UNIVERSITY OF BIRMINGHAM
University of Birmingham
Research at Birmingham

Wind Turbine Tower Collapse Cases: A Historical Overview

Ma, Yang; Martinez-Vazquez, Pedro; Baniotopoulos, Charalampos

DOI:
10.1680/jstbu.17.00167

License:
None: All rights reserved

Document Version
Peer reviewed version

Citation for published version (Harvard):
Ma, Y, Martinez-Vazquez, P & Baniotopoulos, C 2018, 'Wind Turbine Tower Collapse Cases: A Historical Overview', *Institution of Civil Engineers. Proceedings. Structures and Buildings*. https://doi.org/10.1680/jstbu.17.00167

Link to publication on Research at Birmingham portal

Publisher Rights Statement:
Checked for eligibility: 16/05/2018
Final version of record available at: https://doi.org/10.1680/jstbu.17.00167

General rights
Unless a licence is specified above, all rights (including copyright and moral rights) in this document are retained by the authors and/or the copyright holders. The express permission of the copyright holder must be obtained for any use of this material other than for purposes permitted by law.

- Users may freely distribute the URL that is used to identify this publication.
- Users may download and/or print one copy of the publication from the University of Birmingham research portal for the purpose of private study or non-commercial research.
- User may use extracts from the document in line with the concept of 'fair dealing' under the Copyright, Designs and Patents Act 1988 (?)
- Users may not further distribute the material nor use it for the purposes of commercial gain.

Where a licence is displayed above, please note the terms and conditions of the licence govern your use of this document.

When citing, please reference the published version.

Take down policy
While the University of Birmingham exercises care and attention in making items available there are rare occasions when an item has been uploaded in error or has been deemed to be commercially or otherwise sensitive.

If you believe that this is the case for this document, please contact UBIRA@lists.bham.ac.uk providing details and we will remove access to the work immediately and investigate.

Download date: 21. Sep. 2020

Wind Turbine Tower Collapse Cases: A Historical Overview

Y. Ma, P. Martinez-Vazquez, C. Baniotopoulos
School of Engineering, University of Birmingham, Edgbaston B15 2TT, Birmingham, United Kingdom

Abstract

Wind turbines are conceived, designed and operated to interact with the environment including through extreme events. However, engineering malpractices combined with human or mechanical errors and defects of constituent members and materials, still derive in hundreds of structural collapse cases annually from which at least 6% have fatal consequences and about the half involve human injury. It seems therefore, necessary to reflect on factual wind turbine performance against the target. The present paper summarises the most severe tubular wind tower collapse incidents recorded over the past four decades, makes an account of the damage and discusses the respective potential causes. The investigation indicates that although accidental load induced by typhoons and wind storms is the most usual reason of failure, fatal events concentrate at either early or late stage of the designed service life. Unexpected load conditions seemed to derive from defective blade positioning or braking which in turn over-stress areas of transition such as joints and openings. On the other hand, a critical examination of design standards suggests that in general, wind turbine towers as designed and built nowadays are stable and reliable. Hence, the chain relationship determined by the design, manufacturing, construction, operation and maintenance, needs enhancement and further cohesion, at the time that our understanding of and adaptation to extreme events continue developing.

Introduction

Wind energy plays a decisive role in the global renewable energy development which derives from the increasing demand for electricity. The Global Wind Energy Council reported that in 2016, wind energy annual installed capacity exceeded 54 GW and global cumulative installed wind capacity reached about 487 GW (GWEC, 2017b). At the same time in Europe, where the second largest wind market operates, wind energy now surpasses coal as the second most primary source of power generation which accounts for 17% of the total installed capacity. From the World Energy Outlook Report 2016 of the 450 scenario, it is foreseeable that wind power will provide 22% of the global electricity demand at the amount of 9,318 TWh by the year 2050 (GWEC, 2017a).

The ambitious target for wind energy harvest demands higher efficiency of wind power plants. These are now risen up to 200 m high and are in the multi-megawatt capacity class. The efficiency of power conversion increases considerably both with the enlargement of wind turbines and with the availability of more advanced manufacturing and construction techniques. Despite the prominent development of turbines, the supporting structures still face various challenges ranging from improving buckling and fatigue resistance to implement reliable mitigation measures against multi-hazards imposed by fire, earthquakes, and wind. The pursuing of higher wind power generation rates thus increases the risk of failure of wind power plants which is reflected in statistics associated to damage.

The aim of this review is to identify common causes of wind turbine tower failure based on a detailed scrutiny of recorded cases. This is expected to enhance our understanding of collapse mechanisms and to develop some potential mitigation measures. The review strictly focuses on tower collapse cases of onshore mega-watt-class wind turbines, which are built up with tubular steel sections.

Overview of Historical Cases

To date, a fair amount of wind turbine accidents are still recorded each year whilst the rate of occurrence over the last 20 years has increased. A report of Caithness Windfarm Information Forum (CWIF) revealed that in the past four decades and till 31 Dec 2016, there were 1,999 wind power plant accidents among which 126 were classified as fatal (CWIF, 2017). Fig. 1 shows that blade failure accumulates the largest number of incidents accounting for 17.9% of the total, followed by fire which accumulates 14.5%. Structural failure, including tower collapse and turbine damage, is the fourth largest type in the list accumulating 9.2% of the overall toll.

