Report on Field Surveys and Subsequent Investigations of Building Damage Following the May 6, 2012 Tornado in Tsukuba City, Ibaraki Prefecture, Japan

by

Yasuo Okuda[1], Atsuo Fukai[1], Takahiro Tsuchimoto[1], Toshikazu Kabeyasawa[1], Hitomitsu Kikitsu[2], Takafumi Nakagawa[2], Norimitsu Ishii[2] and Yasuhiro Araki[2]

ABSTRACT

Field surveys were taken in the city of Tsukuba, Ibaraki Prefecture, Japan immediately after the tornado of 6 May 2012 in order to evaluate the state of damage to buildings and other structures. Photographs were also taken of damaged buildings, etc., immediately after the disaster. Beginning May 7, a detailed audit was made, focusing on the Hojo district of Tsukuba, and an evaluation was made of the damage to each structure based on the wind damage ranking. In addition, measurements were taken of the dimensions of structural members of damaged buildings, etc., and estimates were made of the wind velocity at which damage occurred based on the resistance of buildings, etc. Furthermore, there was an investigation into the causes of damage to wooden buildings, and an examination of the destruction mechanism of wind force based on floor plans, etc., of wooden houses that were collected after the 2011 Great East Japan Earthquake.

KEYWORDS: Tornado, Fujita Scale 3, Tsukuba

1. INTRODUCTION

At around 12:35 p.m. on May 6, 2012, a tornado formed in Joso City, Ibaraki Prefecture, Japan and moved toward the city of Tsukuba, where it caused extensive damage, particularly to buildings in the districts of Hojo and the Tsukuba North Industrial Park. An announcement from the Japan Meteorological Agency acknowledged that the phenomenon that caused this windblast was a tornado. The damage the tornado inflicted covered a 17 km-long area from Joso to Tsukuba, with a maximum width of 500 meters. Based on the degree of damage, it was estimated to be of the F3 class on the Fujita Scale. In addition, at approximately the same time, there were two other tornados, one that formed at Chikusei City in Ibaraki (ab. 12:30 p.m.), and one that formed in the city of Moka, Tochigi Prefecture (ab. 12:40 p.m.). The Chikusei tornado covered a distance of 21 km, had a maximum width of 600 m, and was estimated to be of the F1 class, while the Moka tornado covered a distance of 32 km, had a maximum width of 650 m, and was estimated to be of the F1 or F2 class.

2. SUMMARY OF DAMAGES

2.1 Damage Statistics

According to an announcement by Tsukuba city officials, one person was killed and 37 were injured, 209 buildings were completely destroyed, 47 buildings sustained major damage, 197 buildings sustained partial damage, and 639 buildings sustained light damage. There was also damage to public facilities (such as Hojo Elementary School, Tsukuba Kindergarten, Hojo Nursery School, municipal housing units, community centers, etc.), damage to the agricultural infrastructure (including facilities such as warehouses, “pipe houses,” etc., crops, machinery, forest trees, scattering of debris on farmlands, falling hail), as well as power outages caused by broken utility poles (affecting about 21,000 households immediately after the disaster). There was also damage sustained by research labs, industrial facilities, etc., at the North Industrial Park.

2.2. Distribution of Damage

The National Institute for Land and Infrastructure Management of the Ministry of Land, Infrastructure, Transport and Tourism and the

[1] National Institute for Land and Infrastructure Management (NILIM), Ministry of Land, Infrastructure and Transport (MLIT), Tsukuba, Japan
[2] Building Research Institute (BRI), Tsukuba, Japan

Building Research Institute started conducting surveys of affected sites immediately after the disaster to study the state of damage to buildings, etc.2.5) Starting on May 7 (the day after the disaster), each building, especially in the Hojo district, was surveyed, and evaluated based on the wind damage ranking system described earlier. In addition, damage to roofs that could not be seen in ground-based surveys was evaluated from interpretations of high-resolution aerial photographs taken by the Geospatial Information Authority of Japan on May 7. A total of 697 buildings were evaluated through the on-site surveys and aerial photo interpretations. A total of 548 of these buildings had damage of Rank 1 or greater, while the remaining 149 structures had no damage. Table 1 shows the number of buildings for each wind damage rank.

Figure 1 shows an enlarged map of the Hojo and Koizumi districts. Hojo, which has long been a densely built-up area, was the district sustaining the greatest amount of damage in Tsukuba.

