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An Analysis of Damaged Wind Turbines by Typhoon Maemi in 2003

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ABSTRACT

This paper reports damages of wind turbines on Miyakojima Island by Typhoon Maemi on September 11, 2003. Maemi struck the island with an average wind speed of 38.4m/s and a maximum gust of 74.1m/s, recorded at Miyakojima meteorological station. All six wind turbines operated by Okinawa Electric Power Company were extensively damaged. Two Micon M750/400kW turbines collapsed by the buckling of the towers and one Enercon E40/500kW turbine turned over due to the destruction of the foundation. For the other three, the blades were broken and the nacelle cover was damaged. From wind tunnel test and numerical simulation, the maximum wind speed was estimated to be approximately 60m/s and the maximum gust to be 90m/s at the turbine sites. The maximum bending moment of the destructed foundation was larger than the ultimate bending moment because only one blade was feathering. The maximum bending moment of the collapsed towers were larger than the ultimate bending moment because of undesirable slippage of locked yaw while the maximum bending moment of the survived tower was lower than the ultimate bending moment.

INTRODUCTION

Miyakojima Island is one of the largest inhabited islands in Okinawa Prefecture with the population of 47,000, which is located 1,800km away from Tokyo as shown in Fig. 1. The island is mostly flat, and the highest elevation point is 113 meters above sea level and the area is 150 square kilometers.

On September 11, 2003, Typhoon Maemi struck the island with a central pressure of 912hPa, which is the fourth lowest in the history of Japan. The maximum gust of 86.6m/s was observed with northerly wind at the Air Self Defense Force Miyakojima Base located on top of a hill about 100m above sea level.

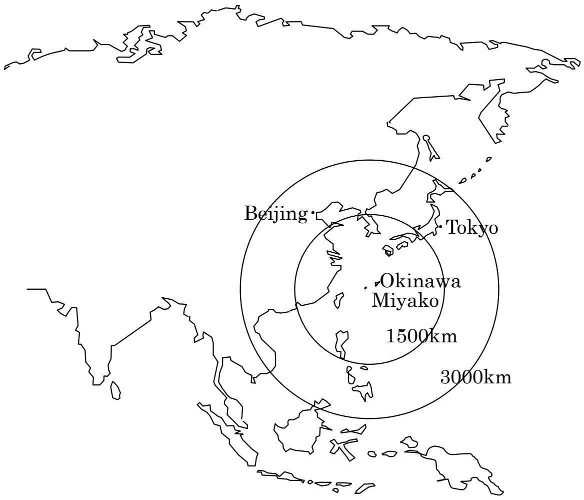

Fig. 1 Location of Miyakojima Island

All the wind turbines on the island, operated by Okinawa Electric Power Company, manufactured by Micon, Enercon and Vestas, were extensively damaged. Three of six turbines collapsed and the other three suffered destructive damage, whose blades were broken or the nacelle cover drooped.

The aim of this study is to clarify the damage of wind turbines located on the island caused by this typhoon. First, an onsite investigation and material test was conducted. Then, maximum wind speed and the maximum gust were estimated by wind tunnel test and numerical simulation. Finally, FEM simulation and wind response analysis were performed to evaluate the ultimate bending moment and maximum bending moment acting on the turbine towers and the foundation.

TYPHOON MAEMI (T0314)

Typhoon Maemi originated near Mariana Islands at around 3 p.m. on September 6th, 2003. By 9 p.m. on the 10th, it had grown to a maximum velocity of 55 m/s. The Miyakojima Island was exploded to strong wind higher than 25m/s from 5 p.m. on the 10th to 5 p.m. on the 11th. Maximum wind speed of 38.4 m/s (northerly) was recorded at 3 a.m. and maximum gust of 74.1 m/s at 3:12 a.m. which is the seventh highest in Japanese history. Fig. 2 shows a satellite image when Typhoon Maemi hit Miyakojima Island.

