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

Offshore Wind R&D 2018, Bremerhaven, 14.11.2018

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Franck Schoefs, University of Nantes

Context – The grouted connection of OWTs

Grout filled space between the two steel components of the

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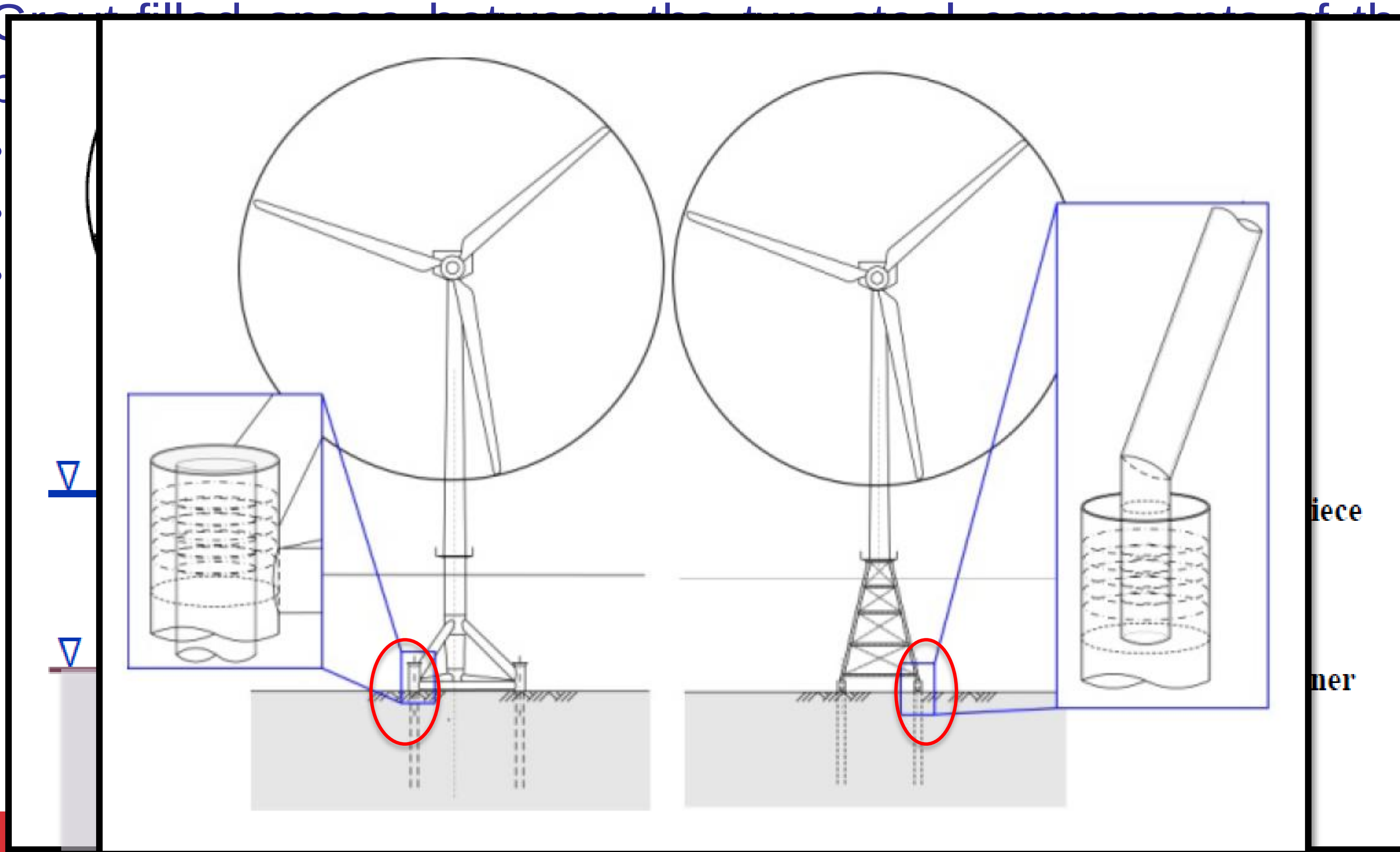

Context – The grouted connection of OWTs

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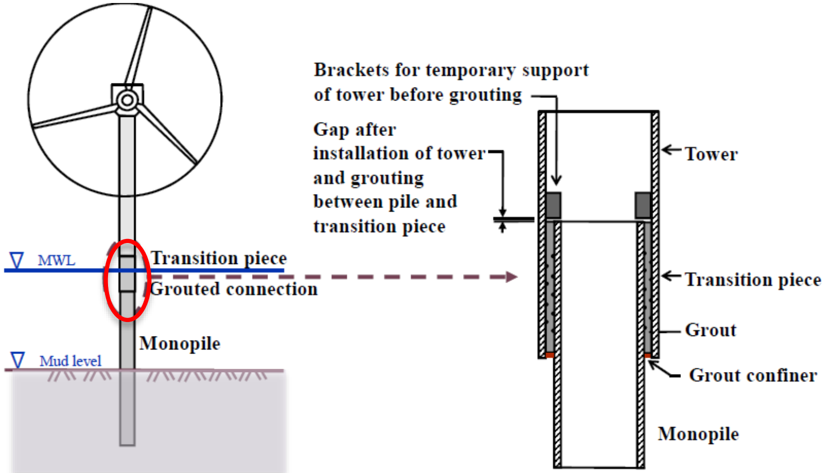
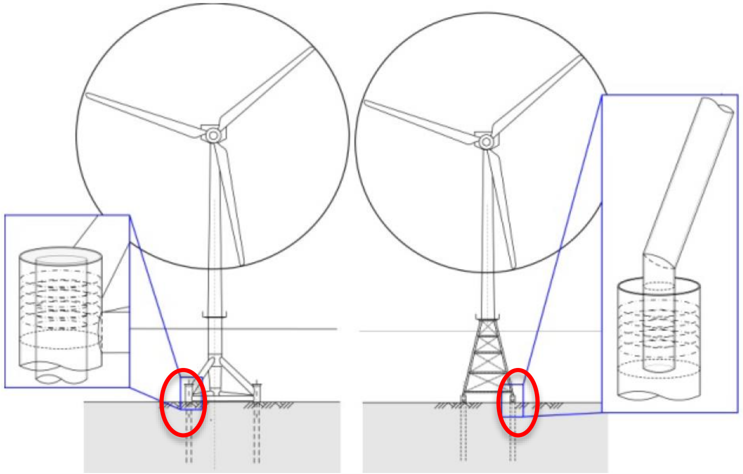
Significant sliding damages of grouted connections have been reported in 2009-2010

→ 600 of the 988 monopile OWTs in the North Sea

→ Cylindrical with shear keys + conical design recommended (DNV-OS-J101 (2014), DNV-OS-C502 (2012), DNVGL-ST-0126 (2016))



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)

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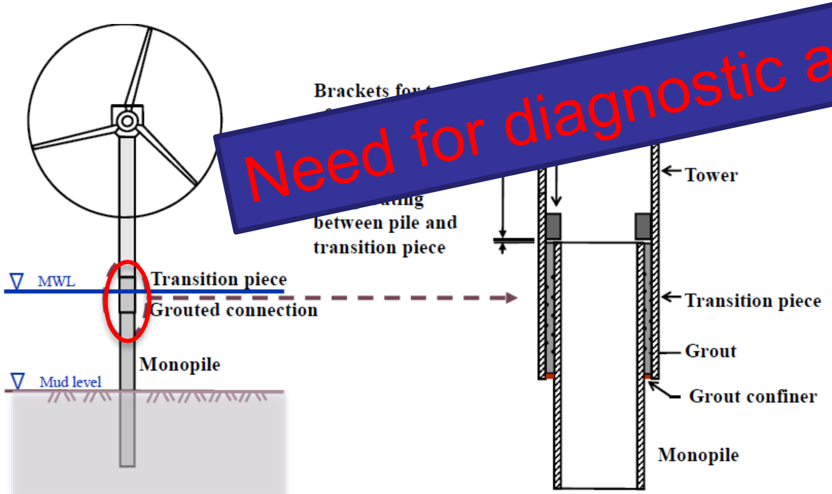
Need for diagnostic and damage detection !



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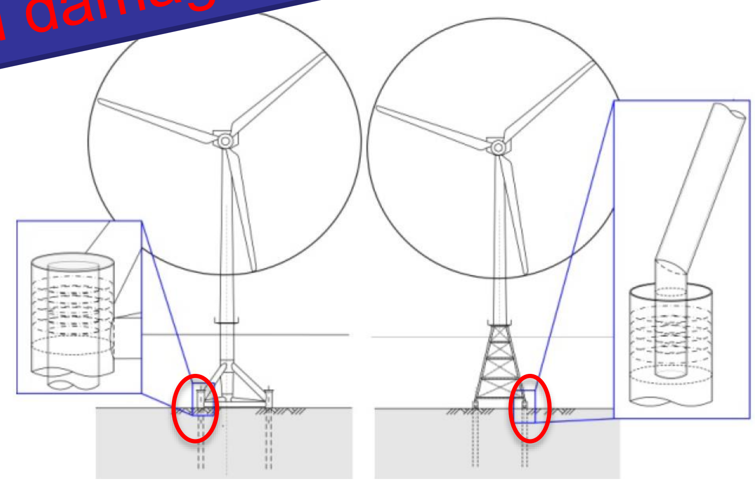

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Context – Structural Health Monitoring

