



Optical fibre distributed strain measurement for H₂ COPV damage assessment

Laurent Maurin, Pierre Ferdinand, Fabien Nony, Stéphane Villalonga

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FROM RESEARCH TO INDUSTRY
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OPTICAL FIBRE DISTRIBUTED STRAIN MEASUREMENTS FOR H₂ COPV DAMAGE ASSESSMENT

PHASE 2018 Convention – Tours – the 15th of May, 2018 | L. Maurin

CEA LIST | Laurent Maurin – Pierre Ferdinand

CEA DAM | Fabien Nony – Stéphane Villalonga

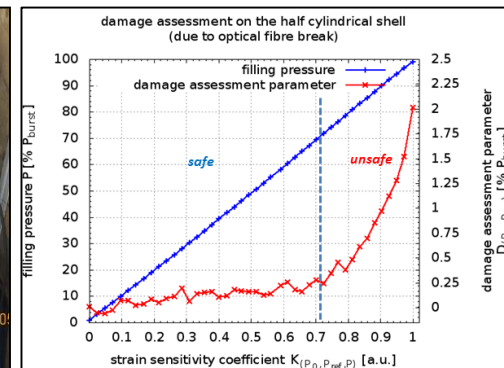
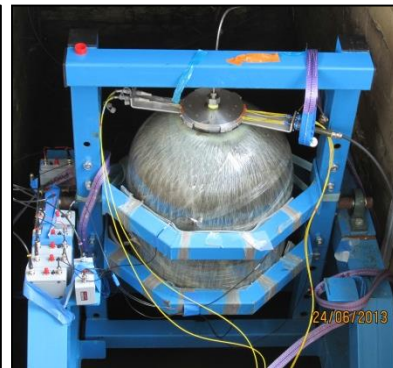
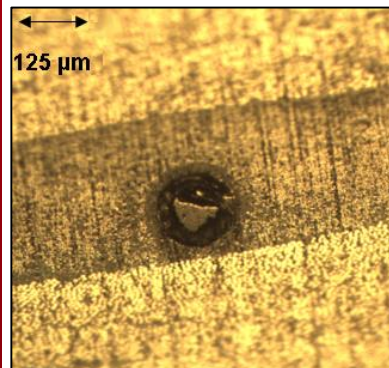


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- A brief overview of H2E research program
- Technological background, advantages of distributed measurements for COPV
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- Differential strain profiles analysis principle
- Low pressure, and residual differential strain analysis
- Additional SHM criteria: differential strain sensitivity and damage assessment
- One page key results

H2E RESEARCH PROGRAM



- **A response to an energy challenge**
 - Durable mobility
 - Greenhouse gas reduction
 - Petroleum dependence reduction
- **Hydrogen is a short term answer to these challenges**
- **Main markets**
 - Uninterruptible power supply in isolated areas
 - Emergency power supply (telecom, hospitals, data centres...)
 - On-board **vehicle** electrical energy production for a clean and silent propulsion
- Technologies: fuel cell, **high pressure storage vessels**, ...
- Technological research program co-funded by **OSEO** for 67,6 M€, for a global investment close to 200 M€ during 7 years (started on the 8th of October, 2008)
- This research program ended in 2015

website : <http://www.planete-hydrogene.com/>



TYPE IV HIGH PRESSURE STORAGE VESSELS

- type IV pressure vessel: composite materials structure with polymer liner



fireman's vessel



- H2E research program: **type IV Composite Overwrapped Pressure Vessels (COPV)**
 - storage: **700 bar** (security factor: 2.25)
 - transportable: **525 bar** (security factor: 3)
 - regulation: **directive 97/23/EC** of the European Parliament and the Council of 29 May 1997 and the approximation of the laws of the Member States **concerning pressure equipment**. OJ L 181 (1997)
 - project goal: to set-up a new inspection method capable to:
 - Determine whether the vessel is **safe or not**
- source: EADS Composites Aquitaine™. **Raise vessel lifetime** thanks to a better **Structural Health Monitoring**

STANDARDS

- **ISO 11623**: “Transportable gas cylinders – Periodic inspection and testing of composite gas cylinders”

OPTICAL FIBRE SENSORS FOR SHM OF COMPOSITE VESSELS (1/3)

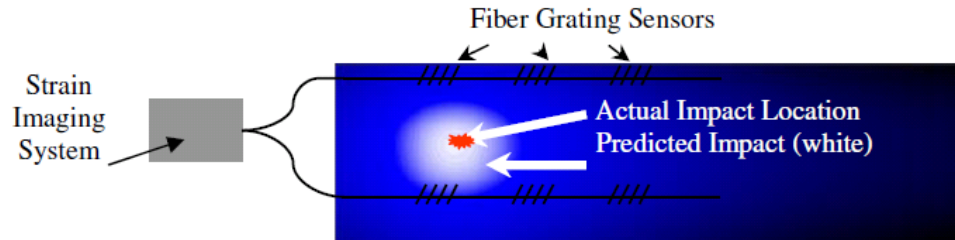


Figure 1. Strain imaging system scans fiber sensor arrays to locate damage

sources: Blue Road Research™ (Eric Udd)

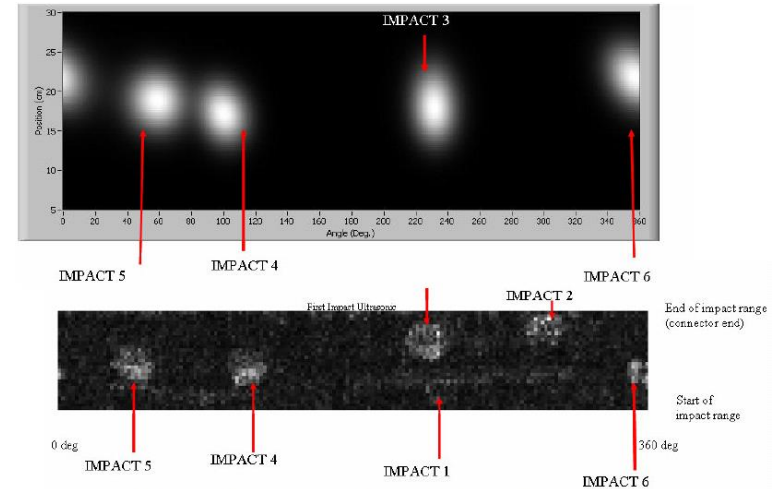
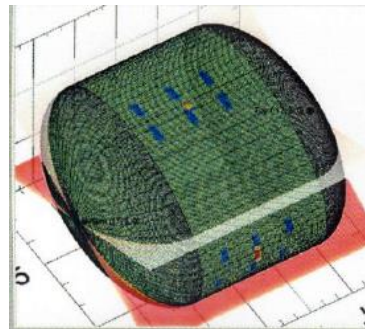


Figure 7. Ultrasonic (bottom) scans compare impact damage with strain imaging (top)

acoustic emission

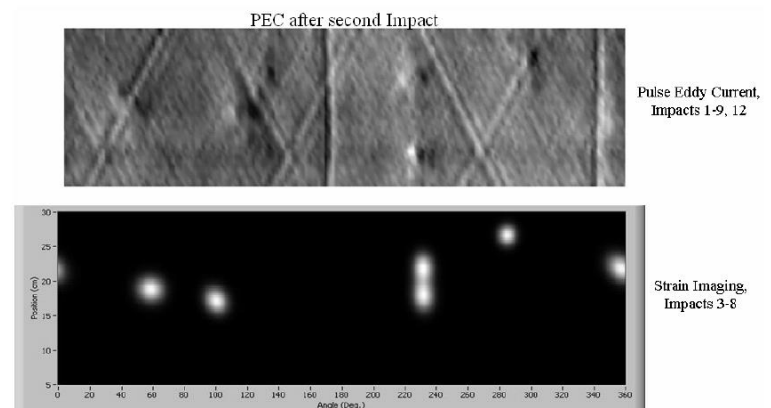


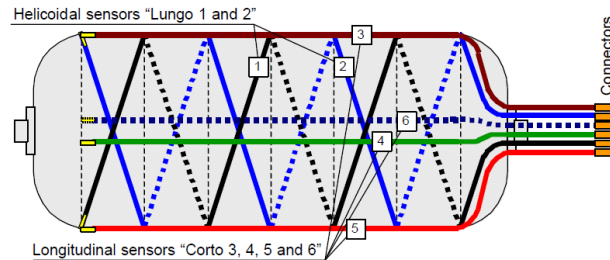
Figure 9. Strain imaging (bottom) compares damage with eddy current (top) NDE