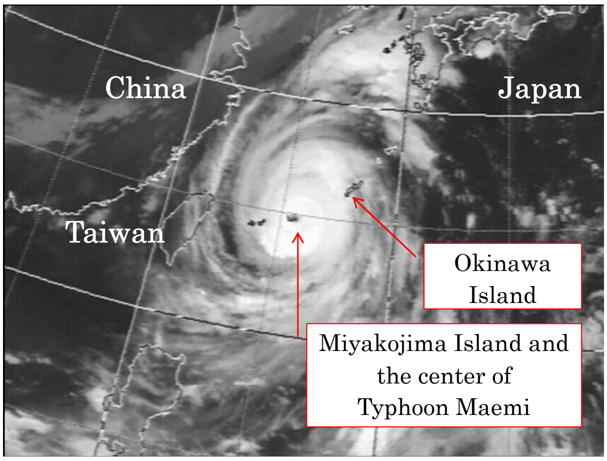

Fig. 2 Satellite image of typhoon Maemi at 3 a.m. September 11, 2003

THE DAMAGE OF THE WIND TURBINES

Fig. 3 shows the locations of the wind power plants on Miyakojima Island. Six turbines were located at Karimata on the north side of the island, and Nanamata along the southern coastline of the island. Three of six turbines collapsed and the other three suffered destructive damage, whose blades were broken or the nacelle cover drooped.

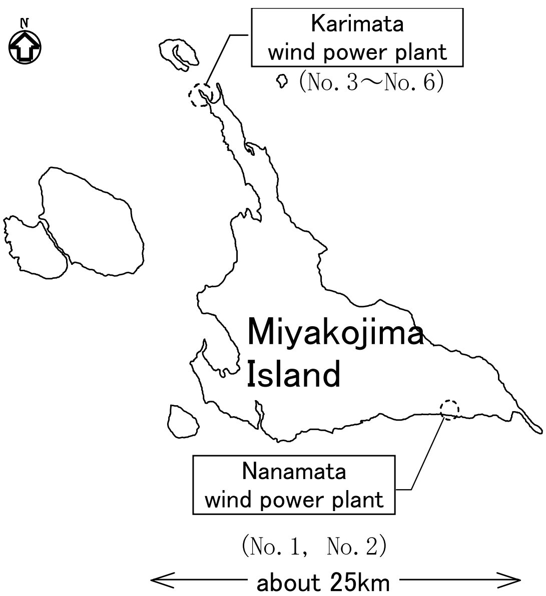

Fig. 3 The locations of wind power plants

Damage of the wind power plant at Nanamata

Fig. 4 shows the Nanamata wind power plant before the damage. Wind Turbine (WT) No. 1 is supplied by Enercon with a rated power of 500 kW and WT No. 2 by Vestas with the rated power of 600 kW. A solar power generation system with a capacity of 750 kW is located at the south to the turbines.

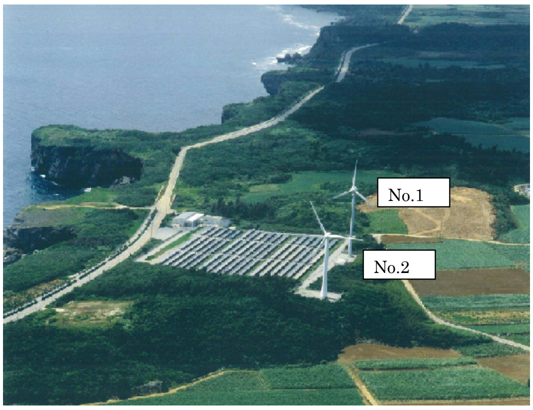

Fig. 4 Turbines at Nanamata before the damage

Table 1 shows the damages on the turbines in detail. WT No.1 was collapsed down onto solar power equipment due to foundation destruction, and the blades of WT No.2 were also damaged as shown in Fig. 5.

Table 1 Damage to the Nanamata Turbines

	System specifications	Damage
WT No. 1	Manufacturer: Enercon Rated power: 500 kW Regulation: Pitch Hub height: 44m	・Collapsed due to foundation destruction
WT No 2	Manufacturer: Vestas Rated power: 600 kW Regulation: Pitch Hub height: 35m	・Nacelle cover cracked ・Blades broken

(a) WT No. 1 (b) WT No. 2

Fig. 5 Damaged turbines at Nanamata

Damage of the wind power plant at Karimata

Fig. 6 shows the Karimata wind power plant before the damage. WT No. 3 to 5 are supplied by NEG Micon with a rated power of 400 kW and WT No. 6 by Enercon with the rated power of 600 kW.

