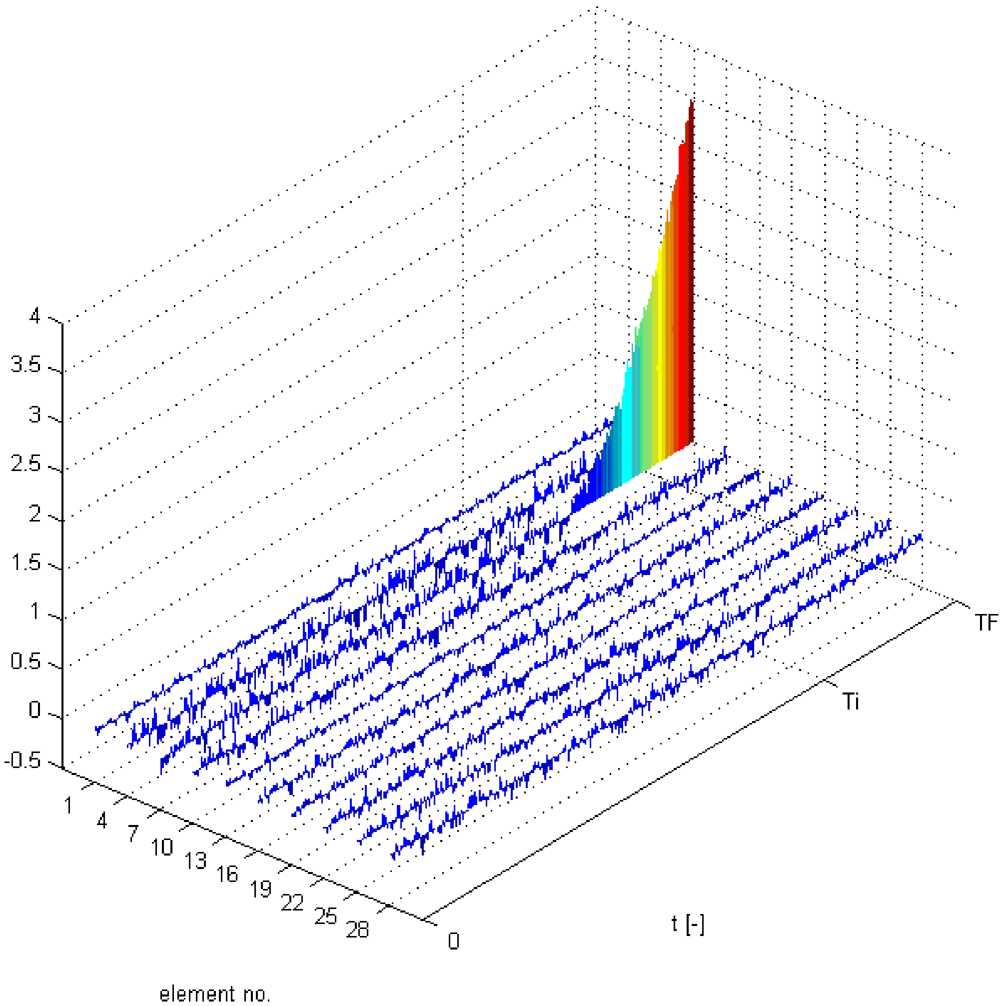
INCORPORATION STRUCTURAL HEALTH MONITORING IN THE DESIGN OF SLIP FORMED CONCRETE WIND TURBINE TOWERS – PROGRESS REPORT

Civil and Architectural Engineering
Technical Report CAE-TR-1



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In the overall perspective, the project combines many different engineering disciplines and thus the report displays a variety of content. The reliability theory ties the different disciplines together, and the focus is chosen on the dominant uncertainties of the modal damage detection as a consequence barrier (risk reduction by decision rule), as the initial studies in the project indicated this as an interesting and innovative approach.

Keywords: Fracture mechanics, Non-linear FE modeling, Concrete structures, Steel structures, Theoretical dynamics, Experimental dynamics, Damage detection, Structural health monitoring.

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This report contains introduction to the subject as well as descriptions of the problems, a state-of-art overview, descriptions of the methods applied and of the results achieved so far. Furthermore, the report contains a plan for the remaining part of the project period. In the overall perspective, the project combines many different engineering disciplines and thus the report displays a variety of content. The reliability theory ties the different disciplines together, and the focus is chosen on the dominant uncertainties of the modal damage detection as a consequence barrier (risk reduction by decision rule), as the initial studies in the project indicated this as an interesting and innovative approach.

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Paper accepted for presentation at the 2013 IWSHM
[removed due to copyrights]

1. SHORT INTRODUCTION

1.1 Damage detection

SHM (structural health monitoring) in the form of damage detection has seen a worldwide increase in interest from researchers in the last decade or two. New methods, primarily based on old methods, occur frequently but most times the same difficulties and weaknesses block the path to successful, simple and robust damage detection.
For structural damage detection to work stand-alone on a global level (i.e. changes in structural response characteristics feed the algorithm) the method must be proven robust to many pitfalls, for example:

- Damage localization
- Damage type
- Damage severity
- Changes in the environment
- Sensor degradation
- Probabilities of false detections.

As structures usually have a very high level of reliability, the damage detection system naturally must live up to this standard.

1.2 Wind turbine towers

Along with the above mentioned pitfalls, wind turbine structural components induce further complications because of the controller. Generator torque, nacelle yaw and blade pitch are continuously optimized to maximize the power curve while reducing the loading on components. This creates nonstationary conditions as well as strongly periodic and non-gaussian loading which in turn complicate structural identification, for instance using output only modal analysis (OMA).
Most structural components in a modern wind turbine have designs governed by fatigue, as the number of equivalent loading cycles reaches the 10^8's during the 20 years of service.

1.3 Concrete as the construction material

Concrete towers may be slipformed on-site, saving the costly need for transportation of tower sections. The durability of the slipformed towers is not as good as normally placed concrete or precast sections, but the method has proven itself through testing and use, in DK three multi-MW towers are in operation and in Germany Enercon have made several prototypes before completely turning to a precast solution.
To ensure the needed stiffness as well as the required fatigue capacity, the towers must be strongly prestressed to counter tensile stresses and tensile cracking. The costs for the prestressing systems constitute roughly 10% of the total cost of the slipformed tower.

Slipformed concrete towers of 90m and more are cost-competitive with tubular steel towers in DK but the ratio of [cost of labour]/[steel unit price] decides when concrete towers are feasible.
The pitfalls for damage detection on a concrete structure are:

- What is the mechanism driving the deterioration?
- Does fatigue govern the design
- Does the damage affect the structural response properties
- The durability of concrete in severe environments is good, the offshore sturc-tures on the North Sea have shown us this.
- The "true" failure rate of slipformed concrete towers can't be observed, be-cause the population is too small.

1.4 Why waste time monitoring concrete towers if they don't break ?

As no large scale failures have been observed, this brings us to the motivation for the project. Damage detection is effectively a mean of risk reduction, if proper decision rules are implement-ed.
The risk, concerning economical loss or loss of life, the societal impact, is what governs the re-quired safety [read: reliability] level that is required for structures so by reducing the risk – we can <u>reduce the initial cost</u> of the structure, and yet meet the societal requirements.

2. STATE OF THE ART IN FIELD OF RESEARCH

The concept of including a SHM system in the life-time reliability assessment is a relatively new research topic.
SHM is a buzz word and has come to cover many quite different disciplines, thus I differ between Usage Monitoring (UM) and Damage Detection (DD), as first conceived in (Los Alamos, 2004)[1] .
UM is the act of monitoring measurable quantities over time.
A threshold rule may be implemented, meaning that a flag is raised if a variable exceeds a user defines threshold. The variable may or may not be averaged to reduce the effect of outliers. This is not DD. To call such a routine DD, the influence of the operating and environmental state must be included. A good example of this issue is the running man. By observing that his heart rate, his perspiration and his ventilatory rate are elevated you cannot deduct that the man is sick. You must account for the operating state, i.e. "running", which completely changes the conclusion.
UM of civil structures has been treated extensively in research groups around the world, the mo-tivation often being assessment or reassessment of offshore structures (very high economic risk) and high consequences civil structures and infrastructure such as highway bridges (high econom-ic risk due to the population size), dams and large bridges (large societal and economic risk).

Examples of the state of art, under their separate headlines, are
(only few, important publications are included):

Value of information

(Raiffa & Schlaeffer, 1961)[2] and (Benjamin & Cornell, 1970)[3]: Bayesian pre-posterior decision analysis and the concept of value of information.

