Damage detection using self-sensing concepts

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Abstract: Self-sensing refers to the structural material sensing itself. Real-time self-sensing of damage in carbon fibre polymer–matrix composites by electrical resistance measurement is reviewed. The resistance changes irreversibly upon damage, as shown for damage inflicted by flexure, tension, fatigue, and impact. Delamination increases the through-thickness resistance. Fibre breakage increases the longitudinal resistance. The oblique resistance, as measured at an angle between the longitudinal and through-thickness directions, is particularly sensitive. Minor flexural damage causes the oblique resistance in the unloaded state to decrease. Current spreading enables the sensing of localized damage by measurement away from the damage, though it reduces the spatial resolution of the sensing. The resistance method is more sensitive than the potential method. Two-dimensional sensing is complicated by the anisotropic spreading of the current. Thermal damage and through-thickness (fastening) compression effect are indicated by the contact resistivity of the interlaminar interface. The through-thickness compression effect is alternately indicated by the longitudinal volume resistivity. The condition of a composite fastening joint is indicated by the contact resistivity of the joint interface.

Keywords: damage, sensing, detection, composites, electrical resistance, carbon fibre, polymer

1 NEED FOR DETECTION OF AEROSPACE STRUCTURAL DAMAGE

Owing to the strategic importance of airframes, helicopter rotors, satellites, space-launch and aerospace flight vehicles, and other aerospace structures, damage of such structures is of great concern to the structural performance, operation reliability, homeland security, and human safety. The damage appears in different types, levels, and locations in composite structural components. The different types, levels, and locations of damage have different effects on the fatigue life of a composite structural component under a given fatigue load [**1**]. It may be relatively easy to predict the fatigue life of a composite structural component with different damage levels based on a series of laboratory fatigue tests on identical specimens if the damage level is the only controlling factor. However, because of the various effects of the types, levels, and locations of damage, it is not reliable to predict the fatigue life of a particular structural component based on laboratory tests in a simplified approach, unless the above factors are considered in a systematic manner. Thus, the monitoring of the location and extent of damage (including all types of damage) of the structural component is necessary. The need for monitoring is heightened by the aging of the flight vehicles, especially the 2001 accident of a passenger jet due to a composite joint failure of the vertical tail wing section [**2**].

Damage in a structure can occur due to stress and its variation (which can cause fatigue, creep, impact damage, and so on), temperature and its variation and non-uniformity (which can cause thermal stress and thermal fatigue), lightning, corrosion, moisture, and other factors. The stress may be due to turbulence, live loads (such as the accidental dropping of a heavy object), the impact by objects such as birds, and the fastening of a component to another in a structure (such as the fastening of the tail section of an aircraft to the main body of the aircraft). Temperature variation may be due to the change in ambient condition (such as the difference in temperature between air and ground), re-entry of a spacecraft to the atmosphere, deicing, and repair (such as welding and soldering).

2 COMPOSITES FOR AEROSPACE STRUCTURES

Owing to the requirement of low density, aluminium (a lightweight metal) and polymer–matrix composites are most commonly used. Because of the high modulus of carbon fibre, the composites are reinforced with continuous and oriented carbon fibre at a high volume fraction that is typically around 60 per cent. Compared with aluminium, the composites are attractive in their high strength, high modulus, and low density.

The propensity for damage and the type of damage depend on the structural material. Structures made of carbon fibre polymer–matrix composites are prone to lightning damage, due to the low electrical conductivity of the composites compared with that of metals. The epoxy used in polymer–matrix structural composites tends to degrade in the presence of moisture. In the presence of moisture and heat (i.e. hygrothermal condition), the degradation tends to be even more severe. Furthermore, due to the difference in thermal expansion coefficient between the fibre and the polymer matrix, the fibre–matrix interface can degrade when the temperature is too high or too low, thereby leading to composite degradation. The thermal damage is worsened when the temperature excursion occurs repeatedly. On the other hand, structures made of metals such as aluminium suffer from corrosion, creep, and plastic deformation. Plastic deformation (yielding) causes the dimensions of a component to change irreversibly. In general, both metallic and composite structures are liable to suffer from damage.

The reliability of composites is complicated by the fact that flaws such as fibre waviness and delamination (local separation of the laminae, which refer to the fibre layers or plies) can occur in a composite component even before its initial structural use and that the type and spatial distribution of the flaws in a composite component can vary from piece to piece of the same component, even though the process of manufacturing is identical for the various pieces. The inherent flaws, though small in size, can be the sites for the initiation and growth of more dangerous flaws during the use of the composite component. The growth can occur slowly, as in the case of fatigue. The variability in quality tends to be smaller for metallic components than composite components. As a result, the prediction of the service life of a composite component based on prior use records of similar components is relatively unreliable. This situation makes the need for structural health monitoring greater for composite components than metallic components.

Another complication of composite components relates to their anisotropy. The fibres are commonly in the form of laminae, with the fibres in the plane of the laminae. As a consequence, the strength and modulus of a composite are much higher in the plane of the laminae (particularly in the direction of the fibres) than in the direction perpendicular to the laminae (known as the through-thickness direction). The interface between adjacent laminae (known as the interlaminar interface) constitutes a weak link, so composites are prone to damage in the form of delamination. In contrast, metals tend to be quite isotropic.

Owing to the above considerations, structural health monitoring is more critically needed for composite components than metal components. The monitoring means sensing the damage, preferably in real time, so that the damage can be detected in a timely fashion. Thus, this paper is focused on the detection of damage in carbon fibre polymer–matrix composites.

