Title: **Cyclone-Glazing and Façade Resilience for the Asia-Pacific Region: Market and Code Study**

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Cyclone-Glazing and Façade Resilience for the Asia-Pacific Region: Market and Code Study

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Abstract

This paper summarizes the Stage 1 results of the CTBUH Research Division's project "Cyclone-Glazing and Facade Resilience for the Asia-Pacific Region." The project was possible thanks to a US$202,000 sponsorship by Trosifol World of Interlayers/Kuraray Group. The core scope of the Stage 1 research was the analysis of existing codes, standards and best practices for the design, construction, and installation of cyclone-resistant curtain walls in 12 cyclone-prone areas. Statistics on the number of tall buildings that have been affected by cyclone events, currently at risk, or are under construction in cyclone-prone areas are presented.

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Introduction

The curtain wall is the primary barrier protecting a tall building and its occupants from external threats, in addition to controlling a building's internal climate and lighting. However, through surveys of buildings constructed after Cyclone Tracy hit Darwin, Australia in 1974, it was evident that damage to glazing systems, caused by wind-borne debris, represented a serious threat to the safety of building occupants during storms, and could contribute significantly to post-event recovery costs. This influenced Australia to develop a building standard with glazing-strength requirements, with the view to preventing future damage, making buildings places of refuge, and instilling a sense of security and safety.

Similarly, Hurricane Andrew, which hit Florida in 1992, became the costliest natural disaster in the history of the United States. In the following years, the Florida Building Code developed curtain-wall provisions, which include strengthening building openings and glass surfaces to limit damage caused by high-velocity winds. This code, and the revisions introduced since, still represents the most demanding in the United States when it comes to impact-resistant façade systems.

Southeast Asia is also affected by storms of similar strength, which are referred to as cyclones or typhoons (see Table 1). Highly-populated jurisdictions, including the Philippines, Vietnam, China, South Korea, and Japan, have been affected by these storms, which are of such magnitude they can 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 new high-rise buildings.

Worldwide, climate-change-induced disasters have been consistently increasing in both frequency and severity over the past 30 years. This has become especially evident following the Hurricane Harvey, Irma and Maria disasters, which destroyed major, highly-populated areas in the United States and the Caribbean between August and September 2017. These areas are still recovering from the damage. Currently, the Asia-Pacific region is the most disaster-prone area in the world, and coastal megacities in this area are extremely susceptible, especially because they are new, and may not have the standards or infrastructure in place to accommodate such an event. Unlike Australia or United States, there is a need to preemptively develop standards for these jurisdictions, before a major storm occurs.

Research Methodology

Initially, 137 documents from 12 locations were identified and analyzed. Of these, 18 were selected for an in-depth review, during which numerous 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. 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.

At the same time, geographic analyses of past storm events and tall buildings were compared using Geographic Information System (GIS) mapping. Using historic cyclone data produced by the United Nations Environmental Program, along with the CTBUH Skyscraper Center database of tall building information, the concentration of tall buildings, the number of buildings that have previously been affected by storm events, and buildings that are currently in threatening areas were identified for a select 12 jurisdictions within or near the Asia-Pacific region (see Tables 2, 3, and 4).

Development of Standards For Cyclone-Resistant Façades

Australia and New Zealand standards

After Cyclone Tracy, the Darwin Reconstruction Commission developed the Darwin Area Building Manual and introduced requirements for all houses to be engineered and designed according to performance tests on building components (DRC 1975). These tests specified that openings had to be resistant to a 4-kilogram, 100-by-50-millimeter mass moving at 20 m/s from any angle, without affecting internal design pressure. The glass could be fractured, but had to withstand this test without penetration. This test was developed to simulate tree branches or other debris that would typically collide with buildings close to ground level during a storm event.

Following the development of these testing requirements, the Experimental Building Station issued the Technical Record 440 (TR440), in which building envelopes in all of Australia were to be tested for resilience against the 4-kilogram timber missile moving at 15 m/s (EBS 1978).

Currently, both Australia and New Zealand follow the testing requirements described in the 2011 edition and subsequent Amendment No. 4 of AS/NZS 1170.2:2011. These included significant increases to the speed of the large (four-kilogram mass) missile, which are now higher than those specified in TR440, and in the United States.

