Aggregately conductive composite materials

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Abstract

It was found in our previous work that by adding an optimal amount of carbon nanotubes in the epoxy matrix in long fiber polymer matrix composites, it is possible not only to detect damages in large composite structures, but also to locate and quantify these damages. The detection can be done in-situ while the structure is in operation. What is more important is that the technique can detect matrix damages, such as Barely Visible Impact Damage, that can not be detected using many current NDT techniques. For this to happen, good mixing and a proper amount of nanotubes is necessary. It is essential for the material to be conductive, but not too conductive. In this paper, we introduce a concept called "aggregately conductive" materials, to distinguish them from the homogeneously conductive materials such as metals. Aggregately conductive materials represent materials such as epoxy (or other polymers) containing carbon nanotubes or other particles. In the work presented in this paper, the electrical conductivity (or resistance) across different points of large composite plates made from the aggregately conductive material would change significantly on the occurrence of cracks or damages . This change can be used for damage detection in these structures. A model was developed to explain the behavior.

1. Introduction

Carbon nanotubes have been added into epoxy resin to enhance many properties of the resin, one particular property is the enhancement of the electrical conductivity. This particular characteristic has been used to provide sensors in an effort to detect failure in the composite materials [1,2,3]. In the augmentation of the electrical conductivity of the resin, there exists a percolation threshold where there is a dramatic change in electrical conductivity. The percolation has been found to be about 0.188 wt% for epoxies [4]. This value has been taken to be a characteristic of the material system. However when applied to a large structure, there is spatial variation in the degree of dispersion of the carbon nantobues in the epoxy. As such using carbon nanotubes with exactly the percolation percentage sometimes can give sporadic results in terms of electrical conductivity at different locations in the large structure. In order to achieve more uniformity in the dispersion of the nanotubes, a large percentage of the particles needs to be used. However, there is an upper limit for the percentage, since it is more difficult to disperse larger amounts of nanotbues in the epoxy, due to the fast increase in the viscosity of the material. At higher percentages of CNTs, this tends to give rise to the occurrence of voids, and spatial non-uniformity in the electrical conductivity. As such, only amounts of nanotubes within a window of percentages can be used. The use of carbon nanotubes within this range gives rise to a material with a particular behavior in electrical conductivity. We denote this behavior as "Aggregately conductive", meaning that the material is conductive at the aggregate level, but not homogeneously conductive. It is shown in this paper that this behavior can be used for the detection of damages in the composite structures.

2. Concept:

Figure 1 shows the micrograph of an epoxy sample containing carbon nanotubes. Examining the left figure, it can be seen that the distribution of carbon nanotubes is uniform to a certain degree. The right figure is a magnification of a small region in the left figure. It can be seen that there are clusters or aggregates of epoxy with CNTs. The uniformity is limited to the aggregate level.

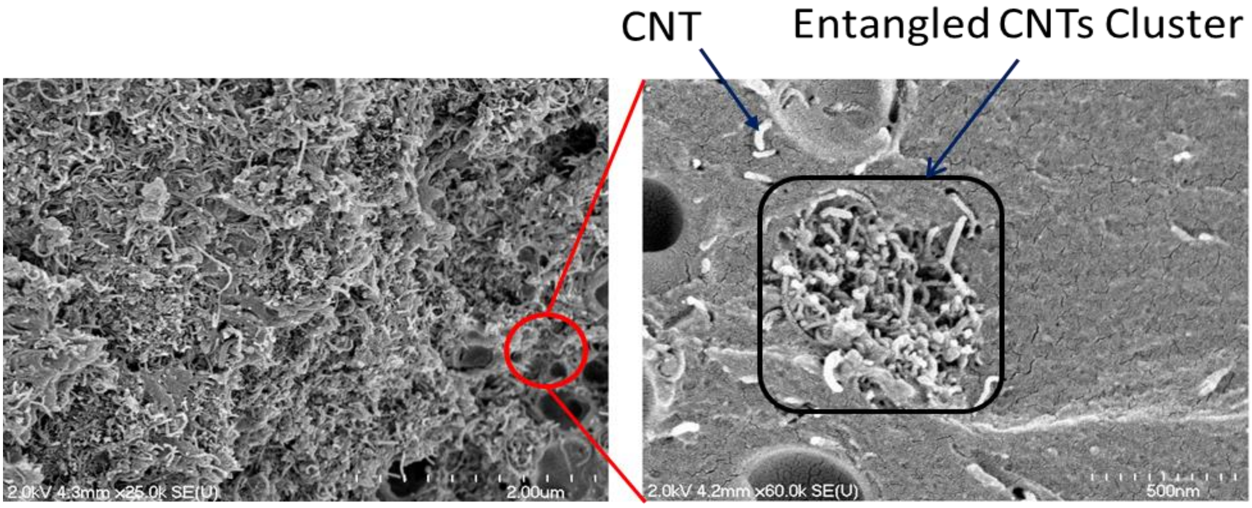
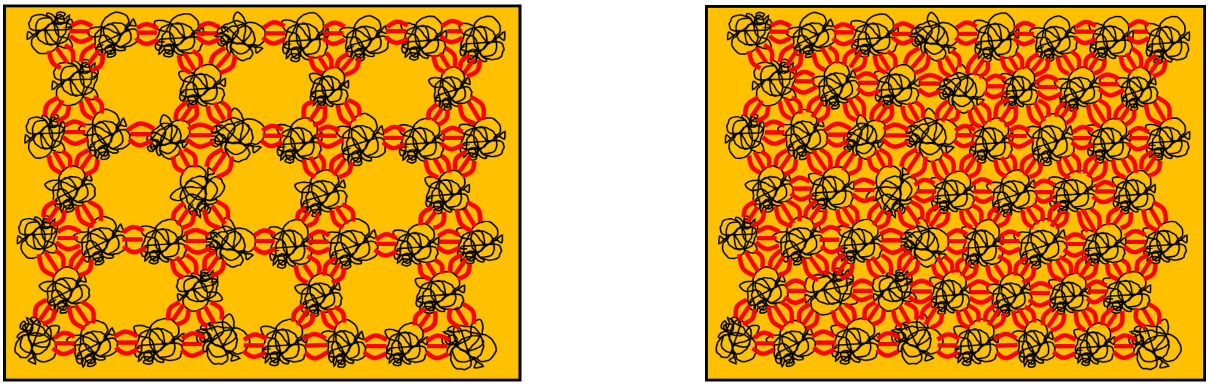