3 DAMAGE SENSING TECHNOLOGY

Visual inspection and tapping are the most widely used methods of damage assessment of aircraft. However, they are insufficient in sensitivity. Visual inspection cannot detect subsurface flaws, such as subsurface delamination in the fibre composite. In general, flaws do not necessarily initiate at the surface. Moreover, visual inspection cannot detect flaws that are smaller than what the human eyes can see. Tapping can detect subsurface flaws, but only those that are macroscopic.

Ultrasonic inspection [**3–5**] is more sensitive than visual inspection or tapping, but it is typically limited to flaws that are of size at least a few millimetres. Since a reinforcing fibre in a structural composite is typically around 10 μm in diameter, the breaking of as many of 1000 fibres may escape detection by the ultrasonic technique. In addition, delamination cracks cannot be detected by ultrasonics until the cracks have grown to a sufficiently large size.

Damage sensing can be performed by the use of sensors that are embedded in a structure or attached on the surface of the structure. Alternately, it can be performed by using the structural material itself as the sensor. The latter method is referred to as self-sensing [**6**]. The attraction of self-sensing relates to the fact that a structural material is relatively low in cost and high in durability (attributes that are required for any practical structural material).

Self-sensing is attained by exploiting the intrinsic behaviour of a structural material [**6**, **7**]. An example of such behaviour is the effect of damage on the electrical resistivity of a carbon fibre composite [**6–9**]. This effect was first reported by Baron and Schulte in 1988 [**8**]. Although electrical contacts and a meter are typically needed in electrical resistance measurement and the meter needs to send a small current to the specimen under test in order to measure the resistance, the composite is the sensor. Neither the fibres nor the electrical contacts are sensors.

A variation of the resistance method of self-sensing involves the combined use of glass fibre (non-conductive) and carbon fibre in the same direction in the same composite, with the carbon fibre designed to fracture, thereby increasing the electrical resistance, while the glass fibre remains to bear load [**10**, **11**]. The resistance method is to be distinguished from self-sensing by using fibres (e.g. glass fibres acting as light guides) that are themselves sensors [**12**].

Advantages of self-sensing compared with the use of embedded or attached devices are low cost, high durability, large sensing volume, and absence of mechanical property loss. Mechanical property loss tends to occur in the case of embedded sensors, which are much larger than the diameter of carbon fibre, thereby causing bending of the carbon fibre around an embedded sensor. Durability is particularly poor for attached devices, which can be detached. Embedded sensors also suffer from the difficulty (or impossibility) of repair. Examples of embedded or attached sensors include optical fibres and piezoelectric sensors.

In spite of its advantages, self-sensing has received less attention than the use of embedded or attached devices. This is due to the scientific challenge of developing self-sensing structural materials. Although much attention has been given to the mechanical properties and durability, relatively little attention has been directed to the sensing behaviour, which relates to the electrical behaviour. This paper is a review on the self-sensing behaviour of carbon fibre polymer–matrix composites.

4 SELF-SENSING OF DAMAGE BY ELECTRICAL RESISTANCE MEASUREMENT

The measurement of electrical resistance is most reliable for intermediate levels of resistance, such as resistance in the range from 0.1 Ω to 1 MΩ [**13**]. A large resistance exceeding 1 MΩ is relatively difficult to measure, due to the need for a high voltage in order to pass a current through the large resistor. Conventional meters are incapable of measuring resistances exceeding 1 MΩ, due to their voltage limitation. A small resistance below 0.1 Ω poses a challenge in relation to measuring a small resistance change upon damage of the component under test. The lower limit of the resistance to be measured depends on the precision of the meter used.

Metals tend to be too conductive, so that their resistance is too low for effective sensing. The same problem applies to metal–matrix composites. On the other hand, continuous carbon fibre polymer–matrix composites tend to be in a resistance range that is well suited for sensing by resistance measurement. For a given composite specimen, the surface resistance is higher than the volume resistance. Obviously, the larger the specimen, the higher is the resistance. For small laboratory carbon composite specimens, the surface resistance tends to in a range that is more suitable for accurate resistance measurement than the volume resistance.

Because carbon fibres are much more conductive electrically than the polymer matrix, the electrical conductivity of a composite is affected by damage [**6–9**, **14–22**]. Damage in the form of fibre breakage causes the electrical conductivity in the fibre direction of the composite to decrease. On the other hand, damage in the form of delamination causes the electrical conductivity in the through-thickness direction of the composite to increase, as explained below.

Although the polymer matrix is electrically non-conductive, the through-thickness conductivity of a composite is never zero, due to the flow of the resin during composite fabrication and the waviness of the fibre, and the consequent direct contact of fibres that belong to adjacent laminae. The contact occurs at certain random points of the interlaminar interface. When delamination occurs, a crack occurs at this interface. This crack diminishes the extent of fibre–fibre contact, thereby causing the through-thickness conductivity of the composite to decrease.

As a consequence of the effects mentioned above, the electrical conductivity (the reciprocal of the electrical resistivity) provides an indicator of the damage. By selecting the direction of measurement of the conductivity, the type of the damage can be selectively detected.

A related method of damage self-sensing involves the measurement of the capacitance in the through-thickness direction of the composite [**14**, **19**]. The capacitance decreases upon damage in the form of fibre–matrix debonding.

