DETECTABILITY COMPARISON OF THE SENSORS EMBEDDED IN GLASS-EPOXY WOVEN COMPOSITY LAMINATES

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Abstract

To evaluate and compare detectability of the strain gauge, a thermocouple wire and the PVDF (polyvinylidene fluoride) piezoelectric thin film embedded in Glass-Epoxy 2-D woven composite laminates as health monitoring technologies, these sensors are first embedded into 2-D woven glass reinforced laminate by demanding fabrication technology, then quasi-static and tension-tension fatigue tests are carried out, signal output are simultaneously detected, the interfaces between the sensor and resin are analysed through micrographic observations. The results show that, before the fatigue damage and failure, the resin of the woven composite often present thermo-soft and further results in the temperature rise, in this wise the strain gauge, a thermocouple and PVDF piezoelectric thin film can totally sense the temperature rise and forecast material damage, but because the strain gauge and PVDF thin film also is sensitive to stress, therefore a thermocouple wire is better way to detect thermo-damage of the composite laminates. Comparatively, the source of the damage near PVDF thin film is biggest, next a strain gauge, final a thermocouple wire, the damage often is due to stress concentration at the sensor-resin interfaces.

1 Introduction

To reduce the weight of the aircraft structure, a lot of composite laminates have been used as the wing structures and airframe structure. It is also noticeable that interior damage or delamination of the composite laminates often cannot be directly observed before catastrophic failure, so that, health monitoring technologies has strongly attracted researcher interest. One requirement related to the airframe structure of high-efficiency airplanes is a diagnosis of structural integrity. Many NDI (non-destructive inspection) technologies have been contrived and developed for this objective. When in-flight monitoring is needed, the FBG (fiber Bragg grating) sensors and AE (acoustic emission) sensors are promising sensing devices [1, 2]. Recent advances of health monitoring technologies have resulted in development of micro-dimensional sensors that can be embedded into composite laminates [3, 4]. On-line health monitoring sensors must meet three requirements. They must be small in size (with no damage to the structure), offer the possibility of being located in remote and inaccessible areas of the structure, and they must be able to transmit information to a central processor [5]. It is also known that the laminates embedded sensors for structural health monitoring can degrade their tensile, compressive and fatigue properties when the inclusion or damage exceed a critical size [6]. In this paper, the strain gauge, a thermocouple wire and the PVDF (polyvinylidene fluoride) piezoelectric thin film are embedded in Glass-Epoxy 2-D woven composite laminates as health monitoring technologies, detectability of these sensors is examined and analysed.

2 Experimental procedure and results

2.1 Sample preparation

In the present work, the sensors is first embedded in the 2-D glass woven, the Glass-

Epoxy 2-D woven composite laminates consist of 6 layer glass woven, see Fig. 1 as paving orders, the glue in the preparing sample is PA(polyamide) epoxy resin. In this work three kinds of sensors (see Fig.2) are embedded in the 2-D woven E-glass reinforced laminates by using epoxy resin, they are the strain gauge, a thermocouple wire and PVDF piezoelectric thin film, respectively. During resin solidification, the composite panel then is clamped to a thick glass plate mounted in a vise for 24 hours.

