Damage Detection in Bolted Joints by Fibre Optics Distributed Sensing

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Abstract. Only recently available, the fibre optic distributed sensing technique is becoming a powerful tool for structural tests. Among the different techniques available, we were using OBR. The OBR uses swept wavelength interferometry (SWI) to measure the Rayleigh backscatter as a function of length in optical fiber with high spatial resolution. The SWI approach enables robust and practical distributed temperature and strain measurements in standard fiber with millimeter-scale spatial resolution over hundreds of meters of fiber with strain and temperature resolution as fine as 1 microstrain and 0.1 °C.

Structural damage detection from direct strain measurements can be done only when the sensors are very closely located to the damage initiation point, which is generally impossible to predict. With the availability of high resolution distributed sensing, strains along a continuous line can be obtained, so a crack crossing or growing near to the sensing line will be detected. As a classical aeronautical structure, an experiment for detecting the fatigue cracks developed at a rivet joint were done. The high potential of the technique has been demonstrated.

Introduction

FBG (Fibre Bragg Grating) sensors have been used for the last 20 years, and they have built up a confidence in its performances. FBGs can measure the strain with accuracy similar to the standard strain gages and extensometers, and also they are comparable in many aspects from a user's point of view. A main advantage is that FBGs can be easily multiplexed, with several sensors in a single optical fibre. A detailed description of the behavior of free and embedded optical sensors can be found at Ref 1 to 5. By using a special technique called SWI, NASA was able to read more than one hundred sensors located in the same optical fibre (Ref 6). The OBR technique is quite similar, both are using the same principle for locating the position; the only difference is that sensors do not need to be engraved at the optical fiber, the naturally occurring refractive index disturbances act as local FBGs, and a continuous reading of the strains along the fibre is obtained, with the inconvenient that it is limited to static measurements, compared to the NASA technique.

A description of the physical principles and applications of the OBR technique has been recently published (ref 7) and will not be repeated here. Understanding the principles is useful, but not absolutely necessary to use the system as a tool for strain and damage detection. The application of the technique to the bolted joints, is done in this paper.
Damage detection based on strain measurements

Very few papers are dealing with this approach, for two main reasons:

a) A local crack will produce a strong change in the strain field at the crack tip, but this perturbation will smooth out very rapidly, so it is nearly unfeasible to detect cracks from strain measurements, unless the sensor happen to be located very close to the crack.

b) Strains measurements are related to the external loads, which are usually unknown, and with a fluctuating component by environmental changes. Consequently, small changes at the strain readings cannot univocally related to growing cracks.

Ref [8] discusses the difficulties of the approach, and Ref [9] are some steps in this direction.

Ref [10] proposed a way to overcome this situation, and they demonstrated (numerically) the validity of the method to the prediction of fatigue damage states of a typical aircraft cracked lap-joint structure (fig 1). The principle is to compare the strain measurements obtained close to the crack prone area (line B) with a remote region (line A). In the uncracked condition, the rivets promotes a uniform small ripple in the strain field (fig 2 A), which will be modified in case a fatigue crack develops around some hole (fig 2B). The authors of the paper Ref 10 were not aware of the possibilities offered by the distributed sensing, so they validated the approach by numerical simulation. In this paper the experimental validation of this approach is done, opening the way for a damage detection procedure, valid over large areas, based on strain measurements.

Figure 1. Typical aeronautic structure, with a riveted joint. Fatigue cracks use to develop at this crack prone area. Sensing line is located close, but not ever this line.
Numerical modelling of a cracked bolted joint

A conventional finite element model of a lap-joint would require a very large number of elements, and a very long computational time. The super-element methodology overcomes the model size and solution time problems, without affecting the solution accuracy, provided that the assumptions of a linear elastic analysis are valid. The substructuring approach is based in the segmentation of the entire structure’s FE model in suitable FE super-elements, taking advantage of the geometrical repetitive pattern. A stiffness sub-matrix comprising only the interface Degrees of Freedom (MDoF) of these super-elements, which is considerably smaller compared to the full stiffness matrix, is calculated and solved. Further details are given at Ref 12.

Solution of the above described super-element model under uniaxial remote tensile stress loading, leads to the calculation of the transversal strains at distinct points. It is interesting to compare the results of the far field, which are uniform, to the results close to the fasteners. In the proximity of the fasteners a ripple is found, which is more intense in the presence of a crack.

![Diagram](image)

**Figure 2.** (from Ref 12) LEFT: Points were strain tranversal strains are calculated

RIGHT: (a) Strain along close and remote paths of a healthy (uncracked) joint.
(b) Strain along close and remote paths of a cracked joint.
Experimental Validation

Two aluminium plates, 1.5 mm thickness and 100 mm width, were joined in a single lap geometry, by two rows of fasteners. Bolted joint design follows classical recommendation for this kind of joints:

- Fastener diameter: 4 mm (total joint thickness, to avoid fastener failure)
- Fastener pitch: 10 mm (2.5 times the fastener diameter, to avoid net tension failure, promoting the safer bearing failure mode)
- Distance to the free edge and between rows: 10 mm (larger than 2 diameters, to avoid shear failure and rows interference).

A continuous plain monomode optical fiber was bonded to the surface, parallel to the row of fasteners, doing several loops before and after load bypass. The bending radius at the optical fibre was large enough to avoid large optical losses.

The optical fiber was near enough to the fasteners, about one diameter, but the distance cannot be fixed with absolute accuracy. Also note that the measured strains are transversal to the applied load, because this is the only practical configuration that can be arranged for joints with a large number of fasteners. In longitudinal direction the influence of the holes is stronger, and transverse cracks would be much more easily detectable.

Figure 3. Experimental set-up. Single lap joint, with two rows of fasteners. Strains are measured perpendicularly to the load direction. Note that two fasteners are missing, to verify if this defect may be identified.
Results.

The obtained experimental strain measurements, for two levels of load, are shown at figure 4. First note that they are negative strains, as correspond to Poisson effect, with a maximum about 150 microstrains. Each peak correspond to one loop of the optical fiber, about 100 mm., as zoomed in the lower figure.

With the current capabilities of the OBR system, there is a balance among the spatial resolution and the strain resolution. Consequently, trying to look into the finest details, or looking for the strain concentration caused by holes of 4 mm, it is not compatible with the low strain level rippling, the strain variation will be fade out by the noise of the measurements. Clearly the two missing fasteners were undetected.

![Graph showing transversal strain measurements](image)

**Figure 4.** Measurements of the transversal strain in the bolted lap joint.
Conclusions

Distributed sensing appears as a powerful tool for strain monitoring and damage detection. Still a main limitation is that interrogation procedure is quite slow, consequently it can only be used for static load cases. This is related to the large number of data to be collected and processed, over 1 Gb, and also to the low signal to noise ratio, which require repeating the measurements several times for averaging. These limitations are overcome if an engraved OF is used as sensor, instead of a standard OF.

Local damage do not change the global strain field, but only near to the damage, so it will be detected only when it happens very close to the sensor location; because damage location is generally unpredictable, detecting damage from strain measurements is rather difficult. A distributed sensor is the only approach to overcome this condition

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References