Damage detection in offshore wind turbine grouted connection by nonlinear harmonic identification

Offshore Wind R&D 2018, Bremerhaven, 14.11.2018

Nathalie MÜLLER, Research Institute of Civil Engineering and Mechanics GeM (University of Nantes) / Fraunhofer IWES

Peter Kraemer, University of Siegen
Dominique Leduc, University of Nantes
Franck Schoefs, University of Nantes
Context – The grouted connection of OWTs

Grout filled space between the two steel components of the pile and sleeve of Offshore Wind Turbines (OWTs)

- Composition: Cement + admixtures, aggregates (eventually fibre)
- Grain size: 0 to 5 mm
- Ultra-high strength grouts and high strength grouts

OWT with a monopile substructure and detail of a grouted joint (DNV, 2014)

OWT with a tripod / jacket substructure and detail of a grouted joint (Schaumann et al., 2013)
Context – The grouted connection of OWTs

Significant sliding damages of grouted connections have been reported in 2009-2010

→ 600 of the 988 monopile OWTs in the North Sea

OWT with a monopile substructure and detail of a grouted joint (DNV, 2014)

OWT with a tripod / jacket substructure and detail of a grouted joint (Schaumann et al., 2013)
Significant sliding damages of grouted connections have been reported in 2009-2010

→ 600 of the 988 monopile OWTs in the North Sea

Need for diagnostic and damage detection!
Context – Structural Health Monitoring

Structural Health Monitoring (SHM)

– Real-time information from permanently fixed sensing or actuation devices (accelerometers, strain gages, inclinometers, acoustic sensors …)
– Recording, analyzing and predicting the structural health conditions of a structure
→ condition-based maintenance strategy

Fiber optic sensors (FBG)

Vibration-based, nonlinear approach

Diagnostics

GC diagnostic
Objectives

A Numerical model for analyzing the nonlinear behavior of the grouted connection

Fatigue tests of grouted connection specimens
  – At the Leibniz University of Hannover (LUH), Institute for Steel Construction
  – Under the GROWup Project
  ➔ Fatigue behavior of the grouted connection

A SHM for detecting the damages during the test
  – Instrumentation: fiber optic sensors (FBG)
  – Vibration-based detection methodology (nonlinear approach)
  ➔ How effective can be the system?
Numerical modelling of grouted connection

- 2D axisymmetric modelling of a large scale grouted connection (same dimensions as for specimen for fatigue test)
- Pure elastic modelling for the steel parts
- Concrete Damaged Plasticity model (CDP) for the grout
Numerical modelling of grouted connection

- Concrete Damaged Plasticity model (CDP) for the grout
  - the main two failure mechanisms are tensile cracking and compressive crushing
  - The yield surface (Lubliner-Lee-Fenves definition), gives the ability to describe first yield of the material, but also the stiffness degradation due to cyclic loading
    → Defined by following parameters: dilatancy angle, eccentricity, biaxial to uniaxial compressive strength ratio, shape parameter
Numerical modelling – Crack pattern

• ULS calculation for grouted connection (acc. To DNVGL)
  • Interface shear strength $f_{g\_sliding}$ at 10.4 MPa
  • Grout matrice strength, $f_{g\_shear}$ at 7.88 MPa
  → $F_{ULS} = 7.55$ MN

• Numerical results for compressive loading at $F_{ULS}$

• Comparison with experimental results with same GC dimension in dry conditions (Bechtel, 2016)
  → Same crack patterns
    → Crushing at shear keys
    → Cracks between shear keys P1-S1, P1-S2, P4-S5 and P5-S5

Max. principal plastic strain in the grout at ULS compressive load ($F_{ULS} = 7.55$ MN)
Simulation of interface failure between sleeve and grout at the top of the connection, by reduction of friction coefficient FC

- Without damage: FC=0.70; Damage Level 1: FC=0.35; Damage Level 2: FC=0.00
Numerical modelling – Damage and nonlinear behavior

Simulation of compression cracks at the top of the connection

- Damage Level DL1: Crack between shear keys S1 - P1
- Damage Level DL2: Crack between shear keys S1 - P1 and S2 – P1

--> odd subharmonics + appearance of superharmonics
Numerical modelling – Damage and nonlinear behavior

Selection of a Damage Indicator DI

- Calculation of DI at 3 positions along the sleeve
- For 2 damage levels

→ Total change of subharmonics and superharmonics in the normalized ESD spectrum

\[ DI = \sum_{j=1}^{N} (H_{j,\text{damaged}} - H_{j,\text{healthy}}) \]

with \( H_j \) being the peak amplitude of the subharmonic \( j \), and \( N \) the total number of subharmonics
Numerical modelling – Damage and nonlinear behavior

