ABSTRACT

This paper discusses recent wind-induced damage to buildings and structures, including that due to tropical cyclones and severe local storms. It emphasizes the importance of design of cladding and components to minimize wind-induced damage to buildings. Some special features of wind-induce damage such as coherent phenomena and damage chain, the role of wind-borne debris developing damage, and climate change problems are discussed. Finally, the necessity for collaboration among multiple academic associations for different natural disasters and among academic societies and non-academic organizations working on disaster risk reduction are emphasized, and the launch of the International Group for Wind-related Disaster Risk Reduction under the umbrella of the UN/ISDR is introduced.

KEYWORDS: WIND-INDUCED DAMAGE, TROPICAL CYCLONE, TORNADO, WIND-BORNE DEBRIS, INTERNATIONAL COOPERATION, WIND-RELATED DISASTER, DISASTER RISK REDUCTION

Introduction

Katsura et al. (1992) reported that 80% of the 63 fatalities due to Typhoon Mireille, which struck Japan in 1991, were male, and more than 70% were over 60 years old. The causes of death were 31% blown by wind, 30% caught under collapsed or blown obstacles, and 23% hit by wind-borne debris. Fukumasa (1992) reported interesting statistics on the number of fatalities in Japan due to 114 typhoons in the 40 years from 1951 to 1990. The number of fatalities significantly reduced in more recent years, and this might be attributed to improved wind resistant design and construction technologies and also to development and improvement of weather forecasting methods and information transferring technologies.

However, wind-induced damage to buildings and structures, agricultural and forestry products, and so on are still very severe. The property insurance money paid was almost 6 billion US$ for Typhoon Mireille in September, 1991, 18 billion US$ for Hurricane Andrew in August, 1992, and almost 8 billion US$ for 10 typhoons that attacked Japan in 2004. Hurricane Katrina killed 2,541 people in August, 2005 and caused 28 billion US$ economic loss in the US, Cyclone Sidr in November, 2007 killed 4,234 people and caused 1.7 billion US$ economic loss in Bangladesh, and Cyclone Nargis in May, 2008 killed 138,366 people and caused 10 billion US$ economic loss. Very recently, Typhoon Morakot struck Taiwan and neighboring countries in August, 2009, and fatalities and missing numbered 732. It recorded 2,888mm integrated rainfall over four days in Chiayi Province, Taiwan. Almost all of these disasters resulted from the combined effects of strong wind and accompanying water hazards due to heavy rain and storm surge. The social impacts caused by these “wind-related” disasters were some of the most severe in our human society.

There are many emerging issues to be tackled by researchers and engineers in our wind engineering field in order to reduce “wind-related” disaster risk and to realize safer and secure communities worldwide.
Wind Climates and Strong Wind Characteristics

Wind Climates to be Considered in Building Design

Wind is fundamentally caused by the temperature gradient of the atmosphere due to variable solar heating of the earth’s surface. It is initiated, in a more immediate sense, by density difference or pressure gradient between points of equal elevation. Large-scale air flows are so-called global atmospheric circulations, and generation of strong winds is closely related to these circulations, and also to smaller scale temperature differences. There are several wind climates that might result in strong wind, e.g. monsoons, frontal depressions, tropical cyclones, gust-front, downburst, tornadoes, devils, gravity winds (katabatic winds), lee waves, and so on. Monsoons are seasonal winds, and develop around thermally produced continental highs in winter and lows in summer. Tropical cyclones are intense cyclonic storms that occur over tropical oceans, mainly in summer and early autumn. They are known as typhoons in the Far East, cyclones in the region of Australia and the Indian Ocean, and hurricanes in America, with different definitions. A typhoon, for example, is a tropical cyclone whose maximum mean wind speed near the center is greater than 17 m/s. The diameters of tropical cyclones are between 100 km and 2000 km, but usually of the order of several hundred kilometers. The thickness of the atmosphere involved is about 10 - 12 km. From the ratio of diameter to thickness, it is understandable that the entire rotating body of a tropical cyclone is like a “compact disc”. A roughly circular “eye”, or “hot tower”, is formed in the center of the storm. The air inside the eye is relatively dry and light, and rises slowly near its perimeter. Outside the eye wall, there is a vortex in which warm, moist air is convected at high altitude and forms tall convective clouds. Spiral rain-band clouds are often seen near the outside of the vortex. It should be noted that tropical cyclones are often accompanied by severe local storms such as tornados and downbursts.

Characteristics of Strong Winds

The famous power spectrum by van der Hoven (1957) is shown in Fig.1. Two clear peaks can be seen. One is the so-called “macro-meteorological peak”, which shows energy concentration for a period of around 4 days, and the other is called the “micro-meteorological peak”, which has an energy peak for around 1 min (Cook, 1985).

![Figure 1: Van der Hoven Spectrum (1957) of Wind Speed in a Wide Frequency Range (Tamura, 2005)](image)

The former is related to movement of a large-scale weather system due to global circulations. The latter is related to turbulence caused by topographic effects, terrain roughness, obstacles around the site and so on. The frequency range between the two peaks
contains almost no energy. This range is called the “spectral gap”, which separates the two different frequency ranges of the wind fluctuation. The commonly used averaging time, e.g. 10min or 1hr, lies within this range. The wind fluctuation in the micro-meteorological peak should be taken into account in evaluating dynamic wind forces in building design. However, the wind fluctuation in the low-frequency range including the macro-meteorological peak can be taken as the variation of the mean wind speed in building design. Incidentally, the van der Hoven spectrum has “a half-day peak”, but it misses another important peak that is generally observed in many cities. That is the “one-day peak” basically due to a 1-day cycle of solar heating, which provides a periodic change of sea wind and land wind (Tamura, 2005).

