Abstract: A new type of luminescent optical fibre sensor for structural health monitoring of composite laminates (CFRP) is proposed. The Nd$^{3+}$ doped multi-core double-clad fibre incorporated in composite structure was used as a distributed temperature sensor. The change of luminescence intensity (Nd$^{3+}$ ions) at the wavelength of 880 nm ($^{4}F_{3/2} \rightarrow ^{4}I_{9/2}$) and 1060 nm ($^{4}F_{3/2} \rightarrow ^{4}I_{11/2}$) was used for internal temperature monitoring. The special construction of optical fibre was used as it assures an efficient pumping mechanism and, at the same time, it increases the measuring sensitivity. The linear response with relative sensitivity 0.015 K$^{-1}$ was obtained for temperature range from 30 up to 75$^\circ$C. The manufacturing process of CFRP with embedded optical fibre sensor is also discussed.

Keywords: composite materials; carbon fibre reinforced polymer CFRP; optical fibre sensor; lanthanides doped optical fibre; temperature sensor

1 Introduction

In recent years, there has been a rapid growth in the use of fibre reinforced composite materials in engineering applications and there is a clear indication that this will be continuing. Carbon fibre reinforced composite materials have been widely used in automobiles, ships, aircraft, satellites, sporting goods and others as consequence of their stability, light weight and high stiffness. Particularly, in the automotive and aerospace industries, the use of composites follows from reducing structural weight with consequent fuel saving and performance improvement [1]. Fatigue of materials is a typical problem in industries and occurs in components/structures subjected to dynamic (fluctuating) stresses. Under these circumstances, the failures can occur at stress levels significantly lower than tensile or yield strength for a static load. In metallic structures, damage is often localized in the form of cracks, however, in composite materials, damage accumulates throughout the structure. In terms of composites, the damage mechanisms are also very well-known and include fibre breakage, matrix cracking, debonding, transverse-ply cracking and delamination [2–6]. Several techniques have been used to assess damage evolution in composite structures [3, 7–9]. However, some of them are destructive, but in many situations it is necessary to take decisions with components/structures in-service. For this purpose, it is essential to resort to non-destructive techniques (NDT) in order to detect and evaluate the fatigue damages and the consequent loss of fatigue strength. Temperature, for example, increases with fatigue life, especially when close to final failure, and can be related with damage [5, 6, 10–15]. Reis et al. [9] found three stages, which are related with the different damage mechanisms along the fatigue process. In the first stage the temperature increases as consequence of the deformation energy and from energy produced by damage mechanisms. During the second stage, temperature varies linearly with the number of cycles and an equilibrium between the internal energy produced and material’s energy transference capability occurs, mainly by convection. According with to the authors, beyond deformation energy there is a friction energy produced at the interface matrix-fibres as a result of interface separation produced in the first stage. Finally a sudden increase of temperature occurs and the specimen fails [9]. Therefore, all techniques related with temperature measurement, like
thermography [9, 16–18], is an efficient process to evaluate fatigue damage evolution. On the other hand, embedded sensors provide a high sensitivity to subsurface damage due to their proximity to the damage features [19]. Several works can be found in the literature about Fabry-Perot and Bragg grating sensors to characterize the strain due to mechanical behaviour of the CFRP [20–24]. Other more complex sensors are also based on optical fibres which are capable of detecting strain distribution with high spatial resolution and also gradient temperature evolution [25–27]. However, it is still necessary to develop new techniques involving simplified and reliable methods. In fact, as consequence of their cylindrical geometry, optical fibres are easily adapted as sensors in composite materials. Besides, optical fibres ensure good thermal stability and mechanical strength which do not influence the properties of CFRP. In the present study, the luminescence effect in rare earth (RE) doped optical fibre was used to construct temperature sensor. However, luminescence fibre based sensors usually require large core, high numerical aperture (NA) and multimode fibre to increase coupled pump power thereby improving system sensitivity [28, 29]. In order to maximize the coupling power, a special multi-core construction of fibre doped with Nd$^{3+}$ ions was developed for sensing application. A larger number of cores led to higher concentration of RE ions, which increases the measuring sensitivity [30]. Therefore, a temperature sensor based on Nd$^{3+}$ doped multi-core optical fibre is proposed for these applications and its sensitivity is analysed in the present study.