5 ELECTRICAL CONFIGURATIONS FOR SELF-SENSING

The measurement of electrical resistance usually requires electrical contacts. The accuracy tends to be lower for radio-frequency wireless methods [**23**]. By placing the electrical contacts at selected regions of a structure, the resistance may be measured at selected regions. This means that the information on the spatial distribution of damage can be obtained by the measurement of the resistivity distribution.

In general, electrical resistance measurement can be performed using the four-probe method or the two-probe method. The four-probe method uses four electrical contacts that are ideally lined up in the direction of the resistance measurement. The outer two contacts are for passing current, whereas the inner two contacts are for voltage measurement. In contrast, the two-probe method uses two contacts, each of which is both for passing current and for voltage measurement. The two-probe method suffers from the fact that current goes through the voltage measuring leads and, as a consequence, the measured voltage includes the contact potential drop. In case the specimen resistance is low compared with the contact resistance, the resistance obtained by using the two-probe method is highly inaccurate, as it reflects mainly the contact resistance, which is not the quantity to be measured. In the four-probe method, negligible current goes through the voltage contacts, since no current goes through an ideal voltmeter. Thus, the resistance measured by the four-probe method essentially excludes the contact resistance and reflects accurately the resistance of the specimen between the voltage contacts. For carbon fibre polymer–matrix composites, the resistance is not high enough for the two-probe method to be reliable [**24**]. Therefore, the four-probe method is recommended.

An additional problem with the two-probe method relates to the possible degradation of the electrical contacts upon strain or damage of the specimen under test. The degradation of the contacts causes the contact resistance to increase, thus affecting the resistance that is obtained by using the two-probe method [**25**, **26**]. In the case of the four-probe method, degradation of the contacts has relatively little effect on the measured resistance, unless the degradation is excessive. The resistance obtained by using the four-probe method tends to be less noisy than that obtained by using the two-probe method [**25**].

Electrical resistance usually refers to the resistance of a volume, so it is known as the volume resistance. The volume resistance should be measured with a current that goes throughout the whole cross-sectional area perpendicular to the direction of resistance measurement. In other words, the current density is uniform throughout the cross-section. To attain the uniformity, the current contacts should be such that they allow complete current penetration. As an example, consider the measurement of the resistance in a direction in the plane of a composite laminate. A current contact that allows complete current penetration can be in the form of a wire that goes through a through-hole in the direction perpendicular to the plane of the laminate. The wire must be in electrical contact with all the laminae, so it should be electrically connected to the wall of the through-hole by using a conductive adhesive or other conductive media. Silver particle filled epoxy is a conductive adhesive that has been shown to perform well both electrically and mechanically [**26**, **27**]. However, this type of electrical contact suffers from its intrusiveness, as the drilling of a hole may cause some local damage to the composite.

An electrical contact that is less intrusive than the through-hole contact is a surface contact, as provided by applying a conductive medium, such as silver paint, on a surface of the composite. The conductive medium serves to connect electrically the composite surface to a lead wire that goes to a meter. In order to enhance the mechanical integrity and hygrothermal stability of the surface electrical contacts, each contact (such as one made by using silver paint) may be coated with non-conductive epoxy [**26**].

By using current contacts that are on the surface, the current penetration can be limited. The extent of current penetration from these contacts depends on the proximity to these contacts within the region between the two current contacts. Within this region, the current penetration increases, as the distance from either current contact increases [**13**]. Thus, in case the current contacts are sufficiently far apart, current penetration may be complete for a part of the region between the current contacts. The extent of current penetration also depends on the degree of electrical anisotropy, the dimensions of the region for the resistance measurement, and the contact resistance. The electrical anisotropy of the composite is such that the resistivity in the through-thickness direction is higher than that in the fibre direction by several orders of magnitude. This anisotropy increases the difficulty of current penetration in the through-thickness direction. Because of the likelihood of incomplete current penetration, the resistance obtained by using current contacts that are on the same surface is referred to as the surface resistance.

Although a composite may be quasi-isotropic, the fibres are unidirectional within a lamina. The measurement of the surface resistance by using current contacts that are at two points on a composite surface is complicated by the unidirectional nature of the fibre in the surface lamina. The strong electrical anisotropy in the surface lamina causes the current to spread in the fibre direction as it travels from one current contact to the other. If the current contacts are positioned to send current in the transverse direction, current spreading is substantial in the fibre direction, due to the low resistivity in the fibre direction. If the current contacts are positioned to send current in the fibre direction, current spreading is small in the transverse direction, due to the high resistivity in the transverse direction. The extent of current spreading can be as high as 500 mm in the fibre direction [**28**]. Current spreading allows the sensing of damage that is localized at a distance from the electrical contacts. An example of a type of damage that is localized is impact damage. Thus, the ability of sensing damage that is localized at a distance from the electrical contacts is better for the case in which the current contacts are positioned to send current in the transverse direction, than the case in which the current contacts are positioned to send current in the fibre direction [**27**].

In general, the volume resistance of a composite can be measured in a direction in the plane of a composite laminate, in the through-thickness direction, and in an oblique direction (i.e. a direction that is between the in-plane and through-thickness directions) [**29**]. The resistance in the plane of the composite laminate, particularly if the direction is parallel to the fibres, is sensitive to fibre breakage; the resistance in the through-thickness direction is sensitive to delamination; and the resistance in the oblique direction is sensitive to both types of damage.

