The Tornado Damage Mitigation Project

Japan's Building Research Institute (BRI) conducts activities ranging from research and development on housing, building and urban planning technology, to international training on seismology and earthquake engineering. Against the background of significant tornado damage in Japan earlier this year, this article introduces some of the BRI's initiatives in tornado research and the launch of a frontline tornado research project to help reduce damage to buildings.

On May 6, 2012, a mass of cold air entered the skies above Japan. At the same time, warm, moist air was moving towards a low-pressure area over the Sea of Japan. Compounded by elevated ground temperatures due to solar radiation, this caused major atmospheric instability from the central Tokai area all the way up to Tohoku in the north, resulting in cumulonimbus clouds accompanied by lightning, transient winds and hailstorms. These weather conditions led to multiple tornado outbreaks in Ibaraki, Tochigi and Fukushima Prefectures, causing casualties and substantial damage to countless homes and other buildings (see **Photo 1**).

Tornadoes were confirmed at F3 on the Fujita Scale (estimated wind speed: 70–92m/s) near Tsukuba in Ibaraki Prefecture, F1–F2 (33–69m/s) in Moka in Tochigi Prefecture and Hitachiomiya in Ibaraki prefecture, and F1 (33–49m/s) near Chikusei in Ibaraki Prefecture. These transient winds and the accompanying weather conditions left one person dead and fifty-eight injured. In addition to the human toll, 89 homes were also destroyed, with a further 197 partially destroyed and 978 damaged (as of June 13). The trail of destruction had a serious social impact too.

This is not an isolated case. As **Table 1** shows, serious damage caused by tornadoes has become increasingly common in recent years. The Japan Meteorological Agency has responded by providing the public with warning information on tornadoes (since 2008) and up-to-the-minute tornado "nowcasts" (since 2010). The Cabinet Office Central Disaster Management Council meanwhile has included tornadoes as an established weather phenomenon in its Basic Disaster Management Plan, calling for measures to alleviate physical damage and improvements in technical expertise to help companies implement damage mitigation measures.

How Tornadoes Damage Buildings

In order to get a picture of the damage caused to buildings by the tornado that hit Tsukuba, Ibaraki Prefecture, on May 6, 2012, the Building Research Institute joined forces with the National Institute for Land and Infrastructure Management and began conducting a field survey from that same day. In addition to typical damage recorded in the aftermath of other tornadoes (scattering of exterior materials, collapse of wooden roof trusses, impact from flying debris, etc., see **Photos 2 and 3**), the survey found new types of damage that had not been observed previously. **Photo 4** shows a two-story wooden house whose foundations became detached from the ground, causing the entire structure to overturn. **Photo 5** meanwhile shows a five-story reinforced


Photo 1: A tornado in Tsukuba, Ibaraki Prefecture, on May 6, 2012


Photo 2: Destruction caused to a wooden house


Photo 3: Impact from flying debris (roof)


Photo 4: A wooden house overturned with its foundations still attached


Photo 5: An apartment building with extensive damage to non-structural elements

Table 1: Summary of major damage caused by tornadoes in Japan since 2002

Date	Location	Scale			Human toll (no. of people)		Physical damage (no. of homes)	
		Fujita scale	Width of affected area (m)	Length of affected area (km)	Dead	Injured	Completely destroyed	Partially destroyed/ damaged
2002.07.10	Fukaya City, Saitama Pref.	F2	100 ～ 150	4.5	damaged	11	7	87
2004.06.27	Saga City, Saga Pref.	F2	200 ～ 400	8.0	0	15	15	330
2005.12.25	Sakata City, Yamagata Pref.	F1	100	9.0	5	33	0	4
2006.09.17	Nobeoka City, Miyazaki Pref.	F2	150 ～ 300	7.5	3	143	79	1,101
2006.11.07	Saroma Town, Hokkaido Pref.	F3	100 ～ 300	1.4	9	31	7	32
2009.07.19	Mimasaka City, Okayama Pref.	F2	200	6.0	0	2	2	76
2009.07.27	Tatebayashi City, Gunma Pref.	F1 ～ F2	50	6.5	0	21	14	310
2009.10.08	Tsuchiura City, Ibaraki Pref.	F1	200 ～ 300	2.8	0	2	1	105
	Tone Town, Ibaraki Pref.	F1	100 ～ 200	6.0	0	4	0	121
	Kujukuri Town, Chiba Pref.	F1	20 ～ 30	1.6 ～ 1.7	0	0	1	36
2011.11.18	Tokunoshima Town, Kagoshima Pref.	F2	100	0.6	3	0	1	2
2012.05.06	Tsukuba City and other area, Ibaraki Pref.	F3	500	17	1	37	76	158 partially destroyed
	Chikusei City and other area, Ibaraki Pref.	F1	600	21	0	3	0	1 partially destroyed
	Moka City and other area, Tochigi Pref.	F1 ～ F2	650	32	0	12	13	35 partially destroyed
	Aizumisato Town, Fukushima Pref.	F0	300	2	0	0	0	0 partially destroyed

