ONE-LAMINA CARBON FIBER POLYMER-MATRIX COMPOSITE AS A SENSOR OF STRAIN AND DAMAGE

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Introduction

The sensing of the strain, stress and damage of a solid is important for structural solids, such as aircraft, automobile, ships, boats, wind turbines and concrete components. Prior sensing of the strain, stress and damage of a solid involves the use of a sensor (gauge) comprising a bundle of electrically conductive fibers (such as carbon fibers) and two electrical contacts (i.e., terminals) at the two ends of the bundle for measuring the electrical resistance of the bundle [1]. Ref. 1 teaches that irreversible change in the structure of a carbon fiber bundle (the sensor) during loading results in an irreversible increase in the electrical resistance of the fiber bundle. Furthermore, Ref. 1 teaches the use of a sensor with the fiber bundle rupture strength less than the strength of the structure beneath the sensor (i.e., the structure to be evaluated), so that the irreversible resistance increase associated with the fiber bundle rupture occurs before the structure breaks, thereby enabling the sensor to provide warning of the damage of the structure. This means that the sensor must be tailored for the structure to be evaluated by consideration of the rupture strength of the sensor relative to that of the structure to be evaluated. This tailoring limits the applicability of a sensor and means that unexpected premature failure that occurs at stresses below the expected fracture stress may not be detected by the tailored sensor, since the unexpected premature failure stress may be less than the stress for the rupture of the fiber bundle in the sensor. The tailoring also means that damage evolution cannot be sensed.

Prior work by Wang and Chung [2] showed the feasibility of a 24-lamina quasi-isotropic $[0/45/90/-45]_{3s}$ multidirectional carbon fiber epoxy-matrix composite laminate to sense its own flexural strain and damage. The strain is effectively indicated by the surface resistance measured by using four electrical contacts on either of the two opposite surfaces of the composite laminate. The damage is effectively indicated by the resistance (known as the oblique resistance) measured by using two contacts on each of the two surfaces (with the outer one of these two contacts on the same surface serving as a current contact and the inner one of these contacts serving as a voltage contact), such that the contacts on the opposite surfaces are not directly opposite. The surface resistance does not provide a good indicator of damage [2]. The oblique resistance measurement involves the passing of a current through the thickness of the composite, though the direction is oblique (i.e., at an angle to the through-thickness direction). The oblique resistance measurement requires that the composite be conductive throughout its thickness, whereas the surface resistance measurement requires only the surface region of the composite to be conductive. Thus, the scope of applicability of the method involving oblique resistance measurement is relatively narrow. For example, it is not applicable to glass fiber composites, which are not conductive. Moreover, the damage sensing characteristics are complicated.

This paper is aimed at providing a sensor for sensing the strain, stress and damage of a solid. The solid can be electrically nonconductive (e.g., a glass fiber polymer-matrix composite) or conductive (e.g., carbon fiber polymer-matrix composites). In case that the solid is conductive, the lamina should be electrically insulated from the solid, so that the current flowing in the lamina cannot penetrate into the solid.

Sensor concept

The sensor reported here comprises (i) a one-lamina polymer-matrix composite containing continuous, substantially parallel, spatially distributed, and electrically conductive fibers, and (ii) electrical contacts in contact with and positioned on the exterior surface of the lamina. The fibers are substantially in the plane of the lamina. The lamina is in contact with and bonded (as a coating) to a selected surface of the solid. The surface of the solid is preferably in a region of the solid where stress is substantial. The arrangement of the fibers is such that adjacent fibers make contact with one another at points along their length, thereby enabling detouring of the electric current from one fiber to an adjacent fiber in the lamina, so that the degree of damage of the lamina correlates with the degree of damage of the solid both before and after substantial damage of the fibers in the lamina. The electrical contacts are not in contact with the solid. Each of the electrical contacts is in contact with a substantial fraction of the outermost fibers of the lamina, as achieved in this work by sanding (using a 600 grit sand paper) the outer surface of the lamina prior to electrical contact application. Without sanding, the sensor is ineffective for either surface. The outermost fibers are not proximate to the solid. The electrical contacts comprise two for passing a current and two for measuring the voltage, as achieved in this work by having each contact in the form of a strip oriented transverse to the fiber direction of the lamina. The contacts for measuring the voltage are within the region of flow of the current passed by the contacts for passing a current. The contacts enable measurement of the electrical resistance. The current is substantially parallel to a substantial proportion of the fibers. In this work, the fibers are carbon. A small fiber diameter facilitates adjacent fibers in a lamina to make contact at a plurality of points along their length.