The oblique resistance is particularly effective for damage sensing [**29**, **30**]. It can be measured by using two surface contacts on one surface and two other surface contacts on the opposite surface, such that the two sets of contacts are not directly opposite. The distance between the two sets of contacts can be substantial. One contact in each set serves as a current contact, wherease the other contact in each set serves as a voltage contact. Although the current and voltage contacts are not lined up, the current direction is close to the direction of resistance measurement.

The way that current is applied is governed by the electrical contact configuration. The configurations include the following [**27**].

1. The current contacts are on the same surface in the plane of the laminate, so that the current is in the surface region only (Fig. 1(a)).
2. The current contacts are on opposite surfaces in the plane of the laminate, such that they are not directly opposite to one another, thereby providing an oblique current (Fig. 1(b)).
3. The current contacts are on the edge surfaces (surfaces that are perpendicular to the plane of the laminate), so that the current is in the plane of the laminate and goes through the entire cross-section of the specimen (Fig. 1(c)).
4. The current contacts are in holes that are through the thickness of the laminate, so that the current is in the plane of the laminate and goes through the entire cross-section of the specimen (Fig. 1(d)).

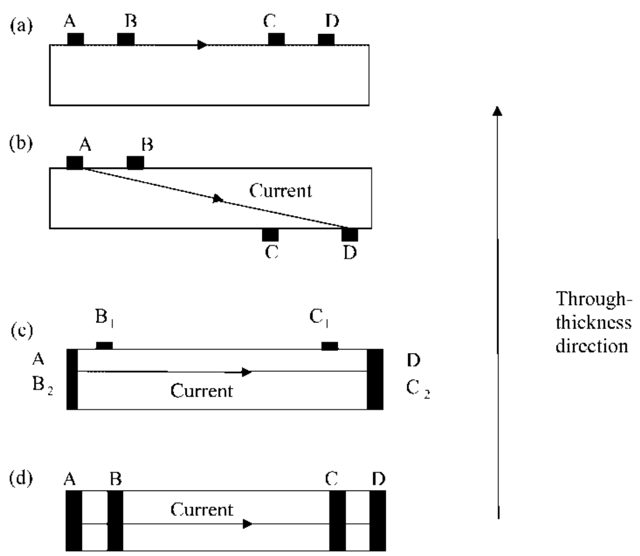

Fig. 1 Electrical contact configurations for sensing without spatial resolution

In case of a composite in the form of a cylinder, the electrical contacts may be circumferential or axial and may be on the inner or outer surface of the cylinder [**31**]. The resistance may be measured in the axial, radial, oblique, or circumferential direction [**31**]. The circumferential resistance is particularly sensitive to damage.

Unless a substantially thick layer of the polymer matrix is present on the composite surface (due to the surface finish of the composite), removal of the surface polymer layer (e.g. by mechanical polishing) prior to application of the electrical contacts is not necessary. In case mechanical polishing is conducted, care should be exercised so that it does not cause damage to the surface fibres.

6 SPATIAL DISTRIBUTION SENSING

A one-dimensional resistance distribution determination, as needed for damage distribution sensing, involves a one-dimensional array of electrical contacts, as illustrated in Fig. 2(a), where contacts are in the form of strips extending along the entire width of the specimen. In Fig. 2(a), contacts 1 and 5 are for passing current, while the remaining contacts are to be used two at a time (i.e. $2 + 3$ and $3 + 4$) for voltage measurement at segments I and II, respectively [**27**].

In order to obtain information on the damage location, the two-dimensional resistance distribution needs to be determined. This determination ideally involves a two-dimensional array of electrical contacts, as illustrated in Fig. 2(b) for the case of a 5×5 array [**27**]. However, in practice, the number of electrical contacts is preferably not large. Furthermore, the contacts are preferably near the edge of the specimen, as illustrated in Fig. 2(c), so that the electrical contacts do not interfere with the usage of the structural component. Therefore, the configuration of Fig. 2(c) is more suitable for practical implementation than that of Fig. 2(b).

In order to obtain a considerable amount of information by using a rather small number of electrical contacts, the potential at each contact can be measured (say, relative to ground) for each of a

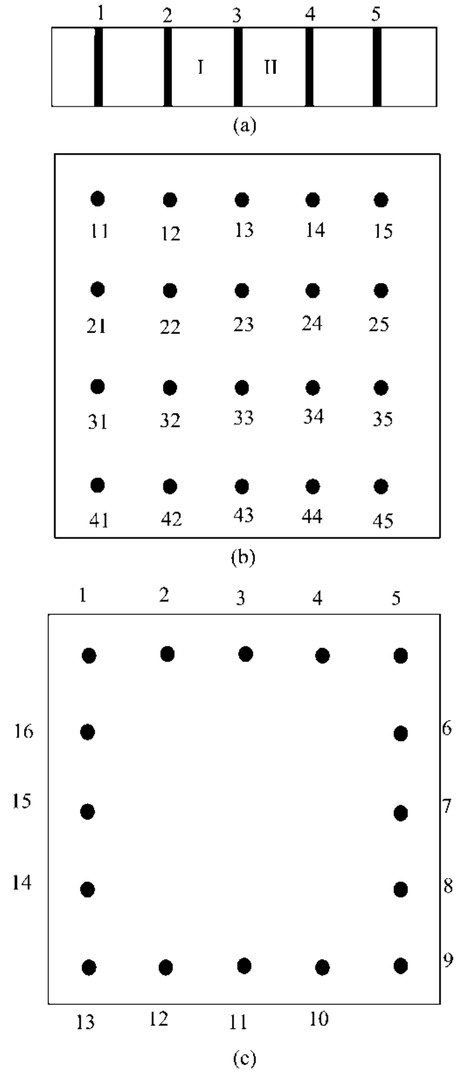

Fig. 2 Electrical contact configurations for sensing with spatial resolution: (a) one-dimensional resistance method, (b) two-dimensional resistance method, and (c) two-dimensional potential method