Source: The Japan Meteorological Agency

concrete apartment building, which sustained extensive damage to non-structural elements such as windows, window frames and aluminum balcony handrails. The buildings in these two photographs are thought to have been in or around the path of the tornado. Nonetheless, the reasons for such extensive damage and the magnitude of pressure caused by transient winds remain unclear. From the standpoint of wind engineering, throwing light on phenomena such as these is proving extremely challenging.

To analyze these atypical examples of damage in greater detail, it is necessary to run tests that recreate the gust load of a tornado and the effects it has on a building, so as to identify damage-causing mechanisms under the relevant load. **Figure 1** is a graphical illustration of what happens when a tornado passes close to a building. When the tornado passes, its horizontal swirling flow and vertical upward flow create lots of flying debris. This means that the effects on the building can be broadly divided into (1) wind pressures caused by the direct action of the air flow, (2) pressures associated with the variation of the atmospheric pressure field and (3) impact forces caused by tornado-borne flying debris. The characteristics of (1) and (2) differ considerably from the wind force generated by strong winds during a tropical cyclone. As a result, it is impossible to realistically recreate the same conditions in tests using a conventional turbulent boundary layer wind tunnel. In order to identify the effects and damage-causing mechanisms of a tornado, we have to leave behind existing testing and assessment methods and adopt a new approach.

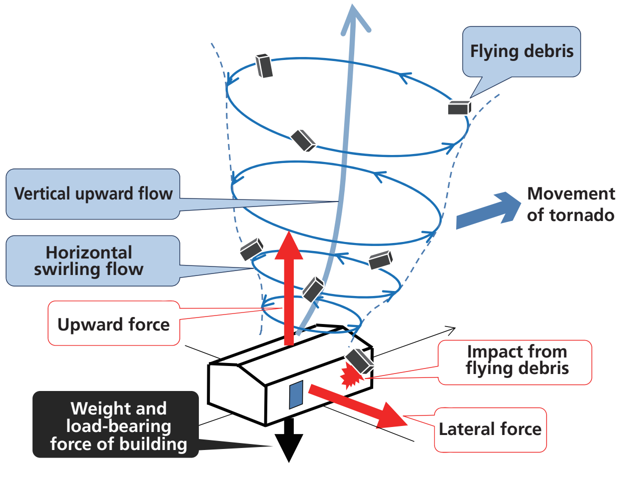
Outline of a Tornado Simulator and Experimental Research

In 2010, the Building Research Institute designed and built a tornado simulator to experimentally recreate the airflow of a tornado, in order to ascertain the wind force characteristics of transient winds and the risk of impact from flying debris (see **Figure 2**). With additional funding courtesy of the Grants-in-Aid for Scientific Research program, experiments were then carried out in conjunction with researchers from the National Institute for Land and Infrastructure Management, the University of Tokyo and the Disaster Prevention Research Institute at Kyoto University. The airflow mechanism used in the simulator is based on a machine developed at Iowa State University in the United States and is able to recreate an unsteady vortex structure similar to an actual tornado, whilst moving sideways at the same time.

Photo 6 shows the exterior of the simulator, with **Figure 3** providing cross-section views. The simulator consists of a main body equipped with a fan, a self-propelled cradle that moves from side to side, a stage that moves up and down, and a control panel. Standing at a full height of around 2.3 meters, the body has an external diameter of 1.5 meters. The cradle meanwhile has a range of 1.4 meters from the center, and a maximum translation speed of 0.4 meters per second. When the fan inside the body spins round, it creates an upward airflow, which then blows downwards from the outside. There are eighteen guide vanes fitted to the upper part of the body, which are then angled (0–55 degrees) to force the downward flow into a swirling motion.