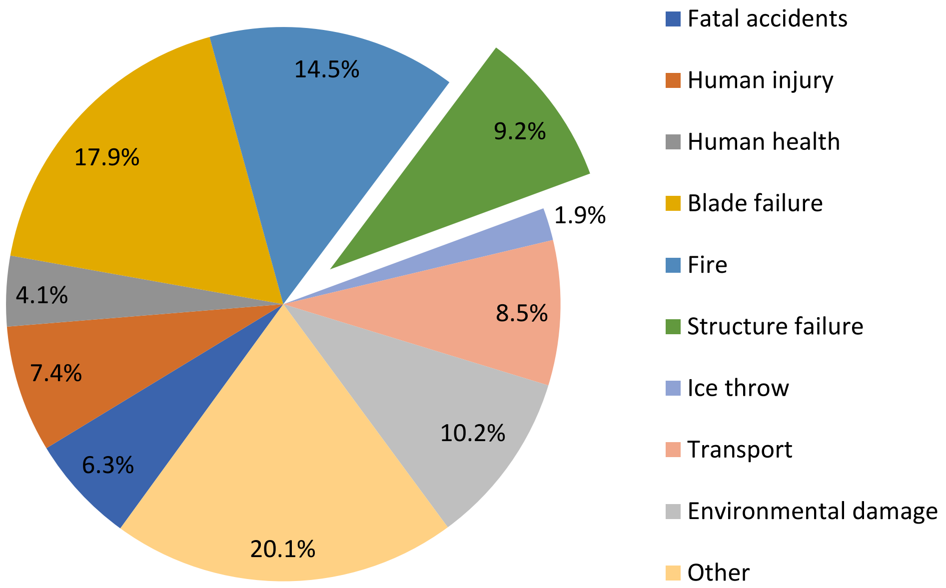

Fig. 1 Failure type distribution of wind turbine incidents recorded between 1980 – 2016 (CWIF, 2017)

Table 1 shows a detailed list of tower collapse incidents with 47 entries filtered from the full accident list of CWIF 2017. Small turbines under 300 kW and non-steel-tubular towers have been omitted. The recording period spans from year 2000 to 2016 - as not many multi-megawatt class turbines existed before the 21st century.

Table 1

Details of 47 tower collapse accidents

No.	Date	Region	Turbine Character	Cause
1	20/01/2000	Germany	Sudwind S 46/600 kW	Lightning strike
2	10/02/2000	Germany	Enercon E32	Concrete damage
3	15/02/2000	Holland	Lagerwey	Storm
4	11/03/2000	Holland	Newinco in Rhenen, 30m tower	Storm
5	09/12/2000	Spain	Gamesa Eólica G-47 660kW	Blade struck
6	15/01/2001	Spain	Gamesa Eólica G-47 660kW	Unidentified
7	28/01/2002	Germany	Windrad HSW 250 28m tower	Storm
8	15/05/2002	USA	WTC	Blade struck
9	27/10/2002	Germany	GET41a 600kW, Hub height 70m, rotor diameter 41m	Storm
10	19/11/2002	USA	Anemometer	Ice storm
11	18/12/2002	Germany	Vestas V80 2.0MW	Faulty Welding
12	28/12/2002	France	600kW, 75m total height	Storm
13	02/02/2003	Germany	Enercon	Fire
14	20/03/2004	France	Lagerwey 300kW 30m high turbine	Storm
15	11/09/2003	Japan	Micon M750/400kW and Enercon E40/500kW	Typhoon
16	01/01/2004	France	Lagerwey 750kW	Storm
17	28/12/2004	USA	1MW wind turbine	Bolts failure
18	06/05/2005	USA	GE Wind 1.5 MW	Unidentified
19	31/10/2005	Holland	Nedwind 500kW, 41m diameter, 40m tower	Unidentified
20	10/01/2006	Holland	Nedwind, 1MW, 55m diameter, 63m tower	Unidentified
21	06/07/2006	Holland	Nedwind	Lightning
22	15/08/2006	China	Hub height 50m, rotor diameter 50m	Typhoon
23	31/10/2006	Holland	Vestas NM 48/750	Fire
24	04/12/2006	France	30m high turbine tower	Strong Wind
25	09/01/2007	Germany	N/A	Fire
26	13/01/2007	Germany	HSW 100	Storm
27	25/08/2007	USA	Siemens 2.3MW	Unidentified
28	22/02/2008	Denmark	Vestas (Nordtank NKT600 - 180/43)	Braking failure
29	24/02/2008	Denmark	Vestas V47 660kW	Bolts failure
30	28/09/2008	Taiwan	Tower 62m high, blade length 34m	Typhoon
31	16/10/2008	USA	Zond Z-40-FS	Blade struck
32	23/10/2010	China	Z72-2000	Typhoon
33	16/03/2011	USA	Suzlon S88-2.1 MW	Braking failure
34	07/07/2011	USA	N/A	Storm
35	31/10/2011	Norway	Bonus 2MW	Cracking
36	01/12/2011	UK	N/A	Storm
37	15/03/2013	Japan	38 tonnes, 50m tower	Fatigue
38	09/10/2013	China	Total tower height 45m, blade length 22.9m	Typhoon
39	18/07/2014	China	TW1500/77, tower height 75m	Typhoon
40	06/12/2014	Nicaragua	Suzlon S88 2.1 MW	Fire
41	10/12/2014	Germany	60m tower	Bolts failure

42	17/12/2014	USA	GE 1.85MW	Unidentified
43	17/12/2014	Germany	600kW, 70m hub height, 48m rotor diameter	Faulty construction
44	22/12/2015	Brazil	Suzlon S95 2.1MW	Unidentified
45	17/08/2016	Canada	Enercon E82	Erroneous operation
46	21/11/2016	USA	152m height	Design defect
47	28/12/2016	Germany	Tacke TW 600, 95m height	Blade imbalance