Structural deterioration

Fatigue of welded structures (Lassen, 1997)[4]
Compilation of publications in the field of concrete fatigue (ACI, 1982)[5]
Fatigue crack propagation in metals. (Paris & Erdogan, 1963)[6]

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[1] Sohn, Hoon; Farrar, Charles R.; Hemez, Francois M.; Shunk, Devin D.; Stinemates, Daniel W.; Nadler, Brett R.; Czarnecki, Jerry J. (2004). A Review of Structural Health Monitoring Literature: 1996–2001. Los Alamos, NM: Los Alamos National Laboratories.
[2] Raiffa, H. and Schlaifer, R (1961). Applied statistical decision theory. Harvard, Boston.
[3] Probability, statistics, and decision for civil engineers. Benjamin, Jack R. & Cornell, C. Allin. McGraw-Hill. 1970.
[4] Lassen, T. (1997). Experimental Investigation and Stochastic Modeling of the Fatigue Behavior of Welded Steel Joints. PhD thesis, Structural Reliability Theory, paper No. 182, Aalborg University.
[5] ACI SP-75. 1982. ACI.
[6] Paris, P., Erdogan, F. (1963). A Critical Analysis of Crack Propagation Laws. Journal of Basic Engineering, 85, pp. 528-534.

Stress intensity factors for typical crack geometries. (Newman & Raju, 1981)[7]
Concrete high cycle fatigue. (Urban et.al., 2012)[8]
Chloride induced corrosion and Corrosion from carbonisation. (Duracrete, 2000)[9]

SHM
[the list is included as appendix 0]

Usage monitoring and probabilistic assessment of wind turbines or similar structures
(Veldkamp, 2006)[10] and (Toft, 2010)[11]: Probabilistic design of wind turbines.
(Thöns, 2011)[12]: UM using strain gauges is shown to reduce uncertainty on loading and is used to update the inspection plans on an offshore wind turbine (OWT)

Automated identification
(Reynders et.al., 2012)[13] (Andersen et.al.,?)[14]

Modal damage detection (Heylen, 1997)[15] (Parloo et.al., 2003)[16] (Doebling et.al., 1996)[17]

Risk based inspection planning (RBI)
[Straub]: Generic approach to inspection updating of fatigue and corrosion of steel structures.
[Faber]: Bayesian Probability Nets for modelling durability of concrete structures with regards to reinforcement corrosion.

3. SUMMARY OF THE PROJECT SCOPE AND AIM

3.1 Scientific aim

The project shall determine if automated modal DD can contribute to the reliability of a slip formed cast concrete tower for a multi-MW wind turbine so that cost may be reduced in the initial design by reducing the reliability but maintaining the risk.
This implies determining if, and, to what extent

- The initial- and O&M cost is affected by deterioration?
- Damage from deterioration affects the modal response parameters?
- Which modal based DD method is the most reliable and robust?
- The DD can be incorporated into the reliability calculation (Structural Reliability Assessment (SRA)), seeking inspiration in the field of reliability updating based on inspection results?
- If the expected value of the DD system can be estimated using pre-posterior decision analysis, given the number of sensors.
- If the DD can be optimized with regards to the number of sensors.
- If the DD system can provide information of the sized type in a robust and reliable manner for plausible damage scenarios.
- If such sized information can be used to update the reliability using Bayesian methods.¨

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7 Newmann,J. and Raju, I. (1981). An Empirical Stress-Intensity Factor forthe SurfaceCrack. Engineering Fracture Mechanics, Vol.22,No. 6, pp. 185-192.
8 Experimentelle Untersuchung von ermüdungs -beanspruchten Betonstrukturen zur Feststellung des realen Schädigungsgrades. Urban et.al. Beton- und Stahlbetonbau 107 (2012), Heft 7.
9 Duracrete. (2000). Final technical report. R17
10 Veldkamp, H.F. (2006). Chances in Wind Energy. A Probabilistic Approach to Wind Turbine Fatigue Design. PhD thesis. Delft.
11 Probabilistic Design of Wind Turbines. / Toft, Henrik Stensgaard. Aalborg : Aalborg University. Department of Civil Engineering, 2010. 238 s. (DCE Thesis; Nr. 26).
12 Thöns, S. (2011). Monitoring Based Condition Assessment of Offshore Wind Turbine Structures. PhD thesis. ETH Zurich.
13 Reynders, Hourbrecths and De Roeck (2012). Fully automated (operational) modal analysis. MSSP 29 p.228-250.
14 Andersen, Kirkegaard, Brincker. Filtering out evironmental effects in damage detection on civil engineering structures. ?.?.
15 Heylen, R.B., Lammens, S. and Sas, P. (1997) Modal Analysis Theory and Testing. Katholieke Universiteit Leuven, Faculty of Eng., Dept. of Mech. Eng.
16 Parloo, Guillaume, van Overmeire. Damage assessment using mode shape sensitivities. MSSP. 2003.
17 Doebling, Farrar, Prime, Shevitz. Damage identification and health monitoring of structural and mechanical systems from changes in their vibration charachteristics. LANL. 1996.

3.2 Development aim

Feasibility of slip formed towers as an alternative to tubular steel shall be determined. The reason is a market opportunity for MT.Højgaard to use the experience from slip forming large concrete chimneys to slip formning wind turbine towers.

- Are the towers physically competitive? Do they have the same reliability in the limit states?
- Are the towers cost-competitive?
- Where is the cost sensitivity largest? (e.g.: Manpower? Materials?)
- How can the constructions method be optimized?

4. METHODS APPLIED

Load effects are estimated by aero elastic simulation in Rambøll software LACflex. Statistical analysis is performed in Matlab. Load extrapolation for DLC1 (IEC61400-1) is done directly in LACflex.

Only theoretical work has been performed. As a design case, the NREL 5 MW baseline wind turbine has been used (Jonkman et.al., 2007)[18]. All data are included in LACflex.

I have taken part of an inspection of 3 cast concrete wind turbine towers at Nees in western Jutland. For confidentiality reasons no information concerning these is reprinted here.

For probabilistic methods, CMC has been used. The use of CMC is computationally demanding, but it has clear advantages for strongly non-linear limit state functions such as a propagation crack in a surface of limited extent.

Modelling the physics of a damage is done with FEA. Patran is used for shells and solids and beams are done directly in matlab.

Much importance is given to the uncertainties of models, measurements and variables. The key to successful reliability based updating or other reliability methods is to account for uncertainties in a thorough manner.

4.1 Scientific part

4.1.1 Determining the value of SHM by influence diagrams, BPNs and life-time risk analysis

Bayesian Probabilistic networks (BPN) with utility and decision nodes are know as limited memory influence diagrams (LMID). They are useful in deciding which decision of multiple alternatives that has the highest expected decision utility.
This can be used to calculate the expected utility given the (estimated) likelihood of the DD and given the load reducing capabilities of a wind turbine (idling and pitching the blades).

In the case of a civil structure such as a bridge, the detection may serve to evacuate the bridge – this measure reduces consequence AND reduces the loading, i.e. the probability of failure (Pf).

Assumptions about the probabilities of the damage state as well as conditional probabilities for the events of collapse and detection are required as prior knowledge.
The network may then be used to calculate the expected utility with and without monitoring - the difference may then be used as the target for the expected cost of performing the monitoring.

[18] Jonkman, J., Butterfield, S., Musial, W. and Scott, G., "Definition of a 5-MW Reference Wind Turbine for Offshore System Development," NREL/TP-500-38060, Golden, CO: National Renewable Energy Laboratory, February 2007.

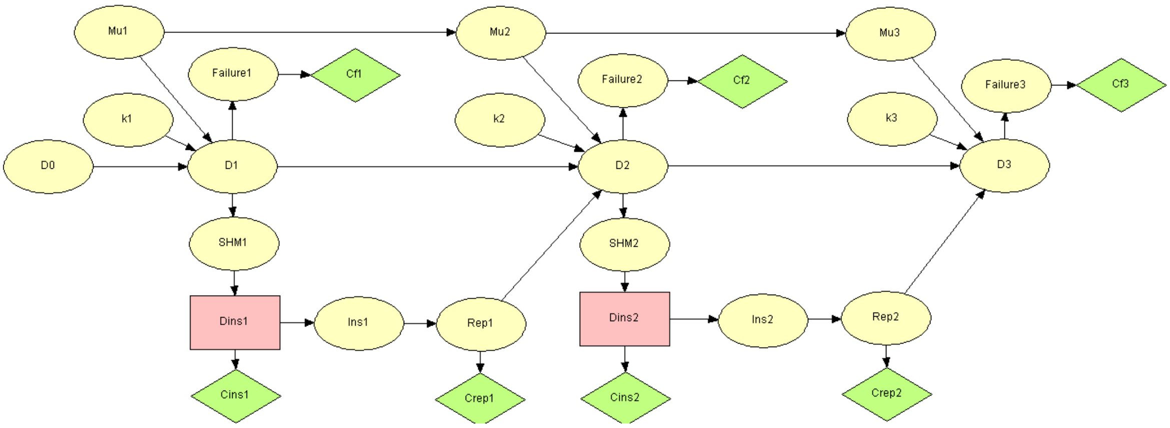


Figure 1, BPN (LMID) for performing pre-posterior decision analysis of DD for a wind turbine tower. Inspired by J. Nielsen's work[19] but using DD as decision node parent.