Eddy current

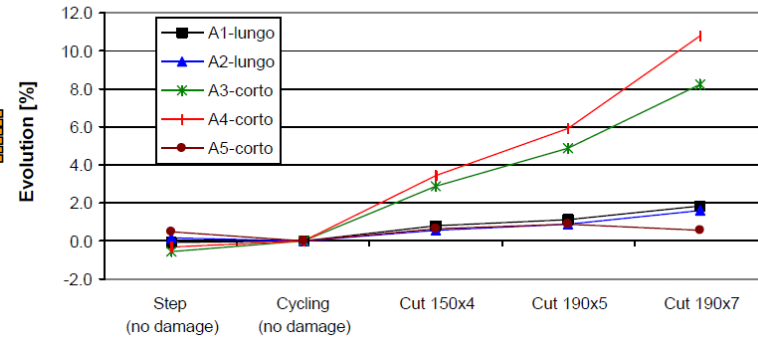
- **Impact detection demonstration** (surface sensors)
 - What about the detection of internal defects?
 - High speed, but **expensive** (several FBGs)
 - Complicated for high volume storage vessels

OPTICAL FIBRE SENSORS FOR SHM OF COMPOSITE VESSELS (2/3)

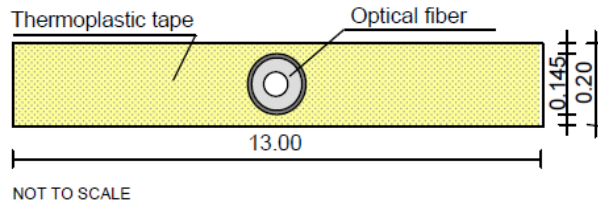
- ZEM project (FP5) : **SOFO** – SMARTape™ (Smartec™ – Branko Glisic)
 - Flaw detection with **strain sensitivity variation vs. pressure**



Damage detection on Tank A, relative sensors correlation evolution



sources: Smartec™, ZEM project



- **Global inspection method** *via* a global sensitivity parameter
- **Sensor intrusivity questionable in case of *in situ* measurements**

OPTICAL FIBRE SENSORS FOR SHM OF COMPOSITE VESSELS (3/3)

- Optical fibre sensors for pressure vessel inspection is not new ...

Philips (1982)

[54] LIGHT CONDUIT ARRANGEMENT FOR MONITORING A PHYSICAL CONDITION OF A STRUCTURAL PART

[75] Inventors: J. Peter Starke, Odothar, Friedrich K. Lescher, Brauweiler; Helmut Federmann, Berg, Gladbach, all of Fed. Rep. of Germany

[73] Assignee: Philips Kommunikations Industrie A. Hamburg, Fed. Rep. of Germany

[21] Appl. No.: 405,095

[22] Filed: Aug. 4, 1982

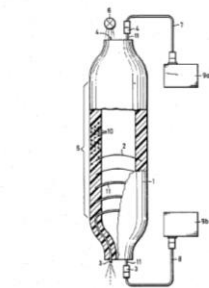
[30] Foreign Application Priority Data

Aug. 12, 1981 [DE] Fed. Rep. of Germany 3131870

[51] Int. Cl.⁴ G01B 11/16

[52] U.S. Cl. 356/32; 356/34; 73/600

[58] Field of Search 356/32, 34; 73/600



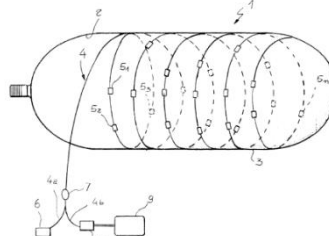
[56] **References Cited**
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4,173,412 11/1979 Ramsey et al. 356/73.1 X
4,272,189 6/1981 Bailey et al. 250/227
4,309,450 6/1981 Knaben 250/227
4,450,434 5/1984 Nielsen 250/227 X
FOREIGN PATENT DOCUMENTS
2917524 10/1980 Fed. Rep. of Germany
3013191 10/1981 Fed. Rep. of Germany
2036330 6/1980 United Kingdom 73/600
2039461 6/1980 United Kingdom 340/350
Primary Examiner—Vincent P. McGraw
Assistant Examiner—S. A. Turner
Attorney, Agent, or Firm—Michael J. Striker

ABSTRACT
[57] A structural element is provided with at least one light conduit which is arranged thereon under a selected mechanical initial stress. In this manner, the deformation or breakage can be detected at loads or deformations which are lower than the breaking loads or deformations of the component parts to be monitored.

4 Claims, 2 Drawing Sheets

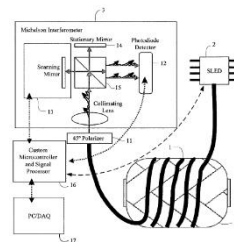
FIAT (1998)

- (54) Check system for monitoring the strain status of high pressure bottles particularly methane gas bottles for motor-vehicles
- (57) A check system for monitoring the strain status of high pressure bottles partially or entirely made of composite material, particularly methane gas bottles for motor-vehicles, comprising an optical fibre (4) wound around the bottle and including Bragg grating reflecting elements $S_1, S_2, S_3, \dots, S_n$ to detect and turn the mechanical and thermal strain condition of the bottle (1) into electrical coded signals.



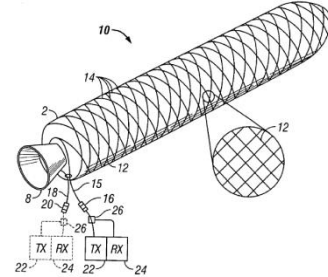
Morgan Research Corp. (2005)

- (54) EMBEDDABLE POLARIMETRIC FIBER OPTIC SENSOR AND METHOD FOR MONITORING OF STRUCTURES
- (57) **Inventors:** Jeffery Lee Williams, Huntsville, AL (US); Michael Scott Kraus, Madison, AL (US); Larry Christopher Horton, Huntsville, AL (US)
- Correspondence Address:**
LANDER FORD SHRYVER & PAXE
P.O. BOX 2407
HUNTSVILLE, AL 35804 (US)
- (73) Assignee: Morgan Research Corporation, Huntsville, AL
- (21) Appl. No.: 11/051,739
- (22) Filed: Oct. 17, 2006
- Related U.S. Application Data**
(60) Provisional application No. 60/619,473, filed on Oct. 17, 2004.
- Publication Classification**
(51) Int. Cl.⁴ G01B 1/81 (2006/01)
- (52) U.S. Cl. 360/227.14
- ABSTRACT**
The present invention provides the capability of accounting, detecting a stress, and simply measuring, insensitive to a structure that may have experienced damage that could result in reduced structural lifetime, strength, or reliability. The sensing system is a cross-sectional section of a polarimetric (PMD) optical fiber, where a length of PMD fiber represents a fully distributed sensor array. Stress-induced changes to the sensor are measured through white-light polarimetric interferometry. The output of the measurement is a data array representing the stress concentration magnitude at an array of locations along the length of the sensor. In no application, the knowledge of the optical fiber position on the structure, coupled with the measurement of stress locations along the fiber length, allows the user to determine locations on the structure with large stress concentration. These locations may signify structural damage. This knowledge would allow the user to employ a more sophisticated sensor, where a larger and denser one or fully characterize and evaluate the area of potential damage and take appropriate action.