Table 1 makes an account of accidents recorded from 2000. The causes are varied and often involve more than one wind energy harvesting tower. For example, in 2003 Typhoon Maemi hit a wind farm on Miyakoji Island damaging six wind turbines out of which three collapsed (Ishihara et al., 2005). Later in the same year, nine turbine blades were damaged by typhoon Dujuan in Guangdong, China, causing $1.6 million loss (Chen et al., 2015). Li et al. (2013) reported that three turbine towers snapped by typhoon Saomai which landfilled in Zhejiang China. During this event two towers overturned and 15 blades were structurally broken, altogether causing $70 million in losses. Riso (2008) reported two towers struck and ruptured by fractured blades in Denmark in 2008. Similar blade struck incidents have occurred in Germany during strong wind events in 1999, 2000 and 2003 (CWIF, 2017). In 2008, Typhoon Jangmi brought a torrential rainfall through the mountains in Taiwan inducing bolt failures and tower wall buckling incidents (Chou and Tu, 2011). Typhoon Megi landed in 2010 in Fujian China, causing the failure of one tower. Later in 2013, a severe tower collapse was recorded in Guangdong China when eight towers snapped as hit by Typhoon Usagi, at the time that 11 blade failures were counted, altogether producing $16 million direct loss (Chen et al., 2015, Chen et al., 2016, Chen and Xu, 2016).

The most tragic wind tower collapse incident has been recorded in China in 2014 when Typhoon Rammasun ravaged in the South China Sea, one tower in Hainan province and 13 others in Guangdong province collapsed (Chen et al., 2016). Bäckstrand and Hurtig (2017) discussed the case of one tower that collapsed in 2015 in Lemnhult, Sweden. It was determined then that the collapse derived from bolt fatigue, presumably derived from insufficient pre-tensioning force applied during construction. Two years later in Germany in 2017, one tower shell buckled at a point localised around 15 meters above the ground. This was caused by a force imbalance induced by the collapse of one of the three blades (PEI, 2017)

The most common identified causes of tower collapse, after the database outlined in Table.1, are listed in Table.2. This categorisation makes evident that extreme wind conditions including typhoons and storms forcefully drive tower structures down as high winds appear involved in about 55.7% of the reports. In a second level of relevance appears blade failure, fire, bolt failure or fatigue. Each of these accumulates 4 recorded cases and has the same frequency of occurrence which individually represents 5.7% of the total. The third most common cause of failure is shared among brake failure, lightning and faulty construction. Each of these has produced two collapse incidents which represent 2.9% of the total number of cases documented.

Table 2

Major causes of tower collapse

Cause of failure	Tower (s)	Occurrence (%)
Typhoon	29	41.4
Storm	10	14.3
Blade failure	4	5.7
Fire	4	5.7
Bolts Failure / Fatigue	4	5.7
Brake Failure	2	2.9
Lightning	2	2.9
Faulty construction	2	2.9
Others	13	18.6

East and Southeast Asia are more frequently affected by typhoon and tropical cyclones whilst Europe and North America accumulate most of the damage seen during strong winds and storms. The impact of wind turbine component failure on the damage caused should also be highlighted. The collapse of the tower leading to total loss will make an average cost of £500,000 to £5,000,000, depending on the particular wind turbine configuration but its construction cost would account for about 10% of the overall investment. In contrast, blades, nacelles and electrical components can, upon failure, be repaired and allow the wind energy harvesting to continue. Hence the reliability status of the wind turbine tower concords with that of the overall structure but it differs from that associated to other assemblies such as electrical or mechanical components(Sheng and O’Connor, 2017).

The overall failure rates of wind turbine components fit a bathtub curve which varies over time (Nielsen, 2013). The bath-tub curve involves three typical stages: early-life, normal operation and wear-out, as shown in Fig. 2.