The simplest descriptor of atmospheric turbulence is turbulence intensity, which is an important parameter, in both estimating buffeting responses of buildings and interpreting fluid-structure interaction. The turbulence intensity is the ratio of the fluctuating component in terms of the standard deviation of a wind speed component $\sigma$ to the mean wind speed $U$, i.e. $\sigma/U$. Incidentally, Cao et al. (2007) observed very high wind speed records exceeding 90m/s as a peak gust by seven sonic-anemometers and nine vane-anemometers set at heights of around 15m - 16m in an experimental site for power transmission cables in Miyakojima Island in Okinawa Prefecture, Japan, during a very strong typhoon, Maemi, in 2003. After a careful check of the reliability of these anemometers using a wind tunnel, they analyzed only wind speed records not exceeding 90m/s as peak gusts for vane-anemometers, and not exceeding 60m/s for sonic-anemometers. Consequently, the maximum 10min-mean wind speeds analyzed were 60.1m/s and 39.2m/s for vane-anemometers and sonic-anemometers, respectively, and the maximum peak wind speeds analyzed were 80.5m/s and 59.8m/s for vane-anemometers and sonic-anemometers, respectively. Figure 2 shows the variation of the turbulence intensity of the longitudinal component, $I_u$, with 10min-mean wind speed $U$ (Cao et al., 2007). The turbulence intensity is around 0.2 for $U \approx 10$m/s and gradually decreases with mean wind speed and 0.14 for $U \approx 40$m/s. The proportion of the three wind speed fluctuating components, $\sigma_u$, $\sigma_v$, and $\sigma_w$, and the friction velocity $u*$, are reported at $\sigma_u : \sigma_v : \sigma_w = 2.5 : 2.1 : 1.4 : 1.0$ for the sonic records (Cao et al., 2007), which is almost the same as the results, $\sigma_u : \sigma_v : \sigma_w : u* = 2.5 : 2.0 : 1.3 : 1.0$ reported by Teunissen (1970), and $\sigma_u : \sigma_v : \sigma_w = 2.6 : 2.0 : 1.3$ by Counihan (1975).

![Figure 2: Variation of Turbulence Intensity, $I_u$, with 10min-mean Wind Speed $U$ during Typhoon Maemi in 2003 (Seaside, Sonic Anemometers, Cao et al., 2007).](image1)

![Figure 3: Variation of Longitudinal Turbulence Scale, $L_{ux}$, with 10min-mean Wind Speed $U$ (Seaside, Sonic Anemometers, Cao et al., 2007).](image2)
Figure 3 shows the variation of longitudinal turbulence scale, $L_{ux}$, with 10min-mean wind speed $U$. The turbulence scale $L_{ux}$ lies around 50m for $U \approx 10$m/s and gradually increases with mean wind speed and reaches around 100m for $U \approx 40$m/s. The averaged ratios of turbulence scale among the turbulence components measured at 15m height are $L_{ux}/L_{vx}/L_{wx} = 5.5/2.3/1.0$. The gust factor $G_u = U_{max}/U = (U+u_{max})/U$ and peak factor $g_u = u_{max}/\sigma_u$ were roughly 1.6 and 3.3, respectively (Cao et al., 2007). Skewness and Kurtosis were 0 and 2.9 and there was no significant effect of the wind speed level (Cao et al., 2007). The Karman spectrum can approximate the wind speed spectra and no significant difference was recognized in the turbulence characteristics of the very strong typhoon data compared to those of synoptic winds.

**Mean Wind Speed Profile of Strong Winds**

Figure 4 compares the mean wind speed profiles of eye wall winds and outer vortex winds based on the profiles given in Powell et al. (2003) and Franklins et al. (2000), respectively, obtained by GPS drop sondes for deep water and open sea conditions. The maximum wind speed appears at around 500 - 600m for eye wall winds and around 900 - 1000m for outer vortex winds. A similar result was obtained by Hayashida et al. (2002) for an open flat terrain using Doppler radars for typhoon eye wall winds showing maximum wind speeds of around 600 - 700m.

In summary, wind-speed profiles near the ground can be approximated by logarithmic-law or power-law both in the eye wall region and in the outer vortex region. Above the sea, the average feature of the gradient heights is basically around 500 - 700m for the eye wall region and 900m or higher for the outer vortex region. There is not enough evidence to conclude that there is a very thin gradient height in tropical cyclone winds. Below 500m, there is no significant difference between the wind-speed profiles in the eye wall and the outer vortex regions.
**Wind-induced Damage to Buildings and Structures**

*Recent Damage due to Typhoons in East Asia*

Several recent typhoons have caused severe wind damage to structures in East Asia. Figure 5 shows damage to the membrane roof of a soccer stadium in Cheju Island, Korea, in August, 2002. Figure 6 shows collapses of power transmission towers near Tokyo in October 2002 caused by Typhoon Higos. The maximum peak gust of 56.7m/s was recorded at the top of the adjacent tower. Precise investigations were made on the reason for these collapses. The wind speed was judged to be less than but close to the design value. The reason was determined to be the poor capability of the friction force of the piles, for which the grout supply method was not appropriate.

![Figure 5: Wind-induced Damage to Soccer Stadium on Cheju Island, Korea (Typhoon Rusa, 2002)](image)

![Figure 6: Collapse of Power Transmission Towers (Typhoon Higos, 2002)](image)

![Figure 7: Damage to Wind Energy Facilities on Miyakojima Island (Typhoon Maemi, 2003)](image)
Typhoon Maemi in 2003 caused severe wind damage on Miyakojima Island, Japan and in Busan, Korea. Figure 7 shows damage to wind energy facilities in Miyakojima Island, while Fig. 8 shows damage to buildings in Busan, Korea. According to the Miyakojima Island Meteorological Station, the maximum 10min-mean wind speed was 34.8m/s, and the maximum peak gust was 74.1m/s, which was the 10th highest recorded in Japan. The lowest pressure was 912 hPa, which was the 8th lowest recorded in Japan. In addition, Miyakojima Self-defense Force had a record of the maximum peak gust of 87m/s, and Cao et al. (2007) analyzed very high wind speed records as mentioned before, see Figs. 2 and 3.