Table 2 shows the damages on the turbines in detail. WT No.3, 4 and 5 were same machine. WT No.3 and 5 were collapsed by the buckling of the towers near the entrance door. The nacelle cover of WT No.4 was drooped and the nosecone was lost. The two blades of WT No.6 were broken at their roots.

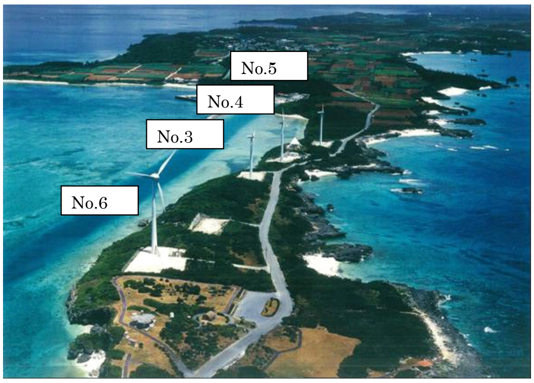

Fig. 6 Turbines at Karimata before the damage

Table 2 Damages of the Karimata Turbines

	System specifications	Damage
WT No. 3	Manufacturer: Micon Rated power: 400/100kW Regulation: Stall Hub height: 36m	・Collapsed due to the buckling of the tower near the entrance door
WT No. 4	Manufacturer: Micon Rated power: 400/100kW Regulation: Stall Hub height: 36m	・Nacelle cover damaged ・Nose cone lost
WT No. 5	Manufacturer: Micon Rated power: 400/100kW Regulation: Stall Hub height: 36m	・Collapsed due to the buckling of the tower near the entrance door
WT No. 6	Manufacturer: Enercon Rated power: 600kW Regulation: Pitch Hub height: 46m	・Blades broken ・Nacelle cover damaged

(a) WT No. 3 (b) WT No. 4

(c) WT No. 5 (d) WT No. 6

Fig. 7 Damaged wind turbines at Karimata

The Micon's turbines were designed with the function that the yaw should be locked with disk-brake after cut-out wind speed. However, it was found that the yaws of WT No.3, 4, 5 were moved clockwise from 94° to 156° when the wind speed exceed 25 m/s as shown in Fig. 8. As a result, they suffered larger wind load during the typhoon than the designed wind load.

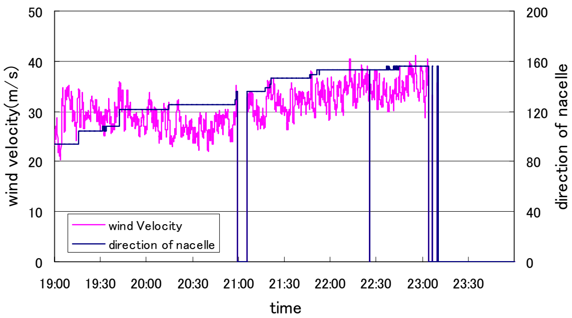

Fig. 8 Time series of yaw direction and the wind speed of turbine No. 5 at Karimata on September 10, 2003

MECHANISM OF THE DAMAGES OF THE TURBINES

To clarify the damage of wind turbines, investigation was performed as shown in Fig. 9. First, an onsite investigation was conducted to measure the direction of collapse, entrance door and nacelle and the position of the blades. Then material test was performed to find the property of the steel tower and the concrete foundation using the specimen extracted at the site (Ishihara et al. 2005). Maximum wind speed and the maximum gust were estimated by wind tunnel test and numerical simulation. Finally, FEM simulation and wind response analysis were performed to evaluate the ultimate bending moment and maximum bending moment acting on the turbine towers and the foundation.

