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Sensitivity of the two-dimensional electric potential/resistance method for damage monitoring in carbon fiber polymer-matrix composite

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Abstract The two-dimensional electric potential/resistance method is much less sensitive than the one-dimensional resistance method for damage monitoring in carbon fiber polymer-matrix composite. In the two-dimensional method, the resistance measurement is more sensitive than the potential gradient measurement. The sensitivity of the potential method is enhanced when the potential gradient line is close to the current line.

Introduction

Polymer-matrix composites with continuous carbon fiber reinforcement are important for lightweight structures, due to their combination of high modulus, high strength and low density [1]. Due to the use of these composites in aircraft, satellites and other strategic structures, the structural health needs to be monitored for the purpose of hazard mitigation. This monitoring means the sensing of damage.

Methods of sensing damage in carbon fiber polymer-matrix composites include the use of optical fibers [2–4], piezoelectric sensors [5–8] and other devices that are embedded in the structure. These methods tend to suffer from the weakening of the structure due to the embedment, in addition to the difficulty of repair of the embedded devices. Nondestructive methods that do not require modification of the composites are desirable. The most common nondestructive method is ultrasonic inspection [9–12], but the ultrasonic technique is only sensitive to well-defined cracks of size typically 1 mm or more. Due to the small size (typically around 10 μm in diameter) of carbon fiber, flaws that are of concern can be much smaller than 1 mm. A more recent nondestructive method involves the measurement of the electrical resistance [13–46] or the electric potential [46–50]. This method is possible in these composites due to the electrical conductivity rendered by the continuous carbon fiber in the composites.

The electrical resistance method involves measuring the potential gradient which is in line with the current, as illustrated in Fig. 1a. The electrical potential method involves measuring the potential gradient which is not in line with the current, as illustrated in Fig. 1b and c. The potential gradient line can be parallel (Fig. 1b) or oblique (Fig. 1c) to the current in the potential method.

The configuration of Fig. 1a has been used in prior work for the one-dimensional case [13, 15, 17, 19–21, 23, 24]. Consider the direction in the one-dimensional case to be a direction in the plane of a laminate. This is the current direction. The electrical contact scheme used, as illustrated in Fig. 2a, involves four contacts, each of which being in the form of a strip in the direction perpendicular to the current direction and extending along the entire width of the specimen. The outer two electrical contacts (A and D in Fig. 2a) are for passing current, whereas the inner two contacts (B and C) are for voltage measurement. This is in accordance with the four-probe method of electrical resistance measurement.

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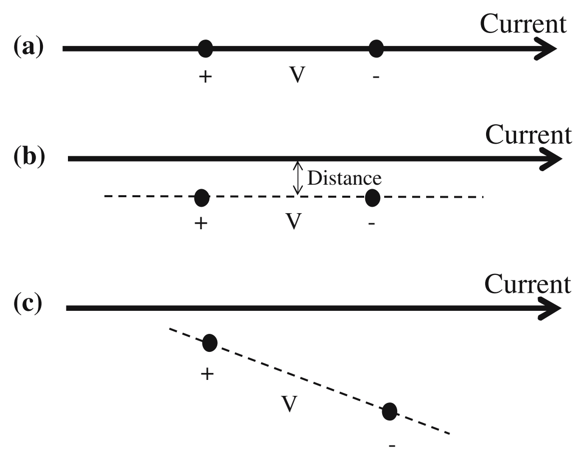

Fig. 1 Current line (solid line with arrow) and potential gradient line (dashed line). (**a**) Resistance method, with current line and potential gradient line overlapping. (**b**) Potential method, with current line and potential gradient line parallel and at a distance from one another. (**c**) Potential method, with current line and potential gradient line at an angle and at a distance from one another

By using more than four electrical contacts, the one-dimensional resistance distribution (which relates to the damage distribution) can be obtained as illustrated in Fig. 2b for the case of eight electrical contacts, labeled 1, 2, ...,8. Contacts 1 and 8 are used for passing current, whereas the remaining contacts are used in pairs (i.e., 2 + 3, 3 + 4, 4 + 5, 5 + 6 and 6 + 7) to obtain the voltage across each segment.