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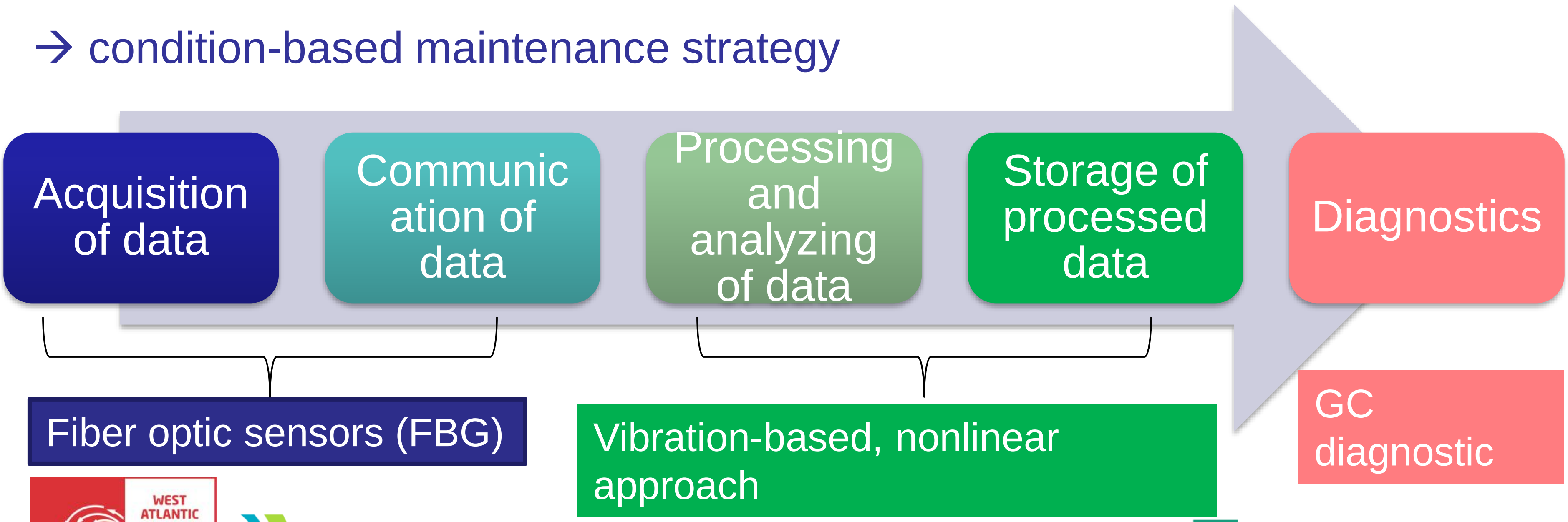
Structural Health Monitoring (SHM)

– 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



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Objectives

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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?

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Numerical modelling of grouted connection

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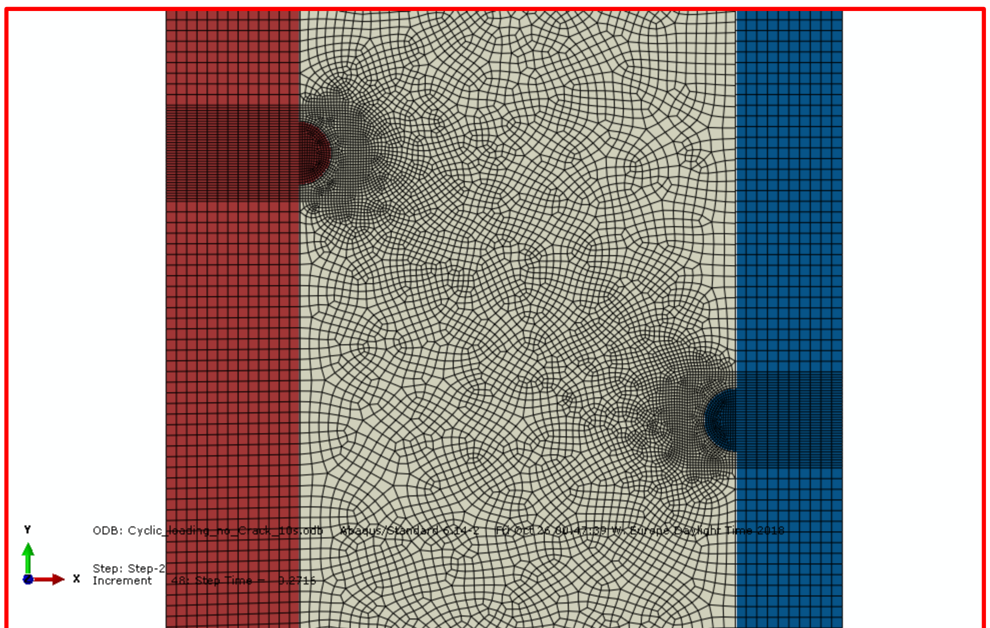
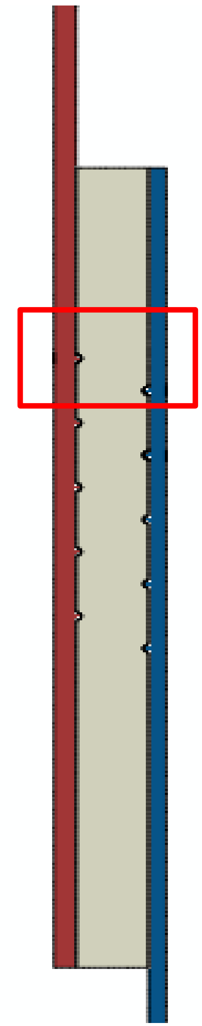
- 2D axisymmetric modelling of a large scale grouted connection (same dimensions as for specimen for fatigue test)
- Pure elastic modelling for the steel parts
- Concrete Damaged Plasticity model (CDP) for the grout





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Numerical modelling of grouted connection

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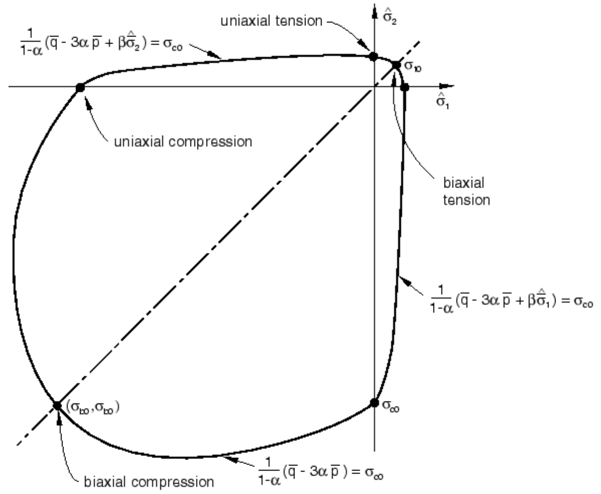
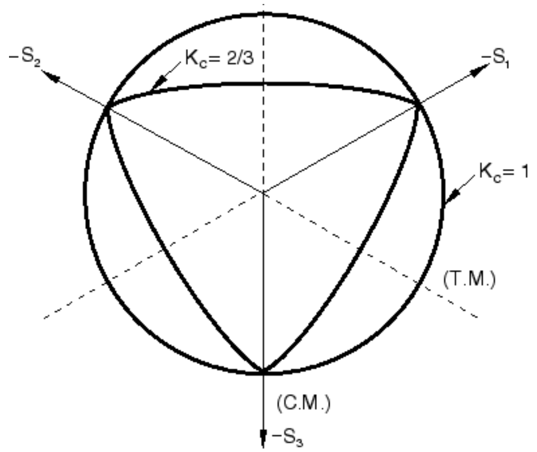
- Concrete Damaged Plasticity model (CDP) for the grout
  - the main two failure mechanisms are tensile cracking and compressive crushing
  - The yield surface (Lubliner-Lee-Fenves definition), gives the ability to describe first yield of the material, but also the stiffness degradation due to cyclic loading

→ Defined by following parameters: dilatancy angle, eccentricity, biaxial to uniaxial compressive strength ratio, shape parameter



Plane stress



Deviatoric plane – pure compression

(Dassault systemes)

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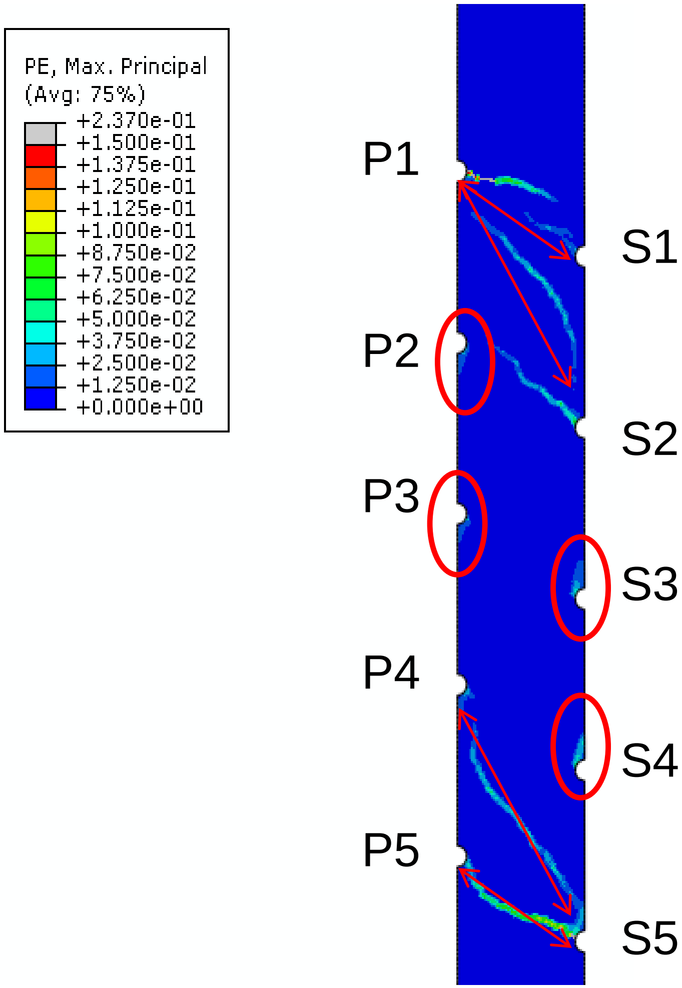
Numerical modelling – Crack pattern

- ULS calculation for grouted connection (acc. To DNVGL)
  - Interface shear strength fg_sliding at 10.4 MPa
  - Grout matrice strength, fg_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)