number of directions of current application. This is the conventional procedure, but other procedures of collecting the potential information are possible. An example of the conventional procedure is described below [**27**]. The current is applied from 1 to 9 (Fig. 2(c)), while the potential is measured at each of the remaining 14 contacts. After that, the current is applied, say, from 5 to 13, while the potential is measured at each of the remaining 14 contacts. Since the current line and the potential gradient line (i.e. the line connecting the two points where potential is measured) do not overlap, this two-dimensional method does not correspond to resistance measurement, which involves overlapping of the current line and the potential gradient line. This two-dimensional method is referred to as the potential method.

The potential method is useful for two-dimensional sensing [**32–40**]. However, it is less sensitive than the resistance method [**36**, **37**], due to the distance between the current line and the potential gradient line. In the case of the resistance method, these two lines coincide. The potential method is further complicated by the current spreading, which makes truly two-dimensional sensing impossible in case of surface contacts [**27**].

7 REAL-TIME SELF-SENSING OF FLEXURAL DAMAGE

Self-sensing by electrical resistance measurement is illustrated below for carbon fibre epoxy–matrix composite under flexure (three-point bending) [**30**]. The surface resistances at both tension and compression sides of the specimen are obtained by using all four contacts on the same surface of the specimen (Fig. 1(a)). The oblique resistance is obtained by using two contacts on each of the two opposite surfaces (Fig. 1(b)). In the plane of the laminate, each electrical contact is in the form of a strip that extends in the direction perpendicular to the long dimension of the specimen (Fig. 2(a)). Silver paint is used for making the electrical contacts.

The surface and oblique resistances are separately and continuously measured during loading and unloading at progressively increasing stress amplitudes [**30**]. The oblique resistance after unloading decreases with increasing highest prior deflection for highest prior deflection of at least 2.5 mm (Fig. 3). This effect is attributed to minor damage, which causes more fibres of one lamina to touch fibres of an adjacent lamina, thereby increasing the degree of current penetration. Thus, the oblique resistance at zero load may serve as an indicator of damage. It is a better indicator of damage than the tension/compression surface resistance, because it probes the interior of the specimen, whereas the surface resistance probes the surface region only.

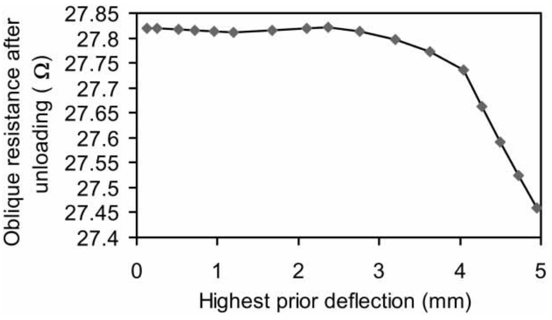

Fig. 3 Oblique resistance after unloading versus highest prior deflection under flexure

8 REAL-TIME SELF-SENSING OF TENSILE DAMAGE

Under uniaxial tension, the volume resistance of a carbon fibre composite in the fibre direction (longitudinal direction) irreversibly increases upon damage, due to fibre breakage [**41**, **42**]. The resistance may be measured by using four electrical contacts that are all around the perimeter of the specimen [**41**] or all on one surface [**42**]. Such damage during tension–tension fatigue is observed as early as 50 per cent of the fatigue life (Fig. 4) [**41**]. That the increase in resistance indeed signifies damage is supported by the observed decrease in the secant modulus (stress divided by strain) [**9**, **41**] as the resistance increases (Fig. 4) [**41**]. The occurrence of damage is also confirmed by simultaneous acoustic emission observation [**43**].

The volume resistance in the through-thickness direction increases irreversibly upon tension–tension fatigue, due to delamination. Such damage is observed as early as 33 per cent of the fatigue life (Fig. 5) [**41**]. The through-thickness resistance is measured by using two contacts (one for current and the other for voltage) on each of the two opposite surfaces, such that the contacts are directly opposite on the two surfaces.

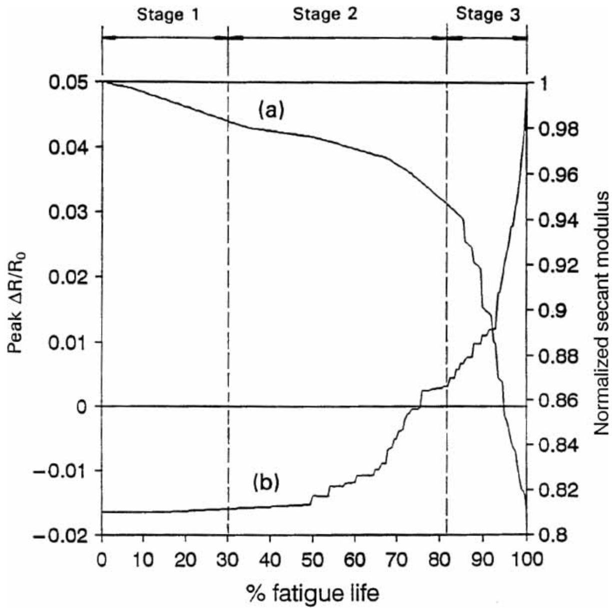

Fig. 4 Evolution of damage in the form of fibre breakage during tension–tension fatigue, as shown by the longitudinal volume resistance: (a) normalized secant modulus and (b) the peak value of the fractional change in resistance (relative to the initial resistance) in a stress cycle. Variation of the resistance within a cycle (not shown) is due to the effect of strain rather than that of damage

