



Deliverable 4.4

SHM data repository



Document History

Revision Nr	Description	Author	Review	Date
1.0	First outline	Agnes Broer (TUD) Dimitrios Zarouchas (TUD)		16/04/2020
1.1	TUD contribution	Agnes Broer (TUD)		21/04/2020
1.2	Addition of Lamb Wave data information	William Briand (ENSAM) Marc Rebillat (ENSAM)		21/04/2020
1.3	Addition of FBG data information	Georgios Galanopoulos (UPAT)		22/04/2020

Index

Abbreviations	4
1. Introduction	5
1.1. Project Summary	5
1.2. Purpose of this Document	5
1.3. Context	5
2. Experimental Campaign	7
2.1 Specimens.....	7
2.2 Test Set-Up	8
3 Data Acquisition	11
3.1 Lamb Wave Detection Method	11
3.2 Acoustic Emission	13
3.3 Fiber Bragg Gratings	14
3.4 Distributed Strain Sensing	15
4 Data Description	16
4.1 Lamb Wave Detection Method	16
4.2 Acoustic Emission	18
4.3 Fiber Bragg Gratings	19
4.4 Distributed Strain Sensing	20
5 Data Repository	22
6 Bibliography	25

Abbreviations

AE	Acoustic Emission
CTEC	Cedrat Technologies S.A.
DASML	Delft Aerospace Structures and Materials Laboratory
ENSAM	Ecole Nationale Supérieure D'Arts et Métiers
FBG	Fiber Bragg Grating
GU	Generation unit
LWDS	Lamb Waves Detection System
NI	National Instruments
SHM	Structural Health Monitoring
TUD	Delft University of Technology
UPAT	University of Patras

1. Introduction

1.1. Project Summary

ReMAP “Real-time Condition-based Maintenance for adaptive Aircraft Maintenance Planning” (hereinafter also referred as “ReMAP” or “the project”), is a European project started on the 1st of June 2018 and has a duration of four years. The project addresses the specific challenge to take a step forward into the adoption of Condition-Based Maintenance in the aviation sector. In order to achieve this, a data-driven approach will be implemented, based on hybrid machine learning & physics-based algorithms for systems, and data-driven probabilistic algorithms for systems and structures. A similar approach will be followed to develop a maintenance management optimisation solution, capable of adapting to real-time health conditions of the aircraft fleet. These algorithms will run on an open-source IT platform, for adaptive fleet maintenance management. The proposed Condition-Based Maintenance solution will be evaluated according to a safety risk assessment, ensuring its reliable implementation and promoting an informed discussion on regulatory challenges and concrete actions towards the certification of Condition-Based Maintenance.

1.2. Purpose of this Document

This document is the Deliverable D4.4 of the ReMAP Project. It addresses the structural health monitoring (SHM) data repository and serves as a main description of the performed structural tests of WP4 up until month 24. This deliverable report can be used as a basis when assessing the collected SHM data, and provides details on the conducted experimental tests, the data acquisition settings of each SHM technique, and the collected raw datasets, as well as the set-up of the SHM data repository.

It provides information about the data repository (www.surfdrive.nl and www.4tu.nl), how the data can be accessed by the partners and the public and whose responsibility is the maintenance of the repository.

1.3. Context

The main purpose of WP4 is to develop validated multi-disciplinary SHM system methodologies that range from damage detection and diagnostics to prognostics. For this purpose, test campaigns are performed in which data is collected using four SHM techniques. The test campaign has been designed in deliverable D4.1, in which a test matrix was defined that is followed in the work of deliverable D4.4. The focus of these test campaigns is on stiffened composite panels (manufactured in task T4.2) that are subjected to compression-compression fatigue loads and are either impacted or contain an artificial disbond. The health of the panels is monitored using four SHM methods, namely 1) lamb wave detection method, 2) acoustic emission (AE), 3) Fiber Bragg Gratings (FBGs), and 4) Rayleigh-scattering based distributed strain sensing. The data collected from these tests results in the construction of an SHM data repository, which is used for the development and validation of diagnostic and prognostic methodologies in task T4.5 and T4.6.

It needs to be noted that in this work, only the first experimental campaign as performed in the Delft Aerospace Structures and Materials Laboratory (DASML) at Delft University of Technology (TUD) is discussed. This is the first of multiple test campaigns that will be conducted throughout the ReMAP project. A second campaign is currently being conducted at the University of Patras (UPAT). Additional campaigns, following the test matrix (D4.1), will be run at both TUD and UPAT. After the finalization of each individual test campaign, the SHM data repository is updated to include the newly collected datafiles.

The report is structured as follows. Section 2 presents the experimental campaign, with a focus on the first test campaign as performed at TUD. Section 3 presents the manner of data acquisition for each SHM technique, followed by Section 4 in which the data files as collected by each SHM technique are described. Lastly, Section 5 describes the set-up of the data repository in which all data files are stored and provides information related to accessibility and maintenance.

2. Experimental Campaign

In this section, the experimental campaign is introduced. Note that only the first test campaign is discussed here. Several campaigns will be performed throughout the duration of the ReMAP project, all of whose contents are based on D4.1 (the test matrix). The first campaign was conducted in November and December of 2019 in the DASML at TUD.

This section starts with a presentation of the tested specimens in the first test campaign. This includes indications of the initial damage locations. This is followed by Section 2.2 in which the set-up of the conducted tests, including the load and damage conditions, is presented.

2.1 Specimens

Five specimens were tested during the first test campaign. Each panel consists of a single T-stiffener and skin, and was made from IM7/8552 carbon fiber-reinforced epoxy unidirectional prepreg. The lay-up of the skin is [45/-45/0/45/90/-45/0]S and the lay-up of the stiffener is [45/-45/0/45/-45]S. For distributed load introduction, resin tabs were added to the top and bottom of each specimen. An example of a specimen placed inside the test bench is shown in Figure 1.

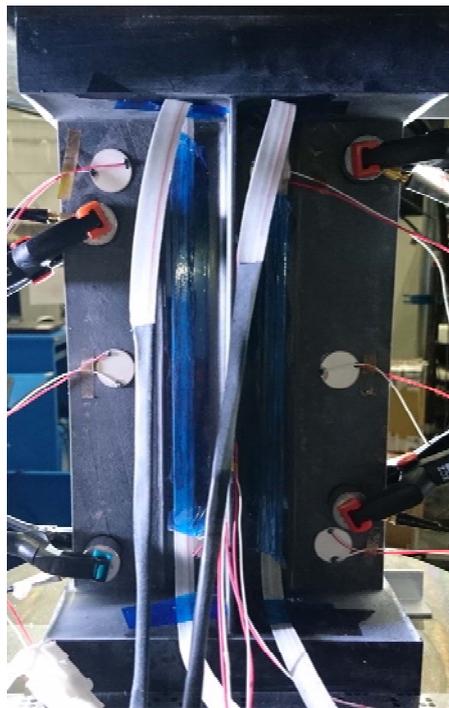


Figure 1: Sensorised test specimen placed inside test bench.

Four specimens contain an impact (L1-03, L1-04, L1-05, and L1-09) and one specimen contains an artificial disbond (L1-23). The first four specimens were impacted with a 10J impact before applying the fatigue load. For this purpose, an impact tower was used. The L1-23 specimen contains an artificial disbond of 30 mm in one of the stiffener feet, which was created during manufacturing by placing a Teflon film between the stiffener foot and skin. The dimensions of the specimens and their respective locations of impact/disbond are shown in Figure 2.