It is possible to vary the maximum speed and diameter of the swirling flow by adjusting the speed of the fan, the angle of the guide vanes and the height of the stage. The airflow conditions created by the simulator have been verified against a tornado

Figure 1: The effects of forces caused by a tornado



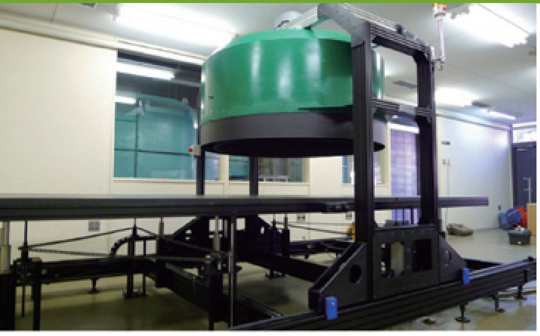


Photo 6: The tornado simulator at the Building Research Institute

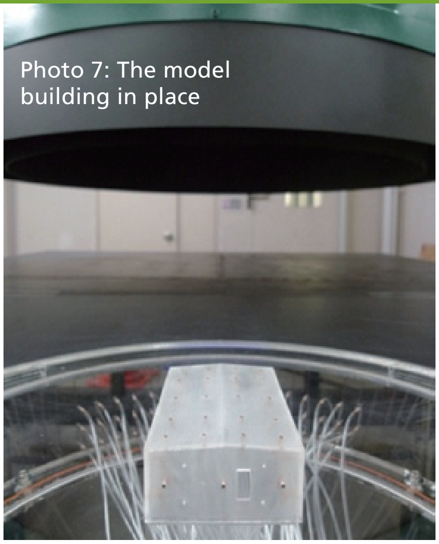


Photo 7: The model building in place

engineering model (the Rankine vortex model) based on tangential wind speed and distribution of low air pressure.

Wind Pressure Tests Using the Tornado Simulator

Using the tornado simulator, researchers conducted wind pressure tests based on the premise of a tornado passing directly over a building. The building was based on a 12-meter high low-rise structure measuring 24 meters across by 38 meters in length. The walls of the model building were made complete with realistic, uniform distributed leakage and a rectangular dominant opening on the right-hand wall, if viewed from the direction of the tornado (see **Photo 7**). The dominant opening was designed to simulate a large hole caused by the impact of tornado-borne flying debris. With wind speeds reduced in scale to 1/10 and distances to 1/350, tests recreated a tornado with a maximum tangential wind speed of 98 meters per second and a core radius of 42 meters.

The following results for wind force characteristics are expressed as “wind force coefficients,” calculated by dividing measured wind force data by reference velocity pressure.

Figure 4 shows wind force characteristics acting vertically on the roof of the building. The horizontal axis shows the moving position of the simulator in relation to the center of the model (xs) divided by the core radius (Rm). The findings indicate that, irrespective of dominant opening, wind force is at its maximum when xs/Rm is -1 or 1. This means that the center of the building would be subjected to the maximum tangential wind speed when the tornado is approaching the building and immediately after the tornado has passed. In terms of dominant opening, the wind force is approximately twice as strong when a dominant opening is present. This suggests that preventing large openings from forming in the wall as the tornado approaches would effectively reduce the force of the wind on the roof.

Figure 5 shows results for horizontal wind force characteristics, divided into Direction X, facing the direction of the tornado head-on, and Direction Y, at right angles to the tornado. As with the vertical results, the wind force is at its strongest when xs/Rm is -1 or 1. In terms of the direction of the tornado meanwhile, the results interestingly show a greater force diagonally backward towards the left as the tornado approaches, and diagonally forward towards the right immediately after the tornado has passed by. **Figure 6** compares these findings against actual damage caused by the tornado in Tsukuba. **Figure 6 (a)** is an aerial photo of a wooden house that was overturned with its foundations still attached, with most of the upper structure of the house scattered diagonally forward towards the right, based on the direction of the tornado. The direction of scattering more or less matches the direction found in the tests (**Figure 6 (b)**). With that in mind, one possible explanation for this damage is that the wooden house was overturned and scattered immediately after the tornado passed close by.

