WP2-INSPECTION & MONITORING

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WP2-INSPECTION AND MONITORING

Aim: Developing a structural health management methodology for in-situ monitoring of adhesively bonded hybrid joints

Work package leader: Technische Universiteit Delft

Involved partners:

- Cambridge University
- Universiteit Gent
- Com&Sens
- Parkwind
- Lloyd's Register EMEA
- Bureau Veritas Marine & Offshore SAS
- BAE Systems Naval Ships
- DAMEN SCHELDE NAVAL SHIPBUILDING

Work package budget: ~ 842 k €

A SUMMARY OF TECHNICAL WORKS @ WP2

SHM Levels

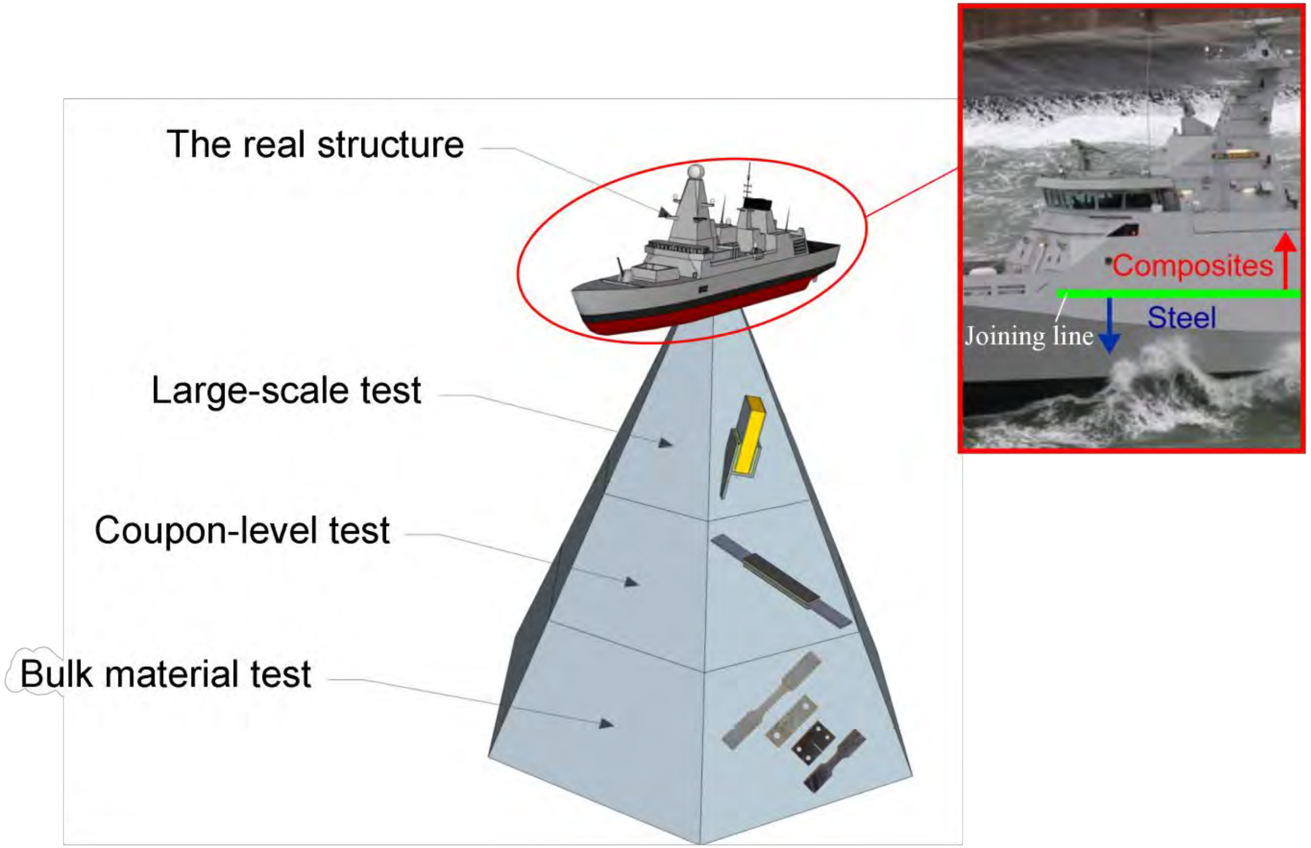
Level IV
Detect presence, type, severity and location of damage