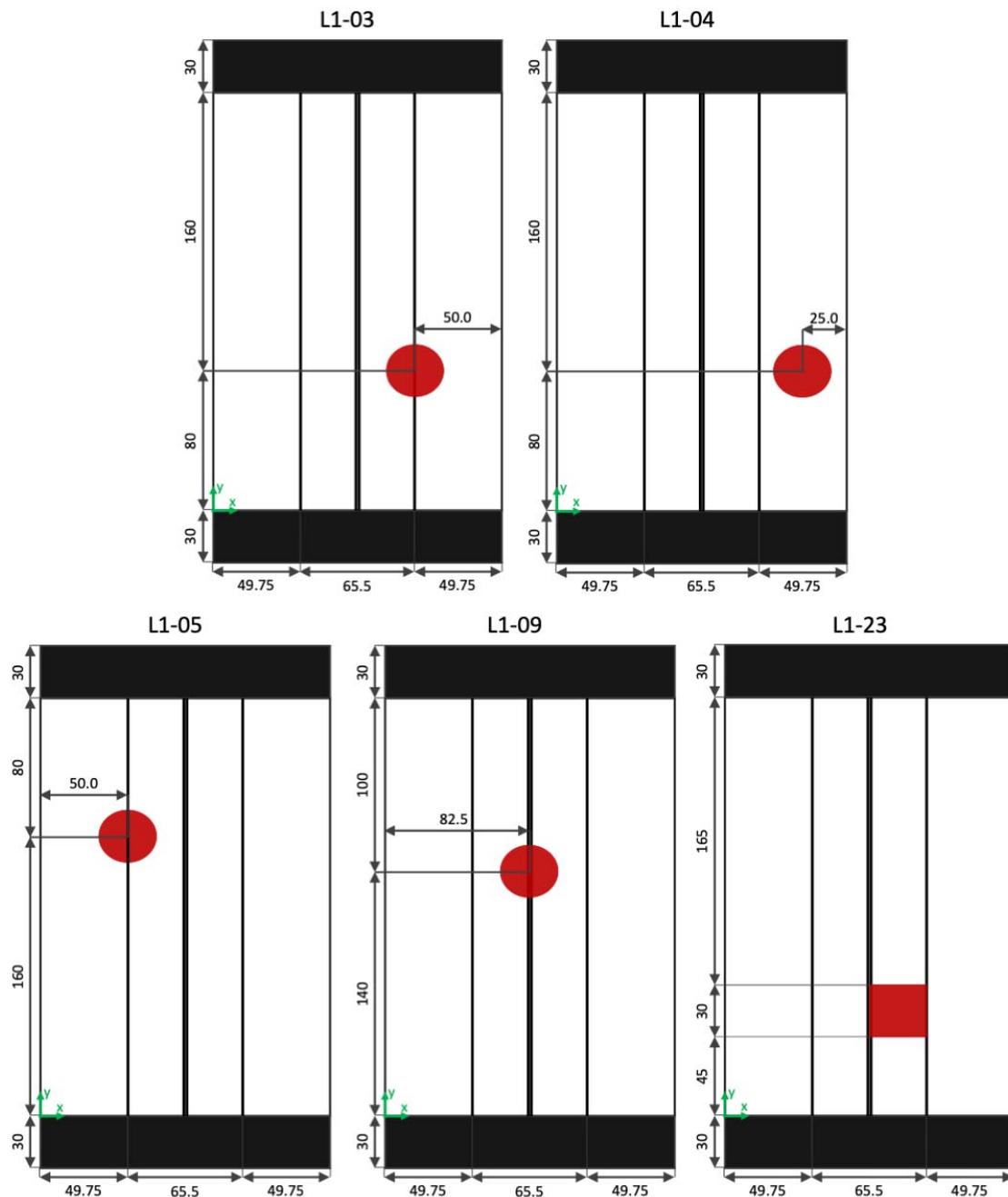


Figure 2: Specimens with indication of initial disbond/impact location in red.

2.2 Test Set-Up

The five composite single stiffener-skin panels, as presented in Section 2.1, were tested in fatigue in an MTS 500 kN test bench, located in the DASML at TUD. Four of the five specimens were impacted before testing in fatigue. For all specimens, the applied fatigue loads are in the compression-compression regime with an R-ratio of 10 and frequency of 2 Hz. A sinusoidal fatigue load was applied, and the minimum and maximum compressive load for each specimen is indicated in Table 1. The table also indicates the initial damage present in the panel and the number of cycles to failure. Note that for the L1-23 specimen, the compressive loads were increased after 100,000 cycles. The indicated load levels were kept until final failure of the panel.

Table 1: Loading conditions of each specimen

Specimens	L1-03	L1-04	L1-05	L1-09	L1-23 < 100,000 cycles	L1-23 > 100,000 cycles
Minimum load	-6.5 kN	-6.5 kN	-6.5 kN	-6.5 kN	-5.0 kN	-6.0 kN
Maximum load	-65.0 kN	-65.0 kN	-65.0 kN	-65.0 kN	-50.0 kN	-60.0 kN
Initial damage	10 J impact	10 J impact	10 J impact	10 J impact	30 mm disbond	
Number of cycles to failure	152,458	280,098	144,969	133,281	438,000	

The damage initiation and propagation in each specimen was monitored using four SHM techniques: 1) lamb wave monitoring, 2) AE, 3) FBGs, and 4) Rayleigh-scattering based distributed strain sensing. Figure 3 shows the test set-up and the SHM systems. To allow for measurements by each technique, the fatigue load cycle had to be interrupted at specified intervals. The following load cycle pattern was used, which is also depicted in Figure 4, and which has a repetition every 5000 cycles. The applied load was reduced to 0 kN every 5000 cycles to allow for lamb wave measurements.¹ Additionally, a quasi-static load was applied from the minimum to the maximum load every 500 cycles with a rate of 0.5 mm/min, with an exception for every 5000th cycle. During the quasi-static loading, the FBG system was measuring, while the distributed strain sensing system was taking strain measurements at the minimum and maximum load. The AE records continuously throughout the testing. The reader is referred to Section 3 for details on the data acquisition procedure of each SHM technique.

¹ For the L1-23 specimen, the load level was changed to -0.2 kN after 50,000 cycles.

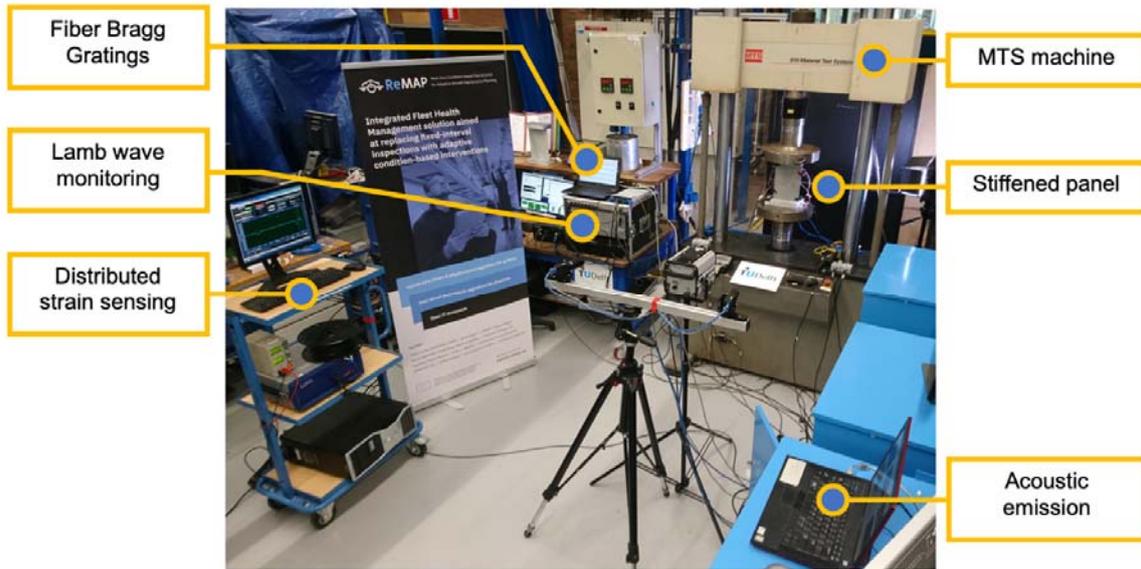


Figure 3: Test set-up at TUD.

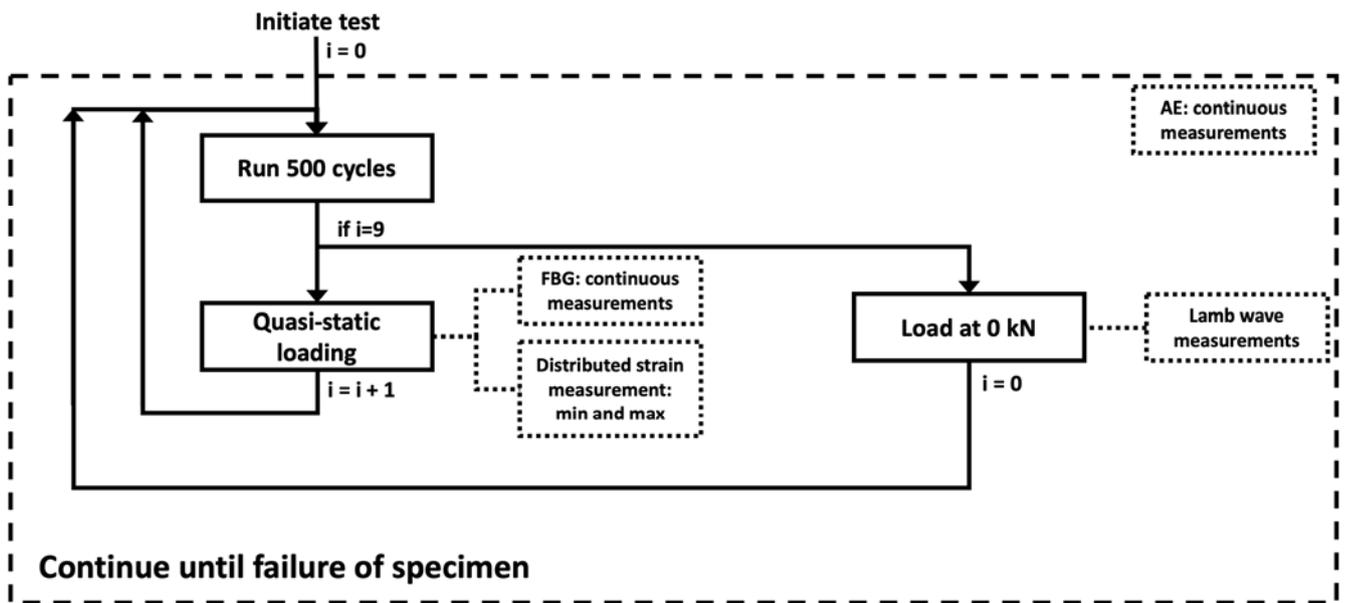


Figure 4: Loading cycle including indication of when each SHM technique takes its measurements. Note that this procedure is repeated until the specimen has lost its load-bearing capability after which the test is stopped.