US standards

Following Hurricane Andrew, curtain wall provisions were added to the Florida Building Code, using Australian TR440 as a foundation. These new US specifications built upon the Australian requirements, and now held that the curtain wall had to withstand 9,000 cycles of positive and negative pressure immediately following the impact test. This is an important distinguishing factor, which is not currently included in the AS/NZS 1170.2:2011. During a cyclone event, positive and negative pressure act on the building envelope. Positive internal pressure can develop if the envelope is breached; therefore, such positive/negative tests can more accurately represent the effects of a real storm event. Also, it was determined that curtain walls could still withstand small debris at height, so additional tests with small 2-gram steel balls were developed for curtain walls 9.1 meters or higher above ground level.

<table>
<tr><th>Beaufort Scale</th><th>One-minute sustained winds (km/h)</th><th>Ten-minute sustained winds (km/h)</th><th>Northeast Pacific & North Atlantic</th><th>Northwest Pacific</th><th>Northwest Pacific</th><th>North Indian Ocean</th><th>Southwest Indian Ocean</th><th>Australia & South Pacific</th></tr>
<tr><td></td><td></td><td></td><td>National Hurricane Center/ Central Pacific Hurricane Center</td><td>Joint Typhoon Warning Center</td><td>Japan Meteorological Agency</td><td>India Meteorological Department</td><td>Meteo France's La Reunion Tropical Cyclone Centre</td><td>Australian Bureau of Meteorology/Fiji Meteorological Service</td></tr>
<tr><td>0–7</td><td><59</td><td><52</td><td rowspan="2">Tropical Depression</td><td rowspan="2">Tropical Depression</td><td rowspan="3">Tropical Depression</td><td>Depression</td><td>Zone of Disturbed Weather</td><td>Tropical Disturbance</td></tr>
<tr><td>7</td><td>61</td><td>52–54</td><td rowspan="2">Deep Depression</td><td>Tropical Disturbance</td><td>Tropical Depression</td></tr>
<tr><td>8</td><td>63–69</td><td>56–61</td><td rowspan="3">Tropical Storm</td><td rowspan="3">Tropical Storm</td><td>Tropical Depression</td><td>Tropical Low</td></tr>
<tr><td>9–10</td><td>70–100</td><td>63–87</td><td>Tropical Storm</td><td>Cyclonic Storm</td><td>Moderate Tropical Storm</td><td>Category 1 Tropical Cyclone</td></tr>
<tr><td>11</td><td>102–117</td><td>89–102</td><td rowspan="2">Severe Tropical Storm</td><td rowspan="2">Severe Cyclonic Storm</td><td rowspan="2">Severe Tropical Storm</td><td rowspan="2">Category 2 Tropical Cyclone</td></tr>
<tr><td rowspan="9">12+</td><td>119–131</td><td>104–117</td><td rowspan="2">Category 1 Hurricane</td><td rowspan="8">Typhoon</td></tr>
<tr><td>133–152</td><td>119–133</td><td rowspan="8">Typhoon</td><td rowspan="3">Very Severe Cyclonic Storm</td><td rowspan="3">Tropical Cyclone</td><td rowspan="3">Category 3 Severe Tropical Cyclone</td></tr>
<tr><td>154–176</td><td>135–154</td><td>Category 2 Hurricane</td></tr>
<tr><td>178–180</td><td>156–157</td><td rowspan="2">Category 3 Major Hurricane</td></tr>
<tr><td>181–207</td><td>159–181</td><td rowspan="3">Extremely Severe Cyclonic Storm</td><td rowspan="3">Intense Tropical Cyclone</td><td rowspan="2">Category 4 Severe Tropical Cyclone</td></tr>
<tr><td>209–226</td><td>183–198</td><td rowspan="3">Category 4 Major Hurricane</td></tr>
<tr><td>228–239</td><td>200–209</td><td rowspan="3">Category 5 Severe Tropical Cyclone</td></tr>
<tr><td>241–252</td><td>211–220</td><td rowspan="2">Super Cyclonic Storm</td><td rowspan="2">Very Intense Tropical Cyclone</td></tr>
<tr><td>>254</td><td>>220</td><td>Category 5 Major Hurricane</td><td>Super Typhoon</td></tr>
</table>

Table 1. Tropical cyclone classifications used by jurisdictions throughout the Asia-Pacific region, showing relative measures of severity.