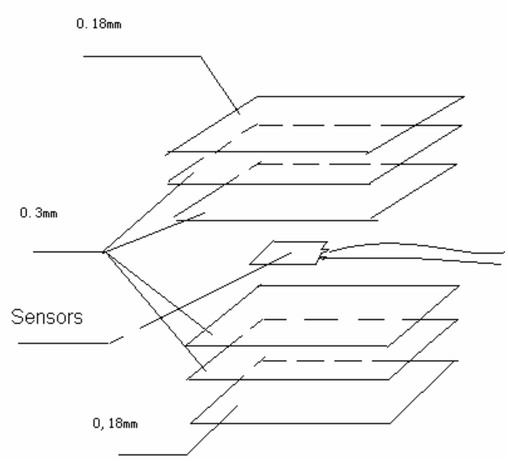

Fig. 1 Embedded sensors in 2-D glass woven layers

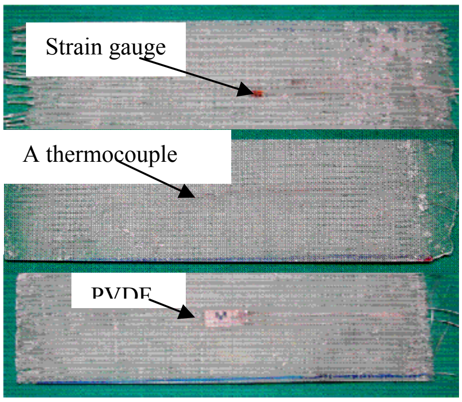

Fig.2 The woven laminates with embedded different sensors

2.2 Temperature sensitivity tests

In order to measure temperature sensitivity of Glass-Epoxy 2-D woven composite laminates (sensors are not embedded), the cubic sample of this laminate material is loaded along in-plane of the woven，seen as Fig. 3. The quasi-static and fatigue tests are totally performed using a MTS Teststar machine (seen in Fig. 4) in the present paper. The quasi-static tests are first carried out at different temperatures and a strain rate of 0.001/s, the results are shown as Fig. 5. It is noticed that strong temperature dependence of this material is seen when the temperature changes from 218K to 373K. In general the epoxy resin belongs to polymer and viscoelasticity material. Thus it is very sensitive to temperature. To further verify strain rate sensitivity for this epoxy resin, the epoxy resin is made to cylindrical shape by solidifying the resin. The cylindrical samples are loaded at different strain rate by using a MTS Teststar machine, the results is shown as Fig. 6. This epoxy resin is also very sensitive to strain rate. According to this testing result, it can further infer that this epoxy resin is highly sensitive to loading frequency under fatigue testing condition.

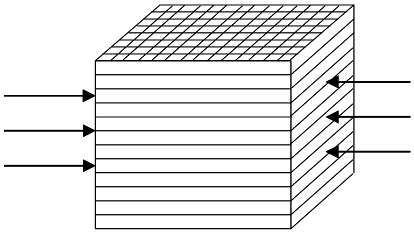

Fig. 3 In-Plane loading direction

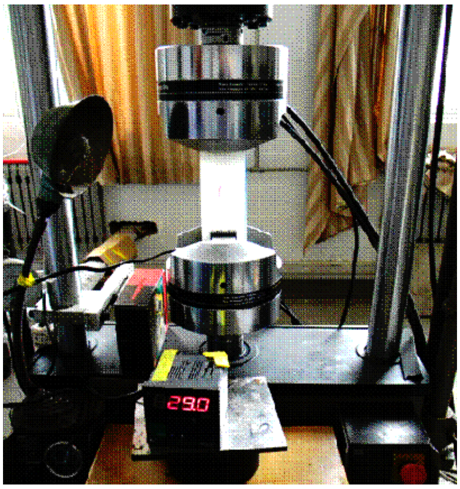

Fig. 4 A MTS testing machine

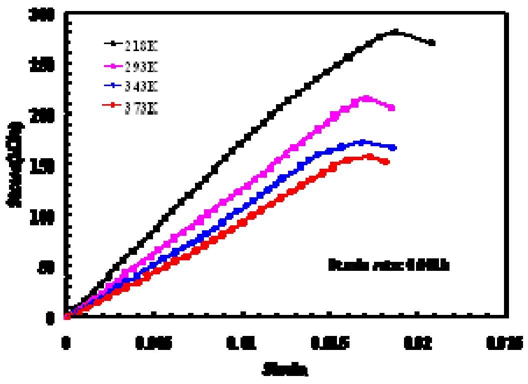

Fig. 5 Stress-strain curves at different temperatures and a strain rate of 0.001/s

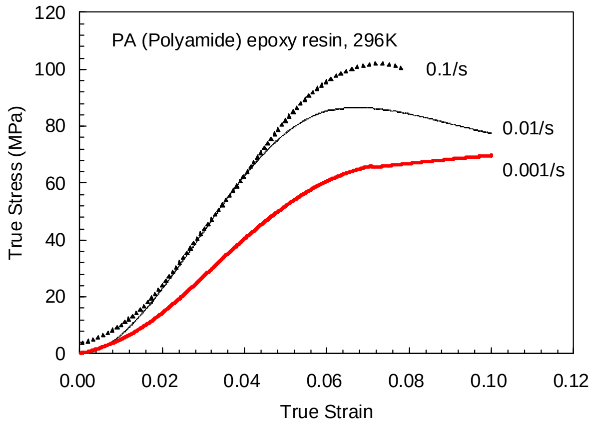

Fig. 6 Stress-strain curves of samples of PA (polyamide) epoxy resin at different strain rates

It is well known that the fiber reinforced resin composite finally fails under fatigue load from the micro-damage accumulation, the crack origination, the epoxy resin matrix crack, the delamination between layer and layer of the laminates or between the resin and the layer, etc. If the fatigue or vibration frequency is high, because the epoxy resin matrix shows remarkable viscoelasticity or viscous plasticity depending of the temperature and cycle load, seen as Fig. 7, the anelasticity hysteresis loop is deformed during fatigue progress, this further will result in interior heat accumulation inside the laminate composite with increasing cycles. This infers 2-D woven E-glass reinforced laminates can be delaminated or damaged as interior heat accumulation because the fatigue loading can result in temperature rise.

