aluminium
- **Façade Testing Lab:** Azuma (cyclone debris impact testing), G.James Glass & Aluminium (air infiltration, water penetration, deflection, and strength)

5.5 Case Study

Australian Institute of Tropical Health and Medicine

Townsville, Australia

Architectural Features of the Building

The Australian Institute of Tropical Health and Medicine facility is located at James Cook University's Douglas Campus, Townsville, Queensland (see Figure 5.15), which is geographically within Australia's cyclonic region. It is a five-story building housing infectious disease research facilities, and it houses Australian Standard PC3 (Physical Containment Level 3)/Australian Standard QC3 (Quarantine Containment Level 3), laboratories, animal holding spaces, offices, a biobank (for clinical and epidemiological samples), and meeting rooms. "PC3/QC3- and PC2-certified" are high-containment laboratories that enable researchers to conduct secure and carefully controlled research on organisms with potential biosecurity risks.

The façade of the building incorporates horizontal strip windows within metal wall cladding, typically to the north and south elevations; and punched windows within in-situ concrete walls, generally to the east and west elevations. An architectural feature of the building is the sunshade screens on the east-, west- and south-facing glazing, and sunshade hoods on the north-facing glazing. These sunshades provide reduced solar heat load to this building, with subsequent energy efficiency and environmental benefits which depict intelligent and responsible architectural design, suitable for the tropical climate of this region. Although these sunshades' primary intent is for solar control, they also offer the façade some inherent resilience to windborne debris[1].

The integrity of the façade of the PC3/QC3 laboratories during a cyclone

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[1] A more detailed understanding of this building's façade can be appreciated through photographs and renderings available for viewing at the following link: http://jacksonarchitecture.com.au/portfolio_page/australian-institute-of-tropical-health-and-medicine-james-cook-university/

event is of specific interest and the focus of this case study.

Building Design Requirements

Code and Guidelines

Among other Australian Standards referenced in the National Construction Code (NCC)/Building Code of Australia, the following were the most pertinent standards relevant to the design of the glazing for this project:

- AS/NZS 1170.0:2002 Structural Design Actions – General Principles
- AS/NZS 1170.1:2002 Structural Design Actions – Permanent, Imposed and Other Actions
- AS/NZS 1170.2:2011 Structural Design Actions – Wind Actions
- AS 1288-2006 Glass in Buildings – Selection and Installation
- AS 2047-2014 Windows and External Glazed Doors in Buildings*
- AS/NZS 1664:1997 Aluminum Structures

** For development applications submitted prior to May 1, 2015, AS 2047-2014 was the only standard referenced in the NCC that mandated water-penetration testing requirements for glazing systems. AS 2047-2014 mandated a static water pressure test method for windows and doors. AS/NZS 4284-2008 Testing of Building Façades was referenced in the 2015 and later NCC; this Australian Standard specifies both a static and cyclic water-penetration testing regime.*

Design Forces

Wind pressures and human impact, where applicable, are typically the critical loads governing the design of glazing in Australia. Earthquake and snow loads (in those isolated regions that are applicable) are generally insignificant compared to wind loads.

Special consideration needs to be taken when designing for wind actions in the cyclonic regions of Australia. Not only does the cladding of a building (including door/window latches, hinges and other hardware) need to resist high local wind pressures without failure, but fatigue-sensitive cladding elements (such as metal cladding and its ancillary fixings) need to demonstrate cyclic resilience to the test methods of AS 4040.3-1992. In the requirements of AS/NZS 1170.2:2011, buildings in cyclonic regions need to consider one of three acceptable solutions relating to windborne debris:

1. Design the entire building envelope (including glazing) to resist cyclone debris impact (both large 4-kilogram timber projectile and small 8-millimeter diameter spherical steel-ball projectile);
2. Design debris screens to prevent the glazing from being subjected to debris impact; or
3. Assume that the envelope is breached by windborne debris, which causes a dominant opening in the building envelope, and the subsequent increased internal pressures result in greater-magnitude net pressures applied to the design of the entire building (i.e., all façade elements and the structure).

Wind Speed Zone and Importance Level of the Building

The majority of the land area of Australia is classified in AS/NZS 1170.2:2011 as non-cyclonic region (A & B). Evaluation of statistical history predicts that only cyclones of "low" category (3 or less) will cross the coastline into these regions, or that higher-category cyclones will have moved inland and subsequently reduced in intensity before entering these regions. The northern coastline of Australia is designated by AS/NZS 1170.2 as a cyclonic region. The *Australasian Wind Engineering Society's Handbook* explains that buildings in Region C are required to resist a maximum of Category 4 cyclones (classified as maximum 77 m/s gust wind speed by the Australian Bureau of Meteorology). Region D (only a portion of Western Australia's coastline) is required by AS/NZS 1170.2:2011 to be designed for Category 5 cyclones (>78 m/s).

Due to the geographical location of this building falling under Cyclonic Region C and the hazardous materials handled in the facility, the structural engineer specified a regional wind speed, V_R, of 73.4 m/s.

Wind Actions

The specification proposed that the glazing and wall cladding of those laboratories designated to engage in biosecurity-risk activities were to resist cyclone debris impact to AS/NZS 1170.2:2011. It was assumed that the remainder of the glazing on the building could be breached by windborne debris in the event of a cyclone. Subsequently, the building was designed for significantly higher-magnitude internal wind pressures. Internal wind-pressure coefficients were determined to equal the external wind-pressure coefficients of +0.7/-0.65, compared to +0.2/-0.0 for an intact façade.

The factored ultimate limit state (ULS) local wind pressure, derived from AS/NZS 1170.2:2011, applied to the cyclone debris impact-resistant glazing for this building was 5.1 kPa. There were higher local façade pressures, up to 6 kPa, designed for glazing located in corner regions of the building, but they were not subject to debris impact-resistance criteria, and subsequently are not the focus of this case study.

The water penetration resistance requirement, by static testing methods, for all the glazing on this building was 461 Pa. As specified in AS 2047-2014, this equates to 30 percent of the 25-year return period serviceability limit state (SLS) positive wind pressure determined for the building.

Building Structure

The structure of this building is predominantly in-situ poured and reinforced-concrete walls, stair core and lift core with post-tensioned concrete floors.

Façade Design

Code and Guidelines

AS 1288-2006 specifies glass maximum deflection limits of span dimension 60 at SLS wind pressures. Glass design stress limits are determined to the formula provided in AS 1288 Section 3 for different glass thicknesses and employing additional capacity factors for heat treatment, surface types, and load durations. AS/NZS 1170.2:2011 nominates the windborne debris impact testing loads for small and large impact projectiles. However, it is only a loading code and does not include a testing method or specific pass/fail criterion. This leaves considerable variability in the interpretation of the test method (e.g., center of glass impact or corner of glass impact, square or rounded tip of the timber projectile, softwood or hardwood timber projectile, etc.) and pass/fail criteria (e.g., allowable size of hole in the glass or length of disengagement of the glass from the frame), which results in vastly inconsistent results and often incomparable products from different manufacturers for what should be a standard test. Another major shortcoming to the Australian standards is that there is currently no requirement to test the glazing system for any sustained wind pressure after the debris impact.

Design Principles

During the initial design stages, it was clarified by the consultant team that the debris impact testing methods and pass criteria of the Technical Note 4 (2013) was to be adopted. This equated to a 4-kilogram, 50-by-100-millimeter) timber projectile with a velocity of 30 m/s for individual tests, and impact would occur in the center of the glass, the edge of the glass, and the corner of the glass for window and door systems. It also clarified the allowable size of the hole permitted in the glass, and/or an acceptable length of glass disengaged from the frame.

Analysis Modeling and Software

Calculations to rational engineering methods were employed to verify the structural adequacy for the fixings and aluminum framing, supplemented by existing system test reports to validate the air infiltration, water penetration, deflection at SLS wind pressure and strength at ULS wind pressures. Required glass thicknesses were checked to deflection limits when subjected to SLS wind pressures, and ULS wind-load strength capacity was checked using in-house developed spreadsheets generated from the formulae nominated in the AS 1288-2006 Section 4 glass charts.

SJ Mepla Finite Element Analysis (FEA) software was employed on rare occasions, for special load conditions not covered in AS1288-2006's uniform pressure load charts or human impact tables, such as concentrated imposed patch loads acting on overhead or balustrade glass.

Capacity for the glass to meet debris impact requirements cannot be practically calculated through rational engineering methods, and there is no known suitable software capable of undertaking accurate FEA modeling, so verifying debris impact resistance was undertaken through a full-scale testing regime.

Design Phase Considerations

The primary focus of this case study relates to windborne debris impact resistance, so this section will summarize the methodology employed to satisfy this design criteria only.

Preliminary design

G.James had previously conducted decades of research, development and testing to the superseded AS/NZS 1170.2:2002 debris impact requirements at 15 m/s. Reasonably affordable products (e.g., 11.14 annealed PVB-laminated glass and structural silicon in a standard-glazing pocketed aluminum frame) had been developed and tested in NATA laboratories for numerous projects completed over past decades, including Brisbane International Airport and Townsville Hospital. However, at the time of this project, the recent change of projectile velocity in AS/NZS 1170.2:2011 to 0.4 x V_R (about double the previous velocity and subsequently about four times the energy), meant that the testing procedures and benchmarks of a new product would essentially need to start from scratch.

Physical testing was the only method deemed accurate enough to evaluate the suitability of a glazing system. In such a test, it is important to consider the entire system, not just the glass. The glass makeup, the required method to maintain glass in the frame, and the subsequent required framing system are all inter-related and equally important in developing a compliant system.

Design development

Several innovative concepts for retaining the glass within the framing and new aluminum framing systems were investigated. Although there is significant merit in these concepts, due to the time constraints of the project, there was insufficient time to develop, test, and cut extrusion dies for a whole new glazing system. As such, existing glazing systems and traditional glazing methods were combined/adapted for this project to comply with this considerably more stringent windborne debris-impact resistance criterion.

Initial, informal simulations of the timber projectile impact were undertaken at the testing facilities using a recalibrated drop-weight method to impart similar impact energy to the new higher-velocity requirements. A glazing system was developed to resist a simulated corner impact of a 36 m/s large projectile, which covered the majority of potential project applications in Australia. This projectile velocity encompassed the design for buildings up to a 10,000-year return period, according to Queensland cyclone shelter criteria in Region C and normal buildings (Building Importance Level 2, 500-year return period wind events) in Cyclone Region C.

Product Approval Process Requirements

The façade contractor had a long working relationship in cyclone debris testing at James Cook University (JCU)'s Cyclone Testing Station (CTS). However, at the time of this project, JCU's CTS

> “Capacity for the glass to meet debris impact requirements cannot be practically calculated through rational engineering methods…”

had not yet been certified by the National Association of Testing Authorities (NATA) to conduct cyclone debris testing to the new requirements of AS/NZS 1170.2:2011. Consequently, The façade contractor undertook formal testing at Azuma's NATA-accredited testing laboratory near Sydney.

The test
The test simulated the wind-driven debris impact loading on an external building sample supplied by the client to the laboratory. The sample supplied shall be capable of resisting a wind load as stated in both AS/NZ 1170.2:2011 Section 2.5.7 and Section 5.3, as well as the Queensland Government Department of Public Works Design Guidelines for Australian Public Cyclone Shelters, Section 3.2(b).

Debris load design guidelines
The structural design guidelines for debris loads state that the external fabric of a building is to be at least capable of "resisting wind debris," defined as:

- One 50-by-100-millimeter piece of timber with a mass of 4 kilograms, impacting end-on at 0.4 x $V_{10,000}$ for horizontal trajectories and 0.1 x $V_{10,000}$ for vertical trajectories.
- One spherical steel ball of 2 grams' mass and 8 millimeters' diameter, impacting at 0.4 x $V_{10,000}$ for horizontal trajectories and 0.3 x $V_{10,000}$ for vertical trajectories.

Test criteria and procedure
For Cyclonic Regions C or D, debris test loads for the external fabric of the building are as follows:

- Test Load A: One end-on impact of a 4-kilogram mass of timber with cross-section dimensions of 50 by 100 millimeters, impacting at the speed specified for the trajectory.
- Test Load B: Five spherical steel balls of 2-gram mass and 8-millimeter diameter, impacting at the speed specified for the trajectory.

Test sequence
A test sample shall be subjected to successive test loads applied in the following order:

1. Debris Test Load A
2. Debris Test Load B

Acceptance criteria
A test sample shall:

1. Prevent a debris projectile from penetrating.
2. If penetrated, have a maximum perforation width of less than 8 millimeters.

Test apparatus and procedure
The sample was tested in Azuma Design's air-cannon testing facility. The air cannon consists of two air cylinders connected to a barrel in which the projectile is loaded. The air cannon is mounted on a platform, which allows for varying height adjustments.

The test sample is mounted on a support frame two meters from the exit opening of the barrel. A digital chronograph is installed at the exit of the barrel to record the velocity of the projectile prior to the impact on the test sample.

To achieve the required velocity, both air cylinders are charged to a predetermined level. On reaching this level, both cylinders are discharged via a solenoid valve, creating an instantaneous release of air to accelerate the projectile towards the sample at the required velocity (see Table 5.8).

Description of the sample/product tested
Model Name: Proprietary Fixed Glazing System
Frame Dimensions: 1,500 millimeters height, 1,200 millimeters width
Infill Material: Laminated glass
Infill Material Thickness: 18.84 millimeters
Retaining System: As per drawing

Results projectile description
Load A: a timber beam of 4-kilogram mass with cross section dimensions of 50 by 100 millimeters.

Load B: a spherical steel ball 2-gram mass, 8-millimeter diameter.

Façade Strategy Utilized

The utilized façade strategy to meet debris impact requirements was an interim solution adapted from existing extrusion suites and traditional glazing methods to meet this project's tight program deadlines. After the completion of the project, progress and ongoing testing has been undertaken with the aim of developing a more economical and innovative product that also has improved aesthetics.

Façade Typologies

The subject debris impact-resistant fenestration types for this project were:

1. A fixed glazed window wall with maximum nominal frame size of 2,700 millimeters' height and 900 millimeters' width
2. An operable awning sash window with a maximum nominal size of 900 millimeters high by 1,800 millimeters wide

Impact No.	Impact Location	Impact Velocity (m/s)	Results and Observations
1. Load A: Bottom RH Corner	Intersection 150 mm from RH stile and 110 mm above the bottom rail	37 m/s	Pass
RH Stile	Intersection 270 mm from RH stile and 700 mm above the bottom rail	37 m/s	Pass
Centre Hit	Intersection 540 mm from RH stile and 700 mm above the bottom rail	37 m/s	Pass
2. Load B: Balls	5 Random impacts	37 m/s	Pass

Table 5.8. A summary of the test results of timber-beam and steel-ball projectiles fired at glass sample from the Australian Institute of Tropical Health and Medicine. © G.James Glass & Aluminium

Façade Typology

Support

The glazing fenestrations of this building were predominantly supported by a well-designed concrete structure (see Figure 5.16) or structural steel square/rectangular hollow sections (see Figure 5.17). There were fortunately only isolated locations of small windows fitted to light-gauge steel stud-wall framing. Although light wall construction is often employed in Australia due to economic benefits, it can pose engineering challenges to producing structural adequacy for support of the windows against wind loads and weather resistance at interfaces with glazing systems.

Mullions/Frame

For superior weather resistance, traditional pressure-equalized and drained aluminum-framed windows were chosen for this project. An additional plant-on aluminum adaptor frame was added to the traditional window framing to achieve the special glazing pocket required for the debris impact-resistant glazing (see Figure 5.18).

Glass

To meet the aesthetic intent of the building, the moderate thermal performance requirements, thermal fracture prevention, and wind load integrity, the glazing for the project that was chosen was typically 13.52-millimeters-thick heat-strengthened (HS) laminated glass with a bronze color.

The debris impact resistant glazing was 18.84-millimeters-thick HS laminated glass.

Experimental Tests.[2]

- Missile Impact Test for Windborne Debris
- Pressure Cycling Test for Cyclone-Prone Areas
- Wind-Related Tests Conducted on the Façade

Lessons Learned and Recommendations

Difficulties in the Design

Marked increases to the projectile velocity tests in a recent revision of the wind code required all research and development works on compliant debris impact-resistant glazing systems to be completely restarted. Program constraints restricted the luxury of exploration and development of an innovative and paradigm-shifting solution to this increased projectile velocity.

Due to the substantial increases in projectile velocity, in order to successfully resist the most onerous projectile impact test to the corner of the glass, the challenge was to balance the best economic utcome considering:

- Brute force resistance through shear thickness of interlayers in the glass.
- Cover of glass in an architecturally acceptable aluminum frame width.
- The economic benefits realized through thin glass restrained in a narrow glazing pocket, by an innovative restraint method that is economically viable, yet able to resist the huge tension membrane reactions at the edges of the glass during impact.

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[2] There is currently no requirement in the Australian National Construction Code or its referenced Australian Standards for testing the capability of a glazing to resist any wind pressure after debris impact testing.

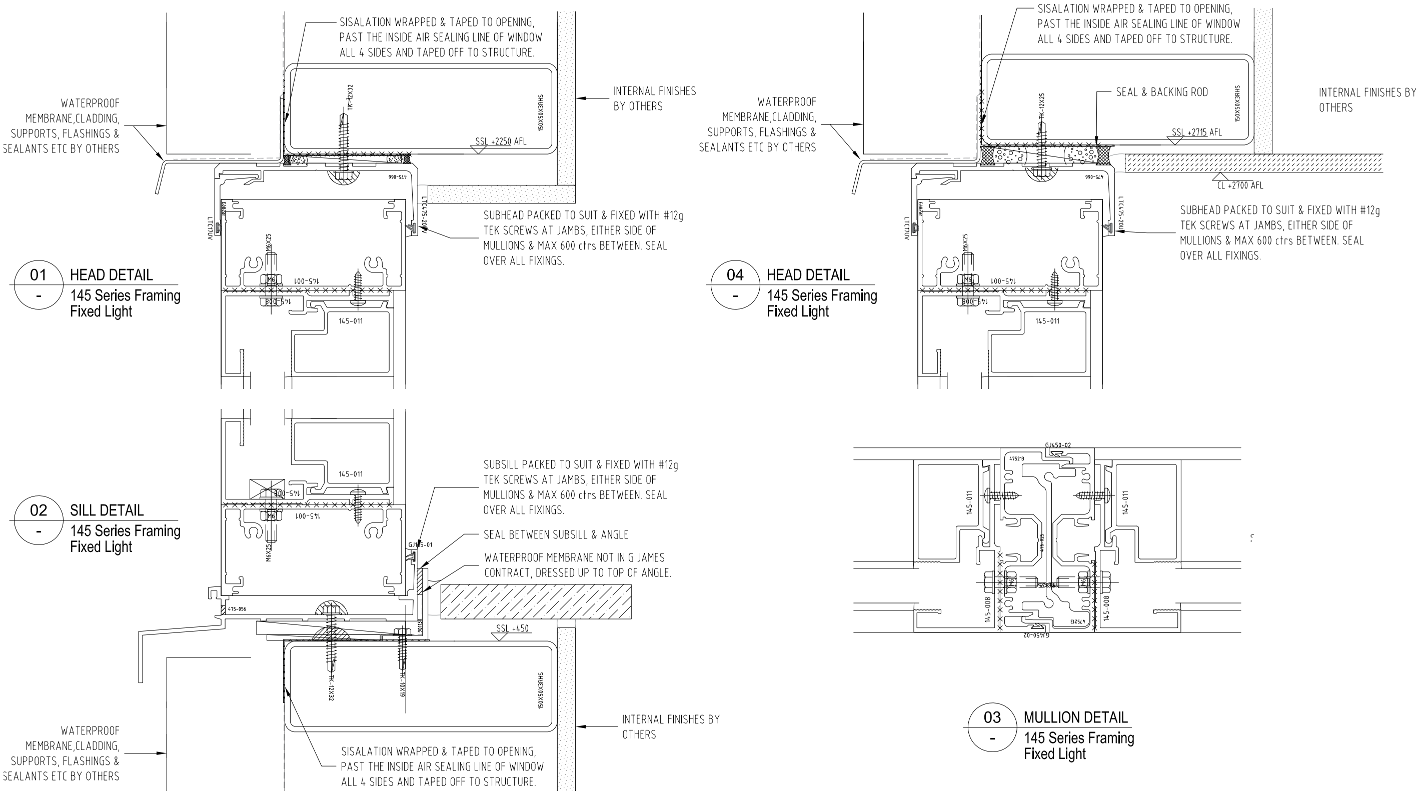


Figure 5.16. Australian Institute of Tropical Health and Medicine, fixed glazing details at openings in concrete wall. © G. James Glass & Aluminium

Possible Improvements

One suggested focus for improvement was addressing the definition of the problem. This case study highlights the validity and comprehensiveness of the current Australian Standards. Has the increased projectile velocity in the latest revision of the wind code achieved an improvement in the safety of the public during cyclone events? From industry experience, unfortunately this increased velocity in projectile testing has caused a detrimental effect to public safety. What was previously a relatively affordable debris impact-resistant glazing system has now become exorbitantly expensive, which has resulted in a marked decline in its use. This has meant inferior, monolithic toughened glass is utilized in almost all buildings (with critical government buildings being the exception).

Improvements in the publishing of an Australian Standard test method for cyclone debris impact (including pass/fail criteria) and the verification of the glass' further resistance to wind pressure after impact are believed to be warranted.

Improvements at the other end of the spectrum are also desirable. Further testing and development of an aluminum framing system, custom-designed to resist debris impact is the ideal path. The objective of the reduced frame width, thinner glass, and

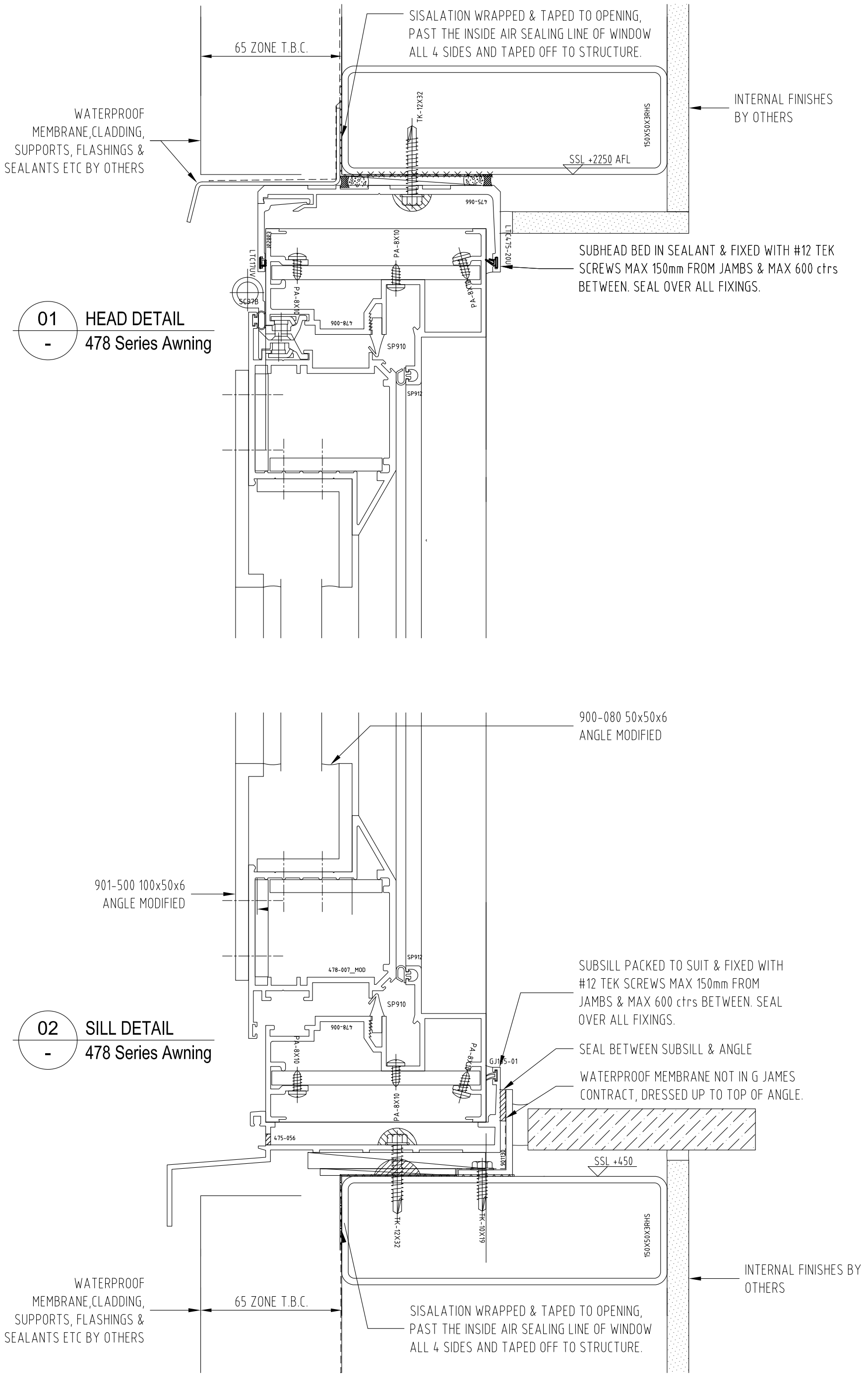


Figure 5.17. Australian Institute of Tropical Health and Medicine, fixed glazing details at structural steel sections.
© G. James Glass & Aluminium

Figure 5.18. Australian Institute of Tropical Health and Medicine, fixed glazing performance mock-up test.
© G. James Glass & Aluminium

innovative attachment of the glass within the glazing pocket could possibly see the development of a more economically-viable product, with market benefits and subsequent increased public safety. The paradox is that it is not commercially viable to commit resources to develop such a system for the current small market of debris impact-resistant glazing.

6.0 Hong Kong

6.1 Principal Design Rules

The principal guidelines for façade design in Hong Kong (see Figure 6.1) are dictated by the Hong Kong Buildings Department (BD). These differ from the requirements adopted in mainland China. Curtain walls must be designed to meet the specific requirements set out in Regulation 43 of the *Building (Construction) Regulations*. Further guidance on curtain wall construction comes from the *2018 Hong Kong Code of Practice for Structural Use of Glass*.

In 1983, the BD released the first edition of the *Code of Practice on Wind Effects* in Hong Kong. Revised in 2004, this document serves as the primary reference for local façade engineers when calculating wind loads for structures in Hong Kong. The code provides a detailed explanation of the use of wind-tunnel testing with regards to identifying and localizing the peak wind zones on a building envelope. This can help avoid over-engineered solutions, identifying and localizing the areas of peak wind on the building envelope. The code explains the safety factors to be considered in wind pressure calculations and the testing procedures to be carried out, specifying design wind pressures and design wind velocities (see Table 6.1).

A second fundamental code for façade design in Hong Kong is the *2018 Code of Practice for Structural Use of Glass*, in force as of 2019. The code provides guidelines on subjects such as the use of safety-laminated glass solutions for exterior building façades, when the size of the glass pane exceeds 2.5 square meters and any point of the glass pane is at a height of 5.0 meters or more above the finished floor level of the accessible areas on either side of the pane where tempered glass is used. Heat-strengthened glass, in principle, can still be used in lieu of laminated glass.

From the 2018 Code of Practice:

> ***5.2 SPECIAL DESIGN REQUIREMENTS***
> *5.2.1 Safety requirement against glass breakage*
>
> 1. *Laminated glass should be used in glass elements resisting long-term load, such as roof, canopy, skylight, sloped glazing, staircase, floor, beam, column, etc., and glass balustrade.*
> 2. *Tempered glass or laminated glass should be used in the parts of building exterior façade also serving as protective barrier.*
> 3. *Where tempered glass is used in building exterior façade, the glass should be in the form of laminated glass if it meets the following conditions:*
>
>   *i. The size of glass pane exceeds 2.5 m^2;*
>
>   *and*
>
>   *ii. Any point of the glass pane installed is at a height 5 m or more above the finished floor level of the accessible area on either side of the pane.*
>
> 4. *Where an insulated glass unit (IGU) is used in building exterior façade, the requirement in item (3) above applies to the outermost pane of the IGU only.*

The BD stipulates guidelines on design submission, construction and testing of façades for private development only. Whereas government buildings and public housing are outside the jurisdiction of the Buildings Ordinance (BO), the 2018 Code of Practice promulgated by BD does serve as a major reference for design of façades in those government projects.

The BD Officer oversees new building submissions. Each new project is referred to a Registered Structural Engineer (RSE) to review all submitted drawings and calculations before any approval and consent for new building works can commence. The BD Officer will regularly consult with his senior manager for any designs that fall outside of common practices and/or HKBD Codes. For major projects, it is common to have a façade engineer who is a separate RSE.

Every step in the façade design approval process in Hong Kong has to be discussed with the BD, for its approval and consent. If a building is applying for an Occupation Permit (OP), the performance test report for the curtain wall is currently required by the BD for approval and review. The designers, together with the façade consultants (if they receive the assignment to directly deal with the BD), have to present the façade design to the BD in the form of drawings, calculations and formal interviews.