Table 1 Number of buildings for each wind damage rank in Hojo distinct

Damage rank	Number of buildings
5	51
4	78
3	149
2	181
1	89
Total	548

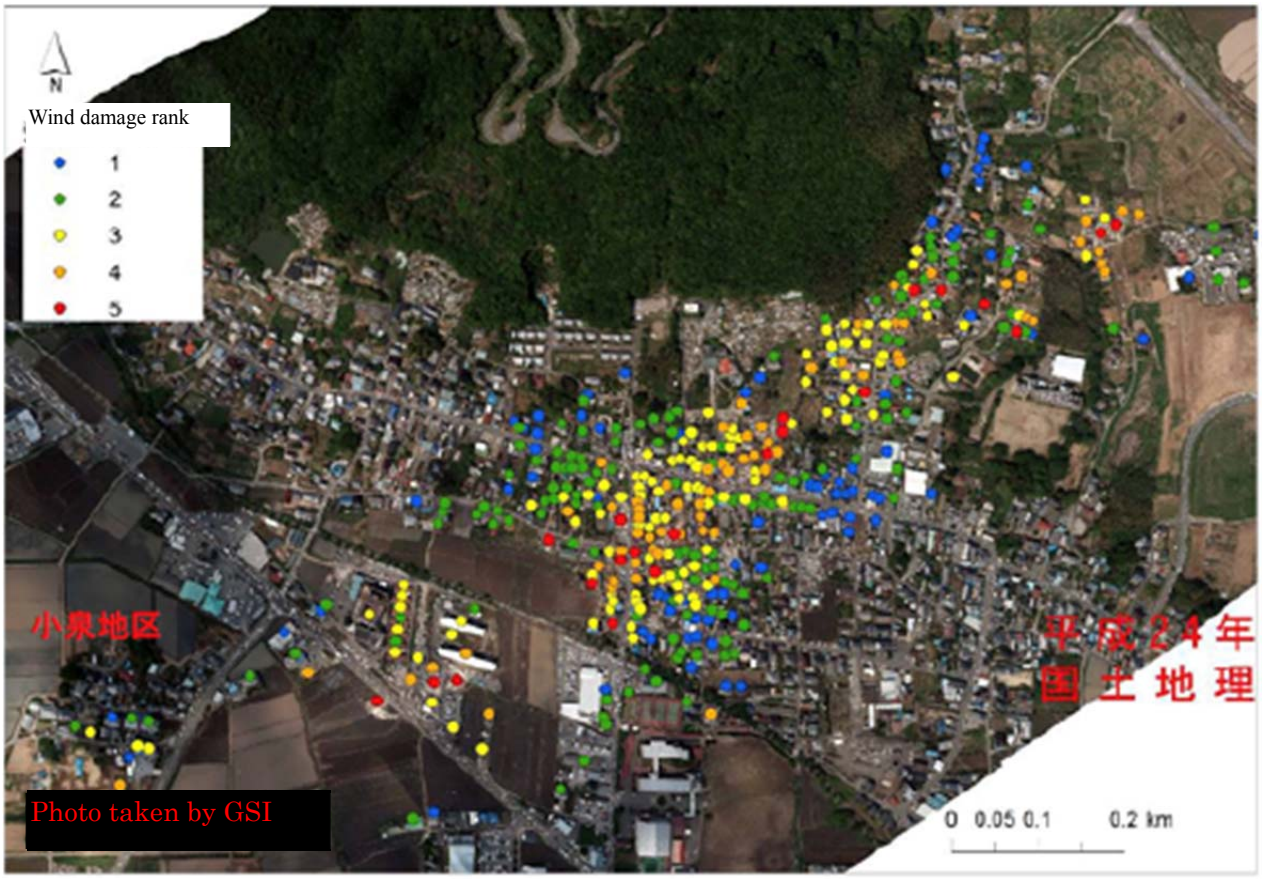


Figure 1 Map of the distribution of damage in the Hojo district

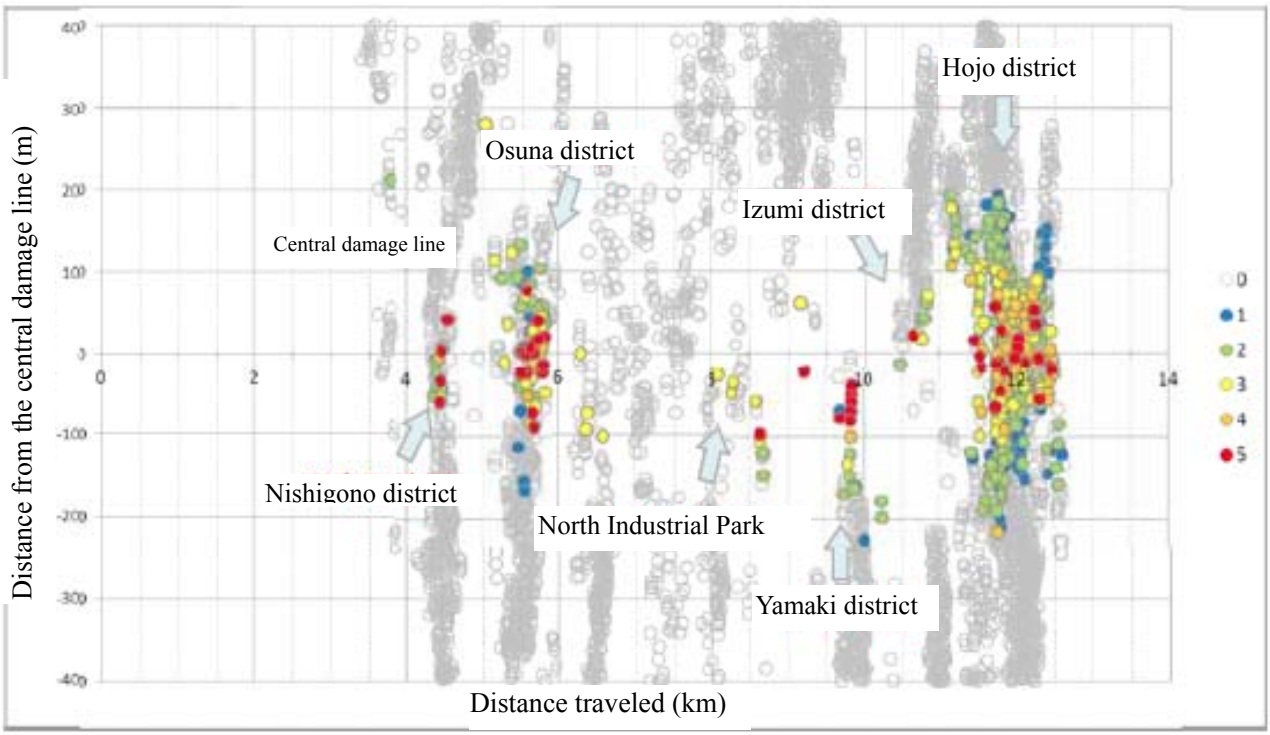


Figure 2 Distribution of building damage in Tsukuba city

Figure 3 Central damage line and central path of the tornado (Hojo district)

It appears that the distribution of damage in the Nishigono, Osuna and Hojo districts was concentrated along the central damage line, the damage in the North Industrial Park and the Yamaki and Izumi districts tended to be unevenly distributed on the underside of this line (the right side of tornado's path). In Figure 2.3-6, the buildings that were not damaged are designated with gray circles. In these latter districts, we can see that there are areas with vacant land near the

exact central damage line, and areas with few buildings. This may account for the skewed damage distribution.

Figure 3 is an enlarged map of Hojo district. The green line in the figure is the central path of the tornado (funnel cloud) that was estimated from the tornado images taken by Dr. Miyagi from the area surrounded by dotted red line. The central damage line described earlier and the estimated central path of the tornado are roughly parallel to each other, with the central damage line proceeding about 35 m to the right of the central tornado path. As a result, it was estimated that the tornado rotated in a counterclockwise