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Functional failure mode, effects and resilience analysis (FMERA) to determine functionality gaps of today's rotor blade on-site inspection and repair

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Already today average rotor blade length of newly installed wind turbines is beyond 80 m in industrialized countries. Geometrical challenges furthermore comprise large circumferences close to nacelle, large differences between circumferences until the rotor blade tip and nacelle heights reaching and much beyond 150m. Thus, the rated power generated per average operation day increases further reaching the order of 4MW even for slow wind rotor blade turbines with their comparatively large rotor blades. However, along with generated electric power revenues of the order of, e.g., 10k€ a day in Europe, ever increasing standstill time costs arise. Thus, the ambition is to strongly minimize and control inspection and maintenance downtimes and costs. The present article presents a novel functional failure mode and effects and resilience analysis (FMERA) analytical approach on extended system level that includes on on-site inspection and repair capabilities to identify key missing functional capabilities. Missing capabilities are assessed using in addition the resilience dimensions preparation, detection and prevention, absorption, response and recovery, and adoption and learning to assess the criticality of the identified capability gaps analytically. The article identifies main physical access technology as well as inspection gap capabilities of today's solutions as well as potential future technological solutions that are expected to close these gaps. Solution space includes operational technician teams, main operation, and inspection times of wind turbines, as well as site access considerations including offshore. Furthermore, technologies much beyond state of best practice are assessed, e.g. glass fiber reinforced plastics, carbon fiber materials, and alternatives to traditional steel ropes. It is discussed how the proposed FMERA system analytical assessment and optimization process could be further improved for the present sample domain of assessment of rotor blade inspection and repair capabilities as well as further application options.

Keywords: Failure Mode Effects and Resilience Analysis, Rotor Blade Inspection, Wind Energy, Analytical Assessment of Maintenance and Repair, Ultra-Lightweight Physical Access and Inspection Technology.

1. Introduction

In the context of the development of safety critical systems analytical methods have proven to be very beneficial and efficient. For instance, tabular inductive failure mode and effects analysis (FMEA) at concept system functional level and failure mode effects and diagnostic coverage analysis (FMEDA) are used in the concept phase and the detailed design phase, respectively.

In a similar way resilience analysis analytical approaches have been developed to conduct system resilience analysis at analytical level such as the functional resonance analysis method (FRAM) (Patriarca et al., 2020), which uses hexagon functional elements that can be coupled focusing on system functional aspects, or nested tabular procedural approaches (Häring et al., 2021a).

However, research communities and practitioners are rather separated. This raises the question of whether a tabular resilience analysis approach can be developed that is both abstract and encompasses system functional aspects. It should integrate seamlessly into system engineering processes, particularly during the early development phases. Furthermore, it should be applicable not only to smaller devices and systems but also to large-scale systems such wind turbines.

The present article aims at a minimum extension of traditional FMEA to cover resilience aspects on tabular analytical level termed failure mode, effects and resilience analysis (FMERA). The aim is to show that the proposed inductive approach is applicable on system, system of system and functional level to characterize technological gaps and potential solutions. An example of application will be in the domain of inspection and repair of large rotor blades, taking into account the current challenges faced by wind power operators with ever-increasing rotor blade sizes.

Section 2 introduces the current challenges faced by wind power operators with ever increasing rotor blade size. Section 3 presents the FMERA approach and compares it to similar approaches emphasizing differences and similarities. Section 4 applies FMERA to large rotor on-site blade inspection and repair. Section 5 draws conclusions and gives an outlook.

2. Large rotor blade inspection and on-site repair challenges prioritization

This section presents the functions on system level that are to be assessed using the proposed FMERA method. It considers as system the wind turbine with focus on the rotor blade, the physical access technology for humans for inspection, maintenance and repair as well as the human operators.

Wind turbine rotor blades can be built longer and longer thanks to the combination of glass and carbon fiber-reinforced plastics (GFRP, CFRP). Already since 2023, sizes of up to 97m (Durakovic, 2022) and 107m (Ge Vernova, 2023) can be purchased and 108m (Lee, 2010) (Durakovic, 2021) as well as 115.5m (Blade Test Center, 2023) are being tested and 250m (Mendoza et al., 2022) designed. Accordingly, rotor blade lengths of up to 120m and hub heights of over 200m are expected in the coming years, even 300m are currently tested in pilot systems (LEE Sachsen, 2024).

Enclosing access technology is already becoming increasingly larger (blade width 7m, blade depth 4m) and heavier (dead weight of platform with winches and rope catchers without ropes approx. 1.75t, ropes weigh approx. 50kg per 100m length), specially for access to blade roots.