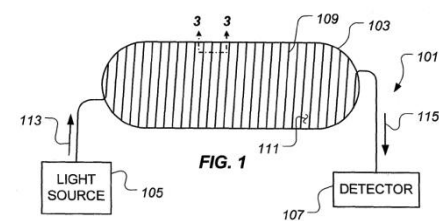
Boeing (2004)

- (56) **FIBER OPTIC DAMAGE DETECTION SYSTEM FOR COMPOSITE PRESSURE VESSELS**
- (57) **Inventors:** Thomas L. Anderson, Norwood Beach, CA (US); Leslie B. Grimes-Johnson, Long Beach, CA (US)
- Correspondence Address:**
KLEIN, SPINELL & SINGH
2 PINE PLAZA
SUITE 210
BOYING, CA 92614 (US)
- (21) Appl. No.: 10/781,062
- (22) Filed: Feb. 16, 2004
- Publication Classification**
(51) Int. Cl.⁴ G02B 6/00
(52) U.S. Cl. 380/13; 382/27.15
- ABSTRACT**
An optical fiber is wound onto an exterior surface of a composite structure, such as a composite overwrapped pressure vessel ("COPV"), in a non-dimensional pattern and adjacent thereto, i.e., with a core, is placed damage to the structure caused by impacts in or loading of the structure. After fabrication, a light source, a negative, or loading, reference signal is established by detecting a light signal transmitted through the length of the fiber. Later, after the structure has been transported, handled, or placed into service, a second signal (relative to the first) is sent through the fiber and compared with the reference signal. Changes detected in the signal indicate that the structure may have sustained structural damage that may be invisible to external visual inspection, but that can be detected by more easily and time consuming conventional non-destructive inspection methods. In another embodiment, a pulsed light signal reflecting from a discontinuity in the optical fiber can be used to determine the location of the damage.



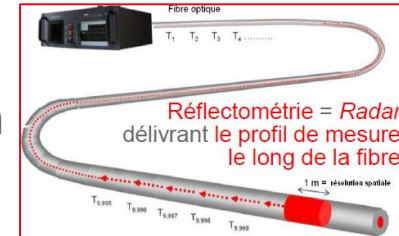
Lockheed Martin (2005)

- (54) Fiber optic impact sensing system and method of using same
- (57) A fiber optic impact sensing system includes a light source, an optical detector, and a sensing optical fiber optically coupled with the light source and the optical detector. The sensing optical fiber being operably associated with an outer surface of a structure. An apparatus includes a structure having an outer surface and a fiber optic impact sensing system operably associated with the outer surface of the structure. The fiber optic impact sensing system includes a light source, an optical detector, and a sensing optical fiber optically coupled with the light source and the optical detector. A method includes operably associating a sensing optical fiber with an outer surface of a structure, monitoring an optical output of the sensing optical fiber, and determining whether an amplitude of the optical output is above or below a predetermined threshold value.



DISTRIBUTED MEASUREMENT TECHNIQUE AND INTERESTS

- **Based on OFDR Rayleigh** with optical fibre(s) embedded into the composite structure during the manufacturing process
- **A distributed measurement / precision & accuracy: a few $\mu\text{m}/\text{m}$**
 - Same sensors during the vessel lifetime
 - In the same carbon reinforcement fibres orientation
 - Close to internal defects (if any ...)
 - Thermo-mechanical information (in our case, only mechanical since the temperature is controlled)
- Internal defects are precisely **located** along the optical fibre (typ.: 2 cm sampling)



OPEN QUESTIONS

- **Intrusive effect of the optical fibre on the mechanical performances** (Pressure Equipment directive and ISO standards)
 - Tests on flat samples → up to their ultimate tensile strength
 - Tests on NOL rings → fatigue tests
- **Structural defects highlighting ?**
 - **A proposal for 4 new SHM criteria, including a Damage Assessment Parameter**

FLAT SAMPLES MANUFACTURING

- 5 series within a same mould
 - 24 sets x 5 samples → **120 samples manufactured and tested**
 - **10 plies/sample**
 - Plies orientations: 0°, 10°, 30°, 45°, 70°, 85°, 90°

optical fibres embedded quantity >>> planned in pressure vessels



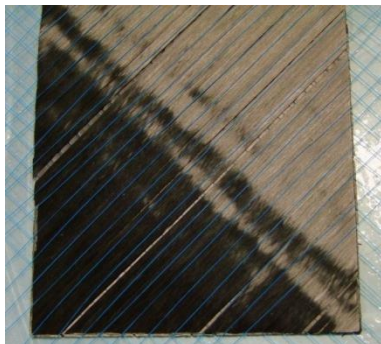
expected impact on mechanical performances is maximised



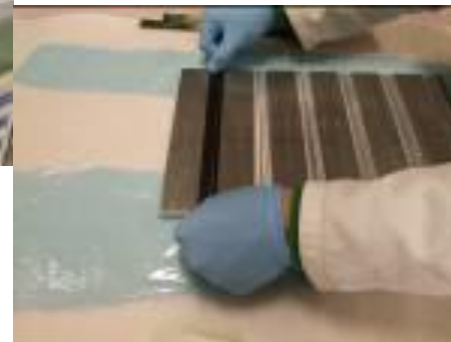
1. pre-preg carbon-expoxy with optical fibres laid on surface



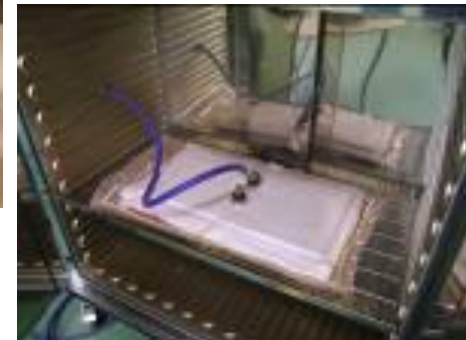
2. flat samples cut at required dimensions



optical fibres are aligned in the direction of the reinforcement carbon fibres



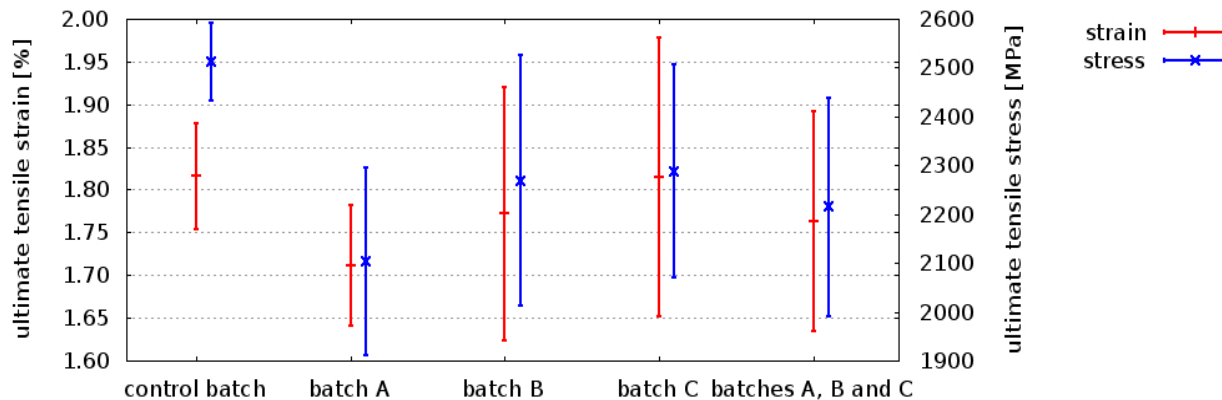
3. plies stacked one on another



4. vacuum moulding

ULTIMATE TENSILE STRENGTH PERFORMANCE ANALYSIS

- 3 kinds optical fibres tested (A, B and C)
- Uniaxial tensile tests (250 kN testing machine)
 - Tests up to the samples ultimate tensile strength
- *In situ* FBG strain measurements
- Strain and stress statistical analysis → no significant influence on the ultimate tensile strength
 - **Therefore, expected impact on pressure vessels should not be significant**