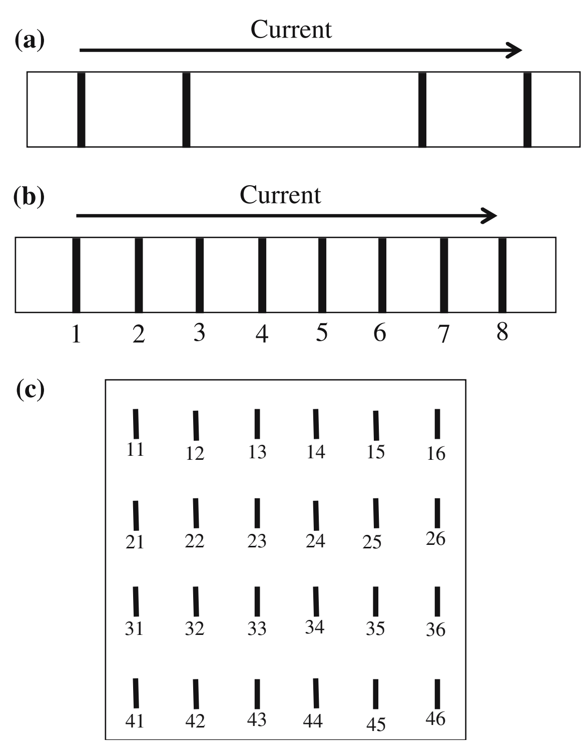

Fig. 2 Resistance method. The thick lines are the electrical contacts. (**a**) One-dimensional method without spatial resolution. (**b**) One-dimensional method with spatial resolution. (**c**) Two-dimensional method with spatial resolution

The extension of Fig. 2a to the two-dimensional case requires a two-dimensional array of electrical contacts, such as that illustrated in Fig. 2c, where contacts 11 and 16 are a pair of current contacts, 21 and 26 are a second pair of current contacts, 31 and 36 are a third pair of current contacts, and 41 and 46 are a fourth pair of current contacts. All the remaining contacts are for voltage measurement. The disadvantage of the configuration of Fig. 2c lies in the inconvenience and, in some cases, impracticality of having a large number of contacts. Moreover, contacts that are not near the edge of the composite component may interfere with the usage of the component. Therefore, the resistance method, which characterizes all of Fig. 2a–c, is not very suitable for two-dimensional sensing.

Compared to the resistance method, the potential method is more suitable for two-dimensional sensing. In the potential method, current is passed between a chosen pair of electrical contacts, while the potential is measured at each of the remaining contacts. This concept is illustrated in Fig. 3, where point contacts are placed near the edge of the plane of the composite for the sake of convenience in practical implementation. An alternate but less practical configuration for the potential method involves a two-dimensional array of point contacts [49], like Fig. 2c, except that the contacts are in the form of points. In Fig. 3, contacts 1 and 9, for instance, can be used as the two current contacts, while all the remaining contacts serve as voltage contacts. The potential at each voltage contact may be measured relative to the electrical ground.

The method illustrated in Fig. 3, though attractive from the viewpoint of implementation, is complicated by the current spreading between the two point current contacts, as illustrated in Fig. 4. The current spreading has been shown to extend for a distance as much as 500 mm in the plane of the laminate [46]. It is significant due to the high electrical conductivity of the carbon fiber causing the

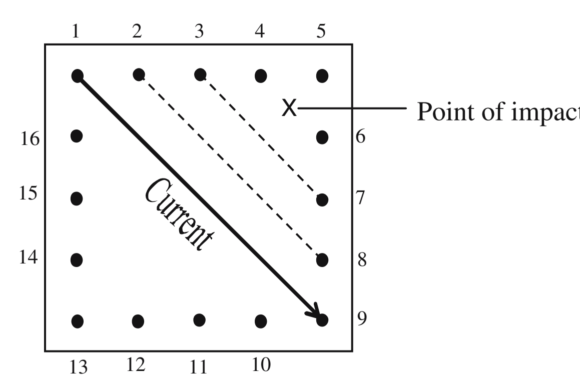

Fig. 3 Two-dimensional potential method. The dots are the electrical contacts, labeled 1, 2, ..., 16