The roofing system of a huge structure called SPring-8 was damaged by Typhoons Chaba (August 30, 2004) and Songda (September 7, 2004), as shown in Figs.9 and 10(a). The plan of the building is donut-shaped. It is approximately 1500m in circumference and 30m in width, and was completed in 1997. The roofing system consists of two-layer folded steel plates with thermal insulating materials between them, and the trough and ridge lines of the folded plates are in the radial direction. The south side of the roof was damaged over an area 270m long by 10m wide by typhoon Chaba, and the east side of the roof was damaged over an area
100m long by 10m wide by typhoon Songda. According to precise post-disaster investigations, the damage was attributed to the fatigue effect on the bolts connecting the roofing system to the tight frames due to daily solar heating effects on the upper layer. The typhoon wind revealed the hidden fatigue damage to the roofing system (Tamura et al., 2005). The main reason for the wind damage was that the roof was designed and constructed without a careful check of the ability of the sliding movement of the upper folded steel plates, so the effect of the repetitive load on the bolts was ignored.

Figure 10: Damage to Roof System due to Typhoon Songda, 2004

Figure 10(b) shows another example of damage to steel roof systems due to the same typhoon, Songda in 2004. Similar damage is often observed to long-span roofs such as gymnasiums, which should survive strong winds and be places of refuge. Special attention has to be given to the cladding/component design and construction of steel plate type roofing systems.

**Recent Damage due to Severe Local Storms in Japan**

In the year from December 2005 to November 2006, there were three tornados in Japan that caused fatalities, as shown in Table 1. Two very rare events, train accidents, occurred in series due to tornados in that one year.

<table>
<thead>
<tr>
<th>Date</th>
<th>Place</th>
<th>Events</th>
<th>Fatalities</th>
</tr>
</thead>
<tbody>
<tr>
<td>December 25, 2005</td>
<td>Shonai, Yamagata</td>
<td>F1</td>
<td>5</td>
</tr>
<tr>
<td>September 17, 2006</td>
<td>Nobeoka, Miyazaki</td>
<td>F2</td>
<td>3</td>
</tr>
<tr>
<td>November 7, 2006</td>
<td>Saroma, Hokkaido</td>
<td>F3</td>
<td>9</td>
</tr>
</tbody>
</table>

At 19:14JST on December 25th, 2005, a JR limited express “Inaho No.14” of 6 cars was overturned and derailed by a strong gust as shown in Fig.11(a). Fatalities numbered 5, and 33 people were injured. The train was running from north to south under strong wind conditions with 10min-mean wind speeds of around 20m/s. The accident site was in open flat
country covered by snow around 50cm deep. The footprint of the wind-induced damage to
trees, green houses and wooden residential houses extended over an area 12km long by 20 -
40m wide, starting at the Sea of Japan coast and heading ENE. The damage scale was
estimated at F1. A low-pressure area developed in the Sea of Japan accompanied by a
southward movement of a cold air mass, and a cold front extended from this low pressure area.
The convection current was very strong, and the wind-damaged area corresponded to a pre-
frontal line of cumulonimbus that formed on the south side of the cold front. A strong and
developed radar echo was observed just above the damaged area. This was a typical type of
tornado observed in winter in Japan, especially in the west coast region facing the Sea of
Japan. An anemometer at the seashore recorded a peak gust of 36.9m/s at 19:06 on December
25. Steel snow fences 5km inland were damaged at 19:08, and the train accident occurred at
19:14 10.5km inland. The Meteorological Agency has not concluded whether the strong wind
event was due to a tornado or a downburst. However, the pattern of damage to a farm
appliance shed located just upstream of the train accident point suggested that it was a tornado
rather than a downburst. The wind speed estimated from the damage to steel snow fences was
39 - 40m/s. The train was running at 105km/h, which was slower than usual because of the
strong wind. Only the first car was struck by the gust, and it overturned, dragging the
following cars with it. The first car weighed 43ton, and the critical overturning wind speed for
this car running at 105km/h is estimated to be in the range of 40 - 45m/s.

At 14:05JST on September 17, 2006, the first and the second cars of a JR limited
express “Nichirin No.9” of 5 cars overturned due to a strong gust in Nobeoka-city, Miyazaki
Prefecture, as shown in Fig.11(b). These cars were the same type as those of Inaho No.14.
The train was running at a slow speed of 25km/h because of the strong wind warning, and the
driver noticed a swirling wind with a lot of flying debris approaching the railway obliquely
from the left front. Then, immediately after the driver stopped the train, the first car
overturned, dragging the second car with it. Thus, the train speed was estimated at almost zero,
and slight injuries to only 5 people were reported. However, the damage scale was estimated
at F2, and the wind speed was apparently higher than in the case of ‘Inaho No.14’. The 150 -
250m-wide damage footprint extended over 7.5km in a residential and urban area in
Nobeoka-city from the Pacific coast. Fatalities due to this tornado numbered 3. They were due
to shock, flying debris and being buried under a display case. The moving speed of the
tornado was estimated at 25m/s. This is a typical tornado observed in summer or autumn in
Japan, which is often accompanied by typhoons. Tornadoes tend to appear in the Northeast
quadrant of typhoons under a group of cumulonimbus called ‘tapering clouds’ at the outer rim of rain bands. According to observations of falling grave stones and damage to buildings and structures, peak gusts of 55 m/s can be estimated. The houses in Fig.12 suffered severe damage from flying debris during a tornado that occurred in 2005 and 2006 in Miyazaki, Japan.