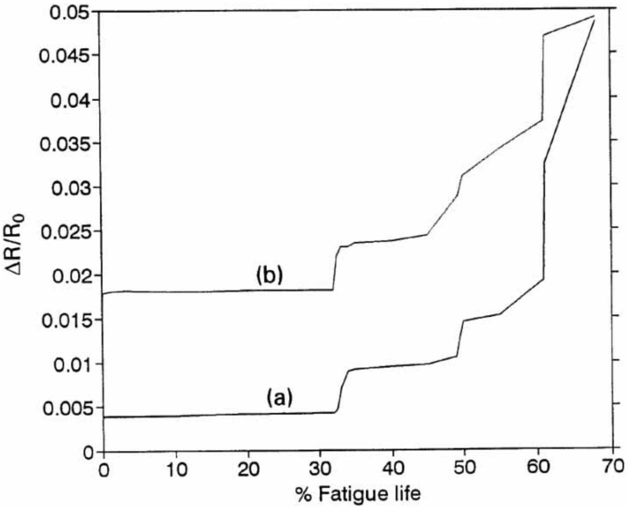

Fig. 5 Evolution of damage in the form of delamination during tension–tension fatigue, as shown by the through-thickness volume resistance: (a) the minimum value of the fractional change in resistance (relative to the initial resistance) in a stress cycle and (b) the maximum value of the fractional change in resistance in a stress cycle. Variation of the resistance within a cycle (not shown) is due to the effect of strain rather than that of damage

9 REAL-TIME SELF-SENSING OF IMPACT DAMAGE

Impact damage is localized in contrast to flexural damage and tensile damage, which are spread out. The sensing of impact damage in carbon fibre composite by surface resistance measurement should be conducted by measuring the resistance in a region that contains the point of impact, unless the extent of current spreading in the chosen direction away from the point of impact is large.

Upon drop impact damage, the resistance increases irreversibly, such that the resistance increases monotonically with increasing impact energy [**38**, **40**, **44**], as shown in Fig. 6 for the oblique resistance [**29**]. The trend is the same for the oblique resistance, the through-thickness resistance, the resistance of the surface receiving the impact, and the resistance of the opposite surface. However, the through-thickness resistance and the oblique resistance are more sensitive than the two surface resistances, as shown in Fig. 7 [**29**].

For through-thickness resistance measurement, the electrical contacts need to be directly opposite to one another on the two opposite surfaces. For oblique resistance measurement, the contacts on the opposite surfaces are not directly opposite to one another (Fig. 1(b)). As a consequence, oblique

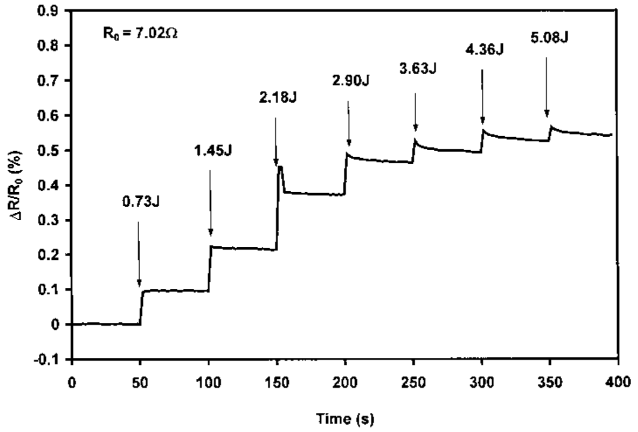

Fig. 6 Fractional change in oblique resistance (relative to the initial resistance) versus time during impact at progressively increasing energy. The arrows indicate the times of the impacts

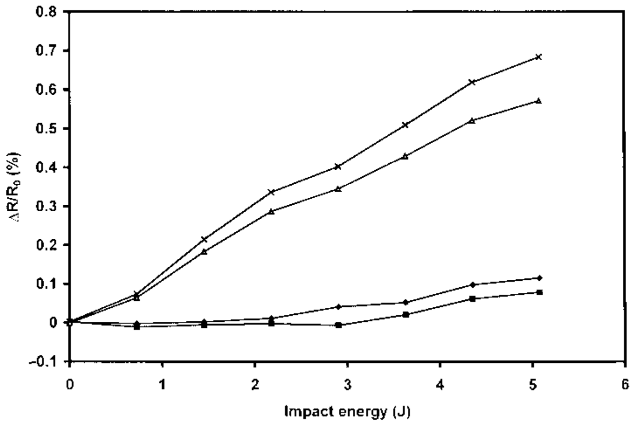

Fig. 7 Fractional change in resistance (relative to the initial resistance) versus time during impact at progressively increasing energy. X, through-thickness resistance; : ▲, oblique resistance; ♦, top surface resistance; ■, bottom surface resistance. The various resistances are simultaneously measured

resistance measurement is more suitable for practical implementation than through-thickness resistance measurement.

An increase in the fibre volume fraction will decrease the resistivity of the composite, thereby affecting the precision of the resistance measurement. However, in a conventional structural composite, the fibre volume fraction is high and does not vary a lot. More significant variables are the fibre lay-up configuration and the thickness [**44**].