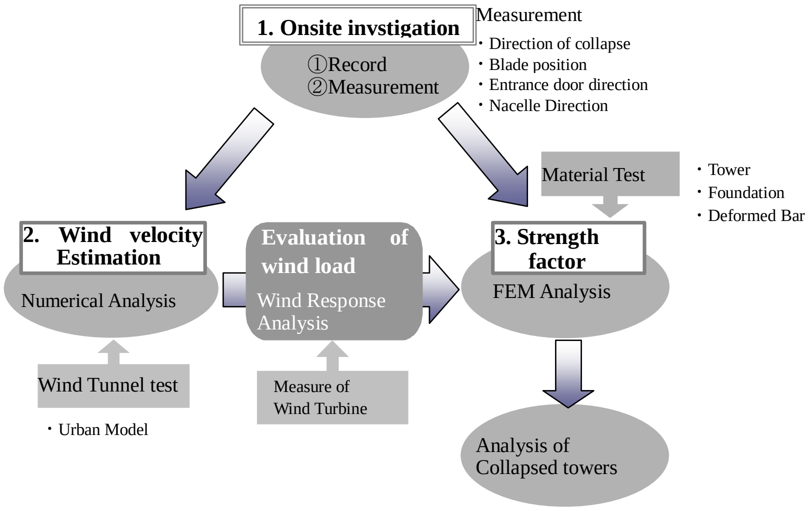

Fig. 9 Flow chart of the investigation

<u>Wind speed estimation</u>

After the loss of grid connection, wind speed at the site was not recorded for the evaluation of maximum wind load. Although time series of wind speed and wind directions was recorded at Miyakojima meteorological station, they could not be directly used to estimate the maximum wind load of the turbines because the station is located in urban area and observed wind speed is strongly affected by surrounding buildings.

Wind tunnel test as described by Yamaguchi et al. (2003) or numerical simulation (Ishihara and Hibi 2002, Ishihara et al. 2003) have been used for the estimation of wind speed. Wind tunnel tests can accurately evaluate the effect of buildings. But it is difficult to simulate the roughness of the ocean. On the other hand, numerical simulation (CFD) can easily simulate the roughness of ocean and the effect of topography. However, it requires numerous grids to estimate the flow around the building.

To overcome these disadvantages, a new hybrid method with a combination of wind tunnel test and numerical simulation was proposed and used to estimate the maximum wind speed and the turbulence at the sites. The detail of the hybrid method is described by Ishihara et al. (2005). In this study, first, a wind tunnel test with urban model was carried out to investigate the effect of urban roughness and to obtain the time series of wind speed over flat terrain. Next, numerical simulation with terrain model was carried out to estimate the wind speed at the sites based on wind speed over flat terrain obtained by wind tunnel test.

<u>Wind tunnel tests</u> The observed wind speed at the meteorological station is strongly affected by surrounding buildings. A wind tunnel test with 1/1000 urban model was carried out to investigate the effect of urban roughness and to estimate the wind speed over flat terrain. Fig. 10 shows the urban model used in wind tunnel test conducted at Wind Engineering Laboratory, the University of Tokyo University.

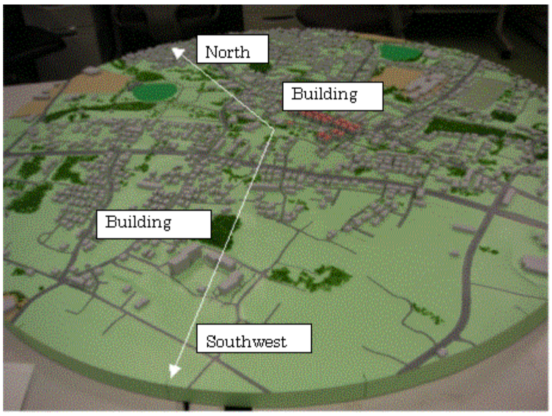

Fig. 10 Urban model surrounding the meteorological station

Fig. 11 shows the time series of mean wind speed recorded at the meteorological station and estimated one over flat terrain. It was noticed that for northerly wind, the wind speed decreases by the factor of 0.77 at the meteorological station compared to flat terrain. Thus, the maximum wind speed during typhoon is estimated to be 49.6m/s over flat terrain.