flat sample after test



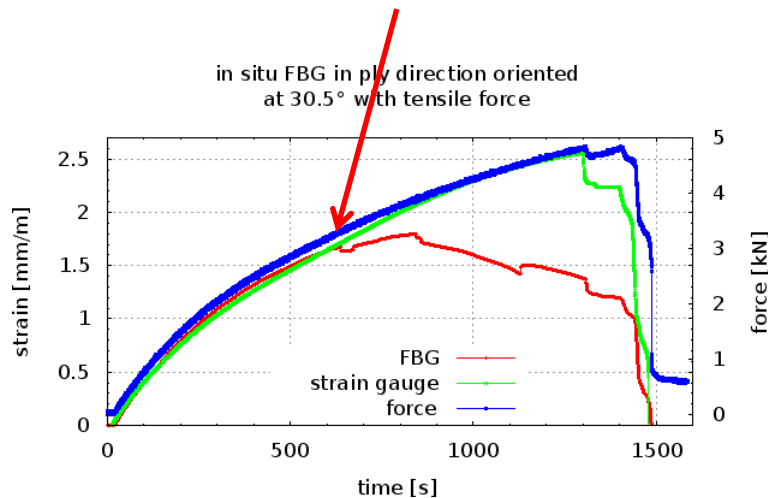
250 kN tensile test machine

IN SITU FBG STRAIN MEASUREMENTS vs. TENSILE FORCE

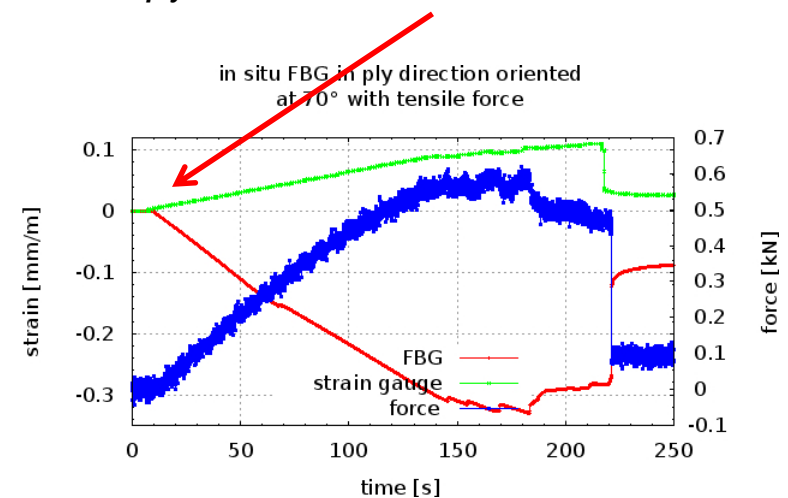
- *In situ* measurements depend on carbon fibre orientation vs. tensile force direction
- Matrix debonding appears sooner when the angle between the tensile force and the reinforcement carbon fibres is greater
- Debonding can be interpreted as a structural defect outlined by the strain (FBG) measurement

As soon as debonding appears, FBG strain measurement deviates from sample average strain
FIRST BASIS FOR A STRUCTURAL DEFECT DETECTION CRITERION

*initial matrix decohesion
ply direction oriented at 30.5° with tensile force*



*initial matrix decohesion
ply direction oriented at 70° with tensile force*



NOL RING FATIGUE TESTS (1/4)

- **ASTM D2290-08 standards:** “ *Standard Test Method for Apparent Hoop Tensile Strength of Plastic or Reinforced Plastic Pipe by Split Disk Method* ”
 - NOL ring geometry more representative of cylindrical shells
 - The optical fibre also acts as a reinforcement fibre
- 4 different NOL rings series were machined in the same cylinders
 - **30 NOL rings tested with different plies orientations**
- **Fatigue cycles monitored in displacements**
 - **15000 cycles** according to EIHP standards (-10% +70% amplitude to ultimate tensile strength)



NOL rings



NOL ring installed on the testing machine

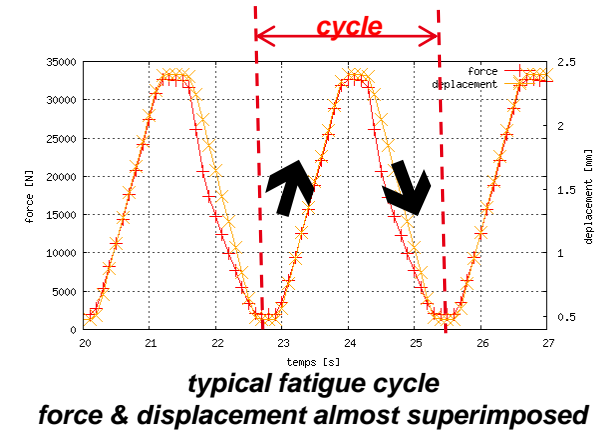


NOL ring after fatigue cycles

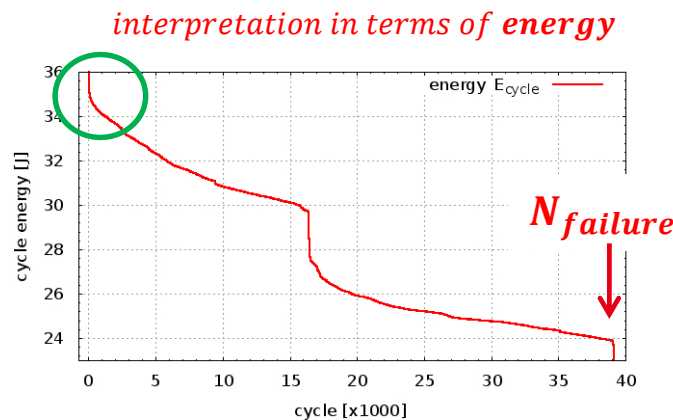
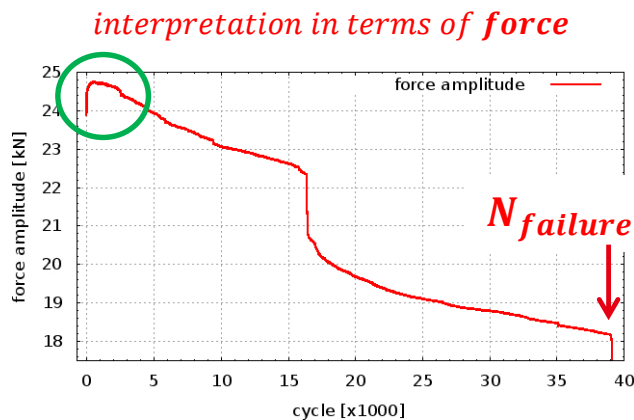
NOL RING FATIGUE TESTS (2/4)

- $\Delta F = 30 \text{ kN}$ and $\Delta h < 2 \text{ mm}$
 - Frequency: 0.4 Hz (40000 cycles \leftrightarrow 28 hours)
 - Displacement accuracy: better than $1 \mu\text{m}$
- Force and displacements continuously recorded
 - Access to strain cycle energy E_{cycle}

$$E_{cycle} = |E_{half-cycle \nearrow}| + |E_{half-cycle \searrow}|$$



- **The energy parameter is the most relevant**, especially during the first cycles
 - Strain energy E_{cycle} always decreases, whereas the force amplitude may increase
 - Energy parameter better describes the sample average resistance $\langle F \rangle$ to strain



$$\langle F \rangle = \frac{E_{cycle}}{2 \Delta h}$$

$\langle F \rangle$: average force

NOL RING FATIGUE TESTS (3/4)