Level III
Detect presence, severity and type of damage

Level II
Detect presence and severity of damage

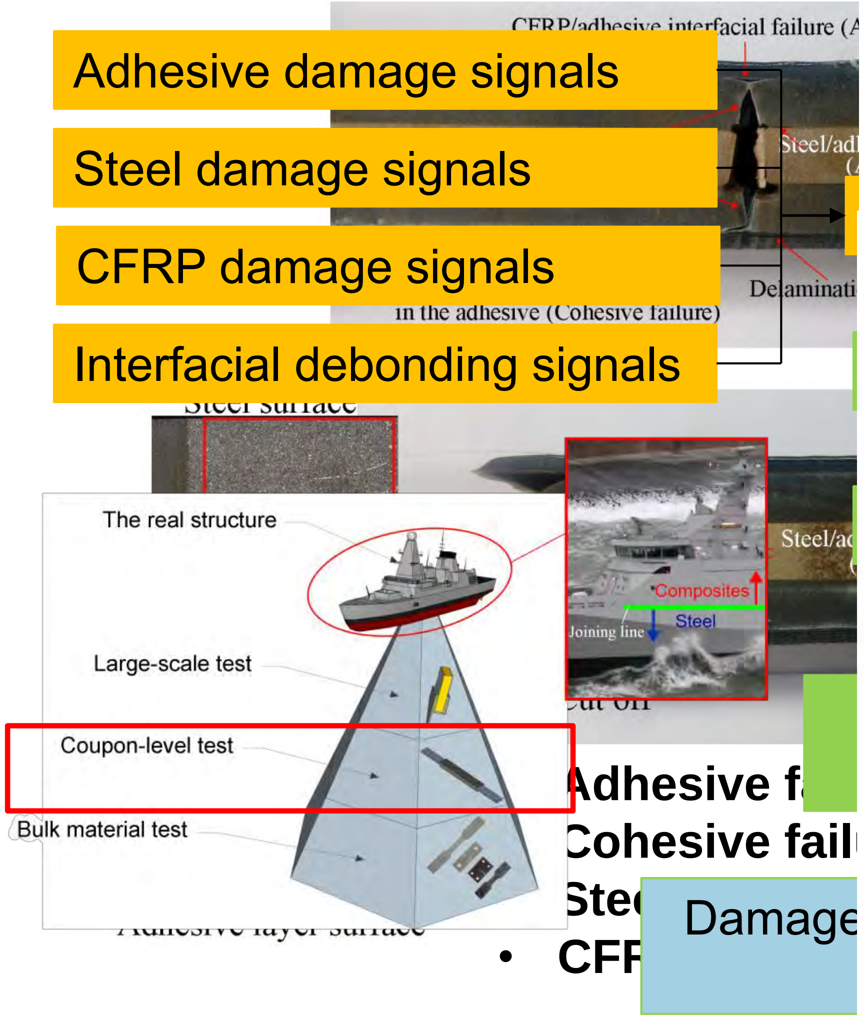
Level I
Detect presence of damage

TEST PYRAMID



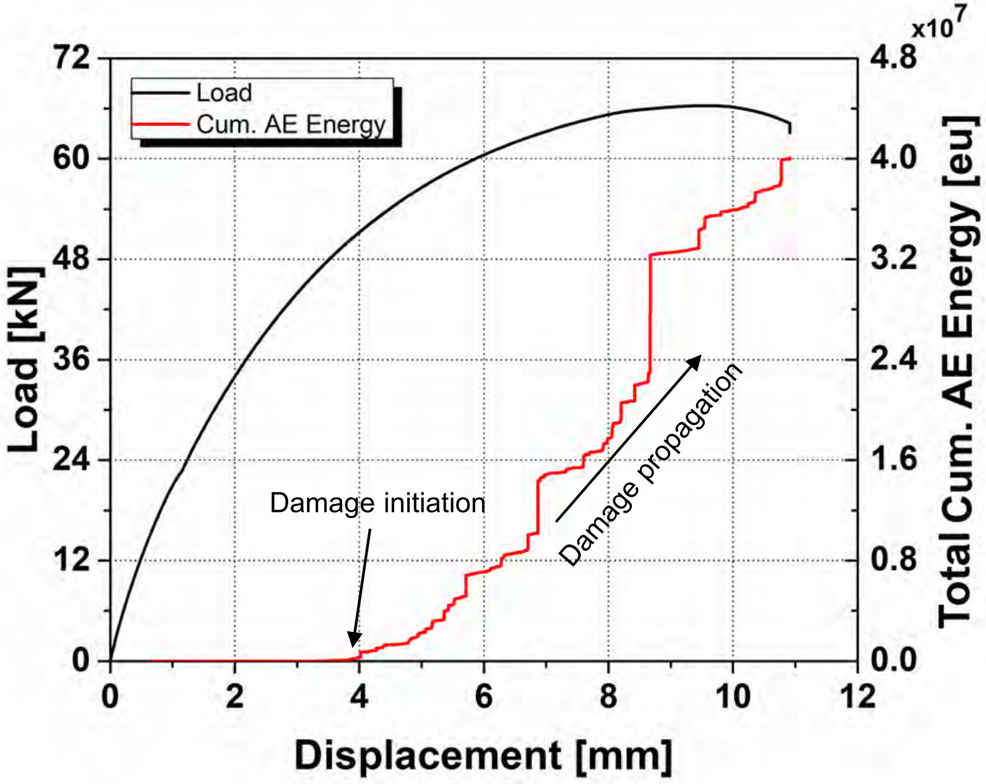
BULK MATERIAL & COUPON-LEVEL TESTS

- Adhesive damage signals
- Steel damage signals
- CFRP damage signals
- Interfacial debonding signals