Sudden change in wind direction as shown in Fig. 12 was observed when the center of the typhoon passed right over the island at 3 a.m. on September 11, 2003. As a result, the change in the wind direction was 120degrees from 360° at 3 a.m. to 240° at 6.a.m.

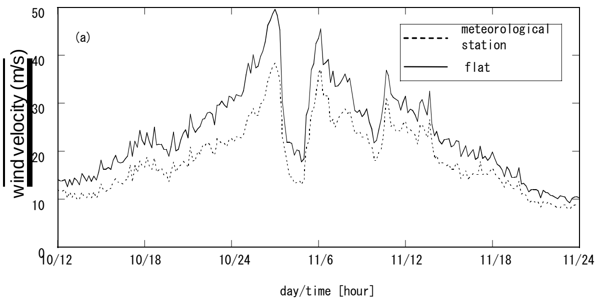

Fig. 11 Wind Velocities Converted for Flat Terrain

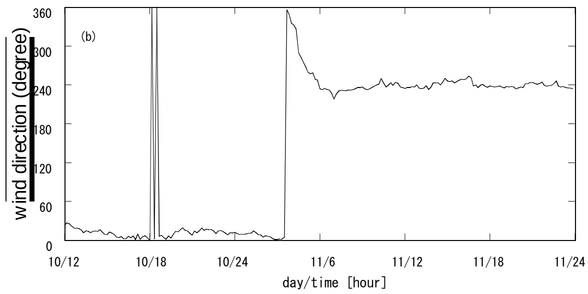

Fig. 12 Wind Directions Changes Across the Flat Terrain

Numerical simulation Numerical simulation with CFD was carried out to take the effect of local terrain into account and to estimate the wind speed at the sites based on those over flat terrain from the wind tunnel test. To verify the simulation, estimated wind speed was compared with records observed at Miyako branch office (Fig. 13) of Okinawa Electric Power Company, which is located slightly north to the meteorological station.

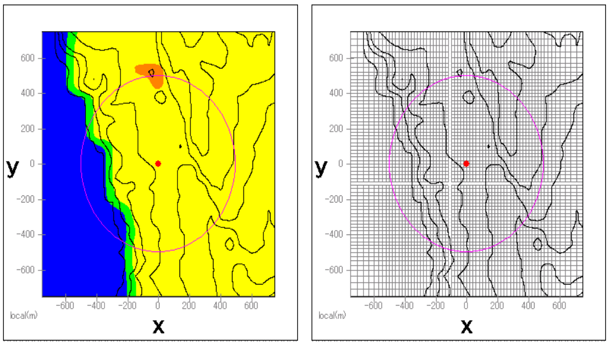

Fig. 13 Elevation contour, surface roughness and computational grid around Miyako branch office of Okinawa Electric Power Company

Fig. 14 and 15 show comparison of the estimated and observed wind speed and direction. It was found that the estimated wind speed and direction give good agreements with the observation.

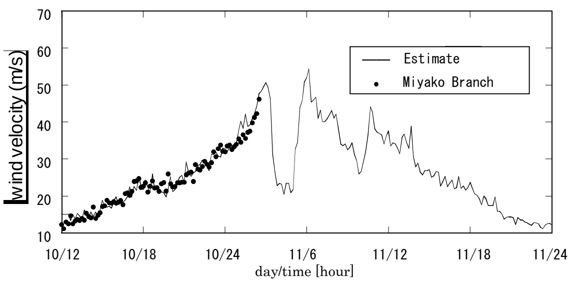

Fig. 14 Comparison of Estimated and Actual Average Wind Velocities

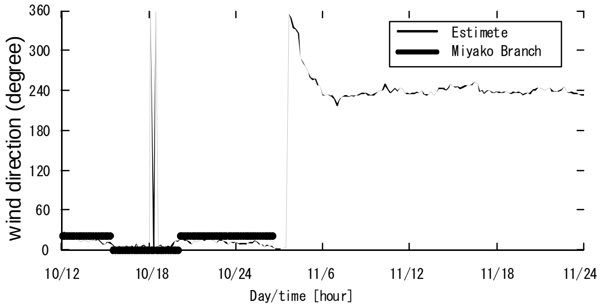

Fig. 15 Comparison of Estimated and Actual Wind Directions

Table 3 shows the maximum wind speed and the maximum gust estimated at the turbine sites. It was found that the maximum wind speed was approximately 60m/s. The maximum gust was also estimated with the method proposed by Ishizaki (1983) and found to be 90m/s.