- Moreover, analysis of the energy parameter, based on first cycles dispersion, demonstrates that **number of cycles to failure $N_{failure}$ is not relevant**
 - Energy dispersion during the first fatigue cycles is the main reason for the dispersion of the numbers of cycles to failure

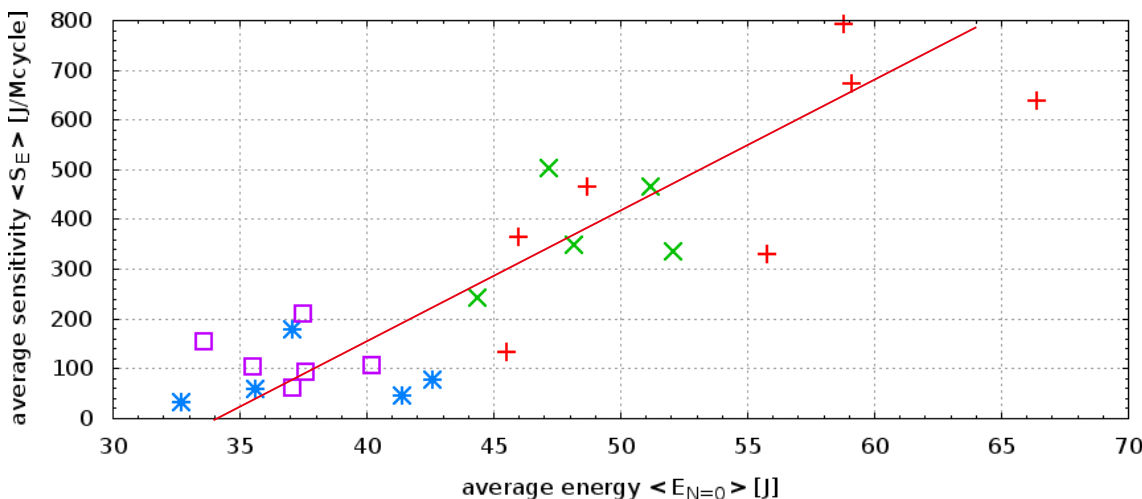
	S [J/Mcycle]	$\langle E \rangle$ [J]	$\Delta E_{N=0}$ [J]	Δh [mm]	position reproducibility $\delta N_{\delta h}$ [cycle/ μm]	first cycles strain energy dispersion $\delta N_{\Delta E_{N=0}}$ [cycle/J]
#1 w/	484,64	45	20,9	1,92	48,36	2063
#1 w/o	378,58	40	9,5	1,92	55,03	2641
#2 w/	77,71	34	9,9	1,65	265,16	12868
#2 w/o	121,2	34	6,6	1,65	170,02	8251

- Number of cycles to failure due to:
 - sample position reproducibility $\delta N_{\delta h}$

$$\delta N_{\delta h} = \frac{1}{S} \frac{\langle E \rangle}{\Delta h} \delta h$$

- first cycles energy dispersion $\delta N_{\Delta E_{N=0}}$

$$\delta N_{\Delta E_{N=0}} = \frac{\Delta E_{N=0}}{S}$$

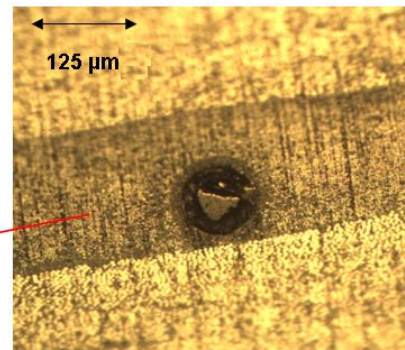
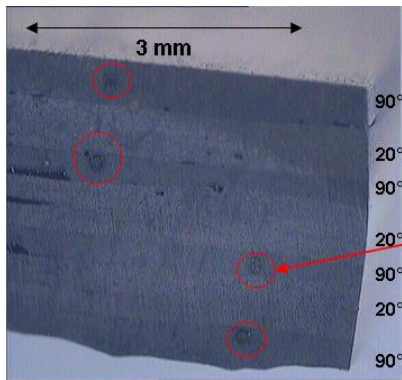


Not possible to conclude about any significant impact of embedded optical fibres on mechanical performances

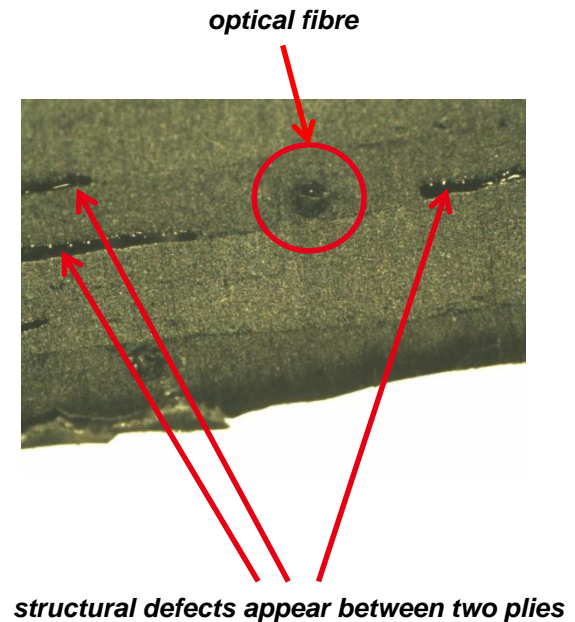
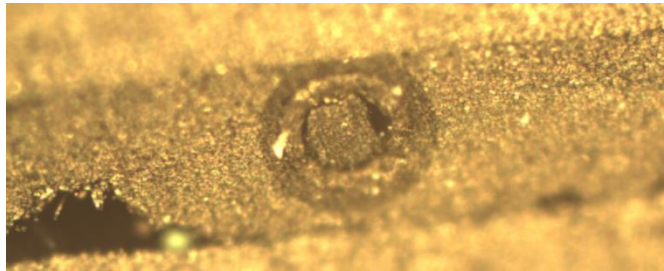
First cycles strain energy has first to be better controlled

NOL RING FATIGUE TESTS (4/4)

- Microscope *post mortem* analyses:
 - No debonding in the optical fibre vicinity
 - Optical fibre **perfect integration** into the carbon composite structure



no structural defect in the optical fibre vicinity



Not enough reasons to conclude about any significant impact of optical fibres on the samples mechanical performances [compliant with previous results: Sansonetti *et al.* 1991]

IN SITU PRESSURE VESSELS MEASUREMENTS

- **Experimental set-up**
 - Semi-automated measurement loop (Luna™ OBR-4600 instrument remotely controlled)
 - 46 pressure steps up to burst pressure