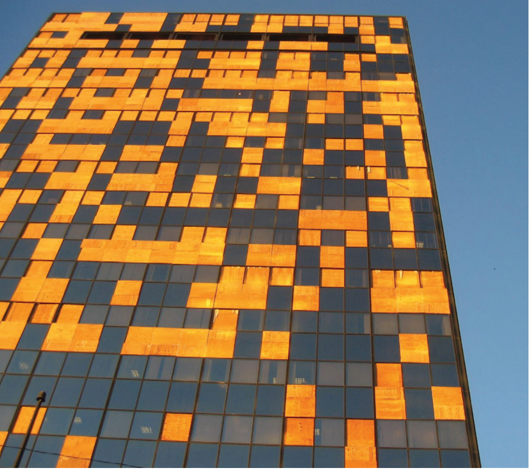

Figure 1. Brickell Avenue, Miami (2006) – plywood repair after Hurricane Wilma damaged the Colonial Bank building. © Jordan Fischer (cc by-sa)

As the Florida Building Code was developed, the product approval program was developed, with the Notice of Acceptance (NOA) ensuring all curtain wall products meet the façade performance requirements specified in the Testing Application Standard (TAS) procedures (ICC 2017b). Currently, it is widely accepted in the curtain wall industry that the impact and pressure cycling testing requirements found in the Florida Building Code are the most stringent and most representative of a real cyclone event.

According to ASCE/SEI 7-16, ASTM E1886 and ASTM E1996, testing requirements must be followed if the building falls within windborne debris regions or hurricane-prone regions, which are specified in wind zone maps. The ASTM E1886 and E1996 requirements are closely related to the previously developed TAS in 1994 (ICC 2017b). The ASTM added further conditions to the testing procedure (such as temperature of the test specimen). The ASCE also specifies that if local standard testing requirements are stricter, buildings must follow local standards (ASCE 2017).

When Florida was hit by Hurricane Wilma in 2005, it represented the first opportunity to truly verify if the prior testing regulations were successful. The Post-Hurricane Wilma Progress Assessment was published in 2006, and proved that the majority of buildings constructed under the most recent building code suffered no damage (Miami-Dade County 2006). In only a few isolated incidents were building envelopes breached and damage caused by water intrusion and internal pressurization (see Figure 1). After the survey, there was a clear indication that construction projects that used laminated glass and followed the new testing standards were much more resistant to storm events, compared to older projects, which were heavily damaged. Currently, there are several additional surveys in development to further reinforce the success of the standards, following an assessment of the damage from Hurricanes Harvey and Irma.

International standards

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

Other Asia-Pacific standards

Looking at the 12 jurisdictions analyzed in this research, only two outside of Australia and New Zealand have introduced standard testing procedures for typhoon-resistant glazing systems: Bangladesh and the Philippines (see Table 2). These standards also reference the ASTM standards, despite their geographic location being closer to Australia, which may have more regionally appropriate requirements. Furthermore, although China and India have been – and continue to be – affected by typhoons, they have not introduced any kind of requirements to ensure the safety of people and property.

Cyclone-Resistant Façade Technologies

In the ASTM E1886 and ASTM E1996 testing procedures and the Miami-Dade County product approval process, the aim is not just for the components, but the entire curtain wall system, to be tested. The success of the system can be significantly impacted by the characteristics of the glass, the interlayer for glass lamination, and the fastening method chosen. This entire system must pass the impact tests, and the subsequent application of pressure cycle tests, before it can be approved and used in a construction project.

The thickness of the glass in laminated curtain wall systems is determined by the wind load and the interlayer type. However, the resistance to penetration by missile impact is almost entirely reliant on the interlayer type and its thickness. Laminated systems utilize two or more layers of glass, separated by one or more interlayer elements, which can ensure glass retention if breakage occurs. The primary types of interlayers used are polyvinyl butyral (PVB) and ionoplast. PVB is typically used for relatively small glass panels and low pressures and is typically 2.28 millimeters thick for large-missile impact resistance applications, and 1.52 millimeters thick for small-missile impact resistance. Ionoplast is typically used for high design pressures, large windows, and large missile impacts; it can be used in dry-glaze systems, which are lower-cost and easier to install, Ionoplast is also 100 times stiffer than PVB, five times more tear-resistant, and less sensitive to moisture intrusion at the laminate edge.

