Sensing of Structural Damage with OBR Based Fibre-Optic Networks

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ABSTRACT

Optical fibre networks based on optical backscatter reflectometry i.e. the OBR technology is a new and promising method for the inspection of safety critical structures. It utilizes regular telecommunications grade optical fibres as sensors, and off the shelf equipment for sending and receiving light through the fibres. The signals can then be interpreted to reveal strains or temperature in the host structure. For this work, the optical fibre sensors were embedded inside composite shells during manufacturing. Experiments on axisymmetric demonstrators (pressure vessels, cylindrical tubes) show how the location, the severity, and the shape of impact damage can conveniently be visualized. Such information can serve as input for decision makers in condition based maintenance. Remaining challenges regarding practical embedding procedures and the signal interpretation are briefly discussed.

Keywords: *optical fibre sensors, impact, damage, identification, condition based maintenance*

1.0 INTRODUCTION

Ensuring structural performance over long spans of time is a costly activity for many types of equipment and structures. Maintenance needs to be carried out, to avoid interruptions and ensure a safe operational life. Depending on the requirements for performance, maintenance can be carried out as reactive (run to failure), preventive (calendar based monitoring), or as predictive condition based maintenance. The last approach can, in principle, provide the longest available performance with the lowest cost.

Condition monitoring with the aim of predictive maintenance is achievable by state-of-the art sensor systems. The sensor systems can provide relevant and reliable data for early detection of faults. Data analytics can be employed to further assist engineers and managers in decision making. However, in reality and in the field, many sensor technologies are still not mature. Predictive maintenance is not mainstream, but constrained to a few types of (safety) critical structures. Warning lights for brakes in cars, or pressure sensors for monitoring pressure spikes in pipelines are a few everyday examples of condition monitoring. Predictive maintenance will be implemented on more applications as the sensor systems become robust, cost-effective, and retrieve increasingly more useful information about the structure. Structural modelling can also assist in decision-making about the health of the structure utilizing measurements received from the sensors, e.g. as in the case of so-called digital twins.

The trend of automatization in manufacturing will eventually enable effortless integration of sensors into structural components. Composite materials are special because the material i.e. the combination of fibres and matrix, and the component, are often manufactured at the same time instance. This enables easier integration of sensors into the structure. If embedding proves to be difficult or even impossible to integrate with the production, sensors can still be surface mounted onto the component, after the manufacturing is finished. Surface mounted optical fibres can be used on composites and conventional metal structures alike.

2.0 NON-DESTRUCTIVE EVALUATION (NDE) OF COMPOSITE PRESSURE VESSELS

The composites and polymers group in NTNU has been working with composite tubes and composite overwrapped pressure vessels (COPVs) for many years. Typical NDE methods employed for COPVs today are visual inspection, acoustic emission, ultrasound, x-ray radiography, and thermography. The application of these methods often requires special conditions, such as removal from service, the presence of a human inspector, immersion in water, pressurization of the structure to high levels, or focusing on a small piece of the structure to ensure sufficient resolution. These NDE methods are therefore more suitable for periodic inspections, and less practicable for continuous monitoring.

The ability to permanently monitor COPVs relieves concerns about their structural integrity under regular or adverse circumstances. Embedding optical fibres (OFs) into composite pressure vessels is a historically well-known method for in-situ structural health monitoring. Many approaches have been tried over the last decades, e.g. using Fibre Bragg Grating (FBG) sensors [1], long gage interferometric sensors [2] or signal intensity based optical sensors [3]. These approaches provide either localized point measurements or an averaged response over the whole fibre/structure. None of these fibre optic solutions provide a high-resolution full field strain measurement over the entire pressure vessel structure.