3 Data Acquisition

The following subsections include a consideration of the used data acquisition systems and software, as well as any pre-set settings. The manner of data acquisition is discussed separately for each SHM technique. Their outcomes are data files containing the raw data, which will be discussed in more detail in Section 4.

3.1 Lamb Wave Detection Method

Lamb waves measurements are made every 5000 cycles using 8 piezoelectric elements. The piezoelectric elements are bonded to the surface with an epoxy glue (Loctite EA9492) following the configuration shown in Figure 5, which is similar for each specimen. The piezoelectric elements used are Noliac NCE51 with a diameter of 20mm and a thickness of 5mm.

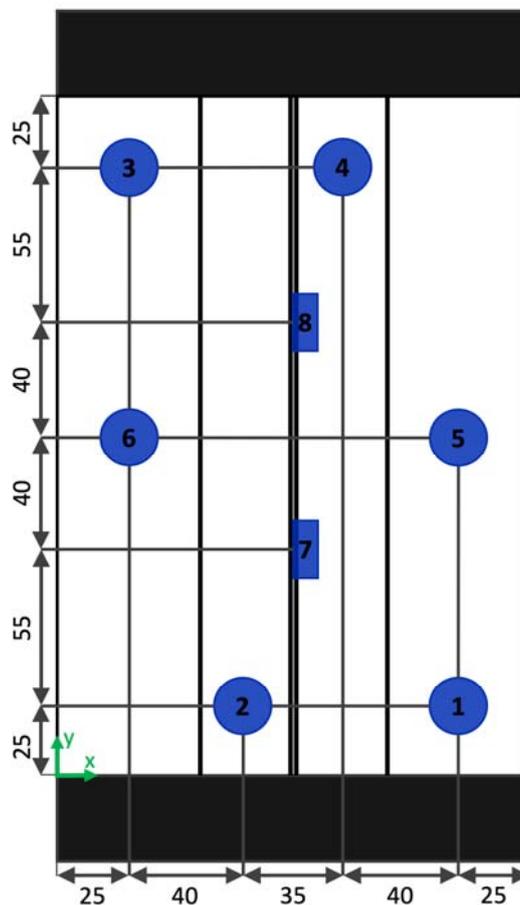


Figure 5: Piezoelectric elements location.

For acquiring the lamb wave measurements, four elements were required in the set-up:

- **Generation Unit (GU):** its role is to generate the adequate input signal for Lamb Wave excitation and to send it over one of its 12 channels to the LWDS system.
- **Lamb Waves Detection System (LWDS):** the role of this element is to amplify the input signal generated by the GU in order to adequately drive the piezoelectric elements and to trigger each channel in order to set them either in emitting or receiving mode.

- **National Instrument USB-6366 acquisition board (NI):** Its role is to act as an analog to digital converter with a sampling rate of 2 MHz and to interact with the other instruments through TTL signals.
- A script in **MATLAB 2018b** is used to perform automatically each step of the acquisition process

Figure 6 provides an overview of the overall acquisition process. Note that in the test campaign performed at TUD, the *External Device* is an MTS fatigue machine.

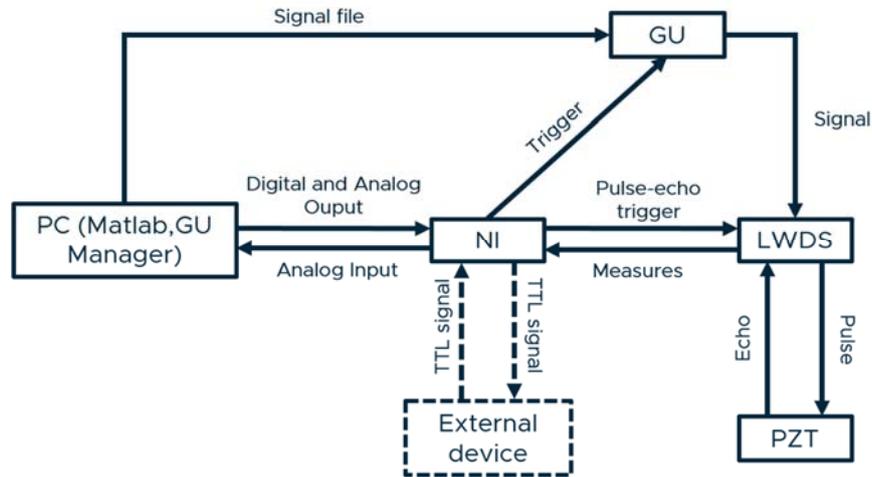


Figure 6: Overview of the acquisition process.

Emission-Reception tests are performed by emitting Lamb waves burst with one piezoelectric element and measure the received signal with the rest of the piezoelectric elements. Each transducer will act sequentially as an actuator and a sensor giving a total of 8 different configurations. The excitation signal is a

$N_c = 5$ -cycles tone burst $x(t)$ with a central frequency f_0 , an amplitude A at 20°C and defined as follows (Figure 7):

$$x(t) = A \sin(2\pi f_0 t) \sin\left(\frac{\pi f_0 t}{N_c}\right) \text{ for } 0 < t < \frac{N_c}{f_0}.$$

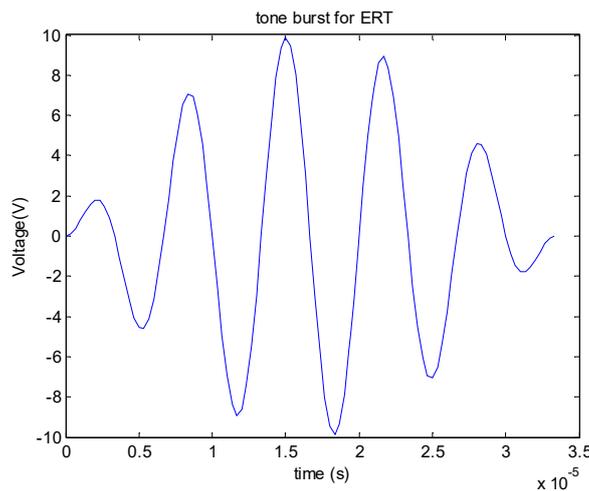


Figure 7: Excitation signal.

Measurements are performed every 5000 cycles at 0 kN load, and are repeated 10 times for each configuration. The acquisition time of one repetition is 1 ms with a sampling rate of 2 MHz. This procedure is repeated for different central frequency of the excitation signal: 50 kHz, 100 kHz, 125 kHz, 150 kHz, 200 kHz and 250 kHz. Note that if the specimen is damaged by an impact, an additional acquisition is performed before and after the impact is made.

3.2 Acoustic Emission

AE signals are recorded continuously during testing using AE sensors. Four AE sensors are clamped on each specimen and ultrasound gel is applied between the sensor and the skin in order to ensure sufficient coupling. The location of the four AE sensors is indicated in Figure 8, and is similar for all specimens. VS900-M broadband sensors from Vallen Systeme GmbH are used with an operating frequency range of 100-900 kHz. The AE signals are recorded continuously throughout the test, for which a Vallen Systeme AMSY-6 digital 8-channel acquisition system is used combined with the Vallen AE-Suite software. Additionally, external preamplifiers with a gain of 34 dB are used for each sensor to amplify the recorded AE amplitudes. An amplitude threshold of 60 dB is set for the impacted specimens, and 50 dB for the disbanded specimen.