Using this, the expected utility (risk) may be calculated for all damage levels, and the total risk may be assessed by weighting with the distribution for the damage level.

4.1.2 Properties of damage

Damage relevant to DD is typically deteriorating processes with exponential growth of the following form

$$\frac{dD}{Dt} = D^k \cdot h(z)$$

k is a constant determining the growth acceleration.
h is a positive function of z
z is the random process of disturbances (load, etc)

The rate of growth of the deterioration mechanism are important for the development of a DD system – fortunately most mechanisms concerning structural steel and concrete are of the slowly progressing type. See the PMC (JCSS, 2006)[20]
In the current project, only slowly progressing deterioration will be considered. Examples hereof are reinforcement corrosion and high cycle fatigue crack growth.

4.1.3 Calculation of the value of damage detection on a baseline tubular steel tower

The phases of this part of work are here quickly summarized:

- Load prediction and analysis using aero elastic code. Statistical analysis in matlab.
  The fatigue loads are estimated from representative simulated time series of the wind turbine in all operation, parked, idling and fault conditions that can occur during the lifetime, as specified by the IEC61400. The time series simulation is done in Rambøll software code LACFlex. From the software LACflex Markov matrices are extracted. They are, in the software version used at that time, not calculated on the basis of a wind-rosette (long term wind direction distribution), but on a uni-directional wind, so this statistical adjustment is made in Matlab. For the case, a wind-rose from a site in DK is used.
  The wind turbine is assumed to be installed onshore at Hvide Sande in the North of Denmark. The Wind conditions at this site are assumed to fit the IEC61400-1:2005 Class II B conditions. The long term 10 minute-mean wind speed distribution is modeled by the Weibull 2 parameter distribution with scale parameter 8,4628 and shape parameter 2. The all-time averaged directional wind rose is found in Dansk Meterologisk Institut's Technical Report 99-13. Only the directional rose is assumed varying with direction, all other variables describing the wind conditions are constant for direction.

[19] Risk-Based Operation and Maintenance of Offshore Wind Turbines. / Nielsen, Jannie Sønderkær. Aalborg : Aalborg University. Department of Civil Engineering, 2013.
[20] JCSS (2006). Probabilistic Model Code, JCSS Joint Committee on Structural Safety.

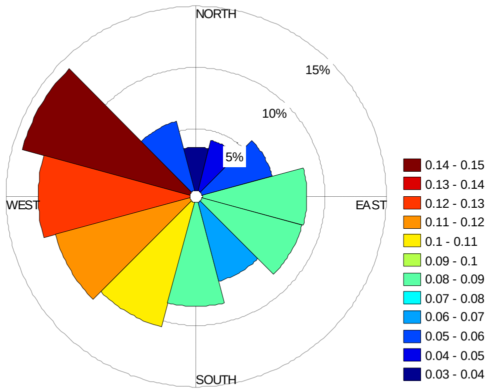


Figure 2, wind rose applied for fatigue calculations

The response is simulated by LACflex as 10-minute time series. The extracted loads are scaled to lifetime equivalent, taking into account the directional distribution of wind and the availability of production. Markov Matrices of the load-bin ranges and corresponding cycle count are extracted for fore-aft (FA) and for side-side (SS) bending moment MxF and MyF at the tower/foundation interface by Rainflow counting.

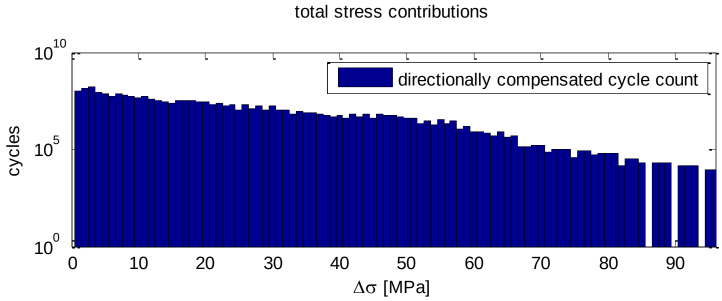


Figure 3, Rainflow counted stress cycles in point W/NW of tower section.

The far field stress ranges in the tower foot are calculated under the assumption of deterministic tower cross-section geometry.

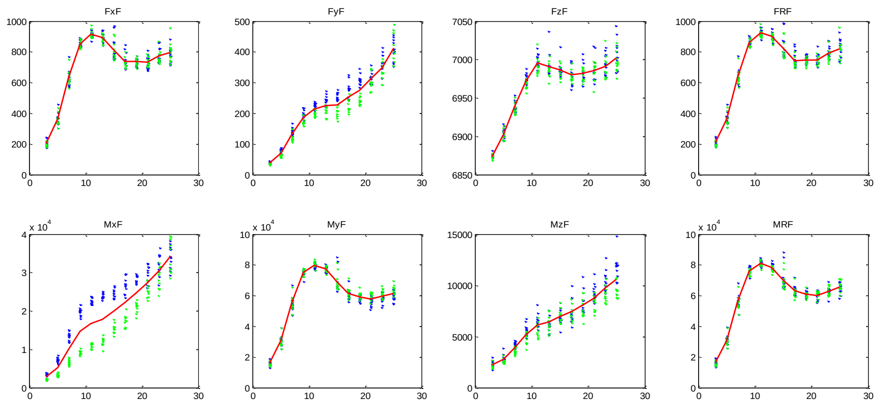


Figure 4, Extreme values of load effects in tower foot for the production state

The above shown load effects are extracted from IEC61400-1:2005 - DLC 1.2 simulations of a NREL 5MW onshore wind turbine. Dots represent absolute values of block maxima of 10 minute simulations in LACflex. Green is results for Yaw Error = -8 degrees and blue is +8 degrees. Red shows the sample mean. Notation: X = Fore/Aft *(FxF=Thrust)*. Y = Side/Side. R = resultant of X and Y. The rpm-controller region is seen to follow normal assumptions of load effect proportionality to deterministic wind, whereas the pitch-controlled region is seen to behave differently.

- Estimating the fatigue life using crude monte carlo (CMC) simulation of Basquinn's stress-life relation, also known as SN theory. From the CMC samples, a distribution for the number of cycles to failure can be estimated using MLE, as shown in the figure below.

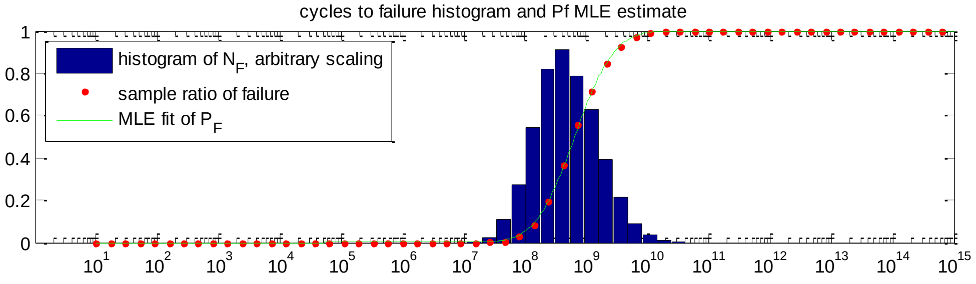


Figure 5, MCS histogram and MLE of the CDF for number of cycles to failure (N_F)

- Fitting a linear elastic fracture mechanics model to obtain the same reliability.