Figure 13 shows an aerial view of the footprints of tornado damage in Saroma-cho, Hokkaido, on November 7, 2006. Nine people holding a meeting on the second floor of a construction site office building were killed. The construction site office building and neighboring buildings were blown over and crashed to the ground. The moving speed of the tornado was estimated at 76 km/h, i.e. 21 m/s, (Suzuki, 2007).

**Actions Taken after Recent Tornado Damage**

Severe local storms such as tornados and downbursts are known to occur mainly over large continental plains in countries such as the US. They cause the severest wind damage to human society. However, even in Japan, more than 20 tornados are reported every year, according to Niino et al. (1997). Considering the small land area of Japan less than 1/20 that of the US, more than 20 tornados per year is not small. However, for an individual building, the probability of being hit by a tornado is very low: the annual probability is $2.61 \times 10^{-5}$ (Tamura et al., 2008) which is almost once every 38,000 years. Thus, it is not rational to design general buildings against tornadoes, but how to save lives is an important issue. A system for predicting tornado events and warning the public should be developed for saving lives, i.e. a now-cast system for severe local storms. Incidentally, the annual probability of an individual city being hit by a tornado is estimated at $1.4 \times 10^{-3}$, i.e., and event happens every 700 years (Tamura et al., 2008). As shown in Fig. 11, train accidents due to severe local storms happen occasionally. It is roughly estimated that almost 8 tornados cross the railways every year in Japan (Tamura et al., 2008). Of course, even if a tornado crosses a railway line, it does not necessarily cause a train accident. That depends upon the wind speed, the train speed, the car number hit by tornado, and so on. Severe local storm-induced train accidents happen almost every four years in Japan. The probability of a tornado hit for line-like structures such as railways, power transmission lines and so on may be larger than that of general buildings. The operating system of the mass transportation systems, buildings and facilities having a particular social importance or containing dangerous materials should take tornado effects into account, e.g. railway systems, airports, computer/data centers, nuclear power plants, containers of radioactive material/wastes and so on. (Tamura et al., 2008).

After the train accident shown in Fig.11(a), a proposal addressed to the Minister of Land Infrastructure and Transport and the Minister of State for Disaster management was laid before the public by the Japan Association for Wind Engineering (JAVE) on April 24, 2006. This proposal emphasized the necessity of stationing Doppler radars at several places to cover almost all tornado- and downburst-prone regions along seashores and in urban areas in Japan. It recommended establishing a Doppler radar network, and developing a ‘now-cast’ technique for predicting tornados and downbursts within several tens of minutes based on the analysis results of data obtained by Doppler radars. It also recommended creating an efficient system for disclosing data and necessary information to local governments, mass transport authorities, power plants, mass media, and researchers. Research projects should be aimed at minimizing disasters due to small-size strong wind events, which are not necessarily the same as those in the US or Australia.

Corresponding to those actions by JAVE, the Japan Meteorological Agency decided to initiate an early warning system for severe local storms mainly targeting tornados on March 26, 2008. The running control rule of JR is also being reviewed, and various measures are being taken to cope with situations due to tornadoes and downbursts. (JR East, 2006).
Figure 12: Damage Marks by Wind-borne Debris due to Tornados (Tamura, 2007)

Figure 13: Damage Footprints in Saroma-cho in Hokkaido due to Tornado on November 7, 2006 (Tamura, 2007)

<table>
<thead>
<tr>
<th>Wind speed (10m above ground)</th>
<th>3s gust</th>
<th>Phenomena/Damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>5m/s 7~10m/s</td>
<td></td>
<td>- Vortex resonance/fatigue damage of truss members</td>
</tr>
</tbody>
</table>
| 10~15m/s 15~20m/s             |         |  - Handrail vibration/wind-induced noise  
  - Vortex resonance of steel chimneys  
  - Vibration perception in flexible high-rise buildings |
| 20m/s 30m/s                   |         |  - Seasickness and discomfort in high-rise buildings  
  - Damage to garage shutters  
  - Falling down of pedestrians |
| 25m/s 40m/s                   |         |  - Damage to roof tiles  
  - Damage to window panes due to wind-borne debris |
| 30m/s 45m/s                   |         |  - Collapse of RC block fences  
  - Damage to steel sheet roofing  
  - Overall roof lift-off  
  - Falling down of gravestones |
| 35m/s 50m/s                   |         |  - Damage to window panes due to wind pressure of high-rise buildings  
  - Blown over of heavy tombstones |
| 40m/s 60m/s                   |         |  - Damage to cladding of high-rise buildings  
  - Limit of allowable distortion of external sealing compounds |
| 45m/s 70m/s                   |         |  - Main frame stresses in high-rise buildings exceed elastic limit |
**Wind-induced Phenomena/Damage**

Various phenomena occur to buildings and their surroundings during strong winds, sometimes leading to failure. Table 2 summarizes wind-induced phenomena/damage and their onset wind speeds (Tamura, 2005). It should be noted that the damage depends not only on wind speed but also on the strength or quality of structures, and the phenomena/damage in the table can be different.

**Various Features of Damage to Building Elements**

(a) Roofs

Damage to roofs of wooden or steel-framed houses occurs either directly or is triggered by breakage of openings. Most damage to roofs themselves is caused by local high suction and large pressure fluctuations around the roof periphery and protruding portions. These local failures enable wind to enter under the roof members, thus increasing the underneath pressure and rapidly increasing lift forces as shown in Fig.14. Thus, local roof damage can lead to total roof destruction. Total roof lift-off can also be triggered by damage to openings such as glass windows, allowing wind into the room and increasing the underneath pressure.