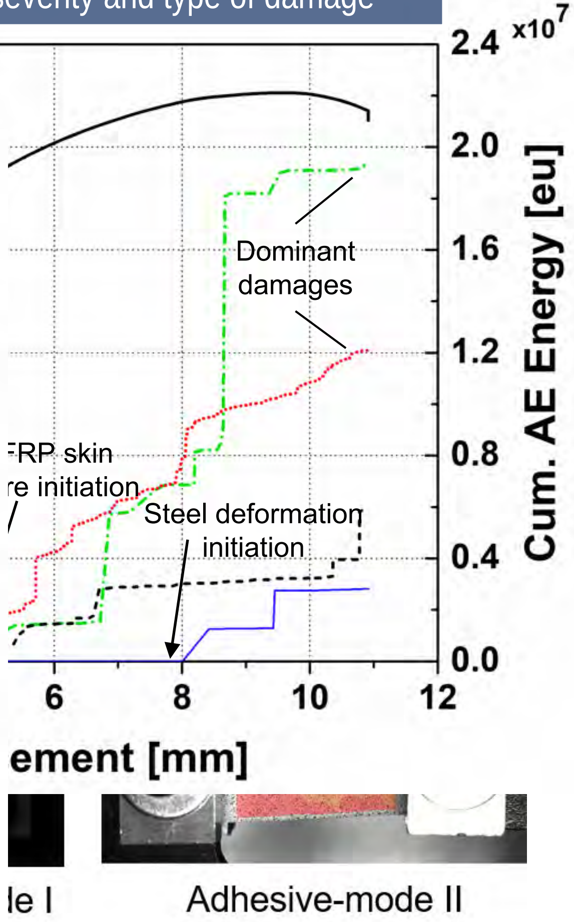
Level II

Detect presence and severity of damage

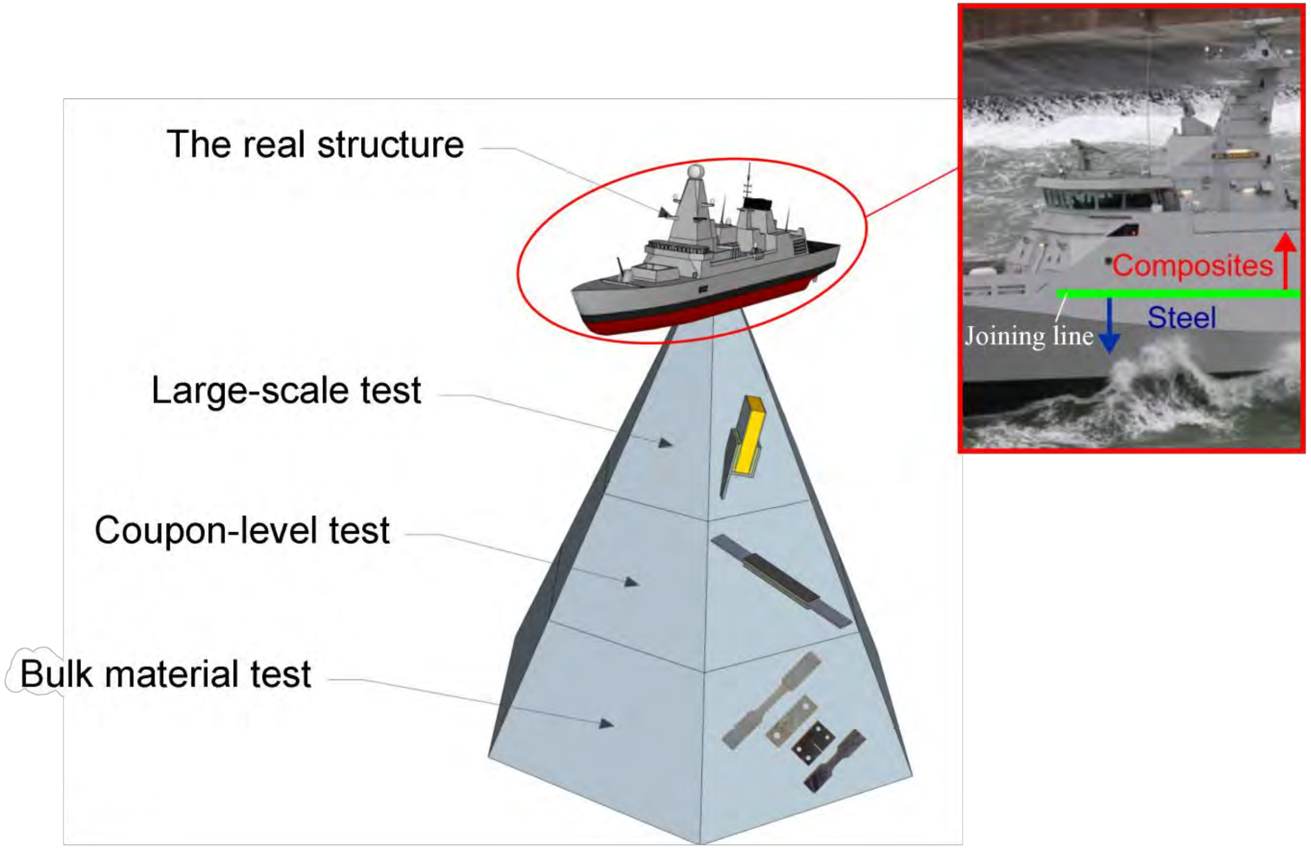


Level III

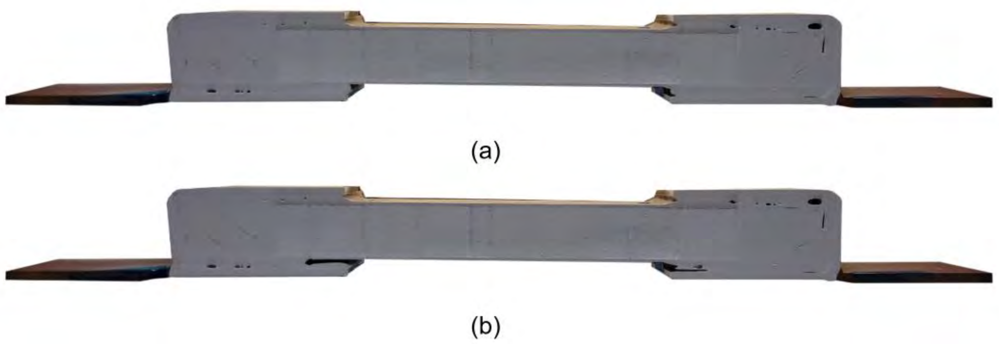
Detect presence, severity and type of damage



NEXT STEP

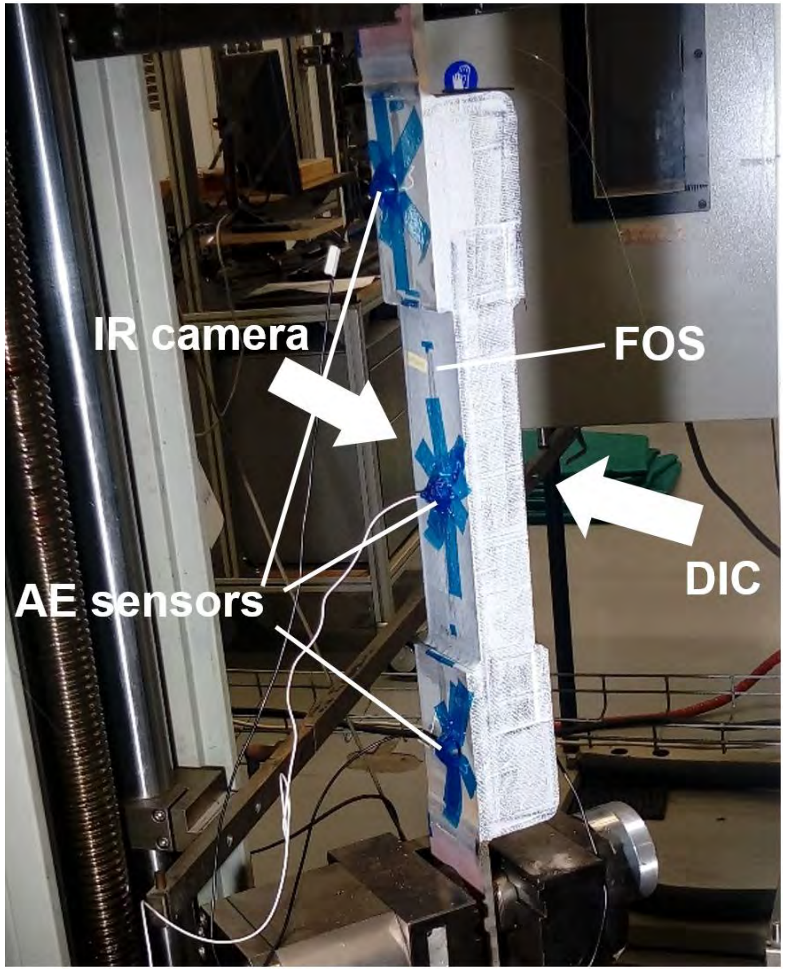

The real structure
Large-scale test
Coupon-level test
Bulk material test
Composites
Steel
Joining line