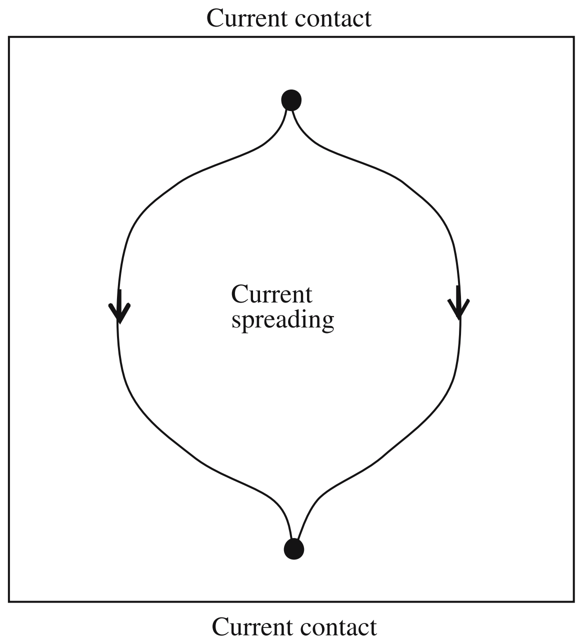

Fig. 4 Two-dimensional current spreading between two electrical contacts (dots)

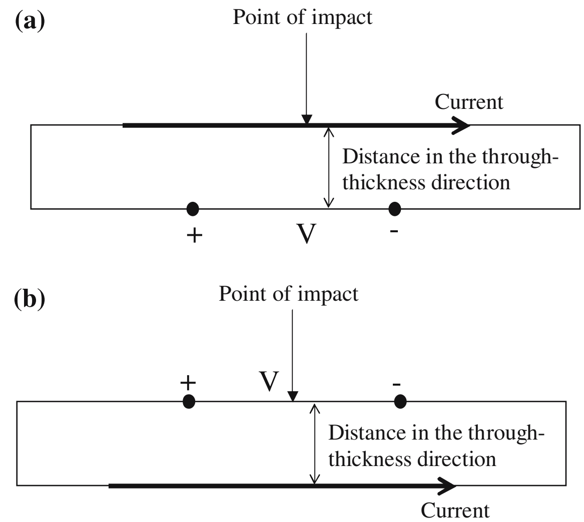

Fig. 5 Potential method, with the current line (thick arrow) at a distance from the potential gradient line (+ V −), such that the distance is along the through-thickness direction of the composite. (**a**) Current at the top surface, which receives the impact. (**b**) Current at the bottom surface

resistivity of the composite to be much lower in the plane of the composite than in the through-thickness direction. In contrast, in Fig. 2a and b, the current is only in one direction. The configuration of Fig. 2c also suffers from current spreading, but the current contacts in strip form (Fig. 2c) give less current spreading than those in point form (Fig. 3). The current spreading (Fig. 4), which reduces the current density, is expected to diminish the sensitivity for damage detection. However, comparison of the sensitivity for the one-dimensional method (Fig. 2a) and the two-dimensional method (Fig. 3) has not been previously reported. Such a comparison is one of the objectives of this paper.

The larger is the distance between the current line and the potential gradient line (Fig. 1b), the more is the expected reduction in sensitivity. This is due to the decrease in current density and the consequent decrease in the signal-to-noise ratio as the distance increases. This reduction in sensitivity and its dependence on the distance between the current line and the potential gradient line have been shown for distances that are in the through-thickness direction (current and potential gradient lines being in the plane of the laminae), as illustrated in Fig. 5 [51]. However, they have not been shown for distances that are in the plane of the laminae. This is partly because (i) the damage tends to be localized in a region of the plane (particularly in the case of impact damage) and (ii) the proximity of the potential gradient line to the damage zone as well as the proximity of the potential gradient line to the current line affect the sensitivity, as explained below.

In Fig. 3, consider that contacts 1 and 9 are for passing current. The distance between the current lines 1–9 and the potential gradient lines 2–8 is less than that between the current lines 1–9 and the potential gradient lines 3–7. However, the potential gradient lines 3–7 is closer to the point of impact than the potential gradient lines 2–8. Therefore, in spite of the larger distance between the current line and the potential gradient lines 3–7, it is possible for the potential gradient lines 3–7 to give higher sensitivity then the potential gradient lines 2–8. In spite of the complexity resulting from the influence of two distances (i.e., the distance between the current line and the potential gradient line, and the distance between the potential gradient line and the damage location), it is important for a comparative study to be made of the sensitivity associated with the use of various combinations of voltage contacts (for a fixed combination of current contacts and a fixed damage location), as the results of such a study provide the basis for implementing the two-dimensional potential method of damage monitoring. This paper is aimed at such a study. In addition, this paper is aimed at comparing the potential method (Fig. 1b, c) and the resistance method (Fig. 1a) in terms of the sensitivity.