Numerical modelling – Damage and nonlinear behavior

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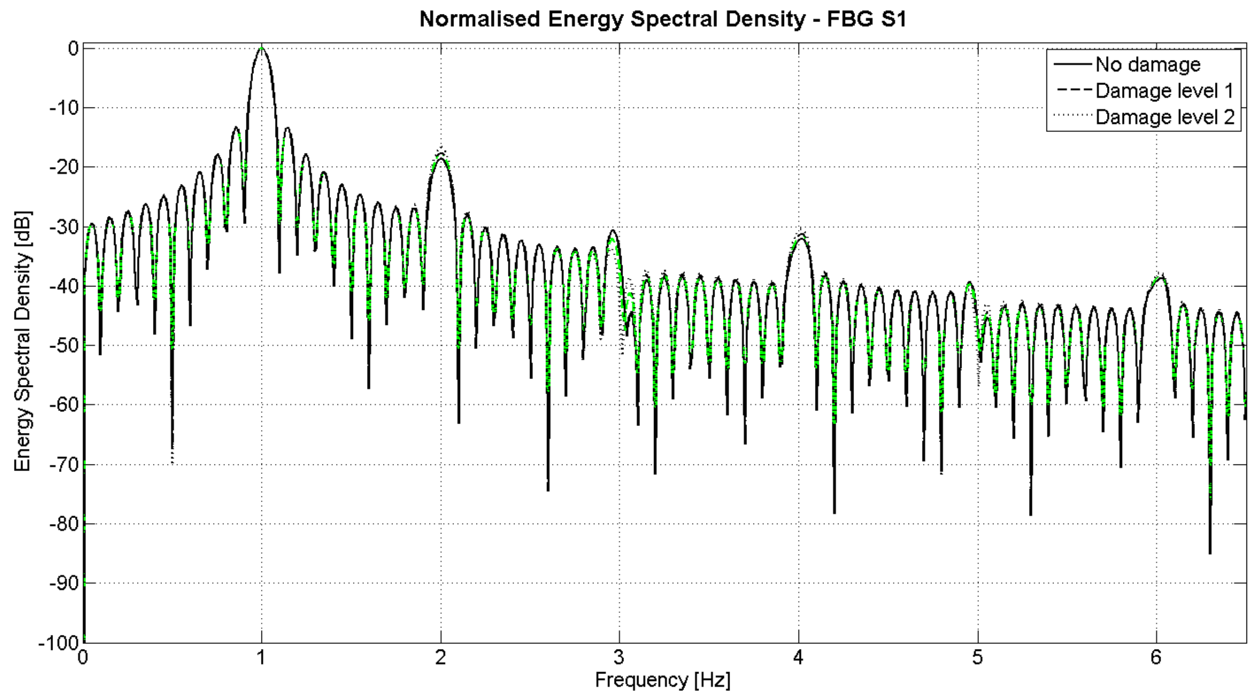
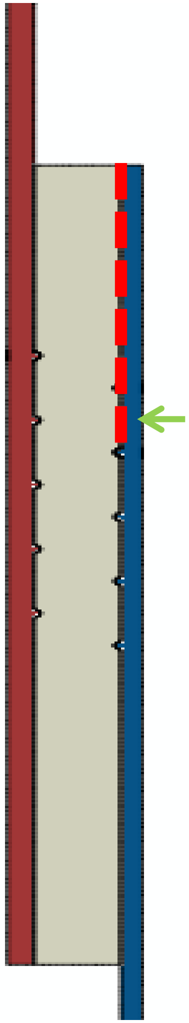
Simulation of interface failure between sleeve and grout at the top of the connection, by reduction of friction coefficient FC

- Without damage: FC=0.70; Damage Level 1: FC=0.35; Damage Level 2: FC=0.00





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Numerical modelling – Damage and nonlinear behavior

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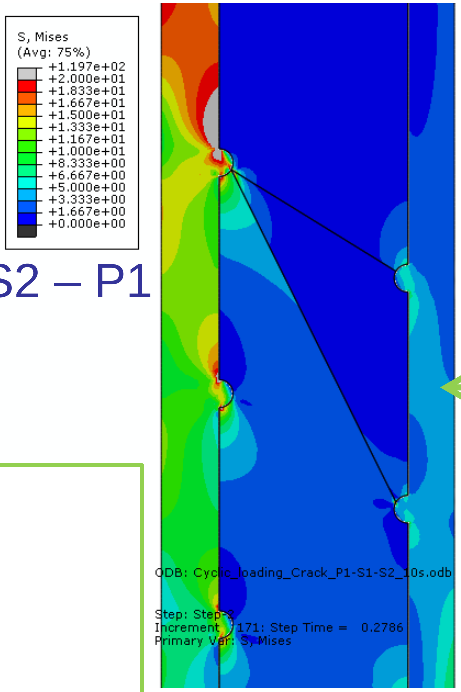
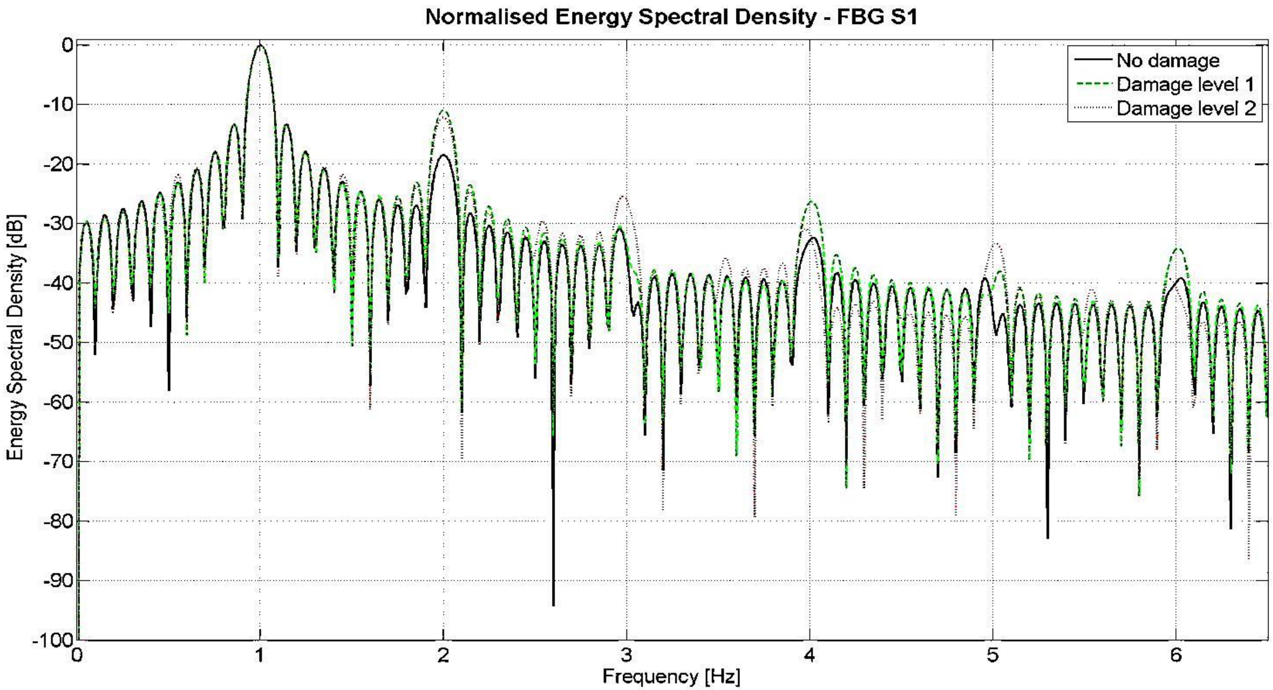
Simulation of compression cracks at the top of the connection

- 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





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Numerical modelling – Damage and nonlinear behavior

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Selection of a Damage Indicator DI

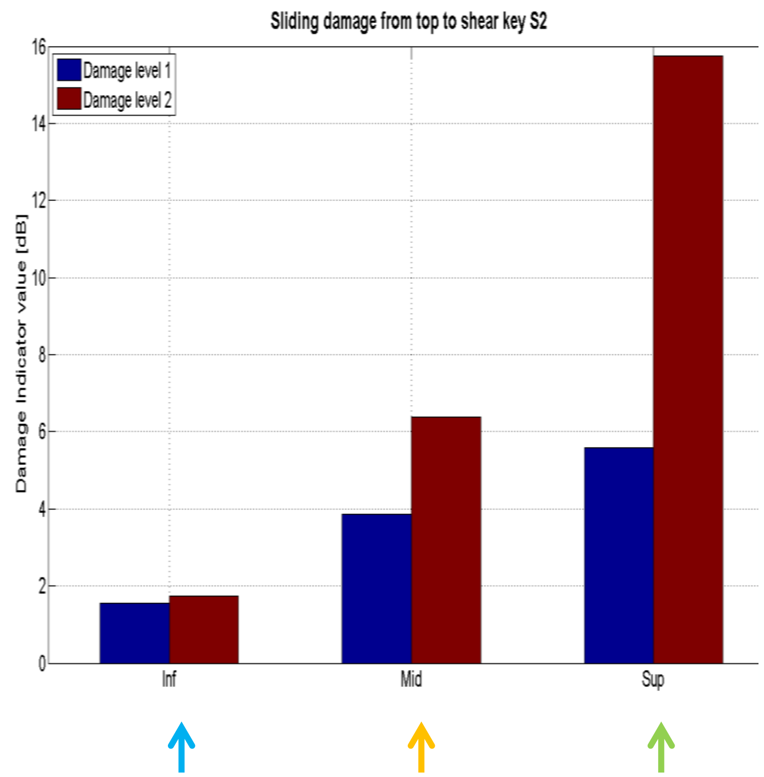
- Calculation of DI at 3 positions along the sleeve
- For 2 damage levels

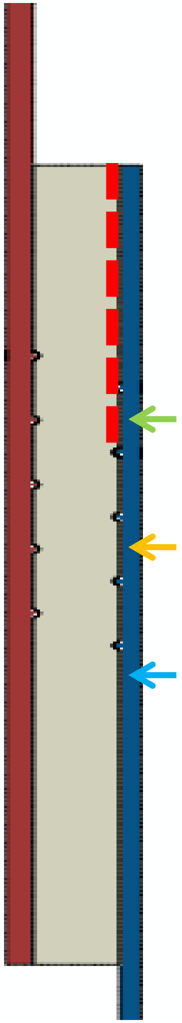
→ Total change of subharmonics and superharmonics in the normalized ESD spectrum

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

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

Case 1: Interface failure





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Numerical modelling – Damage and nonlinear behavior