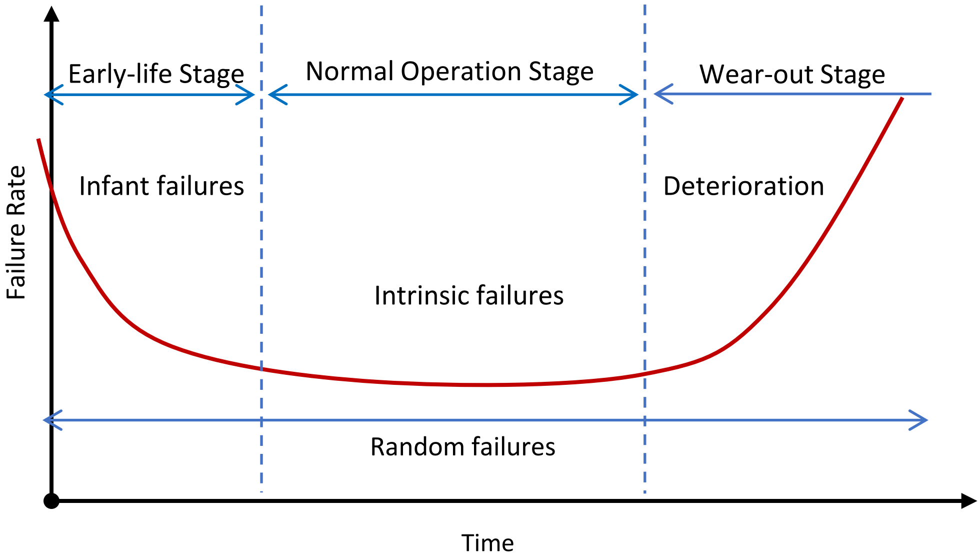

Fig. 2. A Bathtub Curve for Failure Rate vs. Time

Tower failure tends to occur in the early-life stage, also called infant failure. This mostly relates to faulty construction, material defects, and defective design. During normal operation, the failure rate keeps fairly steady and the structure exhibits the lowest hazard in its lifespan. Common causes of failure during this period relate to defective operation, improper maintenance, and early material deterioration. The failure rate increases again near the end stage of the life span mainly due to wear-out of parts after considerable operational time, consequences of inadequate maintenance, or fatigue effects (Hau, 2013). The timing of structural failure has also been examined by Stenberg (2010) to find that the number of failures in Finland raises after 15 years of operation. This observation was reinforced by (Carlstedt, 2004) who reported that annual failure rates in Sweden increase after the 14th operation year. Overall, failure rates at any stage of the Bathtub curve seem to correspond to two major reasons:

- Extreme load conditions
- Human or mechanical errors

The immediate consequences of these include an exceedance of design strength of structural components which can trigger chain effects. Blade failure for example, increases load assymetries which over-stress the tower section or can become windborne debris that impact adjacent structures. Human errors result in faulty construction, poor maintenance or operation. Altogether increasing risk to unnacceptable levels. The following sections discuss some historical tower collapse cases which illustrate those identified collapse causes.

Collapse Cases under Extreme Wind Events

Wind turbine tower collapse under extreme wind events are commonly due to insufficient bearing and buckling strength. Notably, the buckling strength is the most demanding requirement of tower design due to the availability of steel tube manufacturing technologies which attenuate deformities of wall thicknesses. However weak points on walls still emerge in wall thickness changing zones, door opening areas, and welding seams. Historical cases recorded showed that local buckling across tower shells could have led to total loss of wind turbines triggered by a domino-like effect (Chen and Xu, 2016, Chen et al., 2015, Ishihara et al., 2005). On the other hand, although the entire wind turbine can sometimes be regarded as a stationary structure (IEC, 2005), aeroelastic effects stand up as a major risk. This is demonstrated by the recurrent failure of rotor blades and by the fact that recorded tower collapse cases did not only fracture when the design wind speed was exceeded but also under lower wind speed levels, such as in case No. 38 reported in Table 1 - which refers to tower collapse occurring under design wind conditions.

Typhoon Saomai

Li et al. (2013) reported a five-tower collapsed incident happening in 2006 when Typhoon Saomai landed in Zhejiang province of China. Two towers out of the five buckled around the middle height of the steel tower tube whilst the overall system resisted dangerous intense vibrations caused by gust speeds exceeding 80 m/s. Two other towers collapsed following failure of their foundation system whilst one another structure failed because the welded joint between two tower segments fractured. This outcome would be linked to both along-wind and cross-wind effects. Records taken in the locality showed that the wind direction changed about 100˚ at interval of 20 min (Li et al., 2013) - whilst extreme cross-winds usually deviates ±15˚ relative to the along wind velocity component. This feature has been replicated elsewhere. For example, during Typhoon Maemi the wind direction varied 120˚ over short periods of time (Ishihara et al., 2005). The lack of synchronisation between yawing azimuth adjustment and rapid wind direction changes apparently enhanced crosswind load as well as torsional vibrations of the tower (Li et al., 2013). Seemingly, operational changes induced by the pitching system which tend to mitigate the effective forces acting on the tower (Hau, 2013), and the shutting-down mechanism which activates when wind speed exceeds certain threshold value to prevent rotor revolution over-speed, were insufficient to mitigate the peak forces that occurred during the incident.

Typhoon Usagi

Another catastrophic tower failure incident happened in 2013 in China, as reported by Chen et al. (2015). That refers to Typhoon Usagi, whose maximum wind velocity reached 69.4 m/s around Shanwei City. In this case, 8 out of 25 steel tube towers of the Shanwei wind farm were blown down. Chen and Xu (2016) conducted forensic studies of the turbine collapsed and observed that the critical wind force direction covered a range within SSW - SW (Chen et al., 2015). The investigators initially assumed that strong winds from NNW and NW would have caused those failures. However, according to the meteorological records and simulated CFD results, it was found that the direction of the maximum wind at hub height was SSW instead of NNE or NE, with average wind speeds of 62.8 m/s. This observation however could not explain the collapse cases of the wind turbines in the farm, which were designed as class S at survival wind speed 70 m/s. The relative orientation of the peak velocity of 75.8 m/s with respect to the structure was apparently not as critical as it would be if the predominant wind direction was NNE – NE. The computational work showed however that faulty blade stop position under relatively little wind could experience considerably higher forces than favourable locking position against higher velocity levels. This aspect of wind turbine performance has also been highlighted by Bas et al. (2012). They examined the relationship between tower strain and yawing angle to show the nacelle orientation could impact strain configurations across the tower shell during low wind speed conditions. Furthermore, Chen et al. (2015) found that the buckled points of all the eight collapsed towers were located about 9 to 10 meters over the ground. These points coincided with changes of the tube shell thickness. According to the numerical modelling undertaken, substantial compressive stress was prone to occur in between 8.2 m to 11.4 m above the ground, which coincided with the actual turbine buckle points. Thus, the collapse cases could be explained in terms of the original design, which disregarded the concentration of stress due to drastic stiffness changes along the tower shell, as well as in terms of complex aeroelastic effects derived from the relative positioning of the wind turbines and the wind flow.