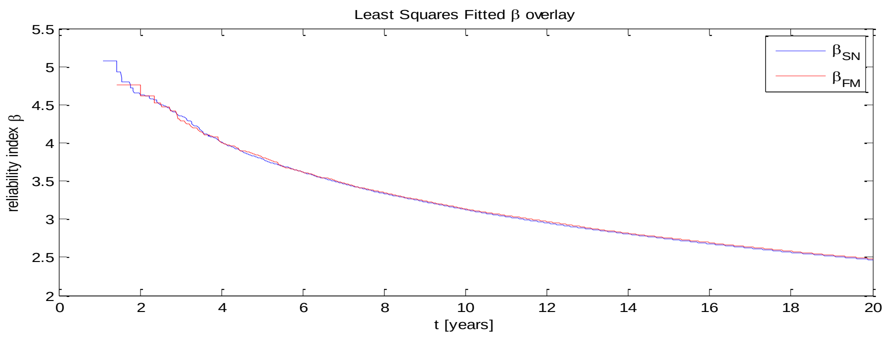


Figure 6, fitting the reliability of the LEFM model to the stress-life model (SN model)

The fit is done using least-squares regression in beta-domain and is computationally very demanding; 2e6 crack growth simulations are performed for the figure shown above.

- Compensation for the numeric analysis bias
  The LEFM crack growth calculation is performed by a numerically solving **Paris** Law for each sample of variables.
  The approach used here is an incremental numeric calculation, applying a constant value of the Geometry function **Y** in the expression for the Stress Intensity Factor for each numeric increment of crack growth. This approach decreases the computational effort but introduces a bias on the calculated number of cycles to failure as the value of the geometry function is consequently underestimated. The bias is quantified by performing a sensitivity analysis of the crack increments influence on the calculated number of cycles to failure. An example of the increments correlation with bias and computation time is shown in the figure below.

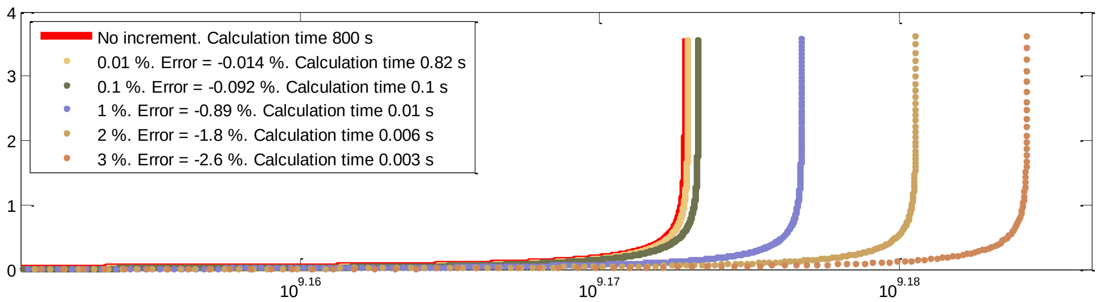


Figure 7, Zoomed view of crack growth curves for various degrees of numeric precision

- Estimating the compliance (geometry function)

If no analytical solution for the stress intensity factor (SIF) can be found. For a circular hollow section with a circumferential crack, the solution by (Laham, 1998)[21] can be applied.

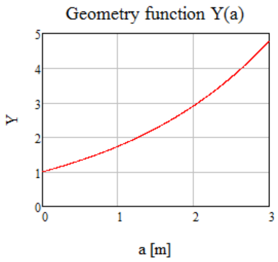


Figure 8, Geometry function for circumferential through-crack in hollow cylinder

- Use shell element FEA to approximate a damaged element with geometric damage (a crack) by an undamaged element with reduced stiffness (E and G). A model of a tower section (FEA elements of tower top and bottom in the matlab model) is modelled in Msc Patran, and the reduced stiffness parameters are estimated by direct linear elastic analysis in Nastran.

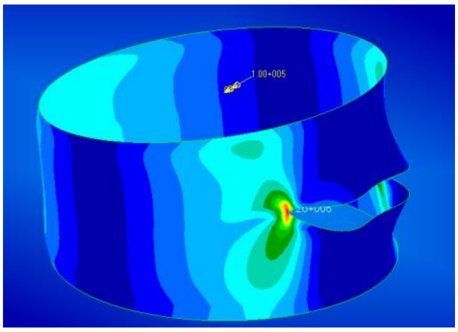


Figure 9, Example of FEA model of damaged element, stress and deformation from elastic analysis

- Using the calculated values for a number of damage severities (cracks lengths), least squares regression is used to fit a polynomial which is used to simulate modal parameters of the damaged tower for any crack increment.

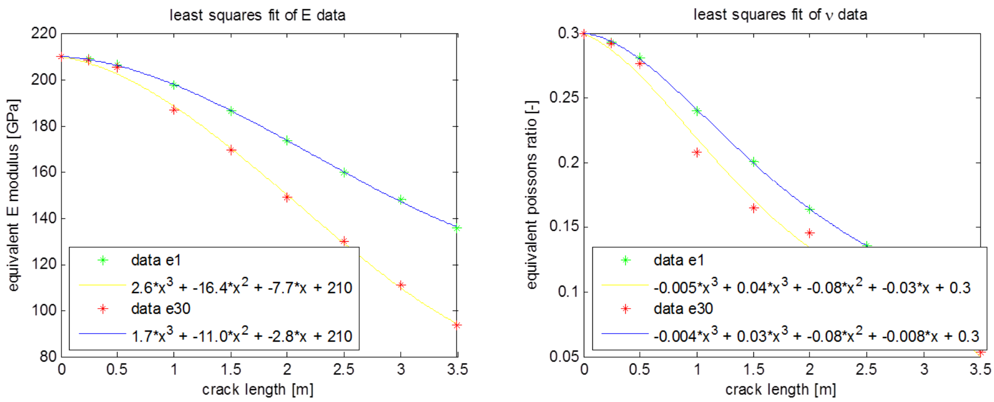


Figure 10, Estimating the damage equivalent stiffness properties

- Calculate modeshapes and frequencies using eigenvalues of a 90 degree of freedom (DOF) FEA beam model in matlab.

[21] Laham, S. Al. Stress Intensity Factor and Limit Load Handbook. Issue 2 April 1998. British Energy Generation Ltd for SINTAP.

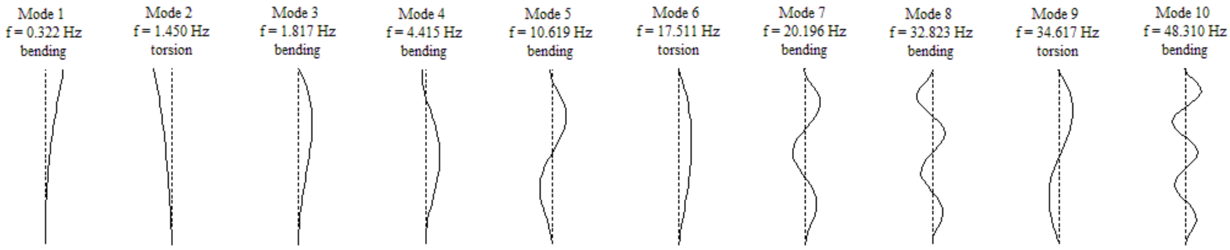


Figure 11, mode shapes of the NREL 5MW tower

- Using a mode shape based method (Heylen et. Al, 1997), calculate the "damage vector" from 10 possible scenarios.

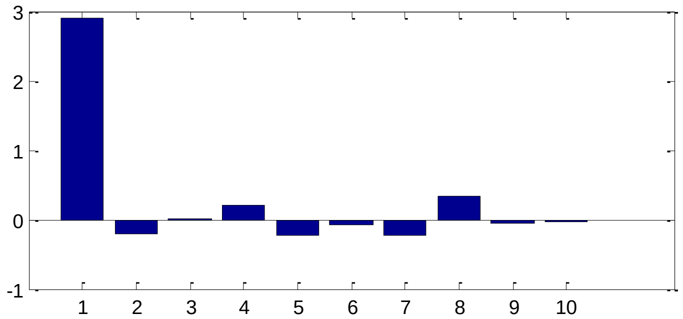


Figure 12, example of damage vector indicating scenario #1 damage

The differences in mode shape derivatives are used to localize the change in stiffness.