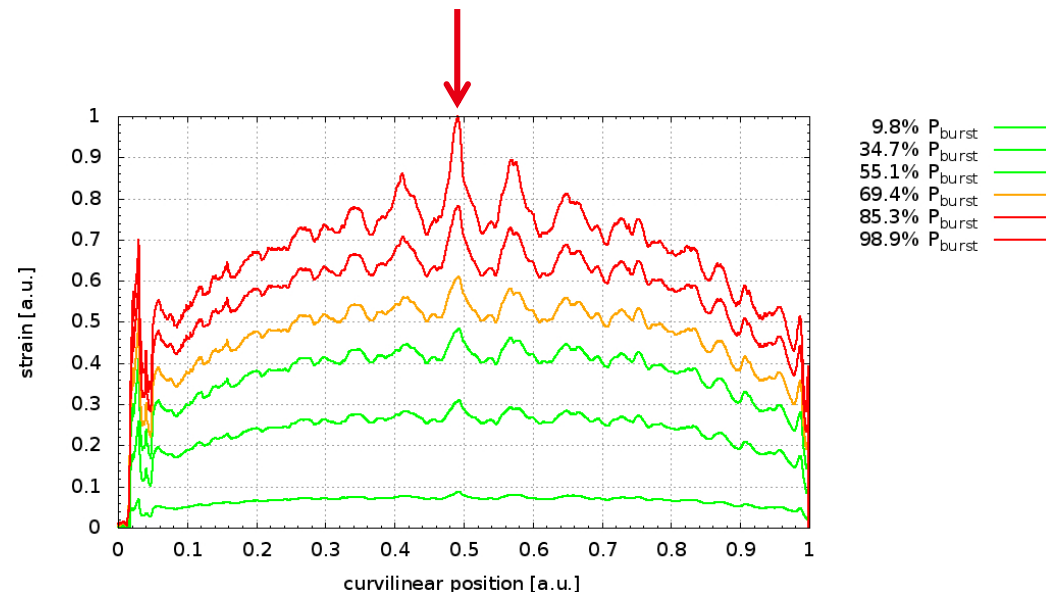
- Small pressure steps enable more complete analyses

- **Strain profile analysis**
$$\Delta \epsilon_{P_0 \rightarrow P_n}(s) = \sum_{i=1}^{i=n} \Delta \epsilon_{P_{i-1} \rightarrow P_i}(s)$$



surface impact

pressure vessel initial failure (burst test)



Composites Aquitaine™ burst test facility

DIFFERENTIAL STRAIN PROFILE PRINCIPLE

Defect detection criterion relies on flat samples FBG observations

One hypothesis amongst others is to consider internal defects as structural weaknesses resulting, in their vicinity, in local strains different from the rest of the structure supposed undamaged.

With a set of appropriate differences between strain profiles, it must be possible to reveal these defects.

A proposal is to compute a “**differential strain profile**” between 2 pressure states at P_{ref} and P

$$\delta_K \Delta \varepsilon_{(P_0, P_{ref}, P)}(s) = \Delta \varepsilon_{P_0 \rightarrow P}(s) - K_{(P_0, P_{ref}, P)} \times \Delta \varepsilon_{P_0 \rightarrow P_{ref}}(s)$$

$K_{(P_0, P_{ref}, P)}$ calculated by least-squares minimisation of $\|\delta_K \Delta \varepsilon\|$

→ $\delta_K \Delta \varepsilon$ is always centered on zero

→ any significant deviation from zero points out local abnormal strains → defect occurrence probability

DIFFERENTIAL STRAIN ANALYSES TO HIGHLIGHT INTERNAL DEFECTS

- Pressure vessels with embedded optical fibres, manufactured by **Composites Aquitaine™**

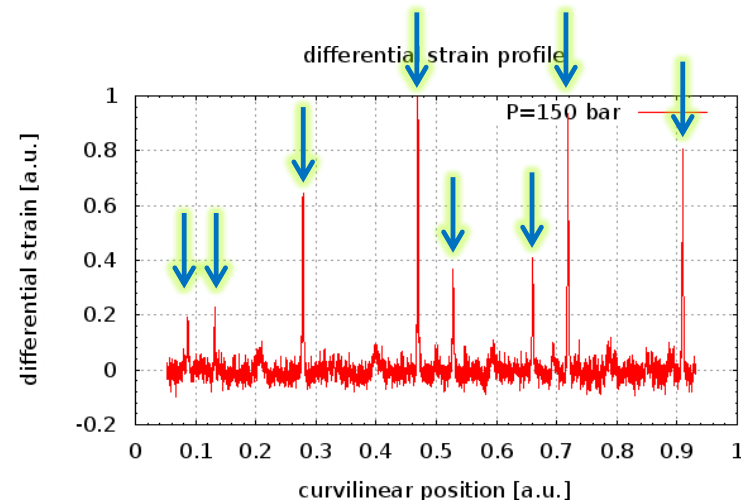
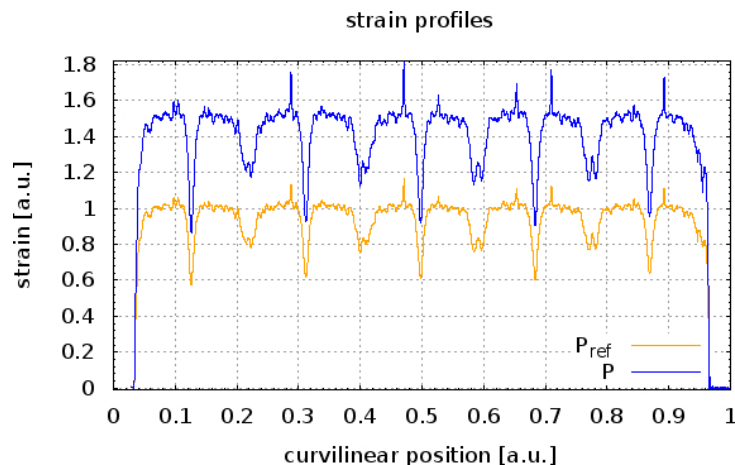


Composites Aquitaine™ pressure vessels



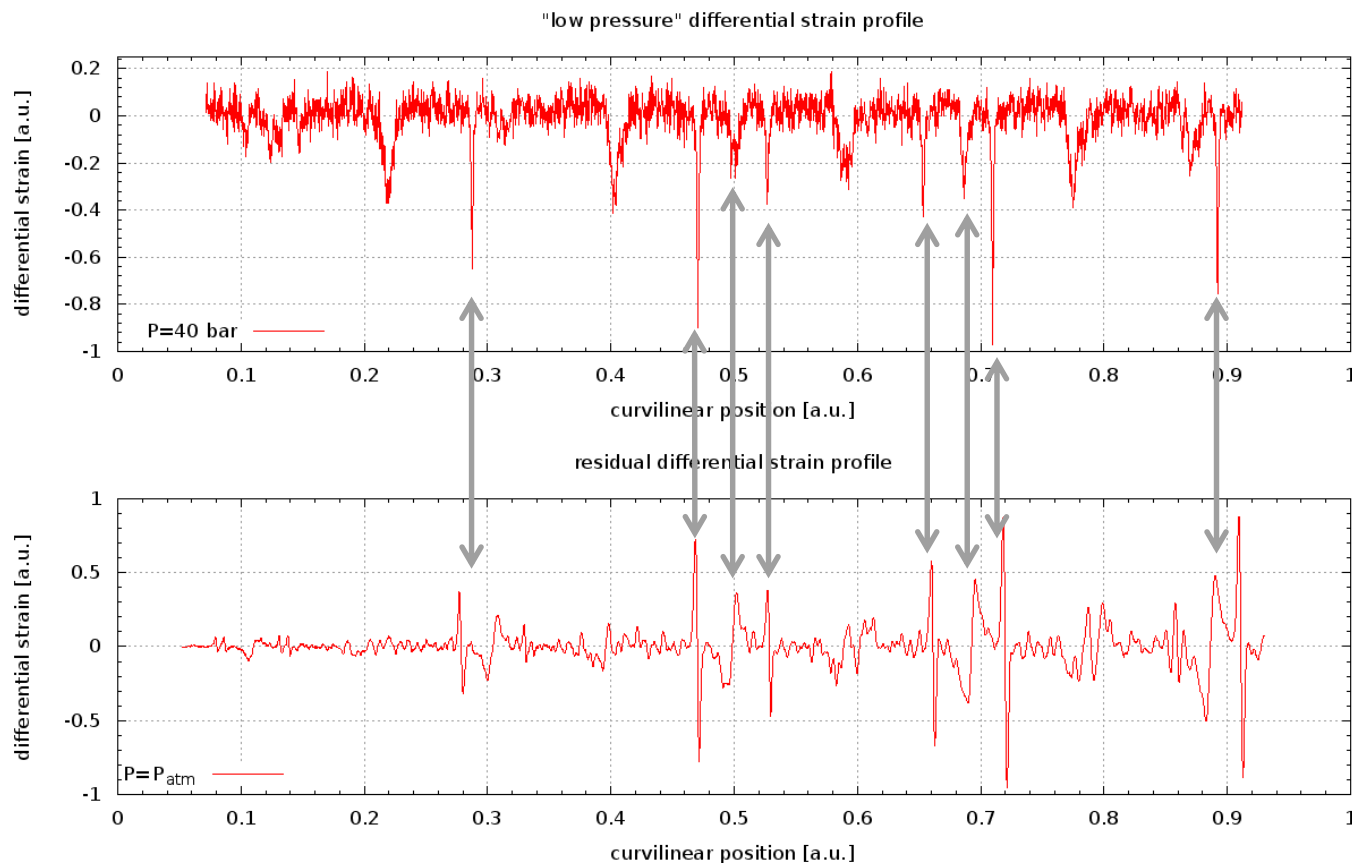
surface defect

- Water-filling procedure / no temperature crosstalk effect
- High signal / noise ratio