Typhoon Maemi

Ishihara et al. (2005) investigated three tower collapse cases occurred in Japan. These were apparently related that to blade positioning and stresses around the access door. Typhoon

Maemi landed on Miyakojima Island in 2003 where maximum wind speed 38.4 m/s and gust speed of 74.1 m/s were recorded. One of these incidents derived from foundation failure and the other two from buckling near the entry doorway. Post-disaster analyses showed that adjacent towers exhibited different performances. For example, wind turbines numbered 3 and 5 suffered damages but the tower 4 did not. Following a computational simulation, Ishihara et al. (2005) argued that the survival of tower 4 was due to the fact that the rotor was operating at a different yaw angle that the other two, which resulted in a lower bending moment in the tower. Further studies seem to confirm that the relative positioning of the wind tower components with respect to the wind flow plays an important role in the structural performance of wind turbine towers. For example, Nuta et al. (2011) undertook a pushover analysis on a 1.65 MW wind turbine model to concluded that the critical stress configuration around the door opening occurred at the relative angle of 22.5˚. This links with the reports by (Ishihara et al., 2005) whose numerical simulation showed that high compression stress around the door opening would occur when the angle between horizontal wind direction and center line of the door opening was less than 40 degrees. In the two towers that collapsed, buckling occurred around the door opening (Ishihara et al., 2005). Their simulation results showed however that the bending moment at the base of the structure was only about 3% higher than the design value. The local bucking that originated the collapse of the towers was thus interpreted in terms of insufficient strength redundancy that could otherwise enable stress redistribution across the affected area. However, some arguments against such a conclusion there exist. Based on experimental work, Dimopoulos and Gantes (2012) pointed out that the effect of the relative angle between the wind flow and the structure would be negligible if stiffeners are set appropriately. Similar conclusions have been reached by (Dimopoulos and Gantes, 2012, Hao et al., 2015, Hu et al., 2014, Lagaros and Karlaftis, 2016). Thus whilst there is not a definitive conclusion regarding directionality effects, yet it is well understood that design provisions against buckling need to be well in place otherwise enhanced by codes of practice.

Most Common Failure Cases Involving Blade Failure

Fig. 1 shows that blade failure concentrates the maximum percentage of collapse cases, arguably due to the fact that this failure type often derives in chain reactions. Blades are made up of composite fibre having stable performance against aerodynamic forces although depending highly on the quality of their manufacturing. Blades may deform flapwise or be subject to significant lagged and torsional deformations, hence exhibiting ductile performance. Their connection components however tend to be exposed to large deformation occurring at high rates over time which makes them susceptible to fracture (Hau, 2013).

Past experimental and numerical research on blades demonstrated that the root area and regions where geometry changes drastically is where blade damage tends to originate (Sundaresan et al., 2002, Van Leeuwen et al., 2002, Herbert et al., 2007). Furthermore, Ciang et al. (2008) concluded that the damage-prone area along blades locates around one and two thirds of the chord length measured from the joint.

Those tower collapse incidents recorded to date often involve two failure mechanisms: blade struck and imbalance load.

Blade struck

If blade fractures whilst the rotor revolves, it is likely to hit the tower shell. The impact force would locate on the middle or upper tower tube where the wall is thinner compared to bottom sections. Riso (2008) discussed a collapse case recorded in Denmark related to a fractured blade striking the upper section of the tower. After this impact, other two blades fractured and fell apart, the upper tower snapped and the nacelle and rotor hub went down to the ground although the base cylindrical shell stood intact. According to this report, the overall system went through repair but once in operation the rotor was unable to stop during strong winds due to malfunction of the braking mechanism. This unstoppable rotor exceeded its design rotational speed and ended up in blade fracture once again. The fractured blade hit the tubular tower causing a sudden serrated dent on the shell, the massive nacelle and hub bent down instantly. This localised discontinuity on the tower shell produced eccentric load which eventually fractured the steel tower. Riso (2008) highlighted the fact that bolts in the hub connecting the blades and the rotor could not withstand the excessive tension force derived from the chain effect. Hence the airfoil underwent large deformations thus causing the impact to the tower shell as it bent excessively whilst still in operation.

There is also evidence of cases in which blade fracture did not lead to overall collapse. For example, when typhoon Dujuan landfilled in China 2003 carrying 1-min average 63.9 m/s wind speed, destroyed blades of 9 turbines out of all 25 wind power plants but did not cause wind turbine tower collapse (Chen et al., 2015). The aforementioned Typhoon Saomai which occurred in 2006, damaged 15 blades but collapsed 3 structures (Li et al., 2013). During typhoon Maemi which occurred in 2003, two tower blades snapped but the towers survived (Ishihara et al., 2005). Some other studies suggest that blade fracture reduces the effective wind loads on towers hence limiting net loads acting on them.

Tower collapse induced by blade struck is thus considered to be random in nature however subject to high probability of occurrence, as the statistics show (CWIF, 2017).

Imbalance load

Another collapse cause often seen in the past is the force imbalance force generated by a failed blade. To some extent, and due to the configuration of members in the rotor which is distant from being symmetric, force imbalance is a common load type on wind turbines. It is actually modelled as cyclic load by rotor designers. However force eccentricity cannot be taken by wind turbine structures when exceeding certain limit. A case that can illustrate that was recorded in Germany in 2017, when a 95-m tall wind turbine was overloaded due to the fracture of one blade. The case, which to date is still under investigation showed that the localised blade failure would have exceeded the tower capacity to take eccentric load (PEI, 2017, WindAction, 2016). The tower snapped at a point located 15 meters above the ground, apparently following buckling effects in the tower shell.

