Final report

1. Project details

Project title	GOTWind – Gode Bolte til vindmøller
File no.	64020-1062
Name of the funding scheme	
Project managing company / institution	Danmarks Tekniske Universitet DTU Wind Energy
CVR number (central business register)	
Project partners	DTU Wind and Energy Systems August Friedberg GmbH JNC-WTG-TECH Sedgwick Leif Hansen European Energy A/S R&D Engineering A/S FORCE Technology
Submission date	22 July 2025

2. Summary

GOTWind is an interdisciplinary collaborative effort aiming at increasing the reliability of large diameter high strength steel bolts in wind turbines from production until end-of-life. About a quarter of registered failures in Danish wind turbines submitted to the Danish Energy Agency are associated with bolted joints, and these are often related to major failures, such as complete turbine collapse or detached blades. *GOTWind* secured its objectives through implementation of a whole family of different developments resolving a multitude of interrelated issues concerning the structural integrity of large diameter bolts for wind turbine towers: *August Friedberg* - through extensive testing - systematically identified a suitable bolt lubricant which outperforms other lubrication systems in terms of robustness toward adverse environmental conditions such as humidity and extreme temperatures. *R&D* has developed a calibration procedure that mitigates common failure modes and misinterpretations during calibration. The new calibration procedure restricts the operator's own interpretation and semi-automatically determines the correct calibration between reference object and ultrasonic probe. *Force Technology* developed a bi-wave ultrasonic bolt pre-load measuring system which can omit calibration of the device for different bolt sizes. Furthermore *R&D* and *Force Technology* have co-invented an early concept to detect gaps between wind turbine tower ring flanges with the use of ultrasound. The project has helped to determine the influence of different parameters to ultrasonic elongation measurements such as difference in clamping lengths, probe types, different surface treatments, crooked surfaces, and temperature deviations. *European Energy*, *Sedgwick*, *JNC-WTG-TECH* and *DTU Wind* investigated the effect of different torquing methods and pre-tensioning sequences on the ring flange gap size, gap distribution and its lockability using a combination of laser measurement data, non-linear 3D finite element analysis and experimental work on a NM 52-900 ring flange at *DTU Wind LSF*. *Force Technology*, *August Friedberg*, *Sedwick* and *DTU Wind* explored the feasibility of reducing O&M cost by re-using wind turbine tower bolts. This investigation stirred the development of an eddy current based NDT method for defects in bolt threads to assess the quality of used bolts. High cycle fatigue tests conducted on used bolts indicated a remaining fatigue life above the expectations supporting the future prospect of bolt re-use.

GOTWind er et tværfagligt samarbejdsprojekt, som har til formål at øge pålideligheden af de store højstyrke-bolte fra produktion og igennem hele møllens livscyklus. Omkring en fjerdedel af registrerede nedbrud i danske vindmøller som er rapporteret til Energistyrelsen kan henføres til problemer med boltede samlinger, ofte med støre skader eller havari som følge af komplet møllekollaps eller løsrevne vinger. Projektet har endvidere til formål at sænke CO_2 fodaftrykket fra møllen med forbedrede kvalitetstjek af brugte bolte med henblik på at fremme genbrug. Projektet sikrer sine mål gennem ved at indføre et mere robust og pålideligt boltsmøremiddel, nye innovative metoder til installation og nyt mere pålideligt og brugervenligt ultralyds-måleudstyr. Det sidste punkt sikrer en korrekt installation af bolte og danner grundlaget for defekt-karakteriseringsmetoder, der er afgørende for at etablere genbrug af boltene.
R&D har i projektet udviklet en ny ultrasonisk kalibreringsmetode, der skal mitigere typiske fejl og misforståelser under kalibreringen af ultralydsudstyr samt under genskabelse af tidligere kalibreringer. Den nye kalibreringsmetode begrænser operatørens stillingtagen under processen og på en semi-automatisk måde afgør hvorvidt en kalibrering mellem referenceobjekt og ultralydssensor er korrekt. Ydermere har R&D samskabt et tidligt koncept til at detektere gab mellem flanger i vindmøller ved brugen af ultralyd. Yderligere begrænsninger og faldgruber for dette koncept skal undersøges

nærmere. Projektet har dannet basis for undersøgelser, der gør industrien klogere på de implikationer opstår ved brug af ultralyd i vindmøller såsom forskellige klemlængder, sensortyper, forskellige overfladebehandlinger, skæve overflader og varians i temperaturer.

3. Project objectives

The project objectives of *GOTWind* are the optimization of bolt technology for wind turbines from production until end-of-life. Specifically, the project will implement a new robust lubricant for operation and installation under humid environment, a new reliable and easy-to-handle bolt preload measurement equipment, new installation procedures for closing flange gaps, and establish a Non-Destructive Test (NDT) method for checking defects in reused bolts.
Overall, this project will ensure that there are set out general rules in handling bolts during manufacturing, transport, installation, service, and reuse. The impact from a successfully implemented project is estimated as follows:

- This project aims at reducing the wind turbine failure rate. Currently 25% of all registered failures submitted to the Danish Energy Agency are attributed to bolted joints, and these are often related to major failures, such as complete turbine collapse or blades flying off. The reduction of costs covered by insurance and turbine operators from more reliable bolted joints would correspond to around 1% of LCOE.

- This project aims at mitigating the health and safety risks caused by major failures. Such momentous incidents not only harm the reputation of the wind energy sector, but they also pose a very real risk for people exposed to the gathering ground around wind turbines, such as residential housing, public roads and personnel working in or on turbines.

- This project aims at alleviating the carbon footprint through exploitation of reuse technology. While reuse already takes place in certain circumstances, this project will facilitate more reliable procedures for checking quality of used bolts, reducing risks for implementation of reuse procedures.

4. Project implementation

The project evolved with better success that expected. Once the project participants started to unravel the technical details of the pre-project generation of the ultrasonic bolt-elongation tool, many aspects of technology were evidently missing refinement prior to commercialization of the specific tool. The work packages assigned to R&D were completed prior to project completion and further hours and purchase were allocated to explore and develop further. The work packages assigned to FORCE Technology was completed as scheduled, with good results that are foundation for further refinement of the methods. The work package assigned to August Friedberg was processed as scheduled. The project scope was further extended to fatigue investigation on used bolts in an end phase of the project. However, it could also be implemented to the project scope without considerable delay. JNC-WTG-TECH and Sedgwick: The partner mix in the project was very fruitful as the high knowledge level on the full value chain issues was still present despite no OEM was participating in the project. The advisory board further ensured that any critical technical or regulatory questions could be covered as well.

Risks

Risk	Probability	Effect	Mitigation measures
New bi-wave method for preload measurements will not function properly	Medium	Medium	Revert to current R&D prototype equipment concept to improve accuracy, robustness and user friendliness
No suitable alternative lubricant system for bolts can be found	Medium	High	The effect of environment on current lubricant will be catalogued and handling guidelines published
NDT technique for reuse of bolts will not detect small defects	Medium	Medium	Consider using a combination of different NDT methods increasing the probability of detecting defect
Acquiring sufficient amount of used bolts with documented history	Low	High	Start storing supplies of used bolts in an early phase of the project
Management changes and resource shortage	Medium	Medium	Contingency planning with sufficient redundancy such that available resources can be redirected from other WPs

- *Did the project experience problems not expected?*

For August Friedberg lubrication approach, it was not possible to consider one and the same lubrication system across all sizes, in specific for humidity impacts. Lager sizes (>M36) will need a further improvement of the lubrication system.