FULL-SCALE TEST CONFIGURATIONS

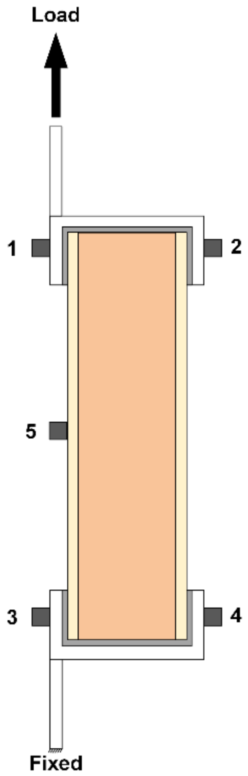


a) Non-cracked and b) Cracked joints

Fiber Optic Sensor (FOS) path



Test setup



AE sensors position

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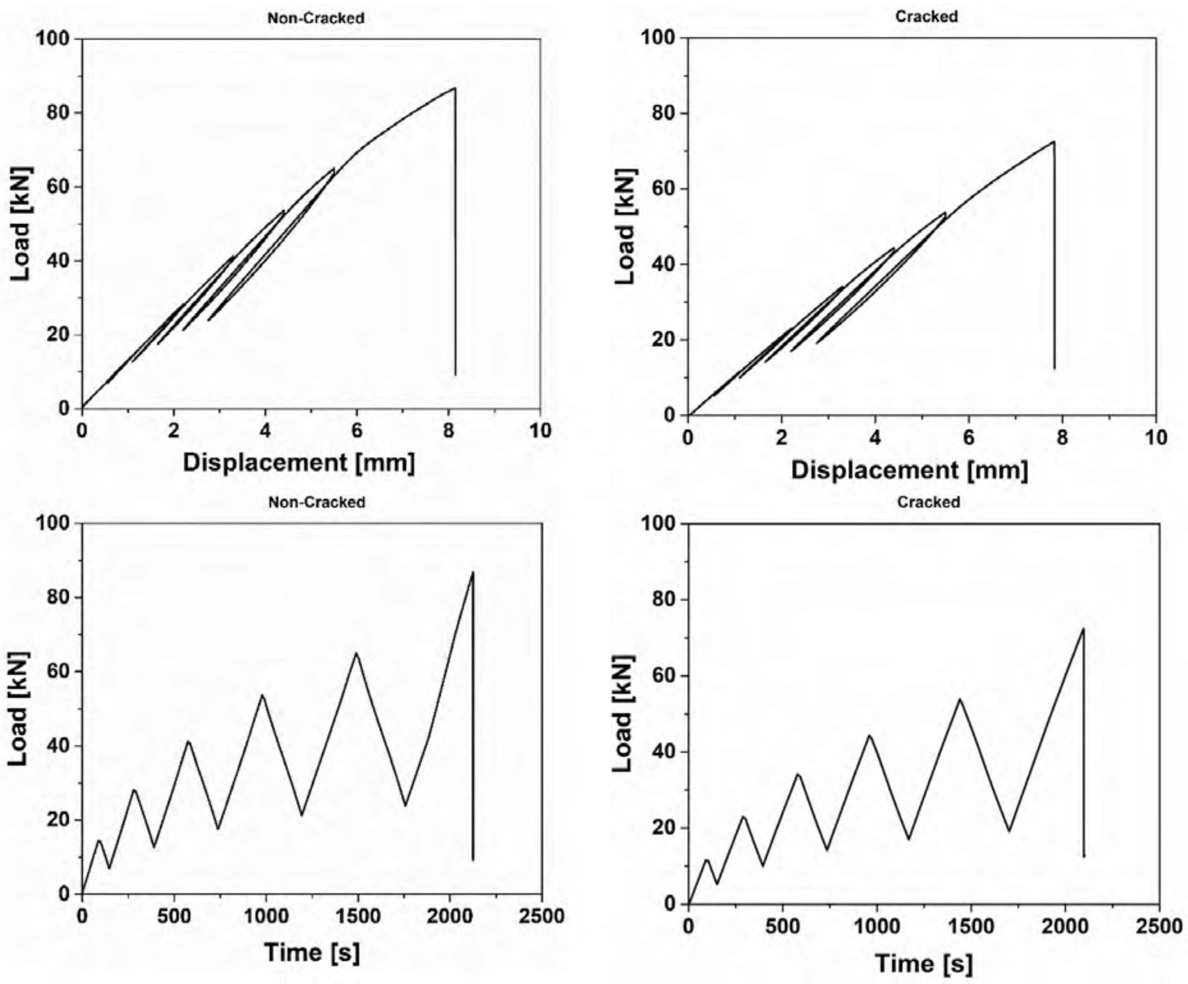
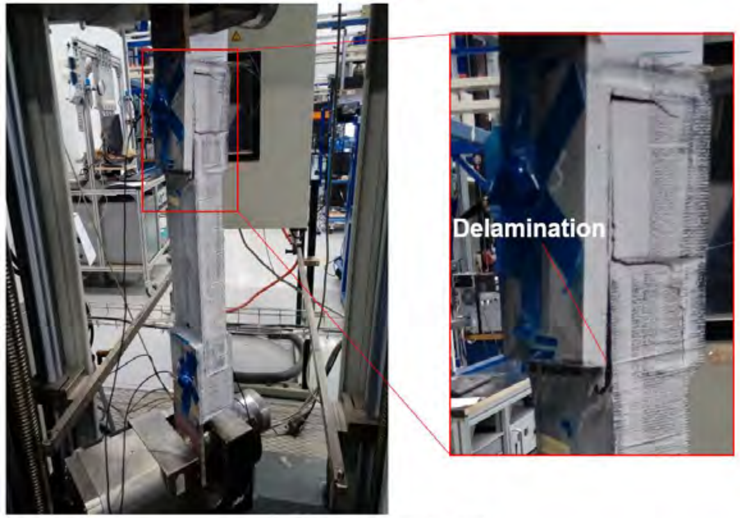
LOAD-DISP. AND LOAD-TIME CURVES