Current work employs a novel distributed strain sensing system utilizing optical backscatter reflectometry (OBR) based on the principle of Rayleigh backscattering [4]. Regular telecommunications grade optical fibres were embedded into the composite layup i.e. wound between carbon fibre layers as seen in Fig. 1. The cylinders were struck with controlled impacts and the backscattered light from optical fibres was analysed to visualize the position and the severity of damage. The following study demonstrates how the interrogation of an embedded network of optical fibres provides high-resolution strain measurements covering the entire surface of the structure. OBR based optical fibre networks are shown to be a promising method for structural health monitoring of composite cylinders.

Figure 1: Embedding optical fibres during the manufacturing of carbon fibre COPVs [5].

3.0 OPTICAL REFLECTOMETRY BASED ON RAYLEIGH BACKSCATTERING (OBR)

3.1 Working principle

The OBR technology is based on the principle that any perturbations in the host material (i.e. composite), such as deformations or temperature changes, affect the optical signals propagating in the fibre. OBR reveals the temperature or strain change from any point along the optical fibre by using backward propagating Rayleigh scattered light – a kind of interaction between the light and the fibre. The reflectometer/interrogator sends a laser signal through the fibre, and the backscattered signal is then captured and interpreted as distributed strain along the entire fibre length.

The spatial resolution of measurements can be lowered to 1 mm or less, unparalleled by other distributed sensing methods today, such as Brillouin or Raman backscattering. The sensing length is limited to approximately 70 m, but can be extended at the expense of coarser spatial resolutions. The noise in typical strain measurements is low, a cut-off filter at ±10…±50 microstrain is usually sufficient to remove it. Comparison to electrical strain gauges gives good agreement, e.g. see the results reported in [5, 6]. The optical fibre sensor, when utilized in the temperature measurement mode, also compares well to conventional temperature gages, as seen in Fig. 2. The OBR measurement takes a few seconds to perform, and this limits the technology currently to quasi-static measurements. For this work, the OBR apparatus and its accompanying software were purchased from Luna Innovations [7].

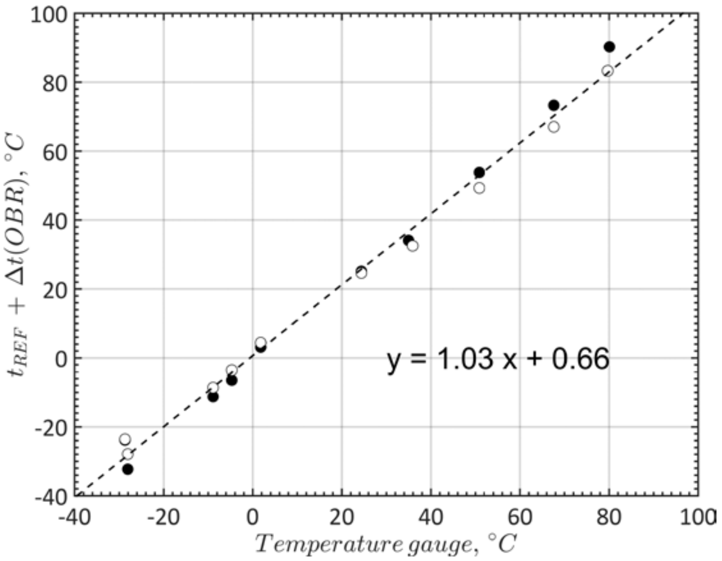


Figure 2: Ambient temperatures measured by the optical fibre sensor and a conventional temperature gauge.

3.2 Challenges

There are several challenges regarding the practical implementation of optical fibres, and post-processing of signals. Difficulties in handling bare optical fibres during embedding are well known, especially at the ingress and egress locations. Fibres are brittle and can be broken by small radius bends. However, a lot of useful knowledge can be drawn from earlier work with other methods such as FBG optical fibres. The experience in NTNU shows that most handling challenges can eventually be overcome by planning and well-established procedures.