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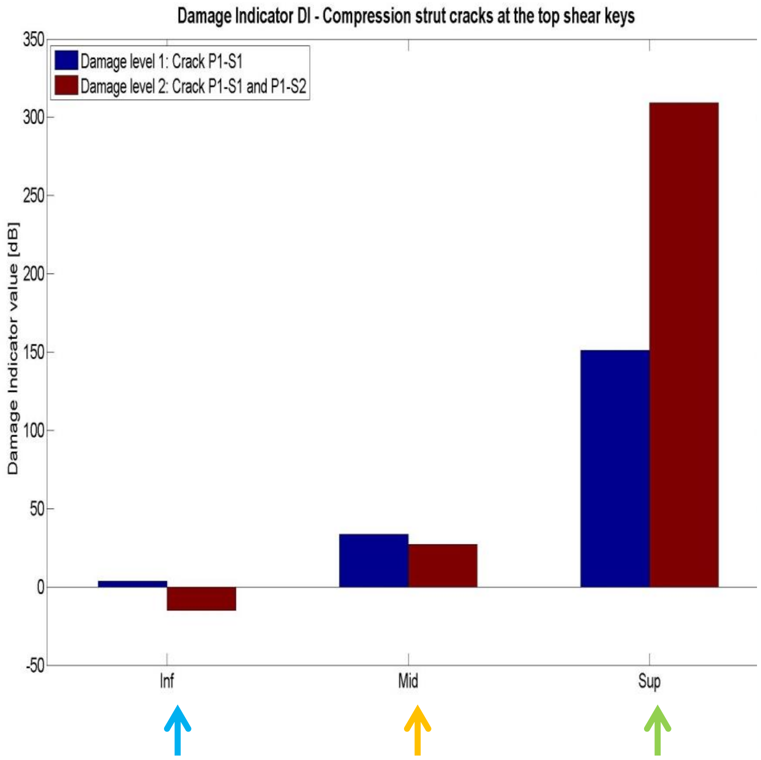
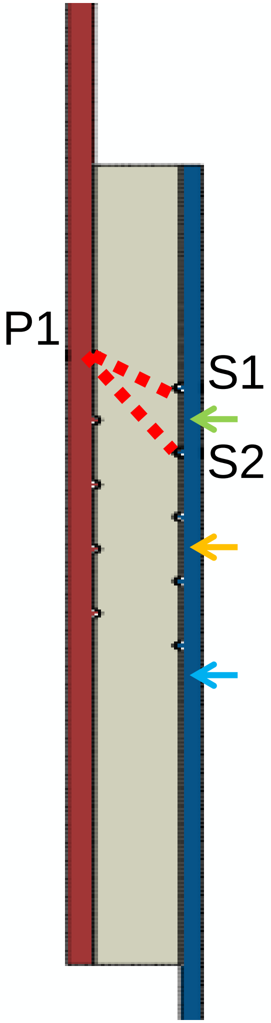
Case 2: Crack failure





Numerical modelling – Damage and nonlinear behavior

Selection of a Damage Indicator DI

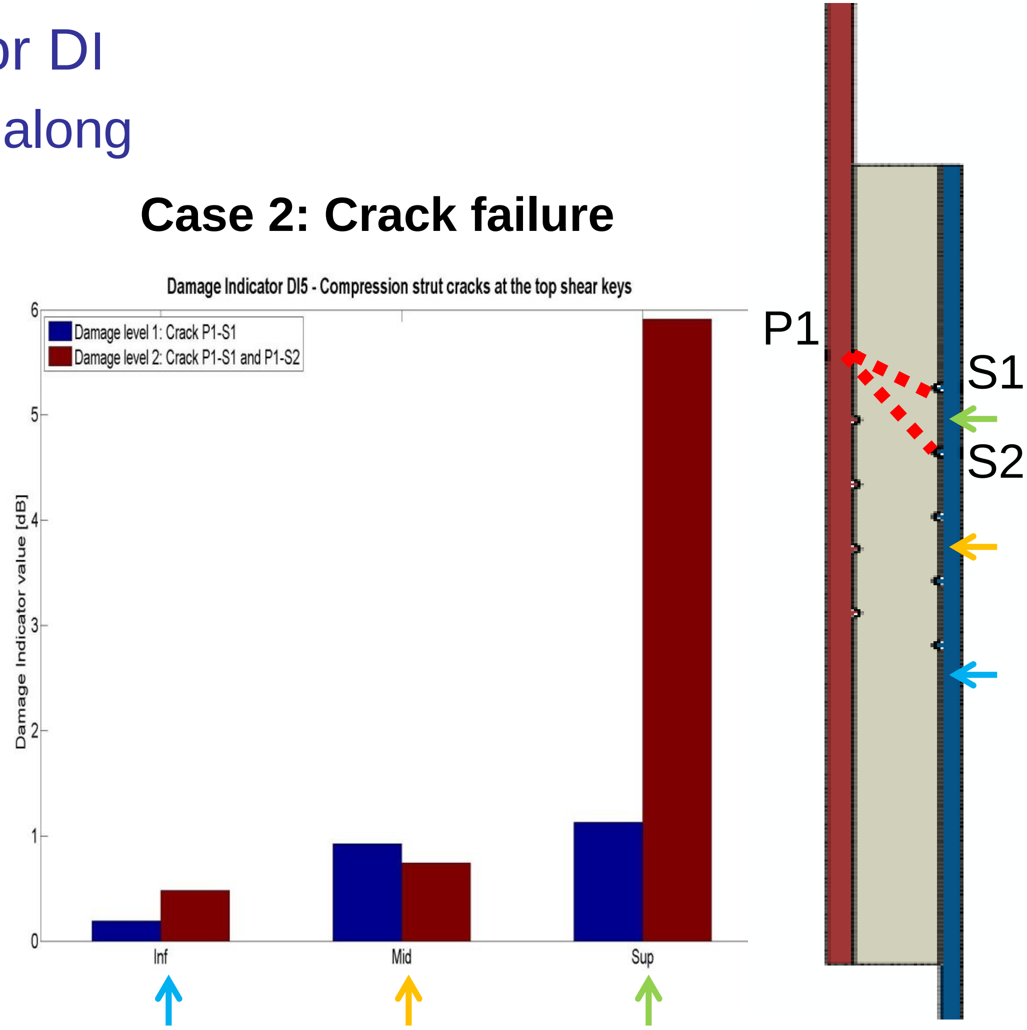
- Calculation of DI at 3 positions along the sleeve
- For 2 damage levels

→ Evolution of one specified odd subharmonic f5 in the normalized ESD spectrum

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

with H_j being the peak amplitude of the subharmonic j

Case 2: Crack failure



Numerical modelling – Damage and nonlinear behavior

Selection of a Damage Indicator DI

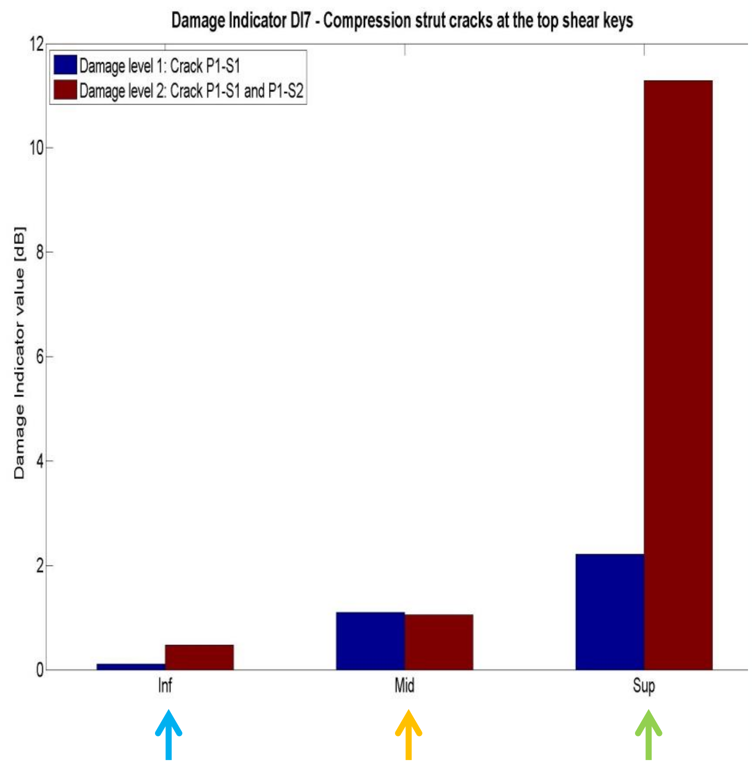
- Calculation of DI at 3 positions along the sleeve
- For 2 damage levels

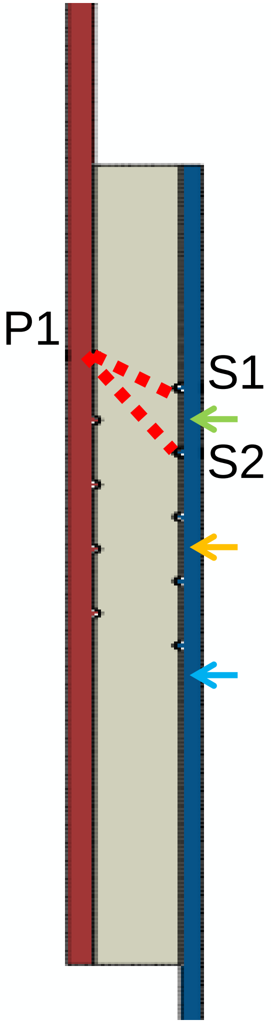
→ <u>Evolution of one specified odd subharmonic f7</u> in the normalized ESD spectrum