For Force Technology the focus of the project was to prove the theoretical concept of the connection between ultrasonic velocity and preload experimentally, and to find and control the influential parameters. It took a lot of effort to optimize the experimental setup and measurement accuracy to prove the connection between ultrasonic velocity and preload.

European Energy was not able to perform the originally planned measurements on flanges on site due to the COVID19 pandemic and the planed flange gap measurements on a wind turbine in Esbjerg to be performed in November 2023 were called off due to rain weather.

JNC-WTG-TECH and Sedgwick issue the following statement: The sudden and uncoordinated lay-off and exit of project manager Hilmar Danielsen from DTU severely disrupted the project management process and closure of GOTWind. The industrial project participants and steering committee members highly appreciate the great work of project manager Hilmar Danielsen in terms of excellent project management and for keeping the project going on the right track.

5. Project results

- *Was the original objective of the project obtained? If not, explain which obstacles that caused it and which changes that were made to project plan to mitigate the obstacles.*

The original objectives of the project were obtained with great success. These can be categorised as follows:

- Performance investigation of a pre-developed lubrication system against competing lubrication candidates.
- Improvement of bolt pre-tension measurement equipment through a novel calibration method.
- Development of a new bi-wave flange gap measurement technique to reduce the gaps in bolted ring flange connections.
- Investigation of the effect of different torquing techniques on flange gaps and the effect of water and low temperature on the preload.
- Investigation of max./min. flange gaps based on real life flange waviness measurements.
- Investigation of the critical crack sizes of bolts and promising test results pointing towards the potential of bolt reuse.

European Energy could not conduct the originally planned flange flatness measurements due to the impact of the COVID19 pandemic. As a mitigation European Energy provided laser measurement data obtained from the wind turbine suppliers which is part of the regular as-built documentation for their wind turbines.

- *Describe the obtained technological results. Did the project produce results not expected?*

August Friedberg: A new lubrication approach for tower bolt assemblies. Three different lubricants (MoS_2 Reference Lube RL, Lube L1 'Kema RG-1100' and Lube L2) were applied to the nuts of bolt garnitures (see Fig.1 left). These garnitures were subsequently tested in a tension-torque machine under preload by August Friedberg at ambient temperature +20ºC, hot conditions +60ºC and at sub-zero conditions -20ºC. Moreover, the lubricants were tested under different humidity conditions. Figure 1 right shows the bolts subject to different environmental conditions in the laboratory.

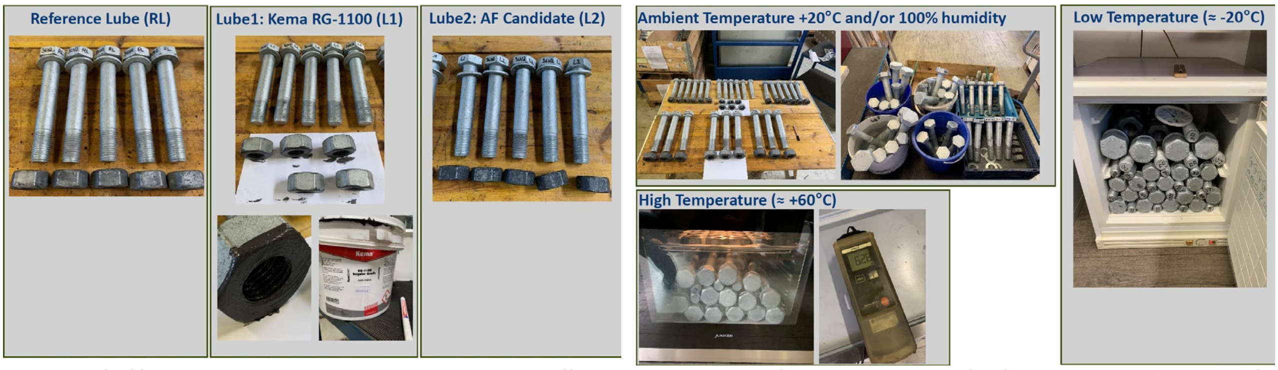


Figure 1: (left) bolt garnitures prepared with three different lubricants; reference lubricant (RL) and Lube 1 'Kema RG-1100' (L1) and Lube 2 'AF Candidate' (L2) and (right) exposure of bolt garnitures to different environmental conditions such as humidity, high temperature and low (sub-zero) temperature.

In case of water impact the reference lubrication RL shows increase of friction and tends to stick-slip during installation. Concerned series were stopped on early stage (<2800Nm) to avoid damage of the testing equipment. Stick-slip was not present for L1 and L2. Exposure time of 48h to water immersion (simulating the effect of rain precipitation) for the reference lubrication RL resulted in a severe stick-slip effect for 36-N3-RL with extreme torque oscillations accompanied by distinct sound vibrations. The RL used in combination with water exposure shows that the preload values in the bolt were lower than the required minimum. On the other hand, water exposure to lube L1 shows very high preload level, close to ultimate limit. Lubricant L2 showed overall good and stable performance under all tested environmental conditions (see Fig.2).

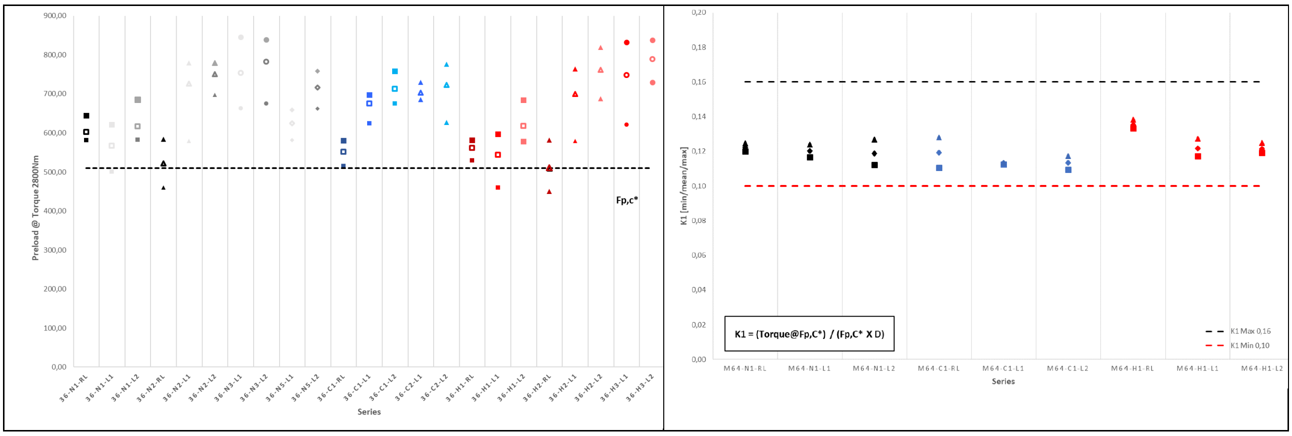


Figure 2: (left) Summary of torque-tension results for different exposure conditions and lubricants N1: Normal ambient condition, N2: Short term moisture for 5 min fully immersed in water, N3: Long term moisture for 48 hours fully immersed in water, N5: After 48 hours moisture, drying completely for 48 hours, H1: High Temperature +60°C for 48 hours, H2: High Temperature +60°C for 48 hours followed by 5 min fully water immersion, H3: High Temperature +60°C for 48 hours followed by 48 hours fully water immersion, C1: Low Temperature -20°C for 48 hours and C2: Low Temperature -20°C for 48 hours followed by short water impact and (right) K1 value for different lubricant systems show torque tension condition of different lubrication systems by example of size M64. Exposure conditions are low and high temperature.