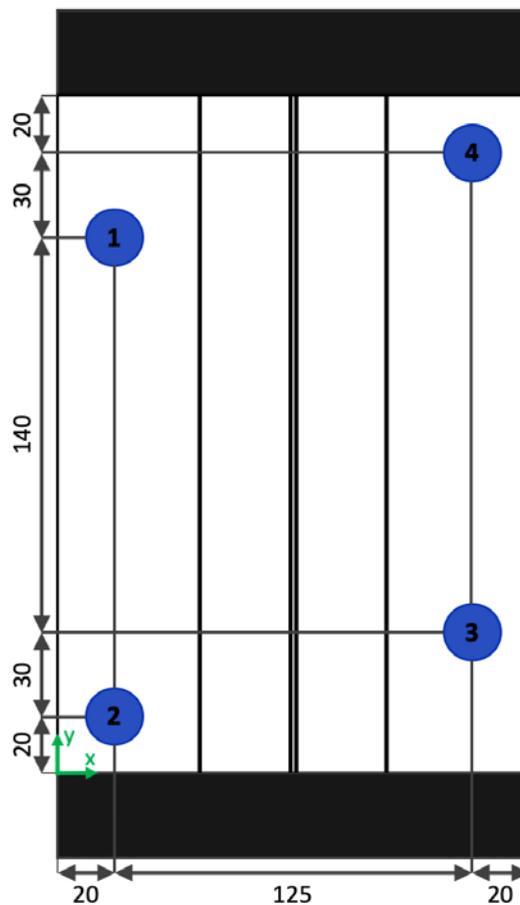


Figure 8: AE sensor locations.

3.3 Fiber Bragg Gratings

Fiber Bragg Gratings sensors are used to measure strain at specified locations at the surface of the stiffener feet. The FBGs are embedded in the SMARTape alongside the distributed sensing optical fiber (Section 3.4), which is bonded to the surface of the stiffener’s feet using an epoxy-based glue. There is a total of 10 FBG sensors, 5 located on each stiffener foot and spread across a 140 mm length. The theoretical distance between consecutive sensors is 30 mm, center to center, and the sensor length is 10 mm (Figure 9). In reality, however, the actual position of the FBG sensors may vary in a margin of ±10 mm.

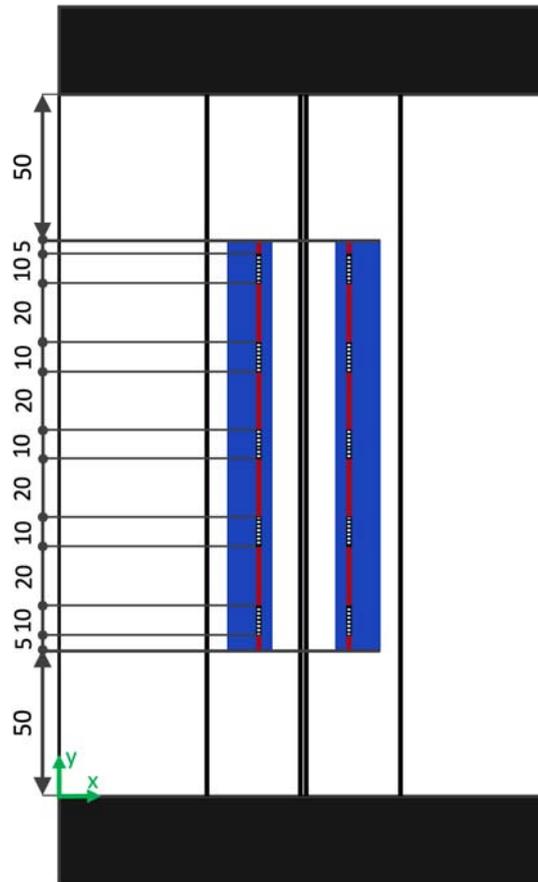


Figure 9: FBG sensor locations.

A Micron Optics interrogator was used for recording the measurements, in combination with the corresponding software ENLIGHT. To allow for triggered acquisition, a LabVIEW VI as created by Micron Optics was employed. The acquisition frequency is set at 10 Hz and the gain level is set at 8.0 dB. The noise threshold is at the default value of 200. Before each experiment, the sensor values needed to be adjusted, so that at 0 kN load the measured strain is close to 0. The equation to convert wavelength to strain is presented below:

$$\epsilon = \frac{FBG - FBG_0}{FBG_0} * f_g * 10^6,$$

where FBG is the wavelength value at each time point, FBG₀ is the value at time 0 and f_g is the gauge factor which is a manufacturing property, and in our case is 1.2 pm/microstrain. Each of the 5 FBGs along the stiffener foot corresponds to a specific wavelength to track, from 1520-1560 nm, per 10 nm intervals.

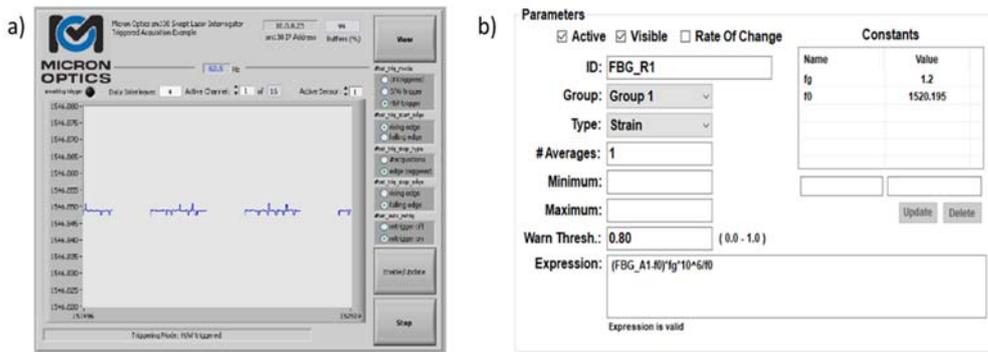


Figure 10: a) The LabVIEW VI for H/W triggering of the interrogator, b) Sensor creation tab.

3.4 Distributed Strain Sensing

In order to obtain measurements of the strain distribution along the stiffener feet, a SMARTape has been glued to the surface of each stiffener foot using an epoxy-based glue. This SMARTape contains two optical fiber sensors, of which one is employed for distributed strain sensing along the stiffener foot. The two fibres meant for distributed strain sensing were spliced to create one optical fiber. Moreover, a coreless fiber was included at the end of the fiber. The location of the SMARTape on the stiffener foot is indicated in Figure 11, and is similar for all specimens. The distributed strains are measured by connecting the fiber to a LUNA ODISI-B Optical Distributed Sensor Interrogator [1]. For recording the strains, the corresponding LUNA ODISI-B processing software was used. The acquisition rate was set at 23.8 Hz and the gauge pitch is 0.65 mm.

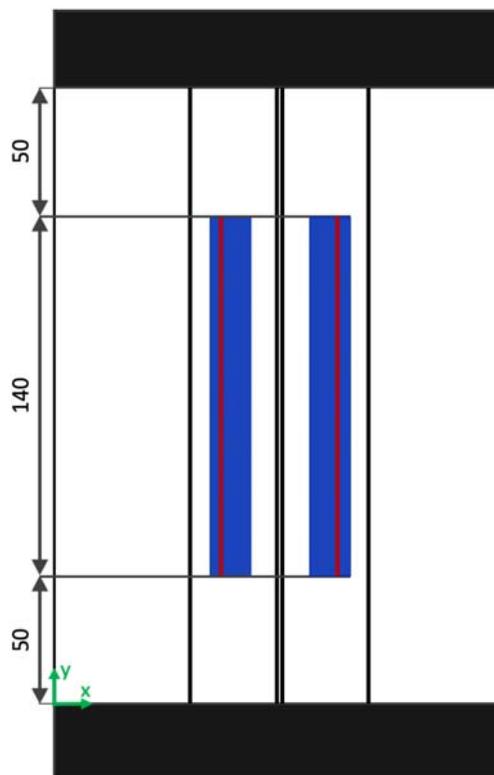


Figure 11: SMARTape location with optical fiber for distributed strain sensing.

4 Data Description

This section discusses the collected datasets as obtained from each test campaign following the data acquisition process in Section 3. Here, focus lies on the format of the output files and a description of the raw datasets as uploaded to the SHM data repository. In Table 2, a summary is shown indicating the data output file formats of each technique, as well as the number of files for each specimen tested. These files are included in the data repository, which is described in Section 5. The content of each datafile is discussed next separately for each SHM technique.

Table 2: Summary of output file formats and number of files per specimen for each SHM technique, as included in the data repository.