direction. Assuming the vortex of the tornado to be a Rankine vortex, and the central damage line to represent the greatest velocity of the tornado (the sum of the swirling flow vector and traveling speed vector), the maximum wind speed radius of this tornado in this area (inside the dotted red line in Figure 3) was estimated to be 35 m.

3. STATE OF DAMAGE TO BUILDINGS

3.1 Damage to Wooden Buildings

During the on-site survey conducted in Tsukuba City, Ibaraki Prefecture, information on tornado-induced damage to numerous buildings and other structures and objects was collected. This chapter presents an overview of damage patterns that were found in wooden, steel-frame and concrete buildings, as well as in non-buildings such as walls, automobiles, and trees.

(1) Overturned superstructure with foundation (one building)

A wooden superstructure in the Hojo district, was overturned with its foundation by the force of tornado. The condition of the second floor confirmed that it had been flipped upside down, but the roof truss and the first floor section could not be found (Photo 1). In addition, the mat foundation was overturned (Photos 2). There were almost no traces of the crushed stone beneath the foundation having been dragged (Photos 3). An aerial photo taken after the disaster confirmed that members on the right side of the tornado's traveling direction were scattered about (Photo 4).

Photo 1 Wooden structure overturned from its foundation

Photo 2 Relation between the building's position and the position of the overturned section