This failure mode thus originates when high vertical load becomes eccentric with respect to the center line of the structure. The weight of large blade of modern wind turbines can reach dozens of tons whilst the chord length could exceed 60 meters. Therefore, a significant unbalanced rotational inertia will generate if any blade fails during rotor revolving without an effective emergency braking operation mechanism. Deflections and vibrations derived from such failure event could rise to unsafe levels if the cyclic load approaches the natural vibration frequency of the tower (Hau, 2013, Hu et al., 2015).

There seems thus required to fine tune the balance between the tower’s resilience to take eccentric load and the timeliness of the emergency stop mechanism. This type of vibration under critical conditions thus sets up a challenge for designers who should examine the dynamic performance of the tower in light of potential resonance effects derived from the chain mechanisms depicted in the paragraphs above.

Most Common Failure Cases Involving Human Errors

The recorded collapse cases have often derived from human errors such as poor quality control, faulty construction, erroneous operation, and improper maintenance during the normal operation and wear-out stages represented in Fig. 2. This is therefore an area of improvement which well-managed operation and maintenance could raise power generation over sustained periods of 20 years or more(Kovács et al., 2011, Ding and Tian, 2012, Walford, 2006).

Poor quality control

Quality control weakens for example when unqualified components are installed onto the wind turbine. This practice usually leads to infant failure as per Fig. 2.Chou and Tu (2011) conducted an investigation on the tower collapse that occurred when Typhoon Jangmi hit Southeast China in 2008. Then, a 62 m high wind turbine tower located in Taichung Harbor collapsed. A post-failure analysis revealed that at 17.3 m above the ground, where the joint between the lower and middle shell segments lied, the 30 mm-diameter connecting bolts were fractured. Due to this, the middle and upper section snapped down to the ground. Investigators collected samples of both the broken and other intact bolts found on site and tested the mechanical properties. The report revealed that both failed and intact bolts did not meet the requirements of the relevant design standard JIS-B1051 (JIS, 2000). According to this, all broken bolts did not have the required yield and ultimate strength while only half of the intact bolts have properties close to the strength baseline. In this event, the wind speed recorded fell within limits where structural survival is expected. The forensic study also revealed that the inaccurate installation of bolts generated locked-in effects involving stress concentration and creep, which undermined the effective bolt strength.

Faulty construction

This ill-practice in construction typically leads to infant failure. A wind turbine tower located in Lemnhult wind farm in Sweden, 2015 failed whilst in operation. Bäckstrand and Hurtig

(2017) concluded faulty bolt installation lead to their failure. These connection components underwent some fatigue course after which the bolts in the first joint fractured causing the upper part of the wind turbine falling down. However the connection failure was sudden, the bottom tower shell stood without severe damage. The investigators concluded that the cause of bolt malfunctioning was insufficient pre-tension at the connection between section flanges. There, the bolts were subject to load repetitions for a sustained period of time. This combined with insufficient lubricant (MOS_2) around screw threads induced high friction between the stem of the connectors and their nut. In this connection mechanism, high friction decreases the bias force in the nut hence lowers the locking force (Bäckstrand and Hurtig, 2017, Liu et al., 2017). As the wind turbines in Lemnhult continued harvesting energy, the lowered pre-tension force on bolts allowed larger gaps between flanges which ended up deforming the clamping devises until the joint between tower shell segments fractured. Beyond this case, even when failure does not occur, imbalance across clamping joint mechanisms can lead to local plastification of connection components whilst setting up conditions for local corrosion. Loose and broken bolts have apparently been found whilst energy is being harvested however those incidents have apparently not been reported by the operator to the supervisory authorities (Bäckstrand and Hurtig, 2017).

Erroneous operation

The erroneous operation commonly leads to the rotor having unfavourable pitch or yaw and blade stopping position. Those conditions could increase wind effects considerable as the net forces acting on the tower are highly sensitive to the motion of the rotor. Examples of tower collapse failures include those induced by Typhoon Maemi which affected Miyakojima Island in 2003. Ishihara et al. (2005) reported that the yaw systems of turbine identified as number 3, 4, and 5 failed to lock at critical timings so that yaw angle moved clockwise from 94˚ to 156˚ which increased the effective loads on the towers beyond acceptable limits which eventually led to the collapse of two towers. A similar case happened in Point Tupper, Canada, when the rotor of an 80-meter high turbine pitched in 2˚ instead of 90˚ resulting in higher wind loads than expected. The blades hit the tower shell leading to the total collapsed of one tower (CBCnews, 2016).

The relevance of proper operation maneuvering has generated research on structural health monitoring aiming at improving tower damage detection strategies based on data operation collected on-site (Ciang et al., 2008, Ghoshal et al., 2000). To cite one example, (Bas et al., 2012) discussed the relationship between tower strains and risk factors involving nacelle orientation, rotation speed, wind velocity, pitch angle and temperature, based on a monitoring data base spanning over two years.

Improper maintenance

Improper service to maintain wind turbines is identified as a factor responsible of tower collapses in the past. Regular preventive maintenance such as structure checks, rust proofing, paint touch-ups, gearbox lubrication, blade repair, and oil changes – to cite some, is fundamental guarantee healthy working conditions. Maintenance schedules can thus become a key reliability factor during the worn-out stage of wind turbines. To illustrate this let us refer to the wind turbine identified as 43 in the Chinese Zuoyun wind farm which collapsed in 2010 under normal weather conditions. In this event, components of the joint between the middle and bottom shell fractured apparently due to bolts and flanges being poorly maintained (Zhang, 2010). That report also made evident that nearly 40% of the bolts connecting shell segments of tower number 61 were also broken although the tower was standing intact. This undesired incident could thus have been avoided if a proper maintenance schedule had been in place.