SHM Technique	Output file format in data repository	# of files per specimen test
4.1 Lamb Waves	.mat .m	# dependent on length of test 1
4.2 Acoustic Emission	.pridb	1
4.3 Fiber Bragg Gratings	.txt	1
4.4 Distributed Strain Sensing	.txt	1

4.1 Lamb Wave Detection Method

For every lamb wave measurement repetition, the raw data is stored in a separate MATLAB file with a .mat format ('measured_data_rep_#.mat', with # being the repetition number). Each .mat file has a size of about 60kb, giving a total of 22Mb for each damage state. Lamb wave acquisition data are stored with the following tree view for each specimen:

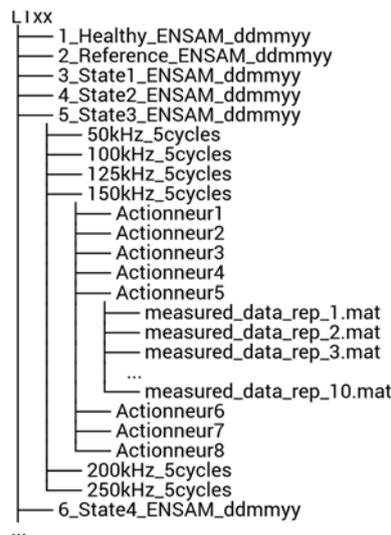


Figure 12: Tree view of the raw files for 1 tested specimen.

Where xx is the reference number of the specimen under test and ddmmyy stands for the date of the test in the format day/month/year (ex: 200420 for 20/04/2020).

Each .mat file contains 2 matrices: 1) Trigger_Info (a vector containing the commutation signal sent to the CTEC hardware) and 2) Time_Response. The columns of Time_Response when actuator “n” is used are shown in Table 3. MATLAB, Python or any other scientific computing language can be used to post-process the raw datafiles. A visualization of the data acquired is shown in Figure 13.

Table 3: Columns of the Time_Response matrix when actuator n is used.

Time [s]	Signal from actuator n [V]	Signal from sensor 1 [V]	...	Signal from sensor n-1 [V]	Signal from sensor n+1 [V]	...	Signal from sensor 8 [V]
----------	----------------------------	--------------------------	-----	----------------------------	----------------------------	-----	--------------------------

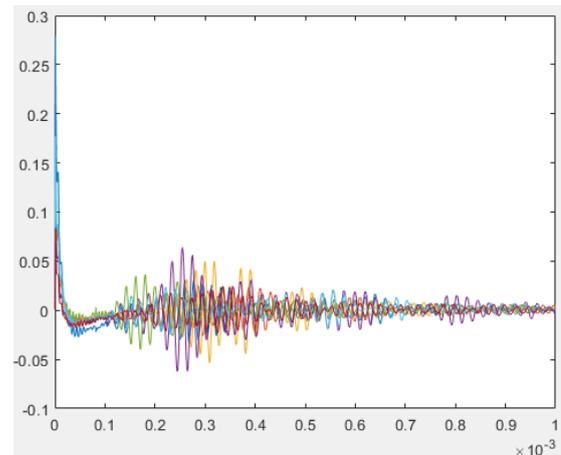
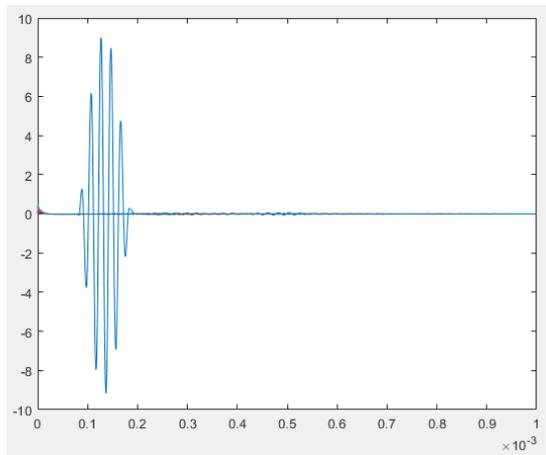


Figure 13: Example of data acquired. Left: excitation signal. Right: received signal.

Additional to the gathered measurement data, the lamb wave files for each specimen are accompanied by a descriptive ‘structure_info.m’ file in which the specimen under test is described. Note that this file is partially filled by the user and is provided as additional information for when post-processing the datafiles. It is only given for the lamb wave measurement data. The parameters describing the specimen are separated into structure parameters and signal parameters and are stated as follows:

- Structure parameters

- ⇒ **STRUCTURE.image**: defines the name of the structure image.
- ⇒ **STRUCTURE.PZT_info**: This field defines the PZT pixel positions relatively to STRUCTURE.image.
- ⇒ **STRUCTURE.PZT_info_geo**: This field defines the geometrical positions of the PZT in meters.
- ⇒ **STRUCTURE.v_max**: defines the maximum expected group velocity of the Lamb waves within the material.
- ⇒ **STRUCTURE.damage_info**: defines all the parameters of the different cases under study as follows:
 - Row #1 : Damage state description
 - Row #2 : Name of the set in the database
 - Row #3 : Damage pixel position (relatively to STRUCTURE.image)
 - Row #4 : Damage geometrical position (in m)
 - Row #5 : Damage size (in mm)
 - Row #6 : Temperature in °C (unknown = NaN)
 - Row #7 : Reference or Damaged (REF can be used to learn temperature compensation if temperature is available for this database).

- **Signals parameters**

- ⇒ **STRUCTURE.SIGNALS** defines all the parameters of the signals for which measurements are available
 - Row #1 : Signal name
 - Row #2 : Folder name
 - Row #3 : Central frequency (Hz)
 - Row #4 : Number of cycles
 - Row #5 : Sampling frequency (Hz)

4.2 Acoustic Emission

For each specimen test, a single file containing the AE hit data is obtained. The AE hit data is stored in a primary data base file (.pridb), which is a database following the SQLite3 standard. The datafiles have approximate sizes ranging in the order from 100 MB to several GBs, dependent on the length of the test and number of hits collected. The primary data base file stores AE feature data, status data, and parametric data. The external parametric data is received from the test machine; in the case of the TUD test campaign, this data is obtained from the MTS fatigue machine. An overview of what is stored for each type of data is shown in Table 4.

Table 4: Data stored in primary database file (adapted from [2]).

Data type	Parameter stored
AE feature data	Peak amplitude, duration, risetime, counts, energy
Parametric data	Load, displacement
Status data	RMS

The .pridb datafiles can be post-processed using Vallen VisualAE software, or any other software with the capability of reading SQLite3 databases, such as Matlab or Python. For post-processing of the data, several stored parameters require unit transformation; for example, the load and displacement are recorded in [mV] and have to be transformed to [kN] and [mm], respectively. An excerpt of the AE data from the L1-09 specimen is shown in Table 5, to which several unit transformations were applied.

Table 5: Excerpt of AE data from L1-09.

ID [-]	Time [s]	Channel [-]	Amplitude [dB]	RiseTime [μs]	Duration [μs]	Energy [eu]	RMS [μV]	Counts [-]	Load [kN]	Displacement [mm]
1050915	56887.53	1	65.2	7.5	77.0	6.65e3	31.4	7	-22.31	-0.40
1050916	56887.53	4	61.1	4.3	4.9	2.46e3	20.6	1	-22.31	-0.40
1050918	56887.54	3	60.4	0.2	3.5	2.14e3	50.7	1	-18.91	-0.35
1050919	56887.54	2	63.0	4.6	28.0	3.78e3	47.0	3	-18.91	-0.35
1050921	56887.56	2	65.7	11.5	87.5	1.05e4	47.3	12	-13.06	-0.27

A visualization of the AE data is shown in Figure 14, in which the cumulative AE energy has been plotted with respect to the number of cycles (bins of 5000 cycles).

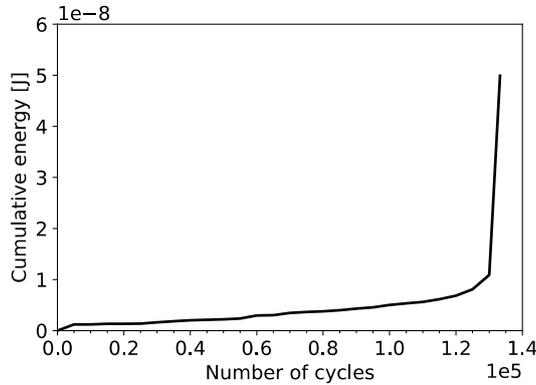


Figure 14: Cumulative AE energy with respect to number of fatigue cycles for L1-09.