Loading conditions:

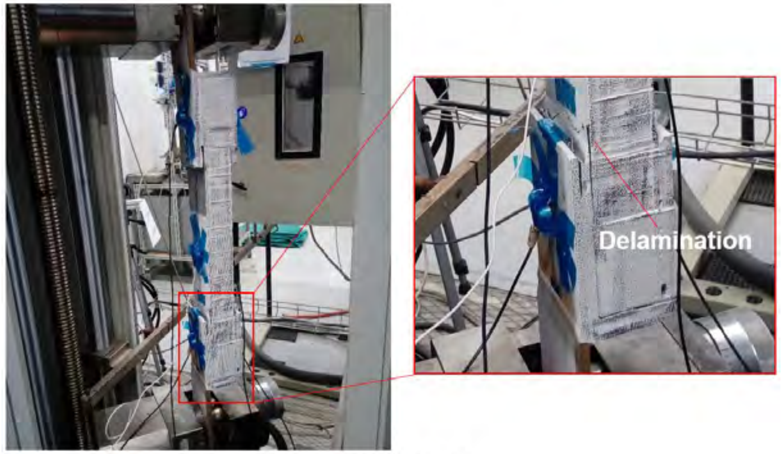
- Displacement-control mode
- Crosshead rate of 0.75 mm/min
- Five load cycles+ one to the final failure
- At the end of each loading cycle, the joint was held for 30 s at the same displacement level and then it was followed by an unloading to 50% of the maximum displacement of the previous cycle