As these results were obtained under restricted experimental conditions, there are plans to conduct more systematic wind pressure tests in the future, taking into account other parameters that need to be examined. It is hoped that the planned series of experiments will help assess the transient wind load of approaching tornadoes under different circumstances. The results should also provide evidence to support the damage-causing mechanisms of tornadoes.

Figure 2: Assessment of risks from transient wind due to a passing tornado

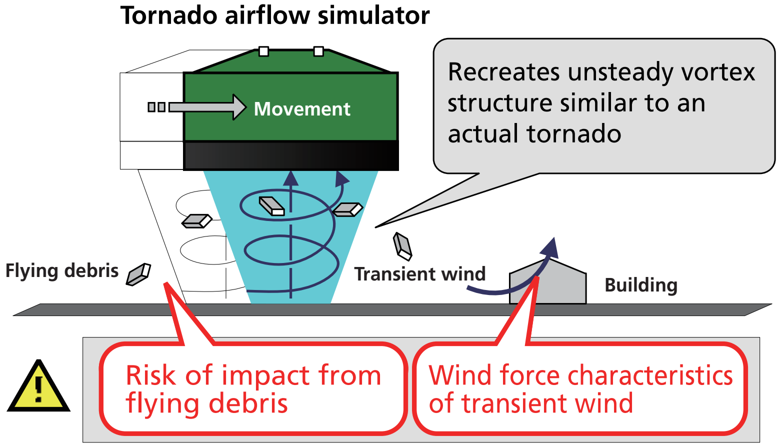


Figure 3: Cross sections of the tornado simulator

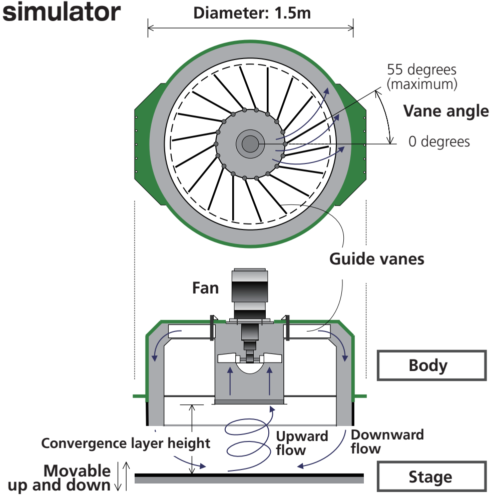


Figure 4: Vertical force from a passing tornado

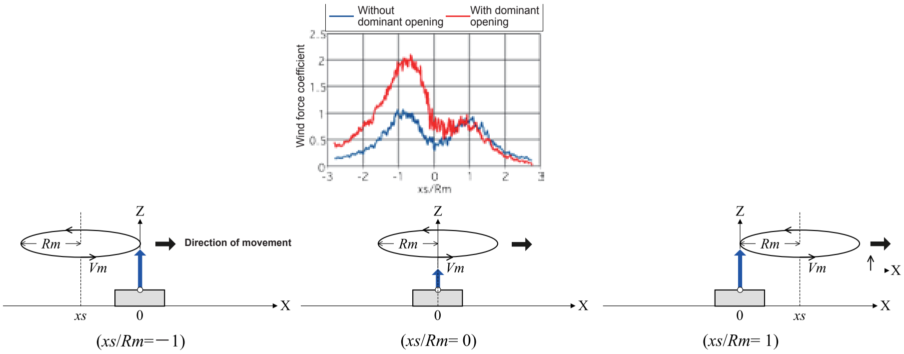
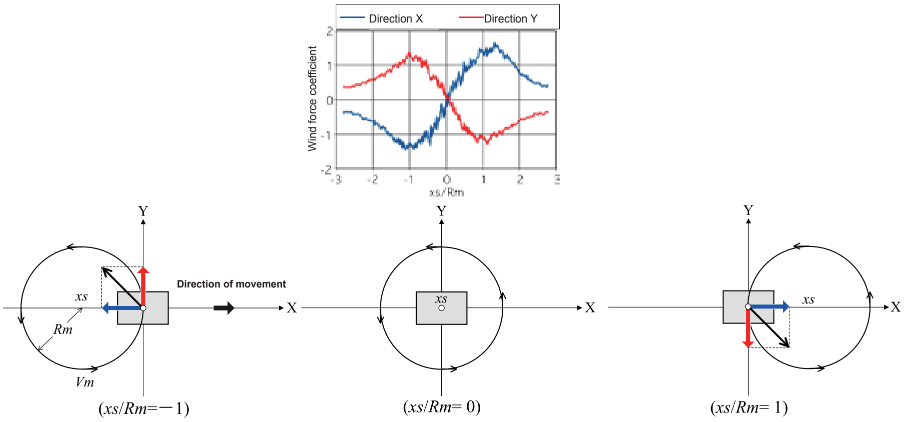