Access technology is therefore becoming increasingly complex to use and can no longer be moved with 3.5t trailers in the foreseeable future. There are no certified attachment points for larger loads on nacelles for wind turbines. Small teams (3-4 people) can no longer meet operationally reasonable set-up times (< 3h) and therefore also deployment times in normal fair-weather windows.

In addition, the requirements regarding wind protection and temperature control inside the working platforms are increasing in order to be able to repair large and deep damage up to 10m and more on-site in early spring and into late fall in order to avoid expensive and downtime-consuming dismantling on site or even repair in assembly halls. Even now, very heavy wire ropes with a diameter of 11.5mm (0.5kg/m) require preparatory work such as unloading, moving on the ground, attaching auxiliary winches and ropes and therefore require increasingly longer set-up times. The highly dangerous inspection by industrial climbers (often in just one day) (Ertek & Kailas, 2021) is no longer scalable and unsuitable for major repairs. In addition, there is a lack of resource-efficient inspection methods (Tazi et al., 2017) (Liu et al., 2022) for decisions regarding on-site repairability and costs.

The question therefore arises as to whether an easy-to-operate manual access technology (rotor blade access system, rope access technology) can be developed to adapt to different rotor blade shapes. This technology should facilitate on-site inspection, maintenance and, above all, repair work by small teams, even as rotor blade sizes continue to increase, both onshore and offshore. Ultrasound could also significantly facilitate resource-efficient on-site and hand-guided assessment.

Six exemplary functions (F1 to F6) can already be formulated verbally in advance, which are explained below. These functions are considered relevant and will be systematically analyzed below in detail using FMERA method.

Firstly, the ability to use G/CFRP structures in combination with lightweight metal manufacturing processes for ultra-light, torsion-resistant access technology (F1), which is in addition actively stabilizable (F6). The fully enclosing access platforms should also reach rotor blade tips far away from the tower structure (15 to 26m), the rotor center section as well as the rotor blade root. It is expected that it will be necessary to adapt positioning procedures and reactive stabilization procedures to the increased dynamics and flexibility of the access technology (F1, F4).

The access technology should be applicable for acceptance tests, recurring tests, but above all for complex on-site repairs (planned and event-related) and associated damage assessments. The entire inspection, maintenance and on-site repair operation should be covered (El-Thalji & Liyanage, 2012). This is intended to avoid the expensive dismantling of rotor blades with mobile crawler cranes, on-site repairs on the ground or even repairs in assembly halls for as many cases of damage as possible. This holds especially for more complex and larger damage patterns (≥ 10m in length or areas ≥ 20m² as well as in case of damage of load-bearing layers, entire leading or trailing edges of the rotor edges), e.g. caused by lightning strikes, erosion, manufacturing defects and ageing.

The described capability functions (F1, F4, F6) are expected to enable significant savings through a more flexible access technology that can be quickly installed and used even in bad weather (e.g. set-up and dismantling times including establishing safety, pulling up the ropes and laying power ≤ 3h at 150m hub height). This minimizes downtimes and makes repair work more economical.

In addition, the function of using coated textile ropes (e.g. (Seilflechter, 2021)) or possibly kernmantle ropes (e.g. (DIN EN 1891, 1998)) instead of wire ropes should be investigated (e.g. based on and extended to (DIN EN 1891, 1998), (DIN EN 1808, 2015) (F2). Furthermore, the detection and assessment of wear damage and the discard maturity of the ropes is a related functionality (F3).

These capabilities F2 and F3 should lead to a reduction in the rope weight (by approx. 70% for nominal loads of 700 to 1600kg), to support or further enable manual handling of the ropes, reduce the rope drop load and thus the effort required for fall arrest and emergency devices if a rope slips, breaks or a geared motor fails (F4). Even a few cm of slippage can result in high impact factors.

With comparatively inelastic wire ropes, for example, the protection factors are 4 to 5 times the dead weight at a drop height of 2-3cm and 13 to 14 times at 10cm (dynamic load compared to static load with payload). Here, a protection factor from a height of 3m for the selected textile rope must be methodically determined and justified (expected approx. 10 to 14) (F1, F2, F3, F4). Furthermore, the limit speed of 0.5m/s for the rope catcher (block stop) according to (DIN EN 1808, 2015) may also have to be adapted to textile ropes in order to limit sagging and after-swinging. For this reason, existing continuous rope winches, rope winches, and rope fall arresters would have to be substantially adapted, newly developed or further developed. The subjective perception (yielding, sagging) and the expected lower dynamic load must also be considered for textile rope loads.