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

with H_j being the peak amplitude of the subharmonic j

Case 2: Crack failure

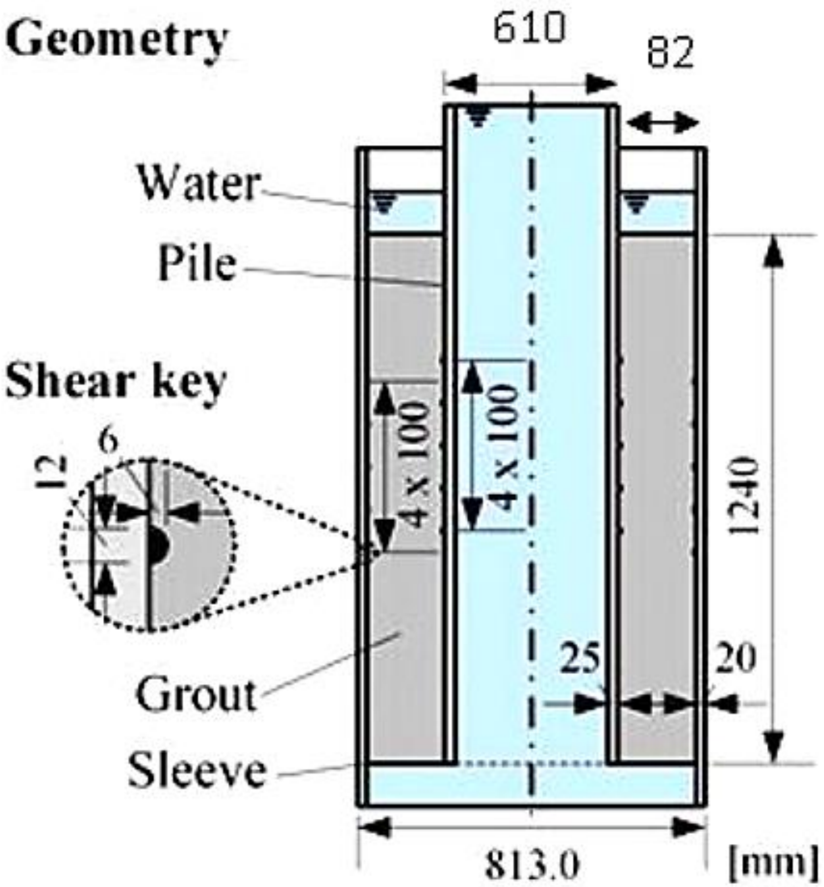




Fatigue tests of grouted connection specimens

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



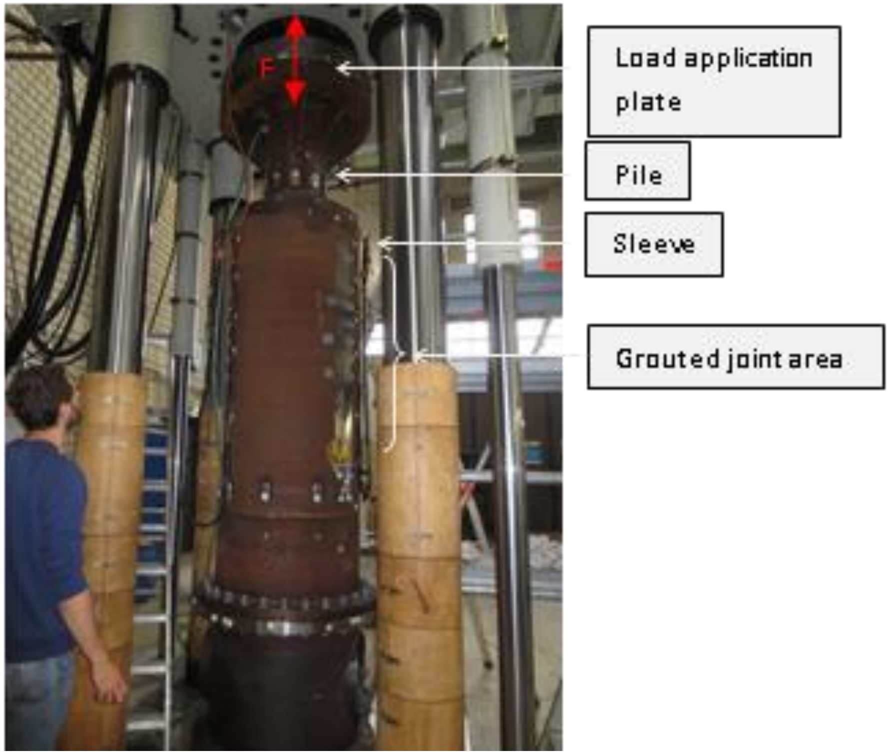
Cut-off view of a grouted connection specimen (tripod structure in a scale of 1:4)

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

Load Scenario	LS1	LS2
F_{max} / F_{min} [MN]	+1 / -1	+2 / -2



Grouted connection specimen in the servo-hydraulic testing machine

Instrumentation: Fiber Bragg Grating sensors

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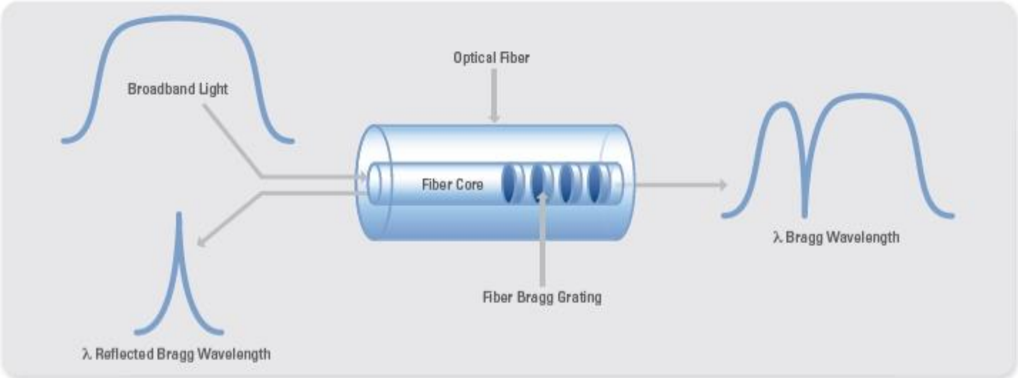
FBG Working principle:



$$\Delta\lambda / \lambda_0 = (1-p_e) * \varepsilon_z + (\alpha_\Lambda + \alpha_n) * \Delta T$$

with $\Delta\lambda$ the wavelength variation, ε_z the strain, λ_0 the initial wavelength, p_e the photo-elastic coefficient, α_Λ the thermal dilatation, α_n the thermo-optic coefficient, and ΔT the temperature variation

FBG advantages: robust (harsh conditions), immune to electromagnetic interferences, multiplexing …

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Instrumentation: Fiber Bragg Grating sensors

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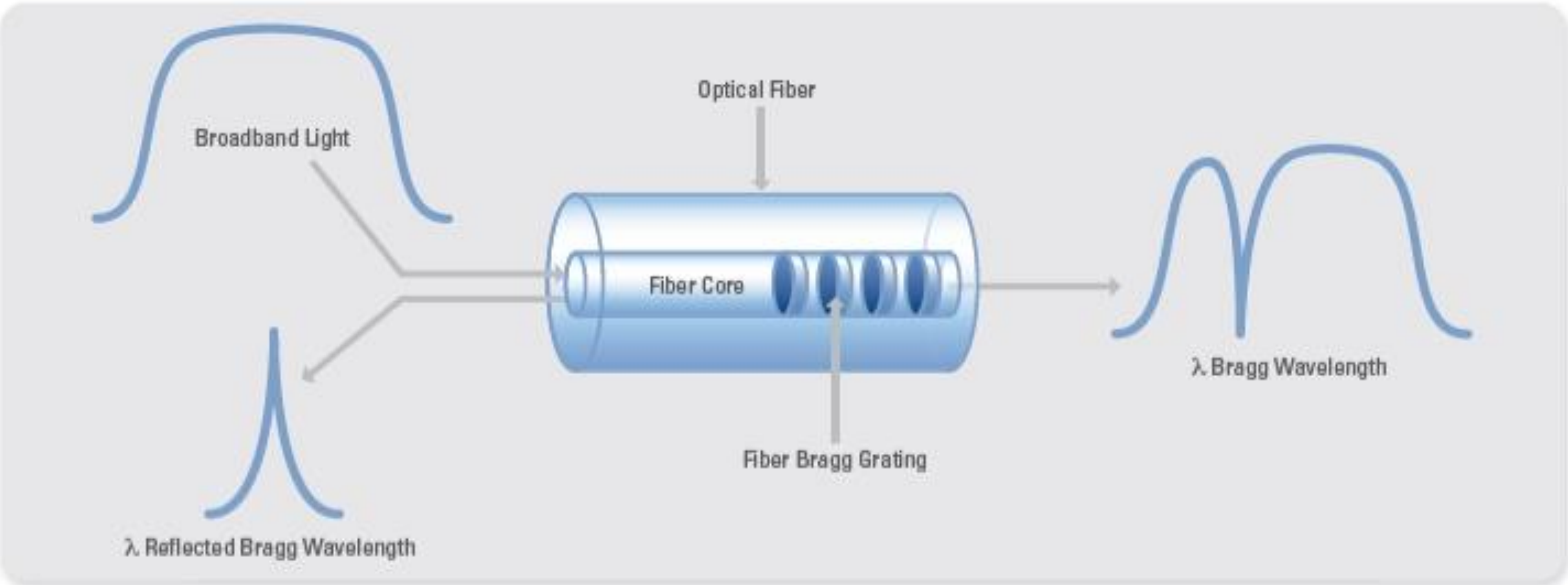

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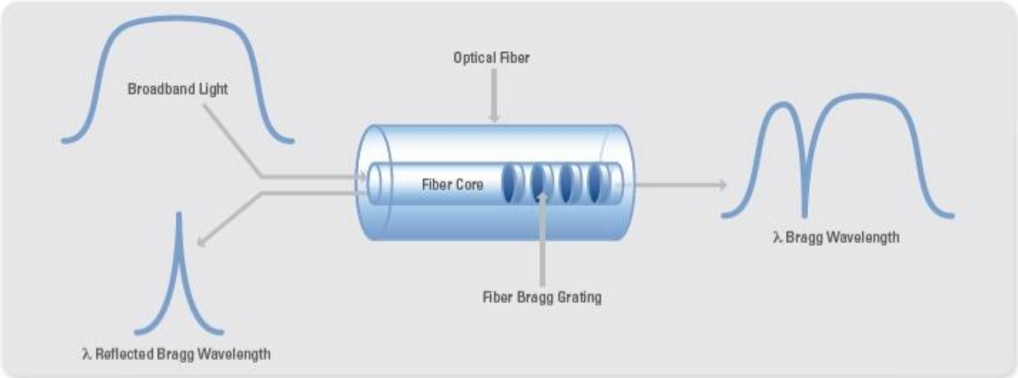