(b) Clay tile roofing

There have been many instances of partial lift-off of clay tiles fixed at eaves of gable roofs and at ridges and corners of hipped roofs. Almost all roof tile fixing is done with nails and steel wires only at the roof periphery, including eaves and ridge. However, lift-off of non-fixed tiles also occurs at middle parts of roofs. Cases of damage to tile roofs increase with simplification of the substrate, i.e., decreasing the weight by eliminating the roofing cement and thus forming openings between substrate and tiles. Once an unfixed tile in the middle part is lifted, wind can inflow to the underneath, leading to sequential lift-off of tiles (Fig.14). Tiles are peeled off by negative pressure with large turbulence on the leeward side of a hipped roof.

If there is insufficient rust-proofing of nails and steel wire, they lose their strength within a few years and thereafter cannot fulfill their original function. Thus, countermeasures are necessary, such as nailing the sheathing roof boards over the entire roof area including the central part, filling gaps with lime plaster, and so on. It is desirable to carry out inspections every 5 - 6 years and replacement every 20 - 30 years.

(c) Steel plate roofs

Most damage to these roofs is induced by local suction at the eaves and periphery. Many breakdowns are found in the joint metal where there is a tight frame at the seam end. However, in a significant number of cases, total breakdown occurs due to insufficient strength of connections between the tight frame and its supporting beam or between the supporting beam and the lower structure. This can be controlled by increasing the thickness of the folded plate in the peripheral areas, selecting individual assembling members that can maintain sufficient wind resistant performance, and ensuring tight fixing to the lower structure. To ensure the required performance even under strong wind conditions, it is necessary to prevent large deformations. Particular attention must be paid to the installation of deformation-preventing bars near the peripheral areas.

The fatigue phenomena on the connecting elements between the roofing system and the frames due to daily solar heating effects should be also taken seriously as already mentioned and shown in Fig.10.

(d) Canopies

A lot of damage is found in canopies and pent roofs. Even if canopies are horizontal, they take a large upward or downward fluctuating load, depending on the size and shape of the building, the locations of the canopies, objects placed underneath them, and so on. The tips vibrate a lot, thus causing repeated deformation and fatigue conditions there. Furthermore,
if they project from the wall, there is a high possibility of wind-borne debris hitting them.

(e) Protrusions on roofs

If a roof has protruding parts like short chimneys, skylight roof windows, and dormer windows, the flow over the roof surface is locally disturbed, sometimes producing local high suction and turbulence. Special attention to wind resistant design is therefore necessary around these protrusions.

(f) Rain gutters, gables, verges and copings

There is often insufficient consideration of the wind resistance of rain gutters, spoutings, verges and copings in roof peripheral areas, where local wind pressures become large. Damage to these lightweight members may trigger large-scale damage to roof cladding, leading to total roof destruction as shown in Fig.14. It is therefore necessary to design the plate thickness and the connection spacing.

(g) Lift-off of waterproofing material with heat insulation

There have been cases where heat insulation blocks with aged roof joints have been lifted off. Parapets are effective in easing conditions where extreme local negative pressure and largely fluctuating wind pressure act directly on roof heat insulation materials. Another effective measure is a heat insulation block system having an airspace underneath it connected to the outer surface.

(h) Windowpanes

Windowpanes are often damaged by wind pressure or wind-borne debris as shown in Fig.15. Breakage of windows not only damages property inside the building, but also induces total roof lift-off. Wind resistant performance of glass is improved by increasing the rigidity of the supporting members such as sashes, and decreasing sealing and gasket deformation. Sufficient sash rigidity needs to be ensured not only in the out-of-plane direction but also in torsion. It is desirable to suppress deformation by increasing gasket rigidity.

For the various types of window glass for buildings, the allowable maximum area is given by codes or standards. Recently, few instances have been reported of glass broken by wind pressure. The majority of window breakages have been caused by heat.

A lot of damage during strong winds has been due to wind-borne debris. An extraordinary amount and variety of materials are blown off in strong winds, not only cladding materials such as clay tiles and steel plate roofs, but also other materials such as gravel and square timbers as shown in Figs.12 and 16. Therefore, it is important to adopt countermeasures to collision of wind-borne debris with windows and walls. Rain shutter doors or metal shutters are indispensable for house windows.

For tall buildings, there is also a high possibility of wind-borne debris hitting the lower levels. It is therefore desirable to protect them with metal shutters. Furthermore, measures such as the use of glass with an internal plastic film is effective in preventing escalation of damage if the window is hit by wind-borne debris.

(i) Steel shutters

Warehouses, factories, garages, and so on suffer a lot of damage to their steel shutters. Damage starts with dislocation of slats and central guide columns. Damaged shutters can lead to total building destruction due to increased internal pressure. Thus, shutters can never be neglected just because they are light. It is important to ensure sufficient plate thickness, rigidity and strength of slats, and depth of rail grooves. Other important points are management of construction and maintenance, such as anchorage of central guide columns to concrete foundations.

(j) Buildings under construction

In some cases, steel frames of buildings under construction collapse during strong winds. Especially in the case of steel-encased reinforced concrete buildings, the cross sectional area of steel frames themselves is relatively small. Thus, they are very vulnerable to
wind during erection, and it is therefore necessary to thoroughly plan for construction and safety.

(k) Signboards

A lot of damage occurs to building accessories such as signboards. This sometimes extends to large-scale damage to roofs and walls, leading to secondary damage by wind-borne debris. When dealing with wind, design of signboards, as well as cladding materials, should not be taken lightly just because they are accessories.