Before obtaining the completion certification of a new building (in order to receive the OP), the developer's representatives are required to submit

Figure 6.1. A major street in Hong Kong, one of the world's most densely-populated cities. © Angela Mejorin

Height above site-ground level (m)	Design wind pressure q_z (kPa)	Design hourly-mean wind velocity V (m/s)
≤ 5	1.82	35.8
10	2.01	38.7
20	2.23	41.7
30	2.37	43.6
50	2.57	46.2
75	2.73	48.3
100	2.86	49.8
150	3.05	52.1
200	3.2	53.8
250	3.31	55.1
300	3.41	56.2
400	3.58	58
≥ 500	3.84	59.17

Table 6.1. Design wind pressures and hourly-mean wind velocities, relative to building heights. Source: Code of Practice on Wind Effects in Hong Kong, 2004

any performance mock-up (PMU) results, material certificates and test reports as set out by BD in the approval letter. These documents are required to prove that the design and materials used have been tested and are structurally sound.

Currently, the design wind loads on façades in Hong Kong are derived based on statistical estimation of historical wind speeds of typhoons of the past; therefore, façade glazing is designed to resist cyclone wind loads. Although there is no legal requirement for glazing to resist windborne debris, the BD always keeps an open mind on the issue. The BD has already developed various Hong Kong local requirements, basing its standard tests and codes on international practices and codes, including ASTM. Moreover, developers and owners of private buildings are always welcome to exceed the minimum requirements set out in the Code of Practice to suit their own needs.

Finally, the BD also requires a structural performance test report, conducted according to the Practice Note for Authorized Persons (PNAP) APP-37 (BD, 2012) or the 2018 Hong Kong Code of Practice for Structural Use of Glass (BD, 2018). The test is to be conducted and issued by an independent Hong Kong Laboratory Accreditation Scheme (HOKLAS) curtain-wall-testing laboratory. These are extensions to the Building Regulations, and are endorsed by the RSE to prove the proposed façade is structurally safe to the public. The endorsed test report is then submitted to the BD for obtaining the OP certificate upon completion of construction.

6.2 Professional Roles and Responsibilities

Developers

Developers in Hong Kong are required to submit and present their façade design, inclusive of colored plans, calculations and application forms, to the Hong Kong BD in order to receive the authorization to start construction. Hong Kong has some of the strictest statutory regulations and approval processes in the Asia-Pacific region. This does make it a comparatively safe built environment, especially during strong-wind events. The high standards do lead to higher construction costs and potentially longer construction programs. However, these are offset by the potential yields gained by developers when selling or renting floor space upon completion. Generally, real estate developers, including those in Hong Kong, will employ a specialist façade consultant to develop the specifications and performance criteria for the façade components.

In recent years, there has been an increase in the requirements for sustainable construction included in specifications, through the adoption of LEED, BREEAM, and ASHRAE certification schemes. Once acquired, this certification can bring higher commercial yields for the developer, but also means that, generally, a higher quality of façade is constructed in order to achieve the energy-efficient demands of the specification. Currently, the typhoon resistance of façades is not a typical parameter for these certifications and, as previously mentioned, there are no current requirements to design for resistance to windborne debris. If such regulations or guidelines were in place, then this might lead to further improvements in the standard of design and materials used in curtain wall construction. Additionally, a façade that is marketed as "resistant to windborne debris" may also allow for higher profits for developers, if this could be marketed to potential customers.

Figure 6.2. Hong Kong: Before the arrival of a typhoon, buildings use "X-tapes" to prevent injuries caused by glass failure that could occur due to wind pressure and windborne debris impact. © Msiuurjcos (cc by-sa)

Most Hong Kongers are aware of the potential for damage during typhoons, and it is a common sight for the inside of windows to be taped across diagonal corners in an "X"-shape as a typhoon approaches, both in private and public buildings (see Figure 6.2). This provides a practical solution for holding together non-safety glass, which could shatter into large shards if broken under impact. This X-taping practice can also be found on some curtain wall units, although this is not necessary, as safety glass is typically used. In this last example, the only advantage that the tape provides is psychological.

Designers

The architects responsible for the design and construction process in Hong Kong normally identify a specialist façade consultant to be responsible for the façade design. Together, the architect and façade consultant will develop the façade solution, usually dictated by the visual appearance and total budget requirements.

Typically, any new building or alterations and additions works will need the developer to submit the plans for formal approval to the BD. A suitably qualified professional, who is BD registered, known as an Authorized Person (AP) can, along with the RSE, advise on works to be submitted. Where the structural details of a window and wall system are not required to be submitted for approval, the AP and RSE should ensure that the design, fabrication and installation of the systems still meet the required safety standards. Attention should be given to the requirements on horizontal imposed loads, protection of openings, function of protective barriers, corrosion protection, quality control of materials, and protection against the spread of fire and smoke between floors.

For curtain walls, windows, and window-wall installations, a specialized RSE may be appointed to prepare the design and supervise fabrication and installation. Under such circumstances, the specified Forms BA4 and BA5 indicating the appointment of the separate RSE, and the scope of works for which s/he is responsible, are required to be submitted, together with the plans submitted for approval.

The separate RSE who is appointed for the curtain walls, windows, or window-wall installations shall be responsible for the supervision of the construction of such works, including the installation of any cast-in anchorage (e.g., anchor plates, cast-in embeds and through-bolts, etc.), except in the event where the cast-in anchorage has been pre-installed in the parent structure prior to their appointment. For such cases, the structural details and layout of the pre-installed parts should be included in the superstructure plans, which are to be submitted for approval by the project RSE, who shall then be responsible for the supervision of the installation of these parts. The separate RSE should refer to the pre-installed connection details when designing the curtain walls, windows, or window-wall installations, and should coordinate with the project RSE for any necessary amendment if different connection details are to be used. Upon completion of the works, the separate RSE is required to certify satisfactory completion of the works in accordance with Regulation 25(3) of the Building (Administration) Regulations.

Façade Consultants

Hong Kong façade consultants are engaged by the architect or developer to develop designs for new buildings and recladding works. Hong Kong is continuously changing through various cultural, political and economic factors. The changes are often reflected in buildings, where an existing structure is reclad to suit a different use, or simply to update or "rebrand" the façade. This is especially true at the podium level of tall buildings, which is often the main commercial area of the building. Local façade consultants have substantial experience in providing design and consultation advice for these works.

The local façade consultants are often very familiar with international best practices and testing procedures used abroad (e.g., Australia or the United States) to certify windstorm-resistant glazing. This is due to the fact that the largest façade consultant firms in Hong Kong generally operate internationally.

When providing design and advice for Hong Kong buildings, one of the primary concerns is achieving a first-time approval from the BD on behalf of the client and architect. Any design must be focused on all guidelines set out in the BD Codes of Practice. The rules in the region are very conservative and, consequently, the façade consultants must be conservative in order to follow the codes, although as mentioned before, there are still no mandatory requirements for windborne debris-impact testing. Thus, the Hong Kong market's conservative approach is sometimes experienced as limiting the potential for both architectural and technical innovation, according to the local façade consultants interviewed for this research project.

The local expectation is that a façade consultant or separate façade engineer will be appointed by the developer or the principal consultant for a large façade project. Currently, it is very common to have a façade engineer who is also an RSE for major, new projects. This is the professional figure who will deal with the BD, and who will be responsible for the first BD submission for procedural purposes. This professional doesn't continue to deal with the BD on an ongoing basis for a major project, because usually the façade contractor has its own project RSE.

The project architect for small projects typically has façade assessment in his/her scope. Also, this professional holds responsibility for the entire project submission of the façade solution, the certification submission, and the building-product and materials-approval process.

Façade Suppliers

Façade suppliers in Hong Kong primarily deal with the façade consultants, or with the façade

> "Although the guidelines for the region are conservative, there are still no mandatory requirements for windborne debris-impact testing of façades."

contractors, who often get fully involved in the design of, and take on design liability for, both technical reviews and approvals of their products. When there is a façade contractor, in major projects, the RSE for the façade is included as part of the scope of façade specialist contractor, and not the façade consultants.

The developer or client is often involved, both to manage the budgetary constraints, as well as to review specific issues, mainly concerning the possible finishes of materials or the overall aesthetic. A common scenario that drives client involvement could be the need to achieve a distinct façade. Often this involves having the largest possible glass panels at podium levels of tall buildings. In these cases, the client will often prefer to deal directly with the façade supplier or glass manufacturer, so as to understand the production process and achieve a unique result.

Currently, the products to be installed locally follow the guidelines developed by the BD. Clients often demand upgraded solutions in order to achieve a particular level of performance in specific aspects, usually related to aesthetics, glass and system performance, and sustainability. No upgraded façade solutions are currently required, by BD or requested by developers, in terms of flying-debris resistance in Hong Kong, even though windborne debris often appears during the frequent strong-wind conditions of typhoon season. Instead, there are some examples of secondary measures for protecting the façade. One example is temporary netting installed at podium levels around the façade to "catch" windborne debris and protect large, heavy and expensive glass panels from damage.

Façade suppliers in Hong Kong have their own industry association, the Hong Kong Façade Association (HKFA). Previously named the Hong Kong Architectural Aluminium Association, the HKFA is a non-profit group. Its aim is to bring various façade industry parties together through social events, to unite members on industry issues, achieve co-operation in the competitive market and promote healthy development of the trade.

Façade Test Labs

The testing centers in Hong Kong have been in existence for several decades allowing them to build up a large degree of experience, to develop their own test equipment (which must adapt to the advancement of tests being conducted), and develop software control management for the testing process review. Façade testing in Hong Kong is normally required to be conducted in a testing center accredited by the Hong Kong government. The Hong Kong Accreditation Service (HKAS) is the government-run body which provides certification of test centers through the Hong Kong Laboratory Accreditation Scheme (HOKLAS). HOKLAS is open to voluntary participation from any laboratory to demonstrate to its inspectors that specific tests can be competently carried out. This is done through proficiency-testing providers, reference material producers that perform objective testing and calibration, provision of proficiency tests, and the production of reference materials that fall within the scope of the scheme and meet the HOKLAS criteria of competence.

After the accreditation process, the laboratory will receive a formal HOKLAS report, showing which tests can be carried out and certified with a HOKLAS endorsement. The HOKLAS scheme can also be used to certify testing centers outside of Hong Kong. This is typically carried out in laboratories in mainland China, usually close to the façade component assembly factories in Guangzhou.

The performance mock-up test (PMU) labs in Hong Kong are very familiar with international standard tests such as BS, ISO, and ASTM, due to the large number of professionals in Hong Kong who also operate internationally. Furthermore, they use specialized software in order to employ controls during the testing process. These technologies could remotely and graphically highlight the possible points of failure during testing. The main laboratories in Hong Kong also offer consultancy services to architects, contractors, and suppliers in order to verify the design solution before potential problems occur (see Figure 6.3).

Government Institutes

The BD provides services for owners and occupants of both existing and new buildings through enforcement of the Buildings Ordinance. In relation to existing buildings, the BD's services include: reducing risks and nuisances caused by unauthorized building works and advertisement signboards;

Figure 6.3. A façade assembly is tested for water-tightness under dynamic pressure façade testing at the Hong Kong Curtain Wall Testing Center. © Angela Mejorin

Figure 6.4. Typhoon York's winds shattered the curtain walls of several buildings in Wan Chai, Hong Kong, September 1999. © Joe Khoury/ALT Cladding

promoting the importance of proper repairs and maintenance of old buildings, drainage, and slopes; considering and approving alterations and additional works; processing submissions under the simplified requirements and the household minor works validation scheme of the minor works control system; improving fire safety measures in buildings; and advising on the suitability of premises for the issue of licenses for specified commercial uses. Regarding new buildings, the department scrutinizes and approves building plans; carries out audit checks on construction works and site safety; and issues occupation permits upon completion of new buildings.

In 2004, the BD updated the *Code of Practice on Wind Effects in Hong Kong,* which is the basis for local façade designers for wind-pressure calculation. The code is currently under revision, and soon a new issue will be available. Furthermore, the BD prepared the 2018 Hong Kong Code of Practice for Structural Use of Glass, based off a study on the structural use of glass commissioned by the BD and overseen by a steering committee with members from academia, professional institutions, and relevant government departments. This document also does not reference any procedure for windborne debris simulations, related to buildings in Hong Kong's typhoon-prone areas.

Buildings 150 m or taller in 1995	61
Buildings 150 m or taller in 2005	247
Buildings 150 m or taller in 2017	317
Buildings 150 m or taller in cyclone-prone areas	317
Buildings 150 m or taller affected by cyclones	276

Table 6.2. Tall buildings in cyclone-prone areas of Hong Kong, December 2017. Sources: Prevention Web, UNEP/UNISDR, and CTBUH

In Hong Kong, recladding processes are routinely undertaken, and there is a high concentration of tall buildings and of curtain walls (see Figure 6.4). The introduction of precise reference test methods for the typhoon resistance of new curtain walls, such as ASTM, should be considered by the BD.

The approval of the façade design and test reports by the BD is fundamental for the progress of any curtain-wall projects in Hong Kong. The rigorous processes at all stages of design and construction ensures structural integrity and compliance with strict safety standards. The retention of a façade engineer is not a statutory requirement in Hong Kong, though it is common for major developments of all functions, and most commercial developments.

Finally, the number of fatalities caused by typhoon events in Hong Kong is low, because of the quality of information provided to the public and the high level of preparedness for storms.

6.3 Tall Buildings in Cyclone-Prone Areas of Hong Kong

In 1995 the Hong Kong area used to have 61 buildings taller than 150 according to the data available on the Skyscraper Center database. This number enlarged for much more than five times, reaching 317 constructions above 150 meters in December 2017. Considering the 2018 typhoon season, all these buildings experienced a typhoon event, even if the December 2017 analysis shows that just 87 percent were hit by typhoons (see Table 6.2).

Figure 6.5. Hong Kong Children's Hospital, Hong Kong. © Wpcpey (cc by-sa)

Project Data

- **Official Name:** Hong Kong Children's Hospital (formerly known as Centre of Excellence in Paediatrics)
- **Location:** Hong Kong, China
- **Developer:** Hong Kong Government
- **Architect:** Simon Kwan & Associates.
- **Structural Engineer:** Meinhardt (C&S)
- **Façade Consultant:** Meinhardt Façade Technology (HK)
- **Façade Contractor:** Far East Aluminium Works
- **Façade Testing Lab:** Hong Kong Curtain

6.4 Case Study

Hong Kong Children's Hospital

Hong Kong, China

Architectural Features of the Building

The Hong Kong Children's Hospital (HKCH) consists of two independent 11-story buildings, with a central courtyard, basement, and other related facilities. Covering a 21,685-square-meter site, the buildings have a gross floor area of approximately 179,223 square meters. The clinical services and facilities that will be provided include inpatient and outpatient services with 468 beds; ambulatory care services including specialist outpatient clinics; community care services; diagnostic and treatment facilities; children-related facilities such as recreation areas, play therapy, classrooms and family rest area; and other general support and administrative services and facilities.

The project, under construction at the time of this case study (see Figures 6.5 and 6.6), is conceived as two separate buildings in a podium-free design, with one tower housing the clinical services, such as an integrated rehabilitation center, main operating theaters, laboratories, data center, and education and training facilities. The other tower will provide patient-related facilities and will include various children-friendly designs and support facilities alongside the clinical facilities. The two towers will be linked by three bridges above a landscaped courtyard at ground level.

Building Design Requirements

The following standards and guidelines form the basis of the building design from the Buildings Department of the Government of the Hong Kong Special Administrative Region:

- Code of Practice for Dead & Imposed Loads 2011
- Code of Practice for Wind Effects in Hong Kong 2004
- Code of Practice for Structural Use of Steel 2011

- Code of Practice for Structural Use of Concrete 2004
- Code of Practice for Fire Resisting Construction 1996
- Practice Notes for Authorized Persons and Registered Structural Engineers
- Building (Construction) Regulation

The basic wind pressure considered for the two buildings is 2.7 kPa, and wind tunnel tests have not been conducted for unusual wind effects.

Façade Design

Code and Guidelines

The Hong Kong Buildings Department (BD) was in charge of the verification of the adequacy of the design and realization choices for the façade solutions of this building complex. The choices were made in order to guarantee a higher-than-normal requested level of performance for the façade, partly due to the complex and important functions of these buildings.

Safety glass solutions were chosen for both the external and the internal glass panes, aiming to strongly avoid any occupant injury resulting from the impact of people or of internal/external objects against the glazed envelope.

For the façade code and guidelines to follow for the HKCH project, a design architect and registered structural engineer (RSE) were appointed for the step-by-step presentation of the requested documentation to the BD.

Figure 6.6. Alternate view of the Hong Kong Children's Hospital (HKCH) under construction. © Prosperity Horizons (cc by-sa)

The façade-related local and international main code and guidelines that have been followed include:

- Code of Practice for Wind Effects in Hong Kong 2004
- Code of Practice for Structural Use of Steel 2011
- Code of Practice for Structural Use of Concrete 2004
- Code of Practice for Fire Resisting Construction 1996
- Building (Construction) Regulation
- BS 8118 Structural Use of Aluminum
- BS 6262 Glazing for Building
- AS 1288 Glass in Buildings – Selection and Installation

Design Principles

In the HKCH project, the primary driving forces for the curtain wall design derived from the desire for a system that ensures safety, energy efficiency, ease of maintenance, and acoustic performance.

The external surface of the façade is comprised of glass and aluminum, painted with four-coat fluorocarbon (PVF2) coating. Both the glass surface and the clear coat of the PVF2 paint provide a smooth and durable surface for future weathering and potential abrasion caused by cleaning.

The façade interior (glass and metal surfaces) can be easily cleaned from the building interior. At locations where acoustic performance is of particular concern, an additional laminated internal glass screen is added to the curtain wall unit. In these instances, cleaning of the façade glass can be conveniently done by opening the top-hung framed internal glass screen.

The hinged glazed acoustic screen attachment will be installed to the curtain wall unit where it is determined to be required, while the parent curtain wall units will be a universal system. The standardization of the curtain wall unit, regardless of whether an acoustic glass screen is attached to it, will reduce the need for different curtain wall components, such as interfacing pieces with partition walls and associated spare parts.

Analysis Modeling and Software

For the development of the façade solution, the Strand 7 Finite Element Analysis (FEA) System software has been used.

Design Phase Considerations

preliminary design

The curtain wall design relied on aesthetic performance and structural efficiency during the schematic design stage. Based on different design parameters, suitable curtain wall systems are applied to the building envelope to ensure technical feasibility and to achieve the design intent.

> “To ease replacement, all horizontally-projected metal features have been engineered to sustain the weight of the replacement glass fin or metal sun-shade during the process.”

Design development
All external shading devices, including the horizontal aluminum sun-shade and the vertical laminated glass fins, have been projected at a finely-tuned 900 millimeters, in order to strike a balance between maximizing daylight, reducing glare, and simplifying cleaning and maintenance. All external façade surfaces are accessible for cleaning via the use of the roof-mounted building maintenance unit (BMU) system.

The sun-shading devices will be factory-assembled, and can be independently detached from the curtain. In the event that replacement of the shading devices or façade glass is needed, the replacement assembly (façade glass or metal feature) will be lifted up using the electric hoist integrated with the roof-mounted BMU system. To ease replacement, all horizontally-projected metal features have been engineered to sustain the weight of the replacement glass fin or metal sun-shade during the process. To avoid direct impact and damage by the BMU cradle, the outer edges of all glass fins are to be trimmed with an extruded aluminum bumper piece.

Product Approval Process Requirements
Coordinated designs and specifications were developed by architects, design engineers, and consultants. These professionals worked together in order to present a solution to the BD that would satisfy the performance criteria. Furthermore, this specific complex had to deal with upgraded solutions in terms of safety, energy efficiency, and acoustic insulation.

After the preliminary design phase of the façade, the process followed the following steps:

- Structural calculation submissions
- Shop drawing submissions
- Materials and samples submission
- Testing standard and method statement submissions
- Visual mock-up, scale 1:1 (see Figure 6.7)
- Performance mock-up tests
- Off-site and on-site tests
- Independent checker's approval

The Government submissions occurred during various phases of the project development, starting before the construction of the envelope system even began, when the BD pre-authorized the façade installation.

Façade Typologies

The following façade solutions have been used for the HKCH project:

- Unitized curtain wall system with vision glass, operable windows, spandrel glass and shadow box, and external glass feature
- Glass wall system
- Aluminum cladding system
- Stone cladding system
- Glass canopy
- Glazed skylight
- Balustrade
- Sun-shading devices
- Performance louver system at tower and podium areas

Support
The following support solutions have been adopted for the various glazed façade typologies:

- Jordahl cast-in channel
- GMS cast-in embed
- Hilti anchor bolt

Figure 6.7. Full-scale visual mock-up of tower curtain wall. © Meinhardt Façade Technology (HK)

Figure 6.8. The curtain wall, as assembled on the Hong Kong Children's Hospital tower. © Meinhardt Façade Technology (HK)

Figure 6.9. The canopy as constructed. © Meinhardt Façade Technology (HK)

Mullions/Frame

Curtain wall

The curtain wall (see Figure 6.8) is designed as a fully unitized system, incorporating the rainscreen principle, resulting in a pressure-equalized system. Aluminum framing will be finished with four-coat metallic fluorocarbon finished to AAMA 2605-02 (AAMA 2002) or equivalent for all exposed surfaces, both inside and outside the building.

Glass wall, glass canopy, and skylight

The glass wall, glass canopy (see Figure 6.9), and skylight systems will include:

- Proprietary metal roofing, forming part of the skylight and canopy system and greenhouse
- Aluminum external ceiling to canopy
- All structures necessary for supporting the skylight/canopy system and greenhouse to the base structure
- All purpose-built mounting brackets and collars necessary for the installation of the building services installations attached to the system
- Fall arrest systems for cleaning and maintenance access

Glass

Curtain wall

Vision panels will be laminated insulated glass units (IGUs) with low-E coating on surface #2. All laminated IGUs shall be fabricated with autoclaved edges on all four sides. The spandrel panels will be made with either heat-strengthened glass with a minimum 10-millimeter thickness, proprietary aluminum cladding panels with fluorocarbon finish, or a combination of the two, to achieve an integrated and distinctive building façade with an image appropriate to the hospital.

The typical solution for the glass makeup of the insulated glass unit (IGU) is 10-mm high-strengthened (HS) + 12 mm air + 6-mm HS + 1.52-mm PVB + 6-mm HS with low-E coating on surface #2. Windborne impact testing was not required.

Spandrel

The spandrels consist of 10-millimeter HS with frit pattern on surface #2.

Glass wall, glass canopy, and skylight

The glass wall, glass canopy and skylight systems include:

- Laminated glass mounted on a proprietary point-fixed glazing system
- Electrically operated horizontal roller blinds underneath the skylight for shading

The glass adopted for the project consists of vision-panel, double-glazed, heat-strengthened glass with low-E coating on surface #2 (see Figures 6.9, 6.10, and 6.11).

Sun-shading devices

Sun-shading devices are incorporated into the design of the glass wall, curtain wall system, aluminum windows and/or skylight system to achieve an overall thermal transfer value (OTTV) below 18W/m^2.

Experimental Tests

The full-scale prototype specimens, for both the tower curtain wall and podium glass wall, with their respective sizes and systems, have been tested (see Figures 6.12 and 6.13). Numerous performance mock-up test procedures for the curtain wall, shown below for reference, have been performed on the curtain wall to ensure the safety, serviceability, and water-tightness performance:

1. Open and close all vents 50 times for operable windows
2. Preloading at 50% of inward design pressure
3. Air Infiltration and Ex-filtration Test – Static (ASTM E283)
4. Water Penetration Test – Static (ASTM E331)

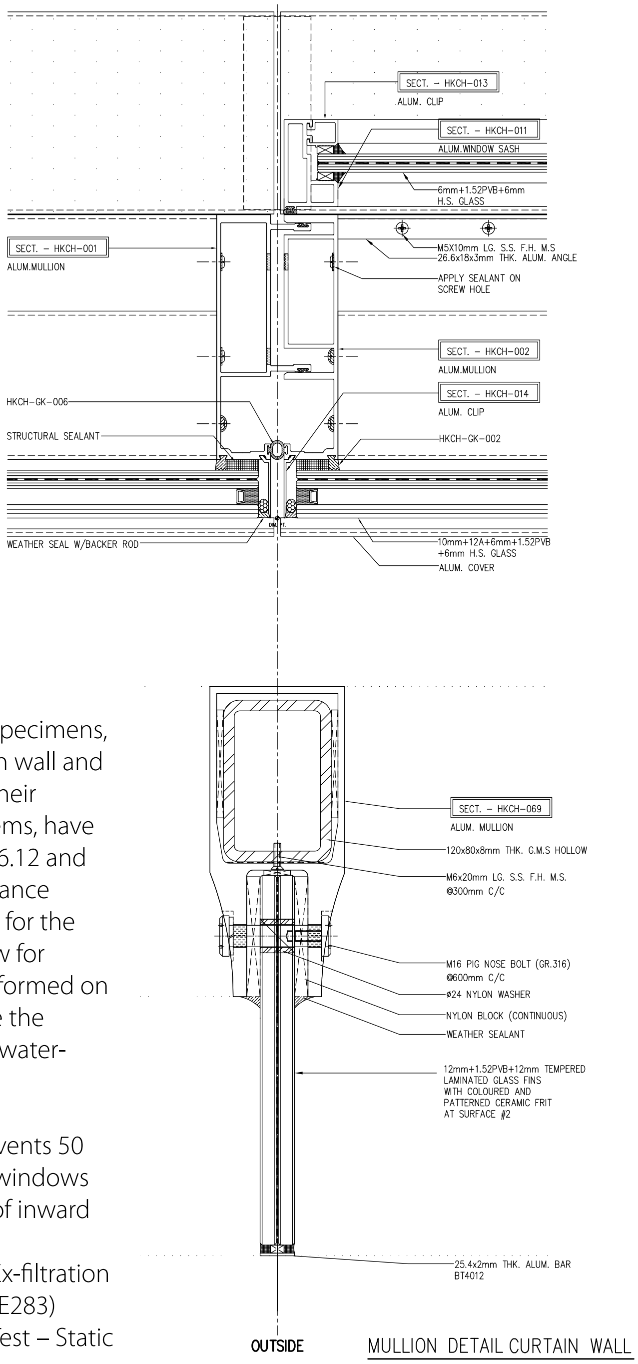


Figure 6.10. Plan and section details of the curtain wall.
© Meinhardt Façade Technology (HK)

5. Water Penetration Test – Dynamic (AAMA 501.1)
6. Structural Adequacy Test at 100% of Design Pressure – Static (ASTM E330)
7. Repeated Water Penetration Test – Static (ASTM E331)
8. Vertical Movement Test
9. Repeated Water Penetration Test – Static (ASTM E331)
10. Horizontal Movement Test (Parallel to One Face)
11. Repeated Water Penetration Test – Static (ASTM E331)
12. Horizontal Movement Test (Parallel to Another Face)
13. Repeated Water Penetration – Static (ASTM E331)
14. Repeated Air Infiltration and Ex-filtration Test – Static (ASTM E283)
15. Structural Adequacy Test – Cyclic (PNAP APP 37)

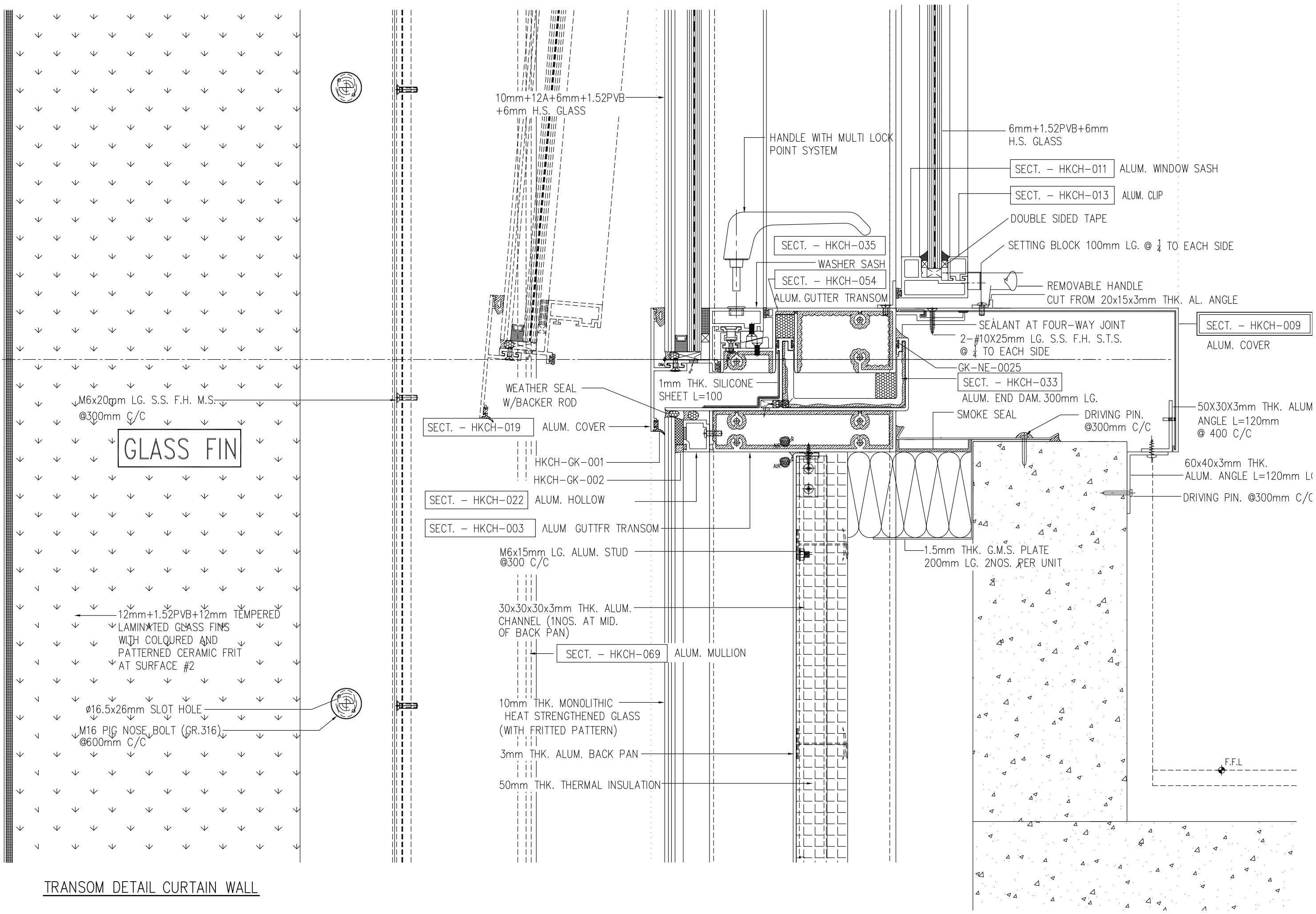


Figure 6.11. Section details of curtain wall. © Meinhardt Façade Technology (HK)

16. Structural Safety Load Test at 150% of Design Pressure – Static (ASTM E330)
17. BMU Restrain Socket Test

Lessons Learned and Recommendations

Difficulties in the Design

The HKCH project has specific acoustic requirement. The internal acoustic window in elevation faces the emergency service flight path thus the helicopter noise had to be considered in the design.