The greatest challenge for textile ropes is to examine and define the application-specific requirements and to ensure that their fulfillment is analyzable, testable and, if possible, physically-simulatively predictable and assessable (F3). This concerns, among other things, the effects of bending cycles, mechanical jamming/shear loads in winches/drums and rope catchers, continuous and impact loads, UV radiation, salty air, static charging, in each case with the aim of realistically assessing the discard maturity. This should be carried out in combination with human, sensory and automated inspection, annually or continuously, e.g. as a safety function.

By using G/CFRP structures and textile ropes, a total weight of less than 1400kg (F1, F2) and a weight reduction of 20% to 40% for the platform itself can be achieved compared to lightweight aluminum structures or steel structure components with the same functions can be expected (see (Tran, 2024)). The discussed access technology should thus lead to a controlled and significantly lower load on the nacelle with insufficiently provided or certified attachment points and be installable without a crane.

Further overarching functions (F1 to F6) are the quantitative assessment and containment of risks, procedural and methodological preparations for the approval of the ultra-lightweight access technology funcitons for the example application of large rotor blades and investigations into the necessary (functional) safety certificates, e.g. in accordance with the Machinery Directive (European Union, 2023).

For efficient detailed assessment beyond visual and knocking inspection, the particularly suitable (Raišutis et al., 2008; Roach et al., 2015; Du et al., 2020) multi-frequency and phased array ultrasonic inspection technology functionality, e.g. (Holstein et al., 2014), if promising possibly also using only air coupling, e.g., (Hillger et al., 2019) (Hillger, 2020), is proposed to determine defect types (Ashwill et al., 2013), the exact repair requirements (e.g. for serial damage and evaluation of warranty cases) and for quality assessment of repairs (F5). The focus here is on efficiency, quality of the statements and lower resource requirements, especially for coupling water, for hand-held applications (weight < 15kg), which can also be used independently of the access technology with a sufficient power connection.

Given the six functionalities F1 to F6 the question arises how to assess their relevancy for on-site inspection, maintenance and mainly repair of large-scale rotor blades.

3. Methodology

Failure modes and effects analysis (FMEA) variants include Failure Modes Effects and Criticality Analysis (FMECA), which has been applied to tabulate grid resilience simulation results (Hwang et al., 2015), and failure modes effects and diagnostic coverage analysis (FMEDA) (Häring, 2021a). An approach that combines FMEA with resilience focuses on down and recover time as well as fuzzification while using traditional risk priority numbers (Seiti et al., 2021). The summarizing failure mode and effect analysis and supply chain resilience (FMEA-SCR) approach in (Marco-Ferreira et al., 2023) is tabular while being however not oriented on classical FMEA tables. In summary, a failure mode effects and resilience analysis (FMERA) has not yet been proposed, that further resolves in a minimal way the effects on the system in terms of resilience categories has not yet been proposed, only the potential has been mentioned (Häring, 2021c).

The general idea is to extend FMEA to FMEXA, where X represents "Consequence", "Diagnostic Coverage", or "System Resilience". If system resilience is understood as a set of system capabilities that become relevant and accessible in different resilience cycle phases or equivalently system response phases to disruptions, FMERA can be understood as a refinement of FMECA that resolves to much more detail which consequences occur if a subsystem or component of the system fails or a function of subfunction of system.

For simplicity in the following a single resilience dimension (concept, perspective) (Häring et al., 2016) to convey the concept of resilience is used for which also resilience indicators could be provided, see e.g. (Assarkhaniki et al., 2020). To this end we use 5 classical resilience cycle phases and ask if the system performs acceptable in the phases (i) preparation, (ii) prevention, (iii) protection/absorption, (iv) response/recovery, and (v) adoption/learning/improvement. See e.g. (Häring et al., 2021b) for several application examples in combination with system performance functions to different types of systems.

Hence, instead of a single column that contains the effect on system level of a failure mode of a subsystem or function of a system, we assess the effect of a subsystem or system function failure in addition with respect to the capability reduction in the all resilience cycle phases.

For definiteness, the following columns are proposed for a sample functional system FMERA:

(1) Identification number
(2) Function of subsystem name
(3) Optional: Short description
(4) Failure mode
(5) Failure cause
(6) Optional: Failure trigger
(7) Optional: Failure diagnostic
(8) Optional: Immediate/Local effect
(9) Overall effect on system: Frequency
(10) Overall effect on system: Severity
(11) Overall effect on system: Non-Detectability
(12) Resilience: Effect on preparation against hazards
(13) Resilience: Effect on prevention of hazards
(14) Resilience: Effect on protection/absorption of hazards
(15) Resilience: Effect on response/recovery from hazards
(16) Resilience: Effect on adaption/learning of system
(17) Optional: Counter measures selected for implementation
(18) Optional: Status of implementation
(19) to (32) Optional: Reassessment of (3) to (16)

Table 1. Failure mode, effects, and resilience analysis (FMERA) applied to on-site rotor blade ultra-light-weight inspection platform functions on system level.