The following results can be summarized as follows:

- Weathering conditions have a considerable impact on the preload of structural bolting assemblies. Depending on the applied lubrication type, it can increase or decrease the friction during torquing operations.
- Low and high temperature separately considered do not show a critical impact on all investigated lubricant types. However, water impact can be considered as a worst case.

- RL when exposed to water shows a high increase of friction in all cases. L1 and L2 are quite similar in behaviour and tend to rather decrease the friction.
- After drying again, L1 and L2 achieve acceptable load levels. The RL on the other hand, did not achieve the designated preload level again, as the lubricant is washed out.
- For sizes > M36 in combination with L1 and L2 the water impact is quite critical as friction is dropping down considerably, posing a risk of over-tensioning. An angle-controlled assembly of torque would avoid overloading and introduce uniformly distributed preloads.

<u>August Friedberg, Sedgwick</u>: Fatigue tests with used hot dip galvanized HV-bolting assemblies M36x230-10.9 with more than 20 years in operation. All bolts in the connection were replaced by new bolts. Approximately 50% of the bolting assemblies, these were bolts with lower preloads and bolts from critical locations, were considered for investigation regarding residual fatigue resistance (i.e. residual fatigue lifetime) and for the evaluation of probable crack initiation. Bolting assemblies still showing compliance with preload requirements were considered for testing the residual fatigue resistance, too. A microscopical characterization of the fractography of fatigue tested items was conducted with regards to crack initiation for the different failure types (see Fig. 3).

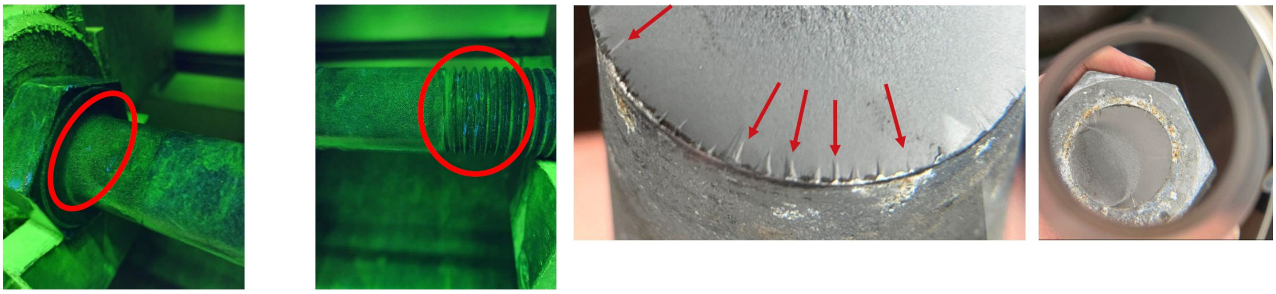
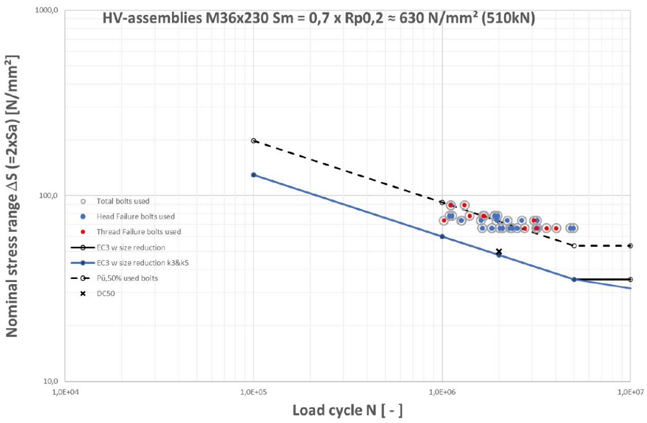


Figure 3: (left) magnetic particle investigation of used bolts and (right) ratchet marks and fractography after fracture of fatigue tested M36x230-10.9 bolt.

The used bolting assemblies have been tested in a uniaxial high frequency resonant testing at different stress ranges in the high cycle regime until failure. Figure 4 (left) shows the fatigue test results superimposed with the bi-linear SN-curve stipulated in EC3; this indicates that the residual fatigue life of used bolts still complies with the standard. Figure 4 (right) shows the effect of pre-load on the total cycle number of used bolts distinguished between thread failure and head failure.



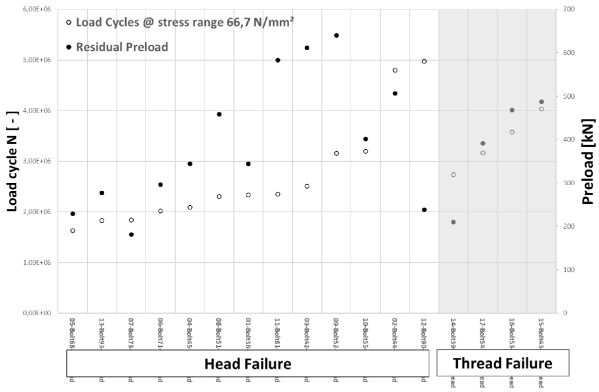


Figure 4: (left) fatigue test results (red thread failure and blue head failure) superimposed with EC3 SN-curves and (right) linear increase of load cycles with increase of residual pre-load in the case of thread failure; linearity not as clear in the head failure types.

The following results can be summarized as follows:

- Fatigue tests on used bolts confirm DC50 according to EC3, even after concerned corrosion occurrences visible on the tower segments. Fatigue failure types on used bolts (rolled after heat treatment) are bolt head failure or bolt thread failure.
- Cracks possibly initiated during operation of the wind turbine are detected by microscopical investigation of the cracked surface after fatigue testing. In some cases, the defects are even visible by the unaided eye.
- SEM analysis shows a high oxygen content on the defects, most probably contained in the corrosion products formed during operation.
- No correlation between residual preload (ultrasound measured before dismantling) and fatigue load cycles could be found for the bolt head failure type. For the thread failure type there seems to be an increase in fatigue life with a higher preload level.

Force Technology, August Friedberg: The determination of preload in the already installed bolts, is based on the linear relationship between the ratio of time of flights of shear waves and longitudinal waves, and the preload in the bolt. The linear relationship is specific for the bolt type, bolt length, flange thickness, temperature etc. and shown in Fig.5 for a given bolt.

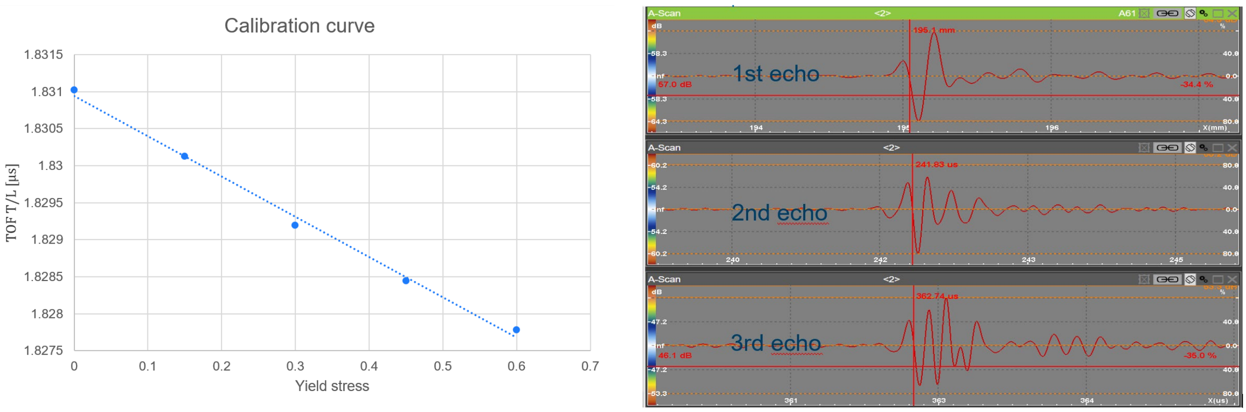


Figure 5: (left) Calibration curve of the bi-wave method as a function of the yield strength and (right) shear wave echoes used for optimization of the device.