Sensor characteristics

The test vehicle is an epoxy-matrix composite (4.5 mm thick) with 24 laminae (thickness 0.2 mm per lamina), such that the outer two laminae are made of carbon fibers and the inner 22 laminae are made of glass fiber. Thus, this test vehicle has two sensors, each in the form of a one-lamina carbon fiber epoxy-matrix composite. The solid to be evaluated by the sensors is the 22-lamina glass fiber epoxy-matrix composite, which is nonconductive. The two sensors are on the two opposite surfaces of the solid. Under flexure, the surfaces of the solid (and hence the sensors) are at positions of maximum stress. One surface is at maximum tensile stress while the opposite surface is at maximum compressive stress. The test vehicle is fabricated from carbon fiber epoxy prepreg and glass fiber prepreg with the same type epoxy resin (DA409). The carbon fiber is IM6 (PAN-based). The glass fiber is S2. The resin content is 45%. Electrical contacts are silver paint in conjunction with copper wire.

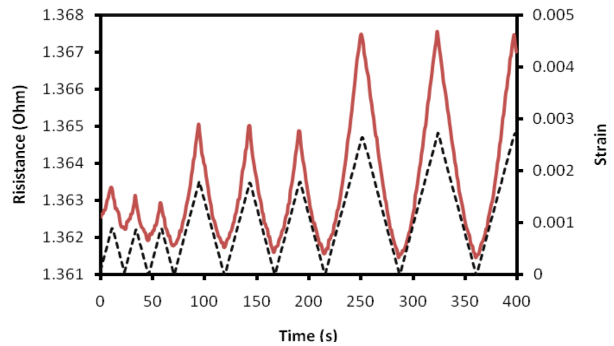
Figure 1 shows the variation of the surface resistance of the sensor on the tension surface and the surface resistance of the sensor on the compression surface during flexure at progressively increasing flexural strain up to 0.003, with three loading cycles for each strain amplitude. The tension surface resistance increases reversibly, while that on the compression side decreases reversibly in every cycle. The fractional change in resistance per unit flexural strain in the first cycle (cycle with the lowest deflection amplitude) is 37 for the tension side and 66 for the compression side. The extent of resistance change increases with the strain amplitude. The noise is lower for the tension side than the compression side.

The tension surface resistance of the unloaded state increases irreversibly as the strain amplitude increases within the elastic regime. This is attributed to minor damage, which increases continuously as the strain amplitude increases. The compression surface resistance increases significantly, abruptly and quite reversibly in every cycle near the completion of unloading when the strain amplitude exceeds 0.015. The tension surface resistance increases significantly and quite reversibly in every cycle upon loading when the strain amplitude exceeds 0.025, such that the increase is very abrupt, occurring at the maximum load, when this significant increase occurs for the first time. These resistance increases on both tension and compression surfaces is attributed to fiber breakage. Such damage starts to occur on the compression side before the tension side. The minimum value of the compression surface resistance occurs at the maximum load of a cycle and it increases irreversibly cycle by cycle at high strains (above 0.02), due to damage. Major damage is detected more sensitively by the sensor on the compression surface than that on the tension surface.

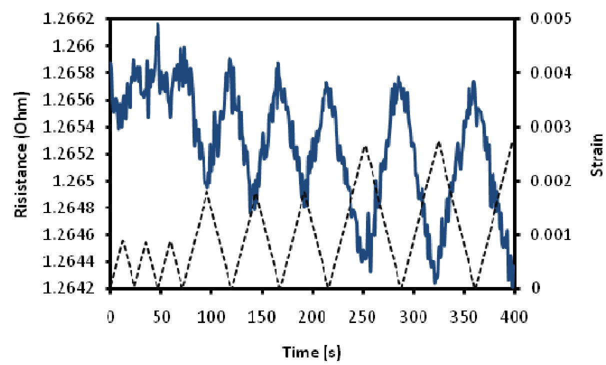
For a sensor in the form of a two-lamina carbon fiber composite, the strain sensing effectiveness is lower (with the fractional change in resistance per unit strain being lower and the resistance change being more noisy and less reversible) and the damage sensing is less quantitative. The damage sensing characteristics are simpler and easier to interpret than those of previously reported 24-lamina carbon fiber composites without glass fiber [2].

Conclusions

This paper provides a sensor for sensing the strain, stress and damage of a solid. The sensor comprises a one-lamina polymer-matrix composite. Upon flexure in the elastic regime, the resistance of the compression surface decreases reversibly upon strain, while that of the tension surface increases reversibly. For the compression surface, the fractional change in resistance per unit strain is essentially independent of the strain. The ability to sense damage and its evolution is due to the sensor increasing its surface resistance upon any level of damage. This ability stems from the fiber-fiber contacts in the transverse direction.



(a)



(b)

Fig. 1 Strain sensing characteristics of a one-lamina carbon fiber epoxy-matrix composite sensor attached to a solid in the form of a 22-lamina glass fiber epoxy-matrix composite. The resistance is obtained during repeated flexural loading at progressively higher strain amplitudes up to 0.003. The resistance is shown by solid curves. The flexural strain is shown by dashed curves. (a) Tension surface. (b) Compression surface.

References

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[2] Wang S and Chung D D L 2006 Self-Sensing of flexural strain and damage in carbon fiber polymer-matrix composite by electrical resistance measurement Carbon 2006;**44**(13):2739-51.