Such that, measuring temperature rise is a reasonable health monitoring way for the glass reinforced laminate.

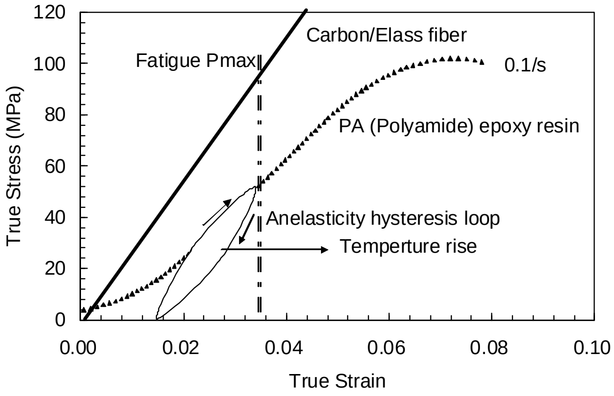

Fig. 7 Temperature rise origin inside the composite

3 Detectability comparison

3.1 Not fault tests

To compare detectability of the sensors, the strain gauge, a thermocouple wire and the PVDF (polyvinylidene fluoride) piezoelectric thin film are embedded in Glass-Epoxy 2-D woven composite laminates as health monitoring technologies, then they are loading under the same constant amplitude fatigue loading as a stress ration of 0.1 (R = 0.1), respectively. Fig. 8 is the measuring results of the strain gauge under the constant fatigue loading. The fatigue loading generally is a constant strain processes, therefore, this max strain continuously increases with increasing the fatigue cycles, that is possibly due to the strain gauge temperature sensitivity and residual strain.

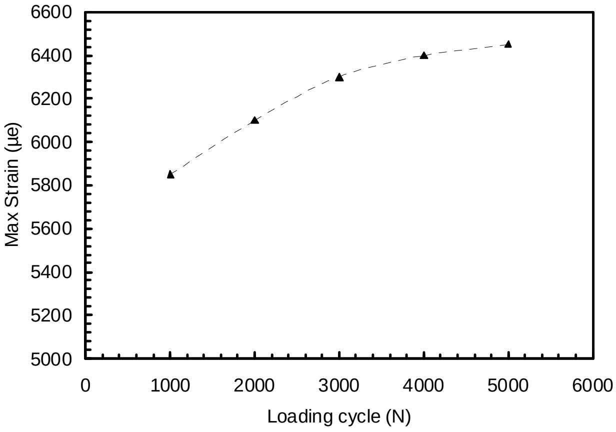

Fig. 8 Max strain as a function of loading cycle for the strain gauge

Fig. 9 is the measuring results of the PVDF (polyvinylidene fluoride) piezoelectric thin film under the constant fatigue loading. The voltage output of the PVDF first increases, then keeps continuously decreases with the fatigue cycles. It is known that the PVDF can measure temperature and deformation, so that this decreasing process possibly is due to failure or delamination of the composite.

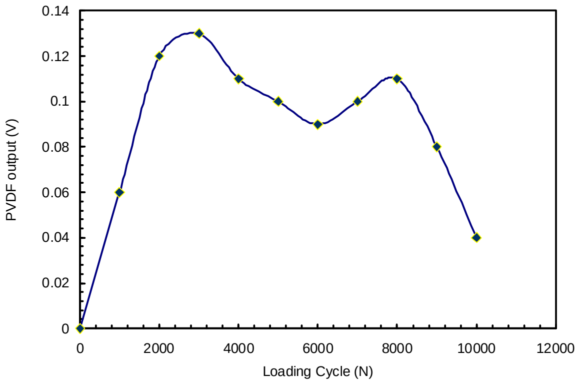

Fig. 9 Max output as a function of loading cycle for the PVDF piezoelectric thin film

Fig. 10 is the measuring results of a thermocouple wire under the constant fatigue loading. It is seen that temperature is monotonously rise with increasing cycles although the fatigue loading generally is a constant sine wave. Therefore a thermocouple is better way for temperature rise measurement because it is purely temperature sensor.