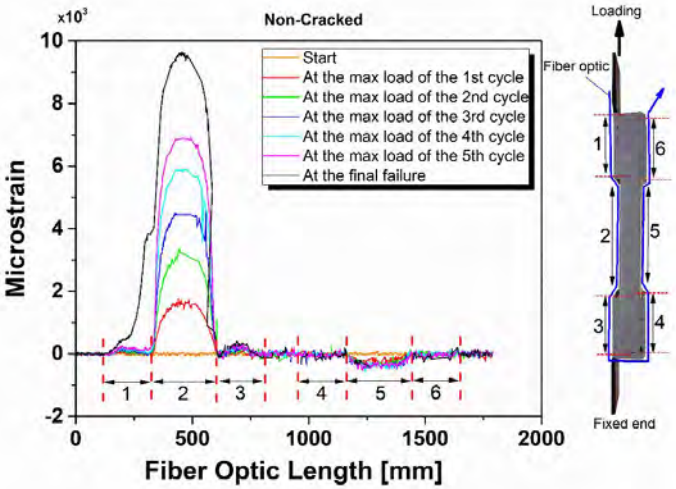
DAMAGE MODES + AE AND FOS RESULTS

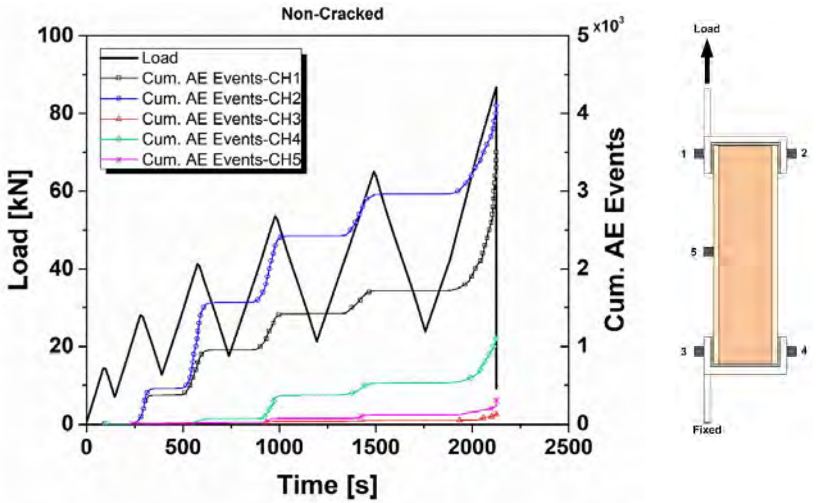


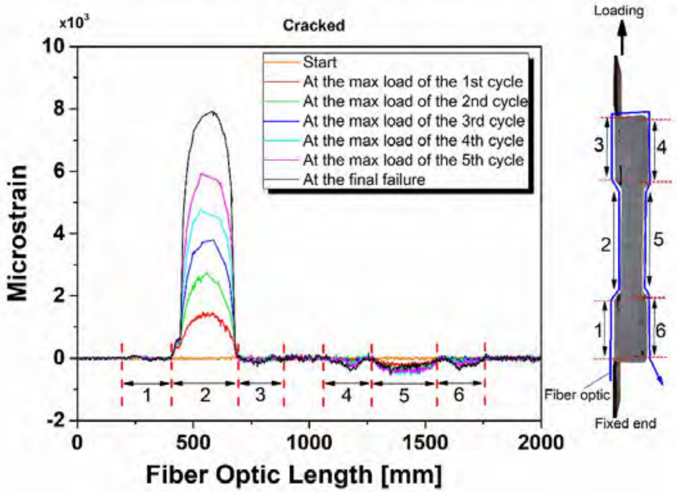
Non-cracked specimen

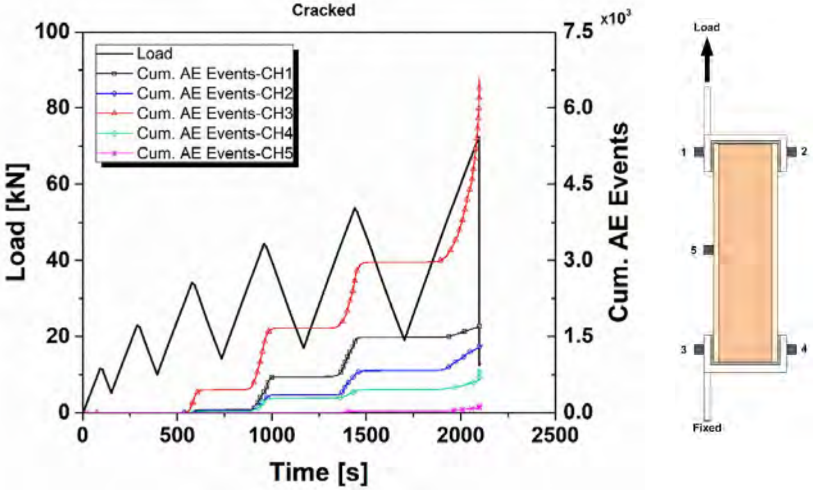


Cracked specimen

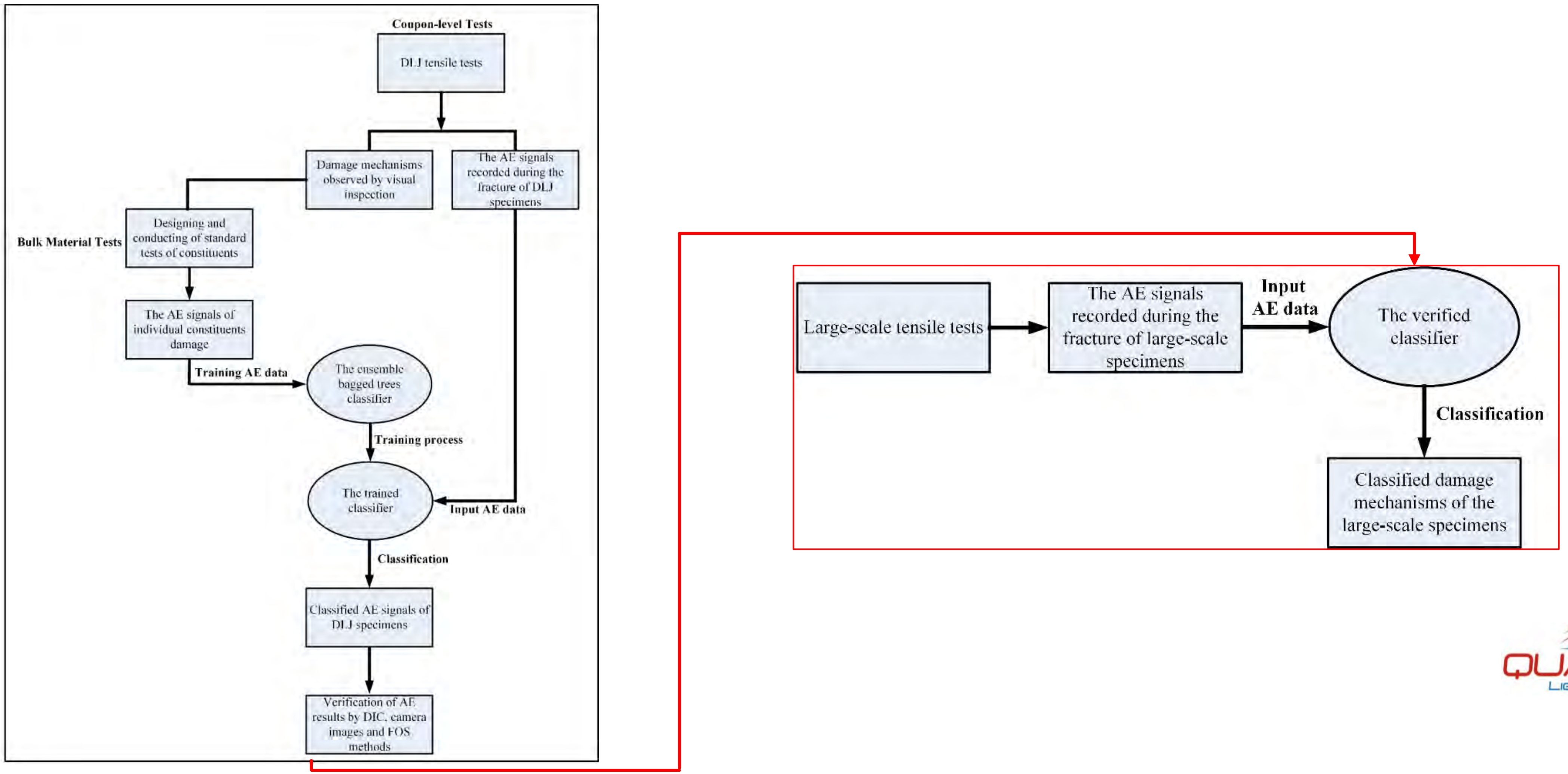




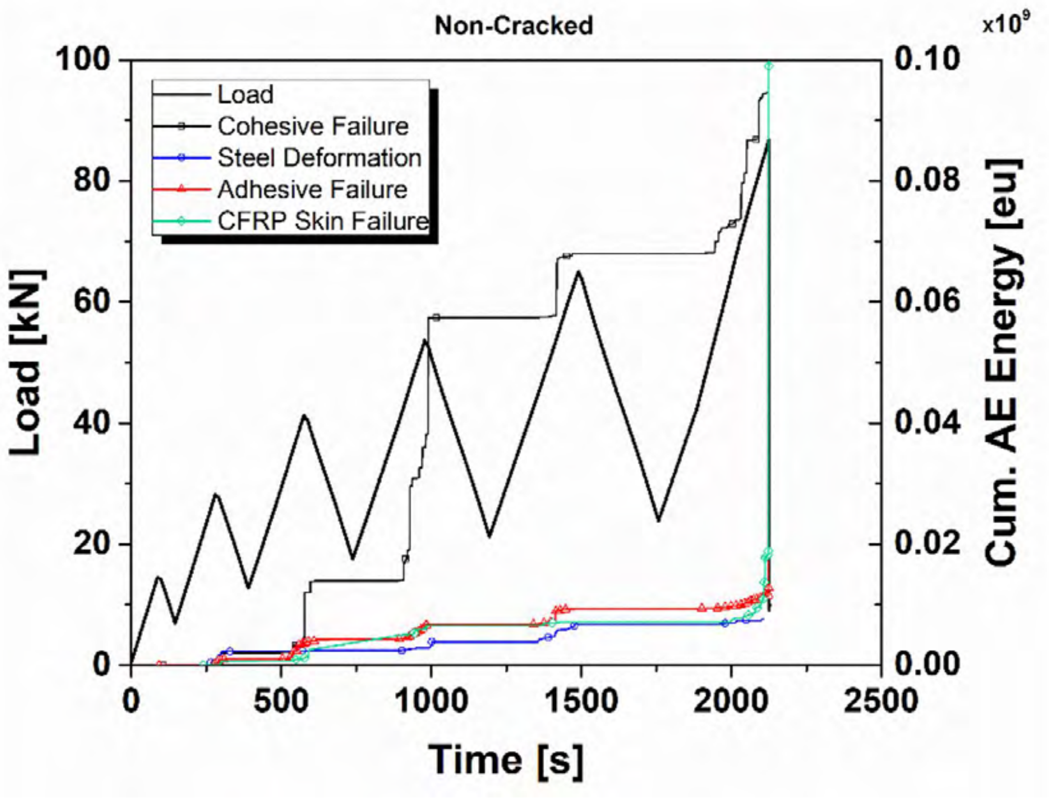


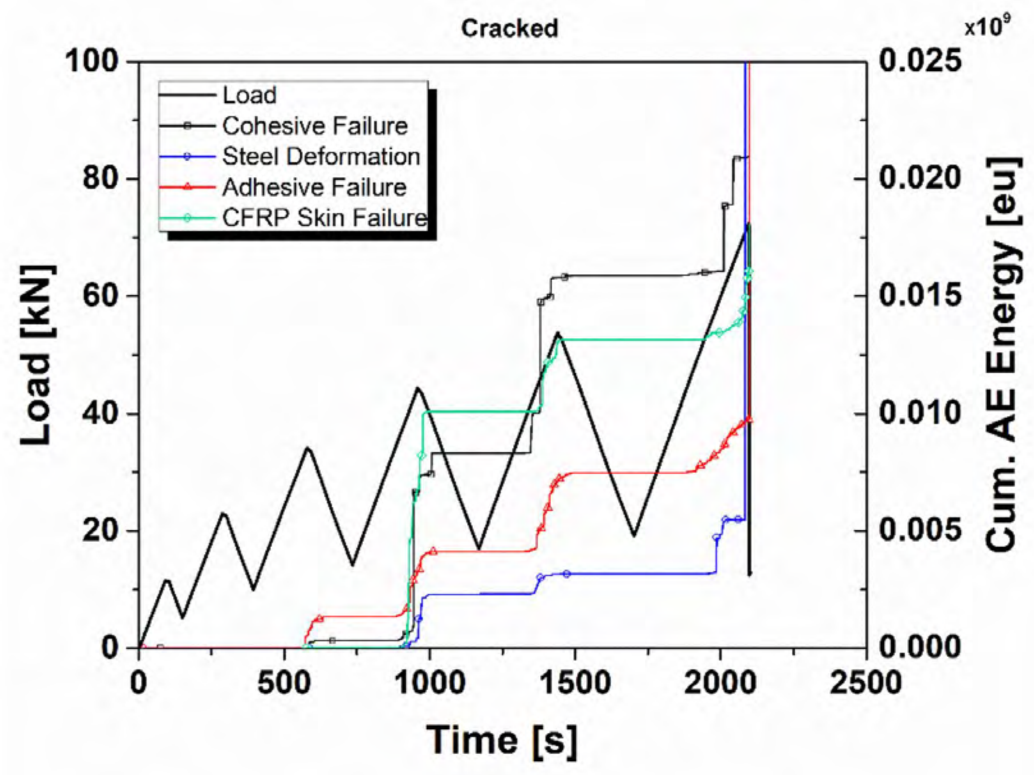


DAMAGE CLASSIFICATION USING THE SUPERVISED TRAINED MODEL



DAMAGE CLASSIFICATION USING THE SUPERVISED TRAINED MODEL





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PROTOCOL-OUTLINES

- **Introduction**
- **The Final Candidate SHM Techniques**
- **Capabilities And Disabilities Of The Proposed SHM System**
- **The Specifications Of The Sensors And Equipment**
- **The Sensors Installation Guideline**
- **Data Measuring Procedure**
- **Analyzing Methods And Algorithms**
- **The Maintenance Program Of The SHM System**
- **Conclusion**

• THE FINAL CANDIDATE SHM TECHNIQUES

Based on the laboratory tests of QUALIFY, from the 7 utilized SHM techniques, AE and FBG were finally selected for the monitoring of the real structure because of the following reasons:

AE

- The capability of in-situ continuous monitoring of the real joint.
- High sensitivity to early-stage damage.
- Fulfils all the four levels of SHM: damage initiation detection, damage severity assessment, damage localization, and damage type identification.

FBG

- The capability of condition monitoring of the real joint.
- High sensitivity to the crack initiation and the capability of sizing the crack.
- In-situ monitoring of the joint.

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• CAPABILITIES AND DISABILITIES OF THE PROPOSED SHM SYSTEM

AE

Capabilities