The two-dimensional potential method has been previously applied to locate high levels of damage (such as a macroscopic delamination of size 10 mm [48], 20 mm [49] or 100 mm [47]) in carbon fiber epoxy-matrix composites [46–49]. The capability of this method for sensing lower levels of damage has been shown for impact damage at energy 4 J (or above) for the case of a 2-mm thick 16-lamina composite [49]. For practical use of this method, it is important to investigate in more detail the capability of this method for sensing minor damage. Therefore, this paper is aimed at evaluating the sensitivity of the two-dimensional potential method, with impact energy as low as 1 J for the case of a 24-lamina composite of thickness 3.2 mm.

The damage sensitivity of the potential method can be quantitatively described by the fractional change in potential gradient (potential difference divided by the distance between the two voltage contacts) in response to a given level of damage. The sensitivity depends not only on the level of damage, but also on the proximity of the voltage contacts to the current contacts and on the proximity of the voltage contacts to the location of the heart of the damage. This paper addresses all these aspects of dependence by systematic variation of each of these parameters. The focus of this paper is damage sensitivity evaluation, rather than damage location determination. The latter was the emphasis of prior work on the potential method.

The objectives of this paper are (i) to compare the one-dimensional resistance method (Fig. 2a) and the two-dimensional potential/resistance method (Fig. 3) in terms of the sensitivity for damage monitoring, (ii) to compare the two-dimensional resistance (Fig. 1a) and potential (Fig. 1b, c) methods in terms of the sensitivity for damage monitoring, (iii) to compare the sensitivity in the two-dimensional potential method for various combinations of voltage contacts in the two-dimensional plane, (iv) to evaluate the sensitivity of the two-dimensional potential/resistance method for the entire range of damage levels, particularly the low levels, which demand high sensitivity.

Experimental methods

Commercially manufactured composites in the form of continuous carbon fiber (Hercules IM6, a high-performance intermediate-modulus, PAN-based fiber in the form of 12,000 filament count tows) epoxy-matrix (Hercules 3501-6, cured at 177 °C) laminates of fiber volume fraction 63.5% were cut into strips of length 120 mm (or more) in the 0° direction and width either 80 mm in the 90° direction and then sanded by using 600 grit silicon carbide sand paper for the purpose of removing the surface layer (about 20 μm thick) of epoxy matrix prior to the application of electrical contacts. The contacts were in the form of silver paint in conjunction with copper wire.

The sanding step is not essential, but it helps the electrical measurement by increasing the accuracy and decreasing the noise. Although the entire surface was sanded in this work, only the portions beneath the electrical contacts needed to be sanded. The laminate had 24 laminae in the quasi-isotropic $[0/45/90/\text{-}45]_{3s}$ lay-up configuration. The thickness was 3.2 mm.

DC electrical resistance or potential measurement was conducted using the four-probe method. In this method, the outer two electrical contacts are for passing current, while the inner two electrical contacts are for voltage measurement. In this way, the measured resistance of the part of the specimen between the voltage contacts does not include the resistance of the two voltage contacts. In contrast, the two-probe method involves two rather than four electrical contacts, and consequently the measured resistance includes the resistance of the two contacts. A Keithley 2002 multimeter was used.

The specimen was of size $120 \times 80 \times 3.2$ mm^3. Twelve electrical contacts (Fig. 6) were applied on the surface of the laminate—the surface which was to receive impact for the purpose of damage infliction. Each contact was in the form of a dot made from silver paint and of diameter 3 mm. In order to enhance the mechanical integrity, each contact was covered with an epoxy (non-conductive) coating after the silver paint had dried. Contacts 11 and 12 were for passing current, whereas the remaining contacts were for potential measurement. The potential at each of contacts 1–10 was measured relative to ground. After that, the difference in potential between selected potential contacts was calculated.