Photo 3 Condition of crushed stone under the foundation

Photo 4 Aerial photo of the same area after the disaster

Photo 5 Foundation (corner section) of the structure in Photo 7

Photo 6 View of the 1st story floor of the structure in Photo 7

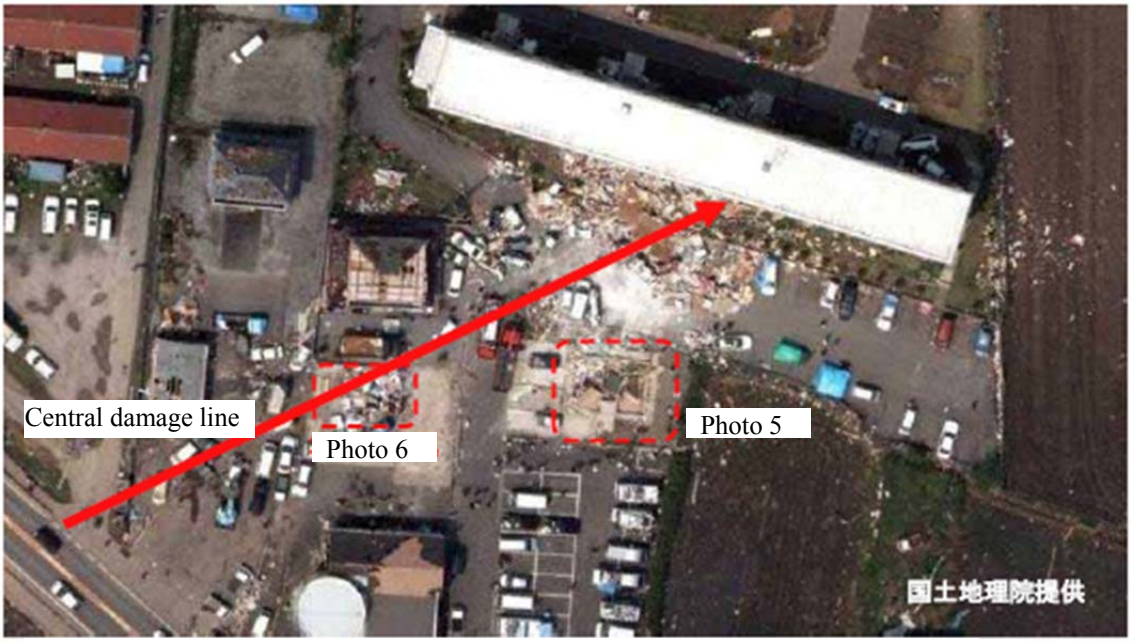


Photo 7 Aerial photograph of the same buildings after the disaster

(2) Scattering of the superstructure (6 buildings)
Several examples of the scattering of superstructures were found. Photos 5 and 6 show examples of scattering of superstructure, including the ground sill, while there were cases where only the floor framing of the 1st story, including the ground sill, remained. Aerial photos taken after the disaster (Photos 7) confirm that members of damaged buildings were crashed onto the reinforced concrete structure behind them.

(3) Collapse and other damage of superstructures
Numerous examples of buildings that had been collapsed were found. Some features of buildings (roofs, outer walls) remained, while nothing remained of the buildings. There were numerous examples of residual deformation caused. In Hojo district, the force of the tornado moved the superstructure of one building off of its foundation and into the adjoining street.

(4) Damage to roof trusses (about 70 buildings)
Numerous examples of damage to roof trusses were found. Wind pressure coefficients on the roofs are changed according to the shape of

Photo 8　A damaged gable roof

Photo 9　A damaged gable roof

Photo 10　A damaged hip roof

Photo 11　A damaged pent roof

Photo 12 Collapse of Steel-frame building

Photo 13 Residual deformation of Steel-frame structure

the roof. However, it was determined that damage was not related to roof shape, as it occurred in gable roofs of both relatively old houses (Photo 8) and relatively new houses (Photo 9), hip roofs (Photo 10), pent roofs (Photo 11), among others.

3.2 Damage to Steel-Frame Buildings

Information was collected on the pattern of damage to 3 steel-frame buildings that appeared to have structural damage. The present section focuses on damage to the structures themselves. Damage to exterior materials, roofing materials, etc., is examined in detail in Section 3.4.

Photo 12 shows a damaged 2-story steel-frame building. Its frame and foundation were moved, the frame was destroyed in the main-beam direction, and there was partial damage in the foundation. The superstructure of this building is believed

Photo 14 Displaced roof tiles

Photo 15 Metal roofing hung on power lines

Photo 16 Finishing materials torn off the underside of an elevated walkway

Photo 17 Damage to storefront glass

Photo 18 Damage to a 5-story apartment building

to have moved with the foundation after it was destroyed. The 1st story column capitals of the building were severely bent in the main-beam direction (weak axis), and column base bolts were severed in the base plate. The foundation was partially damaged, although a clear pattern could not be discerned.

Photo 13 shows a one-storied steel-frame structure that appears to have been a storage building. The deformation angle of about 1/10 (rad) in the ridge (longitudinal) direction of the steel frame was confirmed to have been residual deformation. There were only furring strips in the ridge direction of the structure, and no compressed beams were found. The shear bolts on the ends of the tensile braces in the ridge direction were severed. The location of the shearing, (top end or bottom end) differed among braces.

3.3 Damage to Reinforced Concrete Buildings

Within the range of the tornado in the present study, there were no frames of reinforced concrete structures that were found to have been damaged by the tornado winds. Also, as will be described in Section 3.4, in the area around a steel-reinforced concrete apartment building (Hojo housing built by Employment Promotion Corp.), there was major damage, such as scattering of superstructure members of the wooden buildings, but the only damage confirmed in the apartment building was at the door or window openings. Similarly to other steel-reinforced concrete buildings, no damage to the frames of this apartment building was found.

3.4 Damage to Building Exteriors

This section describes the main types of damage patterns to materials of building exteriors that were categorized as roofing materials, external wall materials, opening section members, etc. Exterior materials are the most vulnerable to tornado winds, and there were numerous examples of damage in the study area. In addition, at work facilities in the North Industrial Park, not only were the exterior materials damaged, but interior materials were also damaged at the same time, as well equipment systems installed outside of buildings.