Damage initiation detection: Early-stage damage detection at a load level of ~30% of the maximum load (final failure).

Damage classification: The proposed supervised classifier can identify the type of the damage in the joint.

Damage severity assessment: Detection of the critical damage occurrence in the joint at a load level of 60% of the maximum load (final failure).

Damage localization: A linear localization along the joining line of the real structure.

Disabilities

AE cannot size the damage and the its results should be considered just as a qualitative damage indicator.

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• THE SENSORS INSTALLATION GUIDELINE

- **Determining the Maximum allowable Sensor-to-Damage source Distance (MSDD):** Based on the utilized AE threshold and the attenuation of the structure.
- **AE sensors coupling:** High-durable Epoxy-based adhesive.
- **The connection cables, preamplifiers, and multi-channel AE system:** The preamplifiers and multi-channel AE system should not be exposed to the humidity and seawater.
- **Magnet holders:** Keeping the AE sensor in position.
- **AE sensors arrangement:** A linear arrangement along the joining line with an interval equals to MSDD.

• DATA MEASURING PROCEDUREAE

Threshold adjustment: +6 dB higher than the environmental noises.

Sampling rate (Nyquist theorem): At least two times of the highest frequency of the AE signals of the damage.

Feature extraction: . These features are including but not limited to: Amplitude, Rise time, Duration time, Counts, Root Mean Square (RMS), Energy, Peak frequency, Centroid frequency, Average frequency, and Partial power

Measurement strategy: The AE measurement should be performed continuously for 24/7/365.