Similar to the Post-Hurricane Wilma Progress Assessment, the "Performance of Laminated Glass During Hurricane Wilma in South Florida" study was published in 2006, with the aim to survey buildings that utilized laminated glass systems and were in the path of Hurricane Wilma (Beers & Alzamora 2006). Eighty-two properties were surveyed, and 71% showed absolutely no damage, with 18% reporting broken glass but no overall glazed system failure. The remaining 11% did not respond.

Threats to the Asia-Pacific Region

Economy and population

From 1990 to 2016, the GDP of the Asia-Pacific region has experienced an incredible increase, and now, Australia, Hong Kong, Japan, and South Korea are some of the jurisdictions that have the highest GDP PPP (gross domestic product based on purchasing power parity) globally (see Table 3).

Alongside the economy, the Asia-Pacific region has also seen unprecedented growth in urban population (see Table 4). 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.

This area has recently seen the emergence of a new urban typology: the megacity. 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 regional economy.

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, 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. With the geographic and time data for 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 located in 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 of 150 meters' or greater height within the 12 select developing jurisdictions have experienced at least one cyclone event. Many of these buildings 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. Currently, more than double the amount of buildings (3,987) are now built in these same areas that have experienced a cyclone event in the past, with a further 582 currently under construction in these areas. In this analysis, 7,086 complete or under-construction buildings were examined. More than half of those (4,569) are located in typhoon-prone areas.

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 (see Table 5 and Figure 2)

Problems and Gaps in Existing Standards

The first – and perhaps most obvious – problem with cyclone-resistant curtain wall requirements is that there are many growing

	Code/standard requirements
Australia	AS/NZS 1170.2
Bangladesh	ASTM E1886, ASTM E1996
China	None
Hong Kong	None
India	None
Japan	None
New Zealand	AS/NZS 1170.2
Philippines	ASTM E1886, ASTM E1996
South Korea	None
Taiwan	None
Thailand	None
Vietnam	None

Table 2. Asian jurisdictions' cyclone-glazing test requirements. Sources: ASEP 2010 and HBRI 2014.

	GDP (2016, million US$)	GDP per capita (1990, US$)	GDP per capita (2016, US$)	GDP, PPP per capita (2016, US$)	GDP, PPP per capita (2016, world ranking)
Australia	1,204,616.44	18,249.00	49,927.00	46,789.90	17
Bangladesh	221,415.28	297.00	1,358.00	3,580.70	137
China	11,199,145.16	317.00	8,123.00	15,534.70	70
Hong Kong	320,912.24	16,485.00	43,681.00	58,552.70	8
India	2,263,522.52	363.96	1,709.00	6,572.30	113
Japan	4,939,383.91	25,417.00	38,894.00	41,469.90	22
New Zealand	185,017.32	13,663.00	39,426.00	39,058.70	24
Philippines	304,905.41	715.00	2,951.00	7,806.20	111
South Korea	1,411,345.59	6,516.00	27,538.00	35,750.80	29
Thailand	406,839.68	1,508.00	5,907.00	16,916.50	64
Vietnam	202,615.89	98.00	2,185.00	6,424.10	117
Key:	PPP = Purchasing Power Parity		GDP= Gross domestic product		

Table 3. The GDP of the Asia-Pacific studied jurisdictions (Taiwan data not available). Source: The World Bank