The most common type of damage to roofing materials that was found was the displacement of roof tiles of wooden structures. This has also been one of the most common types of tornado damage seen in previous disasters. Photo 14 shows examples of such damage. Damaged roofing materials included not only tiles, but also such things as long sheet metal roofing, which was found hanging from power lines, etc., or which had fallen or crashed onto nearby houses (Photo 15).

In steel-frame office facilities in the North Industrial Park, damage to exterior siding, framework ceilings, etc., was found (Photo16). In addition, finishing materials on the underside of an elevated walkway at a medical facility were also damaged.

Photo 17 shows damage to glass shop windows. Most of this damage was caused by either wind pressure of tornado or by impacts from flying debris. The arrow in Photo 17 shows damage that is believed to have been caused by flying debris.

Photo 18 shows damage to opening and other areas of the Hojo housing built by Employment Promotion Corp. (completed in October 1984). This is a 5-story reinforced concrete housing unit. As can be seen in Photo 7, there was remarkable damage extending to all floors facing the south of the building. Looking at the damage to lower stories, we found that much flying debris had accumulated on 2nd story verandas, and cracks were found in the reinforced concrete rail in the central on 1st floor in the ridge direction. As a result, it appears that damage was caused by numerous pieces of flying debris. In contrast, there was less accumulated debris on the 4th and 5th floor verandas, but the rail near the central on 4th floor in the ridge direction was yanked outward. From this condition, there is a possibility that near the central part in the ridge direction, especially on the upper floors, there was an extremely large negative

Photo 19 Damage to interior materials

Photo 20 Damage to a ceiling

Photo 21 Remarkable deformation to the roof of a bicycle parking area

Photo 22 Broken and tilting utility poles

Photo 23 Overturned passenger cars

Photo 24 Toppled tree

pressure that developed as the tornado approached. However, the aluminum sashes on the north side showed the same type of damage, and numerous aluminum sashes of small, movable windows were also knocked out. Furthermore, it can be confirmed that objects such as bedclothes inside these apartments were moved toward the outside.

3.5 Damage to Interior Materials

Office facilities in the North Industrial Park sustained damage to exterior materials, which was found to have led to damage to interior materials like ceiling materials

(Photos 19 and 20). Some office furniture such as desks and chairs were overturned. However, no damage was found in the structure skeletons of these buildings.

3.6 Other Damage

Besides buildings in the study area, there were numerous examples of damage to other types of structures, automobiles, and trees, among other things.

Photos 21 shows damage to a bicycle parking area whose roof shows wave-like destruction. Bending of road signs can be seen, while Photo 22 shows a series of utility poles that were toppled.

In the study area, numerous automobiles were overturned (Photo 23). In addition, not only light passenger cars but also relatively heavy vehicles like sedans and trucks were overturned. A tree in Photo 24 was toppled and the skin of the tree was peeled off.

4. ESTIMATION OF WIND VELOCITY BASED ON DAMAGE PATTERNS IN BUILDINGS

In the following investigation for buildings and other structures that were confirmed to have been damaged by the tornado, several calculation assumptions such as the power generated by the horizontal rotation flow and a sudden drop in atmospheric pressure, the mechanism for destruction of buildings, the weight of buildings, longitudinal sections of structural members, etc., were used as a basis for estimating the wind velocity that attained the mechanism for destruction of buildings, and the wind velocity at which the windward end of foundations and floor sections of structures began to rise.

4.1 Evaluation of Wind Force

Generally, the wind forces that act upon buildings during a tornado are considered to be the following:

i) Forces generated by horizontal rotational flow
ii) Forces generated by a sudden drop in atmospheric pressure near the center of tornado
iii) Impact forces from flying debris (not examined in the present study)

In i), a uniform horizontal flow is assumed to act upon a building, and the force of the wind pressure ω (N/m^2) is expressed with the following equation. Here, ρ is the air density (1.2 kg/m^3), V (m/s) is the wind velocity of the tornado, and C_f is the wind force coefficient. V is added to the calculation as a vector representation of the wind velocity of the horizontal rotational flow and the velocity at which the tornado progresses.

$$\omega = 0.5\,\rho\, V^2 \times C_f$$

On the other hand, in the case of ii), which includes things that are not considered in the wind force calculations which assume a uniform horizontal flow, for cases where the center of a tornado passes near a building, vertically uplifting suction forces resulting in the sudden drop in air pressure caused by the tornado act upon the entire building, including all parts of the roof, etc.

It should be noted that in the present estimations, several considerations were made for the buildings that were examined for the overturning moment resulting from wind force: integral values of wind pressure from the average height of the roof to the ground surface, and of wind pressure at the range of roof surface for the vertical direction (excluding the range of the eaves). Each of these wind forces is considered to act upon a building. For the horizontal direction of buildings that were studied for horizontal force resulting from wind force, the integral value of the wind pressure from the building height to the center of the 1st story was considered to act as wind for upon a building in the same way as normal wind force calculations. In addition, for structures that were examined for the overturning moment resulting from wind force, the integral value of wind pressure from the structure height to the ground surface was considered to act as wind force, in the same way as on buildings, while the wind force acting in the vertical direction was ignored.