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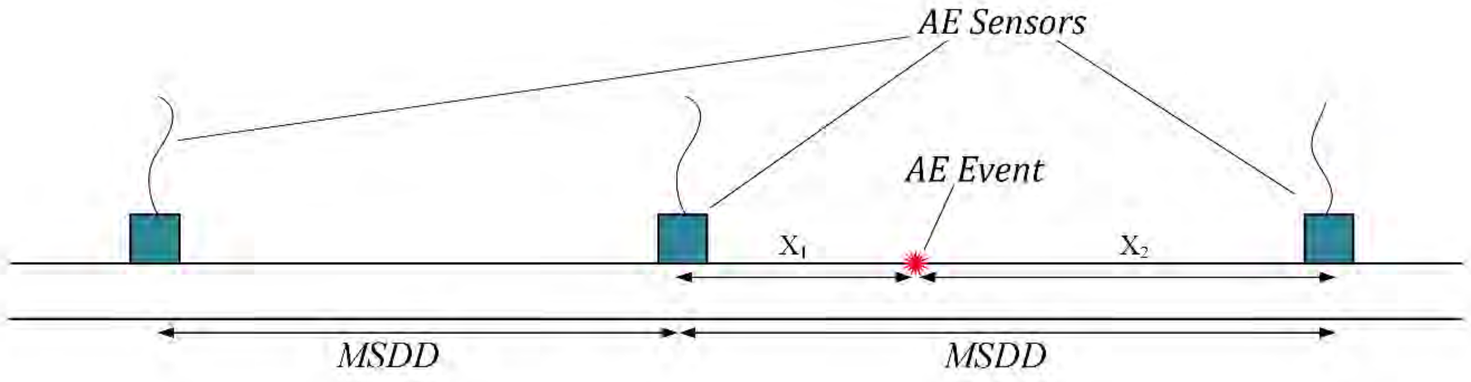
• ANALYZING METHODS AND ALGORITHMS

Damage initiation and propagation detection: The best parameters the damage initiation detection are cumulative Energy, cumulative events, and cumulative RMS curves.

Damage classification: A supervised classifier that has been trained by the constituents' AE dataset adequately.

Damage localization: A linear localization by a linear arrangement of the AE sensors along the joining line.

$$\begin{cases} x_1 + x_2 = MSDD \\ |x_2 - x_1| = C.(t_2 - t_1) \end{cases} \quad , \Delta t < \frac{MSDD}{V}$$



• THE MAINTENANCE PROGRAM OF THE SHM SYSTEM

The reliability and reproducibility of the AE system are checked by conducting the standard pencil lead breakage test (SPLBT). This procedure is performed when one of the following conditions happens:

- Once the FBG sensor indicates an abnormal strain at a point, but the AE sensors, which are close to that point, have not recorded any AE signals. In this case, SPLBT should be performed for those AE sensors.
- Once one AE sensor is recording AE events but the adjacent AE sensors of that sensor do not record anything. In this case, SPLBT should be performed for the adjacent AE sensors. If the adjacent sensors could record the signal of the SPLBT correctly, then the SPLBT test should be performed for the first AE sensor.
- Once several AE sensors, which are close to each other, are recording AE hits but one of the sensors in between does not record any signals. In this case, SPLBT should be performed for that AE sensor.
- Besides the three aforementioned conditions, a periodic (schedule-based) SPLBT can be also performed for all the AE sensors. The time intervals of this periodic inspection can be merged with the inspection program of the FBGs.

• THE MAINTENANCE PROGRAM OF THE SHM SYSTEM

After conducting the SPLBT, if the results are not consistent with the SPLBT standard, the debugging procedure should be followed as follows:

1. First, the magnetic holder is checked to make sure that it has held the AE sensor in place properly. If the magnetic holder is working properly, go to step 2.
2. The connection of the AE sensor to the structure (adhesive) should be checked. if it is not perfect, it should be redone. If the connection was perfect, go to step 3.
3. The AE sensor must be replaced by a new one, and after attaching the new sensor to the structure, the SPLBT should be performed for the new sensor. If the new sensor works properly, then the issue has been solved, otherwise, go to step 4.
4. The cable that connects the AE sensor to the preamplifier should be checked and replaced by a new cable if it is needed. If the problem is still there, go to step 5.
5. The preamplifier should be replaced by a new one. If the problem is still there, go to step 6.
6. The cable that connects the preamplifier to the multi-channel AE system should be checked and replaced by a new cable, if it is needed. If the problem is still there, go to step 7.
7. The multi-channel AE system should be checked by the manufacturer company.

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DISSEMINATIONS

Journal Papers

[1] M Saeedifar, MN Saleh, S Teixeira De Freitas, D Zarouchas. Damage characterization of adhesively-bonded Bi-material joints using acoustic emission. ***Composites Part B*** 176 (2019) 107356.

[2] M N Saleh, M Saeedifar, D Zarouchas, S Teixeira De Freitas. Stress analysis of double-lap bi-material joints bonded with thick adhesive. ***International Journal of Adhesion & Adhesives*** 97 (2020) 102480.

[3] PR Jaiswal, RI Kumar, M Saeedifar, MN Saleh, G Luyckx, W De Waele. Deformation and damage evolution of a full-scale adhesive joint between a steel bracket and a sandwich panel for naval application. ***Proc IMechE Part C: J Mechanical Engineering Science*** 0(0) 1–14.

[4] In-situ Structural Integrity Assessment of a Full-Scale Adhesively-Bonded Bi-Material Joint for Maritime Applications. ***In progress***

Conference Papers

[1] M Saeedifar, MN Saleh, S Teixeira De Freitas, D Zarouchas, Structural Health Monitoring of Adhesively-Bonded Hybrid Joints by Acoustic Emission, ***12th International Workshop on Structural Health Monitoring (IWSHM2019)***, Stanford, USA, 2019.

[2] MN Saleh, M Saeedifar, S Teixeira De Freitas, D Zarouchas, Stress analysis of double lap bimaterial joints bonded with thick adhesive, ***5th international conference on structural adhesive bonding (AB2019)***, Porto, Portugal, 2019.

[3] PR Jaiswal, RI Kumar, M Saeedifar, MN Saleh, J Windels, W De Waele. The QUALIFY project: Damage characterization of a full-scale steel/composite adhesive joint for naval application. ***1st International Conference On Industrial Applications Of Adhesives 2020 (IAA2020)***, Madeira–Portugal, 2020.

This research was carried out within the project "QUALIFY – Enabling Qualification of Hybrid Joints for Lightweight and Safe Maritime Transport", co-funded by the INTERREG 2SeasMers Zeeën programme http://www.interreg2seas.eu/qualify