4.3 Fiber Bragg Gratings

The FBG measurement data is stored in a .txt file generated by the ENLIGHT software. For each specimen test, a single .txt file is obtained. The size is dependent on the length of the experiment; a longer experiment will lead to a larger file. For example, for a test running for 150k cycles, the output .txt file is approximately 70 MB. The data contained in the output file is comprised of a matrix with 21 columns: the first corresponding to the Datetime and the remainder to the the strain and wavelength measurements of each FBG sensor. The first rows in each file contain detailed information regarding the software and the set parameters used, as well as the creation parameters for each sensor. An excerpt of the raw data file is provided in Figure 15.

```

Sensors.20191211152746 - Notepad
File Edit Format View Help
36
Culture: nl-NL
Date: 11-12-2019 15:27:46.65572
ENLIGHT Version: 1.14.0.0
Data Save Interval: 1
Timestamp Format: Full

Name:
Description:
Module type: s3x36
Max Level: No Switch
HW Acquisition Rate: 1000 Hz
WaveLength Tracking: 400 nm / acquisition
Data Interval: 100

IP Address: 10.0.0.126
Port: 1882

IDN: s3x36
Image ID: 2.0m
S/N: 151000

Ch 1 Configuration:
Distance Compensation Enabled: False
Spectral Average Count: 1
Gain (dB): 8.0 dB
Noise Thresh.: 200

Ch 2 Configuration:
Distance Compensation Enabled: False
Spectral Average Count: 1
Gain (dB): 8.0 dB
Noise Thresh.: 200

FBG_A1 (FBG): "FBG_A1-FB" Range (-6661,795, 981,999), Limits (NA, NA), Constants ( fgc1,200, fbc1320,323 ), Description: ""
FBG_A2 (FBG): "FBG_A2-FB" Range (-7423,699, 418,789), Limits (NA, NA), Constants ( fgc1,200, fbc1330,713 ), Description: ""
FBG_A3 (FBG): "FBG_A3-FB" Range (-6680,712, 120,884), Limits (NA, NA), Constants ( fgc1,200, fbc1340,740 ), Description: ""
FBG_A4 (FBG): "FBG_A4-FB" Range (-7246,899, 482,975), Limits (NA, NA), Constants ( fgc1,200, fbc1350,185 ), Description: ""
FBG_B1 (FBG): "FBG_B1-FB" Range (-6562,252, 424,163), Limits (NA, NA), Constants ( fgc1,200, fbc1360,379 ), Description: ""
B1 (NA, STRAIN): "FBG_B1-FB" Range (-4549,816, 554,106), Limits (NA, NA), Constants ( fgc1,200, fbc1320,287 ), Description: ""
B2 (NA, STRAIN): "FBG_B2-FB" Range (-4727,666, 320,904), Limits (NA, NA), Constants ( fgc1,200, fbc1330,375 ), Description: ""
B3 (NA, STRAIN): "FBG_B3-FB" Range (-7376,989, 412,883), Limits (NA, NA), Constants ( fgc1,200, fbc1340,478 ), Description: ""
B4 (NA, STRAIN): "FBG_B4-FB" Range (-7176,676, 583,483), Limits (NA, NA), Constants ( fgc1,200, fbc1350,356 ), Description: ""
B5 (NA, STRAIN): "FBG_B5-FB" Range (-4469,824, 554,905), Limits (NA, NA), Constants ( fbc1360,287, fgc1,200 ), Description: ""

FBG_A1 (FBG): Avg = 1, Alpha = 0.00, Range (1511,959, 1520,899), Distance = 0 m
FBG_A2 (FBG): Avg = 1, Alpha = 0.00, Range (1512,237, 1513,237), Distance = 0 m
FBG_A3 (FBG): Avg = 1, Alpha = 0.00, Range (1512,157, 1513,157), Distance = 0 m
FBG_A4 (FBG): Avg = 1, Alpha = 0.00, Range (1512,222, 1513,222), Distance = 0 m
FBG_B1 (FBG): Avg = 1, Alpha = 0.00, Range (1511,946, 1513,946), Distance = 0 m
FBG_B2 (FBG): Avg = 1, Alpha = 0.00, Range (1512,994, 1513,994), Distance = 0 m
FBG_B3 (FBG): Avg = 1, Alpha = 0.00, Range (1511,969, 1513,969), Distance = 0 m
FBG_B4 (FBG): Avg = 1, Alpha = 0.00, Range (1511,969, 1513,969), Distance = 0 m
FBG_B5 (FBG): Avg = 1, Alpha = 0.00, Range (1511,946, 1513,946), Distance = 0 m

Timestamp fgc1 fgc2 fgc3 fgc4 fgc5 fgc6 fgc7 fgc8 fgc9 fgc10 fgc11 fgc12 fgc13 fgc14 fgc15 fgc16 fgc17 fgc18 fgc19 fgc20 fgc21
11-12-2019 15:15:10.97971 -21,878 19,512 19,241 19,009 18,608 8,799 -7,731 -11,629 -14,346 -14,862 1120,29587 1530,6811 1549,72988 1559,06644 1568,39593 1528,27986 1538,56514 1548,49588 1558,33754 1568,24784
11-12-2019 15:15:10.97971 -21,878 -22,848 -20,999 -21,367 -19,151 -7,373 -10,567 -11,628 -14,347 -14,864 1120,29587 1530,6810 1549,72988 1559,06644 1568,39593 1528,27986 1538,56514 1548,49588 1558,33754 1568,24784
11-12-2019 15:15:10.97971 -22,994 -23,876 -21,793 -22,488 -20,438 8,798 -10,097 -11,496 -14,347 -14,864 1120,29187 1530,6817 1549,72782 1559,06484 1568,39228 1528,27984 1538,56212 1548,49324 1558,33462 1568,24466
11-12-2019 15:15:10.97971 -24,283 -23,876 -21,793 -22,437 -20,438 -10,111 -10,097 -11,477 -14,350 -14,864 1120,29224 1530,6817 1549,72782 1559,06484 1568,39228 1528,27419 1538,56212 1548,49322 1558,33339 1568,24466
11-12-2019 15:15:10.97971 -25,790 -24,487 -23,683 -22,480 -22,489 -10,111 -11,477 -14,351 -14,864 1120,29040 1530,68276 1549,72478 1559,06548 1568,39283 1528,27419 1538,56011 1548,49322 1558,33272 1568,24312
11-12-2019 15:15:10.97971 -24,418 -25,138 -24,706 -24,154 -22,600 -10,238 -12,472 -14,514 -14,864 1120,29286 1530,68082 1549,73128 1559,06588 1568,39074 1528,27486 1538,56089 1548,49134 1558,33272 1568,24312
11-12-2019 15:15:10.97971 -27,268 -25,184 -24,164 -24,913 -23,197 -11,637 -11,608 -14,484 -14,868 -11,256 1120,28846 1530,67888 1549,73173 1559,06183 1568,34684 1528,27226 1538,55971 1548,49101 1558,33142 1568,24326
11-12-2019 15:15:10.97971 -27,268 -26,614 -26,164 -24,913 -23,400 -10,214 -12,472 -14,514 -14,864 1120,28846 1530,67908 1549,73141 1559,06181 1568,34648 1528,27486 1538,55909 1548,49134 1558,33142 1568,24326
11-12-2019 15:15:10.97971 -27,990 -27,839 -26,164 -26,392 -23,893 -10,219 -12,939 -15,992 -20,194 -22,433 1120,28938 1530,67913 1549,73141 1559,06099 1568,34782 1528,27793 1538,55909 1548,49487 1558,32951 1568,23983
11-12-2019 15:15:10.97971 -28,482 -28,656 -27,176 -28,193 -25,009 -11,637 -12,472 -15,992 -20,194 -23,112 1120,28646 1530,67908 1549,72988 1559,06099 1568,34648 1528,27216 1538,55909 1548,49487 1558,32951 1568,23983
11-12-2019 15:15:10.97971 -28,183 -28,768 -27,363 -28,735 -26,349 -11,059 -12,939 -16,127 -20,441 -23,917 1120,28446 1530,67913 1549,72989 1559,06187 1568,34938 1528,27846 1538,55909 1548,49328 1558,32791 1568,23790

```

Figure 15: Raw FBG data.

For post-processing, any software capable of reading .txt files can be employed, such as MATLAB, Python, or any other scientific computing language. Data must be imported to the software and plotted in a diagram to visualize the raw sensor measurements. In Figure 16, a visualization of the data is provided after being processed with MATLAB. For each FBG, the measured strain values with respect to the number of cycles can be observed.

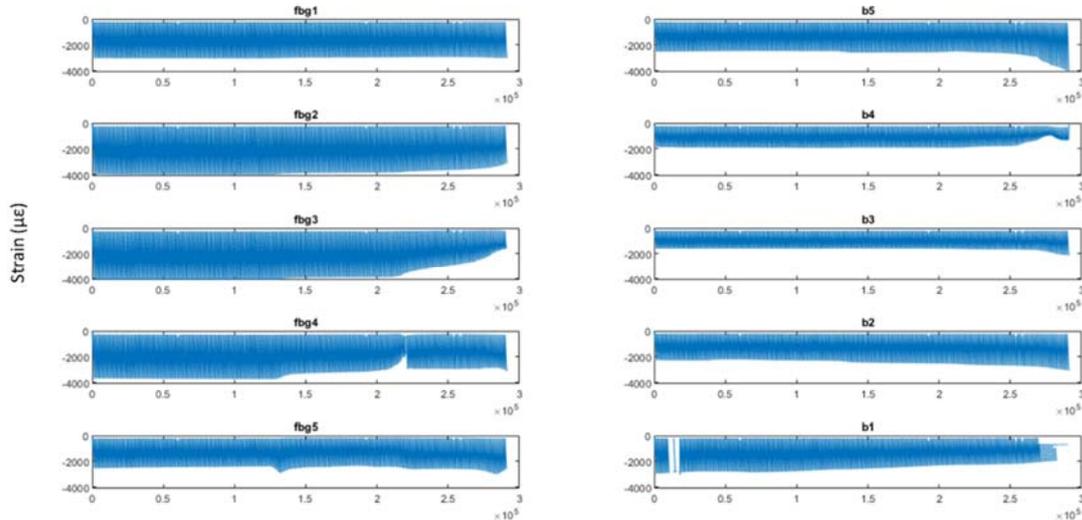


Figure 16: Visualization of FBG raw data after processing with MATLAB.