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Instrumentation: Fiber Bragg Grating sensors

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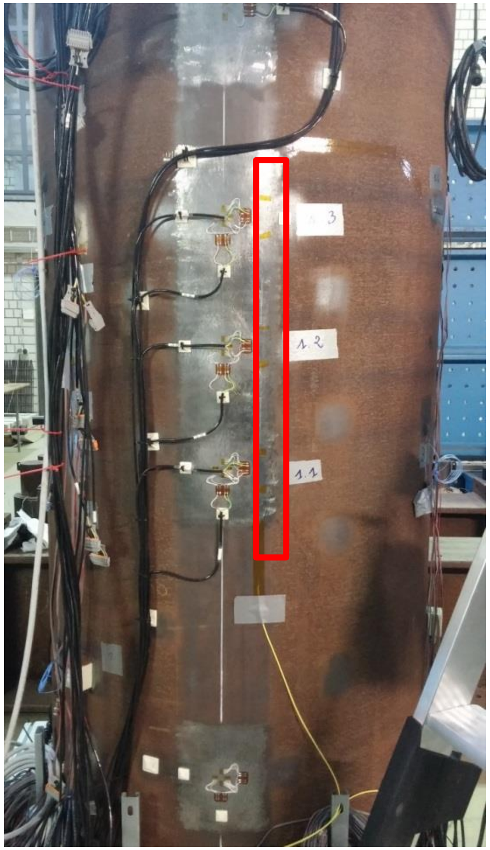
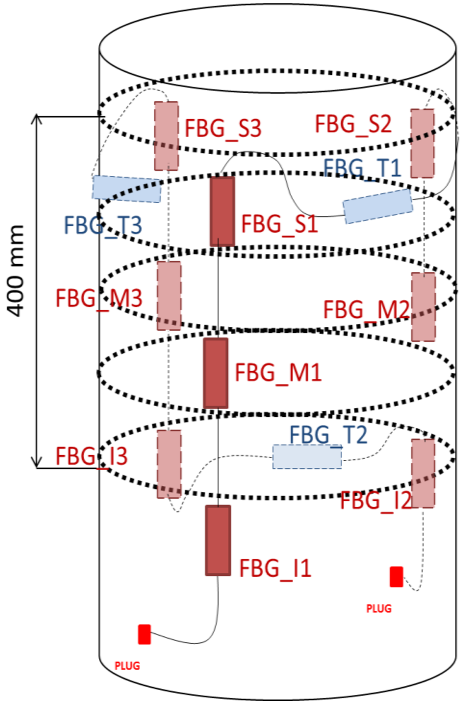
Design & application:

- 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)





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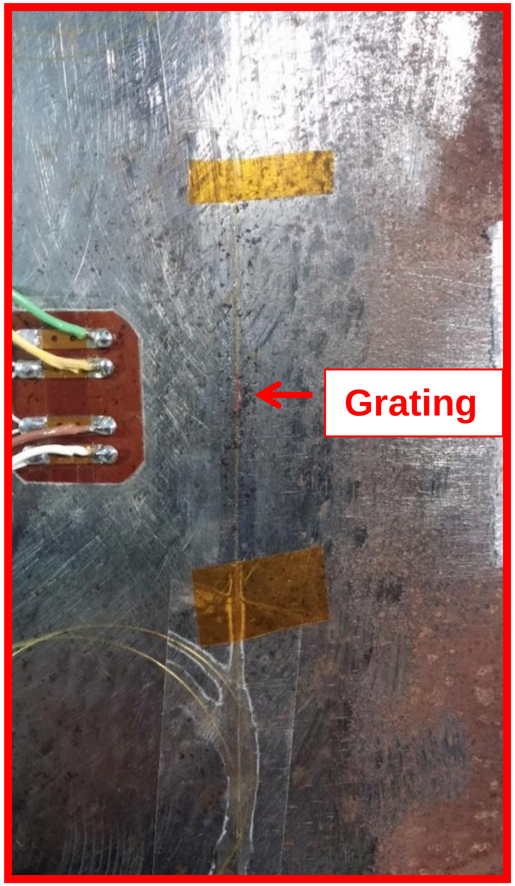

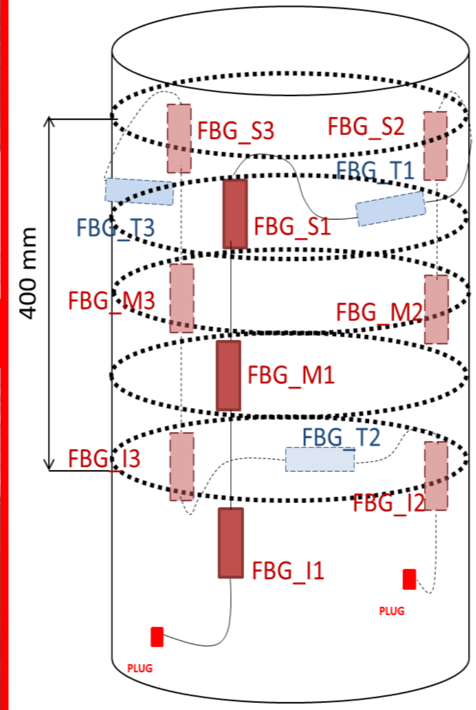

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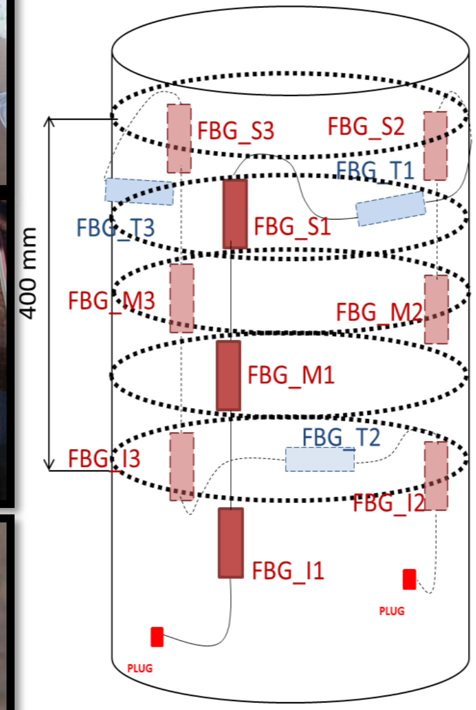

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Data analysis and damage detection

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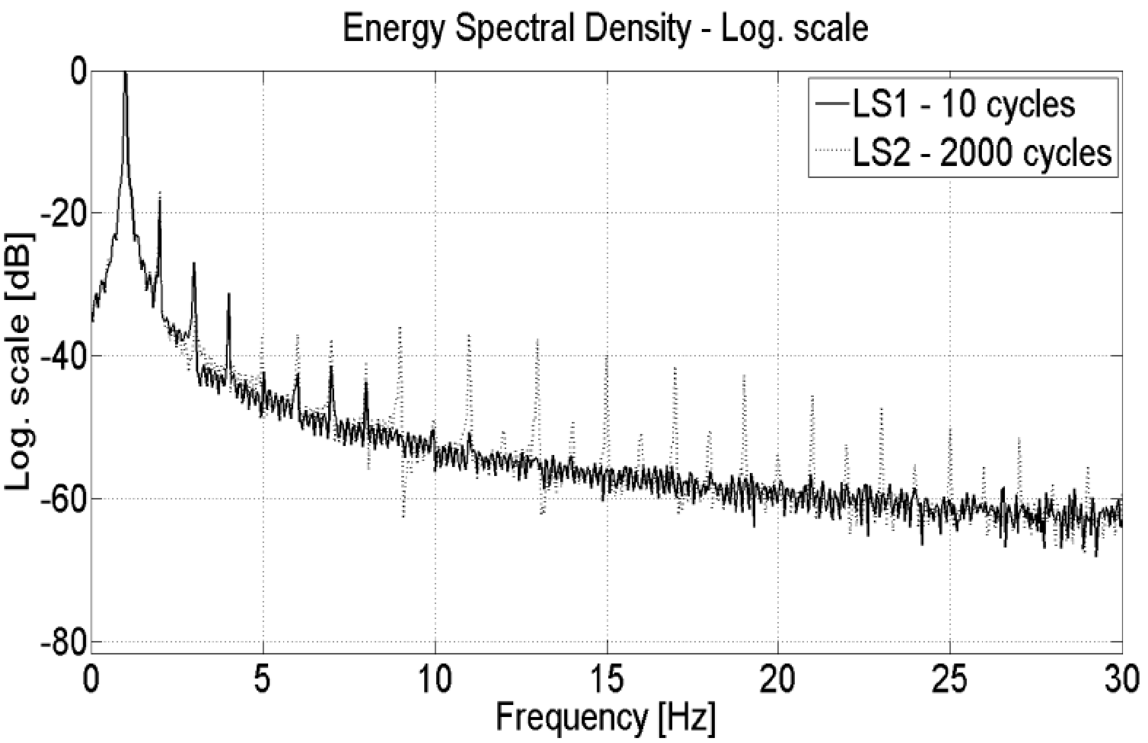
Monitoring of the appearance of nonlinearities and calculation of the Damage Indicator DI (all subharmonics)