Frontier Pro Services conducted an informal survey considering 75 wind farm operators across the USA (WindAction, 2008). Various respondents indicated they had fallen behind on scheduled preventive maintenance such as oil changes and gearbox lubrication because of a shortage of qualified technicians. According to Frontier Pro Services, the survey found that many wind farm operation and maintenance teams are so resource-constrained that they can barely keep up with unscheduled breakdown repairs to wind turbines (WindAction, 2008). Maintenance thus seems to be a major area of improvement for increasing safety and reliability of wind energy infrastructure.

Discussion and Concluding Remarks

This paper presented the historical wind turbine tower collapse cases aiming to identify the most common failure mechanisms. These turned out to be unexpected extreme wind load levels combined with human errors such as poor quality control, faulty construction, erroneous operation, and improper maintenance. Inevitably, the identified collapse cases would hardly be due to onle single factor but to a combination of these. Extreme wind events concentrate about 56% of the total number of failures but in most cases these coincided with human errors. It is worth to note that most collapsed structures discussed in this paper were designed according to the governing design standards. Thus suggesting that prevention of wind energy infrastructure failure would necessarily pass through a filter including quality control, construction and operation techniques. It would thus be expected that by attending those secondary issues infant and wear-out stage failures would be lessen.

Special attention should also been given to cyclic effects, given the fact that rotors will typically revolve for over 10^9 cycles spanning over 20 years or more (Hau, 2013) but noting that wind turbines are designed for 20 – 30 years' energy harvesting. Fatigue effects can thus be seen as a major cause of collapse when combined with human errors which magnify its primary effect. Those including faulty soldering, geometry imperfections, and substandard installation or maintenance, as discussed above. Cyclic loading becomes more dangerous when its oscillation frequency approximates the natural frequency of the tower or joint components.

Based on the scrutiny of the collapse cases reviewed:

- Most failure incidents of wind turbine tower are due to a combination of factors among which extreme wind is identified as the most common one.

- Current design standards have not been referred to in the forensic studied consulted. These threfore seem reliable but might reuiqre some fine tunning based on the multi-factorial incidences discussed in this investigation.
- Aeroelastic effects do not seem fully understood by scientist nor designers. Hence, further research on the subject seems appropriate to be undertaken.
- Human or mechanical errors have been identified here as a secondary factor leading to wind tower collapse failure. The risk associated to these factors however could be mitigated via the identification and enforcement of best practices during construction, operation, and maintenance.

Acknowledgement

The authors acknowledge with thanks the support by the TU1304 WINERCOST Action (www.winercost.com) and the AEOLUS4FUTURE ITN Network (http://www.aeolus4future.eu).

References

ASHLEY F, C. R. J., BRECKENRIDGE S, BRIGGS G A, GROSS L E, HINKSON J AND LEWIS P A 2007. 2007 Bethany Wind Turbine Study Committee Report

B CKSTRAND, J. & HURTIG 2017. Final report RO 2017: 01. Statens Haverikommission.

BAS, J., CARRIVEAU, R., CHENG, S. & NEWSON, T. Strain response of a wind turbine tower as a function of nacelle orientation. BIONATURE 2012, The Third International Conference on Bioenvironment, Biodiversity and Renewable Energies, 2012. 12-18.

CARLSTEDT & ERIC, N. 2004. Driftuppföljning av vindkraftverk: årsrapport 2003. Energimyndigheten.

CBCNEWS. 2016. *'Forgotten washer' heard in hub before N.S. wind turbine collapsed* [Online]. Canada. Available: http://www.cbc.ca/news/canada/nova-scotia/forgotten-washer-heard-in-hub-before-wind-turbine-collapsed-in-cape-breton-1.4112090 [Accessed].

CHEN, X., LI, C. & TANG, J. Structural integrity of wind turbines impacted by tropical cyclones: A case study from China. Journal of Physics: Conference Series, 2016. IOP Publishing, 042003.

CHEN, X., LI, C. & XU, J. 2015. Failure investigation on a coastal wind farm damaged by super typhoon: A forensic engineering study. *Journal of Wind Engineering and Industrial Aerodynamics,* 147**,** 132-142.

CHEN, X. & XU, J. Z. 2016. Structural failure analysis of wind turbines impacted by super typhoon Usagi. *Engineering Failure Analysis,* 60**,** 391-404.

CHOU, J.-S. & TU, W.-T. 2011. Failure analysis and risk management of a collapsed large wind turbine tower. *Engineering Failure Analysis,* 18**,** 295-313.

CIANG, C. C., LEE, J.-R. & BANG, H.-J. 2008. Structural health monitoring for a wind turbine system: a review of damage detection methods. *Measurement Science and Technology,* 19**,** 122001.

CWIF. 2017. *Caithness Windfarm Information Forum* [Online]. Available: http://www.caithnesswindfarms.co.uk/AccidentStatistics.htm [Accessed].

DANSKSTANDARD 2007. DS 472:2007 Conditions for the Construction of Wind Turbines in Denmark. Denmark.

DEKKER, J. & PIERIK, J. 2013. European wind turbine standards II. *Solar Energy,* 2012.

DIMOPOULOS, C. A. & GANTES, C. J. 2012. Experimental investigation of buckling of wind turbine tower cylindrical shells with opening and stiffening under bending. *Thin-Walled Structures,* 54**,** 140-155.

DNV 2002. Guidelines for Design of Wind Turbines. Det Norske Veritas, Copenhagen and Wind Energy Department, Risø National Laboratory.

GASCH, R. & TWELE, J. 2012. Wind power plants : fundamentals, design, construction and operation. 2nd ed. Berlin,London: Springer.