Innovative Design Solutions

A U-frame was provided for supporting the external glass feature.

Figure 6.12. Performance mock-up for tower curtain wall.
© Meinhardt Façade Technology (HK)

Figure 6.13. Performance mock-up for glass wall (alternate view).
© Meinhardt Façade Technology (HK)

6.5 Case Study

One Taikoo Place

Hong Kong, China

Architectural Features of the Building

One Taikoo Place is the latest redevelopment project in Taikoo Place, involving the demolition of existing Somerset House and building a new Grade-A, 200-meter curtain-wall office building with entrance lobbies and footbridge connections to the existing buildings in Taikoo Place (see Figure 6.14 and 6.17). It sits on a prime site with its dominant façades facing Victoria Harbour to the north and the green space of Taikoo Square to the south. On the east, it faces Westlands

Project Data

- **Official Name:** One Taikoo Place
- **Location:** Hong Kong, China
- **Developer:** Swire Properties
- **Architect:** Wong & Ouyang
- **Structural Engineer:** Arup
- **Façade Consultant:** Arup
- **Wind Consultant :** Arup
- **Façade Contractor:** Far East Aluminium Works (Tower); G&M Engineering Company (Podium)
- **Façade Testing Lab:** Façadetech Laboratory (Tower); Leading Edge Construction Materials Testing Company (Podium)

◀ Figure 6.14. One Taikoo Place, Hong Kong.
© Swire Properties

Road with Oxford House and Berkshire House, and on the west, it faces Lincoln House, which is across the internal road of Taikoo Place.

One Taikoo Place is a Grade-A office building with 41 floors of offices, three podium floors, three mechanical floors, one refuge floor and two stories of basement car parks. Each office floor has a gross floor area of about 2,200 square meters. It has a total gross floor area of about 94,000 square meters.

The typical office floor has a rectilinear layout, with a dimension of about 62 by 39 meters, and is designed to achieve flexibility in internal layout. It has a wide span of about 16 meters from window to core on the north, west and south, with inset corners of about three meters (see Figure 6.15). The curtain wall of the building is designed on a 3-meter module, offering an expansive view to the harbor and to the surrounding green environment (see Figure 6.16). Standard provisions on the

Floor 45

Gross Floor Area: ▢ ■ ▨
24,040 sq. ft.
Lettable Area: ▢ ■
21,849 sq. ft.
Net Lettable Area: ▢
20,230 sq. ft.

Raised Floor to False Ceiling Height: 3.0 m
Raised Floor Void: 150 mm clear

KP = Knockout Panel
PL = Passenger Lifts
SL = Service Lifts
AHU = Air Handling Unit

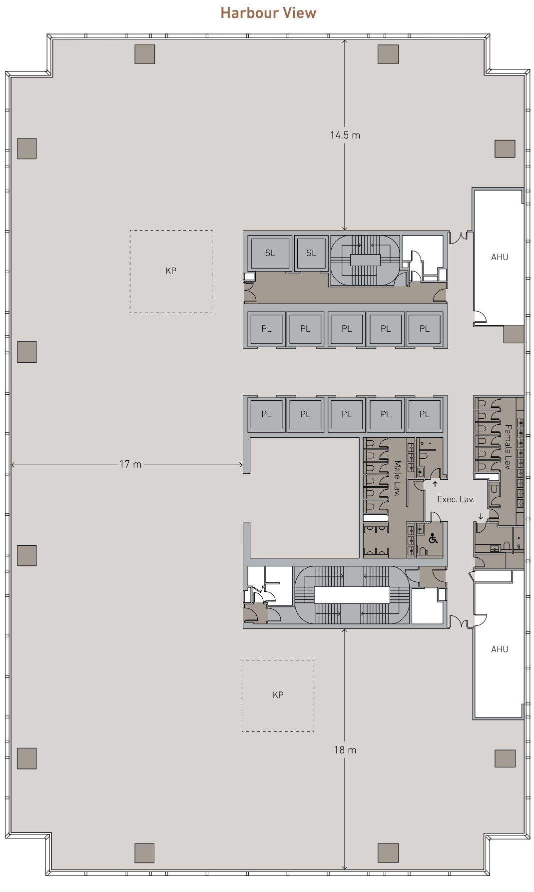


Figure 6.15. Typical high-zone floor plan. © Swire Properties

Figure 6.16. The view from the inside. The glazed curtain wall has modules measuring 2.4 meters high by 3 meters wide. © Swire Properties

office levels include a raised floor, modular ceiling with a clear height of 3 meters, and well-appointed lobby and toilet facilities.

The façade features solar shading devices of varying depths (from 200 to 700 millimeters), and high-performance insulated glass panels with low-E and reflective coatings. Sustainable design features include state-of-the-art air-conditioning with free cooling, PV panels, and a bio-diesel tri-generation system.

Building Design Requirements

The following standards and guidelines issued by the government of Hong Kong, among others, form the basis of the building design:

- Code of Practice on Wind Effects in Hong Kong, 2004
- Explanatory Materials to the Code of Practice on Wind Effects in Hong Kong, 2004
- Code of Practice for Structural Use of Concrete, 2004
- Code of Practice for the Structural Use of Steel, 2011
- Building Authority APP-37 Curtain Wall, Window and Window Wall Systems, 2012

Wind tunnel tests have been considered to predict unusual wind effects around the buildings and to locate any "hot spots" prone to cladding pressure.

- Maximum wind pressure for the tower curtain wall is 5.5 kPa
- Maximum wind pressure for the podium glass wall is 3.5 kPa

Façade Design

Code and Guidelines

In Hong Kong, the Buildings Department (BD) is one of the key regulators that govern façade-related works. The façade was designed to comply with the Hong Kong (Construction) Regulations, BD Practice Note for Authorized Persons and Registered Structural Engineers (PNAP). Also, there are codes of practice issued to facilitate the technical aspects of the design and construction requirements for curtain walls. Similar overseas codes or standards like ASTM, British standards, and Australian standards could be considered if applicable, subject to the acceptance of the appropriate statutory authorities.

Local codes of practices for the main structural components, which have been followed in this project for reference:

- Wind: Code of Practice on Wind Effects in Hong Kong, 2004
- Concrete: Code of Practice for Structural Use of Concrete, 2004
- Structural steel: Code of Practice for the Structural Use of Steel, 2011

There is no specific code of practice to be followed for aluminum or glass design; overseas standards have been followed:

- Glass: AS 1288:2006 – Glass in Buildings - Selection and Installation
- Aluminum: BS 8118 - Structural Use of Aluminum

Hong Kong's own *Code of Practice for Structural Use of Glass* was published for consultation in February 2018. The code provides guidance on design, construction, testing and quality assurance of structural glass works.

Design Principles

The curtain wall system of One Taikoo Place focuses on the following aspects: aesthetics, water-tightness, safety, buildability, sustainability, durability, maintenance, acoustical control, and fire safety.

Two main façade typologies have been identified (see Figure 6.17):

- The tower uses a 3-meter-wide by 4.2-meter-high panel modulation with low shading coefficient (SC) value on the glazing panel. It also uses a unitized and pressure-equalized system, consisting of extruded curved profiled mullions and transoms, with a typical 3-meter module for all elevations from the third floor to the roof.
- The podium uses a 3-meter-wide by 17-meter-high glass wall, which runs from floor to floor. The glass wall system consists of full-height laminated glass fins and glass louvers spanning from the ground floor to the third floor.

Analysis, Modeling, and Software

The methods of analysis for the structural members (e.g., glass, aluminum, etc.) were based mainly on formulas in design standards. Finite element analysis software was also been used for the project.

Design Phase Considerations

Preliminary design. Curtain wall design focused on aesthetic performance and structural efficiency during the schematic design stage. Based on different design parameters, suitable types of curtain wall system were designated to be applied to the building envelope to ensure technical feasibility and to achieve the design intent.

Design Development. Further detail development in the design and installation of the façade system was followed by a specialist sub-contractor during the detail design stage. The purpose was to enhance its buildability, durability, maintenance, operation, and safety, as well as to ensure that sustainability performance would be achieved in an integrated design.

Prior to construction, a visual mock-up was constructed to ensure the aesthetic requirements were met before master production or fabrication. Additionally, performance mock-up tests of the system, as well as other materials, were carried out to justify its safety and performance, and also to ensure proper and high-quality workmanship.

Figure 6.17. One Taikoo Place façade with connecting footbridge at podium level. © Swire Properties

Product Approval Process Requirements

Structural calculations comprising design checks on the parent structure, analysis of the structural adequacy, and stability of the entire proposed façade system were required to be submitted to the BD for approvals prior to the construction of the façade works. Scale 1:1 mock-ups had to be realized and tested following the testing procedures presented to the BD.

Façade Typology: Tower

Support

The curtain wall systems are supported by aluminum brackets, which are mounted onto cast-in embeds in primary concrete structure (see Figures 6.18 and 6.19).

Mullions/Frame

The selection of mullions and transoms was governed by the wind loading and the stiffness of the components used. The mullions span from floor to floor (typically 4.3 meters) of the building, and the transoms are spaced to maximize the vision glazing. The framework of the unitized curtain wall is made up with extruded profiled mullions, transoms, and external

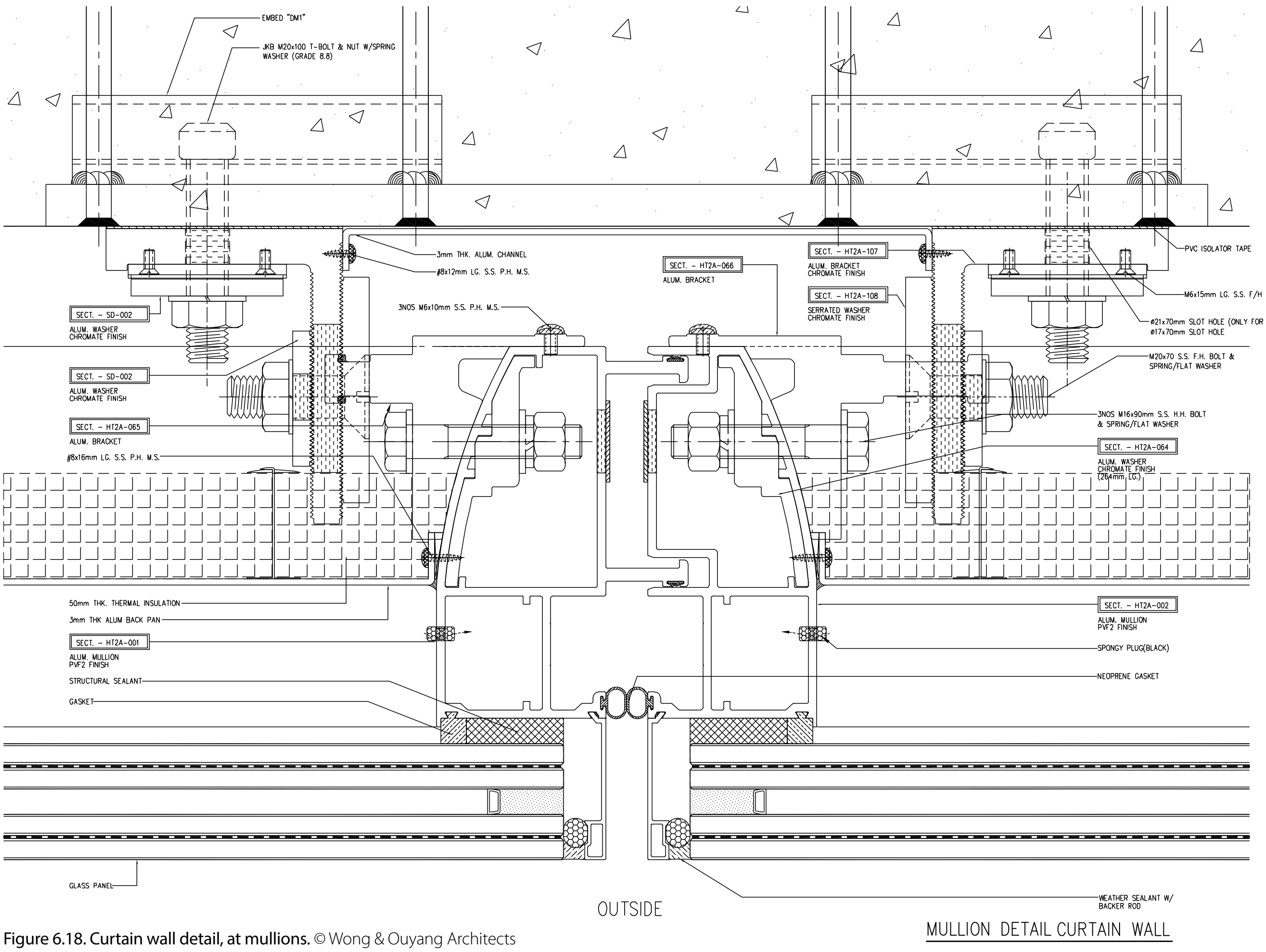


Figure 6.18. Curtain wall detail, at mullions. © Wong & Ouyang Architects

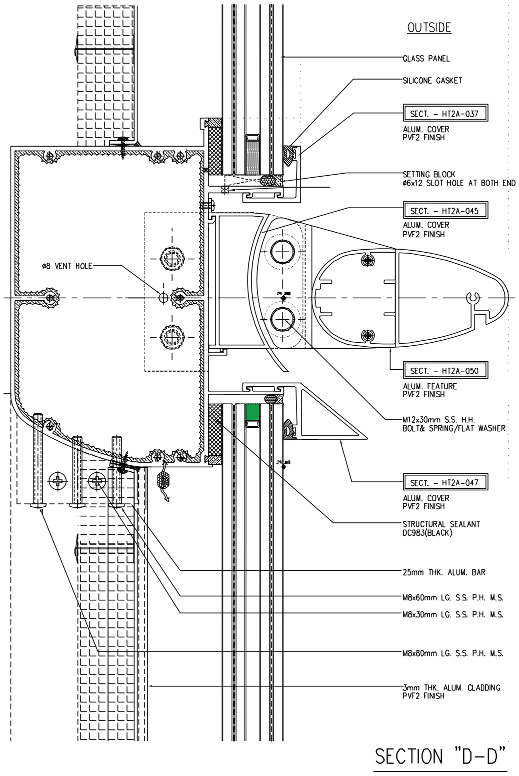
horizontal architectural features, for which the exposed areas are painted with the PVF2 four-coat system.

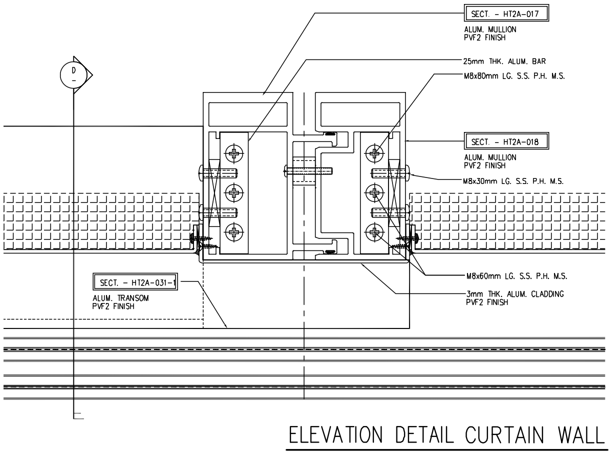
Glass

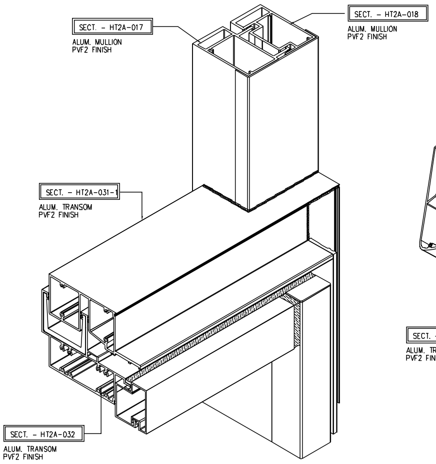
The maximum size of the vision glass pane in this project is 2.4 meters high by 3 meters wide. All the vision and spandrel glass is composed of double-laminated IGUs with reflective and low-E coating. The panes of the double-laminated IGUs are heat-strengthened glass with built-up 10-mm heat-strengthened (HS) + 12 mm air + 10-mm HS, but the inclined curtain wall was decided to have a safer laminated glass solution in order to prevent the glass from falling on pedestrians in case of breakage. It uses a 5-mm HS + 1.52-mm PVB + 5-mm HS configuration. Windborne impact testing was not required.

Experimental Tests

The full-scale prototype specimens, for both the tower curtain wall and podium glass wall with their respective sizes and systems, were tested. Eighteen performance mock-up test procedures for the curtain wall, shown below for reference, were tested on the curtain wall to ensure safety, serviceability and water-tightness performance:







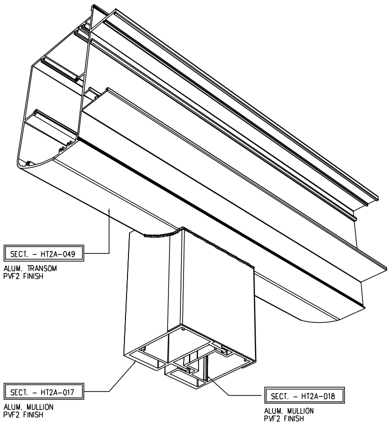


Figure 6.19. Curtain wall details for One Taikoo Place. © Wong & Ouyang Architects

1. Open and close all vents 50 times for operable windows
2. Preloading at 50% of inward design pressure
3. Air Infiltration and Ex-filtration Test – Static (ASTM E283)
4. Water Penetration Test – Static (ASTM E331)
5. Water Penetration Test – Dynamic (AAMA 501.1)
6. Structural Adequacy Test at 50% and 100% of Design Pressure – Static (ASTM E330)
7. Repeated Water Penetration Test – Static (ASTM E331)
8. Vertical Movement Test
9. Repeated Water Penetration Test – Static (ASTM E331)
10. Horizontal Movement Test (Parallel To One Face)
11. Repeated Water Penetration Test – Static (ASTM E331)
12. Horizontal Movement Test (Parallel To Another Face)
13. Repeated Water Penetration – Static (ASTM E331)
14. Repeated Air Infiltration and Ex-filtration Test – Static (ASTM E283)
15. Repeated Water Penetration – Static (ASTM E331)
16. Structural Adequacy Test – Cyclic (PNAP APP 37)
17. Structural Safety Load Test at 75% and 150% of Design Pressure – Static (ASTM E330)
18. Gondola Tieback Load Test

> “There is no precedent case in the Hong Kong property industry of using a 3-meter-wide by 4.3-meter-high unitized panel.”

Façade Typology: Podium

Support

The full-height fin-supported glass wall system, where the typical façade is formed of ground-supported laminated glass panes, and fixed via structural sealant to the laminated glass fins, spans between the ground floor and the third floor.

The glass pane louvers are simply supported on two sides, via structural sealants to the glass fins through the aluminum capping. The glass fins, which span 17.26 meters, including the top and bottom channels, could be considered as a simple supported beam, and were laterally restrained at the front edge by the facial glass panes after installation.

Glass

Facial glass

Comprised of three plies of 12-millimeter heat-soaked fully- tempered glass with maximum size of 17.12 meters high by 3 meters wide, the glass panels are clear-laminated and low-iron tempered, with an SG5000 interlayer.

Glass fins

Comprised of six plies of 12-millimeter heat-soaked fully-tempered glass with a maximum size of 17.12 meters high by 1.15 meters deep, the glass panels are clear-laminated and low-iron tempered, with an SG5000 interlayer.

Experimental Tests

The full-scale prototype specimens, for both the tower curtain wall and podium glass wall with their respective sizes and systems, were tested (see Figure 6.20).

Figure 6.20. Performance mock-up of the podium façade. © Wong & Ouyang Architects

Project-specific tests on the podium glass wall included:

- Weathering Conditioning Test of Laminated Glass to ANSI Z97.1: 2009
- Bending Strength Test at 50°C of glass to BS 1288-3:2000
- Samples of 1,100 by 360 millimeters, as stipulated in BS EN 1288-3:2000 have been requested by the building authority to demonstrate the bending strength and durability of the SG5000 laminated glass.

The samples were first conditioned by accelerated xenon-arc type operating light exposure, with a total of 6,000 hours of continuous irradiation on the SG5000 laminated glass, under dry and wet conditions; and temperatures, and under ultraviolet exposures according to ANSI Z97.1: 2009. The bending test was carried out at controlled temperature 50°C, according to BS EN 10088, after prolonged weathering.

The purpose of the tests was to show that the bending stiffness of the samples had no reduction after the weather conditions specified in ANSI Z97.1:2009 were applied.

Lessons Learned and Recommendations

Difficulties in the Design

- *Heavy panels*
  Tower: glazing on each curtain wall panel ≈ 1.3 metric tons
  Podium: facial glass ≈ 4.6 metric tons
- Specific considerations on fabrication, packaging, logistic, equipment, handling method, etc.
- Stringent requirements on energy performance: Stringent requirements for an Overall Thermal Transfer Value (OTTV) of 15W/m^2 and low SC value (< 0.19) of the tower glass panel to enhance thermal energy performance.

Innovative Design Solutions

- There is no precedent case in the Hong Kong property industry of using a 3-meter-wide by 4.3-meter-high unitized panel. Several issues of manufacturing and fabrication, logistics and delivery, site handling, and installation were brought to the team at the early design stage.
- In achieving the full-height panes for the glass wall, SG5000 composite actions have been considered in the design to reduce the required number of layers.

7.0 Japan

7.1 Principal Design Rules

In Japan, the design of a curtain wall has to guarantee performance against strong winds depending on the location. The *Recommendations for Loads in Buildings* (AIJ 2015) is the fundamental code referenced. This document directly refers to the building cladding and provides the references for the correct design. The principal elements to take into account for estimating wind load are: the design velocity pressure, the peak wind force coefficient, and the subject area of components/cladding.

The design velocity pressure is based on the air density and on the design wind speed, which depends on the direction of the wind. The basic wind speed is based off of a 100-year return period (AIJ 2015) and on a 10-minute mean wind speed over an open and flat terrain at an elevation of 10 meters' height. This value changes depending on the area of Japan being examined (see Figure 7.1). The peak wind force for the design of the cladding depends on the external pressure coefficient and the factor for the effect of fluctuating internal pressures.

Although the Architectural Institute of Japan (AIJ) Recommendation gives useful information, the legal minimum requirements for wind design of curtain walls are stipulated in *Ministry of Construction Public Notice No. 1458* of Ministry of Land, Infrastructure and Transport and Tourism (MLIT) of Japan. MLIT Notices are issued to implement requirements in *Building Standard Law of Japan;* the Enforcement Order and the AIJ Recommendation are applicable only if these give more conservative requirements than those given by the MLIT Notices. The Standard Wind Speed, which provides the basis for requirements in the Public Notice No. 1458, is the expectation for a return period of 50 years. For the purposes of code, a building in Japan is considered a "tall building" if it is higher than 60 meters (AIJ 2015).

Focusing on the flying-debris resistance of glazed building envelopes, the *JIS R 3109:2018 Glass in Building – Destructive-Windstorm-Resistant Security Glazing – Test Method* was established on July 20, 2018 (investigated by the Japanese Industrial Standard Committee and published by the Japanese Standards Association). Currently, glass is certified according to this industrial standard, which is based on ISO 16932; the framing system and the panel sizes are not related to any mock-up. They are standardized in order to test the glass.

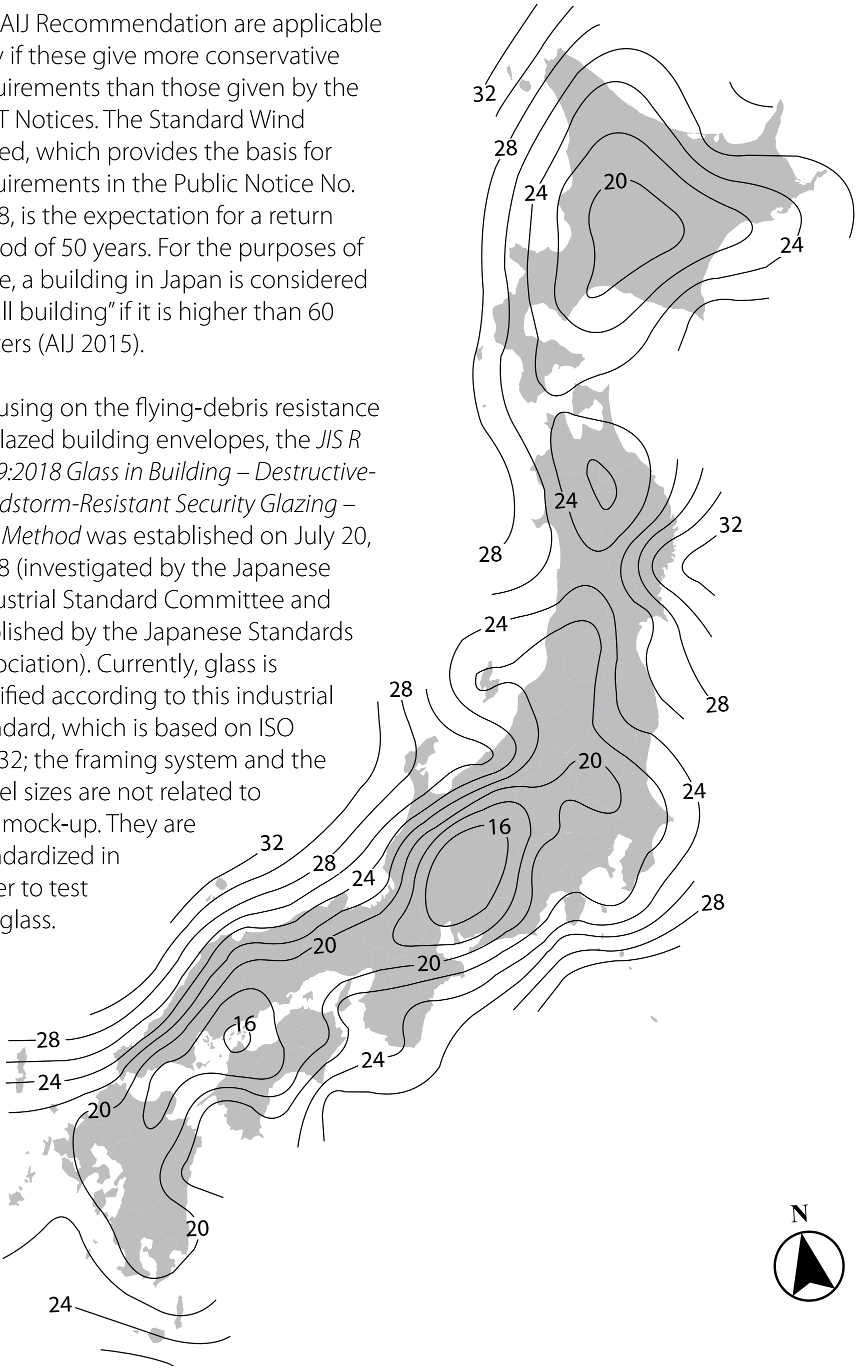


Figure 7.1 Map showing the locations of 100-year mean wind speed events (in m/s), sustained for at least 10 minutes at 10 meters above ground over a flat and open terrain in winter. Source: AIJ

Currently, the 1:1-scale façade mock-ups are tested for many other performance criteria, other than typhoon resistance, such as wind pressure, earthquake resistance, water penetration, etc. The present procedure could be implemented in order to test the entire façade system's flying-debris resistance (following a procedure such as the ASTM E1886 and ASTM E1996).