Table 3 The maximum wind speed and the maximum gust estimated at the turbine sites

Site	Wind Turbine	Hub Height (m)	Estimated value	
			Max. wind speed (m/s)	Max. gusts (m/s)
Karimata wind power plant	No. 3	36	59.7	87.9
	No. 4	36	59.2	87.3
	No. 5	36	59.4	87.6
	No. 6	46	61.5	90.3
Nanamata wind power plant	No. 1	44	59.8	90.7
	No. 2	35	56.8	87.4

FEM analysis for the destructed foundation

FEM analysis A FEM analysis with solid elements was performed using the property obtained from material test. The specimens were extracted from the destructed foundation. Fig. 16 shows the foundation model, in which anchor bolts, rings and steel bars were modeled.

Fig. 17 shows the relationship between the displacement at the tower top and base bending moment. The ultimate bending moment was 23,864kNm. It was found that the bending moment suddenly falls down at the tower top displacement of 1.0m, the shear strain at which stage is shown in Fig. 18. This indicates that the tenacity of the foundation is low causing easy destruction.

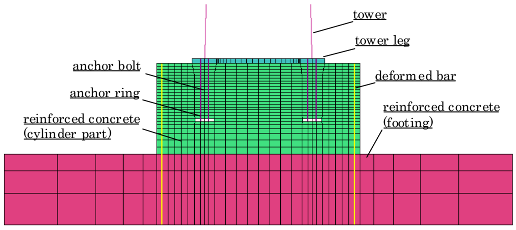

Fig. 16 Foundation model

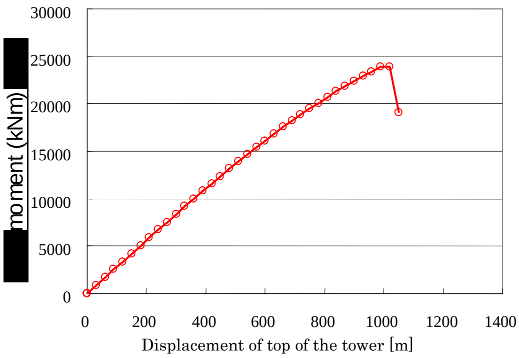

Fig. 17 Relationship between the displacement at the tower top and base bending moment

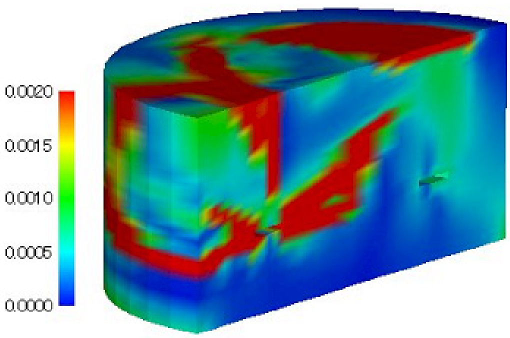

Fig. 18 Perspective view primary shear strain contour

Wind Response Analysis To clarify the reason why the foundation of turbine No. 1 was destructed, full dynamic simulation was performed using a FEM model (Shimizu and Sato 2001) with beam elements to estimate the maximum bending moment during the typhoon. The pitch angles of the blades were determined based on the field investigation (Ishihara et al. 2005), which indicated only one blade was feathering.

It was found that the maximum bending moment exceeded the ultimate bending moment during the typhoon as shown in table 4.