No.	Function; Short description	Fai-lure mode	Failure causes	Overall effect on system: Severity (S), Frequency (F), Non-Detectability (D); Comments	Resilience: Effect on preparation against hazards; Comments	Resilience: Effect on detection and prevention of hazards; Comments	Resilience: Effect on protection, successful absorption of hazards; Comments	Resilience: Effect on response and recovery from hazards; Comments	Resilience: Effect on adaption and learning of system; Comments
1	**Ultra-light-weight physical access working platform, catchment technology and distance keeping:** Self-supporting G/CFRP platform (or with load-bearing structure made of G/CFRP); Recognizable damage to the access technology itself by design; Operational inspection rules;	Mechanical failure during set up or operation;	Undetected wear out or meacha-nical damage during handling; Joint failure;	**S: 10** **F: 2** **D: 2** Safety critical for persons during set up and operation; Recognizable damage by design; Operational inspection rules;	**8** Cannot prepare adequately for all phases of resilience cycle; Fast response and recovery by respective service teams is limited as transport and mainly set-up require rather long time with conventional means	**6** Less close-in on-site detailed inspections using physical access technology; Remote inspection with drone-based cameras not affected	**3** Not relevant as hazards affecting rotor blade such as lightning stroke, erosion, aging cannot be influenced by ultra-lightweight physical access and inspection; See No. 2, 3;	**8** Classical means of on-site inspection are available but take longer time; In practice often only industrial climbers conduct close-in inspection; See No. 2;	**9** Adoption to future ever increasing and higher installed rotor blades is limited; Total weight of platform including cables, cable winches and cable catchers < 1400kg; Tip distance up to 15m; hub height up to 180m; rotor blade length e.g. up to 80m
2	**Textile rope technology for passenger transportation** Nominal load range (ca. 700kg to 1600kg); safety factors (ca. 10 to 14 (e.g. EU (DIN EN 1808, 2015) or Australia (AS 1418.1 (2021); AS 2550.1 (2011))), also under dynamic load; Can also be used in continuous winches; Also use for	Mechanical failure during set up or operation of textile rope;	Undetected wear-out, aging, brittleness, UAV loading effects; Fire effects; Overloading during operation	**S: 10** **F: 2** **D: 2** Safety critical; Consideration of hybrid ropes, different rope types; Additional rope fastening points;	**8** Handling of steel-ropes is increasingly challenging for small teams and requires supporting devices; Generic challenge due to regulation that does not yet allow person transport with textile ropes	**6** As No. 1 on system level, in addition: Heavy human labor moving heavy steel ropes challenges operational personnel	**3** Improved on-site inspection and repair will improve robustness of rotor-blades; Shortening of inspection, maintenance and repair intervals also; See No. 1, 3	**8** As No. 1; Unfeasibility to use short good weather windows to repair on site; Longer down-times; Less repair in autumn and winter time; See below	**9** Ultra-lightweight ropes are a key factor for new physical access design; Potentially uncontrolled hazards, e.g. fire, or failure modes, e.g. failure that cannot be detected by humans or inspection devices