→ Total change of subharmonics in the normalized ESD spectrum

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

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

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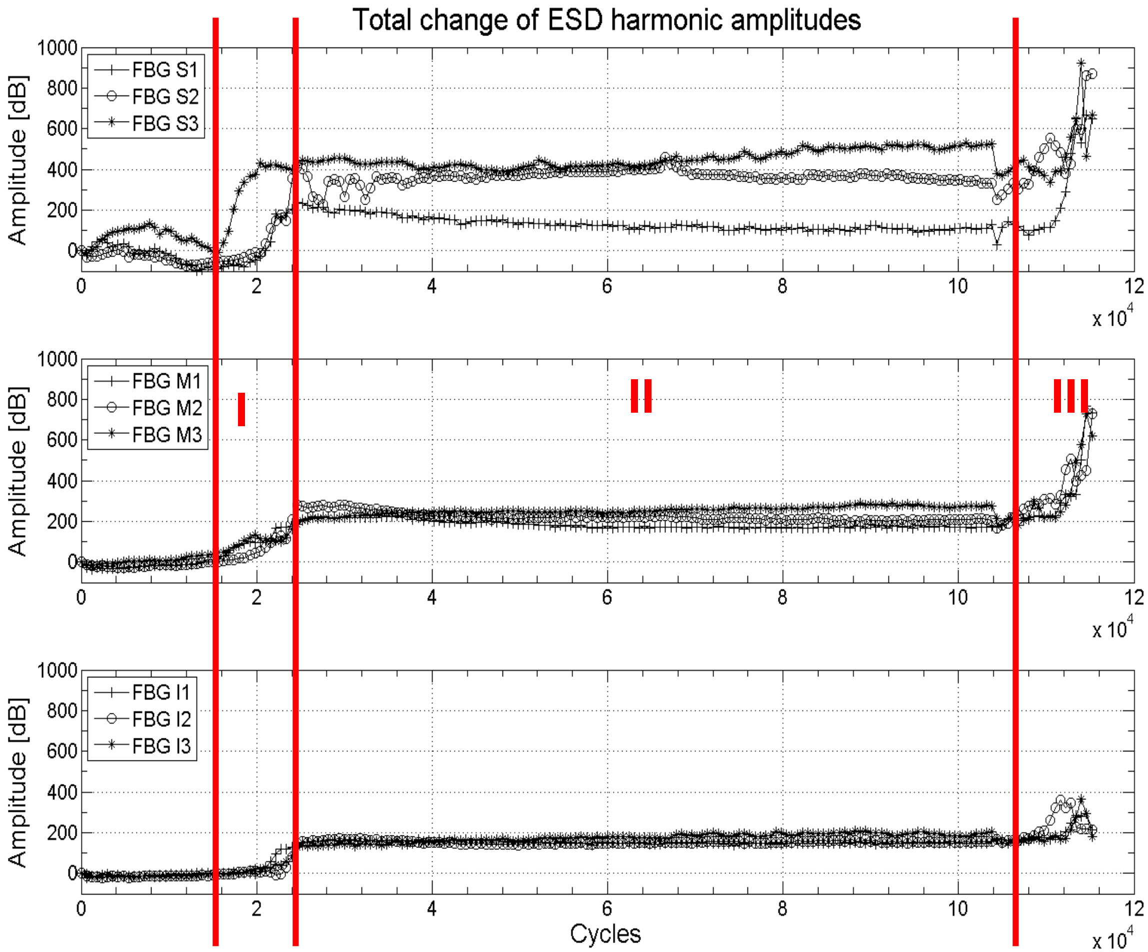

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→ Cyclic creep curve

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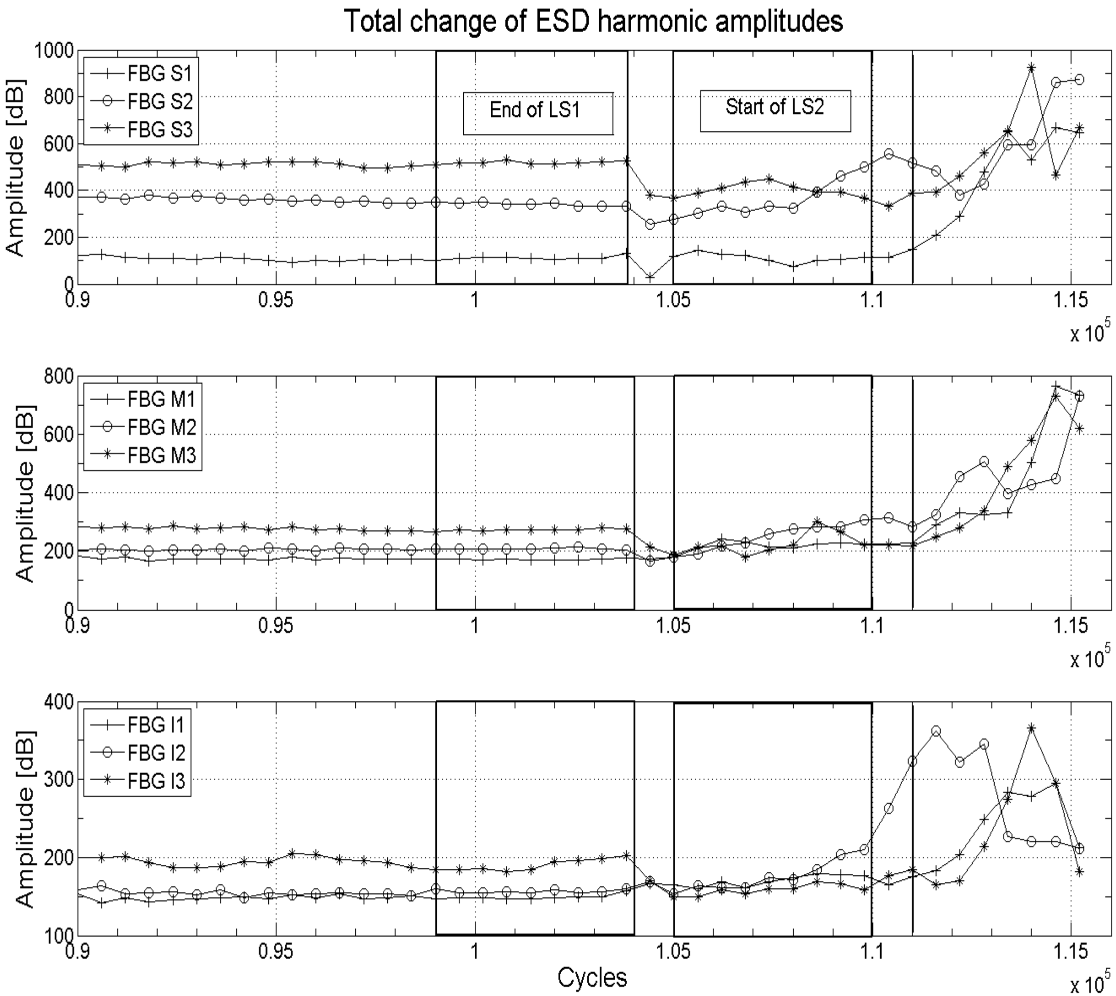

Damage Indicator Values for every sensor at 2.52*10^4 cycles [dB]			
	Inferior level	Mid-level	Superior level
Angle 1	154.1	210.7	231.5
Angle 2	158.9	275.8	403.6
Angle 3	137.1	205.9	445.9

Damage indicator – curve slope for FBG S2, FBG M2 and FBG I2 at the end of LS1 and start of LS2 [dB/1000 cycles]		
	End of LS1	Start of LS2
FBG S2	- 3.3	+ 44.9
FBG M2	+ 0.9	+ 24.38
FBG I2	- 0.18	+ 11.36

→ **Early detection**

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Data analysis and damage detection

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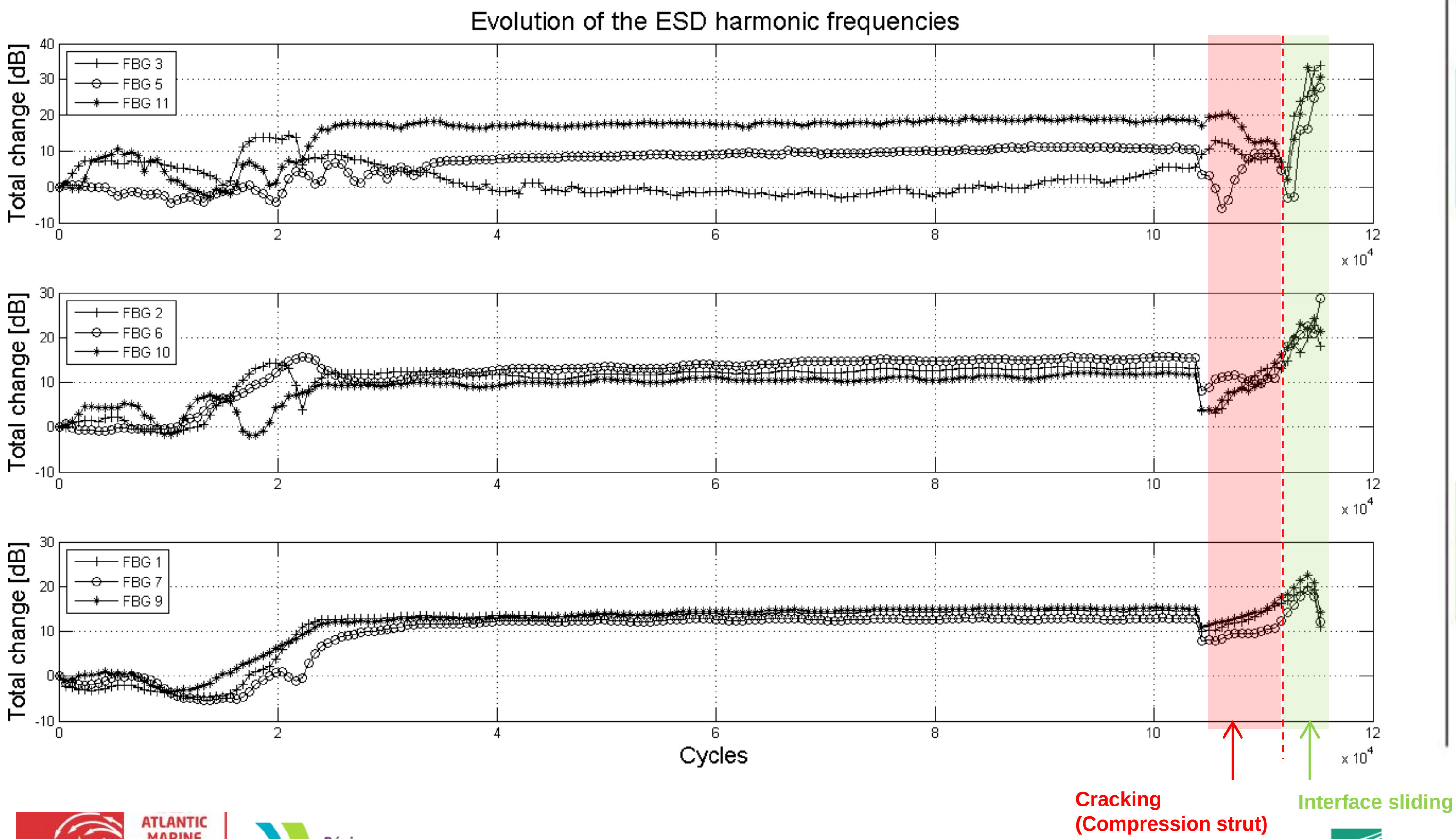
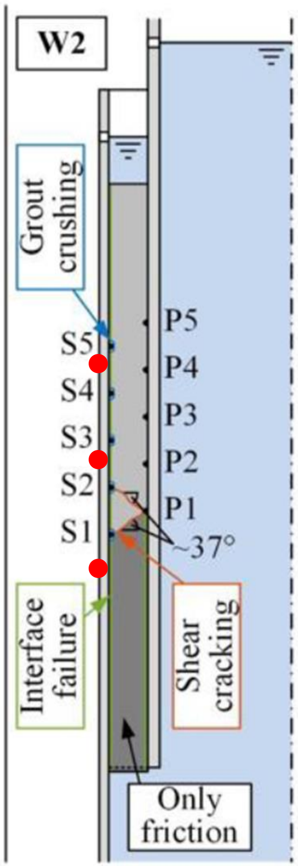
Monitoring of the appearance of nonlinearities and calculation of the Damage Indicator DI5 (subharmonic f5)