Table 4 Bending Moment Values used for the Foundation

	Maximum bending moment A (kNm)	Ultimate bending moment B(kNm)	Maximum bending moment C (kNm)	Comment
No. 1	8,273	23,868	24,740	B<C

Buckling analysis for the collapsed towers

FEM analysis A FEM analysis with shell elements was performed using the property obtained from material test. The specimens were extracted from the collapsed tower. The variations of the ultimate bending moment of the tower with wind direction were evaluated by the horizontal load acting on the top of the tower. Fig. 19 shows the notation and the dimension of the tower model. The thickness of the tower is 10cm at the upper section and 12cm at the lower section. 0 degree denotes the directions of the entrance door.

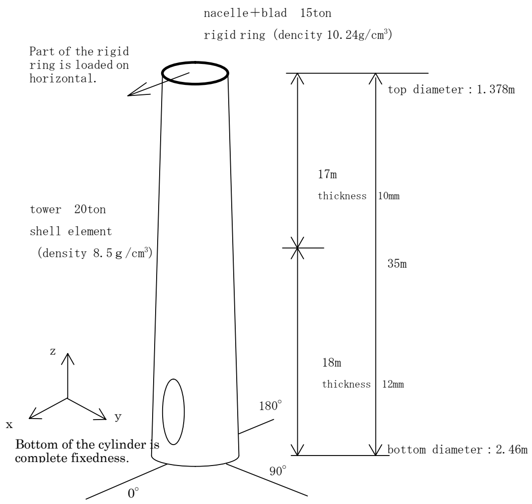

Fig. 19 The notation and the dimension of the tower model

Fig. 20 shows the relationship between the wind load and the displacement at the tower top. It was found that the horizontal load suddenly falls down at the tower top displacement of 0.6m when the wind load is acting on the opposite side of the entrance door (0°) and that the ultimate bending moment was 12,540kNm.

Fig. 21 shoes the variation of the ultimate load with the direction of wind load. It is obvious that the tower buckles easy when the wind load acts on the tower with the angle ranges from 0° to 40°.

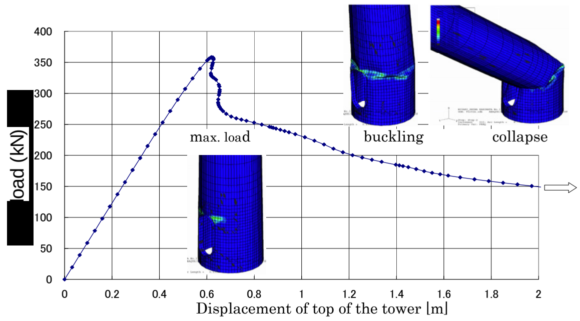

Fig. 20 Load Variables

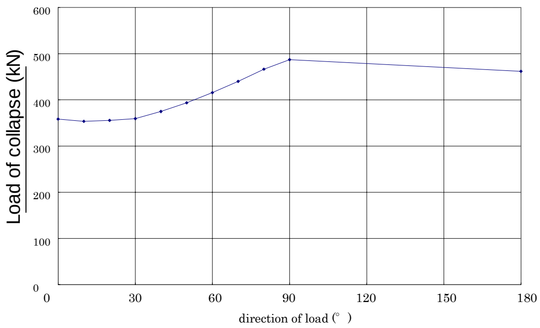

Fig. 21 Buckling Strength Against Direction of Load

Wind Response Analysis To clarify the reason why turbine No. 3 and 5 collapsed while No. 4 survived, the maximum bending moment acting on each wind turbines during the typhoon was evaluated by FEM model with beam elements. Full dynamic simulation was performed to find the response of the blade, nacelle and tower. Vertical profile of mean wind and turbulence from the wind tunnel test and the numerical simulation was used to generate three-dimensional turbulent field using the method proposed by Iwatani (1982). Blade shape as well as position and nacelle direction of each turbine used in this simulation were obtained from onsite investigation.