Before, during and after impact using a steel hemisphere (19 mm or 0.75 in diameter) dropped from a controlled height, potential measurement was made with a fixed DC current (75 mA, applied through contacts 11 and 12). The impact energy was calculated from the weight of the ball assembly (either 0.740 or 2.640 kg) and the initial height of the ball (up to 760 mm). The impact was directed at the same point of the specimen (Fig. 6) at progressively increasing energy. Hence, the cumulative damage was analyzed. Although cumulative damage is more than damage resulting from a single impact at the maximum impact energy used in inflicting cumulative damage, it is meaningful in providing the damage evolution for the same specimen as the impact energy progressively increased.

All the data reported in this paper were obtained on one specimen, but testing had been performed on three specimens to confirm the general reproducibility of the results.

Results and discussion

Fig. 7 shows the fractional change in potential gradient at lines 1–7, 2–8, 3–9 and 4–10, which are all at an angle to the current lines 11–12. Among these potential gradient lines, lines 4–10 is closest to the point of impact, and it gives the highest fractional change in potential gradient for the same high impact energy of 13 J or above. At 15 J, the fractional change in potential gradient decreases in the order 4–10, 3–9, 2–8 and 1–7, i.e., it decreases with

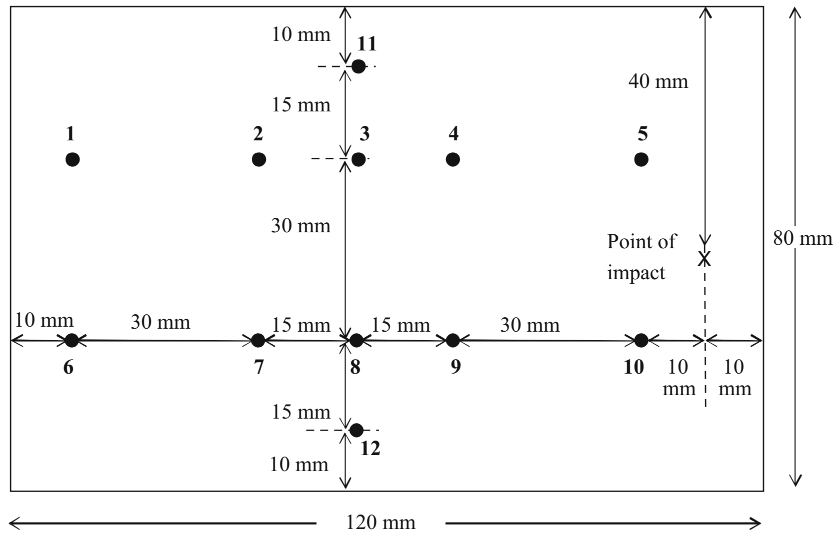

Fig. 6 Specimen configuration for investigating the two-dimensional potential/resistance method. The dots, labeled 1, ...,10, are the voltage contacts; 11 and 12 are the current contacts

increasing distance from the point of impact. However, at 10 J and below, the fractional change in potential gradient is highest for 3–9 and 2–8, due to their proximity to the current line. Thus, the sensitivity for damage monitoring is best for potential gradient lines that are closest to the damage location when the damage is major, but is best for potential gradient lines that are closest to the current line when the damage is minor.

That proximity of the potential gradient line to the current line is favorable for the monitoring of minor damage is also supported by Fig. 8, which shows the results for various potential gradient lines that are parallel to the current line, i.e., lines 1–6, 2–7, 3–8, 4–9 and 5–10. Lines 3–8 coincides with the current line, so it corresponds to the resistance method (Fig. 1a). The rest corresponds to the potential method (Fig. 1b). Lines 3–8 gives the highest fractional change in potential gradient for most of the impact energies in Fig. 8. Moreover, it gives a relatively smooth curve compared to lines 2–7, 1–6 and 4–9. Lines 5–10, in spite of its proximity to the point of impact, gives lower fractional change in potential gradient than lines 3–8. Thus, in the regime of minor damage, the resistance method is more sensitive than the potential method.

Fig. 9 shows comparison of the results for lines 3–8 (resistance method), lines 2–8 (potential method) and lines 4–8 (potential method). Lines 3–8 gives higher fractional change in potential gradient than lines 2–8 or 4–8 at all impact energies up to the highest energy studied (15 J). This means that the resistance method is more sensitive than the potential method.