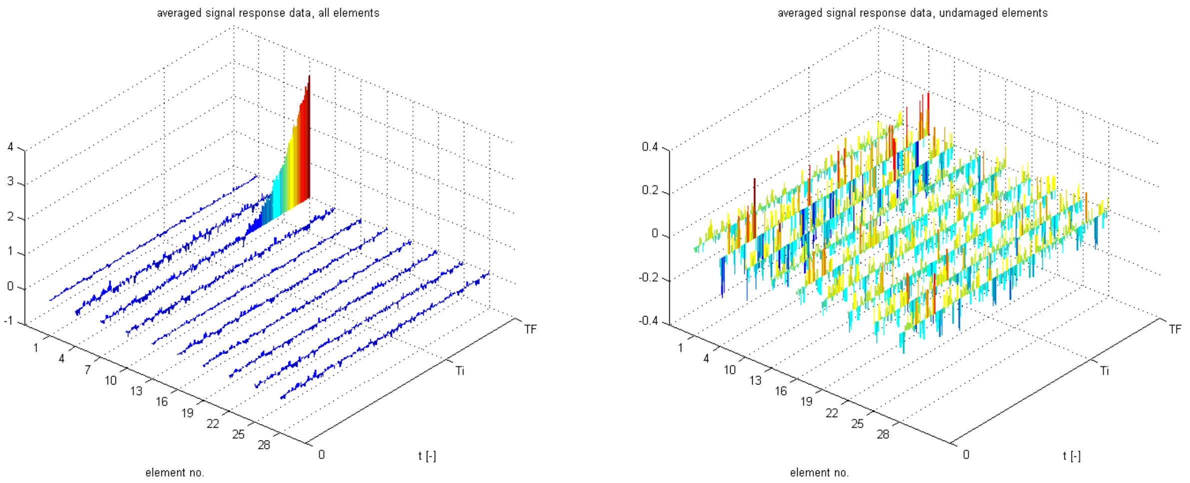


Figure 13, "Waterfall" plot of the 10 damage scenarios. At t = Ti a crack starts to propagate in element 4, and it then propagates linearly, for purpose of illustration, in time until failure, when the crack is ap-proximately 3m long.

- Use logistic regression and maximum likelihood estimators (MLE) on sampled damage vector data, perform statistical analysis of the damage vector, and thus calculate the probability of detection (POD) and its confidence bounds.
  Censoring may be accounted for by using the maximum likelihood estimation **MLE**. The result of an MLE regression is shown in the figure below, left for uncensored data and right for censored data.

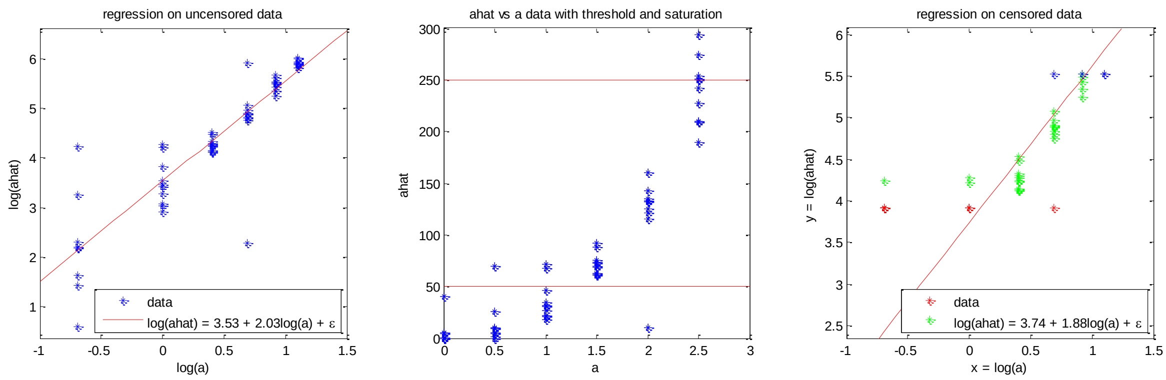


Figure 14, example of signal response data, blue = data points, red = threshold and saturation

The threshold is realized to strongly influence the POD, as well the probability of false alarm (PFA) that is equally important in the risk analysis.

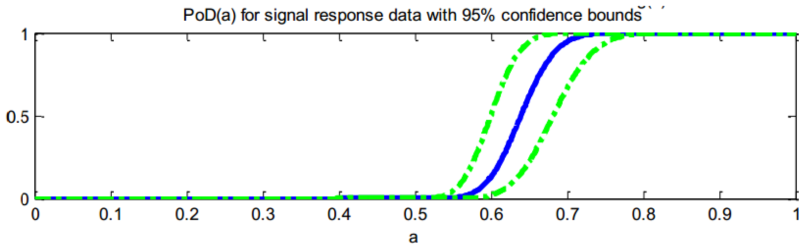


Figure 15, MLE of the PoD along with 95% confidence bounds

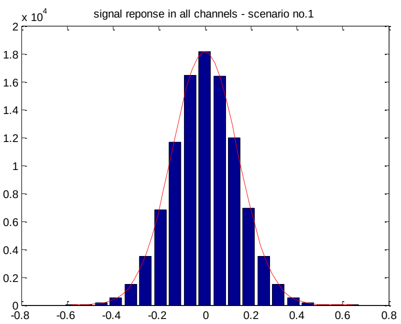


Figure 16, histogram of the components of the damage vector for zero damage – the noise floor

The sources of uncertainty are

1. Error introduced by the FEA Eigensolver. The error is in the order of 10^{-8}, causing a threshold value of $2.3*10^{-8}$. The error distribution is non-gaussian, and as the variance is marginal, the error is ignored.
2. Model error on the DD **Xu**. Taken as Gaussian with V=10%. The error accounts for the uncertainty on the FEA damage modelling and the regression to a linear relationship between damage parameter and E-modulus and Poisson's ratio. Sensitivity is high to the model error.
3. Error on identified eigenfrequencies **e1**. The DD method does not incorporate eigenfrequencies, thus naturally the sensitivity is zero.
4. Error on the identified mode shapes **e2** (modal coordinates). This is the primary source of uncertainty.

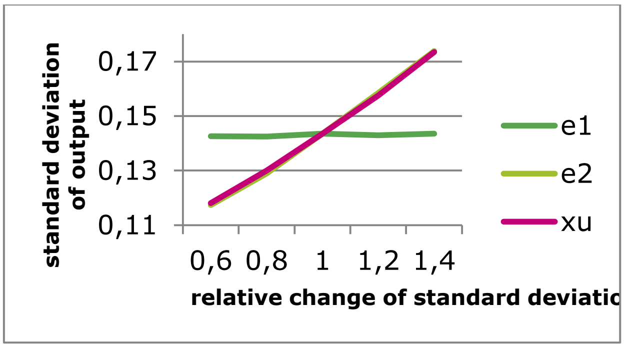


Figure 17, sensitivity analysis of the threshold

The sensitivity of Xu and e1 is seem to be approximately the same.
The threshold is set using the t-location scale distribution, as a Normal distribution fits badly for the tail. A characteristic value corresponding to e.g. the 99.9% fractile can be used as the threshold.
The threshold may also be decided using the peak over threshold method to extract extreme data, which may then be used to fit an appropriate distribution. In simplified terms, the following optimization must be performed for the choice of the threshold:

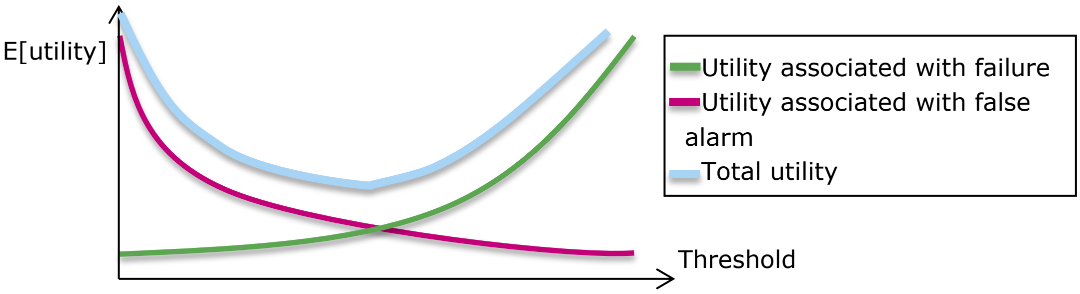


Figure 18, Sketch of the threshold optimization problem

ıd a response time variable is carried out. The difference in beta is used to illustrate the value of SHM.