Figure 14: Damage Correlation (Uematsu et al., 1992)

Figure 15: Damage Chain

**Importance of Cladding/Components Design**

Wind pressure is first applied to a building's external cladding, and is then propagated to substrates, secondary components, main structural frames and foundations. However, cladding materials are scarcely considered in structural design. As a result, they can have insufficient strength, resulting in local damage, which then leads to structural damage by the total wind force. That is, the building breaks down by being gradually eroded, starting with local surface damage and finally reaching total destruction. Thus, the importance of design and construction of cladding and components should be recognized.

As Tamura (2009) discussed, there are some problems in the current codes and standards that need to be clarified, and one of them is the recurrence periods of design wind loads for structural frames and for cladding/components.

They tend to design cladding and components based on lower level wind loads than the main structural frames, i.e. a shorter recurrence wind load is used for cladding design than for frame design. For example, according to the Building Standard Law of Japan (BSLJ), 50-year-recurrence wind loads are applied for structural frame design with allowable-stress design criteria, and the same recurrence wind loads are estimated for cladding and component design. However, 500-year-recurrence wind loads are applied for the ultimate state structural
frame design, but only 100- or 200-year-recurrence loads are applied for cladding and components.

Structural designers are interested in main frame design, but not in cladding design. However, wind-induced damage is generally triggered by small damage to cladding and components. This can be developed to a larger scale and more severe damage including that to main frames. This “coherent phenomenon” in damage progress is a special feature of wind-induced building damage, as shown in Fig.14. The fractured parts of cladding and components can easily become wind-borne debris and strike downstream buildings. Debris impacts also initiate cladding and component damage to downstream buildings. This “damage chain” shown in Fig. 15 is another special feature of wind-induced damage to buildings in urban areas.

If the windowpanes and claddings of a tall building are damaged, property inside the building can be seriously damaged and lose its value, and this property loss can be very significant, especially if only the main structural frames remain. The miserable situation of a building with damaged window panes is often reported after extreme wind attacks in urban areas, e.g. Brewick et al. (2009). Furthermore, in general, the structural design of the main frames assumes the aerodynamic coefficient for the original shape of the building without cladding damage, so that the cladding and components are implicitly assumed to keep their original shape. Therefore, theoretically, there is no reason to accept a lower level of wind load for cladding, except for cases considering the possibility of change of aerodynamic coefficient or reaching a consensus with building owners and occupants or guaranteeing preventive measures for damage coherence or damage chain.

It is said that cladding and components are replaced more frequently than main structural frames, so the existing return periods for them are shorter than that of main frames. It is also said that the design recurrence period for cladding and components can be less than that of main frames, but this is not appropriate. A specific cladding element with a proper noun may become expired in a shorter period, but another cladding element with a different proper noun may replace it, and the cladding itself with a common noun always exists as long as the building exists. Replacement is only maintenance action to keep the element’s quality up to the level assumed in the design stage. Thus, the existing shorter period of a specific cladding element has no meaning in wind load estimation. As cladding and component damage directly relates to the safety of building and property, the structural designer should play an important role in guaranteeing their performance during strong winds.

It is also clear that there is no relation between the design wind load level and its existing period at an individual site. As Tamura (2009) pointed out, there is no relation between the design load level and the life-time or the period of individual usage of a building or its elements. Even for the design wind load for main structural frames, it may not be possible to determine the design load level based on the lifetime of an individual building.

**Coherent Phenomena and Damage Chain**

Uematsu (1992) described a wind damage process on a roof as shown in Fig.14. First, there is high local suction at the eaves. Once there is damage to the eaves, internal pressure rises and lift force increases. Resultantly, surface and underneath roof materials are blown off, and sometimes the whole roof structure is damaged if tie-down is insufficient. This “coherent phenomenon” of damage should be taken into account in the wind resistant design of buildings. Wind damage may take place successively. As exhibited in Fig.15, flying tiles or roofs may hit and break dwellings in the downwind direction, and cause the same phenomenon as that illustrated in Fig.14 and already shown in Fig.12. The so-called “damage chain” is also an important feature of wind-induced damage.
Wind-borne Debris

Wind-borne debris during typhoons and tornados causes severe damage as already shown in Fig.12. Figure 16 shows roof sheets and massive obstacles that flew from upstream and hit a dwelling and a warehouse. Tachikawa studied experimentally and numerically the trajectories of generic debris types in the 1980s (Tachikawa, 1983, 1988). He was a pioneer in the study of wind-borne debris, and amongst his significant insights was his recognition of the importance of the non-dimensional ratio of aerodynamic forces to gravity forces to the flights of flat plates, referring to this ratio as a parameter ‘\( K \)’ in his 1983 paper. This parameter has been officially authorized to be called ‘Tachikawa number’. This was proposed by Holmes et al. (2005), at the General Assembly of the International Association for Wind Engineering (IAWE) in July 2007. It was also agreed to use ‘\( T_a \)’ after his family name instead of ‘\( K \)’. Thus, ‘Tachikawa number’ is defined as:

\[
T_a = \frac{\rho_a U^2 l^2}{2mg}
\]  

where \( \rho_a \) : air density, \( U \) : wind speed, \( l \) : side dimension of the plate, \( m \) : plate mass, and \( g \) : acceleration of gravity. Baker (2004), Holmes et al. (2006) and Lin et al. (2006) have been developing further studies on flying debris.