4.2 Collapsed Wooden Buildings

The building in Photo 1 was a 2-story wooden structure located in the Hojo district of Tsukuba City. The 1st story section was destroyed. Nearby

were such structures as a tilting steel-frame building (Photo 13) and wooden buildings whose superstructures were blown away while their foundations remained (Photo 6 and 7).

From measurements taken of overturned foundations (estimated from laser distance measurements and photographs), it was estimated that the floor area was 6.5 m span× 9.2 m ridge. The roof was a tiled hip roof with an estimated pitch of 16.7 degrees. The length of the eaves was estimated to be 0.455 m (one side) based on comparisons between roof surface and floor area from an aerial photograph and based on standard dimensions of wooden buildings. From this information, the average roof height from the ground surface was calculated to be 6.45m. Regarding the destruction mechanism, it was assumed that the overturning center was the base of foundation on the downwind side on the structure plane of span (the base of foundation in Photo 3), and that a height H of 6.65m was the summation of the average roof height from ground, 6.45 m and 0.2m, the thickness of the floorboards of the foundation. In addition, the weight of the building was calculated to be 630.5 kN.

<u>(1) Cases where only horizontal rotational flow of a tornado acts upon a building</u>

For the wind force calculated using the wind force coefficients (horizontal and vertical directions) in a uniform horizontal flow for the building, when the wind force reached the overturning resistance moment, the wind velocity is calculated as follows:

$$M_w = W \times (D/2) \times 1000 \quad \text{(Nm)} \tag{1}$$

$$M_h = B\int_{H'}^{H} (0.5\rho C_{fh} V^2) x\, dx \quad \text{(Nm)} \tag{2}$$

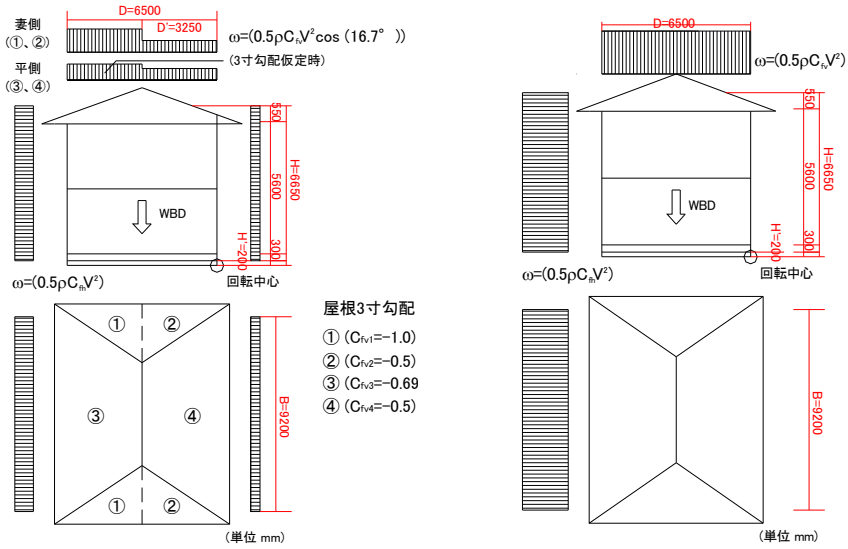
$$q = 0.5\rho V^2 \quad \text{(N/m}^2\text{)} \tag{3}$$

$$\begin{aligned} M_v &= \int_0^{D/2} 2C_{fv2} q\cos(16.7°) x^2 dx + \int_{D/2}^{D} 2C_{fv1} q\cos(16.7°) x(D-x) dx \\ &+ \int_0^{D/2} C_{fv4} q\cos(16.7°) x(B-2x) dx + \int_{D/2}^{D} C_{fv3} q\cos(16.7°) x(B-2D+2x) dx \\ &= \left\{ \frac{1}{12}D^3 C_{fv2} + \frac{1}{6}D^3 C_{fv1} + \left(\frac{1}{8}BD^2 - \frac{1}{12}D^3\right) C_{fv4} + \left(\frac{3}{8}BD^2 - \frac{1}{6}D^3\right) C_{fv3} \right\} q\cos(16.7°) \quad \text{(Nm)} \end{aligned} \tag{4}$$

The calculations were made using ridge length B (m), span length D (m), and height H (m). Also, total building weight is W (kN), and thickness of the floorboards of the foundation is H', with overturning resistance moment M_w (Nm), overturning moment due to horizontal wind force M_h (Nm), and overturning moment due to vertical wind force M_v.