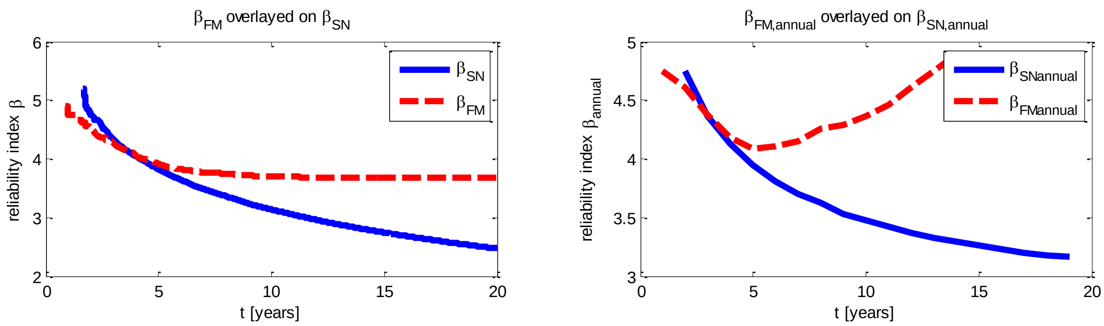


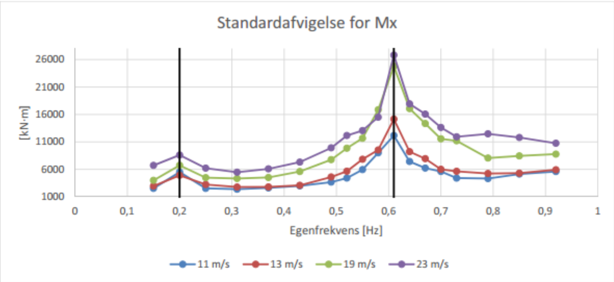
Figure 19, $\beta_{accumulated}$ and β_{annual} with- and without monitoring.

It is apparent that the DD system becomes increasingly effective as the structure ages, this being due to the fact that slowly growing cracks are more likely to be detected before failure.

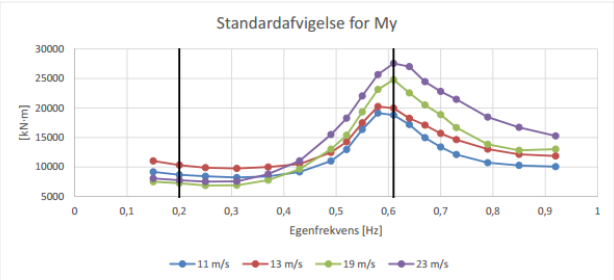
- The approach has neglected the following / made the following assumptions:
    No utilities have been associated with outcomes - this means that actual expected value of SHM is not estimated. Probability of false indications is not included. The error is reduced by setting a high threshold (to ensure few false indication).
    - The modal parameters were noised with a low level of Gaussian noise, same level on all modes. (10 modes were used). The actual automated system identification may provide the greatest source of uncertainty and this has only been estimated so far.
    - The event of timely response was approximated to equal survival in the lifetime. In reality, a new crack could initiate and lead to failure within the remaining period of the 20 years.

4.2 Development part

- Sensitivity study on load effects dependency (transfer) of excitation frequencies.
  The Bachelor student Thomas Westergaard has just completed his degree with the project "Vindmølletårne i beton", a work focused on the sensivity of load effects on dynamic properties of the tower. Using aero elastic analysis, the load response was analysed for variation of the fundamental frequency of the system and the mean wind speed.
  The standard deviation of the load effects were sampled as a direct measure of fatigue loads, and as show in the figure below, the dependency on the fundamental frequency is pronounced.



Figur 16 Resultater for standardafvigelse for Mx



Figur 17 Resultater for stanard afgivelse for My

Figure 20, Fatigue load dependency on the systems fundamental mode (reprinted from Westergaard)

The black lines are rotor frequencies 1P and 3P. It is seen that the load effects are have minimum values at 0.3 Hz, which is also the fundamental frequency of the NREL 5 MW turbine. Comparing the above figure with the Cambell diagram on Figure 23, it is now apparent that 1P excitation may be overestimated in the "frequency avoidance" approach of the codes (i.e. +/- 10% to either side of 1P and 3P) (See also APS, 2010)[22] However, as 1P loading depends mostly on the rotor balance and unbalance of the blades, it is hard to generalize. I lack statistical data of blade mass and center of gravity (cog) variance to conclude that 1P forcing actually is small compared to 3P.

Mx is moment caused by side-side movement and My is similar for fore-aft movement. The aerodynamic damping is typically much higher for fore-aft movement, and this effect is profound in comparing Mx (the less damped motion) with My (the motion with high damping) in the figure above.

5. RESULTS SO FAR

5.1 The three contributions to reliability

Initial studies of self-constructed influence diagrams indicated that SHM (not just DD) has three separable contributions to overall reliability.

[22] EVALUATE THE EFFECT OF TURBINE PERIOD OF VIBRATION REQUIREMENTS ON STRUCTURAL DESIGN PARAMETERS: TECHNICAL REPORT OF FINDINGS
Report Number: M10PC00066-8. Applied Physical Sciences for Department of the Interior, Bureau of Ocean Energy Management, Regulation, and Enforcement, Engineering & Research Branch. September 1, 2010.

1. **Usage monitoring of internal forces acting on the structure may be used to update the reliability of the fatigue limit state (FLS) thus reducing inspections costs. (Thöns, 2011)[23] and (Hjelm et.al. 2004)[24].**

The monitoring must provide information valuable in the limit state context – either about statistical parameters of variables or about model uncertainties.
Thöns showed that information from strain gauges (far field stress monitoring) can be used to reduce the uncertainties on the load effects and this increases the reliability. This information can only be produced AFTER the structure is realized, and thus does not benefit the initial design but may benefit the O&M costs, as the number of required inspections may be significantly reduced.
Hjelm et.al showed that modal monitoring can be used to provide stress information (instead of the strain gauges) with small uncertainties.

2. **Damage detection may provide information similar to that of inspections. This may increase reliability in the FLS. (Madsen, 1987)[25]**

The theory for performing this updating is well established and is incorporated into various structural codes. The benefit will depend on the likelihood of detecting damage before the growth rate reaches critical levels, as well as likelihood detection of multiple locations.
The methology was quickly adopted by DNV in their recommendations, and the figure below is reprinted from a DNV publication.

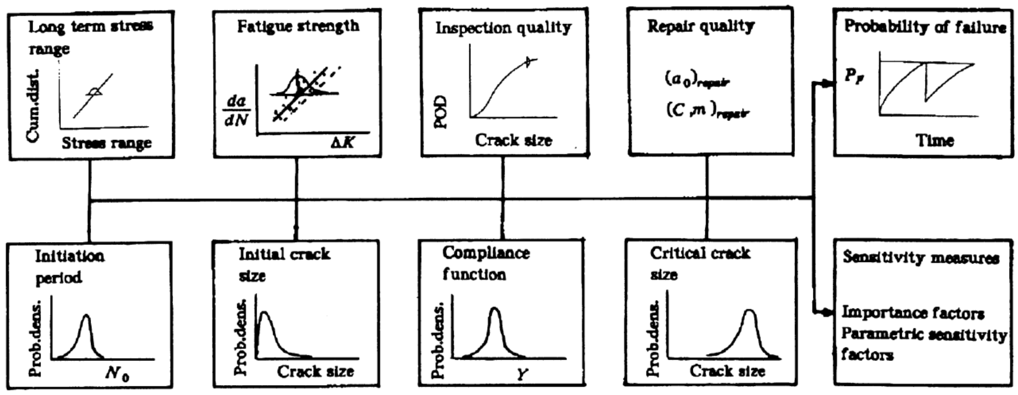


Fig. 4.23
A schematic presentation of the input to the inspection analysis.

Figure 21, DNV. Structural reliability analysis of marine structures. (1992)

3. **DD can work as a barrier in the decision tree analysis, thereby introducing a method of consequence reduction**

For a wind turbine, where operational loads are high and extreme loads are experienced often, the damage detection can prove risk reducing by enabling decision rules, reducing the load and increasing the reliability until inspection and repair is performed.
Naturally, the reliability for extreme wind events where the turbine is already parked or idle is not affected. Using the typical long term distribution for 10-min mean wind speeds, the wind turbine will be in the production state for approximately 85% of the lifetime.
The loading is dramatically reduced by going into the idling state. The figure below shows three time series of aero elastic 10 minute simulations in which the turbine state is changed for "power production" to "idle" after 535 seconds. The wind speeds (mean) used as input shown are Red = 3 m/s. Green = 11m/s. Orange = 25 m/s.

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[23] Thöns, S. (2011). Monitoring Based Condition Assessment of Offshore Wind Turbine Structures. PhD thesis. ETH Zurich.
[24] Graugaard-Jensen, J., Hjelm,H. P. and Munch, K. (2004). ModalBased Fatigue Estimation.M.Sc. thesis, Aalborg University, Denmark
[25] Madsen HO. Model updating in reliability theory. Proceeding of ICASP-5, Vancouver, 1987. p. 564–77.