(Raba, 2018)

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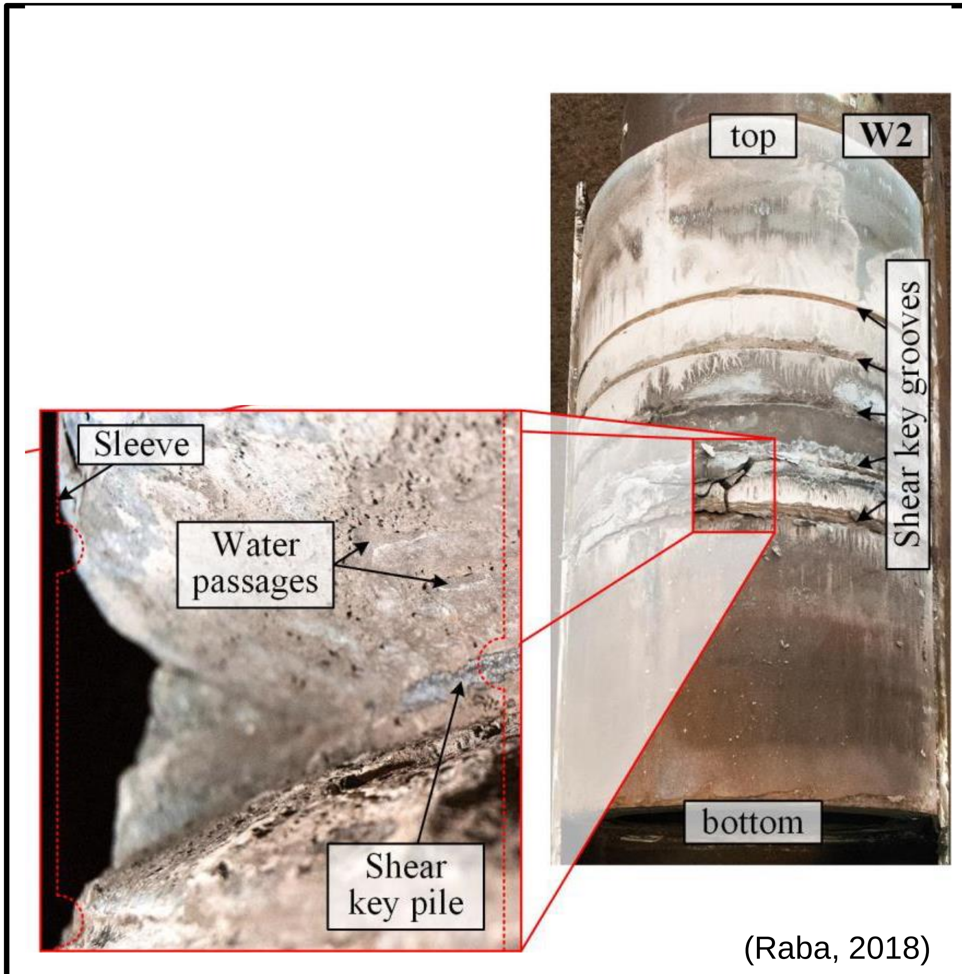

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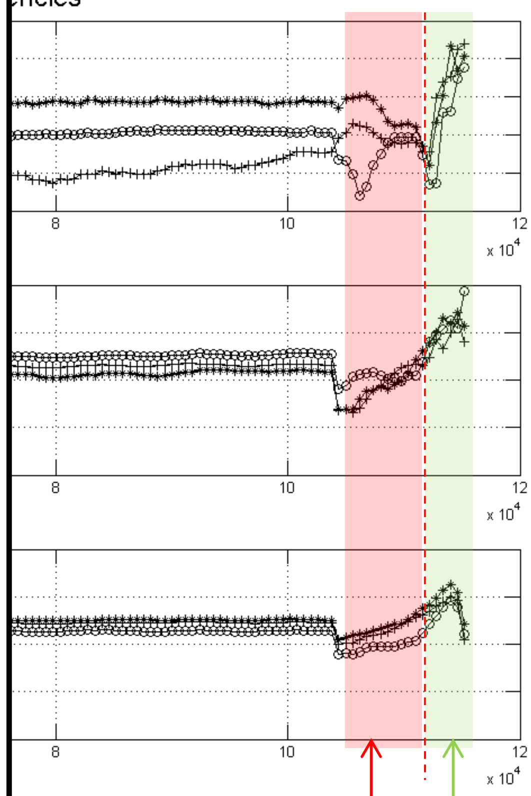

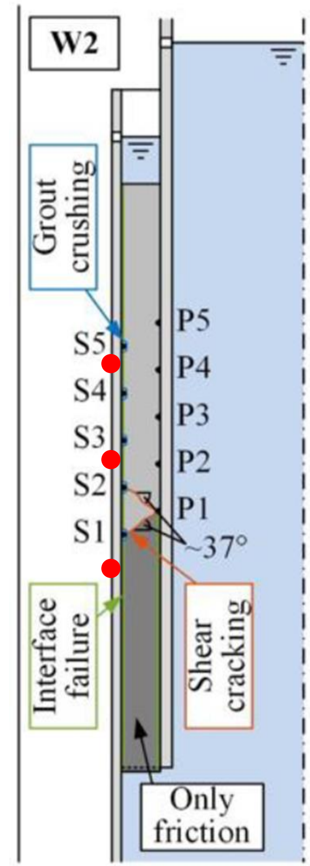

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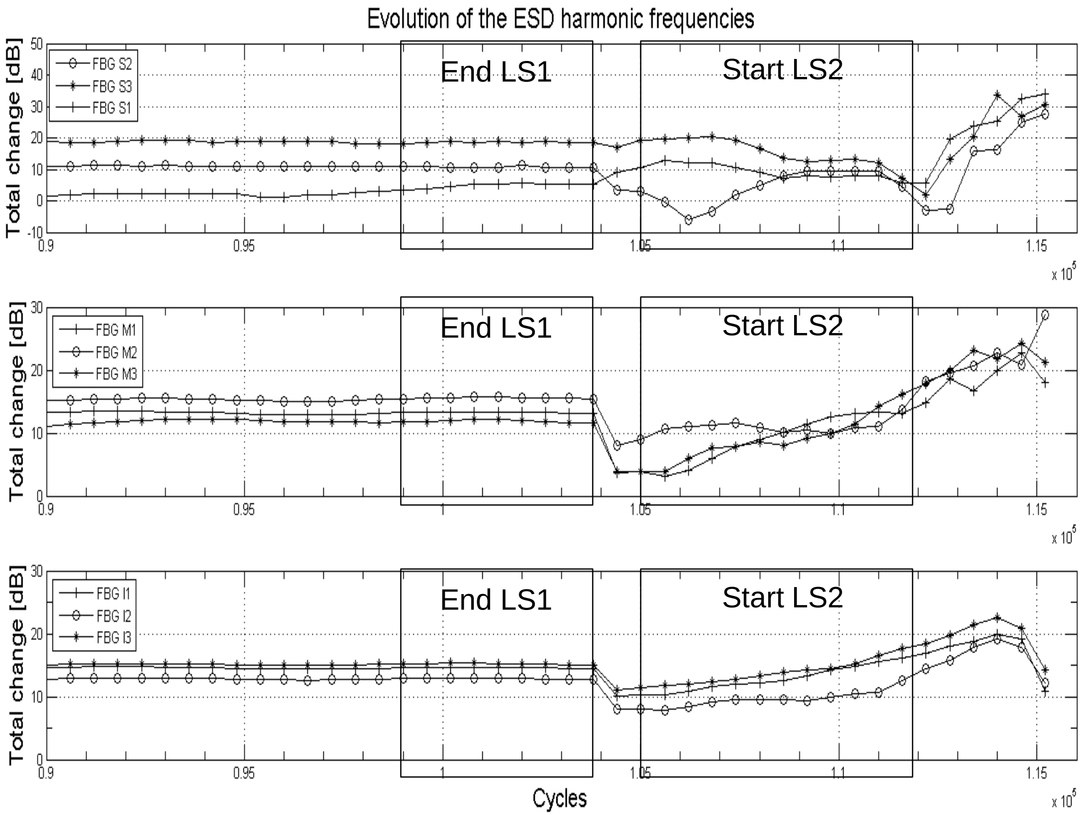

Damage indicator – DI5 relative evolution		
	End of LS1	Start of LS2
FBG S1	0.55	-0.48
FBG S2	-0.03	-1.97
FBG S3	0.03	-0.90
FBG M1	-0.01	**2.75**
FBG M2	0.00	**1.03**
FBG M3	-0.02	**3.60**
FBG I1	-0.01	**0.63**
FBG I2	-0.01	**0.79**
FBG I3	-0.01	**0.59**

→ Detection of damage in the Mid-Inf section of the grout before break (interface failure)

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Conclusion

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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

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THANK YOU FOR YOUR ATTENTION

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