## 2 Material and experimental procedure

Composite samples were prepared in the laboratory from carbon pre-impregnated Texipreg® HS 160 REM (Seal) with 150 g/m$^2$ and 36% resin and processed in agreement with the manufacturer recommendations, using the autoclave/vacuum-bag moulding process. The laminates were manufactured with the following stacking sequence [0$^\circ$, 90$^\circ$, 0$^\circ$, 90$^\circ$, 0$^\circ$]. The processing setup consisted of several steps: make the hermetic bag and apply 0.1 MPa vacuum; heat up to 125°C at a 3–5°C/min rate; apply a pressure of 0.5 MPa when a temperature of 120–125°C is reached; maintain pressure and temperature for 60 min; cool down to room temperature while maintaining pressure and finally get the part out from the mould. The samples were manufactured in a useful size of 150 × 25 × 2.6 mm$^3$. The optical fibre sensors (250 µm outer diameters) were embedded parallel to the adjacent reinforcement carbon fibres, in the middle plan. The optical fibres typically have diameters bigger than glass fibres used for laminate reinforcement and locally change the structure of CFRP. The “resin eye” effect promotes the cracking of laminate and additional layers are required to reinforce the laminate. These disadvantages can be limited by decreasing the diameter of sensor and will be investigated in the future work. The CFRP laminate with embedded optical fibres is shown in Figure 1. The Nd$^{3+}$ doped double-clad optical fibres are used to measure temperature behaviour. CFRP laminate with embedded fibre was put into the tube furnace with temperature control system. The luminescence spectra was measured at a station equipped with a Stellarnet GreenWave spectrometer and a laser diode ($\lambda_{\text{exc}} = 808$ nm, $P_{\text{max}} = 30$ W) with an optical fibre output. Luminescence spectra were obtained by direct pumping of multi-core optical fibre. The measurement of the influence of temperature on the luminescent properties of the used Nd$^{3+}$ doped optical fibre was performed in the range of 30–75°C. Temperature of CFRP laminate was measured with platinum-rhodium thermocouple.

![Figure 1: The CFRP laminate with embedded optical fibres.](image)

## 3 Results and Discussion

The influence of temperature on NIR luminescence in Nd$^{3+}$ doped optical fibre embedded in composite is shown in Figure 2. Simplified energy diagram of Nd$^{3+}$ ions with observed transitions at 880 nm ($^4F_{3/2} \rightarrow ^4I_{9/2}$) and 1060 nm ($^4F_{3/2} \rightarrow ^4I_{11/2}$) is simultaneously presented. It is evident that an increase in temperature promotes inverse tendency in terms of intensity for all emission bands. In fact it has been noticed that for higher temperatures the probability of multiphoton rate relatively to the $^4F_{3/2} \rightarrow ^4I_{5/2}$ transition (dashed arrow in energy diagram) is higher than for radiative transitions, which leads to the fast depopulation of metastable energy level $^4F_{3/2}$ and, consequently, the luminescence quenching occurs [31].
Carbon laminates with RE doped optical fibre sensors

4 Conclusions

A temperature sensor based on Nd$^{3+}$ doped multi-core double-clad fibre was embedded in CFRP laminate. It is possible to conclude that, for the different emission transitions (wavelength of 880 nm and 1060 nm) and temperatures analysed (30 to 75°C), the signal intensity can be expressed by a linear function. The sensitivity of the signal is 0.015 K$^{-1}$. For a typical maximum service temperature, the sensor studied shows its ability to detect fatigue damages. Finally, this sensor can be easily incorporated in CFRP laminate during fabrication process.

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References

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