The embedded optical fibres are significantly larger than typical reinforcing fibres inside the composite (see Fig. 3). Inserting new entities into the composite can create defects. The biggest disruptions occur when OFs run perpendicular to neighbouring fibres. Reinforcing fibres have to bend around the optical fibres, forming so-called resin eyes i.e. pockets of matrix around the OFs. Conversely, the defects caused by embedding are kept to minimum when fibres are placed parallel to surrounding fibres. Fig. 3 shows how the material closely surrounding the optical fibre is then no different from the surrounding bulk composite.

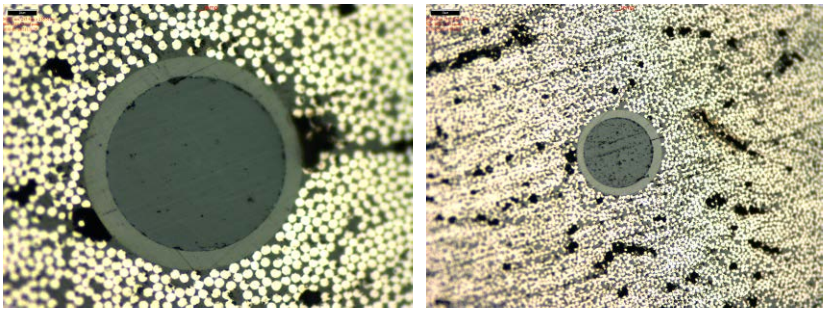


Figure 3: Micrographs of OFs embedded nearly parallel to surrounding carbon fibres.

Some measurements have also displayed excessive noise, much larger than the usual ±10…±50 microstrain described earlier. This noise most likely has its origins in post-processing. Without going into too much detail, the level of such noise can be mitigated by using a specific approach for post-processing, referred to as the running reference method [5, 8].

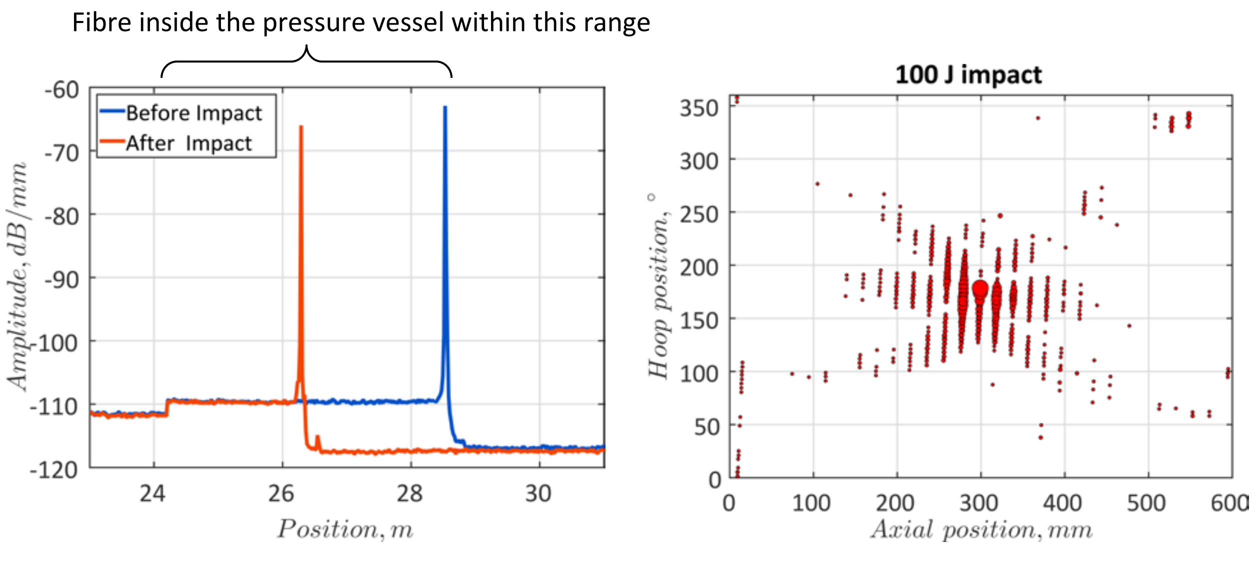
Last but not least, environmental conditions (temperature and even humidity), and the manufacturing process needs to be accounted when interpreting the optical signals. Mechanical strain measurements are affected by secondary effects such as temperature, and thermal strains from the curing process. These effects may be non-uniform and mask the sought damage or create false flags. The standard OBR equipment and software is not configured to simultaneously measure temperature and strain, and de-coupling of these effects needs to happen during post-processing.