Upon impact, the resistance of the surface receiving the impact in a segment including the point of impact increases irreversibly [**25**, **29**]. However, the surface resistance of each of the two segments that are immediately next to the segment containing the point of impact decreases slightly upon impact damage (Fig. 8) [**25**]. The latter phenomenon, which is weak and involves the resistance decreasing, is negligible in the regions that are not immediately adjacent to the segment containing the point of impact, i.e. regions that are more than about 20 mm away from the point of impact.

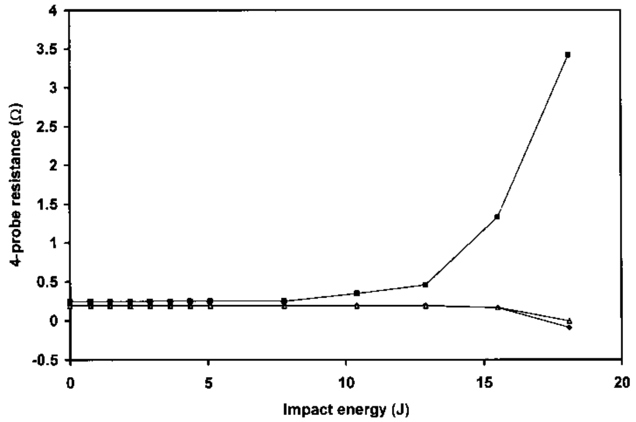

Fig. 8 The resistance of the surface receiving the impact versus the impact energy as the energy is progressively increased. ♦, segment L; ■, segment M; △, segment R. Segment M is the segment containing the point of impact. Segment L is the segment immediately to the left of segment M, such that the centres of the two segments are 18 mm apart. Segment R is the segment immediately to the right of segment M, such that the centres of the two segments are 18 mm apart. The various segments are simultaneously measured

The trend of the resistance increasing with increasing impact energy is attributed to major damage (such as delamination and fibre fracture), which is encountered by the segment containing the point of impact (i.e. segment M in Fig. 8). The opposite trend, which is weak and is mainly exhibited by the segments adjacent to the segment containing the point of impact, may be due to several reasons [**25**]. One possible reason relates to the distortion of the current path away from the top surface due to the major damage at the top surface nearby. This distortion can involve the current crossing from one lamina to the adjacent one, since the contact resistivity of the interlaminar interface is limited [**45**]. The distortion results in less current at the top surface, and hence a decrease of the measured resistance at the top surface. Another possible reason relates to residual stress relief in the segments adjacent to the segment containing the point of impact, due to the damage in the segment containing the point of impact.

The effectiveness of the two-dimensional electric potential method of impact damage sensing in a quasi-isotropic carbon fibre polymer–matrix composite depends on the electrical configuration, i.e. the current direction relative to the surface fibres and the electrical contact scheme [**27**]. Oblique current application in any direction provides effective damage sensing, as shown by using electrical contacts on the opposite in-plane surfaces. In-plane current application through the entire cross-section in any direction also provides effective damage sensing, as shown by using electrical contacts that are either on the edge surfaces or in holes through the composite. In-plane surface current application is effective when the current is perpendicular to the surface fibres (due to the low resistivity in the direction of the fibres) and is ineffective when the current is parallel to the surface fibres (due to the high resistivity in the direction perpendicular to the fibres). The oblique configuration is recommended for practical implementation. In general, the potential method is reliable when (a) the resistance between the electric current line and the nearly parallel electric potential gradient line is sufficiently low, as attained when these lines are sufficiently close, and (b) the resistance between the current line and the damage location is sufficiently low, as attained when the distance of separation is sufficiently small.

The interlaminar interface is a particularly sensitive impact sensor, as the contact electrical resistivity of this interface changes irreversibly upon impact at energy as low as 0.8 mJ ($1\,\text{mJ} = 10^{-3}$ Joule) [**46**]. That the damage is minor is indicated by the absence of even a shallow dent after the impact. The contact resistivity is more sensitive to minor damage than the volume resistance in the oblique, through-thickness, or longitudinal direction [**29**].

10 REAL-TIME SELF-SENSING OF FASTENING DAMAGE

The through-thickness compression that accompanies the joining of composite components by fastening can affect the joint, due to the weakness of the composite in the through-thickness direction. The microstructure of the joint is irreversibly affected by through-thickness compressive stress at just 5 per cent of the yield strength of the polymer matrix, as shown by irreversible decrease of the contact electrical resistivity of the joint interface [**47**]. Thus, this quantity serves as an indicator of the condition of the joint.

11 REAL-TIME SELF-SENSING OF THROUGH-THICKNESS COMPRESSIVE DAMAGE

Through-thickness compression is encountered in the fastening of composite components. The effect of the compression is not only at the joint interface, but is also within each of the components being joined.

The longitudinal volume resistivity of a composite is diminished by the through-thickness compression, due to the decrease in the through-thickness volume resistivity [**48, 49**]. The decrease in through-thickness volume resistivity is partly due to the decrease in the contact resistivity of the interlaminar interface [**45**]. The measurement of the longitudinal volume resistivity is more amenable to implementation than that of the through-thickness resistivity or the interlaminar interface contact resistivity.