LOW PRESSURE AND RESIDUAL STRAINS DIFFERENTIAL ANALYSIS

- High signal / noise ratio enables low pressure analyses
 - No additional damage due to the inspection method
 - Residual differential strain profile gives relevant and complementary information



"low pressure" (40 bar)
differential strain profile

residual
differential strain profile

ADDITIONAL SHM CRITERIA

- **Strains profiles $\Delta\epsilon_{P_0 \rightarrow P_n}$**
 - Highlights pressure vessel mechanical behaviour vs. inflating pressure

$$\Delta\epsilon_{P_0 \rightarrow P_n}(s) = \sum_{i=1}^{i=n} \Delta\epsilon_{P_{i-1} \rightarrow P_i}(s)$$

- **Differential strain profiles $\delta_K \Delta\epsilon$**
 - Early defect detection and localisation along the optical fibre

$$\delta_K \Delta\epsilon_{(P_0, P_{ref}, P)}(s) = \Delta\epsilon_{P_0 \rightarrow P}(s) - K_{(P_0, P_{ref}, P)} \times \Delta\epsilon_{P_0 \rightarrow P_{ref}}(s)$$

- **Differential strain profile sensitivity $\mathcal{S}_{(P_0, P_{ref}, P)}$ vs. inflating pressure P**
 - Highlights structural damage acceleration (requires simultaneous pressure measurement)

$$\mathcal{S}_{(P_0, P_{ref}, P)}(s) = \frac{\partial \delta_K \Delta\epsilon_{(P_0, P_{ref}, P)}(s)}{\partial P}$$

- **Damage Assessment Parameter $\mathcal{D}_{(P_0, P_{ref})}$**

- Global damage parameter

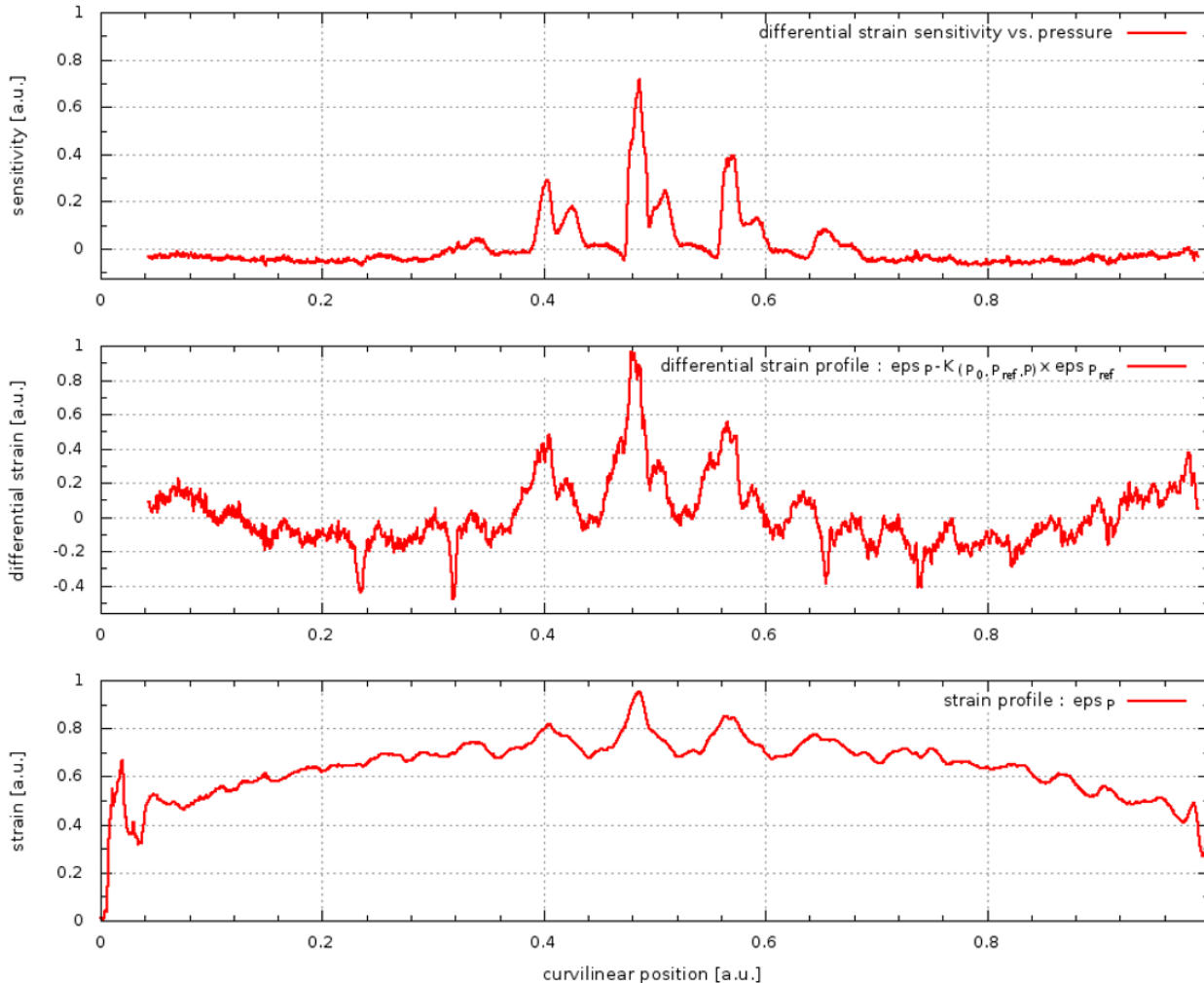
$$\mathcal{D}_{(P_0, P_{ref})}(P) = \frac{P(K_{0(P_0, P_{ref}, P)}) - P(K_{(P_0, P_{ref}, P)})}{P_{burst}}$$



DIFFERENTIAL STRAIN PROFILE SENSITIVITY \mathcal{S}

- Highlights instantaneous structural damage during filling pressure

$P = 98.8 \% P_{burst}$



animated GIF

differential strain profile
sensitivity \mathcal{S}



differential strain profile
 $\delta\Delta\epsilon$



strain profile $\Delta\epsilon$

DAMAGE ASSESSMENT PARAMETER \mathcal{D}

- Highlights structural damage
- Global and robust parameter: **relevant even in case of optical fibre break**