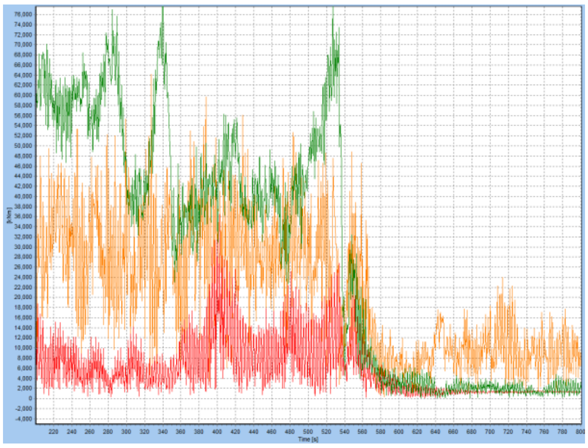

Figure 22, arbitrary load effect simulated for 3, 11 and 25 m/s windspeeds for production followed by shutdown (to idle)

If the likelihood of the DD system is known along with the probabilities of the relevant events and the model uncertainty may be accurately assessed.

Citing the definition from (Skleth, 2005)[26], who worked with barrier analysis:

> *"Based on experience from several projects and a synthesis of the reviewed literature, it is recommended to address the following attributes to characterize the performance of safety barriers; a) functionality/effectiveness, b) reliability/availability, c) response time, d) robustness, and e) triggering event or condition. […]. For some types of barriers, not all the attributes are relevant or necessary in order to describe the barrier performance."*

W.r.t. a), the effectiveness for the DD can be characterized as the expected load reduction leading to increased reliability. (if it works, how good is it?)

W.r.t. b), the reliability of the system involves knowledge of hardware degradation and redundancy.

W.r.t. c), response time depends mostly on the automated identification, unless a human decision is included (example: the DD sends an sms to the owner, ant the owner must then make a decision of preventive action).

W.r.t. d), Robustness is here regarded as the sturdiness of the system.

W.r.t. e), The triggering events are important to know – not just the ones that are expected, but also "robustness for unpredicted scenarios" is an important property.

The consequence reduction approach can be treated with BPN's for a pre-posterior analysis. See section 4.1.1.

5.2 The increased fatigue reliability

The reliability has been shown to increase for a Paris-type growth. See Figure 19.

5.3 The developed concrete tower design model/program

So far, the work has shown that the concrete tower is a plausible competitor.

- Cost is comparable or less for hub heights of 90 m or more.
- The heavier the rotor nacelle assembly (RNA) -> the higher the benefit of using concrete. For heavy direct drive (Enercon) generators, concrete is optimal.
- Labour cost is the highest threat against concrete.
- Concrete towers most likely to be used in countries with low labour costs and high steel prices.
- Not likely to be used offshore unless fabricated onshore and towed to site.

[26] Snorre Sklet . Safety Barriers on Oil and Gas Platforms - Means to Prevent Hydrocarbon Releases. pp.15. PhD thesis. Trondheim, December 2005 Norwegian University of Science and Technology.

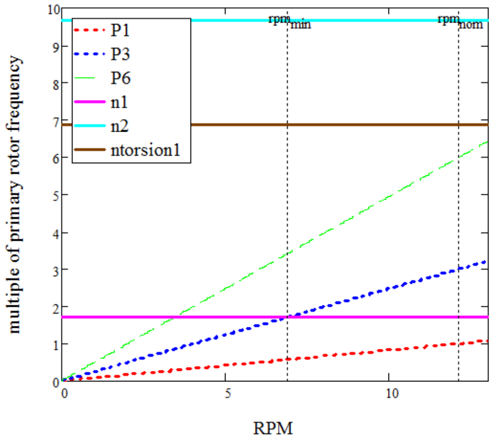

Figure 23, Sparse Campbell diagram

5.3.1 Designing the tower in accordance with codes and guidelines

The codes have used an endurance limit approach, giving a "fatigue strength" corresponding to a fixed number of load cycles.

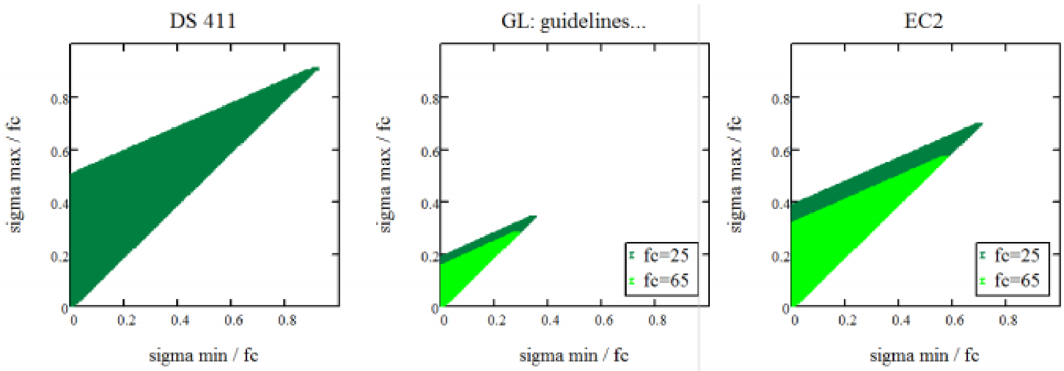

Figure 24, Verifying concrete for fatigue using DS, GL and DS/EN

MC1990 and MC2010 have more sophisticated rules for concrete fatigue, which I will not repeat here, but they are based mainly on empirical data fitting.

Current research in Germany by (Urban et.al. 2012)[27] is using full-scale tests of a offshore wind turbine gravity base foundation to investigate the impact of actual high cycle fatigue damage on various types of monitoring (ultrasound, acoustic emission).
I'm keeping an eye on the progress there.

5.4 Deciding the long- and short term properties of the concrete

Having shown that the uncertainties in the dynamic response properties of the system heavily influence the structural design (load calculations and limit state verification) a method for dealing with the uncertainties related to concrete's stiffness properties is needed.

1. The concrete mix properties, as well as parameters of the casting process are important
2. The loading velocity affects the stress/strain curve. The effect of this has given grounds for the term "dynamic modulus of elasticity".
3. The creep affects the long term dynamic properties, softening.
4. Long term stiffening due to hydration.
   A literature review by (Westergaard, 2013)[28] suggests that a stiffness increase in the order of 10% is likely. For small stiffness changes, the relationship between relative stiffness change (E+ΔE)/E is approximately linearly proportional to relative fundamental fre-

[27] Experimentelle Untersuchung von ermüdungs -beanspruchten Betonstrukturen zur Feststellung des realen Schädigungsgrades. Urban et.al. Beton- und Stahlbetonbau 107 (2012), Heft 7.
[28] Westergaard, T. Bachelors project, Vindmølletårne i beton. 2013. IHA.

quency change $\propto$ (f+Δf)/f which means that this change will cause a 5% increase in frequency over the life time.

5. Aero elastic load calculation assumes linear structural properties, how severe the error introduced by assuming linearity of the stress/strain relationship must be calculated.
   In civil engineering, concrete is typically considered fully linear elastic in the serviceability limit state. For small strain ranges – which is the case for high cycle fatigue loading – this assumption holds true, especially if strong (high cement content) mix is used, e.g. a C40 concrete.
6. Construction: slipforming e.g. a C45 is possible, but if the mix becomes low in viscocity, the placing becomes difficult, and "flaking" occurs as the form slides up. Flaking causes durability issues and the concrete must be mended immediately after casting. (Fosså, 2001)[29] and (Fossa, Kreiner & Moksnes, 2001)[30] have treated the subject.

6. PLAN FOR THE REMAINING PART OF THE STUDY

A keystone to the remaining part of the time is to turn the focus towards concrete deterioration. Not much research has been done in the field of high cycle fatigue (compared to the same area for steel) even though the knowledge is needed – especially as structures are becoming increasingly designed with lower reliability as a result of optimization.

First, the DD study must be expanded:

6.1 Expand the case study of the NREL wind turbine, step 2

- Recalibrating the DD to give more weight to, and accuracy for, smaller damages.
- Perform automated identification (frequency domain decomposition, FDD) to get a better estimate of the noise level on the identified modes.
- Perform simulations of automated identification to estimate the statistical distribution of response time (in the early life, the sensitivity of the reliability to the variable "response time" is very high, due to the fact the deterioration that leads to failure in this stage, have very rapid growth rate.
- Investigate the sensitivity of the DD robustness to the FEA model. The DD is based on mode shape derivatives[31] and the mode shapes are defined in the geometry of the FEA model. This discretization introduces uncertainties in damage localization, as damage must be present in one of the "scenario elements" for the DD to work. I.e. if the damage is between two elements, the DD outputs elevated values, but of no physical meaning that can be used to localize or quantify damage.
  This becomes an issue of condensing high order FEA mode shapes into low order experimental modes for results to be robust.
- How robust is the DD to multiple simultaneous damage locations?
- Damage quantification is possible using the DD method, but is it robust, reliable? The quantification will only work for the exact damage scenario.
- How sensitive is the OMA identification to input correlation/frequency contents?
- How many sensors/ modes must be included?
- Optimum sensor position to identify the needed modes?