	Material transport (Safety factors 3 – 5)								
3	**Detection of discard maturity of textile ropes for passenger transport** Optical detection of torn fibers and/or sheath wear; evaluation of different fiber types, colors, layers and sheaths for the detection of discard maturity; Possibly mechanical detection	False positive , i.e. necessit y of rope discard not detecte d	Lack of training data; Lack of empirical operational data; Unexpected failure modes; Operational (mis-)use	**S: 10** **F: 1** **D: 1** Safety critical; Human operator back procedures in operation; Preparation and follow-up of operations	**9** Safety critical; Textile rope and need of rope discard detection technology are expected to be assessed jointly; Might be replaced by human inspection;	**8** As No. 1, 2 on system level, in addition: Monitoring and failure detection of critical subsystem textile rope key enabling system property	**3** Less cost and resource intensive inspection and on-site repair will improve robustness of rotor blades; See No. 1, 2.	**6** As No.1, 2, in addition: Novel technology is expected to need validated tools to assess key safety critical component; Interval tests	**7** Analytical, experimental and simulative justification rope selection and inspection modes; Key for certification; Operational human inspection rules need to be adopted; Inspection might be replaced by human
4	**Textile rope catching and winch technology for passenger transportation** Development of drums, control and safety technology for rope winches, rope winches and rope catchers for textile ropes for passenger transportation, especially suitable for rotor blades of wind turbines	Mecha nical-electric al Failure of rope catchin g safety functio n	Wear out or mechanical failure; Wrong combinatio n of materials; Unexpected weather (fast transition) effects;	**S: 10** **F: 1** **D: 3** Safety critical; No human operator back-up procedures in operation; False alarms should be minimized;	**10** Safety critical; Design of the winch and block stop safety function considers rope aging, rope-friendly propulsion and fixation, avoidance of excessive bending and clamping loads wherever possible; Key system capability;	**10** As No. 1, 2 on system level, in addition: winch and on-demand rope catching safety functions cannot be replaced by human operator	**3** As No. 1,2,3;	**6** As No.1, 2, in addition: Considerable weight savings also for winches and rope catchers; Numerous other applications; Key component for overall system (F1);	**7** Criteria for slipping behavior, reaction times, control accuracy comparable to steel ropes need to be fulfilled; use and modification and adaptation of previous steering criteria and of criteria for activation of safety function; Consideration of the elasticity of textile ropes when sagging
5	**Hand-held local deep (air) ultrasonic inspection** For rotor blades; Detection of typical deep (i.e. in the structure) production, fatigue and damage patterns; Digital twin for rotor blade measurement section; Data sufficient for repair decisions	Deep structur al failures not detecte d; Over- or underes timated	Challenging measureme nt without contact liquid, limited contact liquid and/or energy resources;	**S: 6** **F: 2** **D: 3** Rather mature human inspection procedures on-site close-in to rotor blades	**7** Improvement of the planning capability; Device weighs less than approx. 15kg in total including on-site evaluation and contact liquid, if necessary;	**8** Improvement of inspection; Decision making of repair processes on-site for rotor blades; Monitoring of repair process; Quality assurance;	**1** As No. 1,2,3;	**6** Requires less energy than active thermal measurement; No surface in-spection as optical, thermal; less effort and safer compared to computer tomography	**7** Learning loop feasible using defined test setups in the hall and field data of on rotor blades that are inspected and subsequently repaired; Support of human expert judgement

(33) Optional: Responsible units/persons
(34) Optional: Status comment
(35) General Comments

Note that a notation has been chosen that is similar with respect to the classical FMEA columns similar as in (Häring, 2021a), which shows that FMECA and hazard analyses (HA) (Häring, 2021b) share a lot of columns when considered in extended forms, respectively.

4. Results and discussion

For sample application of the methodology described in section 3 let us assume we have already available a system with capabilities F1 to F5 as described in section 2. Now we assess the system using FMERA approach applied to the sample functions F1 to F5 in case the functions are not available, see Table 1. Aim is to determine their relevancy on system functional level in terms of a system understood as wind turbine, physical access system including ultrasound inspection, and related personnel.

Tip distance proposed in Table 1 between rotor tip and tower depends on the angle of inclination of the rotor blades. Semi-quantitative assessments with values 1 - 10 are used.

Table 1 shows that main benefits are expected in through fast human physical access in case of rotor blade damage for on-site decision making based on human inspection and using hand-held inspection regarding feasibility of on-site repair. Furthermore, F1 to F4 enables on site repair also of larger damages.

The proposed system function capabilities F1 to F4 contribute to the physical access system allowing its fast handling by small teams. They are based on C/GRP technology, lightweight textile ropes, discard detection technology, winch and block stop advancements. F5 covers hand-held inspection technology.

Thus, the proposed system functions F1 to F5 cover the resilience cycle phases preparation, detection, and mainly response and recovery and adoption, as ever-increasing rotor blades can be covered similarly as current blades by small teams and flexible means of transport.

5. Summary and conclusions

A FMEA variant was introduced that resolves the classical consequences on system level as in FMECA using five resilience cycle phases for inductive tabular assessment of resilience. The columns of the failure mode, effects and resilience analysis (FMERA) were motivated.

Sample application was ultralightweight physical access technology for ever increasing wind turbines including hand-held inspection technology that is not yet available. The system functional concept FMERA methodology allowed to assess gaps addressed by the proposed innovations.

It was observed that the proposed technologies mainly facilitate being prepared, more detailed on-site inspection in case of damage events, as well as on-site (in-situ) repair also in case of major physical damage events thus contributing to faster response and recovery. Regular, event specific inspections, maintenance and on-site repair are expected to benefit most.

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