In Japan, following the testing, the results do not have to be presented to any government institute in most cases. For some cases, design documents showing that some selected important parts of the building envelope are composed of materials that provide resistance to spread of fire must be submitted to the authority having jurisdiction (AHJ). Also, calculation of energy loss and heat gain through the building envelope is required in some cases.

The *Curtain Wall Performance Standard* is a Japanese guideline for curtain wall design and testing. The wind load section was revised in 2017, and the recommendations correspond to the following building height ranges (see Figure 7.2 and Tables 7.1 and 7.2):

- H < 60 m: Grade 1 or 2
- H ≥ 60 m: Grade 2 or 3

7.2 Professional Roles and Responsibilities

Developers

Real estate developers in Japan typically ask curtain-wall industry professionals for higher performance, as they are the only ones effectively performing the certification processes and reports. Some dialogue with the AHJ can generate benefits for the developers. One example of this is in the instance of choosing a laminated glass solution instead of a single-layer annealed glass product.

This choice could result in the authorization to reduce the minimum setback for new constructions; this means a bigger building volume can be authorized on the same lot, because the external façades could be installed in a position closer to the public street. In recent decades, Japan has had

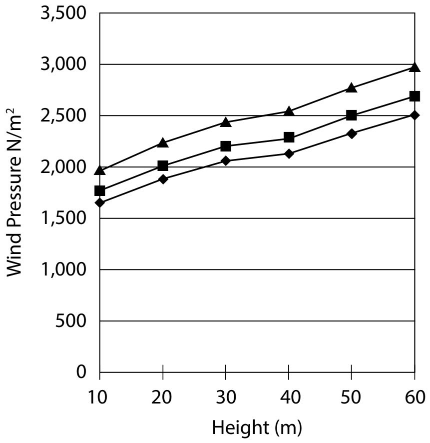


Figure 7.2. Wind pressure (N/m^2) for Grade 1 (♦ return period 50 years), Grade 2 (■ return period 100 years), Grade 3 (▲ return period 50 years) buildings, depending on building height.
Source: Ministry of Construction Public Notice No. 1458

Grade	Wind Load (Pa)
1	Calculated by Ministry of Construction Public Notice No. 1458 The return period is **50** years.
2	Calculated by Ministry of Construction Public Notice No. 1458 With standard wind speed multiplied by **correction coefficient 1.07** that is estimated for return period **100** years
3	Calculated by Ministry of Construction Public Notice No. 1458 With standard wind speed multiplied by **correction coefficient 1.19** that is estimated for return period **300** years

Table 7.1. Recommended curtain wall performance standards for Japan.
Source: Ministry of Construction Public Notice No. 1458

Height (m)	Pressure (N/m^2, Pa)					
	Grade 1		Grade 2		Grade 3	
	Positive (+)	Negative (-)	Positive (+)	Negative (-)	Positive (+)	Negative (-)
13	1,659	874	1,775	935	1974	1,040
20	1,879	1,038	2,011	1,111	2,236	1,235
30	2,055	1,221	2,199	1,306	2,445	1,453
40	2,132	1,370	2,281	1,466	2,537	1,630
50	2,331	1,666	2,494	1,783	2,774	1,983
60	2,507	2,149	2,682	2,299	2,983	2,557

Table 7.2. Recommended wind pressure resistance levels for building heights up to 60 meters.
Source: Ministry of Construction Public Notice No. 1458

several issues related with the breakage of heat-strengthened glass that has not undergone an appropriate quality-control program during the production phase. The resulting rule changes demonstrate a recognition in Japan of the safety performance of laminated glass compared with single-layer solutions.

Insurance company regulations concerning glass performance in Japan are not as significant as in other jurisdictions. Therefore, the developers and building owners are the primary parties deciding the level of performance their building should achieve (beyond referring to the basic requirements established by the law). The biggest developments in Japan currently apply for LEED or ASHRAE certification, because this increases the value to the property when it is sold or rented. A high level of performance for curtain walls is also commonly specified for symbolic buildings that embody the image of a company or region in Japan.

Designers
Design firms must deal with several stakeholders, including the client, the general contractor, the façade supplier, the façade consultant, etc. The professional role of a façade consultant is not a requirement in Japan, and it is not even a common practice to engage this expert during the façade definition process. When they are involved in the design process, they assist the designer in the development of the ideally-performing façade, once the aesthetic qualities have been determined. The designer is responsible for relaying the desired façade concept of the building, its design characteristics, and its safety performance requirements to the façade consultant or, more frequently, directly to the façade supplier. In Japan, it is very common that designers work directly with the façade suppliers for façade design development and, eventually, the production of the detailed drawings. Designers and other professionals work together in order to define the architectural appearance of this technological element, the minimum design requirements to consider, the safety precautions, and the maintenance procedures for the installed product.

In locations that experience strong winds and typhoons, it is very common to conduct wind tunnel testing in order to have a detailed collection of data about the local pressures on the façade, especially for high-rise buildings. This is a method by which performance characteristics can be improved, by determining engineering efficiencies and avoiding over-engineered retaining systems and glass compositions.

Façade Consultants
Façade consultants are not common in Japan; only one large firm with expertise in this field, Arup, works in Japan. Although Arup has been in Japan over the past few decades, the work has been on a small number of projects compared with the total number of façades installed in the country every year; developers and designers more typically work directly with the façade supplier. Using a façade consultant would provide an advantage, as it would involve an expert who can critically analyze the performance that a building envelope must guarantee according to local statutes, international best practices, budget requirements, and the desired aesthetic result.

Architects of major firms operating in the Japanese market generally utilize consultants when they want to develop customized façades for their projects. Following input from façade consultants, the proposed solutions still require the approval of the developer and of the general contractor, so the inputs from the façade consultant still may not be the chosen solution for the final design. This situation results from the lack of a requirement for presenting certifications to the building department, and because tests do not need to be carried out in labs controlled by the government; there is no guidance about third-party supervision of the production process. When a façade consultant is called to participate in a project, it usually concerns a very important development for which the façade isnot standard, and is consequently more demanding than a conventional building.

Façade Suppliers
The façade suppliers have a central and significant role both in the façade design and testing process in Japan. The main façade manufacturers have their own internal equipment and testing facilities inside their factories, in

order to verify the products before they are installed in real buildings. They also have internal design teams, and normally consult directly with the building's designers.

The façade suppliers test their own products internally, and their testing equipment can be even more sophisticated than building research institutes managed by the government institutions. They can self-perform testing because there is no mandatory requirement to designate a third-party association to evaluate façade performance, and the test results do not have to be presented to anyone other than those working directly on the project itself, e.g., the client, the façade consultant (when present), or the architect.

The Japan Sash Manufacturer Association (JSMA), Windows & Doors - is the industry association for façades in the country. It has representatives from the four principal Japanese façade suppliers (YKK AP Inc., LIXIL Corp., SankyoTateyama, Inc., and Fujisash Co. Ltd.) and it is continually dealing with the main international façade associations for the improvement of industry standards. JSMA drew up a guideline in 2003, which contains the best practices for curtain wall design in Japan and explains the testing procedures. In this document, there are design and testing references for construction of façades in locations prone to strong winds and typhoons, earthquakes, and other events. The guidelines elaborate on the minimum safety requirements, based on the AIJ Recommendations for Loads on Buildings and the Building Standard Law of Japan. In its Fifth Edition, the main principles for façade definition are clearly highlighted (AIJ 2015).

Façade Test Labs

The façade test labs in Japan are commonly privately organized and set up by façade manufacturers. The common practice is that the façade manufacturers self-test their own products, because they have the equipment to carry out the tests required by the designers or the façade consultants. Furthermore, the main Japanese façade suppliers have research departments, in which international developments in the façade field are studied and tested, in order to upgrade their products to meet the most advanced building practices. Sometimes manufacturers will invest in new testing devices solely for internal studies.

The General Building Research Corporation (GBRC) of Japan was officially authorized as a non-profit foundation in 1964 by the Japanese government, with the mission of promoting public welfare by improving the quality and safety of buildings, based on a series of research, testing, and evaluating on activities related to building technologies. The GBRC has upheld its reputation by conducting strict and fair analyses on the activities related to overall building technologies. It uses an air cannon to conduct the missile impact tests, which simulate the windborne debris characteristics of

> “All buildings of 150 meters or higher in Japan are located in a typhoon-prone area, and 84 percent of these have experienced a typhoon event.”

typhoon-prone regions (see Figure 7.3). GBRC also has a pressure chamber for conducting positive and negative pressure cycling tests. This allows the company to conduct the entire test procedure according to the ASTM or ISO standards for typhoon-resistant façades. GBRC conducts tests for private clients, and sometimes acts as an external auditor for façade performance.

Figure 7.3. Façade mock-up installation for testing, General Building Research Corporation (GBRC).
© Angela Mejorin

Government Institutes

The Building Research Institute (BRI) is a national research and development agency of Japan. This institute was founded in 1942 and conducts technological investigations, testing, research, and development on buildings, and also provides technical guidance and dissemination of results. The BRI strives to maximize the results of research and development, to contribute to the stable development of the national economy and public welfare through the improvement of science and technology. One of the roles of BRI is to conduct research and development to provide technical bases for requirements in the Building Standard Law of Japan.

The Institute is directed by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT), and it aims to realize a safer urban environment, spearheaded by the "Safe and Secure Program." This is achieved through conducting various research activities that contribute to the mitigation of building damage caused by natural disasters such as typhoons. The research and development activities are carried out in cooperation with stakeholders from industrial and academic sectors, and the results are shown to the public via new governmental policies and technical standards related to building technology.

In 2012, the BRI, in collaboration with the Disaster Prevention Research Institute (DPRI) of Kyoto University, completed a study that clarifies the verification methods for the performance of external building cladding against wind. Since its

Figure 7.4. Air cannon for missile impact-testing of glazing, DPRI, Kyoto University. © Angela Mejorin

Figure 7.5. Typical Japanese roof tile and air cannon adaptor to shoot the tile through a glass sheet, DPRI, Kyoto University. © Angela Mejorin

inception in 1951, the DPRI has been pursuing the reduction of damage from natural disasters, establishing integrated methodologies for disaster prevention on the basis of natural and social sciences. It published the results in the research paper, "Developing Impact-Resistance Test Methods for Flying Debris on Cladding." The paper reported on the testing procedures to be conducted on the building envelope for sensitive buildings, such as: facilities involved with hazardous materials. This procedure refers to the existing impact-resistance test methods for windborne debris on façades in typhoon-prone areas found in ASTM and ISO.

At the DPRI, the ASTM and ISO standard tests have been improved, increasing the range of missile typologies studied for their impact on the cladding, by simulating realistic windborne debris during a typhoon event (see Figure 7.4). This is aimed at verifying the adequacy of the international and US standards for the amount of energy that needs to be absorbed by the building envelope. For example, this includes calculating the energy produced by the typical roof-tile debris that can become airborne. A device developed by the DPRI, which will be added to the air cannon, simulates the impact of a Japanese roof tile on a façade (see Figure 7.5). Currently, the new JIS R 3109:2018 (based on ISO 16932), established in July 2018, was investigated by the Japanese Industrial Standard Committee, and the DPRI took part in the discussion.

Buildings 150 m or taller in 1995	45
Buildings 150 m or taller 2005	107
Buildings 150 m or taller 2017	240
Buildings 150 m or taller in cyclone- prone areas	240
Buildings 150 m or taller in affected by cyclones	186

Table 7.3. Tall buildings in cyclone-prone areas of Japan, December 2017.
Sources: Prevention Web, UNEP/UNISDR, and CTBUH

7.3 Tall Buildings in Typhoon-Prone Areas of Japan

Over the past 30 years, the number of tall buildings in Japan has grown. The number of buildings 150 meters or taller numbered 240 as of December 2017 (see Table 7.3). Furthermore, through a GIS analysis, it has been highlighted that 100 percent of the tall buildings are in typhoon-prone areas, and that the 84 percent of the analyzed tall buildings have experienced a typhoon event in the past.

7.4 Case Study

Tokyo Sky Tree

Tokyo, Japan

Architectural Features of the Building

Six Tokyo television broadcasters joined together at the end of 2003 to initiate the construction on the Tokyo Sky Tree, a 634-meter-tall telecommunications and observation tower (see Figure 7.6). This broadcast tower, completed in 2012, serves as the main source for transmitting broadcast signals throughout the entire Kanto Plain and represents a major landmark in Japan. The resulting tower's design is a reminder of the earth's spherical shape; it serves as a major touristic attraction and a quasi-disaster-prevention center for the Tokyo metropolitan area. The tower is a symbol of Tokyo and is currently the second-tallest man-made structure in the world, behind only the Burj Khalifa in Dubai.

Project Data

- **Official Name:** Tokyo Sky Tree
- **Location:** Tokyo, Japan
- **Developer:** Tobu Tower Skytree
- **Architect:** Nikken Sekkei
- **Structural Engineer:** Nikken Sekkei
- **Façade Contractor:** YKK AP

◀ **Figure 7.6. Tokyo Sky Tree, Tokyo.** © Kakidai (cc by-sa)

The Narihirabashi-Oshiage District, on the east side of Tokyo, was once an area dominated by the Tobu Railway freight yard. Also known as the Koto Delta, a look at the project area on a map reveals it to be in the form of an equilateral triangle, whose sides are formed by the JR Sobu Line, as well as the Sumida River and the Arakawa River. The Tokyo Sky Tree is both a prominent symbol of the district and a strong urban landmark visible all over the city (see Figure 7.7).

The project site is narrow rectangular strip running east to west, bordered on the north by the Tobu Isezaki Line and on the south by the Kitajikkengawa River, with an area of 36,800 square meters . The tower is part of a major project to develop the entire site, which includes shopping facilities, offices, an aquarium, and a planetarium. The fourth floor of the basement also serves as the access point to the Tokyo Sky Tree Tembo Deck (*tembo* means "view" in Japanese). The shape of the site, and constraints posed by the subway that runs under the construction area, dictate the dimension of the Tokyo Sky Tree's footprint, which is essentially a 68-meter-wide equilateral triangle.

Figure 7.7. The Tokyo Sky Tree, seen from the Asakusa Culture and Tourism Center. © Wei Te Wong (cc by-sa)

Figure 7.8. View from the Tembo Deck of the Tokyo Sky Tree. © Daniel Safarik

The Tokyo Sky Tree has 29 floors, but when the project was issued, there was a strong debate regarding its status. The Building Standards Act of Japan defines various building typologies and broadcast towers as "non-buildings". After several meetings with government officials, the Tokyo Sky Tree was defined as a "building erected within an elevated structure," causing the need for those involved in the project to clearly declare which part of the project is a "building" and which is a "non-building" (Schinkenchiku 2012).

The Tokyo Sky Tree has two observation decks. The viewing area of the first one is called Tembo Deck and has three different levels at 340, 345, and 350 meters, while the second observatory is called Tembo Galleria, and is composed of two levels at 445 and 451 meters high. These decks are clad with aluminum curtain walls that are composed of units approximately half the 5-meter heights of each floor. The façades of these observation sections of the tower have an inverted-cone shape that permits tourists to enjoy a full view of Tokyo (see Figure 7.8).

Building Design Requirements

The requirements for structural design in Japan are very demanding, as they take into account the extreme winds and earthquakes that are typical of the area. For this reason, the Tokyo Sky Tree tower was required to adopt the most stringent building regulations in Japan, because of its functional responsibility to send valuable information to the public during major disaster events.

The structure is designed to endure for 100 years, and additionally, the tower is rated L3, a designation exceeding most Japanese requirements: it calls for resistance to major, unparalleled disasters, with a return period of 2,000 years (Konishi & Emura 2015).

When crafting the wind resistance design, it was crucial to learn how wind behaves at altitudes over 600 meters; this began with an investigation of observing how wind behaves in general. Winds are strong along the coastline, but not as strong once within a city's limits. This simple rule about wind strength is immensely useful from an engineering point of view. While the chances that a big typhoon might occur can be calculated using probability theory, it is reliable to calculate probable wind velocities depending on the surface roughness phenomenon (the topography of windward land greatly effects wind velocity). The design team, therefore, deployed balloons equipped with global positioning system (GPS) probes to measure wind velocity at elevations above the tower's highest point, and up to a maximum altitude of 28,000 meters. The wind pressure considered for the highest observatory deck at 451 meters' height was about 10,000 Pa.

The Tokyo Sky Tree has a hybrid structure, combining steel with a structurally independent concrete tower at its center. This core tower, called in Japanese *Shimbashira*, is inspired by the traditional wooden multi-story traditional pagodas. The steel tower is a three-layered structure, which is named the *Gaitou* (an outer frame), the *Nakatou* (a middle frame), and the *Naitou* (an inner frame). The tripod steel trusses that support the tower comprise the *Kanae* truss, named after the ancient three-legged cauldrons with the same name.

The tower's steel structure employs higher-than-usual-strength steel tubes in order to build thinner and lighter structural components. The lighter construction also allowed for faster construction speeds, reduced the tower's wind susceptibility, and improved its overall wind resistance. Furthermore, the dimensions of the steel structural members were determined with the aim of avoiding aerodynamic instability caused by wind pressure, a phenomenon known as vortex-induced response.

The core design for the Shimbashira (core column) control system for wind and earthquake vibration was worked out over six months after the project started, so that it could be incorporated into the main plan. In architectural terms, the central column is an emergency stairwell in the center of the tower enclosed in a 385-meter concrete tower that extends from the ground to the Tembo Deck. The system's operating range is from 125 to 375 meters, where oil dampers are installed between the central column and the steel frame. The dampers keep the central column and steel frame from

> "The design team deployed balloons equipped with Global Positioning System (GPS) probes to measure wind velocity at elevations above the tower's highest point."

colliding during an earthquake. Additionally, there are different vibration cycles of the central column and steel frame, to counteract the vibration of the overall tower. The system has proved to have excellent performance, reducing earthquake vibration up to 50 percent and wind vibration up to 30 percent. The Shimbashira's mass is directly related to its ability to reduce the vibration of the resulting hybrid structure. The structural system identified is the same used for smokestacks and chimneys: cast-in-place concrete, often called the "slip-form method." The core column employs full pre-stressed concrete with high-tensile steel strands to prevent movement in the event of an external disturbance.

The bottom of the Shimbashira is joined with the tower, but it was more logical to join the very bottom with the underground concrete base with a semi-rigid, rubber support connection. Laminated rubber bearings, strong enough to act as dampers for the concrete tower, are used.

The outdoor steel tubes are constantly exposed to natural elements; for this reason, a heavy anti-corrosion fluorine coating, usually utilized on bridges, was used for the Tokyo Sky Tree.

The following law, among others, forms the basis of the building design and was used as a reference in this project. The legal minimum requirements for wind design of the curtain wall solutions are stipulated in the *Ministry of Construction Public Notice No. 1458: Stipulation of Criteria for the Structural Calculation Performed to Confirm Safety of Structural Capacity Under Wind Load of Roofing Materials and Cladding*.

While the expectation of a return period is generally for 50 years, the Tokyo Sky Tree was designed taking a return period of 100 years into consideration.

Wind tunnel tests have been used to predict unusual wind effects around the tower and to locate if there are any "hot spots" prone to cladding pressure. The maximum wind pressure for the tower curtain wall is 9.5 kPa. With safety factors, on the top observation deck of the tower, the wind pressure used for the design calculation is 10.0 kPa.

Façade Design

Code and Guidelines

The Public Notice No. 1458 of the Ministry of Land, Infrastructure and Transport and Tourism of Japan (MLIT) has been taken as a reference document. The design choice accounted for a return period of 50 years. This means that the wind speed has been multiplied by a correction coefficient of 1.07 (that is estimated for return periods of 100 years).

Design Principles

The return value for a maximum 500-year-class wind load, obtained from wind tunnel experiments, was 9.5 kPa. This output is employed as a design specification for the cladding on the highest portion of the Tokyo Sky Tree, where the spiraling galleria is located. The cladding on the Tembo Galleria corridor, connecting the 445- and 451-meter levels, is not only at an extremely high elevation, but is distinguished by the complexity of its form.

Analysis Modeling and Software

Wind-tunnel testing was conducted on a model of the tower. The analysis confirmed the maximum pressure of 9.5 kPa for a maximum 500-year class wind load. This value dictated the design of the Tembo Galleria, the higher portion of the tower that could be used as an observation deck (height 451 meters).

Design Phase Considerations

Preliminary Design. The curtain wall and glazed flooring were designed to reach the desired aesthetic qualities, structural efficiency, safety factors, and resistance to disaster events. Various design parameters influenced the final curtain wall and floor solutions, and the maintenance process of the tower was taken into account from the very beginning of the design. The result is a structure that enables gondola systems to rest on the roofs of both observatories. These building maintenance units (BMUs), used for the cleaning and structural checking of the building envelope, use rails along the horizontal parapets, and use vertical steel mullions on the curtain wall.

Design Development. In the detailed design stage, the façade contractor developed an advanced solution in order to check the subsequent steps of the installation of the façade system and the feasibility of the maintenance process procedures. Furthermore, the various loads on the façade mullions had to be checked by testing 1:1-scale mock-ups. The frame of the curtain

Figure 7.9 Tembo Deck curtain wall connection to the broadcast tower. © Andrew Currie (cc by-sa)

wall solution must withstand earthquake loads, wind loads that reach 10 kPa at the top of the tower, and the impact load that could happen due to strong wind gusts while the gondola is functioning.

Product Approval Process Requirements

The legal minimum requirements for wind design of the curtain wall solutions are stipulated in Public Notice No. 1458. The Notices of MLIT are issued to implement requirements in Building Standard Law of Japan and the Enforcement Order, and the AIJ Recommendation is applicable only if it gives more conservative requirements than those given by the Notices of MLIT.

The façade structure, the analysis of its structural adequacy, and the stability of the entire proposed façade system were tested before the installation. The 1:1-scale mock-ups had to be created and tested in order to check the façade's resilience to earthquake and wind loads.

An interesting test has been conducted on the glazed flooring solution, which examined the adequacy of the system against fire coming from the internal and external portions of the deck.

Façade Typology: Tembo Deck Curtain Wall and Glazed Floor

The Tembo Deck has both an inclined curtain wall solution and a glazed floor at one corner of the 340-meter-high observation point.

Support

The Tembo Deck curtain wall units are fastened to the outer steel mullions of the broadcast tower (see Figure 7.9). The units have been fastened from the

Figure 7.10. Tembo Deck 12-panel unit glazed floor. © Tamaru (cc by-sa)

inside to ensure complete safety during construction. The steel mullions also function as gondola rails for maintenance. Steel and aluminum members have specifications for undergoing 500-year wind loads; this requirement was also adopted for the glass makeup definition.

Mullions/Frame

The curtain wall frames are aluminum, dimensioned by considering various factors. The first factor was the structural resistance of the curtain wall system, which is not vertical in many portions, but in an inclined position facing the ground level, in order to let occupants enjoy the view.

The same frame has to guarantee the façade system integrity in strong wind conditions, and that is why it was dimensioned to withstand 10 kPa wind pressure.

Another factor was the maintenance procedure: a BMU system has been chosen and the façade has some restraining points in order to ensure safe cleaning activities. The steel mullions also function as gondola rails for maintenance. As with the curtain wall support, steel and aluminum members have specifications for undergoing 500-year wind loads; this requirement was also adopted for the glass makeup definition.

Furthermore, the curtain wall has to be designed to resist to the gondola's impact if the restraining pins fail due to strong wind conditions.

Glass

The Tembo Deck curtain wall ensures a high level of safety. The glass salves have a dimension that enables the various glazed surfaces to be replaced from the inside if they break; this design solution permitted the installation of the glazed surface from these observation floors during construction.

The glass makeup consists of a laminated, double-strength, 10-millimeter panel, which is able to safely undergo 500-year wind loads, having a return value deduced in wind tunnel experiments. The decision to use laminated glass panels was also dictated by ensuring a sufficient level of safety.

The Tembo Deck glazed floor solution at the lowest level of this observation deck has a very conservative final solution (see Figure 7.10). It is made up of 12 units of 500 x 1,000-millimeter panels, and the high-resistance glazing covers a total area of 2,000 x 2,000 millimeters. This portion of the building is conceived to perform as a fire-rated floor, rather than a window.

Four 12-millimeter panels of heat-resistant tempered glass are layered on the inside, with the innermost sheet functioning primarily to preserve the surface. On the outside, two layers of 6-millimeter pressure-resistant glazing are installed. An additional three layers of 12-millimeter heat-resistant glass are fixed within, to prevent debris from falling in the event of an interior fire (see Table 7.4).

Experimental Tests

For the Tembo Deck glazed floor, testing simulations with mock-ups were made to minimize structural damage from internal and external hazards. The fire resistance of the glass was tested in order to prove the effectiveness of the selected solution for the glazing assembly.

Façade Typology: Tembo Galleria Curtain Wall and Glazed Floor

The Tembo Galleria connects two different floors of the tower that are located at 445 and 451 meters, respectively. Due to its very complex shape, this sloped corridor had to be designed with a very demanding level of precision; every panel has different dimension. The cladding has a tubular shape, spiraling around an inverted cone.

The Tembo Galleria is distinguished by its progressively changing curvature (see Figure 7.11). It is not a simple spiral form and, therefore, resolving its complex geometry was the first architectural challenge to overcome. Special attention went into the performance of the cladding, in order to avoid issues after its installation, such as water penetration and inadequate resistance to wind loads and seismic loads.

Moreover, the choice also took into account the aesthetic quality of the building envelope, considering the significance of this landmark for Tokyo and Japan.

Location	Glass make up
Tembo Deck curtain wall	10-mm heat strengthened (HS) + 1.52-mm interlayer + 10-mm HS
	Windborne impact testing not required
Tembo Deck glazed floor	Inner floor surface: 4 x 12-mm HS glass layers + 24 mm air gap + Fire-resistant layer: 3 x 12-mm HS glass layers + 24 mm air gap + Pressure-resistant external glass surface: 6-mm HS glass layer + 1.52-mm interlayer + 10-mm HS glass layer
	Windborne impact testing not required

Table 7.4. The location and composition of glazing assemblies at the Sky Tree's Tembo Deck levels. © Nikken Sekkei

Structural Support, Mullions/Frames, and Glass

The supports of the building envelope, mullions/frames, and glass follow the same principles of the Tembo Deck.

The glass make up consists of a laminated double-strength 6-millimeter panel, which is able to safely undergo 500-year wind loads, with the return value deduced through wind tunnel experiments.

Experimental Tests

For the Tembo Galleria, testing simulations with 1:1 scale mock-ups were made to minimize structural damage from internal and external hazards.

Lessons Learned and Recommendations

Difficulties in the Design

Construction work on the tower began on July 14, 2008. The design team worked closely with the construction team to ensure the final design was suited to the unique circumstances of the project. The entire construction took approximately 580,000 man-days of labor.

Precision of unit production, steel structure, and on-site assembly were achieved through careful management of detail and accuracy. A three-dimensional measurement system was developed to deliver the precision needed for the erection of the steel frame. GPS was used to countercheck and adjust possible measurement errors that could accumulate when the

Figure 7.11. View of the Tembo Galleria interior. © kakidai (cc by-sa)

control point was repeatedly relocated to the top during erection.

To construct such a complicated tower, it was essential to use Building Information Modeling (BIM). Almost all aspects of the design, fabrication, and construction were examined, programmed, and executed utilizing three-dimensional digital representations of the structures. The data contained in the BIM files were merged with the collection of 3D information coming from the GPS, achieving remarkable precision during construction.

The installation of the curtain wall of the tower was quite different from that conducted on typical buildings. In the "forest" of steel framing below, there would be no space for working platforms or a temporary elevator to hoist materials; a newly-developed vertical and horizontal conveyor system was used to solve these problems.

The curtain wall panels were unitized and stored in a special container to be hoisted by a high-lift cableway along a vertical support guide. They were transferred to the horizontal conveyor at the temporary platform and delivered to the designated position to be installed. The system was designed so that the entire unit could climb by itself as the curtain wall installation proceeded upward. This system allowed the installation of 2,000 panels of curtain wall without using tower cranes, which instead were very busy erecting the steel frames.

Originally, the exterior curtain walls of the cone-shaped observatories were designed to be installed from the outside. However, for the sake of the safety of the installation work and the eradication of any possibility of the panels falling, the design was changed so that the panels would be installed from the inside. Safety nets were preinstalled so that the external safety, from the threat of any debris or falling materials, could be guaranteed immediately after the steel frame was erected.

External wall units were delivered through the temporary openings on the slab using a tower crane. A winch on the ceiling set the wall panel upright, and the trapezoid-shaped panels were lowered and wedged in between the mullions and set in place.

Innovative Design Solutions

For the Tokyo Sky Tree, an innovative monitoring system was developed to guarantee worker safety during the construction phase. This was because being at such heights in bad weather conditions, in an area prone to earthquakes, could generate disastrous results if not correctly managed. The principal idea was to have precise weather forecasting that took into account the conditions at heights over 300 meters, not just at ground level.