	Total population (1960, millions)	Urban population (1960, millions)	Total population (2016, millions)	Urban population (2016, millions)	Increase of urban population (from 1960 to 2016, millions)	Average increase of urban population (from 1960 to 2016, millions)
Australia	10,276.48	8,378.31	24,127.16	21,606.84	13,228.53	8.03%
Bangladesh	48,199.75	2,475.06	162,951.56	57,090.08	54,615.02	29.90%
China	667,070.00	108,085.35	1,378,665.00	782,778.41	674,693.06	40.58%
Hong Kong	3,075.61	2,620.41	7,346.70	7,346.70	4,726.29	14.80%
India	449,480.61	80,564.90	1,324,171.35	438,777.42	358,212.52	15.21%
Japan	92,500.57	58,526.96	126,994.51	119,283.40	60,756.44	30.66%
New Zealand	2,371.80	1,802.52	4,692.70	4,050.83	2,248.31	10.32%
Philippines	26,273.03	7,959.94	103,320.22	45,759.49	37,799.55	13.99%
South Korea	25,012.37	6,930.93	51,245.71	42,324.85	35,393.92	54.88%
Thailand	27,397.17	5,389.57	68,863.51	35,492.25	30,102.68	31.87%
Vietnam	34,743.00	5,107.22	92,701.10	31,737.15	26,629.93	19.54%

Table 4. Total and urban population data for Asia-Pacific studied jurisdictions (Taiwan data not available). Comparison 1960–2016. Source: The World Bank

	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	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	3 (81.3%)	78	102	12
Thailand	4 (25.7%)	0	0	0
Vietnam	7 (48.7%)	9	102	57

Table 5. Asia-Pacific jurisdictions' tall building development and average typhoon occurrences. December 2017. Sources: Prevention Web, UNEP/UNISDR, and CTBUH.

jurisdictions that do not account for them 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.

Even in jurisdictions such as Australia and New Zealand, it is accepted by the panel of experts involved in this CTBUH research project that amendments must be made to AS/NZS 1170.2:2011 and to its Amendment No. 4 during the next revision process. The increased timber projectile velocities (from 15 m/s to 31–50 m/s, depending on location and building importance) nominated in AS/NZS 1170.2:2111 have caused cyclone debris impact resistant glazing to be too expensive for consideration in residential or commercial buildings. These current, excessive speeds can lead to over-engineering the curtain wall system and incorporation of other cyclone-resistant building features, such as shutters, which are unnecessary in many cases. Furthermore, the cyclic pressure test, which immediately follows the missile impact test in the US standards, is considered a good representation of the effect of real storm events, but is still missing from Australia and New Zealand codes.

Even the US standards, which are generally considered to contain the most comprehensive and effective testing requirements, lack some critical aspects. 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 the United States if it is not specified in the building code. The same issue with water penetration requirements is highlighted by the experience of the Australian AWA Technical Committee visit to the Cyclone Testing Station at James Cook University (Harris 2017); and the Technical Report No. 63 on Tropical Cyclone Debbie (CTS 2017). In regions in where the recorded wind speed exceeded 50 m/s, most water damage was a result of the envelope being defeated.

Another amendment that should be considered for all standards is to increase the requirements for tall buildings, which are often close to each other. If there is a failure of a building component at height, this could launch projectiles at neighboring structures, so it may be necessary to increase the testing requirement from small to large missiles. In addition, with sky gardens and balconies at height becoming more common in tall buildings, the large-missile impact tests may also become mandatory for the entire glazed envelope of a building.

Conclusion

The curtain wall is a building component that continues to undergo innovations. Performance upgrades can help reduce the vulnerability of occupants and property to natural disasters. With the appropriate application of cyclone-resistant systems, tall buildings can serve as refuges for building occupants, instead of remaining urban features that need to be evacuated or risk damage. In Miami-Dade County, Florida, through the effectiveness of the applied standards, curtain wall systems have proven to be cyclone-resistant. Still, it took a major disaster (Hurricane Andrew) before Florida developed local building codes to prevent damage in the future, even though Australia had undergone a similar disaster and implemented similar measures almost 20 years prior, with Cyclone Tracy and Australian TR440.

As mentioned, there are many cities and buildings that are in areas extremely prone to major storms, but there are no standards that dictate their resilience against these threats. How much do these economies and populations need to grow before standards are created? The local authorities in Asia-Pacific jurisdictions should specify a timeline for development of their façade requirements before it is too late.

CTBUH was pleased to launch the second phase of this important research project in January 2018. The research will investigate the current problems and existing solutions for cyclone-resistant façades in the Asia-Pacific region, with the goal of creating a CTBUH Technical Guide, ***Strong Wind- and Cyclone-Resistant Façades: Best Practices.*** To accomplish this, the study will examine specific case studies for new and existing buildings in Australia, Hong Kong, Japan, and the Philippines.