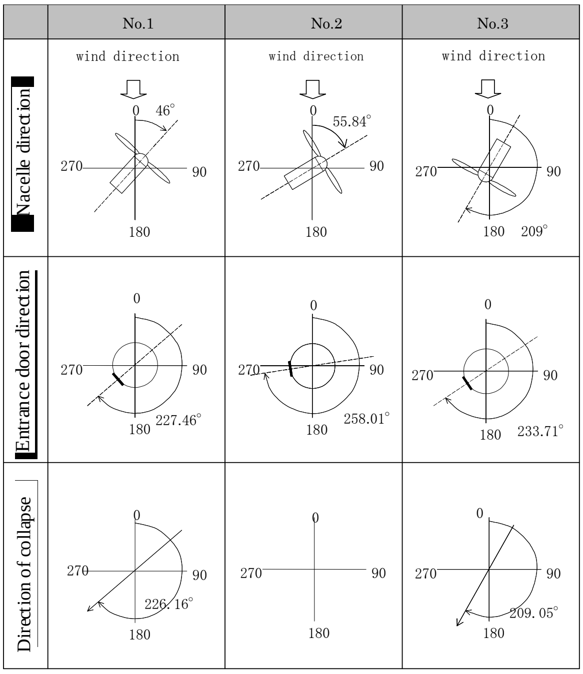

Fig. 22 wind direction, yaw direction and the direction of the entrance door and collapse

Fig. 22 shows the wind direction, yaw direction and the direction of the entrance door and collapse. When the angle between the wind direction and the yaw direction is small, the wind load is large and the tower is likely to buckle when the angle between wind direction and the direction of the door is small.

Table 5 shows the bending moments for each turbine tower. It is obvious that the maximum bending moment for Turbine No. 4 is relatively lower than the values for Turbines No. 3 and 5. This is due to the difference of the nacelle direction among turbines. Despite the fact that all three turbines have the same structure, the maximum bending moment of the wind turbine No.3 and No.5 exceeded ultimate bending moment, while the maximum bending moment of wind turbine No. 4 was lower than the ultimate bending moment. This is why the wind turbine No.3 and No.5 were buckled and collapsed, but wind turbine No. 4 survived during the typhoon.

Table 5 Bending moments for each turbine tower

	Designed bending moment A (kNm)	Ultimate bending moment B (kNm)	Maximum bending moment C (kNm)	Summery
No. 3	12,177	12,808	14,369	B<C
No. 4	12,177	13,878	12,973	B >C
No. 5	12,177	13,492	15,398	B<C

CONCLUSIONS

In this study, field investigation was conducted to clarify the damage of wind turbines located on Miyakojima Island caused by typhoon Maemi in 2003. Maximum wind speed and the maximum gust were estimated by wind tunnel test and numerical simulation. FEM simulation and wind response analysis were performed to evaluate the ultimate bending moment and maximum bending moment acting on the turbine towers and the foundation. Following conclusions were obtained.

(1) Typhoon Maemi struck Miyakojima Island with a central pressure 912hPa. An average wind speed of 38.4m/s and a maximum gust of 74.1m/s were recorded at Miyakojima meteorological station, which was the seventh largest in history. The observed wind direction showed a sudden change in wind direction of 120°.
(2) All the wind turbines on the island manufactured by Micon, Enercon and Vestas were extensively damaged. Three of six turbines collapsed and the other three suffered destructive damage, whose blades were broken or the nacelle cover drooped.
(3) From wind tunnel test and numerical simulation, the maximum wind speed was estimated to be approximately 60m/s and the maximum gust to be 90m/s at the turbine sites.
(4) The maximum bending moment of the foundation of Nanamata wind turbine No.1 was larger than the ultimate bending moment causing the destruction of the foundation.
(5) The reason for the buckling and the collapse of the tower of Karimata wind turbines No.3 and 5 is that the maximum bending moment of the towers were larger than the ultimate bending moment. The maximum bending moment of wind turbine No. 4 was lower than the ultimate bending moment. This is why the wind turbine No.3 and No.5 were buckled and collapsed, but wind turbine No. 4 survived during the typhoon.
(6) Following points were learned and should be useful in wind turbine design in the future: a) the locked yaw can be slipped undesirably; b) the tenacity of the foundation is very low causing the easy destruction; c) some tower have its most weak part at its entrance door, which might cause undesired buckle and collapse of the tower.

In Japan external force is strong, so it is necessary to evaluate the ultimate strength of the turbine in design process and it is important that the manufacturers provide data needed to perform structural analysis and wind resistant design.

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