To obtain the calibration curve, the measurements of time of flights must be measured accurately. Fig.5 (left) shows an example of how the time of flight is measured. It was found that especially the transversal/shear waves were both difficult to generate and measure accurately due to interference between the modes. Therefore, the following parameters must be fulfilled to accomplish necessary accuracy:

- Shear and longitudinal waves must be measured at same position by using a probe centering unit.
- Shear waves must be generated by EMAT probes, to eliminate coupling layer thickness variations.
- For shear waves the time of flight must be measured at the 1st ultrasonic echo.
- The same measurement technique must be used to obtain the calibration curve and the actual preload measurements.

Many different parameters influence the calibration curve, for example temperature, production batches (e.g. bolt manufacturer), flange thickness, temperature, bolt lengths, shear tension etc. To investigate if the calibration curves changed for different bolt manufacturers, even if the bolt type was the same (all 10.9 bolts, same length), the calibration curve was obtained on three different bolts, summarized in Fig.6. It is seen that the slopes of the curves are the same, however the curves are shifted for the different bolt.

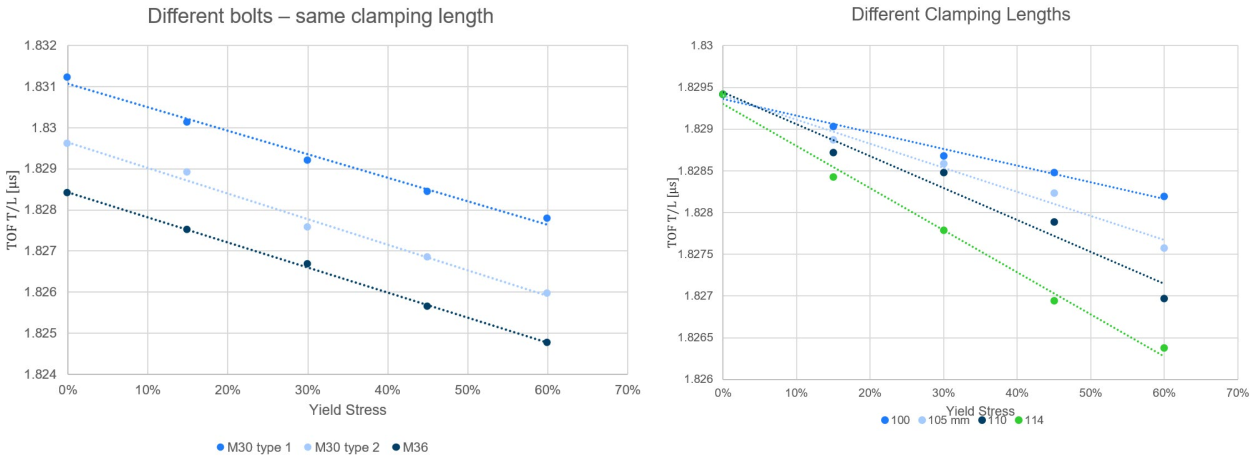


Figure 6: (left) calibration curves for different bolts and same clamping length as a function of yield strength and (right) calibration curve for different clamping lengths as a function of yield strength.

The influence of the clamping length was examined and summarized in Fig.6 (right). It is seen that the slope of the calibration curve changes for different clamping lengths. Similar curves are obtained when keeping the clamping length constant but varying the length of the bolts.

To summarize the most important results:

- Different bolt batches and temperature change q0.
- A variation of the clamping length relative to the bolt size changes the slope of the curve.
- The calibration curve must be obtained using the same parameters as in the measuring sequence.
- Measurements should be made on the 1st echo – Use EMAT for shear waves – especially if the bolt is concave.
- Measure S and L wave at the same probe position – probe centering unit must be used.
- The TOF must be accurately measured on the correct phase of the signal, both for the calibration curve and preload measurements.
- The calibration curve must be measured on 1-3 of the installed bolts, and the preload can be determined in the rest.

R&D, August Friedberg: Bolt-Check has been further improved by introducing a new calibration method that leverages the integrated traceability system to minimize decision-making for the operator, thus mitigating the risk of human-errors. A lot of measurements have been made, to determine the accuracy of the measurements. R&D has developed a spreadsheet, where different types of bolts and surface treatments can be selected. When entering the clamping length, the spreadsheet calculates a spring constant. The calculations are based on a Young's Modulus of 210 GPa but the majority is between 200 to 220 GPa. (210 ±5%). The overall picture confirms the accuracy at 5%, between the measured and calculated values (see Fig.7 (left)). However, a few outliers have been detected: for this test 3 out of 162 points. During the test series R&D has detected a range between 190 GPa to 260 GPa. All determined by ultrasound, rather than by mechanical measurement.

The results from the test led to an improved recommendation regarding the sensor type and the positioning of the sensor on the bolt. Introduction of the positioning pads ensures the same position at the centreline of the bolt, independently of the operator. Recommendation of sensor type / bolt size ensure the same type sensor is used on a given bolt size every time (cf. Fig.7 (right) and Fig.8 (left)).

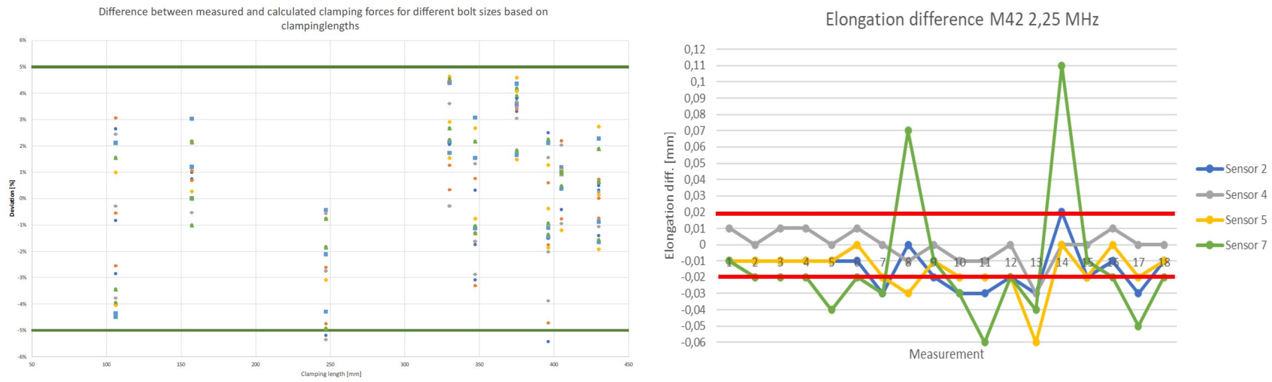


Figure 7: (left) accuracy of measurements within ±5% deviation between the measured and calculated values and (right) elongation difference for different sensor types.