An independent, detailed weather forecasting system was developed, which was able to provide hourly forecasts, looking up to seven days in the future at the heights of 0, 250, 500, and 650 meters, and it was updated twice daily. These forecasts were crucial to avoiding any unpredictable interruptions of work due to bad weather.

The Meteorogical Agency and other organizations used the data collected by these devices and, in cases of potential danger, would sound an alarm. When the wind speed was too high, or if there were thunderstorms, or a seismic movement was recorded, the warning system transmitted the alarm throughout the entire job site. Work safety was ensured, and even during the Tohoku earthquake on March 11, 2011, no workers were injured.

Possible Improvements

The safety nets, attached to the mullions using special fixtures and wires, could have been detached by loosening the wires from the inside. This meant that all work could be carried out from the interior, ensuring even more safety.

> “The 2,000 unitized curtain wall panels were installed via high-lift cableway, then transferred to the horizontal conveyor at the temporary platform and delivered into position.”

7.5 Case Study

Abeno Harukas

Osaka, Japan

Architectural Features of the Building

Abeno Harukas, Osaka, at 300 meters, is the tallest building in Japan (see Figure 7.12). It is located in an area prone to natural disasters, due to the high probability of strong winds and earthquakes recorded in this area. The building rises 60 floors above ground, with five basement levels below.

The Abeno-Tennnoji railway station occupies the podium of the building, connecting the metropolitan railway network to the high-density urban complex. This skyscraper also incorporates a department store, art

Project Data

- **Official Name:** Abeno Harukas
- **Location:** Osaka, Japan
- **Developer:** Kintetsu Corporation
- **Architect:** Takenaka Corporation
- **Structural Engineer:** Takenaka Corporation
- **Façade Consultant:** Takenaka Corporation, Pelli Clarke Pelli Architects
- **Façade Contractor:** LIXIL Corporation
- **Façade Testing Lab:** LIXIL Corporation

◀ **Figure 7.12. Abeno Harukas, Osaka.** © Hisao Suzuki museum, school, hospital, hotel, and offices, capped by an observatory and rooftop gardens. Various horizontal and vertical circulation paths are strategically located around the complex to handle up to 110,000 people at a time. The circulation of occupants, the relation to the scale of the surrounding neighborhood, and the shape of volumes that make up the tower were determined through various factors, such as the impact that wind can have on the surrounding area.

The asymmetric structural megatrusses, optimized for the specific programs of the building, form void spaces, which offer space for vertical transportation as well as air circulation.

Three volumes are shifted and stacked, drawing sunlight and wind into the central voids between offices, creating three-dimensional, cascading gardens. The location of the semi-public green areas at the top of each volume of the complex, as well as the various functions within the building, are relayed to the surrounding area through the transparent façade.

From the very beginning of the various design phases, great attention had been invested in the energy efficiency of the building. Usually, this building typology utilizes a small plant area that consumes a considerable amount of energy in peak hours of the building activity. Abeno Harukas was designed to equalize the energy needed for its functions over the course of the day, contributing to a significant reduction in CO_2 emissions and improving thermal efficiency. Its façade solutions had also been considered to support passive energy efficiency for the building.

Building Design Requirements

Depending on the part of the building, the Abeno Harukas complex utilizes different structures: it is primarily a steel frame, with concrete-encased steel and reinforced concrete in other portions. The result is floor layouts that place rooms on one side of corridors in the hotel portion; a column-free space with a span of 19 meters for the offices; and a highly flexible floor plan for the department store, comprised of a 10-by-10-meter grid.

The structural solutions used are further highlighted in the architectural design. This is clearly evident as the core bracing systems that support the slabs and the horizontal outriggers that transfer the loads to the slab are an aesthetic feature of the 300-meter tower. Two sub-outrigger solutions are also used to transfer the loads in the central part of the building, which are needed due to the asymmetric volumes of the tower.

A very complex system of damping technologies made this project possible, considering the location of the building is highly earthquake-prone. Three kinds of damping devices are used depending on the height: corrugated steel plate walls, oil dampers, and rotational friction dampers. These structural solutions, which are mainly necessary to combat horizontal forces from earthquakes and strong winds, relentlessly work to reduce the building's vibrations. The basis of design, in order to meet the legal minimum requirements for wind design of the curtain wall solutions, is derived from multiple laws, primary the Architectural Institute of Japan (AIJ), *Recommendation for Loads in Buildings*.

In this project, the considered expectation is a return period of 500 years, for 10-minute sustained winds.

Wind tunnel tests were considered to predict unusual wind effects around the building and to determine if there were any "hot spots" prone to cladding pressure.

Façade Design

Code and Guidelines

Public Notice No. 1458 of the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) has been taken as a reference document. The base wind velocity is given in the *Ministry of Construction Public Notice No. 1454: Base Wind Velocity of Various Places for Calculation* (MLIT 2000), with an average of 10 minutes for maximum wind velocity.

The Japan Sash Manufacturer Association (JSMA) and the Curtain Wall Fire Windows Association (CFWA) give some guidelines for sashes and doors, according to Japanese Industrial Standards (JIS) A 4702:2015 and JIS A 4705:2015, and identifies the JIS A 1515:1998 as the appropriate testing method. Currently there are no requirements for the curtain wall performance grades and testing procedures.

Design Principles

One design principle researched early in the design process was the idea of creating a curtain wall solution that provided an elegant appearance, as this building was meant to become one of the most important landmarks in Osaka and Japan. Additionally, the cross-bracing and other strong lines of the building's structural engineering are "displayed" behind glass as part of the design strategy.

Part of the approach suggested changing the exterior façade color so as to stand out against the skyline; at the same time, it also helped the team develop technical details for the curtain wall. Various functions within the building were to be visible from the outside, which is why the appearance of the curtain walls was so important.

Analysis Modeling and Software

The final façade solution was studied and simulated for instances of strong winds. A fluid-structure interaction (FSI) analysis was developed in order to study the curtain wall because of the resonance that was predicted to occur close to the gondola rail guides in the vertical fittings. The Karman Vortex generation was discarded in the final solution, thanks to security-curved surfaces for the mullions, with a one-millimeter radius in the edge section of the guide rail. In this case, sounds that reach a 550-Hertz frequency were avoided.

Design Phase Considerations

Preliminary Design. From the initial stages of the design, various changes had been made for a number of reasons. The 90,000 square meter curtain wall had to represent a transparent landmark for Osaka, but also fall within the client's budget. The façade contractor and the design team worked closely in order to cut some on-site construction costs and still realize a high-quality final curtain wall solution.

Design Development. Due to the external appearance of the building, which has a totally transparent envelope, the design also had to address a strategic technical solution for the curtain wall assembly. The aim was to reduce the construction time by reducing the amount of assembly that was required on-site.

The rubber products for the façade came from Johor Bahru, Malaysia and from Suzhou, China; the high-strength aluminum brackets came from Ansan, South Korea; and the laminated glass came from Samut Prakan, Thailand. All these components were assembled in Thailand; in Nava Nakorn, the extrusion process took place and the curtain wall unit assembly immediately followed this. Next, the various components were shipped to Osaka, together with fasteners that came from Wuxi, China. The development had to take into consideration the locations of the materials that made up the curtain wall, especially for realization of the on-site procedure.

The final façade solution was an airflow system that expels heated air. This was selected through an extensive thermal study, in which three different façade solutions were considered: double-skin windows, push-pull windows, and airflow windows.

> "Various functions within the building were to be visible from the outside, which is why the appearance of the curtain walls was so important."

Product Approval Process Requirements

The legal minimum requirements for wind design on a curtain wall are stipulated in Public Notice No. 1458, issued by the MLIT. MLIT notices are issued to implement requirements in Building Standard Law of Japan and the Enforcement Order, and the AIJ Recommendation is applicable only if it gives more conservative requirements than those given by the Notices of MLIT.

Various façade mock-ups for Abeno Harukas were developed and realized, in order to be tested and analyzed for energy performance. The building envelope, as well as the entire structure of this challenging construction, was designed to perform well in terms of energy efficiency. Safety requirements strongly influenced the final curtain wall solution, which was selected based on its performance in occupant safety during strong earthquake events. Furthermore, the final solution identified by the designers prevents glazed surfaces from falling, ensuring the safety of people walking adjacent to the building. These benefits were delivered by adopting laminated glass solutions that have very high safety factors in terms of their ability to withstand wind pressure, which is especially relevant considering the strong wind that generally surrounds this building.

Façade Typologies: Curtain Wall

The vertical façade solution, the eaves, and the handrails of the department store are entirely composed of glass. Special considerations had to be made due to the fact that the temperature at 300 meters can be as much as 1.8°C lower than the ground-level temperature, due to the strong wind exposure of the building. This meant additional engineering was needed on the coping façade, to avoid snow sliding towards the exterior of the building. The solution was to elevate the edges of the coping by 30 millimeters at a 45° angle.

Once the curtain wall units were assembled overseas, they were then semi-assembled as temporarily on-site 6-by-4-meter units. These portions of curtain wall were lifted by crane; in 10 minutes of work, 24 square meters of façade could be installed.

Osaka is hot and humid during the summer and very cold and windy in the winter. That is why great attention was placed on installing airflow windows, consisting of an external laminated glass and a low-E multilayer glass inner-sink. Between these two layers, a roll-screen could be used for sun protection of the interior. With this system, the heated air generated between the skins by sunlight and heat transfer can be expelled.

Support

The façade units are fastened to the building slabs of the tower. The units were fastened from the inside to completely ensure construction safety. The mullions also function as gondola rails for maintenance crews.

Mullions/Frame

The framing system of Abeno Harukas' curtain wall takes into account the effects that an earthquake could generate on the façade. The tremors that naturally occur during these disaster events could be absorbed thanks to the glass lite fixtures. These were designed at a precise size in order to leave the glass movement free within the metallic frame, preventing any damage that would be caused by the glass and the aluminum crashing into each other. During a large deformation of the frame during an earthquake, the glass slabs can rock without cracking.

The designers also developed the vertical rims in the curtain wall, to allow the possibility of performing maintenance activities during very strong wind conditions (a necessity, due to its location). They have a guide rail function, preventing the building maintenance units from swinging and the cage colliding with the façade.

Furthermore, the aluminum frame has a solution which avoids condensation effects caused by temperature differentials between the inside and outside of the building. This is possible thanks to the final hollow-section design of the frame (see Figure 7.13).

Glass

The building's curtain walls use flat laminated glass with a 0.76-millimeter interlayer solution, in order to avoid glass breakage from earthquakes or the impact of objects during a disaster event.

The portions of the building that require a high level of performance in terms of thermal insulation are treated differently from the general development of the façade. Internal comfort is achieved by installing an

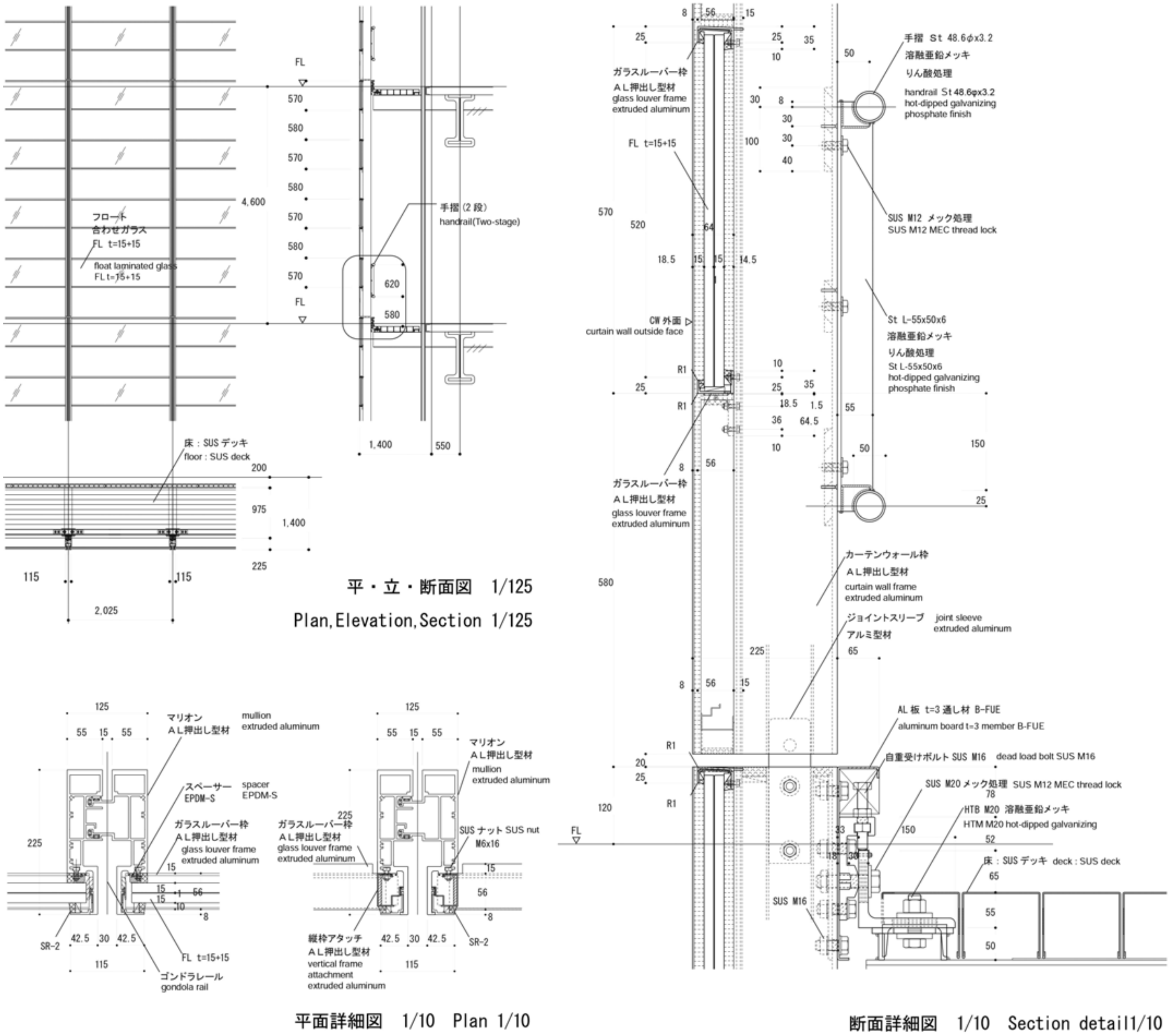


Figure 7.13. Typical curtain wall assembly of Abeno Harukas. Source: Shinkenchiuku-sha Co. Ltd.

inner skin of low-E insulated glass in these sections. The aesthetic appearance of these parts of the building looks consistent with the others and the transparency of the glass does not change.

Machine rooms requiring air supply and exhaust, and some emergency exits, have glass louvers composed of unitized curtain walls. The aluminum curtain wall studs host high-performance glass louvers that work properly even if their thickness is not consistent. Furthermore, there are gondola rails installed within the glass louvers for protection against lightning strikes.

The panes of the curtain wall for the office spaces of the building (see Figure 7.14) have an airflow window consisting of built-up 12-mm + 12-mm floated laminated glass on the external face, a low-E insulated glass unit (IGU) 6 mm + 6 mm air + 8-mm panes on the inner face, and a roll screen between them.

The panes of the airtight double-skin façade are floated laminated glass for the hotel section of Abeno Harukas, consisting of a built-up 10-mm + 10-mm combination on the external face and a low-E IGU 6 mm + 6 mm air + 8-mm composition on the inner face

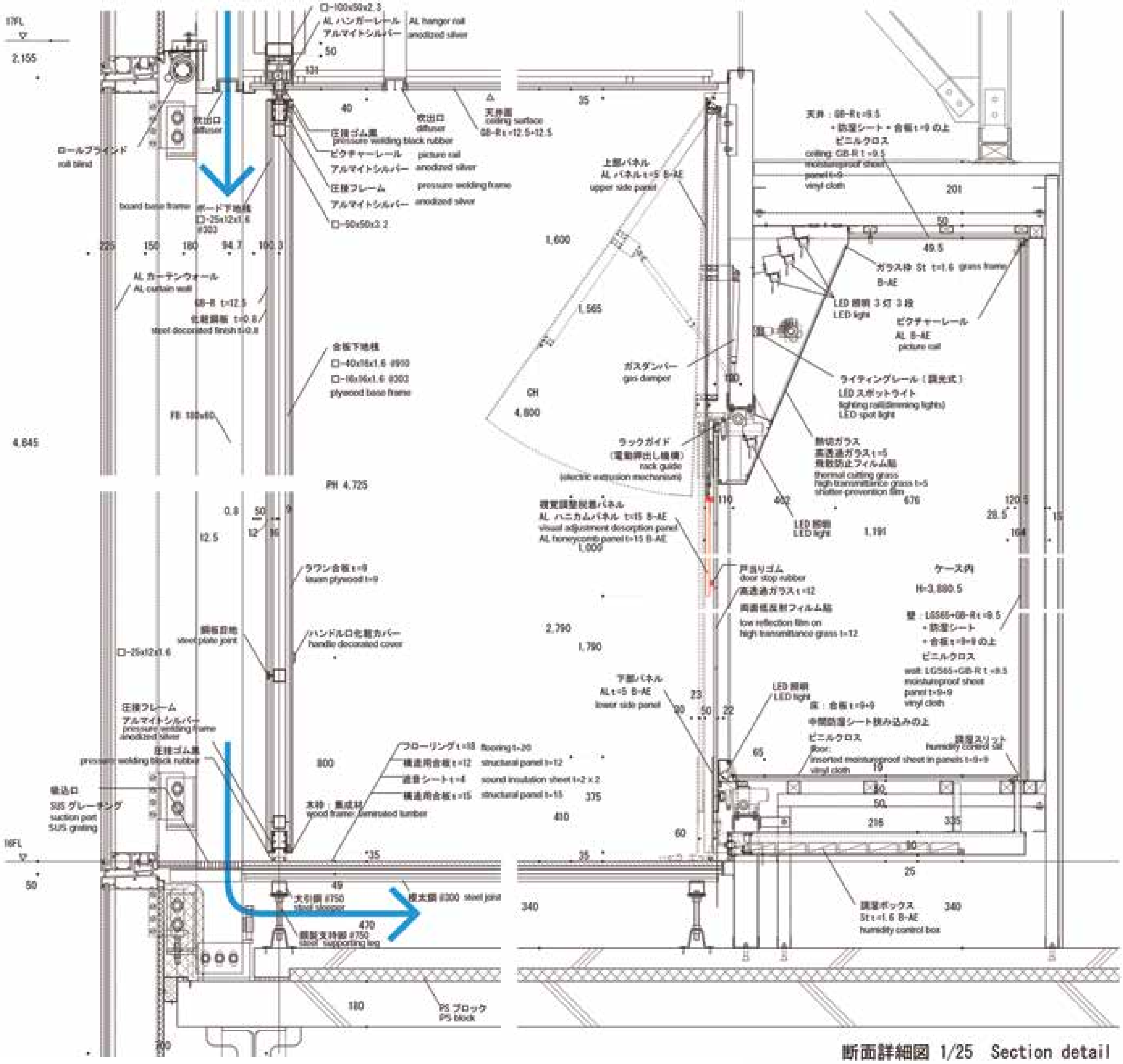


Figure 7.14. Curtain wall of the office spaces showing airflow direction. Source: Shinkenchiuku-sha Co. Ltd.

(see Table 7.5 and Figure 7.15). The hotel rooms are intended to be much more humid than the office spaces, so silicone gel desiccant is injected into the space between the inner and outer skins, which helps make the double-skin façade airtight and controls condensation.

Location	Glass Make Up
Curtain wall hotel space	10-mm float + 0.76-mm interlayer + 10-mm float + 207 mm air + 6-mm float + 6 mm air + 8-mm float
	Windborne impact testing not required
Curtain wall office space	12-mm float + 0.76-mm interlayer + 12-mm float + 305 mm air with electric high-shading roll screens + 6 mm air + 6 mm air + 8-mm float
	Windborne impact testing not required

Table 7.5. The location and composition of glazing assemblies along the height of Abeno Harukas. Source: Shinkenchiuku-sha Co. Ltd.

Experimental Tests

The building's aluminum curtain wall has a total surface of 90,000 square

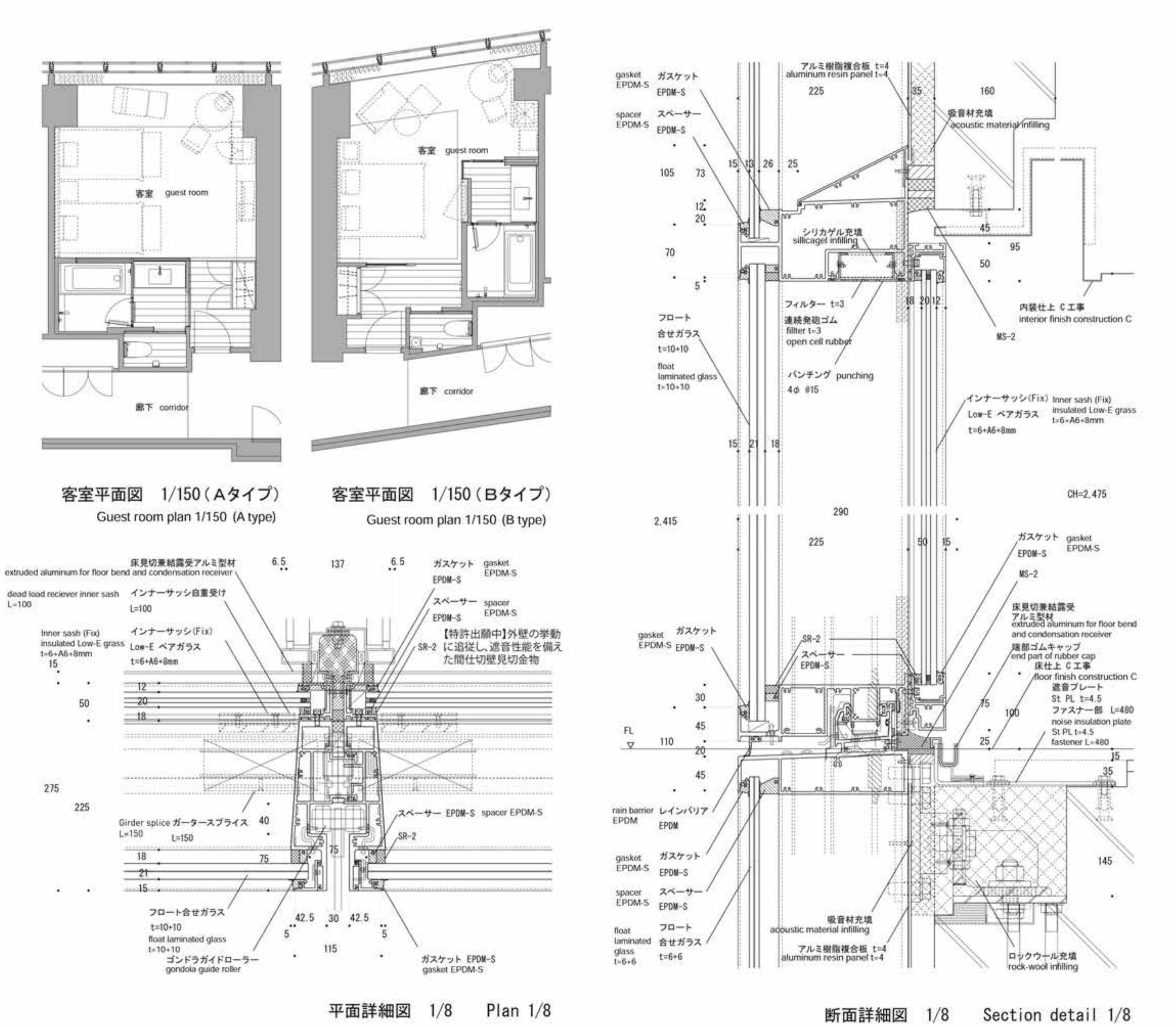


Figure 7.15. Curtain wall details for hotel portion. Source: Shinkenchiuku-sha Co. Ltd.

meters, and it has to guarantee much more than just structural performance. That is why it has been tested in order to verify various characteristics of the final façade solution, such as thermal performance. The interior comfort of the building has been studied and optimized by both designers and contractors.

The tests conducted on the final curtain wall solution focused on verifying the following physical characteristics, before the installation process took place:

1. Wind pressure resistance
2. Earthquake-resistance
3. Water-tightness
4. Air-tightness
5. Fireproof properties
6. Sound insulation
7. Temperature resistance
8. Insulation
9. Durability
10. Solar radiation protection
11. Prevention of dew condensation
12. Anti-lightning grounding
13. Safety in the snow
14. Maintenance and preservation

15. Prevention of sound transmission
16. Prevention of projectile penetration
17. Provision of gondola guide rail

Special experimental tests have been carried out in order to check the resistance of different tree species to strong winds. This was undertaken because of the possibility that tree branches could be blown away from the building's rooftop gardens.

Wind tunnel testing has been conducted, and the precise wind load was determined for the rooftop portion of the tower. Next, due to the inadequacy of existing data on this specific topic, a tension test for the various tree branches was conducted, and in this way, the level of wind resistance of the various species was determined. These tests assisted tree selection; only tree species that were able to withstand the strong windforces of the Abeno Harukas rooftop were selected.

Lessons Learned and Recommendations

Difficulties in the Design

The safety performance of buildings is progressively becoming more sophisticated. Ensuring zero risk is an unattainable goal, especially with reference to natural disasters that have a cyclic occurrence in specific regions. Nevertheless, knowledge regarding strong wind occurrence frequencies, and potential resulting damage, has been developed and enriched in the last 50 years.

The entire design team of Abeno Harukas worked closely from the very beginning of the preliminary design phase in order to solve the various issues related to safety. It was important to verify with the client the maximum tolerable risk that the building was to sustain.

The strong wind location was a major design factor for, both the potential damage that could be caused, and for internal comfort. Vibrations, the sound of the wind, and cracking caused by the wind blowing were all studied, ensuring the building occupants would not be disturbed by these scenarios.

Design Innovative Solutions

Abeno Harukas represented an opportunity for architects to work together with structural engineers in order to design a building that was not just able to reduce the energy of all its activities within the building envelope, but also to perform and provide adequate safety during disaster events such as typhoons (Shinkenchiku 2014).

The passive technologies adopted within this project represented a great challenge and serve as a valuable case study for the entirety of Japan and the world. These technologies adopted within the tower do not just stem from material choices or technical solutions, but also come from the realization of connections between the building and the surrounding urban environment. It is a balance between the city and nature, thanks to the realization of gardens and terraces at height that create comfortable spaces without wasting energy (see Figure 7.16).

Figure 7.16. The partially enclosed observatory makes extensive use of glass treated for variations of wind pressure, based on location within or on the extended glass parapet. ©: Terri Meyer Boake

8.0 The Philippines

8.1 Principal Design Rules

The façade design rules in the Philippines are fundamentally dictated by the National Building Code of the Philippines (NBCP) and by the National Structural Code of the Philippines (NSCP). Imposed design loads, dead and live, are detailed in the structural engineer's design criteria and are found in ***National Structural Code of the Philippines (NSCP) 2015 – Volume I, Building, Towers, and Other Vertical Structures.*** This code is based on US ASCE 7 and identifies the parameters for building protection of façades when located in windborne debris regions within the Philippines. The windborne debris regions are described as areas located within 1.6 kilometers of the coastal mean high-water line (with a wind speed equal to, or greater than 58 m/s), or areas where the basic wind speed is equal to or greater than 63 m/s. When the glazing systems are located more than 18 meters above the ground, and 9 meters above aggregate-surface roofs (including roofs with gravel or stone ballasts) within 450 meters from the coastline, the system shall be considered unprotected. The windborne debris regions are identified depending on the occupancy category of the building (see Table 8.1 and Figure 8.1).

In the Philippines, the NSCP indicates that the ASTM E1886 and ASTM E1996 tests should be conducted in order to verify the effectiveness of the window components in protecting against flying debris for the following building categories and locations:

From the National Structural Code of the Philippines 2015:

§207A.10.3 Protection of Glazed Openings

Glazed openings in Occupancy Category I, II, III or IV building located in tropical cyclone-prone regions shall be protected as specified in this Section.

§207A.10.3.1 Windborne Debris Regions

Glazed openings shall be protected in accordance with Section §207A.10.3.2 in the following locations:

1. *Within 1.6 km of the coastal mean high water line where the basic wind speed is equal to or greater than 58 m/s, or*
2. *In areas where the basic wind speed is equal to or greater than 63 m/s.*

For occupancy category III and IV buildings and structures, except health care facilities and occupancy category II buildings and structures, the windborne debris region shall be based on Figure 8.1. Occupancy category shall be determined in accordance with Section 103.

Exceptions:

Glazing located over 18 m above the ground and over 9 m above aggregate-surfaced-roofs, including roof with gravel or stone ballast, located within 450 m of the building shall be permitted to be unprotected.