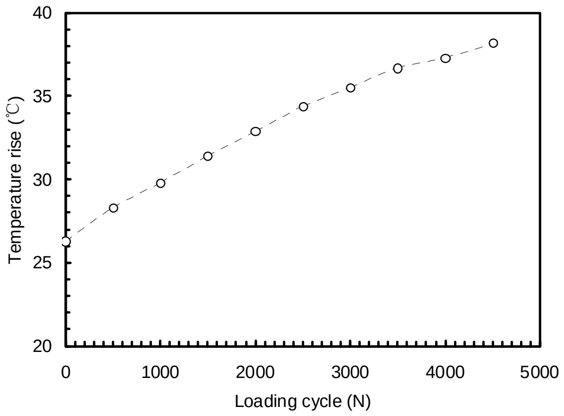

Fig. 10 Temperature as a function of loading cycle for a thermocouple wire

When fatigue loading frequency changes from 0.1Hz to 30Hz under max fatigue stress of 8KN and a stress ratio of 0.1, the temperature rise results are shown in Fig. 11, it is also seen that temperature rise almost is zero when loading frequency is below 1Hz. When loading frequency is over 10Hz, temperature rise is fast, this suggests that, when load is higher, it should avoid higher frequency loading whether in test or not in real use for the composites.

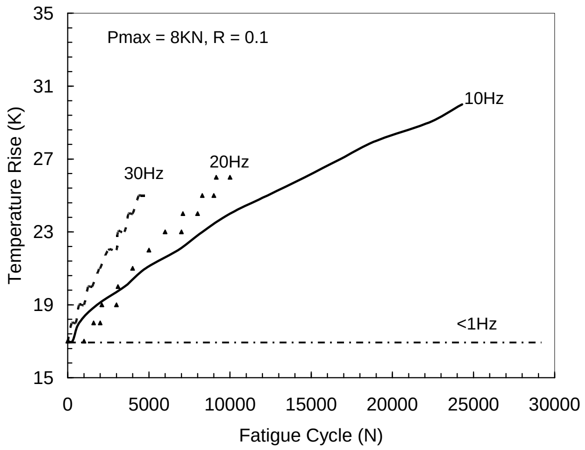

Fig. 11 Temperature as a function of loading cycle for a thermocouple wire under different loading frequency

3.2 Pre-fault tests

In order to check detectability of the sensors for pre-fault damage samples, the strain gauge, a thermocouple wire and the PVDF (polyvinylidene fluoride) piezoelectric thin film are embedded in the pre-fault Glass-Epoxy 2-D woven composite laminates, the pre-fault is about 10mm diameter and is 5mm distance from sensors, seen as in Fig. 12. A typical testing result is shown in Fig. 13 for a pre-fault damage sample with a thermocouple wire. It is seen that the temperature rise increases when the fatigue cycles is over 15000 at 10KN max loading, actually the sample finally fails at about 22000 cycles. The double-notch sheet specimen with a pre-fault damage also is checked by a thermocouple wire, seen in Fig. 14. In Fig.14, max loading is 7.2KN, before the sample is failed, the temperature rise is very rapid (to 45 °C). These results further verify that the temperature measurement by a thermocouple wire can be effectively detect damage emergence and further can prevent catastrophic failure.

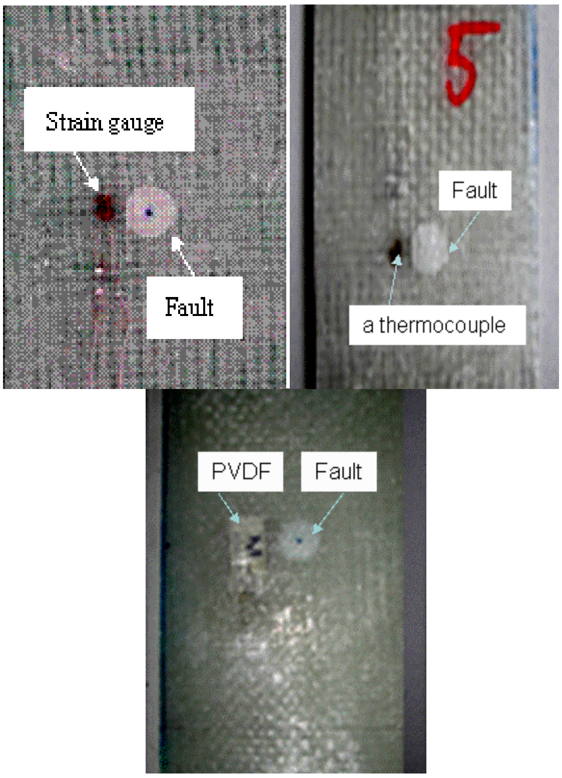

Fig. 12 The woven laminates with embedded different sensors and 10mm diameter pre-fault damage