The results of this work mean that practical two-dimensional damage monitoring using the electrical contact configuration of Fig. 3 is most sensitive by keeping close proximity between the current line and the potential gradient

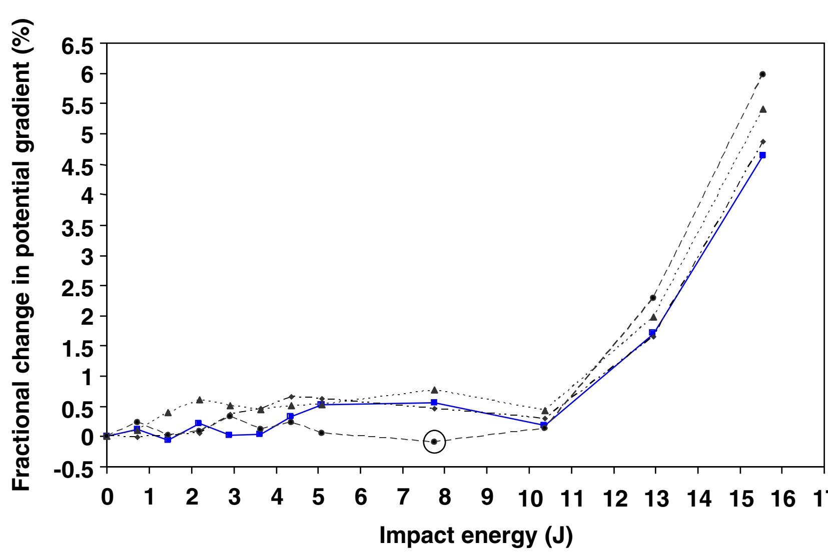

Fig. 7 Fractional change in potential gradient versus impact energy, which was progressively increased. The different sets of data are for different potential gradient lines. ■: Lines 1–7; ♦: Lines 2–8; ▲: Lines 3–9; ● Lines 4–10. The circled data point may be a little off due to a data acquisition problem

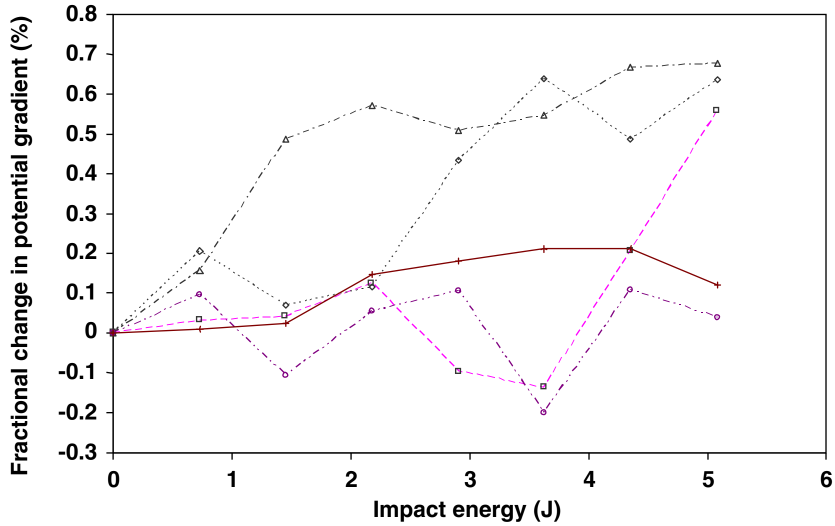

Fig. 8 Fractional change in potential gradient versus impact energy, which was progressively increased. The different sets of data are for different potential gradient lines. □: Lines 1–6; ◇: Lines 2–7; Δ: Lines 3–8; ○: Lines 4–9; +: Lines 5–10