Here, the overturning resistance moment M_w around the basic rotation center of the building was calculated by multiplying total building weight W by half of the span span length D of the building (Eq.1). On the other hand, the overturning moments due to wind force (M_h and M_v) were calculated by integrating the roof area of the building ($B \times D$) with the wind pressure ($0.5\,\rho \times V^2 \times C_f$, or C_{fv1}, C_{fv2}, C_{fv3}, C_{fv4}) upon the wall surface in the building's ridge direction ($B \times (H-H')$) (Eqs. 2, 3 and 4). Here, q is the velocity pressure (N/m2). C_{fh} is the wind force coefficient of the wall surface of the building's ridge direction, and C_{fv1}, C_{fv2}, C_{fv3}, C_{fv4} are all coefficients of vertically uplifting wind force acting upon hipped roofs.

Figure 4(a) shows the distribution of wind pressure. When the vertical wind force coefficients were set as C_{fv1}, C_{fv2}, C_{fv3},and C_{fv4}, the hypothetical external pressure coefficients acting upon buildings with hip roofs were assumed as C_{fv1} = -1.0, C_{fv2} = -0.5, C_{fv3} = -0.69, and C_{fv4} = -0.5. Furthermore, when the



(a) Case of action by only horizontal rotating force (b) Case of action by sudden drop in air pressure

Figure4 Hypothetical distribution of wind pressure

$$M_w = W \times (D/2) \times 1000 \quad \text{(Nm)} \qquad (5.3.5)$$

$$M_h = B\int_{H'}^{H} (0.5\rho C_{fh} V^2) x\, dx \quad \text{(Nm)} \qquad (5.3.6)$$

$$M_v = B\int_{0}^{D} (0.5\rho C_{fv} V^2) x\, dx \quad \text{(Nm)} \qquad (5.3.7)$$

hypothetical wind force coefficient C_{fh} of the wall surface of the building's ridge direction was 1.2, the wind velocity at the start of overturning is estimated

<u>$V = 97$ (m/s)</u> (F4)

<u>(2) Cases where a sudden drop in atmospheric pressure acts upon a building, in addition to (1)</u>

In addition to the wind force generated by the horizontal rotational flow, when a passing tornado causes a sudden drop in air pressure, the wind velocity at the time when the cumulative effect of these forces results in the overturning resistance moment of the building being reached is calculated as follows.

In this case, values of the vertical wind force coefficient C_{fv} and the wind force coefficient C_{fh} of the wall surface of the building's ridge direction were obtained from wind pressure tests that utilized the equipment for generating tornado-like air flow conditions. However, the experimental results were obtained under test conditions that were limited to those listed in Reference 1. Generally, the value of the wind force coefficient is considered to depend on various conditions such as the ratio between the radius of the rotational flow core and the building dimensions and the traveling velocity of the tornado. Therefore, as a wind force coefficient of the wall surface of the building's ridge direction, the investigation was conducted using the coefficient 1.2 which is used when a uniform lateral flow is assumed (this was 60% of the wind force coefficient C_{fh} of the results of pressure experiments that utilized the tornado-like conditions generator). In these investigations, the pressure acting upon the floor surface of the mat foundation was assumed to be roughly equal to inner pressure of the model obtained from the pressure experiments, and the pressure difference (between that acting on the roof surface and that on the foundation floor) when the tornado was passing through was considered to be the maximum vertical uplifting value.

Similar to the investigation in (1), the overturning resistance moment Mw around the rotation center of the base of the building was calculated by multiplying the weight of the building W by half of the of the span length D (Eq.5). On the other hand, the overturning moments due to wind force (M_h and M_v) were calculated by integrating the wind pressure ($0.5\rho V^2 \times C_{fh}$ or Cf_v) which acting upon the roof surface ($B \times D$) of the building and the wall surface of the building's ridge direction ($B \times (H - H')$) with respect to areas (Eqs. 6 and 7).

Figure 4(b) shows the hypothetical wind pressure distribution that was used here. Based on the results of the experiments for generating tornado-like rotational flow in Reference 2 (see Reference Figure 1 and Reference Table 1), the wind force coefficient for vertical uplifting from C_{pe} (x/R ≒ 1.0) was assumed to be -1.8. When the tornado-like rotational flow acted on the building anticlockwise, and when wind force coefficient C_{fh} of the wall surface of the building's ridge direction was assumed to be 2.0 or 1.2, each wind velocity at the start of overturning was estimated respectively,

<u>V = 68 m/s</u> (for wind force coefficient C_{fh} of 2.0 on the wall surface of the building's ridge direction),

or

<u>V =77 m/s</u> (for wind force coefficient C_{fh} of 1.2 on the wall surface of the building's ridge direction).