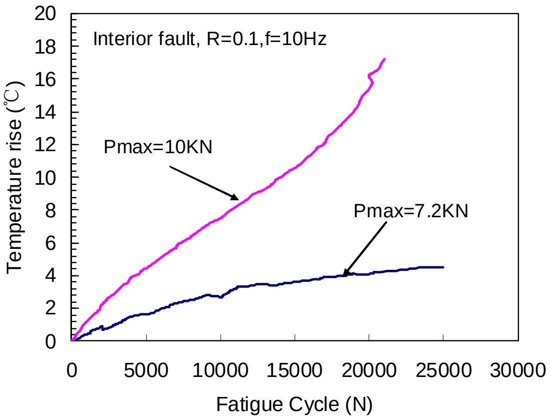

Fig. 13 Temperature as a function of loading cycle for pre-fault damage sample with a thermocouple wire

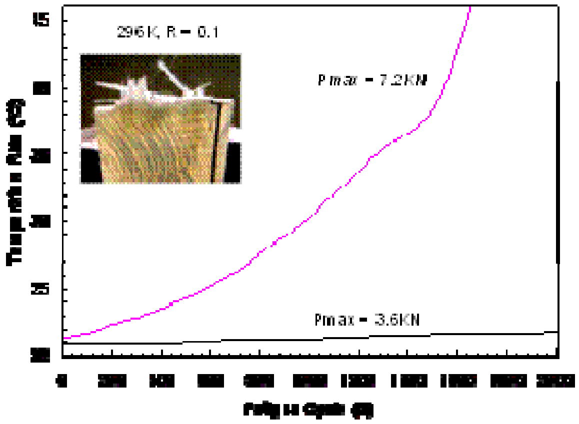

Fig. 14 Temperature as a function of loading cycle for pre-fault damage sample with a thermocouple wire

Here it must emphasize that the composite material is generally very sensitive to the local stress concentration, the laminates with embedded sensors have been shown remarkable fatigue performance loss. The cross section of the laminates including the strain gauge, a thermocouple wire and the PVDF (polyvinylidene fluoride) piezoelectric thin film are examined by an optical microscope. Fig. 15 and Fig.16 show a micro-crack or micro-delamination between sensors and the epoxy resin. These micro-cracks or damages actually results in fatigue performance fail of the composite embedded sensors. Therefore, the composite embedded sensors must be carefully prepared and manufacture.

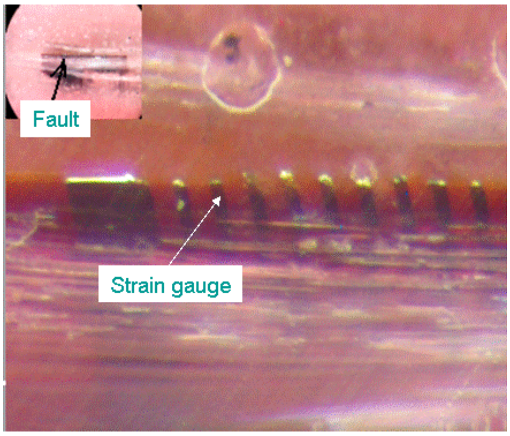

Fig. 15 Micrograph of a section of the laminate embedded a strain gauge

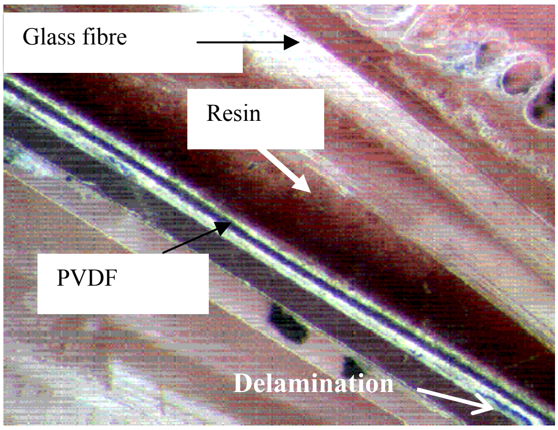

Fig. 16 Micrograph of a section of the laminate embedded the PVDF

Conclusions:

(1) Before the fatigue damage and failure, the woven composite often present the temperature rise;

(2) The strain gauge, a thermocouple wire and PVDF piezoelectric thin film can totally sense the temperature rise and forecast material damage, but because the strain gauge and PVDF thin film also is sensitive to stress, therefore, a thermocouple wire is better way to detect thermo-damage of the composite laminates;

(3) Comparatively, the source of the damage near PVDF thin film is biggest, then a strain gauge, final a thermocouple wire, the damage often is due to stress concentration at the sensor-resin interfaces.

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