8.2 Professional Roles and Responsibilities

Developers

The Philippines are experiencing a considerable boom in the construction sector. There are zones that used to be shanty towns, which have been converted into clusters of skyscrapers with huge shopping malls in their basement floors. This massive demand for more commercial and residential space to sell and rent has seen many of these buildings being constructed in the past few years. In certain cases, the spaces were sold before construction was completed, and this has had an effect on the quality and performance of the curtain walls that have been installed. In several cases, the developers adhered to only the minimum standards required by the contracts and the local laws, in order to save money and increase profits.

No certification or test reports are mandatory to present to the government institutions in the Philippines. As a consequence, the decision to adopt a curtain wall is

Occupancy Category	Description
I	Essential
II	Hazardous
III	Special Occupancy
IV	Standard Occupancy
V	Miscellaneous

Table 8.1. Risk categories of buildings and other structures. Source: National Structural Code of the Philippines 2015.

dictated by cost and façade design, which negatively affects quality and performance. Furthermore, insurance companies are not pushing to upgrade the performance of the building envelope, even though the buildings are in typhoon-prone locations. The developers' priority regarding the façade is simply to protect it from negative consequences that are not covered by the façade suppliers' guarantees. In this way, if damage occurs, the suppliers have to provide assistance and repair or replace the façade components, instead of holding the developer liable.

Sometimes, the developer will demand higher-performance curtain walls in order to add value to the property and to stand out from adjacent properties. The approach to apply for a certification process for the curtain wall is generally to achieve a specific level of performance normally related with energy savings. This practice has become more common in recent years, and could generate further value when the property has to be sold or rented; if the developers and owners request a certification, the building components will certainly increase the property value. In most cases, developers have the final say regarding cost, and are not inclined to go beyond statutory requirements.

Designers

Local architects lack expertise regarding safety performance of curtain walls, beyond the understanding that laminated glass solutions generally

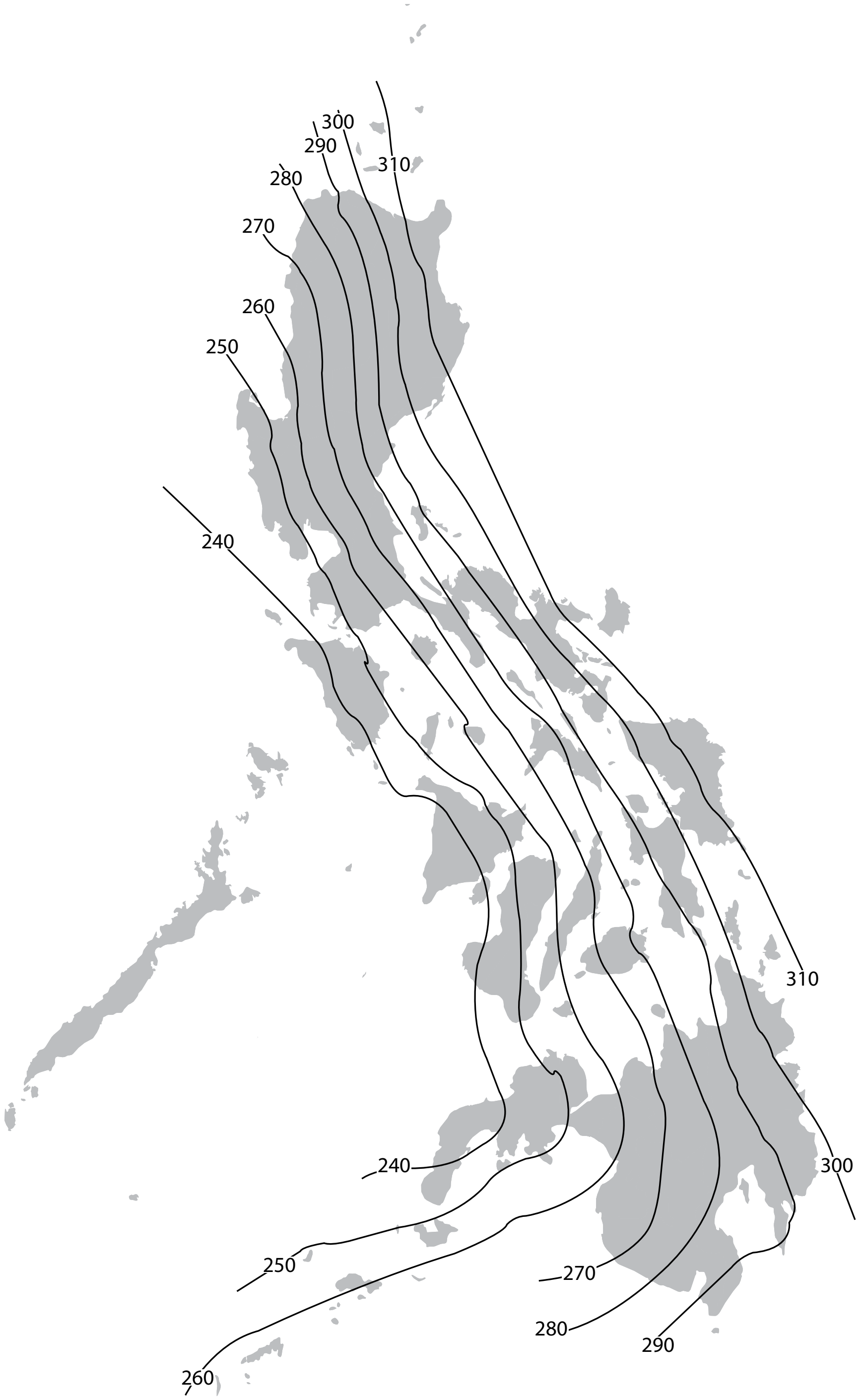


Figure 8.1. Basic wind speeds for occupancy category III, IV, V buildings and other structures. © Source: National Structural Code of the Philippines 2015.

afford better safety outcomes in the event of breakage. In the Philippines, the definition of "safety glass" includes both tempered and laminated glass. This has dangerous consequences in construction because, while tempered glass is of high quality in the region, laminated glass is not. Therefore, tempered glass is more commonly used than laminated glass, where "safety glass" is required. Tempered glass solutions with only one layer of glass are widely used at the street level, and if projectiles from nearby roofs break the glass, it could have fatal consequences.

The lack of applicable tests for flying debris in strong wind conditions could be due to the lack of identified locations within ASTM E1886 and ASTM E1996, which is currently the basis for the NSCP, Section 207A.10.3.1 Windborne Debris Regions. Furthermore, no certification of the building products used for the building envelope need to be presented to the Building Department, and the quality protocol for the tempering of glass is not mandatory. This situation is causing various issues related to the spontaneous breakage of tempered glass in this area of the world, but there are still no calls for quality protocols to be adopted or a requirement for safety solutions.

The architects involved in the design of tall buildings normally conduct wind tunnel testing in order to determine the local pressures on the building. In so doing, the cost of the building envelope could be lower, because the façade consultants can optimize the curtain wall with this data.

> "In the Philippines, 'safety glass' indicates both tempered and laminated glass. This has dangerous implications — laminated glass in the region is of poor quality."

Façade Consultants

In the last 20 years, the role of the façade consultant has taken on ever-greater importance in the Philippines.

A number of the Philippine façade consultants frequently operate worldwide, and are thus very familiar with the technologies developed for hurricane-prone regions in the United States, for instance. Nevertheless, it is not a common practice for them to conduct tests for the certification of flying debris resistance. This is due to the designer and client expectations, as the construction costs would consequently rise if mitigating measures were adopted.

Local façade consultants are aware of the existing rules in the 2015 edition of the NSCP, which requires that the US ASTM testing procedures be followed for flying-debris resistance. Furthermore, they know the on-site effectiveness of the existing certified hurricane-resistant façades in the United States. The ineffectiveness in the application of the codes is largely driven by the budgetary restrictions of the local developers. Currently, there is also a lack of robust risk assessment protocols, and the consequences of this can be a threat to the safety of people and property in typhoon-prone areas of the Philippines. Another reason that the codes are not followed is due to the small amount of power that insurance companies have. In other countries, the safety performance of the building envelopes is improving, thanks to a

Figure 8.2. The interior of a Philippine façade contractor plant. © Angela Mejorin

return on lower annual insurance premiums, based on certification. Usually, the predominant mode of protecting the building interior, related to the performance of the building components, stems from the façade suppliers themselves.

That being said, in the Philippines, owner attention is focused more on energy-saving protocols than the safety performance of the envelopes. Energy-saving measures and solar filtration on the building envelope are very common because of the nature of the local climate. The various protocols used to certify the buildings nevertheless drives value in the construction industry, and the attention given to façade design is rising.

Façade Suppliers

The façade manufacturing industry (see Figure 8.2) is not very large in the Philippines, in part due to geographic location. It is very common for projects in the Philippines to install building envelopes that are not locally sourced. There are many projects adopting curtain wall solutions imported from China, which has huge plants and serves as a convenient location from which these components can be shipped, thanks to its proximity to the Philippines. The façade suppliers based in the Philippines usually buy glass from abroad, so, even in these cases, the final façade solutions are not locally manufactured.

The plants have the option of certifying their equipment and thus their own products. This testing system could be viable, because there is no requirement to ask for a third-party verification of the performance of the façades, and the certificates don't have to be presented to building authorities. The suppliers work in order to meet the requirements of the façade consultants and the budget requests, developing the shop drawings and verifying the final results through tests.

Figure 8.3. A mock-up installation at the Philippine Philco Façade test lab. © Angela Mejorin

The professionals involved in this field are familiar with façade systems built to guarantee safety performance in case of impacts from flying debris in strong wind conditions. Furthermore, they are frequently called to repair or replace portions of installed façades when they have been damaged by a typhoon.

There is no professional association in the façade-supplier field in the Philippines. This current lack of a sector-wide organization could cause a deficiency in the exchange of information and advancement in the industry, especially for new technologies and best practices.

Façade Test Labs

In the Philippines, there are few façade test labs. A considerable number of the curtain walls that have been installed in this Philippines were produced by, and tested close to the manufacturers in other countries, and then shipped to the Philippines.

Currently, there is no government accreditation process for these testing centers, but Philippine regulators are familiar with the accreditation processes for the execution of international standard tests obtained from third-party accreditation bodies. In the Philippines, performance mock-up test labs are used to conduct tests; these use international standards for façade certification (see Figure 8.3). This is a natural consequence of the local building codes that are based on the international codes.

In the Philippines, there are no test labs used to verify the resilience of the building envelope to flying debris in strong wind conditions, even if the National Structural Building Code (NSBC) of the Philippines requires that tests be done according to ASTM E1886 and ASTM E1996 as a primary objective. Currently, the testing labs do not even have the air cannons needed to conduct the missile-impact tests according to the ASTM standards for hurricane-prone regions. This is because there are no façade consultants operating in the region asking labs to verify the resilience of the building envelope to such stresses.

The test labs must perform the test procedures indicated by the façade consultants on the specimens. They normally only take into account: design wind pressures, air infiltration, water penetration under static load, dynamic and cyclic pressure differential, structure, horizontal and vertical building movement, structural safety, and building maintenance unit (BMU) tie-back tests — but no missile impact tests.

Government Institutes

The building code in the Philippines is based on ASCE 7. Due to the local mandatory requirements in the NSBC being derived from the 2010 edition of ASCE 7, the façade must undergo missile-impact tests, which simulate windborne debris during a typhoon event, and the subsequent positive and negative pressure-cycling tests. Therefore, currently, the requirements for flying-debris resistance are listed, but this façade requirement could be more effectively applied if it were added to the main Building Code, instead of just being mentioned in the Structural Building Code.

There is no requirement to present to the Building Department any test report or certification related to the façade at the end of the construction process. As a consequence, when well-funded projects carry out tests on curtain walls, the reports are only reported to the developer and building owners. Other projects can elect not to perform tests, because these are not required by any government department.

The Philippines have centers where typhoons are monitored, called the Philippines Atmospheric, Geophysical and Astronomical Services Administration (PAGASA) stations, which alert citizens to oncoming events, and also record past events.

At Philippine universities, there are several studies related to disaster events taking place, especially with seismic design and monitoring techniques. There are no studies related to the resilience of the building envelope to windborne debris, even in typhoon-damaged Philippine cities (see Figure 8.4).

8.3 Tall Buildings in Typhoon-Prone Areas of the Philippines

The Philippines' tall buildings grew by more than 25 times in the past 30 years. The December 2017 numbers of buildings 150 meters and taller are presented in Table 8.2. Furthermore, CTBUH conducted a GIS analysis in order to highlight how many of these buildings experienced a cyclone event, and how many were in a typhoon-prone area in December 2017: all the analyzed skyscrapers are in a typhoon-prone location (see Table 8.2).

Figure 8.4. Typhoon Glenda, 2016, damaged glazed building envelopes in Manila. © Joe Khoury/ALT Cladding

Buildings 150 m or taller in 1995	3
Buildings 150 m or taller in 2005	27
Buildings 150 m or taller in 2017	78
Buildings 150 m or taller in cyclone-prone areas	78
Buildings 150 m or taller affected by cyclones	43

Table 8.2. Tall buildings and typhoon-prone areas in the Philippines.
Sources: Prevention Web, UNEP/UNISDR & CTBUH

Figure 8.5. SM Megamall Tower, Manila. © SMEDD Corporation

Project Data

- **Official Name:** SM Megamall Tower
- **Location:** Manila, Philippines
- **Developer:** First Asia Realty Development Corporation
- **Architect:** Arquitectonica
- **Structural Engineer:** Aurecon
- **Façade Consultant:** B. L. Gavino Façade Design Consultancy
- **Wind Consultant :** RWDI
- **Façade Contractor:** Far Sincere Façade Philippines
- **Façade Testing Lab:** Winwall Philippines

8.4 Case Study

SM Megamall Tower

Manila, Philippines

Architectural Features of the Building

The Megamall Tower is the latest addition to the SM Megamall master plan, the flagship retail project for the First Asia Realty Development Corporation. Adjoining the semi-circular Mega Fashion Hall, it comprises 111,400 square meters of office gross floor area (GFA) across 50 stories, with six levels of podium and three levels of basement parking. The main entrance lobby is formed by elevating the tower form above the drop-off, making for a grand arrival space. The core intersects with the curved and glazed exterior wall at ground level, creating an interesting intermingling of the landscaped exteriors and corporate interiors. Connections are provided to the Mega Fashion Hall at ground level. Podium and basement parking connections are also provided between the new tower and the existing Megamall blocks. A helipad is provided on top. The tower has a central core with three lift zones and separate service and car parking lifts. Typical office floors have good efficiency and the lease depths allow for good daylight.

The design represents the next step in the architectural evolution of the Megamall master plan. While the original mall was a composition of rectilinear blocks, with the simple, semi-circular Fashion Hall, the project is now identified by an undulating, S-shaped tower. This softer form is in stark contrast to the more prosaic rectilinear extrusions of the surrounding towers (see Figures 8.5 and 8.6).

The S-shaped tower is clad in seamless glass, accented by vertical and horizontal fins on the undulating and flat façades, respectively. The tips of the vertical fins integrate linear LED lighting, while the horizontal fins are floodlit to highlight the undersides.

Building Design Requirements

The following standards and guidelines, among others, form the basis of the building design:

- National Building Code of the Philippines (NBCP) 2015

- National Structural Code of the Philippines (NSCP) 2010
- Uniform Building Code (UBC) 1997
- AISC Manual of Steel Construction - Allowable Stress Design, 9th Edition
- ACI 318M-08 Building Code Requirements for Structural Concrete

The imposed dead and live design loads are specified in the Structural Engineer's design criteria and are as per NSCP 2010. The wind load parameters in accordance with NSCP 2010 are:

- Basic wind speed: 200 kph
- Exposure category: B
- Importance factor: 1.0
- Occupancy category: IV

A cladding wind-load study was commissioned by the client (see Figures 8.7 and 8.8). The objective of the study was to determine the wind loads for the design of the exterior envelope of the building. The negative pressures range from -2.5 kPa to -5.5 kPa, while positive pressures range from +2 kPa to +3.5 kPa. However, it is noted that the design of the cladding, in accordance with the wind loads, will not necessarily prevent breakage due to impact by windborne debris.

Façade Design

Code and Guidelines

The façade system conforms to the minimum requirements as provided by the following codes:

- National Structural Code of the Philippines (NSCP) 2015
- National Building Code 2005
- Fire Code of the Philippines 2008

Design Principles

The façade design follows a process of basic principles comprising a comprehensive interpretation of architectural design intent, to ensure conformance to the aesthetic expression, with reference to form, color, features, dimension, sight lines, and other similar features. The design explores the best possible, available solutions, conformance to its long-term exposure to the actual environmental conditions. A critical part of this design principle is an engineering process with strict conforming to applicable standards and a comprehensive program of work to ensure highest-quality workmanship from factory manufacturing, fabrication, assembly, delivery, and installation. As a result, the façade structure is a proprietary system developed through the engineering process and tested by the façade specialist contractor, in collaboration with the design architect, engineers, and façade consultant (see Figures 8.9 and 8.10). The façade design process conforms to the basic guidelines to ensure optimum performance that addresses the following criteria.

Figure 8.6. SM Megamall Complex master plan. © SMEDD Corporation

Water infiltration and condensation are counteracted by a pressure-equalized framing system, where air barriers and weep holes are integrated in the system to mitigate water penetration.

Lateral load resistance requirements, due to positive and negative wind forces and vertical or gravity loads, are addressed by the structurally adequate profile depth of the vertical framing and the horizontal stack-joint framing, and by the three-way adjustable cast-in anchor support at every floor.

Safety is addressed by fireproofing and smoke sealing between the curtain wall and base building structures, with a fire rating of 120 minutes. Safety against

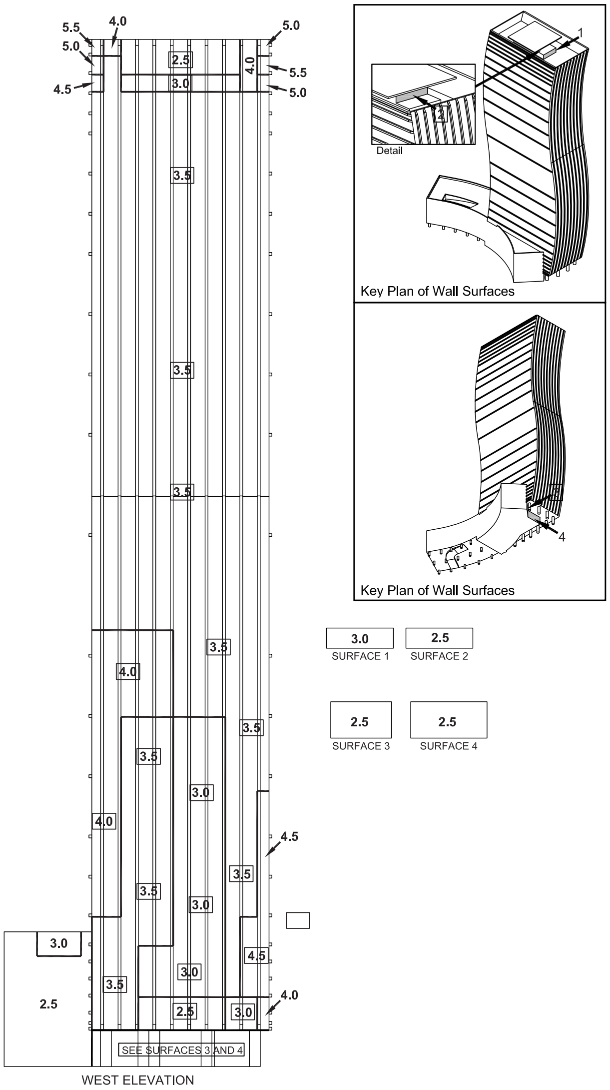


Figure 8.7. Wind tunnel test study, determining wind loads for cladding design. Peak net negative pressures. © RWDI

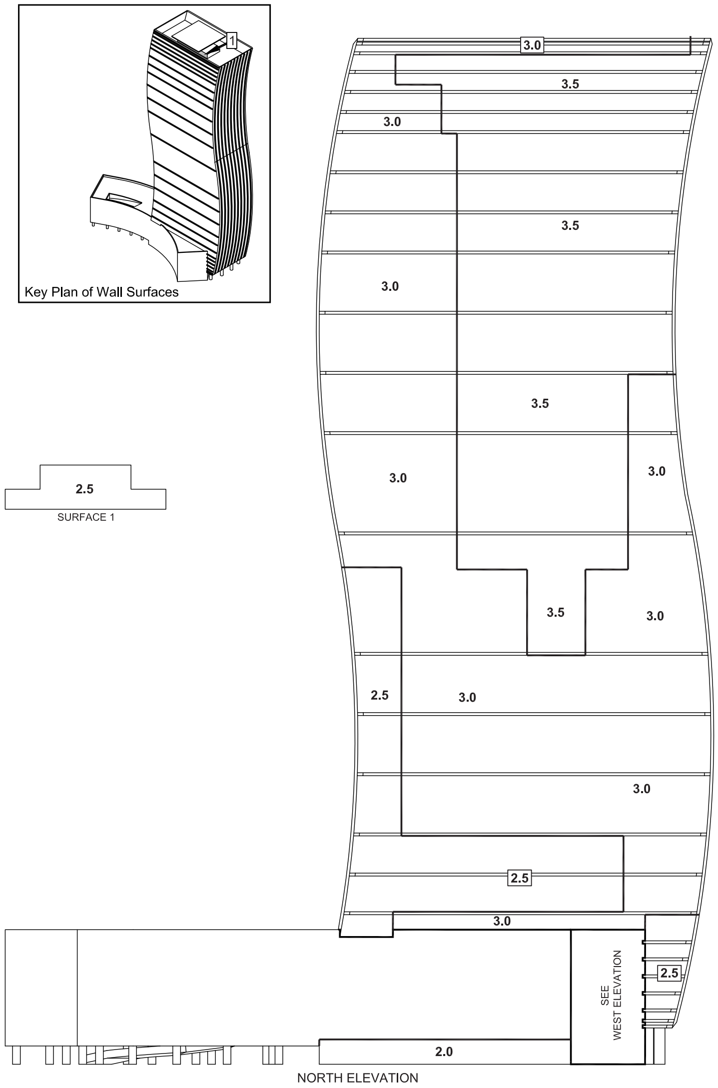


Figure 8.8. Wind tunnel test study, determining wind loads for cladding design. Peak net positive pressures. © RWDI

falling glass due to accidental breakage is addressed by using laminated panels on selected inclined panels. Glazing clips are used as mechanical fixings to ensure glass panels remain supported in the event of structural sealant failures.

Noise transmission due to external sources is addressed by integrating the required noise criteria into the façade system, based on a noise survey by the acoustic designer.

Maintenance of the façade is addressed by ensuring adequate access on all façade external areas, by employing an effective building maintenance unit (BMU), to be used for both cleaning and repair works where needed.

Analysis Modeling and Software

The façade design is a product of system analysis, conforming to the architectural intent and performance requirements, with the use of computer-aided design modeling. The structural design process conforms to the *Aluminum Design Manual 2010* (The Aluminum Association 2010); the glass analysis software is compliant with the *ASTM E1300-16 Standard Practice for Determining Load Resistance of Glass in Buildings* (ASTM 2016b). Heat transfer analysis is conducted using Windows Therm.

Design Phase Considerations

Preliminary design

Establish basis of design (BOD) with the following references:

- Architectural intent or form of the façade
- Façade color scheme and texture
- Material composition, features and elements
- Preliminary façade system design

Figure 8.9. : Inclined curtain wall installation. © SMEDD Corporation

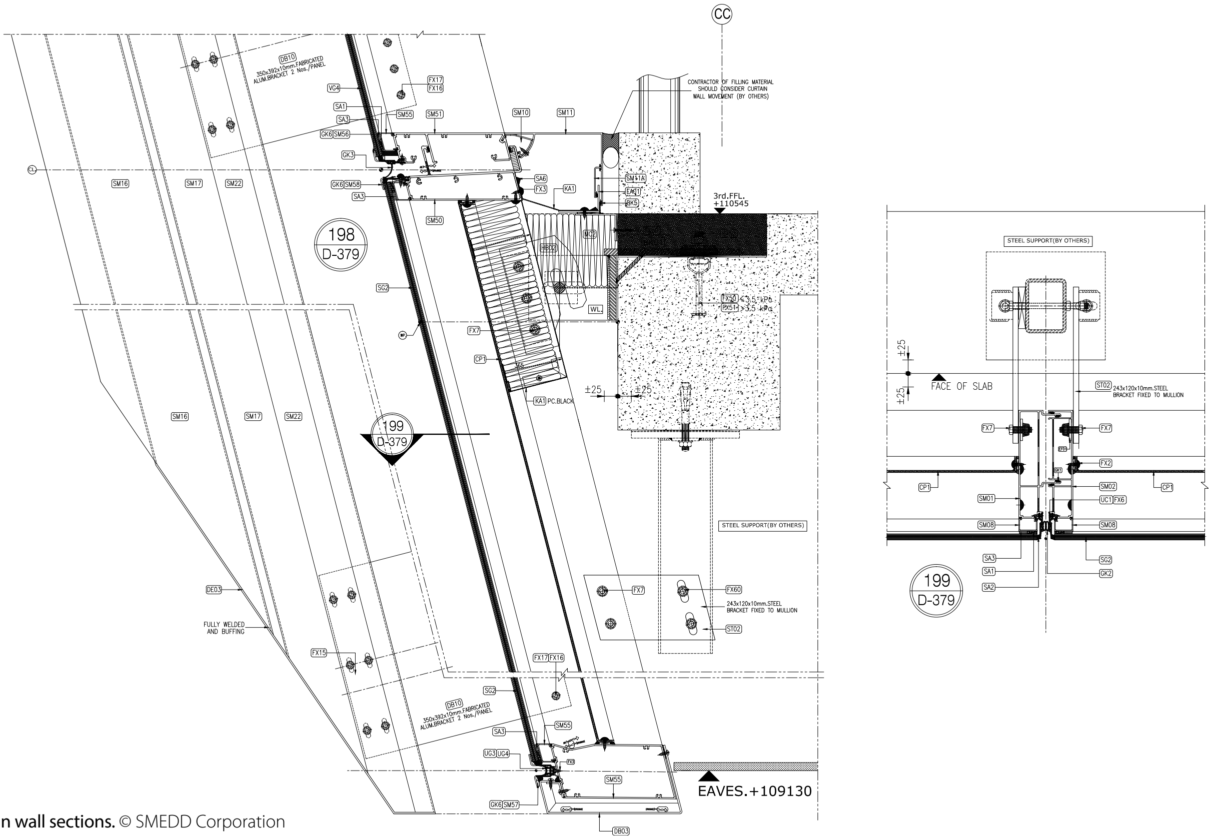


Figure 8.10. Curtain wall sections. © SMEDD Corporation

- Performance requirements
- Selection of standards and performance specification

Design development
The engineering design process was undertaken in collaboration with other design disciplines, covering:

- Cladding pressure loads
- Thermal performance
- Exterior and interior visual requirements
- Glass analysis
- Framing system
- Anchoring system
- Insulating system
- Performance criteria to address structural adequacy, static and dynamic/cyclic water penetration, air infiltration, movement due to seismic and live loads, moisture, noise and fire control
- Exterior lighting
- Maintenance

Product Approval Process Requirements

The product review and approval process follows a work flow in securing control of materials and document records with reference to the project requirements:

- Coordinated design and specifications from the architect of record, design engineers and consultants
- Material properties and product physical samples
- Testing standard records and methodologies
- Visual mock-up unit
- Performance mock-up tests
- Off-site and on-site tests

Figure 8.11. In-progress curtain wall installation. © SMEDD Corporation

- Engineering calculations
- Shop drawings

Façade Typology: Curtain Wall

Support

- Primary bracket: Hilti hot-dipped galvanized channel embeds
- Secondary bracket: Hot-dipped galvanized steel for inclined panels, extruded aluminum for flat panels, three-way adjustable
- Design criteria: 150 percent loading

Mullions/Frame

- Extruded aluminum, 6063-T6 alloy
- Super-durable, powder-coated

Glass

- Double-glazed, heat-strengthened glass with low-E coating at surface 2
- Vision glass, 8-mm YKE-0149 heat-strengthened (HS) low-E #2 + 12 mm air + 8-mm HS
- Spandrel glass, 8-mm YSD-0150 HS low-E #2
- Overall composition: 6-mm HS + 0.76-mm PVB + 6-mm HS + 12 mm air + 10-mm HS + 1.52-mm PVB + 10-mm HS
- Windborne impact testing not required

Experimental Tests

A full-scale prototype specimen has been tested for the presented curtain wall solutions. Eighteen procedures, shown below for reference, have been undertaken on the curtain wall (see Figures 8.11, 8.12, and 8.13) to ensure safety, serviceability, and water penetration performance:

1. Preliminary Loading
2. Open/Close Window
3. Air Infiltration Test

Figure 8.12. Façade mock-up. © B.L. Gavino Façade Design Consultancy

Figure 8.13. Façade mock-up – detail view. © B.L. Gavino Façade Design Consultancy

4. Static Water Penetration Test
5. Cyclic Water Penetration Test
6. Dynamic Water Test
7. Structural Performance Test
8. Open/Close Window
9. Static Water Penetration Test
10. Vertical Movement Test
11. Horizontal Movement Test
12. Open/Close Window
13. Static Water Penetration Test
14. Proof Load Test
15. Open/Close Window
16. Static Water Penetration Test
17. BMU Restrain Test
18. Load Test on Aluminum Fin

Lessons Learned and Recommendations

Difficulties in the Design

The flat façades (north and south) require standard curtain wall construction. However, the vertical curvilinear form of the curtain walls (east and west) present challenges not typical of flat-surface curtain wall installation:

- The curtain wall curvature should look as smooth as possible while using straight glass panels.
- The undulation (8 meters deep at the extremes) presents maintenance issues, requiring an early selection of the type of BMU to be used and subsequent coordination with the contractor. Provisions for the façade's accommodation of the BMU can be put in place at the design stage.
- Because of the angle of inclination, capture pieces have to be provided to help secure the glass panels. These caps have to be as visually unobtrusive as possible.
- The new city ordinance required provision of operable windows, as opposed to the client's preference to have none. Non-provision of operable windows could result in the city authority rejecting a Compliance Certificate.
- On the interior side of the undulating cladding, roller blinds have to be secured in place by tracks attached to the mullions.
- Varying gaps between the inclined wall and the face of the structure (ring beam) require the use of an adjustable aluminum sill cover.