(Reference 1)
Assumptions for calculating building weight

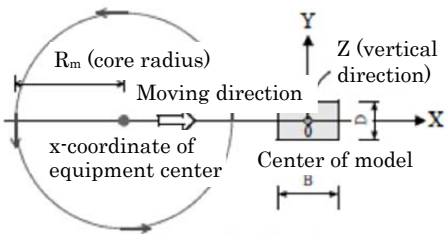
* Wall: Outer wall: siding, inner wall: plasterboard (estimated from flying debris)
* Roof: Hip roof, tiles (estimated from flying debris), 3-sun pitch, eaves of 0.455 m
* Foundation: Mat foundation (considered to be used in ordinary wooden houses, with assumed elevated height of 0.3 m, width of 0.15 m, floorboard thickness of 0.2 m)
* Loaded weight: 0.3 kN/m^2 (half of normal loaded weight for calculating earthquake force)
* Interior wall line: 3 in the ridge direction, 4 in the span direction (estimated from the build-up in the foundation)
* Exterior wall opening ratio: 1st floor 30%, 2nd floor 20% (assuming an ordinary wooden house)
* Average height of the roof from the building's foundation: 6.45 m (= 0.3 m + 2.8 m × 2 + 0.5 × 1.1 m) (see Fig. 4)
* Total building weight: 630.5 kN

(Reference 2)

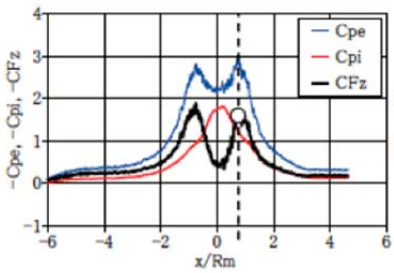
* Definition of coordinates, etc., in Reference, experimental conditions and results of wind pressure experiments
* C_{pe}: External pressure coefficient of vertical uplifting, C_{fy}: wind pressure coefficient of the wall (Y direction)
* (C_{pr}: Internal pressure coefficient; C_{Fz}: wind power coefficient of vertical uplifting; C_{Fx}: wind pressure coefficient of the wall surface (X direction)
* x: central coordinate of the tornado-like air flow generator moved for the center of the model;
* Rm: core radius of rotational flow

Reference Table 1. Experimental conditions
(experimental scale of 1/250)

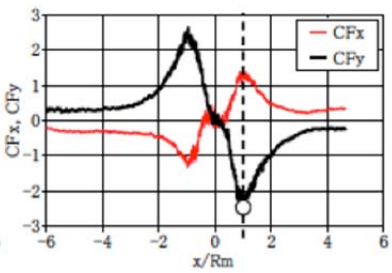
Model dimensions	Span D	98 mm
	Ridge B	152 mm
	Eaves height	49 mm
	Roof pitch	1/12 (gabled roof)
Core radius of rotational flow R_m		0.36 m
Ratio between model dimensions and core radius of rotational flow $(BD)^{0.5}/R_m$		0.34
Maximum tangent velocity V_m of rotational flow		9.6 m/s
Traveling velocity of the equipment		0.15 m/s



Ref. Fig.1 Definition of coordinates, etc.



(a) External pressure coefficients of vertical uplifting



(b) Wind force coefficients of wall surfaces

5. CONCLUSIONS

The National Institute of Land and Infrastructure Management (NILIM) and Building Research Institute (BRI) conducted investigations into the damage to buildings and others caused by the tornado occurred on May 6, 2012 in Tsukuba City, Ibaraki Prefecture. Estimation of wind speed at the time of damage occurrence and damage causing mechanism as well as patterns and distribution of the damage through on-site studies were also examined. The results can be summarized as follows:

(1) Statistics and distribution of damage

Damage of buildings and others in Tsukuba City was evaluated according to the high wind damage scale and the results were summarized in a damage distribution map, and then the distribution patterns were studied. The radius of maximum wind speed of the tornado which was supposed according to Rankine vortex models was estimated at about 35 meters based on damage distribution in Hojo area, Tsukuba City.

(2) Patterns of damage to buildings and others and damage causing mechanism

As for the major patterns of damage to buildings induced by the tornado, following data were obtained from on-site studies; those to wooden houses were overturning, scattering and collapse of upper structure, collapse of roof systems, breakage and peeling of exterior materials (roof materials, exterior walls and opening materials). Those to steel-framed and reinforced concrete buildings were breakage, peeling of exterior materials (roof materials, exterior walls and opening materials), etc. Damage was also extended to interior materials and outdoor equipment. As damage examples other than buildings, data of damaged structures, automobiles, trees, etc. were gathered.

The mechanism to cause damage to wooden buildings was examined based on assumed damage patterns. With regard to two-story wooden housing, wind speed causing collapse (failure of ultimate horizontal strength) and overturning are compared in their destruction modes.

(3) Estimation of wind speed based on patters of damage to buildings, etc.

Wind speed at the time of damage was estimated by assuming collapse mechanism of damaged buildings and structures, wind speed coefficient, etc. The relation between the distance from the tornado center and the estimated velocity was then studied. The results showed good correspondence with the wind speed distribution of tornado based on Rankine vortex models.

6. REFERENCES

1. NILIM and BRI: Quick Report on Damage to Buildings by the Tornado on May 6, 2012 in Tsukuba City, Ibaraki Prefecture, JAPAN http://www.nilim.go.jp/lab/bbg/saigai/h24tsukuba/h24tsukuba-e.pdf