4.4 Distributed Strain Sensing

The raw distributed strain sensing data is stored in an .odb file, as generated during testing by the ODISI-B processor software. For each specimen test, a single .odb file is obtained, which has an approximate size in the order of 1 GB to 5 GB. Using ODISI-B post-processor software, the strain data can be viewed, processed, and exported to a user-friendly file-format, namely a .txt file, which is uploaded to the data repository. The .txt file contains a matrix containing rows of strain measurements and columns indicating the location along the fiber. The first row indicates the length along the fiber, while the first column indicates the timestamp. An example of the raw data matrix is shown in Table 6, where data was taken from the L1-04 test.

Table 6: Excerpt of distributed strain data from L1-04.

Length along fiber [mm] \ Timestamp	1258.61	1259.26	1259.91	1260.57	1261.22	1261.87	1262.52	1263.18
2019-12-11T15:16:17.481311	-167.47	-189.83	-184.75	-187.28	-190.44	-200.53	-204.97	-220.01
2019-12-11T15:18:13.369932	-1758.8	-1777.81	-1791.23	-1801.78	-1814.55	-1838.68	-1847.77	-1866.22
2019-12-11T15:22:25.363716	-160.47	-190.57	-207.95	-235.05	-195.1	-222.98	-222.33	-212.67
2019-12-11T15:24:21.294278	-1757.75	-1781.48	-1791.61	-1809.4	-1826.54	-1853	-1858.25	-1867.72
2019-12-11T15:28:33.330005	-178.26	-193.05	-180.37	-185.83	-196.4	-204.32	-203.71	-205.07
2019-12-11T15:30:29.302511	-1744.96	-1758.5	-1776.72	-1794.23	-1828.24	-1848.96	-1857.31	-1870.34

For post-processing of the distributed strain data files, any software capable of reading .txt files can be employed, such as MATLAB, Python, or any other scientific computing language. After processing of the strain data, the strain measurements can be visualized. Figure 17 shows such a visualization in which the strain measurements at a given time *t* during testing are shown, with on the x-axis the location along the fiber and on the y-axis the recorded strain. Note that the figure indicates two measurements: one taken after 2000 cycles and one taken after 2500 cycles.

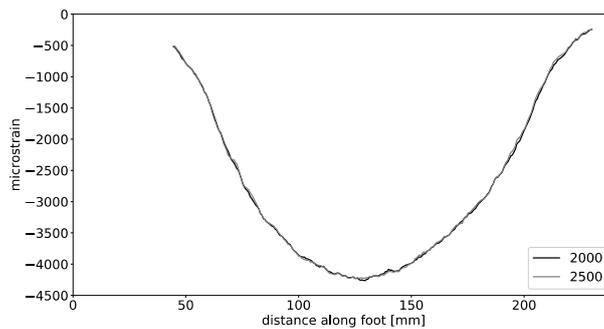


Figure 17: Strain measurements along one stiffener foot of the L1-04 specimen, taken at 2000 and 2500 cycles.

5 Data Repository

After the execution of the experiments, all the raw data, as presented in Section 4, are collected and temporarily stored in the www.surfdrive.nl archive. SURFdrive is a personal cloud service for the Dutch education and research activities where data and documents can be stored, synchronised and shared among people who have access. This cloud service allows the storage of the raw data, as well as the technical documents which describe the details of the testing conditions. The SURFdrive will be used as a short-time repository (until the end of the project). TU Delft has the responsibility to maintain the SHM data-repository during and after the completion of the project. Thus, in the future, as the size of the data to be shared increases, the raw data will be migrated to DataverseNL (<https://dataverse.nl>), an online research data storage service provided by TU Delft that keeps data up to ten years after the completion of the research project. In both repositories, the project coordinator, in consultation with the WP leader, can grant (or revoke) access to the partners of the project.

The two above mentioned platforms will be used to store the raw data from the experiments. The collective final version of data, in conjunction with related journal publications, will be uploaded to the Centre of research data www.4tu.nl for a long-term archive. The final version will have a DOI and will be available to the public (open-access database). This repositories guarantees 15 years open access to the data and promote a Findable, Accessible, Interoperable, and Re-usable policy.

In the current SURFdrive data repository, the data are stored in the folder of 'experimental campaign' within the 'WP4-Structural Health Management folder'. The experimental campaign folder contains:

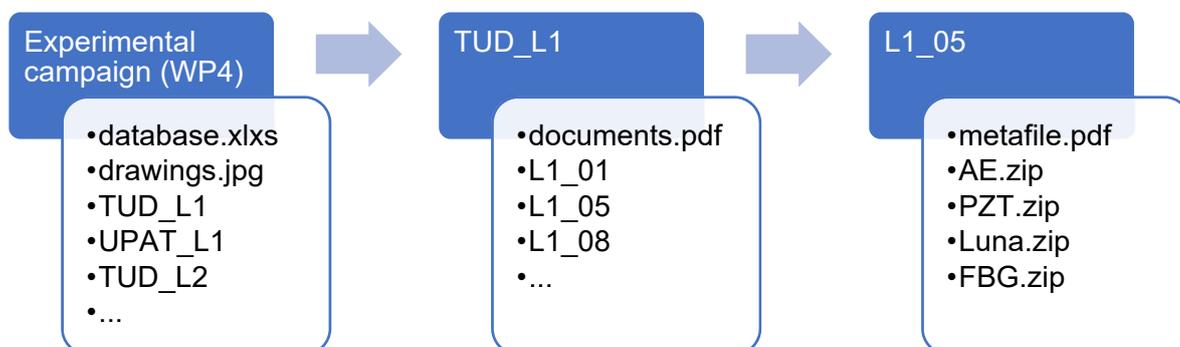
- 1) A database.xlsx file which provides an overview of the tests specimens and the relative testing conditions.
- 2) A subfolder TUD_L1 referring to the first experimental campaign which took place in TUD
- 3) A schematic of the specimens in a jpg format.

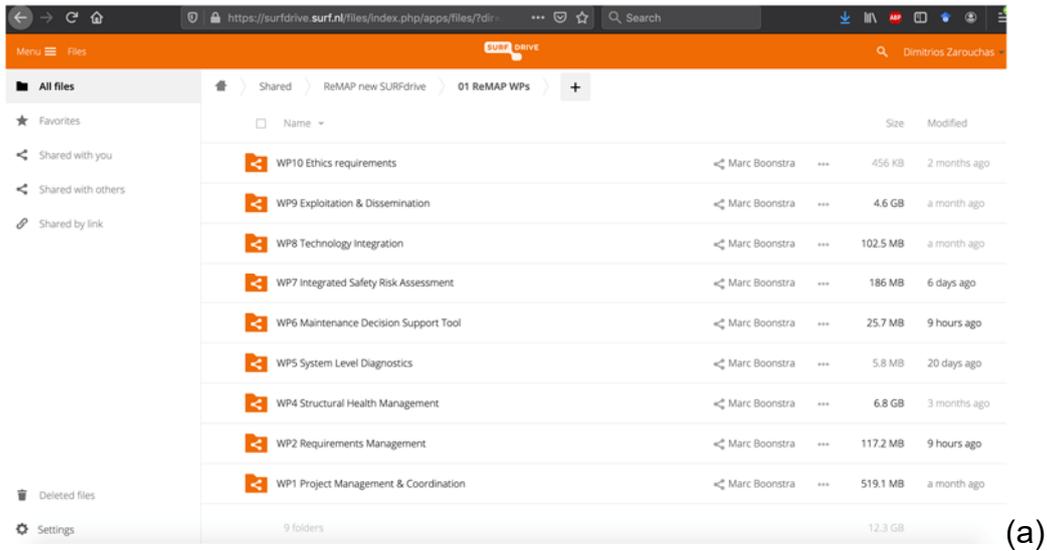
This folder will be populated with more subfolders which will refer to the upcoming experimental campaigns, i.e. UPAT_L1 and TUD_L2.