Design Innovative Solutions

The curtain wall stack-joint profile is engineered to accommodate rotational positioning of the vertical mullion framing, in order to conform to the required outward and inward inclination of the unitized panels. The curvilinear form was also achieved by the introduction of a rigid round bar to the primary bracket support, where the panel hook brackets are secured.

9.0 Research Summary and Conclusion

This research highlighted specific aspects related to cyclone-prone façades, as relates to façade technology development and best practices, code requirements, the Asia-Pacific market, and to design approaches.

9.1 Research Summary

Data on past cyclone events, and on local populations and economies, are briefly presented in the first sections of this publication. These, together with a GIS analysis on past cyclone events and on tall building locations, show the existing threats to cyclone-prone structures in the Asia-Pacific region.

The link between curtain walls and high-rises is deep and, if the application of cyclone-resistant façade systems is appropriate, they could serve as refuges for building occupants (Judah & Cousins 2015), instead of remaining as urban features that need to be evacuated or risk damage. Correlating the GIS analysis to this building typology that is concentrated in cities and megacities, this study's findings present tangible evidence. As of the conclusion of this study in December 2017, more than half of the tall buildings set in the 12 analyzed Asia-Pacific jurisdictions are located in cyclone-prone areas.

Façade engineering in the past few decades has continued to undergo innovations. Among other things, performance upgrades have reduced the vulnerability of occupants and property to natural disasters, and among the others to cyclones/hurricanes.

In Miami-Dade County, Florida, through the effectiveness of the applied standards, curtain wall systems have proven to be cyclone-resistant (Miami-Dade County Building Code Compliance Office 2006). However, it took a major disaster (Hurricane Andrew, 1992) before Florida developed local building codes to prevent damage caused by violent storms (ICC 2014a), even though Australia had undergone a similar disaster and implemented comparable measures almost 20 years prior, with Cyclone Tracy (1974) being followed by the Australian Technical Record 440 (EBS 1978). The requirement for these façades is to withstand impacts that simulate flying debris during strong storms.

Even if most of the projects have a tailor-made solution for their glazed envelopes, and the various solutions change from one to the other, the main characteristics of the façades that have already sustained real-life storm conditions have been presented. The "certified" cyclone-resistant façades must be tested in order to verify specific performance criteria that have been identified as representative of the natural phenomena.

Since the 1970s, the primary cause of building envelope damage during strong wind events has been identified as the impact of flying debris (ASCE 2018). Moreover, during a cyclone event, there are big pressure differentials between the windward and the leeward faces of the building. Therefore, the existing current worldwide testing procedures for cyclone-resistant façades aim to verify two main performance objectives. The first performance criterion is resistance to the impact of flying objects (missile-impact testing). Australia, Bangladesh, Japan, and the Philippines are Asia-Pacific countries where this requirement is settled in the local regulation for cyclone-prone areas. The second performance criterion is the impacted glass withstanding 9,000 cycles of positive and negative pressure (ASEP 2015, HBRI 2014, ICC 2016, JSA 2018). This second step of the testing procedure is still not required across Australia: only Queensland's public cyclone shelters have to perform a wind-load test after the impact test, and even this is only for roofs of buildings and for cyclone-debris screens (Queensland Government 2006).

The research emphasized how, in the Asia-Pacific region, the world's most-prone area to wind-related natural disasters (World Bank Group 2016b), there is still a lack of requirements for certified cyclone-resistant façades. Furthermore, it presents the best practices of four Asia-Pacific jurisdictions, and the building case studies show how the design approaches of the local professionals consider the cyclone-prone location of these constructions.

In Australia, in Japan, and in the Philippines, there are requirements for cyclone-resistant glazing, but in Hong Kong there is still no prescription:

Australia

Australia has a debris-impact loading standard for building façades (AS/NZS 1170.2: 2011), but still has no test standard for debris-impact-resistant glass. According to the Australasian Wind Engineering Society, the façade industry is working on a standard which it hopes to finalize in 2019 (AWES 2018). Furthermore, no pressure cycling is required for a façade that has already been impact-tested, contrasting with the US and international standards, where the test is an essential component. Cyclic pressure-testing of elements of buildings was addressed in the TR440 report, on which US codes were based, but never adopted in Australia, apart from roofs of buildings and cyclone-debris screens on cyclone shelters (Queensland Government 2006; ABCB 2016). This remained the case, even as subsequent testing in the United States following Hurricane Andrew in 1992 validated the application of cyclic pressure testing to cyclone/hurricane-resistant glazing.

Hong Kong

Hong Kong's Buildings Department published in 2018 the *Code of Practice for Structural Use of Glass,* which does not include requirements for flying-debris resistance of glass during typhoon events. In 2018, buildings in this region experienced severe façade damage (especially during Typhoon Mangkhut) due to windborne debris. There are countless objects in the urban environment that could become debris and impact curtain walls in strong wind events. In the future, curtain walls (defined as glass panes with a surface are a greater than 2.5 square meters) will be required to have a laminated glass solution in portions of the building with a height higher than 5 meters. This requirement, however, doesn't aim to prevent the possible glass failure of façades installed at the ground level (lower than 5 meters) that usually host public commercial spaces, especially in Hong Kong's tall buildings.

Japan

Japan introduced the test standard method for "windstorm-resistant glazing" in JIS R 3109:2018. The buildings in typhoon-prone areas now should use windstorm-resistant certified glass. The standard procedure, however, doesn't require the entire system to be tested; instead, it requires only a standard measure of a glass pane in a standard frame. The impact locations are clearly identified in the standard, and subsequent pressure cycling must be conducted on the impacted glass specimen.

The Philippines

The Philippines have requirements for typhoon-resistant façades (ASEP 2015), but there is no control by the local authorities over the implementation of the instituted rules. From the 2010 edition of the National Structural Code of the Philippines (ASEP 2010), the façades in typhoon-prone areas must be tested according to ASTM E1886 and ASTM E1996, but currently no testing reports are required to be

> "In Australia, no pressure cycling is required to permit a façade that has already been impact-tested, contrasting with international standards, where the test is an essential component."

presented to the building authority. Furthermore, there are no local mock-up test labs that have adequate equipment to conduct the missile-impact (air cannon) performance tests.

9.2 Research Conclusion

The research presents the different requirements for four analyzed Asia-Pacific jurisdictions, and the final findings vary from one region to the other.

Australia

Australia currently doesn't have a test standard for cyclone-resistant façades (AWES 2018). Currently, it is up to the façade consultant to choose between the available debris-impact test methods, such as the Technical Note No. 4 (CTS 2017). The analyzed testing reports for the IMOC in Port Hedland highlight the discretion for further checks to the façade specimen that façade specialists have to request, such as the interface-corner impact test. In this case, the façade specialist would have to request to impact the façade (after the standard test is passed) in the critical corner location (close to the façade frame).

Therefore, it is difficult to compare these requirements to the US ASTM E1886 and ASTM E1996, or to the international ones (ISO 16932) for three reasons. The first one is the lack, in the Australian Standard, of precise impact locations for the missile impact test. Second, the projectile impact speeds in the AS/NZS 1170.2:2011 loading code are much higher than those in the US and international debris-impact standards. And third, cyclone-resistant glazing test procedures being used by laboratories in Australia, such as Technical Note No. 4, lack positive and negative pressure cycling (9,000 cycles) following debris-impact testing, which is an essential component of US and international standards.

The code and standard requirements for cyclone-resistant façades that could be implemented for Australia include:

- A test standard for cyclone-resistant façades
- The 9,000 cycles of positive and negative pressure immediately following the (passed) impact test.

Hong Kong

Hong Kong buildings, such as One Taikoo Place or the Hong Kong Children's Hospital, represent buildings that embody local best practices in terms of façade design, even if they have not been tested according to existing procedures. These buildings, for different reasons, prioritized the prevention of glass breakage, the injury of people and of internal property, and thus chose a laminated glass system and used high safety coefficients. This was done before the *2018 Code of Practice for Structural Use of Glass* was released.

The code could be improved, introducing testing requirements that take into account the typhoon-prone location of the building, together with the threat represented by flying debris during these events. The ASTM standard tests could be adopted for Hong Kong projects; the ASTM E1886 and ASTM E1996 could be introduced as requirements. Even if the requirement of laminated safety glass has been introduced, it is not sufficient when it comes to flying debris during typhoons and subsequent pressure cycling (ASTM). Laminated safety glass is just one step — the entire façade assembly (glass, frame, sealant, etc.) should be tested in order to verify its adequacy for a typhoon-prone location.

Japan

Japan in 2018 introduced a test method for "windstorm-resistant glazing" (JIS R 3109: 2018). Even though missile-impact testing for flying debris simulation was not legally required for its façades, the Tokyo Sky Tree's owners had its glass designed to withstand the impact of an operating building maintenance unit (BMU), in case of wind gusts. The tower's public function, and aim to become a symbol of the entire country, make it critical to demonstrate high safety performance in case of strong winds and typhoons. This façade solution could be taken as a reference for the design approach in this typhoon-prone area, because the entire façade system has been studied in order to deliver high performance in case of a strong wind gust.

The existing 2018 Japanese test method for typhoon-resistant glazing should be introduced as a requirement.

Nevertheless, it could be upgraded, in order to verify if the entire façade could be defined as "windstorm-resistant." The current JIS standard doesn't consider the real size of the combined glass pane, frame and sealant, even if these components work together on-site. In Japan, there is a high annual frequency of typhoon events, and the certification of the glass is not sufficient to guard against this. Assemblies that only use typhoon-resistant glass perform poorly, when compared against worldwide best practices (such as ASTM E1886, ASTM E1996).

The Philippines

The Philippines have no control of the implementation of the instituted rules. Typhoon Mangkhut in September 2018 caused 137 fatalities in the northern part of the Philippines, which is not densely populated. But what if it had hit the Metro Manila area? There is no need for an improvement of the local typhoon-resistant façade requirements in the Philippines, but rather, for the implementation of required façade testing procedures according to the NSCP 2015 (ASEP 2015). The lack of local façade testing laboratories equipped to test façade performance according to the ASTM E1886 and ASTM E1996 requirements is hindering the progress of the required façade tests.

This information has been collected during two years of research activity, on the basis of various visits and interviews conducted in the Philippines, with local and international professionals involved in façade design and realization. Adding an air cannon to the local testing facilities, to conduct the missile-impact test according to the ASTM standards, could certainly facilitate verification of performance of Philippine-produced typhoon-resistant façades.

Even though they experience strong typhoon events essentially every year, existing façades in cyclone-prone areas in Hong Kong, Japan, and the Philippines, would very likely not pass tests for flying-debris resistance in accordance with international standards. New façade projects could (and should) have cyclone-resistant façades, so that they could potentially withstand cyclone events with essentially no penetration of debris into the building, and no internal property losses.

Since 2006, in the US hurricane-prone regions, no major penetration of flying debris was recorded for façades tested under the most recent testing methods and certified as hurricane-resistant. Post-disaster event assessments have proven the success of technical procedures to follow in the certification of façades in flying debris-prone areas. Even still, these are expected to receive upgrades (Miami-Dade County Building Code Compliance Office 2006). The adopted hurricane/cyclone/typhoon-resistant glazing solutions represent a reasonably economic and practical solution for windborne-debris protection for people and property. Indeed, in the United States and Australian post-disaster event reports, possible future steps were identified in terms of façade water-tightness performance during hurricane events (CTS 2017b).

Now is the time to build resistance to natural disasters, and to prevent their consequences in our urban environments by improving building resilience. The typhoon-prone Asia-Pacific regions could take the international and US standards as a reference, in order to upgrade their building envelopes and make them typhoon-resistant.

A common procedure in terms of building safeguards could be agreed by the local façade associations in the Asia-Pacific region, in order to deal with local and international insurance companies. And a common standard testing procedure would be useful for better access to certified products that perform well when hit by flying debris.

Appendix: Codes and Standards Analysis

The current requirements related to flying-debris resistance of building envelopes in typhoon-prone regions located within the Asia-Pacific region have been investigated. Consequently, the local requirements have been analyzed; a summary of this analysis is presented in the following tables.

This appendix also examines codes in the United States, where the state-of-the art-technologies are identified in the ASTM standard requirements. These standard requirements are highlighted as the worldwide available best practices that should be adopted for all windborne debris-prone areas (ASCE 2018). The ASTM standard test for windborne-resistant façades is reported, in order to present the various loads a façade has to withstand in order to be certified as "hurricane-resistant".

Finally, the international standards are presented and compared and contrasted against local standards.

A.1 Codes with Cyclone-Resistant Glazing Requirements

Table A.1 summarizes the available information within the building codes relating to the following topics:

- Testing apparatus
- Wind loads
- Windborne-debris impact testing
- Pressure-cycling testing
- Testing procedures
- Technical reports
- Wind speed maps

Author	Title	Year	Testing apparatus	Wind loads	Windborne debris impact test	Pressure-cycling testing	Testing procedure	Technical report	Wind speed maps
ASEP	C101-15 NSCP	2015		X			X		X
AS/NZS	AS/NZS 1170.2:2011 Structural design actions - Part 2: Wind actions. Incorporating Amendment No. 4	2011			X				
HBRI	BNBC	2014		X			X		X
ICC	Florida Building Code	2015	X	X	X	X	X	X	X
ICC	IBC	2015		X			X		X
ICC	ICC 500 Guidelines for Hurricane Resistant Residential Construction	2014					X		
Queensland Government – Dept. of Public Works	Design Guidelines for Australian Public Cyclone Shelter	2006	X	X	X	X			
TDI	2006 Texas Revisions to the 2006 International Residential Code	2006		X	X		X		

AS/NZS = Australian/New Zealand Standard
ASEP = Association of Structural Engineers of the Philippines
BNBC = Bangladesh National Building Code
HBRI = Housing & Building Research Institute
ICC = International Code Council
IBC = International Building Code
NSCP = National Structural Code of the Philippines
TDI = Texas Department of Insurance

Table A.1. Information on the seven main topics identified under the heading "cyclone-resistant façade design," across eight relevant codes.

A.2 Code Comparison

A.2.1 International Building Code, 2015

Test: ASTM E1886; ASTM E1996

1. Glazed openings located within 9,144 mm of grade shall meet the requirements of the large missile test of ASTM E1996.
2. Glazed openings located more than 9,144 mm above grade shall meet the provisions of the small missile test of ASTM E1996.
3. Storage sheds that are not designed for human habitation and that have a floor area of 67 m^2 or less are not required to comply with the mandatory windborne debris impact standard of this code.
4. Openings in sunroofs, balconies or enclosed porches constructed under existing roofs or decks are not required to be protected, provided the spaces are separated from the building interior by a wall, and all openings in the separating wall are protected in accordance with point 2 (above). Such spaces shall be permitted to be designed as either partially enclosed or enclosed structures.

Exceptions:

1. Glazing in Risk Category I buildings, including greenhouses that are occupied for growing plants on a production or research basis, without public access shall be permitted to be unprotected.
2. Glazing in Risk Category II, III, or IV buildings located over 18,288 mm above the ground and over 9,144 mm above aggregate surface roofs located within 458 m of the building shall be permitted to be unprotected.

A.2.2 Florida Building Code – Building, 2015

Test: SSTD 12-97; TAS 201, TAS 202 and TAS 203; AAMA 506; ASTM E1886 and ASTM E1996

1. Glazed openings located within 9,144 mm of grade shall meet the requirements of the large missile test of ASTM E1996.
2. Glazed openings located more than 9,144 mm above grade shall meet the provisions of the small missile test of ASTM E1996.
3. Storage sheds that are not designed for human habitation and that have a floor area of 67 m^2 or less are not required to comply with the mandatory windborne debris impact standard of this code.
4. Openings in sunroofs, balconies or enclosed porches constructed under existing roofs or decks are not required to be protected, provided the spaces are separated from the building interior by a wall and all openings in the separating wall are protected in accordance with point 2 (above) . Such spaces shall be permitted to be designed as either partially enclosed or enclosed structures.

Application of ASTM E1996.

Unless otherwise specified, select the wind zone based on the strength design wind speed, V_{ult}, as follows:

1. Wind Zone 1 – 58 m/s ≤ ultimate design wind speed, V_{ult} < 63 m/s.
2. Wind Zone 2 – 63 m/s ≤ ultimate design wind speed, V_{ult} < 67 m/s at greater than1.6 km from the coastline. The coastline shall be measured from the mean high water mark.
3. Wind Zone 3 – 67 m/s ≤ ultimate design wind speed, V_{ult} ≤76 m/s, or 63 m/s ≤ ultimate design wind speed, V_{ult} ≤ 76 m/s and within 1.6 km of the coastline. The coastline shall be measured from the mean high water mark.
4. Wind Zone 4 – ultimate design wind speed, V_{ult} >76 m/s.

Modifications to ASTM E1886 and ASTM E1996.
The Air Pressure Cycles Table presented in ASTM E1886 and ASTM E1996 should be revised and (…) the third column to read as follows:

Air Pressure Cycles
0.2 to 0.5 Ppos
0.0 to 0.6 Ppos
0.5 to 0.8 Ppos
0.3 to 1.0 Pneg
0.5 to 0.8 Pneg
0.0 to 0.6 Pneg
0.2 to 0.5 Pneg

Notes:
- Ppos=0.6 x positive ultimate design load in accordance with ASCE 7.
- Pneg=0.6 x negative ultimate design load in accordance with ASCE 7.

Exceptions:
1. Glazing in Risk Category I buildings, including greenhouses that are occupied for growing plants on a production or research basis, without public access shall be permitted to be unprotected.
2. Glazing in Risk Category II, III, or IV buildings located over 18,288 mm above the ground and over 9,144 mm above aggregate surface roofs located within 458 m of the building shall be permitted to be unprotected.

A.2.3 Bangladesh National Building Code Vol. 2/3 Structural Design, 2014

Test: ASTM E1886; ASTM E1996
1. Glazed openings located within 9,144 mm of grade shall meet the requirements of the large missile test of ASTM E1996.
2. Glazed openings located more than 9,144 mm above grade shall meet the provisions of the small missile test of ASTM E1996.
3. Storage sheds that are not designed for human habitation and that have a floor area of 67 m^2 or less are not required to comply with the mandatory windborne debris impact standard of this code.
4. Openings in sunroofs, balconies or enclosed porches constructed under existing roofs or decks are not required to be protected, provided the spaces are separated from the building interior by a wall and all openings in the separating wall are protected in accordance with point 2 (above) . Such spaces shall be permitted to be designed as either partially enclosed or enclosed structures.

Exceptions:
1. Glazing in Category II, III, or IV buildings located over 18.3 m above the ground and over 9.2 m above aggregate surface roofs located within 458 m of the building shall be permitted to be unprotected.
2. Glazing in Category I buildings shall be permitted to be unprotected.

A.2.4 NSCP Vol. 1 – Buildings, Towers, and Other Vertical Structures, 2015

Test: ASTM E1886; ASTM E1996

Protection of glazed openings.
Glazed openings in Occupancy Category I, II, III or IV building located in tropical cyclone-prone regions shall be protected as specified (…) in the Code.

Windborne debris regions.
Glazed openings shall be protected in accordance with ASTM E1886 and ASTM E1996.

1. Within 1.6 km of the coastal mean high-water line where the basic wind speed is equal to or greater than 58 m/s, or
2. In areas where the basic wind speed is equal to or greater than 63 m/s.

Exceptions:
Glazing located over 18 m above the ground and over 9 m above aggregate-surfaced-roofs, including roof with gravel or stone ballast, located within 450 m of the building shall be permitted to be unprotected.

A.2.5 ICC 500 Guidelines for Hurricane Resistant Residential Construction, 2014

Test: SSTD 12-97; ASTM E1886 and ASTM E1996 or; AAMA506

A.2.6 AS/NZS 1170.2:2011 Structural Design Actions – Part 2: Wind actions. Incorporating Amendment No. 4, 2011 & 2016

Test: Technical Note No. 4: Simulated Windborne Debris Impact Testing of Building Envelope Components could be chosen as a testing standard procedure.

Clause 2.5.8.
Where windborne debris loading is required for impact resistance testing, the debris impact loading shall be:

a. A timber test member of 4 kg mass, of a density of at least 600 kg/m^3, with a nominal cross-section of 50 x 100 mm impacting end on at 0.4 V_R for the horizontal component of the trajectory, and 0.1 V_R for the vertical component of the trajectory; and
b. A spherical steel ball 8 mm in diameter (approximately 2 grams mass) impacting at 0.4 V_R for the horizontal component of the trajectory, and 0.3 V_R for the vertical component of the trajectory, where V_R is the regional wind speed (which is given in 1170.2 AS/NZS, 2011).

Notes:

- Examples of the use of this Clause would be for the evaluation of internal pressure (…) or the demonstration of resistance to penetration of the building envelope enclosing a shelter room.
- The two test debris items are representative of a large range of windborne debris of varying masses and sizes that can be generated in severe wind storms.
- The spherical ball missile is representative of small missiles, which could penetrate protective screens with large mesh sizes.
- These impact loadings should be applied independently in time and location.
- This Standard does not specify a test method or acceptance criteria. Acceptance criteria may vary according to the purpose of the test. An appropriate test method and acceptance criteria for debris tests are given in Technical Note No. 4: Simulated Windborne Debris Impact Testing 0f Building Envelope Components.

A.2.7 Design Guidelines for Australian Public Cyclone Shelters, 2006

Test: AS/NZS1170.2

Large missile impact test.
A 50 x 100 mm piece of timber of 4 kg impacting end-on at 0.4 x $V_{10,000}$ for horizontal trajectories and 0.1 x $V_{10,000}$ for vertical trajectories.

Small missile impact test.
Five spherical steel balls of 2 g mass {8mm diameter} impacting at 0.4 x $V_{10,000}$ for horizontal trajectories and 0.3 x $V_{10,000}$ for vertical trajectories. Solid steel ball having a mass of 2 grams impacting between 0.40 and 0.75 of basic wind speed (number, size and impact speed specified by user).

Acceptance criteria.
A test specimen shall:

a. prevent a debris missile from penetrating through the screen/cladding;
b. if perforated, have a maximum perforation width of less than 8 mm;
c. in the case of a debris screen, not deflect more than 0.8 times the clear distance between the screen and the glazing, at any stage of the test.
d. be capable of resisting the specified wind load.

In Region C, the impact speeds are:
0.1 x $V_{10,000}$ = 8.5 m/s (30.6 km/h);
0.3 x $V_{10,000}$ = 25.5 m/s (91.8 km/h);
0.4 x $V_{10,000}$ = 34 m/s (122 km/h).

A.2.8 Texas Revisions to the 2006 International Residential Code, 2006

Tests: ASTM E1886 and ASTM E1996; ANSI/DASMA 115

A.3 Standards for Cyclone-Resistant Glazing

The selected documents were compared for the following topics related to flying-debris and strong-wind resistance:

- Small missile impact testing;
- Large missile impact testing;
- Pressure-cycling testing;
- Façade acceptance criteria procedures.

A.3.1 ASCE 7-16 Minimum Design Loads and Associated Criteria for Buildings and Other Structures, 2016

Refers to ASTM E1886 and ASTM E1996 for hurricane-prone regions.

Specifies that glazed building envelopes in regions where the basic wind speed exceeds 225 km/h, or is greater than 209 km/h and within 1.6 km from the coastal high waterline, are required to be protected from windborne debris impact.

A.3.2 ISO 16932 Glass in Building – Destructive-Windstorm-Resistant Security Glazing – Test and Classification, 2015

This industrial standard doesn't take into account the entire façade assembly. It requires testing of the glass surface in a standardized frame (of a standard size).

Large missile impact test.
Below 10 m: 5 x 10 cm timber weighing 4.1 kg impacting end-on at 15.3 m/s (two per specimen).

Small missile impact test.
Above 10 m: 2 g steel balls impacting at 15.3 m/s (two per specimen).

Pressure cycles.
Each of the above impacts is to be followed by 9,000 cycles of pressure representing hurricane wind gusts.

A.3.3 Japanese Industrial Standard (JIS) R 3109 Glass in Building – Destructive-Windstorm-Resistant Security Glazing – Test Method, 2018

Refers to ISO 16932.

Large missile impact test.
Below 10 m: 50 x 100 mm timber weighing 4.1 kg impacting end-on at 15.3 m/s (two per specimen).

Small missile impact test.
Above 10 m: 50 x 100 mm timber weighing 1.0 kg impacting end-on at 15.3 m/s (two per specimen).

Pressure cycles.
Each of the above impacts is to be followed by 9,000 cycles of pressure representing hurricane wind gusts.

A.3.4 Florida Building Code Test Protocols for High-Velocity Hurricane Zones – Testing Application Standard (TAS) 203-94 – Criteria for Testing Products Subject to Cyclic Wind Pressure Loading; TAS 201-94 – Impact Test Procedures, 2014

Large missile impact test.
Below 9,144 mm: 50 x 100 mm timber weighing 4.08 kg impacting end-on at 15.24 m/s (two per specimen).

Small missile impact test.
Above 9,144 mm: 2g steel balls impacting at 15.24 m/s (30 per specimen).

Pressure cycles.
Each of the above impacts is to be followed by 9,000 cycles of pressure, representing hurricane wind gusts.

A.3.5 ASTM E1886-13 and ASTM E1996-17 – Standard Test Method and Specification for Performance of Exterior Windows, Curtain Walls, Doors, and Impact Protective Systems Impacted by Missile(s) and Exposed to Cyclic Pressure Differentials, 2009

Large missile impact test.
Below 9,144 mm: 50 x 100 mm weighing 2.04 – 4.08 kg impacting between 0.10 and 0.55 of basic wind speed (number, size, and impact speed specified by user).

Small missile impact test.
Above 9,144 mm: 50 x 100 mm solid steel ball having a mass of 2 g impacting between 0.40 and 0.75 of basic wind speed (number, size, and impact speed specified by user).

Pressure cycles.
Each of the above impacts is to be followed by 9,000 cycles of pressure, representing hurricane wind gusts.

A.3.6 Texas Department of Insurance (TDI) 1-98 – Test for Impact and Cyclic Wind Pressure Resistance of Impact Protective Systems and Exterior Opening Systems, Building Code for Windstorm Resistant Construction, 1998

Large missile impact test.
50 x 100 mm weighing 4.08 kg impacting at 15.24 m/s. Impact each of three specimens twice (center and corner) or each of six specimens once (three in the center, three in the corner).

Small missile impact test.
2g steel balls impacting at 39.62 m/s. Each of three specimens receives 30 impacts in three groups of 10 (in the center, corner and center of long dimension).

Pressure cycles.
Each of the above impacts is to be followed by 9,000 cycles of pressure, representing hurricane wind gusts.

A.3.7 AAMA 506-16 – Voluntary Specifications for Impact and Cycle Testing of Fenestration Products, 2016

References ASTM E1886 and ASTM E1996, but this standard testing procedure requires that other parameters are controlled while the specimen is tested (such as temperature). It is more demanding than the ASTM test.

Clause 8.2.1.
Mulled assemblies shall be qualified by this document if all of the following conditions are met:

a. When required, the largest assembly with the longest mullion shall be impacted at its midpoint in accordance with ASTM E1996.

b. The assembly shall satisfy the minimum requirements of AAMA 450.
c. Individual units making up the assembly shall also satisfy the minimum requirements of this specification.

Note:

Some specifying authorities require impact of each unique mullion cross section at its midpoint.

Clause 8.2.2.

Impact-resistant assemblies meeting the requirements of point 8.2.1 shall be permitted to follow the same rules of unit substitution that are permitted by AAMA 450.

Clause 8.2.3.

Qualification of an assembly with the longest mullion shall qualify that mullion for other assemblies containing that same mullion at a shorter length, with a tributary area less than or equal to the test specimen. Point 8.2.2 shall apply to these other assemblies.

A.3.8 Technical Note No.4 Simulated Windborne Debris Impact Testing of Building Envelope Components, 2017

All buildings in cyclonic areas.