Selection of a Damage Indicator DI

• Calculation of DI at 3 positions along the sleeve
• For 2 damage levels

→ Total change of subharmonics and superharmonics in the normalized ESD spectrum

\[ DI = \sum_{j=1}^{N} (H_{j,\text{damaged}} - H_{j,\text{healthy}}) \]

with \( H_j \) being the peak amplitude of the subharmonic \( j \), and \( N \) the total number of subharmonics.
Numerical modelling – Damage and nonlinear behavior

Selection of a Damage Indicator DI

- Calculation of DI at 3 positions along the sleeve
- For 2 damage levels

→ Evolution of one specified odd subharmonic $f_5$ in the normalized ESD spectrum

$$DI = (H_{j,damaged} - H_{j,healthy})$$

with $H_j$ being the peak amplitude of the subharmonic $j$
Selection of a Damage Indicator DI

- Calculation of DI at 3 positions along the sleeve
- For 2 damage levels

\[ DI = (H_{j,\text{damaged}} - H_{j,\text{healthy}}) \]

with \( H_j \) being the peak amplitude of the subharmonic \( j \)

→ Evolution of one specified odd subharmonic \( f_7 \) in the normalized ESD spectrum

**Case 2: Crack failure**
Fatigue tests of grouted connection specimens

Grouted-connection specimen:
- Large scale tripod grouted connection specimen
- Designed with 5 shear keys positioned in the center of the grouted connection
- Filled with fresh water 24h before the test

Cut-off view of a grouted connection specimen (tripod structure in a scale of 1:4)
Fatigue tests of grouted connection specimens

Testing procedure:

- 10 MN servo-hydraulic machine of LUH (Institute of Building Material Science)
- Incremental axial and cyclic loads (1Hz), where each load level is applied for 100,000 cycles

<table>
<thead>
<tr>
<th>Load Scenario</th>
<th>LS1</th>
<th>LS2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_{\text{max}} / F_{\text{min}}$ [MN]</td>
<td>+1 / -1</td>
<td>+2 / -2</td>
</tr>
</tbody>
</table>

Grouted connection specimen in the servo-hydraulic testing machine
Instrumentation: Fiber Bragg Grating sensors

FBG Working principle:

\[
\frac{\Delta \lambda}{\lambda_0} = (1-p_e)\varepsilon_z + (\alpha_\Lambda + \alpha_n)\Delta T
\]

with \(\Delta \lambda\) the wavelength variation, \(\varepsilon_z\) the strain, \(\lambda_0\) the initial wavelength, \(p_e\) the photo-elastic coefficient, \(\alpha_\Lambda\) the thermal dilatation, \(\alpha_n\) the thermo-optic coefficient, and \(\Delta T\) the temperature variation.

FBG advantages: robust (harsh conditions), immune to electromagnetic interferences, multiplexing …
Instrumentation: Fiber Bragg Grating sensors

FBG Working principle:

\[ \Delta \lambda / \lambda_0 = (1 - p_e) \varepsilon z + (\alpha \wedge + \alpha n) \Delta T \]

with \( \Delta \lambda \) the wavelength variation, \( \varepsilon z \) the strain, \( \lambda_0 \) the initial wavelength, \( p_e \) the photo-elastic coefficient, \( \alpha \wedge \) the thermal dilatation, \( \alpha n \) the thermo-optic coefficient, and \( \Delta T \) the temperature variation.

FBG advantages: robust (harsh conditions), immune to electromagnetic interferences, multiplexing …
Instrumentation: Fiber Bragg Grating sensors

FBG Working principle:

\[
\frac{\Delta \lambda}{\lambda_0} = (1 - p_e) \varepsilon_z + (\alpha_\Lambda + \alpha_n) \Delta T
\]

with \(\Delta \lambda\) the wavelength variation, \(\varepsilon_z\) the strain, \(\lambda_0\) the initial wavelength, \(p_e\) the photo-elastic coefficient, \(\alpha_\Lambda\) the thermal dilatation, \(\alpha_n\) the thermo-optic coefficient, and \(\Delta T\) the temperature variation.