4.0 RESULTS AND DISCUSSION

4.1 Damage detection

Optical fibres are hereby applied as sensors to detect and localize structural damage caused by impacts. The OBR technology enables to use the OFs for detecting strains with a very high spatial resolution. However, the most basic impact detection approach only utilizes the fibre ability to transfer a signal, without even translating it into strains. The backscattered signal of embedded OF changes abruptly after becoming severed by the impactor, as shown in Fig. 4(*a*). The high peak in the Figure indicates the end/termination of the optical fibre. This approach is the simplest but only useful when the fibre is actually broken by the damage.

The full potential of the OBR technology becomes more apparent by using the strain analysis. The strains can be calculated along the network of optical fibres, and then mapped onto a 2-D surface for improved visualization of damage inside the structure (Fig. 4(*b*)). Strains after an impact are displayed and the dot size is a logarithmic function of absolute strain values. The analysis preceding Fig. 4(*b*) employs several post-processing steps and relies on the knowledge of the positioning of each individual optical fibre.



a) Optical fibre becomes severed by the impact.

b) OF measured strains in the unpressurized vessel overwrap after an impact to the center.

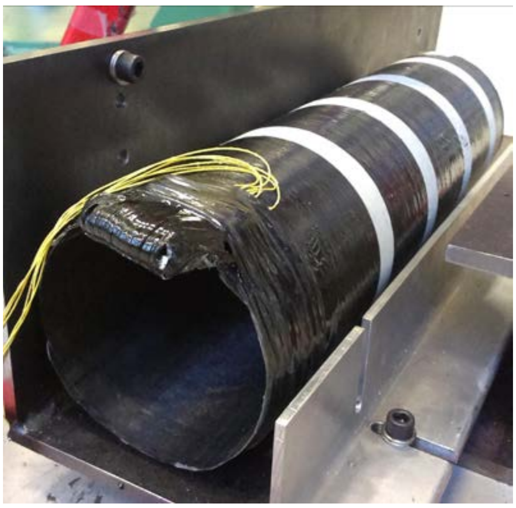
Figure 4: Identifying the impact locations in pressure vessels [5].

The size as well as the shape of the damage is estimated from the area where measured strains exceed a predefined noise threshold, set to ±10 microstrain in Fig. 4(b). Such detailed information about damage can be used for maintenance decisions, or it can be compared to numerical simulations such as finite element analysis. The damage displayed in Fig. 4(b) shows signs from the material layup inside the composite. The diagonal “lobes” of strain are oriented in similar alignment to helical composite layers wound at ±15° angle to the axial direction. Such detail in damage visualization would be impossible with point sensors or with long gage-length sensors referred to earlier. The detected strains are caused by a combination of factors. The release of residual strains and inelastic distortions from the impact are likely to be the main causes.