The new and improved calibration procedure, for bolt check, that is incorporated in the SW (Patent is pending). The new calibration procedure: All the calibration bars are pre-measured at R&D prior to shipping. The measurements are stored as a reference bolt, using a traceability tag. All sensors will have a traceability tag assigned. Center pads are used to secure the calibration position of the sensors. When re-calibrating, the normal functionality in Bolt Check is used. If the elongation <0,005mm then the calibration is approved. Elseif, the elongation >0,005mm then re-calibration is automatically done (adjusted). The Bolt Check software secures that (1) the calibration settings for the individual sensor are loaded automatically, (2) no outdated calibrations can be used, (3) an operator warning is issued if a wrong type of sensor is used and (4) storage of all calibration changes in tracking file.

The current temperature on the bolts, has a significant influence of the elongation measurements (see Fig.8 (right)). The main contributors to this are thermal elongation and reduced speed of sound is ≈1% for each ΔT at 100 ºC. The deviation is found to be 0.0029% / ºC or 0.003mm / (100mm ºC). When the temperature compensation in Bolt Check is activated, the measurement deviations disappear.

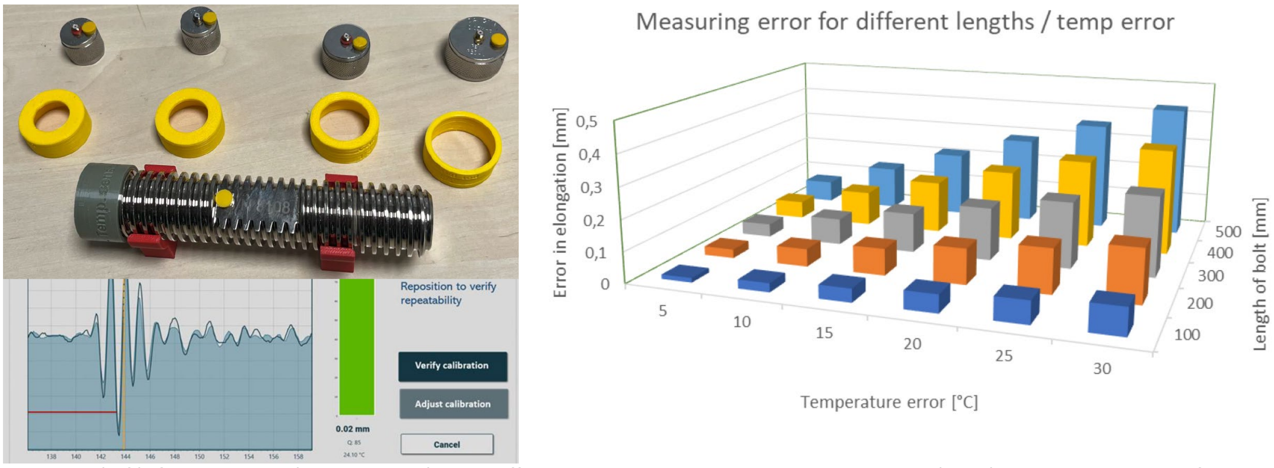


Figure 8: (left) Center pads (yellow rings) and different corresponding sensor types and (right) elongation error of measurements as a function of temperature and bolt length.

To summarize the most important results:

- ➢ The tolerances for different clamping lengths have been determined.
- ➢ Repeatability between different bolt check devices (across devices) has been established.
- ➢ Different types of sensors have been compared, leading to a more controlled usage.
- ➢ The influence of surface treatment and crooked surfaces (bolt head) on the results has been determined.
- ➢ Improved positioning instruction of the sensors to minimize influence of different operators.
- ➢ Established the temperature influence on the measurement results.
- ➢ Stipulated a calibration procedure, leading to an improved and more consistent calibration.

<u>Sedgwick, JNC-WTG-TECH</u>: Controlled testing of a number of prominent bolting issues on a NM 52-900 kW flange made readily available by Sedgwick (see Fig.9 (left)) as follows:

- o Testing the difference between the cross-torque and continuous direction spanning method.
- o Response of the bolt pre-load to artificially introduced flange gaps by shims.
- o Performance evaluation of the three different lubricants (RL, L1 and L2 defined by August Friedberg) under different environmental conditions.
- o Evaluation of preload relaxation and thread locking over time.
- o Investigation of bolt head torque method to allow for flange drainage by installing the bolts in a head-up position.

All three lubricant systems used for the HV bolt sets were tested by torquing and re-torquing the bolt garnitures (see Fig.9 (right)). Eventually two trustworthy lubricant alternatives to common MoS2 lubricant were identified. Especially the impact of humidity on the lubricant performance was investigated and in some cases the impact from moisture seemed to lower friction, where this was unexpected.

Figure 9: (left) Off-cut of a NM 52-900 tower ring flange setup at the Large-Scale Testing Facility at DTU Wind and (right) detail of the ring flange bolts (bolt nuts facing upwards) with a shim placed in-between the flanges to simulate the effects of a flange gap.

The incentive for applying torque to the bolthead is to allow the drainage of any water ingress into the flanges through the thread, avoiding confined ice building up inside the flanges (see Fig.10 (right)). Moreover, head torque would offer the benefit to improvement HSE during bolt installation.

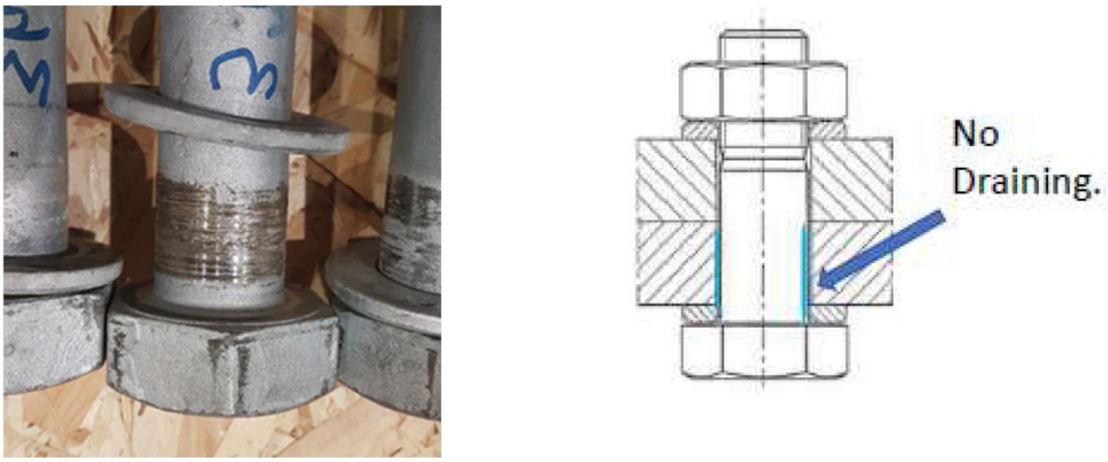


Figure 10: (left) wear damage of the zinc coating on the bolt shank underneath the head due to head-torque and (right) in the bolt garniture assembly shown any water present in the flanges during installation is trapped and can lead to ice formation in sub-zero site conditions.

To summarize the most important results:

- Conclusion in test: Not that sensitive for humidity that expected on the MoS2. Despite well - known problems at some Nordic sites
- Head torque not possible on Standard MoS2 bolt sets as is. (without an additional under head lubrication), but possible with the two other lubricants with controlled lubrication below bolt head.
- At some bolt shafts a damage of the zinc coating due to bolt head torque was seen (see Fig.10 (left)).
- A counter hold on the bolt nut is needed if torque is applied to the bolt head.
- It is recommended to apply the torque to the bolt nut from underneath the flange to solve the drainage problem or to switch to bolt head torque.