FBG advantages: robust (harsh conditions), immune to electromagnetic interferences, multiplexing …
Instrumentation: Fiber Bragg Grating sensors

Design & application:

- Bare fibers bonded on the steel surface of the sleeve in the shear key area
- 9 FBGs for strain measurement
- 3 FBGs for temperature compensation
- Application method: glued with a cyanoacrylate glue + polyurethane lack (humidity and mechanical protection)
Instrumentation: Fiber Bragg Grating sensors

Design & application:

- Bare fibers bonded on the steel surface of the sleeve in the shear key area
- 9 FBGs for strain measurement
- 3 FBGs for temperature compensation
- Application method: glued with a cyanoacrylate glue + polyurethane lack (humidity and mechanical protection)
Instrumentation: Fiber Bragg Grating sensors

Design & application:
- Bare fibers bonded on the steel surface of the sleeve in the shear key area
- 9 FBGs for strain measurement
- 3 FBGs for temperature compensation
- Application method: glued with a cyanoacrylate glue + polyurethane lack (humidity and mechanical protection)
Data analysis and damage detection

Monitoring of the appearance of nonlinearities and calculation of the Damage Indicator DI (all subharmonics)

\[ DI = \sum_{j=1}^{N} (H_{j,\text{damaged}} - H_{j,\text{healthy}}) \]

with \( H_j \) being the peak amplitude of the subharmonic \( j \), and \( N \) the total number of subharmonics.

\( \rightarrow \) Total change of subharmonics in the normalized ESD spectrum
Data analysis and damage detection

Monitoring of the appearance of nonlinearities and calculation of the Damage Indicator $DI$ (all subharmonics)

$\rightarrow$ Total change of subharmonics in the normalized ESD spectrum

$$DI = \sum_{j=1}^{N} (H_{j,\text{damaged}} - H_{j,\text{healthy}})$$

with $H_j$ being the peak amplitude of the subharmonic $j$, and $N$ the total number of subharmonics

$\rightarrow$ Cyclic creep curve
Data analysis and damage detection

Monitoring of the appearance of nonlinearities and calculation of the Damage Indicator DI (all subharmonics)

![Graph showing total change of ESD harmonic amplitudes](image)

<table>
<thead>
<tr>
<th>Damage Indicator Values for every sensor at 2.52*10^4 cycles [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sensor</strong></td>
</tr>
<tr>
<td>------------</td>
</tr>
<tr>
<td>Angle 1</td>
</tr>
<tr>
<td>Angle 2</td>
</tr>
<tr>
<td>Angle 3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Damage indicator – curve slope for FBG S2, FBG M2 and FBG I2 at the end of LS1 and start of LS2 [dB/1000 cycles]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sensor</strong></td>
</tr>
<tr>
<td>------------</td>
</tr>
<tr>
<td>FBG S2</td>
</tr>
<tr>
<td>FBG M2</td>
</tr>
<tr>
<td>FBG I2</td>
</tr>
</tbody>
</table>

→ Early detection
Data analysis and damage detection

Monitoring of the appearance of nonlinearities and calculation of the Damage Indicator DI5 (subharmonic f5)
Data analysis and damage detection

Monitoring of the appearance of nonlinearities and calculation of the Damage Indicator DI5 (subharmonic f5)
Data analysis and damage detection

Monitoring of the appearance of nonlinearities and calculation of the Damage Indicator DI5 (subharmonic f5)

Damage indicator – DI5 relative evolution

<table>
<thead>
<tr>
<th></th>
<th>End of LS1</th>
<th>Start of LS2</th>
</tr>
</thead>
<tbody>
<tr>
<td>FBG S1</td>
<td>0.55</td>
<td>-0.48</td>
</tr>
<tr>
<td>FBG S2</td>
<td>-0.03</td>
<td>-1.97</td>
</tr>
<tr>
<td>FBG S3</td>
<td>0.03</td>
<td>-0.90</td>
</tr>
<tr>
<td>FBG M1</td>
<td>-0.01</td>
<td>2.75</td>
</tr>
<tr>
<td>FBG M2</td>
<td>0.00</td>
<td>1.03</td>
</tr>
<tr>
<td>FBG M3</td>
<td>-0.02</td>
<td>3.60</td>
</tr>
<tr>
<td>FBG I1</td>
<td>-0.01</td>
<td>0.63</td>
</tr>
<tr>
<td>FBG I2</td>
<td>-0.01</td>
<td>0.79</td>
</tr>
<tr>
<td>FBG I3</td>
<td>-0.01</td>
<td>0.59</td>
</tr>
</tbody>
</table>

 détecté de la section Mid-Inf du grout avant la rupture (échec d’interface)
Conclusion

Monitoring of grouted connection
- SHM system based on fiber optic sensors associated with a signal-based detection methodology (vibration-based, nonlinear approach)

Damage detection
- Selection of Damage Indicators based on subharmonics and superharmonics evolution in the output signal
- Detection of the occurrence (early stage)
- Damage localization and severity can be achieved with particular caution (i.e. with a well understanding of the nonlinear behavior of the structure in healthy and damage states)

Future work
THANK YOU FOR YOUR ATTENTION

nathalie.mueller@iwes.fraunhofer.de
nathalie.muller@univ-nantes.fr