CTBUH member firms are encouraged to participate in this research by joining the steering committee and acting as peer reviewers. For more information, contact research@ctbuh.org. ■

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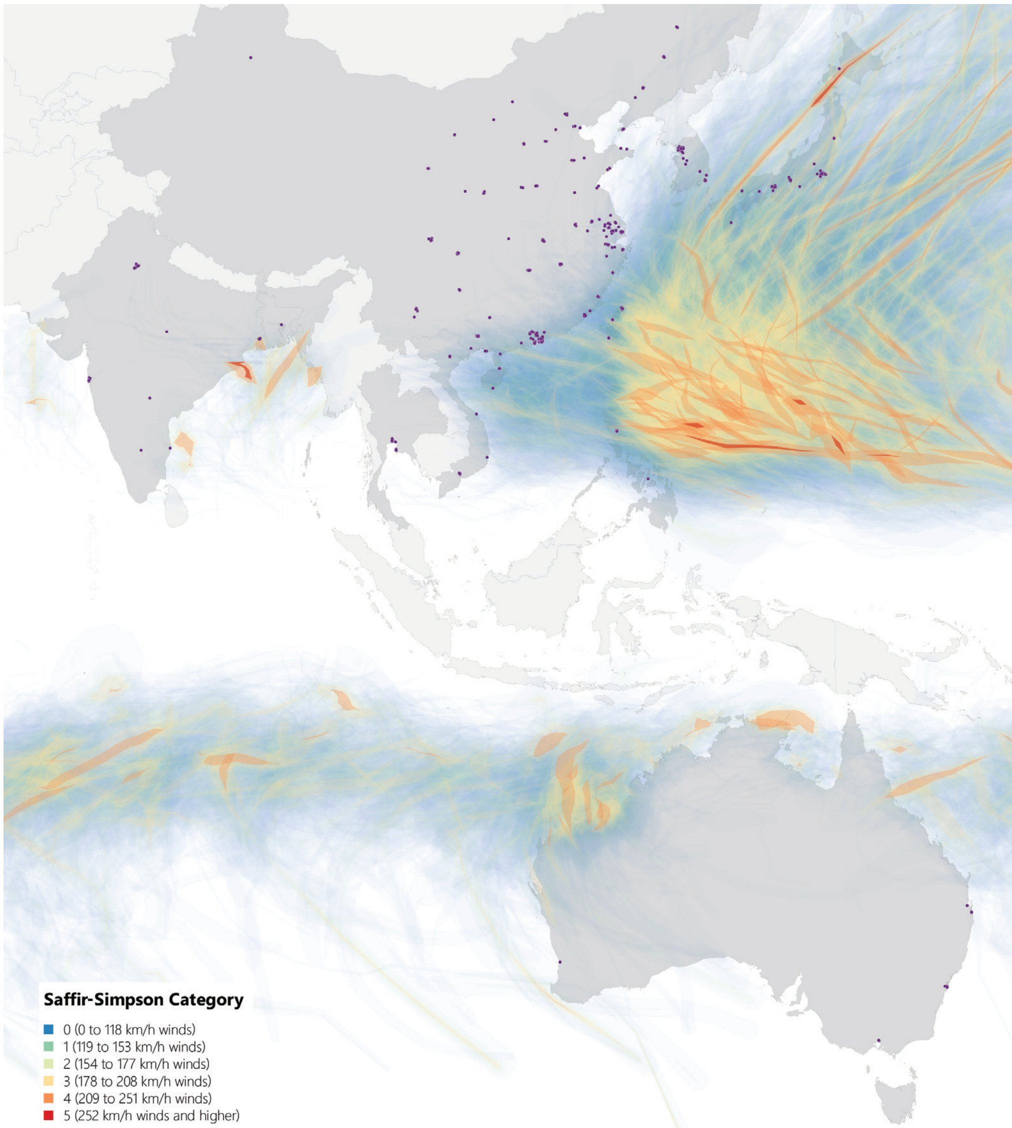

Figure 2. Cities in the Asia-Pacific region with at least one 150-meter-plus building, cross-referenced with historical average of cyclone wind speeds.