line. As the damage location can be anywhere, one cannot control the proximity of a potential gradient line to the damage location. Thus, a recommended procedure involves using numerous current directions one after another, such that, for each current line, the potential gradient lines are close to the current line. Such a procedure is hereby illustrated using Fig. 3. The procedure involves (i) using 1–9 as the current line and successively 2–8, 16–10, 2–10 and 16–8 as the potential gradient lines, (ii) using 2–8 as the current line and successively 1–9, 3–7, 3–9 and 1–7 as the potential gradient lines, and (iii) using 3–7 as the current line and successively 2–8, 4–6, 4–8 and 2–6 as the potential gradient lines. Similarly, 16–10 and 15–11 can be successively used as current lines. Thus, a total of 20 data are obtained. Further data can be obtained by successively using 5–13, 6–12, 7–11, etc., as current lines, thereby yielding 20 additional data. Still further data can be obtained by successively using 16–11, 1–10, 2–9, 3–8, 4–15, 5–14, 6–13 and 7–12 as current lines, thereby yielding 32 additional data. Yet further data can be obtained using successively 3–11 and 7–15 as current lines, thereby yielding eight additional data. Hence, a total of 20 + 20 + 32 + 8 = 80 data are obtained by using the 16 electrical contacts in Fig. 3. Still other current lines can be used, thereby providing a total of more than 80 data. However, these 80 data are the ones that are most sensitive. The collection of 80 data provides a signature for a given combination of damage distribution and severity. In practice, it is desirable to have signatures that allow clear distinction among various combinations of damage distribution and severity, while having each signature consist of a number of data that is not very large. Such signatures form a database that provides the basis of data interpretation for the purpose of damage monitoring. The associated analysis can be facilitated by using neural networks [51].

Greater spatial resolution can be attained by using more than 16 electrical contacts. However, the procedure

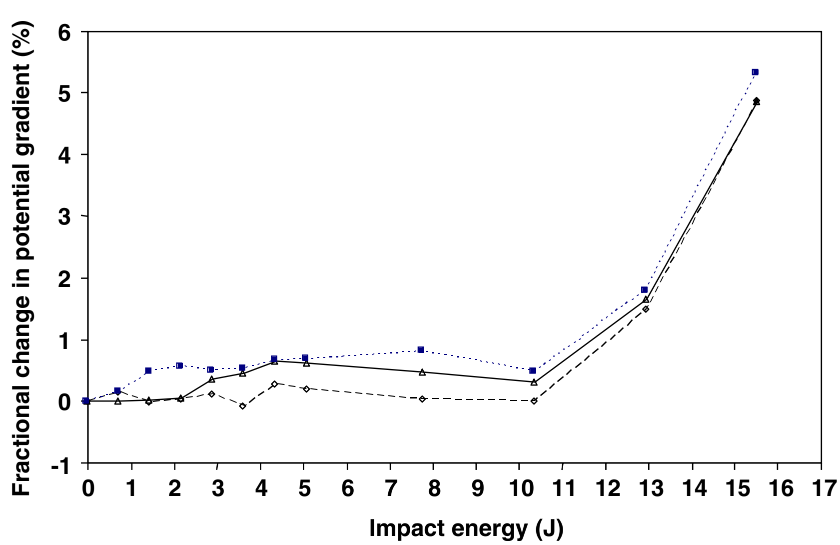

Fig. 9 Fractional change in potential gradient versus impact energy, which was progressively increased. The different sets of data are for different potential gradient lines. Δ: Lines 2–8; ◇: Lines 4–8; ■: Lines 3–8

described above for the case of 16 electrical contacts serves to illustrate the methodology. This methodology is in contrast to that of most prior work using the two-dimensional potential method. The prior work [47, 49] used a single current direction (line) and measured the potential at every electrical contact relative to ground. In one instance [50], prior work involved a significant number of current lines, but no criterion for the choice of current lines was given and the potential was measured at every voltage contact for any particular current line.

The values of the fractional change in potential difference in Figs. 7–9 are all under 6%. In contrast, the value obtained using the one-dimensional configuration of Fig. 2a (i.e., the resistance method) is as high as 1700% [17]. This means that the sensitivity is poor for the two-dimensional potential/resistance method compared to the one-dimensional resistance method, due to current spreading in the former case (Fig. 4).

Conclusion

The two-dimensional electric potential/resistance method is much less sensitive than the one-dimensional resistance method for damage monitoring, due to current spreading in the former method. In the two-dimensional potential/resistance method, resistance measurement is more effective for damage monitoring than potential gradient measurement. The sensitivity of the potential method depends on the position of the potential gradient line. When the damage is major (impact energy of 13 J or above), potential gradient lines that are closest to the damage location tend to be most effective for damage monitoring. However, when the damage is minor (impact energy of 10 J or below), potential gradient lines that are closest to the current line tend to be most effective. Since the damage location is arbitrary in practice, the use of potential gradient lines that are close to the current line is recommended in practical implementation of the two-dimensional potential method.

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