Influence of Topography

Wind speed and turbulence characteristics over a terrain with topographical features such as escarpments, cliffs, ridges, hills and so on are quite different from those over a flat terrain. Significant wind speed and turbulence increase can be observed near these locations. These topographical effects can be combined with more than one kind of topography, producing more severe effects on buildings.
Wind tunnel studies are commonly used to examine topographic effects. However, it may be inappropriate to examine the effects of large scale topography by wind tunnel tests because of some restrictions and the inevitable significant reduction of the length scale. CFD analyses may be better alternatives (Ishihara et al., 2000, 2003, Ishihara 2003, Yamaguchi et al., 2006, Uchida & Ohya, 2008a, 2008b).

**Interference Effects of Neighboring Buildings**

Large, closely-spaced buildings cause some dynamic interaction phenomena providing a larger gust response factor or crosswind oscillations. Wind loads on buildings in a group in real environments can be quite different from those on isolated buildings. Surrounding buildings or downstream buildings can significantly increase or decrease wind loads on buildings. Interference effect studies were carried out in the early seventies. This sudden interest could perhaps be traced back to the collapse of three of the eight natural draft cooling towers at Ferrybridge, England in 1965, which was attributed to interference effects (Armit, 1980). Interference effects have been studied by many researchers over the past several decades, e.g. Saunders & Melbourne (1979), Surry & Mallais (1983), Bailey & Kwok (1985), Taniike (1992), Khanduri et al. (1998), Khanduri (2000), Thepmongkorn et al. (2002), Tang & Kwok (2004), Xie & Gu (2004), Gu & Huang (2005), and Zhao & Lam (2008). However, studies to provide general recommendations have not been successful due to the complex nature of the problem and the large variation of building geometries, relative locations of adjacent buildings, wind directions, upstream terrain conditions and so on. The majority of past studies focused mainly on overall wind loads and responses of tall buildings. Damage to window panes shown in Fig.8 is attributed to the interference effects of adjacent buildings causing higher peak pressures than on an isolated building (Cho et al., 2005). More studies on interference effects on peak pressures are desired.

**Wind-related Disaster Risk Reduction Activities**

**Repeating Wind-induced and Wind-related Disasters**

If you have any reports on post-disaster investigations of disasters by tropical cyclones on your shelves, please open the pages to the concluding remarks. The following may be pointed out: most damage is concentrated in roofs and particularly in their cladding around eaves, ridges and corners; damage to openings such as windowpanes and steel shutters is also significant; these can trigger the complete destruction of the main frames and develop damage to downstream buildings as wind-borne debris. However, by simply reading the concluding remarks, you might not be able to identify the tropical cyclone or which is older. Thus, similar types of damage has been repeated.

One reason is that the majority of damage is concentrated in residential houses and low-rise commercial buildings, which are all non-engineered structures. Thus, the sophisticated design methods developed and adopted in building standards/codes are not reflected in the construction technologies for those buildings. It is inevitable that traditional, historical and cultural aspects in the construction industry in a local community have a strong inertia to acceptance of new technologies. Even for engineered buildings and structures, it is also true that new technologies and methods proposed by researchers and engineers take a long period to improve their quality and performance. The new technologies and methods should be authorized by academic and industrial societies, and then reflected in the revision works of building standards/codes, whose revision is not so frequent. Once they are published as new standards/codes, improvement of the majority of buildings and structures in the local community would require an additional long period. This would take several decades.
Actually, for example, the wind load provisions in the Building Standard Law of Japan were revised in 2000 after an interval of 50 years since 1950.

As mentioned first, almost all facts described in the concluding remarks of post-disaster investigations are already known. However, lessons from those past disasters have not been applied. “Knowing but not acting” is a special feature of human reactions to disasters due to natural hazards. Implementation of the knowledge and technologies is the most difficult and important point.

**Trends of Climate Change Adaptation**

Global warming due to various human activities has been recently treated as a main source of climate change and the increasing variability of weather related events. According to Kitoh (2009), precipitation changes predicted by CMIP3 multi-model results suggest that precipitation increases are very likely in high altitudes and decreases likely in most subtropical land regions. Thus, increases in the frequency of droughts and floods are projected to negatively affect crop production in subsistence sectors at low latitudes. Kitoh (2009) also reported that the number of tropical cyclones averaged globally would decrease but the number of stronger and longer life-time typhoons would increase. Actual meteorological data suggest no significant increasing/decreasing tendency in intensity or frequency of typhoons in the West Pacific region. However, the number of lightning events in winter in Japan has been clearly increasing (Kobayashi, 2006) as shown in Fig.17, which suggests more intense and frequent generation of cumulonimbus caused by strong updraft near the surface of the ground in winter.

![Figure 17: Variation of Number of Lightning in Winter in Japan (Kobayashi, 2006)](image_url)

On the other hand, there have been discussions on the inherent long-term climate change such as glacial and interglacial periods. Sanchez-Sesma (2009) discussed the long-term temporal variation of strong wind events based on historical records since the second century B.C., suggesting that the recent trend can be in the range of inherent long-term variations.

Predictions of climate change and the effects of global warming on weather-related disasters should be made very carefully, based on reliable scientific data and prediction models.
Pressing Needs of Collaboration of Multiple Academic Associations for Different Natural Disasters

Figure 18 shows the yearly variation of the number of devastating natural disasters (Munich Reinsurance, 2004) for four types of event: flood; windstorm; earthquake/Tsunami/volcano-eruption; and others such as heat-wave/drought/wild-fire/winter-damage/frost. This figure clearly shows an increasing tendency of the number of devastating natural disasters, especially floods and windstorms, and the majority of devastating disasters are caused by windstorm and flood.