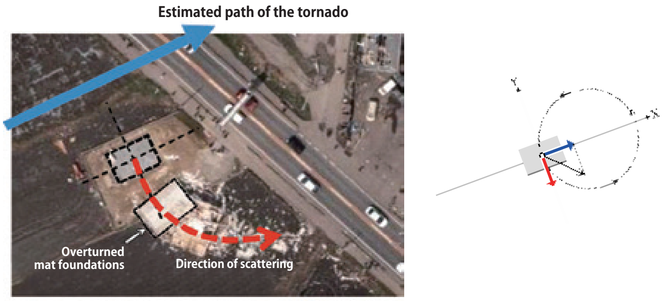
Figure 5: Horizontal force from a passing tornado



Tornado Damage Mitigation Project at the Building Research Institute

Generally speaking, the likelihood of individual buildings being caught in the path of transient winds from a tornado is extremely low. Incorporating measures into regular structural design would therefore be economically unfeasible. Tornadoes are also isolated events that are rarely picked up by normal meteorological observation networks. As it stands, we have insufficient engineering expertise for tornadoes to be reflected in design and verification procedures. It is for reasons such as these that load and external force due to tornadoes are not covered under the Building Standard Law of Japan. Given that serious tornado damage has become increasingly common in recent years however, we are going to have to improve the design of critical facilities that would be crucial to saving lives, protecting property and maintaining social functions in the wake of a disaster (emergency facilities, large-scale commercial facilities, multi-functional facilities, hospitals, schools, etc.), particularly parts and components that would be vulnerable to a tornado.

Figure 6: The tornado simulator at the Building Research Institute



(a) Actual damage

(b) Test results

Source: Geospatial Information Authority of Japan

In light of recent damage caused by tornadoes, the Building Research Institute has started work on a tornado research project to help reduce damage to buildings. The project will use unique research tools such as the tornado simulator and numerical simulation techniques to explain the mechanisms through which tornadoes cause damage. The Institute is also planning to set out a new approach to tornado-resistant design for the aforementioned critical facilities, based on the following underlying policy.

First and foremost is the belief that, as an extension of conventional wind-resistant design, we should make buildings safer and improve their functionality by using building materials with superior wind and impact resistant performances for parts and components that are most vulnerable to tornadoes (particularly roofs and openings). Disaster-resistant roof tiles are a prime example that has already been developed. Tests have shown that such tiles are roughly three times more resistant to tensile force. In terms of openings meanwhile, it has been reported that laminated glass offers greater impact resistance than regular glass. As test results from the tornado simulator show, taking steps to make openings more resistant to impact from flying debris, to prevent larger openings from forming wherever possible, is crucial in terms of disaster prevention during a tornado, because it helps to reduce the force of the wind against roofs.

In the United States, researchers have come up with structural calculation methods for critical facilities and evacuation shelters at risk from tornadoes. These could also provide a valuable source of reference. There is already a framework related to design criteria in place for different scales of tornado, plotted against the Enhanced Fujita Scale. As we put that framework into practice in the future, the key point will be how to reflect findings from damage surveys in Japan and experiments using the tornado simulator on the framework.

Design guidelines for critical facilities in Japan still need to be improved to protect against tornadoes. That's what makes the Building Research Institute's new project such a forward-thinking frontline research project. If we can actively share research results with the structural engineers who design our homes and critical facilities, and with the public, in the near future, it will undoubtedly help to raise awareness of tornado damage and promote measures to protect against transient winds and tornadoes.