The windborne debris impact test is an optional test for envelope components of all buildings in cyclonic regions. Clause 2.5.8 of AS/NZS 1170.2:2011 – Structural Design Actions – Part 2: Wind Actions (incorporating Amendment Nos. 1, 2, 3 & 4), states that: Where windborne debris impact loading is specified, the debris impact shall be equivalent to:

Large missile impact test.

Timber member of 4 kg mass with a nominal cross section of 100 x 50 mm impacting end-on at 0.4 V_R for horizontal trajectories and 0.1 V_R for vertical trajectories; and

Small missile impact test.

Spherical steel ball of 8 mm diameter (approximately 2 grams mass), impacting at 0.4 V_R for horizontal trajectories and 0.3 V_R for vertical trajectories, where V_R is the regional wind speed.

Note:

As this standard does not provide guidance to determine whether an impact test has passed, the CTS has developed acceptance criteria to provide consistency when assessing the results of impact tests.

The external fabric of public cyclone shelters is to be at least capable of resisting wind debris defined as:

Large missile impact test.

Test Load A: A 50 x 100 mm cross-section piece of timber of 4 kg mass impacting end-on at 0.4 x $V_{10,000}$ for horizontal trajectories, and 0.1 x $V_{10,000}$ for vertical trajectories.

Small missile impact test.

Test Load B: Five spherical steel balls of 2 g mass and 8 mm diameter, successively impacting at 0.4 x $V_{10,000}$ for horizontal trajectories and 0.3 x $V_{10,000}$ for vertical trajectories.

Test: Determine the gust wind speed in accordance with AS/NZS 1170.2.

1. Impact test specimen at the specified locations with timber debris item.
2. Inspect test specimen.
   a. If timber debris item did not penetrate and no obvious aperture is present → *Pass*
   b. If test specimen stops timber debris item but is left with an aperture smaller than 5,000 mm^2 → *Pass*
   c. If test specimen stops timber debris item but is left with an aperture greater than 5,000 mm^2 → *Fail*
   d. If test specimen stops timber debris item but timber debris item is visible from the inside (i.e. protruding through test specimen) → *Fail*
3. If test specimen(s) pass the timber debris item test requirements at all critical locations, impact the same, or an identical, new test specimen with five spherical steel balls at various random locations. For a given component and configuration, only one series of five spherical steel balls is required.
4. Inspect test specimen.
   e. If none of the spherical steel balls penetrate through the test specimen → *Pass*
   f. If any of the spherical steel balls penetrates through the test specimen, or test specimen is left with an aperture greater than 5,000 mm^2 → *Fail*

Windows.

Windows shall be tested as an assembly consisting of the glass and its typical frame, including any seals. Note that the frame itself is not being tested; however, the connection between the glass and the frame is being tested. Normally three impact tests are conducted on glass panels at different locations:

- Interface corner
- Interface edge
- Geometric center

Where interior mullions or other glazed section joints and/or latches are present, additional impacts are to be performed at these locations:

- Center of mullion
- Base of mullion

A.4 Standards Comparison

The following standards provide the testing procedure for buildings that have to be protected against windborne debris in cyclone-prone locations. All the standards directly or indirectly refer to the ASTM standards (see ISO 16932, JIS R 3109:2018), except for Australia, which has its own requirements. AS/NZS also differ from the other testing requirements for the lack of the pressure-cycling loading ("as might be expected during the passage of a cyclone event") after the impact test (ASCE 2018).

Table A.2 reports data about a medium level of protection of buildings, providing an opportunity to compare the existing requirements for the same building typology.

Cyclic Static Pressure Differential Loading			
Loading Sequence	**Loading Direction**	**Air Pressure Cycles**	**No. of Air Pressure Cycles**
1	Positive	0.2 P – 0.5 Ppos	3500
2	Positive	0.0 P – 0.6 Ppos	300
3	Positive	0.5 P – 0.8 Ppos	600
4	Positive	0.3 P – 1.0 Ppos	100
5	Negative	0.3 P – 1.0 Pneg	50
6	Negative	0.5 P – 0.8 Pneg	1050
7	Negative	0. 0 P – 0.6 Pneg	50
8	Negative	0.2 P – 0.5 Pneg	3350
Cycling pressure used is determined by design pressure of the building for the maximum inward (Ppos) and maximum outward (Pneg) air pressure differential for which qualification is sought.			

Table A.2. Cyclic static air-pressure loading. Source: ASTM E1996 and ASTM E1886

A.5 Testing Procedures – ASTM E1996 and ASTM E1886

The ASTM E1886-13a and ASTM E1996-17 have been identified as the current best testing procedures that could be widely adopted by cyclone-prone countries that are still without any requirements. They proved their effectiveness with the withstanding to hurricanes of US façades that were previously certified according to these standards. Furthermore, the ASTM standards are extensively used worldwide, and the testing facilities, also in the Asia-Pacific region, are used to conduct tests according to ASTM on a daily basis.

Extract of the testing procedures from ASTM E1996 and ASTM E1886:

4. Test Specimens
4.1 Number of Test Specimens:
4.1.1 Fenestration Assemblies:
4.1.1.1 Three test specimens shall be submitted for the large missile test.
4.1.1.2 Three test specimens shall be submitted for the small missile test.
4.1.1.3 One additional test specimen may be submitted for each of the tests should no more than one of the original three specimens fail any portion of the testing.
4.1.2 Impact Protective Systems:
4.1.2.1 A minimum of three test specimens shall be submitted for the large missile test for the largest span to be qualified.
4.1.2.2 A minimum of three test specimens shall be submitted for the small missile test.
4.1.2.3 One additional test specimen may be submitted for each of the tests should no more than one of the original specimens fail any portion of the testing.
4.2 Test specimens shall be prepared as specified in Test Method E 1886.
4.3 The size of the test specimen shall be determined by the specifying authority. All components of each test specimen shall be full-size.
4.4 Where it is impractical to test the entire fenestration assembly, such as curtain wall and heavy commercial assemblies, test the largest size of each type of panel as required by the specifying authority to qualify the entire assembly.

4.5 Fenestration assemblies and impact-protective systems intended to be mulled together shall be tested separately, or tested by combining three specimens into one mounting frame, separated only by the mullions.

5. Test Procedures

5.1 Test specimens shall be tested according to Test Method E1886.

5.2 Determine the missile based upon building classification, wind speed, and assembly elevation according to Section 6.

5.3 Location of Impact:

5.3.1 Large Missile Test – Impact each impact protective system specimen and each fenestration assembly infill type once as shown in Figure A.1 (empty circles), except for additional impacts specified in 5.3.2.

5.3.1.1 Impact one specimen with the center of the missile within a 65-mm-radius circle, and with the center of the circle located at the center of each type of infill.

5.3.1.2 Impact a different specimen with the center of the missile within a 65-mm-radius circle and with the center of the circle located 150 mm from supporting members at a corner.

5.3.1.3 Impact the remaining specimen with the center of the missile within a 65-mm-radius circle and with the center of the circle located 150 mm from supporting members at a diagonally opposite corner.

5.3.2 Additional Impact Locations in Wind Zone 4 (as previously seen in Figure A.1).

5.3.2.1 Impact the same specimen specified in 5.3.1.1 a second time, with the center of the second missile within a 65-mm-radius circle and with the center of the circle, located 150 mm from supporting member at a corner.

5.3.2.2 Impact the same specimen specified in 5.3.1.2 a second time with the center of the second missile within a 65-mm-radius circle and with the center of the circle located at the center of each type of infill.

5.3.2.3 Impact the same specimen specified in 5.3.1.3 a second time with the center of the second missile within a 65-mm-radius circle and with the center of the circle located at the center of each type of infill, except as specified in 5.3.3.6.

5.3.2.4 For test specimens with bracing at the specified impact location(s), the impact location(s) shall be relocated to the nearest area with no bracing.

5.3.3 Special Considerations:

5.3.3.1 For test specimens containing multiple panels, impact the exterior glazing surface innermost from the exterior plane of the fenestration assembly, or impact protective system panel innermost from the exterior.

5.3.3.2 For test specimens containing fixed and operable panels of the same type of infill, impact the operable portion.

5.3.3.3 For operable test specimens, a corner impact location shall be nearest a locking device, and the other corner impact location shall be at a corner diagonally opposite.

5.3.3.4 For test specimens with bracing at the specified impact location(s), the impact location(s) shall be relocated to the nearest area with no bracing.

5.3.3.5 The impacts on accordion-impact-protective systems shall be at the valleys located closest to the impact locations shown in Figure A.1.

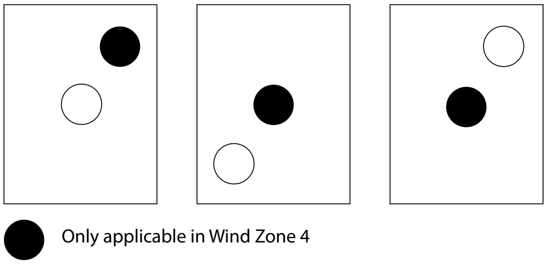


Figure A.1. Impact Locations for Large Missile Test (each type of infill). The white/unfilled circles denote first impact and the black circles denote second impact. © Michele Bettineschi. Source: ASTM E1996

5.3.3.6 In Wind Zone 4, impact the integral mullion and other intermediate members such as a meeting rail, check rail, or meeting stile mid-span in lieu of the impact specified in 5.3.2.3 if applicable (see Figures A.2 and A.3).
5.3.3.7 In Wind Zone 4, for each type of mullion impact one vertical or horizontal combination mullion with the longest span at mid span in addition to impacts specified in 5.3 (see Figure A.4).

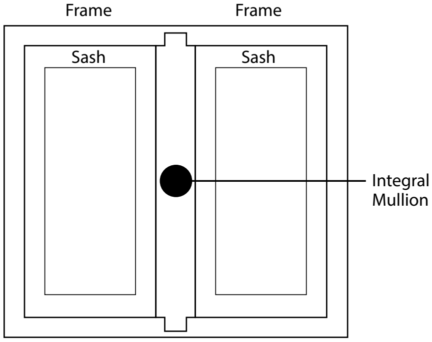


Figure A.2. Wind Zone 4: Integral mullion impact location. © Michele Bettineschi. Source: ASTM E1996

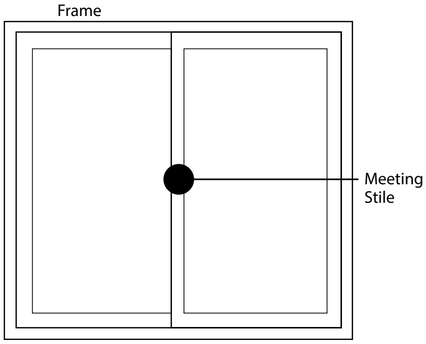


Figure A.3. Wind Zone 4: Meeting stile impact location. © Michele Bettineschi. Source: ASTM E1996

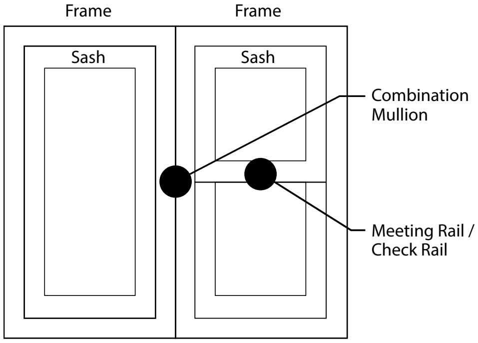


Figure A.4. Wind Zone 4: Combination mullion with meeting or check rail impact locations. © Michele Bettineschi. Source: ASTM E1996

5.3.4 Small Missile Test - Impact each impact protective system specimen and each fenestration assembly infill type three times with 10 steel balls each (see Figure A.5).
5.3.4.1 Each impact location shall receive distributed impacts simultaneously from 10 steel balls. The impact shall be described in the test report.
5.3.4.2 The corner impact locations shall be entirely within a 250-mm-radius circle, having its center located 275 mm from the edges.
5.3.4.3 The edge impact locations shall be entirely within a 250-mm radius circle at the centerline between two corners, having its center located at 275 mm from the edge.
5.3.4.4 The center impact location shall be entirely within a 250-mm radius circle, having its center located at the horizontal and vertical centerline of the infill.

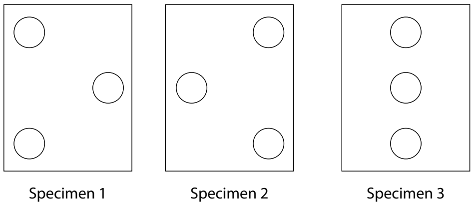


Figure A.5. Impact locations for Small Missile Test (each type of infill). © Michele Bettineschi. Source: ASTM E1996)

5.4 Air Pressure Cycling:
5.4.1 Air Pressure Differential:
5.4.1.1 The air pressure portion of the test shall use the test loading program previously seen in Table A.2. Select Ppos and Pneg for the maximum inward (positive) and maximum outward (negative) air pressure differential for which qualification is sought.
5.4.1.2 The air pressure differential to be used for porous impact protective systems shall be F (the design wind force for other structures as specified in ASCE 7) divided by the horizontally projected area of the entire assembly.
5.4.2 Except in Wind Zone 4, porous impact-protective systems whose aggregate open area exceeds 50% of their projected surface area, which pass the small missile test and that are not subject to the large missile test, need not be tested for the air pressure portion of the test described in this section.

5.5 For impact-protective system specimens that are tested independently of the fenestration assemblies they are intended to protect, measure and record both the maximum dynamic deflection and the residual deflection following the impact test; and measure and record the maximum positive deflection in combination with the residual deflection during the air pressure cycling test. Measure all deflections to the nearest 2 mm.

6. Missiles

6.1 The specifying authority shall select an applicable missile by defining a level of protection, a wind zone, and an assembly elevation above the ground.

6.2 The applicable missile from Table A.2 shall be chosen using Table A.3 or Table A.4, unless otherwise specified.

6.2.1 Unless otherwise specified, select the appropriate level of building protection from 6.2.1.1–6.2.1.3 and enter Table A.3 or Table A.4 at the appropriate column.

6.2.1.1 Enhanced Protection (Essential Facilities – Buildings and other structures designated as essential facilities, including, but not limited to, hospitals; other healthcare facilities having emergency treatment facilities; jails and detention facilities; fire, rescue and police stations, and emergency vehicle garages; designated emergency shelters; communications centers and other facilities required for emergency response; power generating stations; other public utility facilities required in an emergency; and buildings and other structures having critical national defense functions.

6.2.1.2 Basic Protection – All buildings and structures except those listed in 6.2.1.1 and 6.2.1.3.

6.2.1.3 Unprotected – Buildings and other structures that represent a low hazard to human life in a windstorm including, but not limited to: agricultural facilities, production greenhouses, certain temporary facilities, and storage facilities.

7. Pass/Fail Criteria

7.1 In Wind Zones 1, 2, 3, and 4, the specifying authority shall select an applicable pass/fail criterion based on 7.1.1 and 7.1.2.

7.1.1 Fenestration assemblies and non-porous impact protective systems:

7.1.1.1 The test specimen shall resist the large (see Figure A.6) or small missile impacts, or both, with no tear formed longer than 130 mm and wider than 1 mm through which air can pass, or with no opening formed through which a 76 mm-diameter solid sphere can freely pass when evaluated upon completion of missile impacts and test loading program.

Applicable Missiles		
Missile Level	**Missile**	**Impact Speed**
A	2 g (31 grains) ± 5 % steel ball	39.62 m/s
C	2050 g ± 100 g, 50 x 100 mm, 1.2 m ± 100 mm lumber	12.19 m/s
D	4100 g ± 100 g, 50 x 100 mm, 2.4 m ± 100 mm lumber	15.25 m/s
E	4100 g ± 100 g, 50 x 100 mm, 2.4 m ± 100 mm lumber	24.38 m/s

Table A.3. Applicable missiles. Source: ASTM E1996 and ASTM E1886.

Levels of Protection and Impact Test Requirements				
Level of Protection	**Basic Protection**		**Enhanced Protection**	
Assembly elevation	≤ 9.1 m	> 9.1 m	≤ 9.1 m	> 9.1 m
Wind Zone 1: 49 m/s ≤ basic wind speed < 54 m/s	C	A	D	D
Wind Zone 2: 54 m/s ≤ basic wind speed < 58 m/s at greater than 1.6 km from the coastline	C	A	D	D
Wind Zone 3: 58 m/s ≤ basic wind speed ≤ 63 m/s, or 54 m/s ≤ basic wind speed ≤ 63 m/s and within 1.6 km of the coastline	D	A	E	D
Wind Zone 4: basic wind speed > 63 m/s	D	A	E	D

Table A.4. Levels of protection and impact test requirements

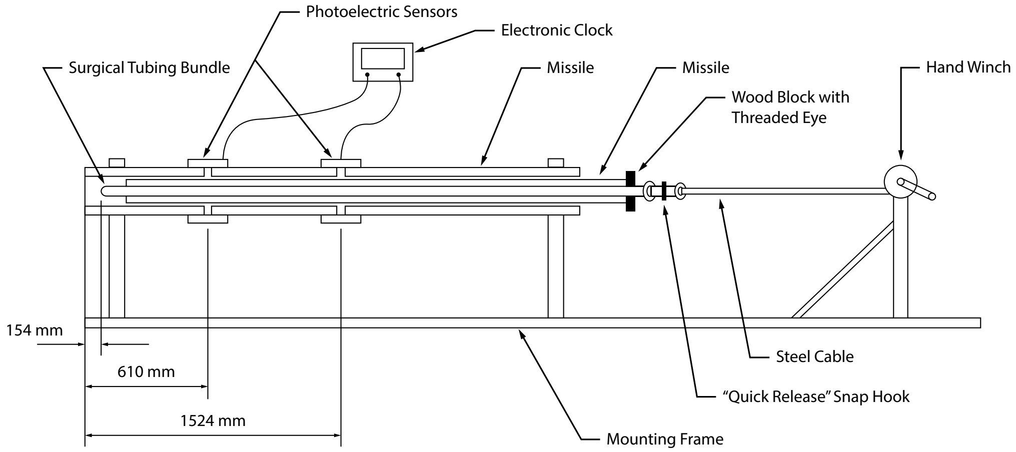


Figure A.6. Testing apparatus for the large missile impact test. © Michele Bettineschi. Source: ASTM E1996)

7.1.1.2 All test specimens meeting the enhanced protection impact levels shall resist the large or small missile impacts, or both, without penetration of the inner plane of the infill or impact-protective system, and resist the cyclic pressure loading specified in Table A.2, with no tear formed longer than 130 mm and wider than 1 mm through which air can pass.

7.1.2 Porous impact protective systems tested independently of the fenestration assemblies they are protecting:

7.1.2.1 There shall be no penetration of the innermost plane of the test specimen by the applicable missile(s) during the impact test(s).

7.1.2.2 Upon completion of the missile impact(s) and test loading program, there shall be no horizontally projected opening formed through which a 76 mm-diameter solid sphere can pass.

7.2 In Wind Zone 4, the specifying authority shall be permitted to select an optional applicable pass/fail criterion based on 7.2.1, 7.2.2, and 7.2.3.

7.2.1 All test specimens shall resist the large or small missile impacts, or both, without penetration of the inner plane of the infill or impact protective system and resist the cyclic pressure loading specified in Table A.2 with no tear formed longer than 130 mm and wider than 1 mm through which air can pass.

7.2.2 The overlap seams of an impact-protective system shall not have a separation greater than 1/180 of the span or 13 mm whichever is less, after impact. The length of the separation shall not be greater than 900 mm or 40 % of the span, whichever is less.

7.2.3 Fasteners, when used, shall not become disengaged during the test procedure.

A.6 Problems and Gaps in Existing Standards

This project aimed to discover problems that professionals involved in façade design and construction think are relevant to market development. These professional experts, together with academics, and the available research papers and reports, highlighted some problems related to the current code and industrial standard requirements for windborne-debris resistance.

The first — and perhaps most obvious — problem with cyclone-resistant curtain wall requirements is that there are many growing jurisdictions that lack such requirements entirely in their building codes. This is not to say that construction projects in these areas do not take cyclone resistance into account. But each project represents a new compromise between the client, contractor, and façade supplier, to which international testing requirements should be applied. Each reflects a choice of building product and attendant costs. This can often result in curtain wall systems that are over- or under-engineered, and which may not be appropriate for the local climate.

The cyclic pressure test, which immediately follows the missile impact test in the US ASTM standards, is considered a good representation of the effect of real storm events, but is still missing from Australia and New Zealand codes, for other than cyclone shelter buildings. The Australian National Construction Code (NCC) requirements for cyclonic regions C and D, through reference to AS/NZS1170.2, does not mandate the façade of buildings to be debris-impact-resistant (ASCE 2017).

Furthermore, the current speeds specified for large-missile impact testing are two times or more the original Australian specification of 15 m/s, depending on location and building importance. The main issue is that, currently it is so expensive to use debris-impact-resistant glazing that it is impractical. What was previously a fairly economical laminated-glass product for meeting debris-impact-resistance has now become exorbitantly expensive. So unfortunately, if the aim of the increased projectile velocities in AS/NZS1170.2:2011 was to improve public safety, the effect has actually been the opposite. Now there is a significant decrease in the use of laminated glass in cyclonic-area façades because of the high cost of debris-impact-resistant glazing. Clients are instead choosing cheap, monolithic toughened glass solutions, and assuming the façade will be breached by debris during a cyclone event.

Finally, in Australia, as mentioned in the previous sections of this document, there is not a clear identification of the testing procedures. There are several test labs that guarantee their adoption of a procedure and of the equipment specified in the AS/NZS 1170.2 but, in reality, they differ from one to the other. A curtain wall system tested in one of these labs has failed the impact test for flying debris simulation but passed in another. Some façade manufacturers have been known to pass their products through testing labs until they pass, which is not indicative of a common standard.

The Philippines currently have the same standard requirement as the United States: the ASTM has to be followed in order to guarantee the façade typhoon resilience, depending on the importance level of the building. These requirements are indicated in the 2015 edition of the National Structural Code of the Philippines (the same standard references also used in the 2010 edition of the same code). But there are no buildings in the Philippines that installed curtain walls that had been tested according to these standards from the information collected by CTBUH during two years of research activities.

The Philippine test labs do not even have the equipment to conduct the missile impact test, because no client has ever asked to conduct ASTM E1886- and ASTM E1996-compliant tests, although in this region, experts are very familiar with other ASTM standards.

One reason identified for this common-practice non-compliance with the current rules is that these requirements are presented in the structural code, which is not the best location for façade requirements. The façade consultants normally first refer to the building code, but in this document, there is no mention of façade performance standards. Finally, no documentation specific to the curtain wall is required to be presented to the Building Authority, so the decision about whether to test the building envelope, and to what level of performance, is left at the discretion of the building owner.

Therefore, in the Philippines, the requirements to guarantee some façade performance against flying debris are in the improper code (the requirements could be present also in the building code). The lack of a mandatory presentation of the façade test certification to the building authority is causing a self-management of this building technology performances. These are dictated by the budget of the project.

Even the US standards, which are generally considered the most comprehensive and effective testing requirements, lack some critical aspects.

The purpose of the ASTM E1886 and ASTM E1996 standards is to safeguard human life and public and private property, and directly refer to cyclone resistances for the glazing building envelope. If a disaster event affects an urbanized territory, the most important criterion is that the primary healthcare activities are not affected and continue to be available to help people who were injured by a cyclone event. Beginning from the primary activities as hospitals, schools, etc., all the cyclone-prone jurisdictions should have to introduce minimum safety (impact and pressure-cycling testing) requirements for curtain wall performances.

Building envelope failure caused by a typhoon event can have consequences of interior damage, internal pressurization, interruption of business during the renovation period, and can furthermore cause potential mold problems. Another gap identified by this research project is the water-penetration façade requirements. The curtain wall, when hit by a typhoon, has to withstand the incoming pressurized water and it is often not sufficiently water penetration-resistant (CTS 2018).

While US standards are appropriate with regard to the resistance required by the impact glass and the "dry" pressure/vacuum cycles, there is, however, no representative test for "real conditions" that takes into account the penetration of water in regions subject to hurricanes. One major gap in the standards is that the positive and negative pressure-cycling test is conducted in dry conditions, and thus is not completely representative of a real-world condition, where water penetration needs to be considered. Even if a façade system is deemed safe for building occupants, if there is water penetration, this could cause potential damage to interior spaces and future mold problems.

There are already standards that simulate wet conditions (i.e., AAMA 520-12), but there is currently no demand for these tests to be carried out in United States if it is not specified in the building code. In regions where the recorded wind speed was in excess of 50 m/s, most water damage involved envelope damage. For example, in Biloxi, in 2005, despite the apparent integrity of the building envelope of MGM Mirage's Beau Rivage Hotel and Casino, after Hurricane Katrina there was extensive damage due to internal mold problems.

The same issue with water-penetration requirements is highlighted by the report of the Australian Windows Association (AWA) Technical Committee visit to the Cyclone Testing Station at James Cook University (AWA 2017).

In Australia, the National Construction Code (NCC) mandates water-penetration resistance of a façade at typically 30 percent of the positive serviceability limit-state wind load, up to 60 percent for curtain walls. This equates to a water penetration resistance requirement of up to 600 Pa in the worst cyclonic regions for standalone single-family residences. Commercial and high-rise residential buildings may have water-penetration resistance requirements up to approximately 1,200 Pa, which is a challenge to achieve. The design ultimate limit-state wind pressures could be up to 5,300 Pa for housing and in excess of 14,000 Pa for commercial and high-rise residential buildings. If this could even be achieved, it would drive the cost of glazing to unaffordable extents, especially in operable doors and windows typically used in housing.

There is a long history of pressure/water testing procedures available. The venerable Australian Sirowet uses a stepped pressure box with spray nozzlers. More complex pressure signals with high frequency applications have appeared more recently at research institutions like Cincinnati Test Systems (CTS), University of Western Ontario (UWO) and University of Florida (UF), for example. In South Carolina there is a high-level facility run by the Institute for Business and Home Safety (IBHS) that can investigate cyclonic winds, rain, hail and fire in a large 105-fan wind tunnel (Kopp, Morrison & Gavanski 2010).

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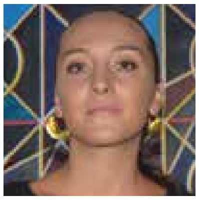

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The Council on Tall Buildings and Urban Habitat (CTBUH) is the world's leading resource for professionals focused on the inception, design, construction, and operation of tall buildings and future cities. Founded in 1969 and headquartered at Chicago's historic Monroe Building, the CTBUH is a not-for-profit organization with an Asia Headquarters office at Tongji University, Shanghai; a Research Office at Iuav University, Venice, Italy; and an Academic Office at the Illinois Institute of Technology, Chicago. CTBUH facilitates the exchange of the latest knowledge available on tall buildings around the world through publications, research, events, working groups, web resources, and its extensive network of international representatives. The Council's research department is spearheading the investigation of the next generation of tall buildings by aiding original research on sustainability and key development issues. The Council's free database on tall buildings, The Skyscraper Center, is updated daily with detailed information, images, data, and news. The CTBUH also developed the international standards for measuring tall building height and is recognized as the arbiter for bestowing such designations as "The World's Tallest Building."

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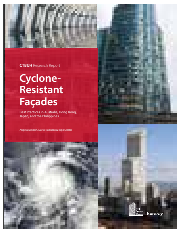

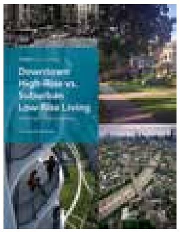

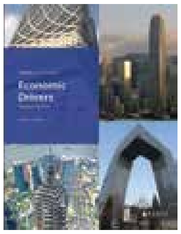

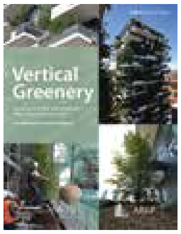

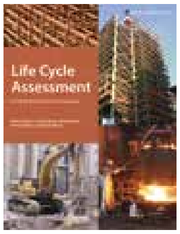

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Alvine Engineering
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Broad Sustainable Building Co.
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Brunkeberg Systems
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CCL
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Enstruct Group Pty Ltd
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EPEXYL S.A.
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FINE DNC
Fletcher Priest Architects
FM Global
Foster + Partners
FXCollaborative
GEI Consultants
GERB Vibration Control Systems (USA/Germany)
GGLO
Gilsanz Murray Steficek
Global Wind Technology Services
Glumac
gmp • Architekten von Gerkan, Marg und Partner GbR
GOA

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Over the past decade, the Asia-Pacific region has seen unprecedented growth in terms of its economy and its urban population. As growth in this area occurs, the demand for additional high-density residential and office space has also increased, resulting in record numbers of high-rise buildings being constructed, concentrated primarily in urban areas. The urban growth in this region has largely occurred in coastal areas, which unfortunately are becoming increasingly vulnerable to cyclones and typhoons. This research report presents the norms and standards of the major tall building markets in 12 jurisdictions within the Asia-Pacific regions (including Australia and New Zealand), for the impact of flying debris on curtain walls during strong wind events in the urban environment. It provides a critical and urgent summary of the gap between the level of risk and the level of regulation concerning façade resilience in these vulnerable, highly populated regions. This report will serve as an indispensable reference document for industries and professionals in the design and renovation of curtain walls, and as a means of presenting tangible examples of the existing best practices in the Asia-Pacific region to developers and building owners.

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