The folder 'TUD_L1' contains subfolders for each specimen separately and pdf documents which present technical details of this specific experimental campaign. Such pdf documents will be available for each experimental campaign where the data user could find relative information about the experimental conditions.

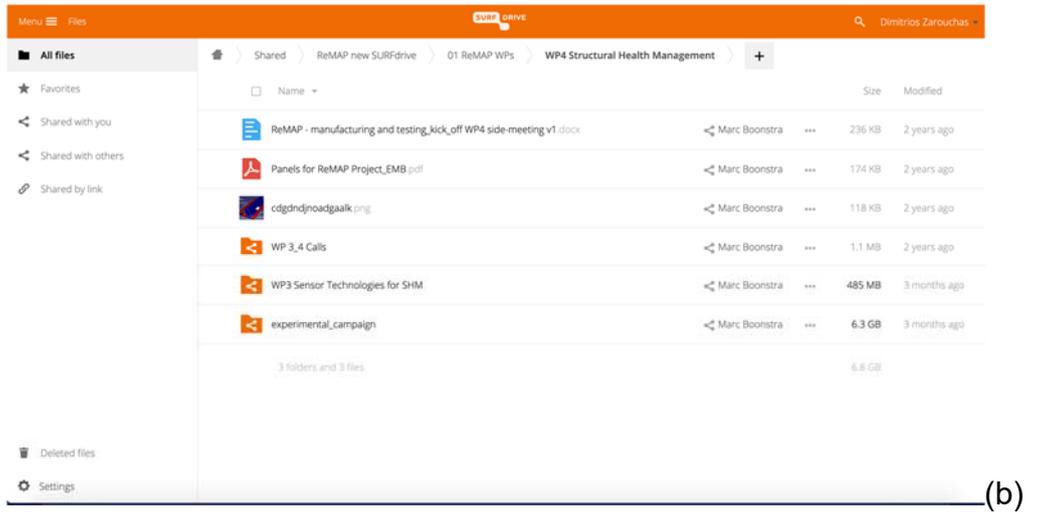
Each specimen's folder, i.e. L1_05 contains a description of this specific experiment, specimen.pdf file and the SHM data in a zip format (AE.zip, LUNA.zip, FBG.zip and PZT.zip).

The flowchart and figures below showchase the data architecture.

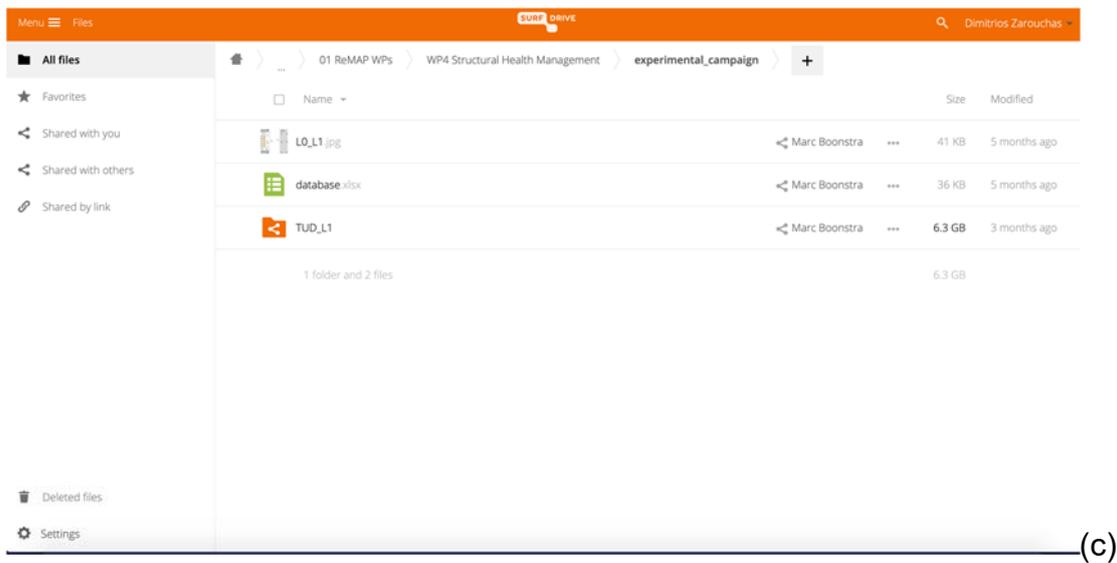




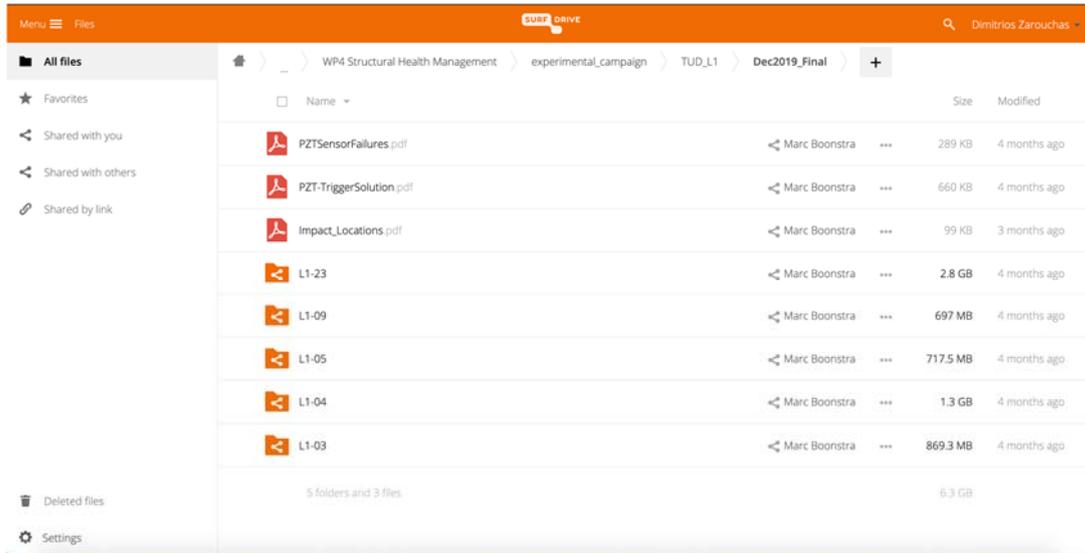
(a)



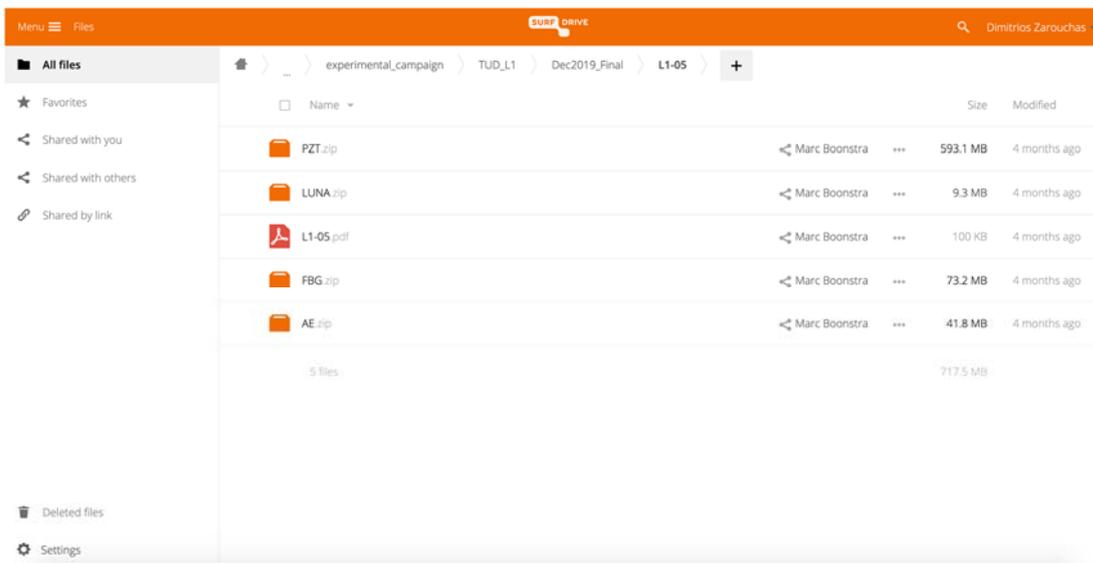
(b)



(c)



(d)



(e)

Figure 20. The allocation of the SHM data in the www.surfdrive.nl archive a) ReMAP’s workpackages -> b)WP4 Structural health management -> c) experimental campaign -> d)TUD_L1 -> e) L1-05 experiment with testing information

6 Bibliography

[1] Luna ODISI-B: Optical Distributed Sensor Interrogator Model ODISI-B: User's Guide. Luna Inc. (2017)

[2] Vallen Systeme GmbH: AMSY-6 System Description. (2019)