These improvements to the case study will form the basis for a journal paper for publication in a "broad topic" journal, such as Engineering Structures.

6.2 Expand the case study of the NREL wind turbine, step 3

Move on to concrete tower.

- Fatigue softening and concrete cover spalling due to corrosion may affect modal parameters much less than a crack in a steel tower.

[29] Fosså, Kjell Tore. Slipforming of Vertical Concrete Structures. Friction between Concrete and Slipform Panel. Norwegian University of Science and Technology. 2001.

[30] Slipforming of advanced concrete structures. Fossa, Kreiner, Moksnes (2001). Tailor Made Concrete Structures – Walraven & Stoelhorst (eds) © 2008 Taylor & Francis Group, London, ISBN 978-0-415-47535-8.

[31] Heylen, R.B., Lammens, S. and Sas, P. (1997) Modal Analysis Theory and Testing. Katholieke Universiteit Leuven, Faculty of Eng., Dept. of Mech. Eng.

- Are there other important mechanisms (Duracrete and background may answer this)
- How many sensors/ modes must be included (different from steel?).
- Optimum sensor position to identify the needed modes? (different from steel?)

The main weights here are the concrete deterioration mechanisms and accurate modelling of these.

Using new knowledge from my course at Stanford and the AAU course on Bayesian methods in the spring 2014, I will seek to progress on to more advanced methods of updating / including the information.

- Bayesian updating
- Neural Networks and Pattern Recocnition for DD, decision making.
- Bayesian networks hold great possibility for modelling updating. Current research at AAU (Jannie, John D.) can be used to implement.

There seems some disagreement whether Bayesian methods are really the thing for SHM. Reasons for are the knowledge of application – updating and pre-posterior analysis.
Reasons against are the amount of information. SHM provides enormous amounts of information, and Bayesian methods are not excellent for handling this – the priors are loosing their "importance" when the updating information is vast.
Nevertheless California is a center of Bayesian thinking (Kirimidjan, Armen Der Kiureghian, Jim Beck, the list goes on..) and of SHM.

7. PLAN FOR COURSES

1. Random vibrations, IHA spring 2012 (planned exam fall 2013). 5 ECTS.
2. Advanced dynamics. AU PhD course (studygroup) 2012. 5 ECTS.
3. Risk and reliability for wind turbines and… PhD course, AAU fall 2013. 3 ECTS.
4. Business Course, DTU Fall 2013 or Spring 2014. 7,5 ECTS. (on waiting list for fall)
5. Academic English, AU Fall 2013. 3 ECTS.
6. Structural Health Monitoring, AU PhD course (studygroup). Fall 2013. 5 ECTS.
7. Structural Health Monitoring Using Statistical Pattern Recognition (California, fall 2013. No ECTS credits)
8. Bayesian Statistics, Simulation and Software – with a View to Application Examples. AU PhD course, spring 2013. 4 ECTS.
9. Participation with presentation of paper at IWSHM 2013 and at IALCCE 2014. 4 ECTS.

Total 36,5 ECTS. Completed = 13. Planned = 23,5.

APPENDIX 7.1
ARTICLES ON STRUCTURAL HEALTH MONITORING

Nr	Authors	Title		
1	Montalvão, Maia, Ribeiro	A review of Vibration-based Structural Health Monitoring with Special Emphasis on Composite Materials	SVD	2006
2	Worden, Farrar, Manson, Park	The fundamental axioms of structural health monitoring	PRSA	2007
3	Doebling, Farrar, Prime, Shevitz	Damage identification and health monitoring of structural and mechanical systems from changes in their vibration charachteristics	LANL	1996
4	Kullaa	Elimination of environmental influence from damage sensitiv features in a structural health monitoring system.	SHM	2001
5	Allemang, Brown	A correlation coefficient for modal vector analysis	IMAC1	1982
6	Bernal	Extracting flexibility matrices from state-space realizations.	COST F3	2000
7	Bernal	Load vectors for damage localization.	JEM	2002
8	Bernal	Phase II of the ASCE Benchmark Study on SHM		2002
9	Choi, Stubbs	Damage identification in structures using time domain re-sponse.	SAV	2004
10	Parloo, Guillaume, van Overmeir	Damage assessment using mode shape sensitivities.	MSSP	2003
11	Stubbs, Kim, Farrar	Field verification of a nondestructive damage localization an severity estimation algorithm	IMAC13	1995
12	Dascotte	Vibration Monitoring of the Hong Kong Stonecutters Bridge	EVACES	2011
13	Lauwagie, Dascotte	A Scenario-Based Damage Identification Framework	IMAC30	2012
14	Taylor, Zimmermann	Damage detection in a cargo bay frame using Ritz vectors	IMAC23	2005
15	Yoon, Heider, Gillespie, Ratcliffe, Crane	Local damage detection usin two-dimensional gapped smoo ing method.	SAV	2005
16	Sohn, Farrar, Hemez, Czarnecki	eview of structural health monitoring litterature from 1996-200	LANL	?
17	Andersen, Kirkegaard, Brincker	Filtering out evironmental effects in damage detection on civil engineering structures	?	?
18	Stubbs, Broome, Osegueda	Nondestructive construction error detection in large space strucures.	AAIA	1990
19	Hearn, Testa	Modal analysis for damage detection in structures.	JSE	1991
20	Aktan, Lee, Chuntavan, Aksel	Modal testing of structural identification and condition asses ment of constructed facilities	IMAC12	1994
21	Gysin	Critical application of an error matrix method for location of finite element modeling inaccuracies.	IMAC4	1986
22	Shirole, Holt	Planning for a comprehensive bridge safetyassurance pro-gram.	TRR	1991
23	Liang, Tong, Lee	Modal enegy measurement for a long steel bridge	IMAC13	1995

SVD=	The Shock and Vibration Digest
PRSA=	Proceedings of the Royal Society A
LANL=	Los Alamos National Laboratory report
SHM=	Structural Health Monitoring - the demands and challenges
IMAC(x)=	IMAC confrence nr. x.
COST F3=	COST F3 conference, Madrid
JEM=	Journal of Engineering Mechanics
SAV=	Sound and Vibratior
MSSP=	Mechanical systems and signal processing
AIAA=	AIAA Journal
JSE=	Journal of structural engineering
TRR=	Transportation reseach record
EVACES=	Experimentel Vibration Analysis for Civil Engineering Structures

APPENDIX 7.2
ABSTRACT SUBMITTED FOR THE IALCCE 2014

Structural Health Monitoring of a RC wind turbine tower using a scenario based approach to modal damage detection

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Abstract

As an alternative to tubular steel, wind turbine towers may be slip formed on site from prestressed reinforced concrete. Depending on site specifics and ratio of cost of manpower vs. cost of steel, the concrete towers become competitive for hub heights of 90m and higher. However a disadvantage of the slip formed concrete is the durability in combination with the high degree of cyclic loading and the very high number of load cycles, in the regime of 10^8 cycles in the lifetime, of a wind turbine.
The knowledge database for the deteriorating mechanism of ultra high cycle fatigue of prestressed reinforced concrete is very limited, and so in effect, the reliability of structure may not be updated based on measurements of damage extent as is the case for fatigue crack growth in metals. Concrete may exhibit better fatigue resistance than carbon steel, especially when the loading is not fully reversed (positive R ratio), but nevertheless the fatigue resistance must be verified in the initial design, and the basis for doing so, using Model Code 2010 or similar, is very uncertain.
For the case of reinforcement corrosion the driving mechanism is taken as carbonisation or chloride ingress following the guidelines in the Duracrete final technical report. The corrosion causes spalling of the concrete cover (loss of section) and severe cracking.
The deterioration caused by these mechanisms affect the modal parameters. Including a probabilistic formulation of the modal based damage detection, the initial predicted reliability may be shown to be increased. The concept is demonstrated through simulation.

APPENDIX 7.3
PAPER ACCEPTED FOR PRESENTATION AT THE 2013 IWSHM

[REMOVED DUE TO COPYRIGHTS]
The proceedings can be acquired at
http://structure.stanford.edu/workshop/proceedings.html

Mads Knude Hovgaard, Incorporation Structural Health Monitoring In the Design of Slip Formed Concrete Wind Turbine Towers - Progress Report, 2013

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