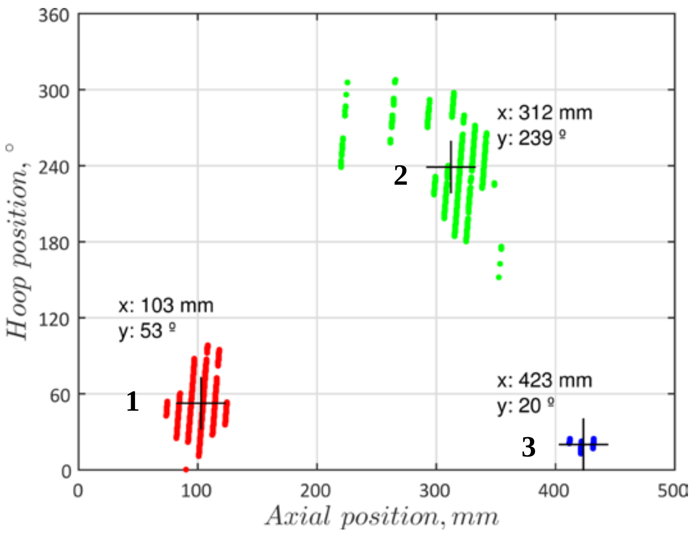
In another experiment, a steel ø = 20 mm hemispherical impactor was devised to struck three impacts – two with 20 J energy, and one with 10 J energy – to controlled locations on one composite cylinder. The specimen is shown in Fig. 5(a) and the eventual impacts could not be seen by visual inspection. An operator was then tasked to determine the locations of impact damage using the OBR method without any other previous information i.e. to perform a blind evaluation. The cylinder had been equipped with a system of six optical fibres, embedded inside the composite cylinder wall, close to its internal and external surfaces. Before proceeding with impacts, the operator also recorded the reference state i.e. backscattered signals from the healthy (un-impacted) cylinder.

Fig. 5(b) shows a visualization of strains from six embedded optical fibre sensors. In this analysis a cut-off filter at ±50 microstrain was used to remove background noise from measured strains. Overall, the operator had little difficulty in identifying the locations of two 20 J impacts, as seen from Fig. 5(b) and Table 1. The operator provided/adjusted a few inputs for post-processing parameters, and then the visualization as well as locations of detected impacts were automatically calculated. While the evidence for 20 J impacts is very clear, the third 10 J impact is barely noticeable, very close to a detection limit. This is expected since impacts, both with 10 J and 20 J energies are indeed very light in the context of real structures. It is, of course, dependent on the structure and on impact specifics, but severe impacts that noticeably reduce the residual performance have typically order(s) of magnitude(s) higher energies.

Table 1 shows that the location for third (lightest) impact also has the largest detection error. This error is either a consequence of a low signal to noise ratio (damage does not distinguish sufficiently from the background), or it can also be a result of human realization. That is, the actual positioning of the reference system, the placement of OFs, and the actual impact location are somewhat uncertain. Considering previous, the errors in detected impact locations can be seen as reasonable/acceptable and the system of optical fibres is shown to perform well, even with very low impact energies.



a) Instrumented composite cylinder.



b) Three detected impact locations.

Figure 5: The automated identification of three impacts on one tube.

Table 1: Impacts, their locations and errors in detection.

Impact No.	Impact energy	Coordinates	Impact location		
			Planned/realized	Detected from OFs	Error
1	20 J	x-dir. (axial)	10 cm	10.3 cm	+0.3 cm
		y-dir. (hoop)	60°	53°	-7°
2	20 J	x-dir. (axial)	30 cm	31.2 cm	+1.2 cm
		y-dir. (hoop)	240°	239°	-1°
3	10 J	x-dir. (axial)	40 cm	42.3 cm	+2.3 cm
		y-dir. (hoop)	0°	20°	+20°

5.0 CONCLUSIONS

- The interrogation of embedded optical fibre networks was successfully demonstrated as a method for structural health monitoring of composite cylinders. The fine spatial resolution of the OBR technology can be utilized for locating and characterizing impact damages.
- Although the OBR technology has been commercialized and current work utilizes off the shelf equipment, challenges remain regarding practical embedding procedures, with further difficulties mostly in signal interpretation.
- The optical fibres are able to display strains in impacted, yet un-pressurized composite vessels and cylinders. The possibility to inspect unloaded structural components is beneficial from the safety point of view. Further, a 2-D or 3-D visualization of the damage area is helpful for assessing the severity of inflicted damage.

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