It is also said that 80 - 85% of natural disaster economic losses in the world are caused by extreme wind and its relevant events. Devastating tropical cyclones are generally accompanied by high waves, storm surge, heavy rains, floods, landslides, lightning and so on. Thus, there is a pressing need for pooling of expertise and cooperative actions to reduce losses from various types of those “wind-related” natural hazards. Interactions among various groups with diverse backgrounds, but with a common focus on disaster reduction, to highlight the issues surrounding wind-related hazard and its impact on constructed facilities and society at large should be facilitated. It should also be noted that other hazards such as ocean waves, storm surge, heavy rains, flooding, landslides, lightning, fires and heat waves are directly or indirectly associated with winds around the globe and should be treated in a holistic manner rather than each in isolation.

Despite this recognition of the critical need for cooperative actions in wind-related disaster risk reduction (WRDRR) activities among various academic associations, there have been no notable collaborative efforts in the past. A symposium entitled “Cooperative Actions for Disaster Risk Reduction (CADRR, 2009)” was held at the United Nations University under the auspices of the UN/ISDR (UN International Strategy for Disaster Reduction) Secretariat and IAWE.

As mentioned, damage to buildings and structures is caused not only by strong wind pressure and debris impacts but also by water-induced forces and others. To identify damage due to wind and that due to water is not easy in some cases. It is also necessary to find an appropriate scale or yardstick to evaluate the damage level caused by the combined effects of wind and water. Friedland & Levitan (2009) studied the loss consistent categorization of wind and water damage to residential buildings.
Pressing Needs of Collaboration among Academic Societies and Non-academic Organizations working on Disaster Risk Reduction

As reported in CADRR (2009), immediate collaboration among area-specific academic associations and international organizations working on disaster risk reduction (DRR) at societal level is also necessary. Closer communications and inputs from academic associations to international organizations working on DRR and reconstruction areas are essential for their relative effectiveness. Post-disaster activities must be well coordinated to reflect the ground realities, e.g., the need for medicines, clothing and food must be critically evaluated by a central organization and conveyed to the donors to avoid arrival of unnecessary aid at the site only to stifle the moribund infrastructure in the wake of a disaster. The discussions at CADRR (2009) emphasized the need for such a critical arm of the disaster risk reduction group to take charge in steering post-disaster investigations, distribution of essential goods and recovery and other related efforts.

Launch of International Group for Wind-related Disaster Risk Reduction under UN/ISDR

While wind-related organizations have been effectively working to develop technologies, codes and standards for wind hazard mitigation, there has been a dearth of coordinated activities with other international groups like the UN and NGO to bring these technologies to work for less fortunate communities in low lying areas, which are often struck by devastating wind storms such as hurricanes/typhoons with attendant escalating loss of life and associated perils they bring to the region (CADRR, 2009).

In order to address this past lack of coordination and to benefit from a large database of technologies developed over the last few decades, an International Group to work on WRDRR (IG-WRDRR) was launched in June 2009 in Geneva, Switzerland. The participant organizations are International Association for Wind Engineering (IAWE), International Center for Water Hazard and Risk Management (ICARM), United Nations/International Strategy for Disaster Reduction (UN/ISDR) Secretariat, United Nations Economic and Social Commission for Asia and the Pacific (UNESCAP), United Nations University Institute for Environment and Human Security (UNU-EHS), World Meteorological Organization (WMO), International Federation of Red Cross and Red Crescent Societies (IFRC), Yayasan HOPE Indonesia, Development Workshop France (DWF), Asia Disaster Reduction Center (ADRC), SEEDS INDIA, SEEDS Asia, Bangladesh Disaster Management Bureau (DMB), Bangladesh Disaster Preparedness Center (BDPC), and L.R. of Iran Meteorological Service. It is also agreed that the IAWE President will serve as Chairman of IG-WRDRR and lead the activities.

The main task of this IG-WRDRR is to establish linkages and coordinate various communities to serve as inter-agency coordinator with a charter to work with international organizations involving agencies of the UN and involved NGOs, and to empower them with the responsibility to serve as a bridge between policy makers and agencies responsible for actually carrying out the DRR at the local community level. It is also anticipated that technologies developed in wind engineering communities can be show-cased in the disaster risk reduction marketplace to offer and share practical tools developed under the umbrella of this specialized group to potential users and partners in communities around the world that can be re-tooled to meet the special needs of a particular region with its local building and land use practices. It is noted that many of the issues facing the world, including poverty, are tied to wind-related storms and accompanying hazards such as waves and storm surge. Therefore, the IG-WRDRR would help meet the goal of poverty reduction through building of disaster resilient communities.

The main objectives of the IG-WRDRR are outlined below:
- to implement the Hyogo Framework for Action in the area of WRDRR;
- to establish a database/warehouse of the latest information/technologies relevant to wind-
related effects and their mitigation;
- to facilitate convenient technology transfer that is attentive to the needs of local communities exposed to disasters around the world;
- to provide assistance to international organizations in the preparation of guidelines to manage the impact of wind-related disasters including evacuation, recovery and reconstruction;
- to organize, dispatch and facilitate ground logistics for quick-response post-disaster investigation teams;
- to establish an international consensus for extreme winds based on damage relevant to different construction practices;
- to establish international guidelines to prepare for wind-related disaster reduction activities;
- to harmonize wind-loading codes and standards including environmental specifications; and
- to facilitate development of a global Engineering Virtual Organization (EVO, see Kareem et al, 2008) for WRDRR

Concluding Remarks

Mr. Ban Ki-moon, the Secretary-General of the UN, said, “Almost as dangerous as the cyclones or earthquakes themselves is the myth that the destruction and deaths they cause are somehow unavoidable, the inevitable result of natural calamity”. He continued that “It is true that we cannot prevent the events themselves. But we can determine our response -- and, through our actions, either compound disasters or diminish them”.

Global action in education and research is a key to achieving this target, where our wind engineering community can surely make a significant contribution by collaboration with other academic associations and international groups. Your keen support of the future activities of IG-WRDRR is essential for its success.

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