12 REAL-TIME SELF-SENSING OF THERMAL CYCLING DAMAGE

Damage due to thermal cycling is sensitively indicated by the contact electrical resistivity of the interlaminar interface. This resistivity increases abruptly upon thermal damage in a thermoset–matrix composite (e.g. an epoxy–matrix composite, as shown in Fig. 9), but it decreases abruptly upon thermal damage in a thermoplastic–matrix composite [**50**]. This electrical effect of thermal damage is due to matrix molecular movement in the case of the thermoplastic–matrix composite and the absence of matrix molecular movement in the case of the thermoset-matrix composite.

13 SELF-SENSING OF ARTIFICIAL DAMAGE

Artificial damage of a selected macroscopic size can be used to test the effectiveness of the self-sensing

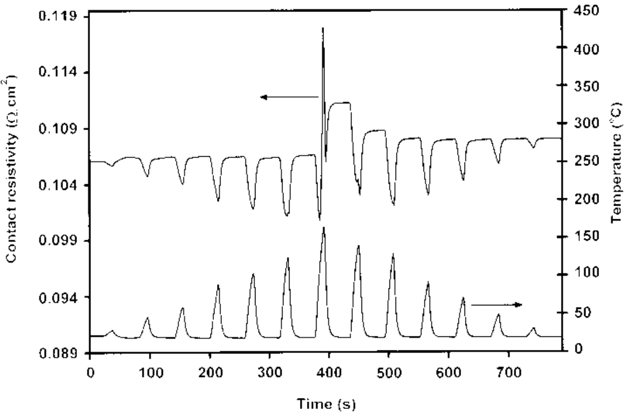

Fig. 9 Contact electrical resistivity of the interlaminar interface during temperature variation. The reversible decrease in resistivity in each heating cycle is due to the effect of temperature rather than damage. The spike of resistivity increase at the highest temperature and the subsequent increase in the baseline resistivity is due to thermal damage

technology. Delamination cracks can be formed by indentation [**34**] or interlaminar interface film embedment [**51**]. Holes through the thickness can be formed by drilling [**52**]. Based on the change in the electric potential (four-probe method) at various points on the back side of the indentation surface, the delamination size ranging from 8 to 25 mm is determined with an error of 3 mm, while the delamination location is determined with an error of 10–15 mm [**34**]. Based on the change in the two-probe resistance, the delamination size ranging from 10 to 51 mm is determined unsatisfactorily, as the relationship of the resistance with the delamination size shows much scatter [**51**]. By using on a two-dimensional potential method, a through hole of diameter 5 mm is detected and its position is estimated [**52**].

14 MODELLING OF DAMAGE SELF-SENSING

Damage in the form of fibre breakage, fibre–matrix debonding, or delamination affects the electrical resistance, as described by a microstructure-based analytical model [**16**]. The electrical effect of damage in the form of fibre breakage can be modelled by using equivalent circuits [**42**, **52**, **53**]. The mechanical effect of damage in the form of fibre breakage can be modelled by using a mechanical network of elastic elements [**53**]. The coupling of these electrical and mechanical models results in an analytical electromechanical model [**53**]. Another approach involves finite element modelling, which is used to calculate the potential distribution [**40**] or the resistance change [**54**] associated with delamination. Furthermore, finite element modelling can be used to provide sets of data for the study of artificial neural networks [**55**]. A related approach that also involves finite element modelling is electrical impedance tomography [**52**].

15 STRAIN/STRESS SENSING VERSUS DAMAGE SENSING

Strain/stress sensing is valuable for structural vibration control, weighing, and other applications. Reversible strain in the absence of damage causes reversible changes in the electrical resistivity of carbon fibre polymer–matrix composites [**30**, **41**, **56**, **57**]. In contrast, the effects due to damage are irreversible. Flexural strain causes the surface resistance in the compression side to decrease reversibly, due to increased current penetration, causes the surface resistance in the tension side to increase reversibly, due to decreased current penetration, and causes the oblique resistance to increase reversibly [**30**, **58**]. Tensile strain in the fibre direction of the composite causes the through-thickness resistivity to increase reversibly [**41**, **56**]. Through-thickness compression causes the longitudinal resistivity to decrease reversibly [**48**, **49**]. These strain effects are known as piezoresistivity, which allows strain/stress sensing [**16**, **24**, **30**, **57**, **59**]. This paper does not address strain/stress sensing. The sensing of both strain and damage is attractive for identifying the cause of damage. The strain-sensing characteristic can be affected by damage [**30**, **60**] and by temperature [**45**].

16 CONCLUSIONS

Damage detection is needed for aerospace structures. The self-sensing of damage in carbon fibre polymer–matrix composites by electrical resistance measurement is effective. The resistance changes irreversibly upon damage, as shown for damage inflicted by flexure, tension (including tension–tension fatigue), and impact. It is applicable to the sensing of damage in the form of delamination (which increases the through-thickness resistance) as well as the damage in the form of fibre breakage (which increases the longitudinal resistance). The oblique resistance is particularly sensitive. Minor flexural damage causes the oblique resistance in the unloaded state to decrease, due to increased contact between fibres of adjacent laminae.

The sensing of the spatial distribution of damage is possible in both one and two dimensions. Current spreading enables the sensing of localized damage by measurement away from the damage, though it reduces the spatial resolution of the sensing. The resistance method is more sensitive than the potential method. Two-dimensional sensing is complicated by the anisotropic spreading of the current.

Thermal damage and through-thickness (fastening) compression effect are indicated by the contact electrical resistivity of the interlaminar interface. More conveniently, the through-thickness compression effect is indicated by the longitudinal volume resistivity, which diminishes upon through-thickness compression. The condition of a composite joint made by fastening is indicated by the contact resistivity of the joint interface.

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