European Energy, DTU Wind and Energy Systems: Measurement and simulation of flange imperfections. European Energy delivered measurements on flange imperfection and provided access to wind turbines for measurement purposes with the aim to assess the flange flatness imperfections and the resulting effect on the flange gaps in turbine towers using:

- Flange flatness measurements for 15 turbine towers from 2 different OEMs.
- Statistical calculations of the mated flanges at different rotational mating positions.
- 3D Finite Element simulations of the tower sections to determine flange gaps.

Numerical analysis of laser measurements on ring flanges of as-built tower segments by two different OEMs showed that the waviness induced by self-weight during horizontal storage conditions is negligible. Statistical evaluation of the flange gap (OEM-1 686 data points and OEM-2 520 data points) depending on the mating rotation showed a maximum gap of approx. 5mm with a mean value of approx. 2mm (see Fig.11).

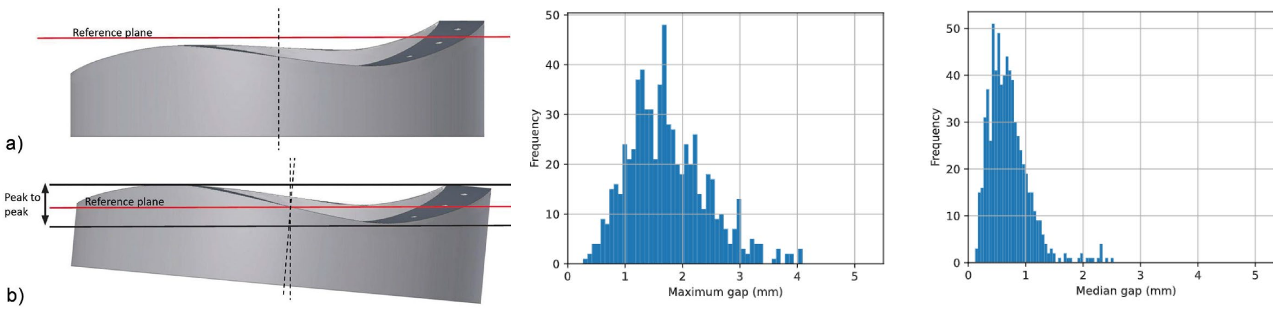


Figure 11: (left) calculation of flange waviness from laser measurements using a reference plane and (right) frequency of maximum & median flange gaps before preload for all relative mating flange rotations (shown here for OEM 1)

3D finite element simulations with and without consideration of the preload induced clamping force showed that the flange gap might not be closed after pre-tensioning (see Fig.12 (left)). Moreover, simulations showed that the flange might appear closed on the inside, whereas a gap appears on the outside – even after pre-tensioning (see Fig.12 (right)).

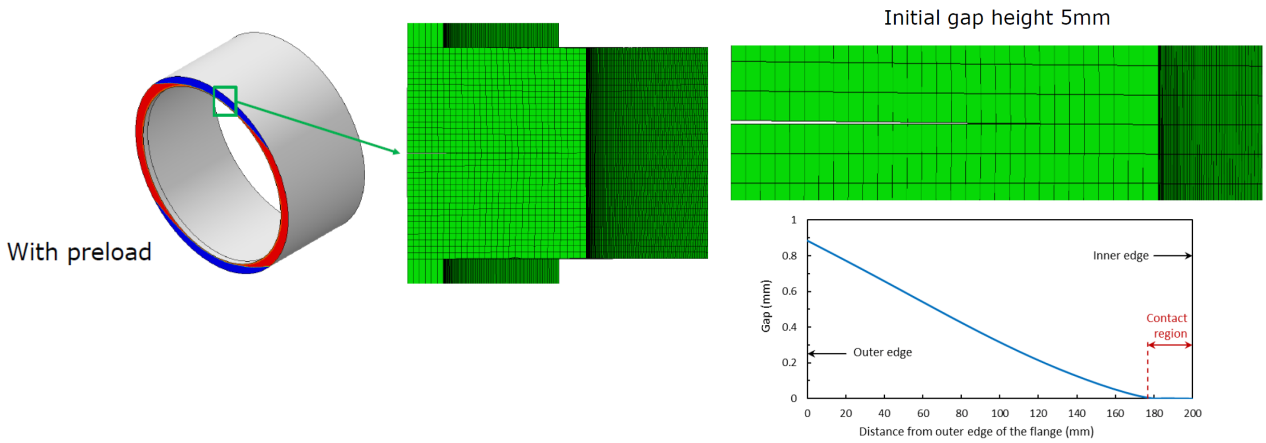


Figure 12: (left) simulation results of mating flanges where blue represents an open gap and the red zone indicates a closed flange gap and (right) radial distribution of the flange gap from the inside (closed) to the outside (open) predicted by 3D finite element analysis.

To summarize the most important results:

- In extreme cases large initial flange gaps (>23mm) can occur when flanges are mated in unfortunate relative rotational positions.
- In such cases the bolt preload might not be sufficient to close such gaps properly.
- The size of the flange gaps might be dependent on the OEM.

DTU Wind and Energy Systems, Force Technology: Reuse and critical crack size of tower bolts. Determine the critical crack size in a wind turbine tower bolt as a detection limit for NDT. An eddy current probe was developed by Force Technology (see Fig.13 (left)) and calibrated against artificially created thread notches introduced by electric discharge milling. It was demonstrated that the eddy current measurement technique (see Fig.13 (right)) can indeed reliably detect the artificial defects applied to the bolt threads.

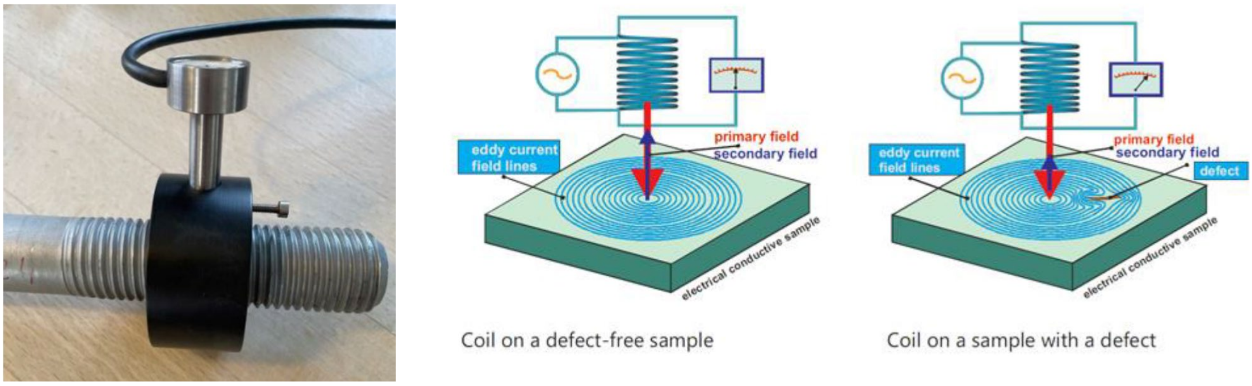


Figure 13: (left) eddy current probe that can be screwed onto the thread of a bolt such that the entire thread can be scanned continuously and (right) eddy current measurement principle applied to an intact sample and a sample with a defect.