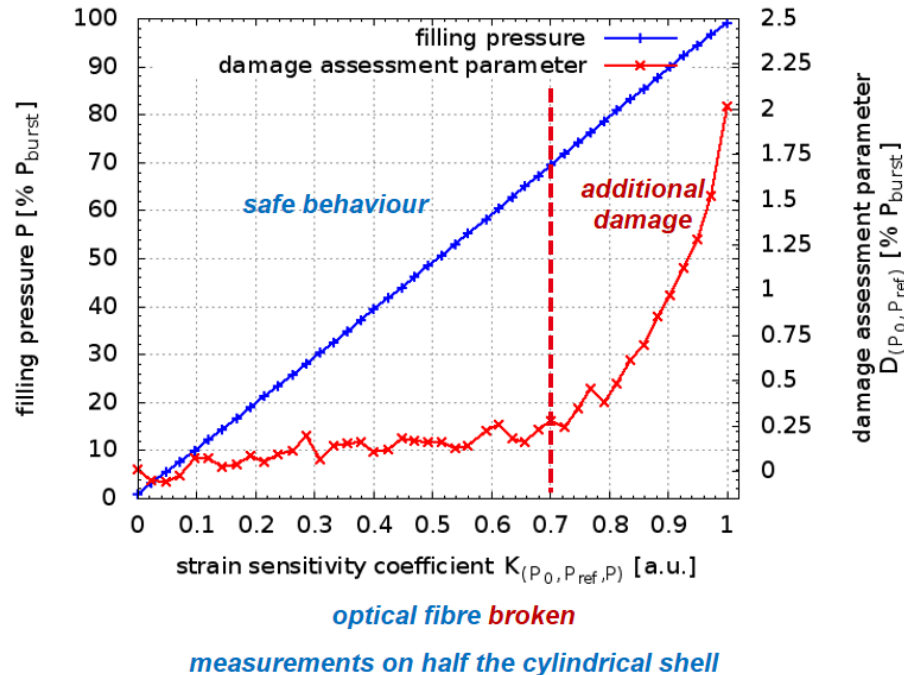
theoretical undamaged behaviour

actual behaviour

$$\mathcal{D}_{(P_0, P_{ref})}(P) = \frac{P(K_{(P_0, P_{ref}, P)}) - P(K_{(P_0, P_{ref}, P)})}{P_{burst}}$$

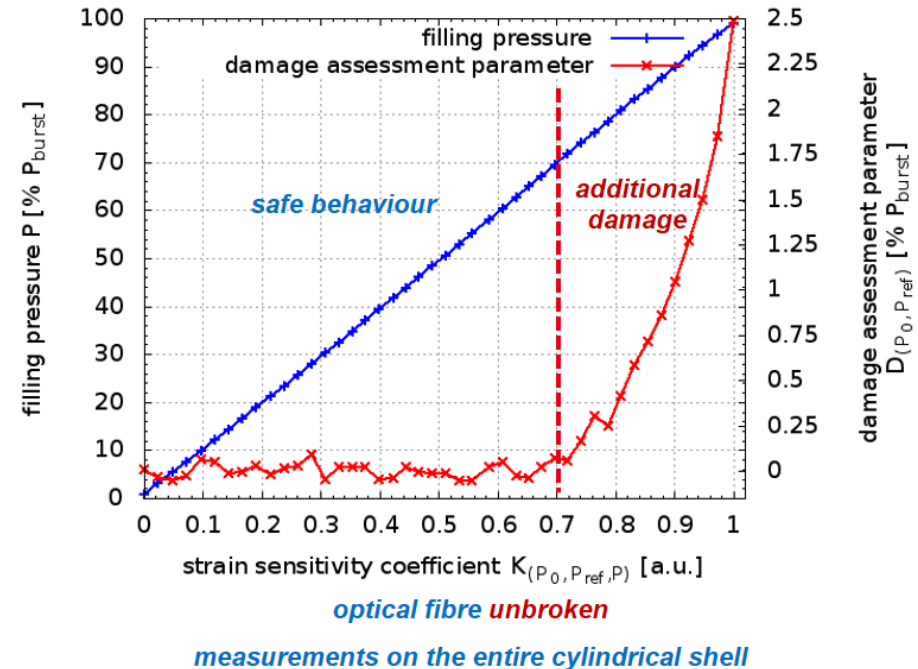
damage assessment on the half cylindrical shell
(due to optical fibre break)

animated GIF



damage assessment on the entire cylindrical shell

animated GIF



EMBEDDED SHM SOLUTION THROUGHOUT VESSEL LIFETIME

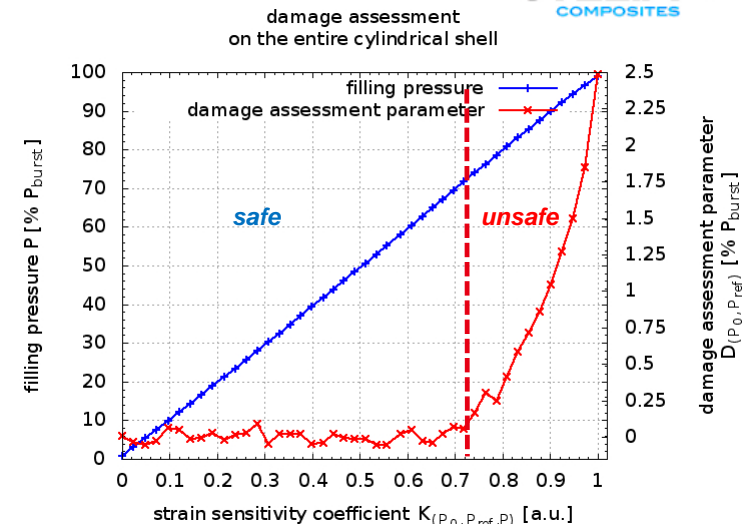
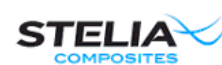
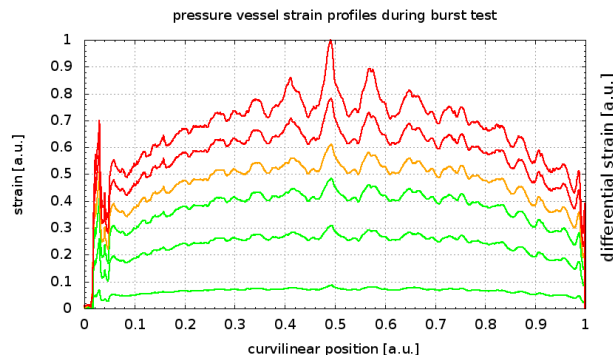
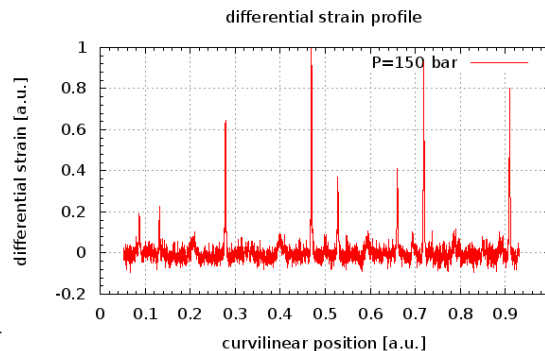
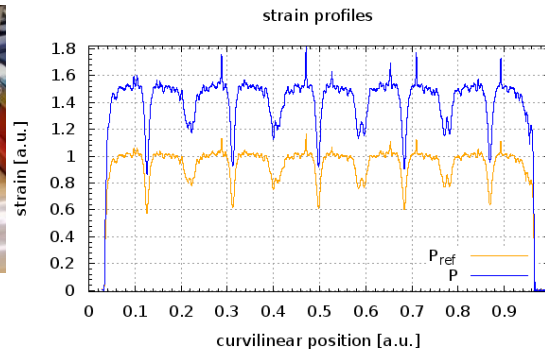
- Distributed measurements based on optical fibre *in situ* strain measurements
- Global structural damage assessment based on differential analysis
- No additional damage due to the inspection method
 - Validated in isothermal conditions on 700 bar H₂ pressure vessels
 - Early damage detection starting from 40 bar
- ATEX compatible measurement



<https://hal.inria.fr/hal-01021252/PDF/0192.pdf>



Composites Aquitaine™ pressure vessels





thank you for your
attention



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