GHOSHAL, A., SUNDARESAN, M. J., SCHULZ, M. J. & PAI, P. F. 2000. Structural health monitoring techniques for wind turbine blades. *Journal of Wind Engineering and Industrial Aerodynamics,* 85**,** 309-324.

GINTAUTAS, T. & S RENSEN, J. D. 2014. Integrated system reliability analysis. Denmark: Department of Civil Engineering Aalborg University, Denmark.

GWEC 2017a. Global Wind Energy Outlook 2016. Brussels: Global Wind Energy Council.

GWEC 2017b. Global Wind Statistics 2016 (2016). Global Wind Energy Council.

HAO, P., WANG, B., TIAN, K., DU, K. & ZHANG, X. 2015. Influence of imperfection distributions for cylindrical stiffened shells with weld lands. *Thin-Walled Structures,* 93**,** 177-187.

HAU, E. 2013. *Wind turbines: fundamentals, technologies, application, economics*, Springer Science & Business Media.

HERBERT, G. J., INIYAN, S., SREEVALSAN, E. & RAJAPANDIAN, S. 2007. A review of wind energy technologies. *Renewable and sustainable energy Reviews,* 11**,** 1117-1145.

HU, Y., BANIOTOPOULOS, C. & YANG, J. 2014. Effect of internal stiffening rings and wall thickness on the structural response of steel wind turbine towers. *Engineering Structures,* 81**,** 148-161.

IEC 2005. IEC 61400-1: Wind turbines part 1: Design requirements. *International Electrotechnical Commission*.

ISHIHARA, T., YAMAGUCHI, A., TAKAHARA, K., MEKARU, T. & MATSUURA, S. An analysis of damaged wind turbines by typhoon Maemi in 2003. Proceedings of the sixth asia-pacific conference on wind engineering, 2005. 1413-1428.

ISO 2015. ISO 2394: 2015 General principles on reliability for structures. Zurich: International Organization for Standardization.

JCSS 2004. Probabilistic Model Code, Part 1–Basis of Design. Joint Comitee on Structure Safety.

JIS 2000. Japanese Industrial Standard B1051 - 2000. Japan.

LAGAROS, N. D. & KARLAFTIS, M. G. 2016. Life-cycle cost structural design optimization of steel wind towers. *Computers & Structures,* 174**,** 122-132.

LAVASSAS, I., NIKOLAIDIS, G., ZERVAS, P., EFTHIMIOU, E., DOUDOUMIS, I. N. & BANIOTOPOULOS, C. C. 2003. Analysis and design of the prototype of a steel 1-MW wind turbine tower. *Engineering Structures,* 25**,** 1097-1106.

LI, Q. S., XIAO, Y. Q., WU, J. R., FU, J. Y. & LI, Z. N. 2008. Typhoon effects on super-tall buildings. *Journal of Sound and Vibration,* 313**,** 581-602.

LI, Z.-Q., CHEN, S.-J., MA, H. & FENG, T. 2013. Design defect of wind turbine operating in typhoon activity zone. *Engineering Failure Analysis,* 27**,** 165-172.

LLOYD, G. 2010. Guideline for the Certification of Wind Turbines. *Rules and Guidelines Industrial Services.* Hamburg: Germanischer Lloyd.

NIELSEN, J. S. 2013. *Risk-based operation and maintenance of offshore wind turbines*, River Publishers.

NUTA, E., CHRISTOPOULOS, C. & PACKER, J. A. 2011. Methodology for seismic risk assessment for tubular steel wind turbine towers: application to Canadian seismic environment. *Canadian Journal of Civil Engineering,* 38**,** 293-304.

PEI 2017. Collapse of wind turbine under investigation. Power Engineering International.

RISO & DTU 2008. Final report on investigation of a catastrophic turbine failures, February 22 and 23, 2008. December.

SHENG, S. & O'CONNOR, R. 2017. Chapter 15 - Reliability of Wind Turbines A2 - Letcher, Trevor M. *Wind Energy Engineering.* Academic Press.

STENBERG, A. 2010. Analys av vindkraftsstatistik i Finland. *Diplomarbete, Aalto-Universitetet, Tekniska Högskolan, Fakulteten för elektronik, kommunikation och automation, Esbo,* 5**,** 2010.

SUNDARESAN, M. J., SCHULZ, M. J. & GHOSHAL, A. 2002. Structural Health Monitoring Static Test of a Wind Turbine Blade: August 1999. National Renewable Energy Lab., Golden, CO.(US).

VAN LEEUWEN, H., VAN DELFT, D., HEIJDRA, J., BRAAM, H., J RGENSEN, E. R., LEKOU, D. & VIONIS, P. 2002. Comparing fatigue strength from full scale blade tests with coupon-based predictions. *Journal of Solar Energy Engineering,* 124**,** 404-411.

WINDACTION. 2008a. *Catastrophic turbine failure at Vermont wind farm raises doubt about turbine safety, longevity* [Online]. Available: http://www.windaction.org/posts/17503-catastrophic-turbine-failure-at-vermont-wind-farm-raises-doubt-about-turbine-safety-longevity#.WaWRVT6GNpj [Accessed].

WINDACTION. 2008b. *Maintaining the wind turbine revolution* [Online]. Available: http://www.windaction.org/posts/16629-maintaining-the-wind-turbine-revolution#.WaWXvk2Wy70 [Accessed].

WINDACTION. 2016. *German Turbine Collapse* [Online]. Available: http://www.windaction.org/posts/46152-german-turbine-collapse#.WZr1X9PyuEI [Accessed].