Fracture based simulations of cracks located in threads (DTU Wind) of bolt garnitures showed that the critical defect size in 10.9 bolt materials is less than 100µm (see Fig.14 (left)). DTU Wind conducted compact tension fatigue tests on specimens extracted from an M36 10.9 bolt shank which were specifically designed to measure the crack growth speed for short cracks < 100µm (see Fig.14 (right)).

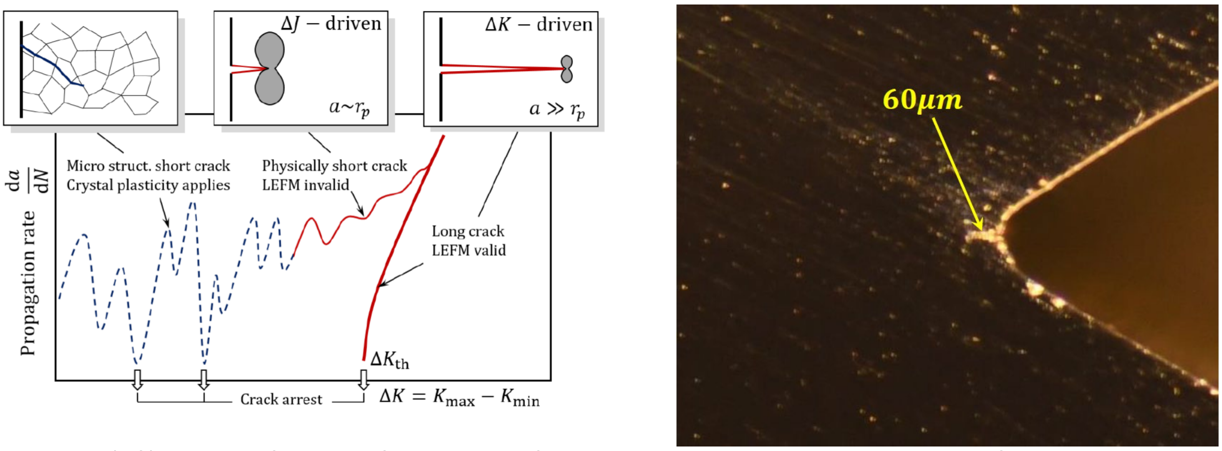


Figure 14: (left) critical defect sizes for high cycle fatigue crack growth in 10.9 bolt materials from microscale to macro scale and (right) microscope image of 60µm long fatigue crack in CT specimen during fatigue testing at *DTU TestLab*.

To summarize the most important results:

- The critical defect size of a bolt remains still unknown; however, the following insights below hold true.
- Defects with a size of 100 µm in bolts can be classified as critical defects; however, even defect sizes <100 µm might remain critical.
- No NDT method is applicable to detect critical defects <100 µm in bolts.
- Short crack growth in 10.9 bolt material is significantly slower than for long cracks.
- The short crack growth phase (and initiation) in bolts needs to be considered for accurate lifetime predictions. Classic LEFM based lifetime predictions are significantly underestimating the life.

- *Describe the obtained commercial results. Did the project produce results not expected?*

August Friedberg: The considered lubrication shows a promising behaviour used for HV structural bolting assemblies. However, some further development is needed with regards to stabilization of friction coefficient when exposed to moisture, which was just implemented and approved (not in project scope).

Force Technology: To have a commercial equipment ready that can go to the market, some optimization needs to be done. This includes the purchase of new probes capable of generating both shear and longitudinal waves by the same EMAT probe. There could beneficially be generated a software for automatic reading of the time signal, to ensure correct reading of the time of flight.

R&D: The project shows a promising use of the ultrasound technology to determine gaps in flanges in wind turbines that are located at the outer periphery of the tower flanges. This will potentially unlock commercial activities in the future. Patents are to be filed for this method.

- *Target group and added value for users: Who should the solutions/technologies be sold to (target group)? Describe for each solutions/technology if several.*

August Friedberg: Different applications for structural engineering constructions, as steel buildings, bridges and towers for wind turbines.

Force Technology: The target group are all industry with bolted connections, hereunder the wind- and oil and gas industry, where the preload are to be determined on already installed bolts.

R&D: Engineers and technicians engaged in the wind turbine industry.

Segdwick, JNC-WTG-TECH: The target group is all users of bolting joints in wind turbine tower design and related maintenance aspects. Bolting specialists need to implement improvement in their designs and take more responsibility for the whole value chain. (e.g. avoiding intruding water in clearance holes in flanges). The common practice that a service check of corroded bolts by applying standard torque is not valid as control method. The value creation is by raising awareness to this relatively simple bolting technology.

- *Where and how have the project results been disseminated? Specify which conferences, journals, etc. where the project has been disseminated.*

The project results of effects of defects on the lifetime of bolts was published by DTU Wind and Energy Systems in a peer reviewed journal paper:

Shakeri, I., Danielsen, H. K., Tribhou, A., Fæster, S., Mishin, O. V., & Eder, M. A. (2022). Effect of manufacturing defects on fatigue life of high strength steel bolts for wind turbines. Engineering Failure Analysis, 141, 106630. https://doi.org/10.1016/j.engfailanal.2022.106630

Another review paper on tower flange imperfections in in preparation. All project results have been disseminated during a GOTWind workshop organised by Sedgwick and DTU Wind on tower flange connections with more than 30 participants from industry, with a particular good turnout from Ørsted, Vattenfall, Vestas and SGRE.

6. Utilisation of project results

- *Describe how the obtained technological results will be utilised in the future and by whom.*

August Friedberg: The improved lubrication technology will bring a further increase in the material resistance of the structures, e.g. fatigue resistance. Thus, it could further increase the lifetime of structures compared to current system and bring further extension of operation time for structures. Due to its robustness the susceptibility to execution/application errors, probably caused by the installation team, will most probably be significantly reduced.

Force Technology: On the short term, the technological results obtained will be utilised as a service, provided by Force Technology. However, before the technology is ready for the market, some additional experiments need to be performed, and if the technology lives up to the promising results obtained in this project, it is possible that Force Technology develops equipment with the aim to sell the product.

Sedgwick, JNC-WTG-TECH: The results from fatigue testing of used bolts with exceeded design lifetime will positively impact future decisions on lifetime extension of existing Wind turbines. Basic for decision making is improved.

- *Describe how the obtained commercial results will be utilised in the future and by whom the results will be commercialised.*

August Friedberg: Product advantages and application properties of the improved lubrication system may be generated for sales activities by August Friedberg. This may be realized by advertising using flyers for exhibitions or theoretical/practical trainings, websites and technical reports/presentations.

Force Technology: The developed equipment will be commercialized by Force Technology. When the equipment is ready for the market, Force Technology provides an active strategy for commercializing the equipment. This could be by writing articles, attaining/speaking at conferences, advertising on our website, and generate a one-pager (flyer) to be distributed to potential customers.

Sedgwick, JNC-WTG-TECH: Service companies working with re-sale of WTG will benefit from the commercial results and lower the carbon footprint as renewing of wind turbine tower bolts is minimized.

European Energy: European Energy will not directly but indirectly benefit from this project; however, it is important to find methods which can assure that bolted connections in wind turbines are correctly installed and maintained during the operational phase. European Energy has seen bolted connections which have been installed incorrectly and bolts which have failed. The results obtained in GOTWind help to avoid such incidents which in the past have resulted in downtime. The EUDP funded GOTWind project has provided evidence that measurements on bolted connections can be performed after installation and thereafter on a regular basis to verify that the bolted connection is still valid. European Energy will use this knowledge to ensure that wind turbine manufactures are using this kind of technology for the coming projects. Vestas has as a side note used R&D to check the bolted connections in two of European Energy's wind turbines in Esbjerg. This project has also shown that handling and the application of proper lubrication of bolts and nuts is important, and this will also serve as a basis for our technical review of wind turbine contracts.

- *Did the project so far lead to increased turnover, exports, employment and additional private investments? Do the project partners expect that the project results in increased turnover, exports, employment and additional private investments?*

August Friedberg: Currently, the project did not lead to increased numbers. Due to the large capacities already implemented in the company prior to the project start no further employment or private investment is considered. A slight increase in turnover may be possible, if the system is accepted by the market.

Force Technology: So far there has not been an increase in turnover, employment etc. However, if/when the technology is ready for the market, we expect a large demand on the service by the industry.

European Energy: The number of wind turbine projects in European Energy will not justify that FTE will be allocated to this going forward, however actions have been taken to ensure that a request for offer (RfQ) includes questions to the method used by the OEM for torquing and handling bolts.

- *Describe the competitive situation in the market you expect to enter.*
  - *Are there competing solutions on the market? Specify who the main competitors are and describe their solutions.*

August Friedberg: Yes, there are competing solutions on the market by other bolt manufacturers. However, no systematic investigation is published so far for their systems. No further specifications can be mentioned regarding their solutions.

Force Technology: The bi-wave method for use to determine preload in already installed bolts, are examined by others throughout the world, so there are competitors using the same technology. There is currently not any comparable commercial equipment on the market yet.

Another technology based on acoustic vibrations to determine preload is also being examined.

- *Describe entry or sales barriers and how these are expected to be overcome.*

August Friedberg: Entry or sales barriers are already existing, as alternative lubrication and tightening systems are in place. However, they are mostly restricted for flexible, fast and easy use and need much more specialization. These barriers may be overcome by training and positive experiencing during application. Marketing is also a key for success but is depending on the cost vs. benefit ratio.

Force Technology: The method must be refined further before entering the market. When this is accomplished, the method must be qualified by a certification body to document its functionality.

- *How does the project results contribute to realise energy policy objectives?*

All project results contribute to the green energy policy objectives in different ways as follows: The development of a humidity inert lubricant enables consistent pretension forces in wind turbine tower bolts independent of the environmental installation conditions. The improvement of the bolt pretension force measurement device makes sure that the designated preload is precisely applied to every single bolt in a wind turbine ring flange, rendering a homogeneous pretension distribution. The development of a novel bi-wave flange gap measurement device supports the installation process and makes sure that flange gaps are detected and closed properly. The investigation of the critical crack size in bolts enables further development of bolt-reuse.

The project results acting together will increase the longevity and reliability of wind turbines and therefore, decrease the likelihood of catastrophic failure and reduce the cost for maintenance and repair. The project results contribute to a reduction of O&M cost and will ultimately contribute to a reduction of the cost of energy.

- *If Ph.D.'s have been part of the project, it must be described how the results from the project are used in teaching and other dissemination activities.*

PhDs have not been part of the GOTWind project.

7. Project conclusion and perspective

- *State the conclusions made in the project.*

The GOTWind project can be classified as highly successful in terms of attaining the ambitious goals initially set in the project proposal through a very fruitful collaboration between all project partners – ensuring the coordinated exchange of key expert knowledge between the different industries and academia. In GOTWind new bolt lubricants have been thoroughly and systematically tested and scrutinized under both, advanced laboratory conditions and in a real ring flange connection under different environmental conditions i.e. temperature, humidity and ice formation; eventually a suitable lubricant candidate has been identified and subsequently commercialized by August Friedberg. This new lubricant system outperforms the commonly used MoS2 lubricant in general and particularly in terms of robustness towards humid environmental conditions. It is expected that this new lubrication system provides August Friedberg with a competitive advantage.

GOTWind supported the development of an advanced ultrasonic bolt preload measurement system. It is empirically known that judging the preload in bolts from torque measurements can lead to preloads which are outside the target value with dire consequences on the structural longevity and reliability. On the other hand, the new bolt preload measurement device enables a consistent and rigorous measurement of every single bolt in a ring flange connection swiftly, accurately, and precisely to ensure optimal preload conditions. Moreover, the new system allows the tagging of each single bolt of each ring flange uniquely which greatly enhances traceability and hence, reduces O&M cost. Furthermore, in GOTWind the device has been made robust and user-friendly by R&D such that it can be reliably handled by the workforce on site with comparatively little training effort. The bolt-measurement device developed by R&D has been certified and is now commercialized.

In parallel Force Technology developed an ultrasonic pretension measurement technique which uses a novel bi-wave ultrasound signal which offers the advantage of avoiding the calibration step. Moreover, GOTWind supported the development of an ultrasonic flange gap measurement device which provided promising results. Closing the flange gaps in bolted ring flange connections is crucial for the structural integrity of wind turbine towers. Yet, the detection of flange gaps – in particular those appearing on the outside of the tower – is known to be hardly possible. Now, the ultrasonic flange gap measurement device developed by Force Technology has the potential to resolve this issue in a time/cost efficient and user-friendly fashion that can conveniently be applied during the tower assembly stage avoiding workflow disruption.

GOTWind enabled the joint venture of European Energy, Sedwick, JNC-WTG-TECH and DTU Wind to investigate the effects of different pre-tensioning methods on the preload distribution and flange gap closure behaviour. It is important to stress that the findings are based on real as-built measurement data and were obtained by measurements conducted on a real ring-flange under controlled testing conditions. The data obtained from this investigation corroborated by numerical finite element analysis provided by DTU benefits European Energy as an operator to improve the risk assessment of its assets. Moreover, the data enables the consultants Sedwick and JNC-WTG-TECH to further enhance their services in terms of pinpointing the root causes of potential ring-flange failure and to advise their customers on how to avoid these. GOTWind supported the initiative of Sedwick and JNC-WTG-TECH to sustain and to improve the work ergonomics (health and safety) of the workforce on site during bolt installation by investigating the possibility to head-torque bolt assemblies.

In GOTWind the possibility of bolt-reuse was explored by a fruitful collaboration between August Friedberg, Force Technology, Sedgwick and DTU Wind. The re-use of bolts in tower flanges mitigates the demand on transport and logistics during O&M operations. Force Technology developed a purpose-built eddy current probe which can detect macroscopic flaws in used bolt threads. DTU investigated the critical flaw size in bolts which was found to be below the detection limit of the eddy current probe. However, high-cycle fatigue tests on used tower bolts performed by August Friedberg and Sedgwick demonstrated that the remaining fatigue life of used bolts is above the expectations. These promising results support future development effort in terms of on-site quality inspection and assessment techniques of used tower bolts.

- *What are the next steps for the developed technology?*
- *Put into perspective how the project results may influence future development*

August Friedberg: Based on WP2 experiences AF new approach L2 is further modified and already implemented for structural bolting assemblies M12-M36. A suitable lubrication system for sizes > M36 is still in development process.

Force Technology: The results obtained in WP1 demonstrated a proof of concept in laboratory conditions, however a few more variables need to be considered. Future development will aim at making measurements more user friendly without compromising the need for accurate measurements and readings.

Sedgwick: Would a controlled tightening to minimum preload level e.g. Fp,C* support further operation of the wind turbine over the designed service life?

8. Appendices

- Add link to relevant documents, publications, home pages etc.