Figure 1: Micrographs of epoxy with carbon nanotubes

This configuration can be idealized into aggregated structures as shown in figure 2, where the structure is represented by a collection of aggregates connected together by conductive wires.



(a) (b)

Figure 2: Conductive aggregates connected together with conductive wires- a) coarse structure, b) fine structure

Figure 3 represents a few conductive paths joining different points together.

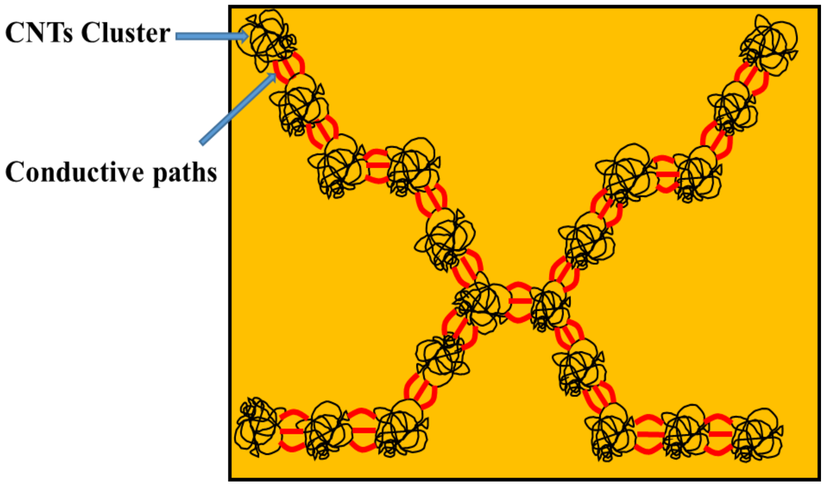


Figure 3: Conductive paths

The concept of Aggregately Conductive Material (ACM) can be illustrated by using the analogy of finite element discretization of a continuous medium. In finite element analysis of a solid structure, even though the structure is continuous, for the sake of practical analysis, it is discretized into a collection of many elements. The smaller is the size of the element, the better is the finite element collection to represent the structure. For engineering purpose, the mesh does not have to be infinitesimally small to obtain an approximately useful result.

Using the above concept, the electrical conductivity of a certain material is represented by a mesh of conductors connected together as shown in figure 4. The constituents of this arrangement consist of lines, intersecting points, and cells which are surrounded by lines. The point is not infinitesimal. Rather, it should have a size similar to the size of a cell, in order to cover the whole domain of the material. Assuming that the conductivity between two points A and B within the material is done by the conduit of current through the lines only. The finer is the mesh, the better is the representation for the continuous material. For the case of highly conductive material such as copper or aluminum, the size of the cell is as small as the grain of the metal. For the case of carbon nanotube incorporated within the epoxy, the mesh size is more coarse, and the cell size is larger, as shown in figure 4.

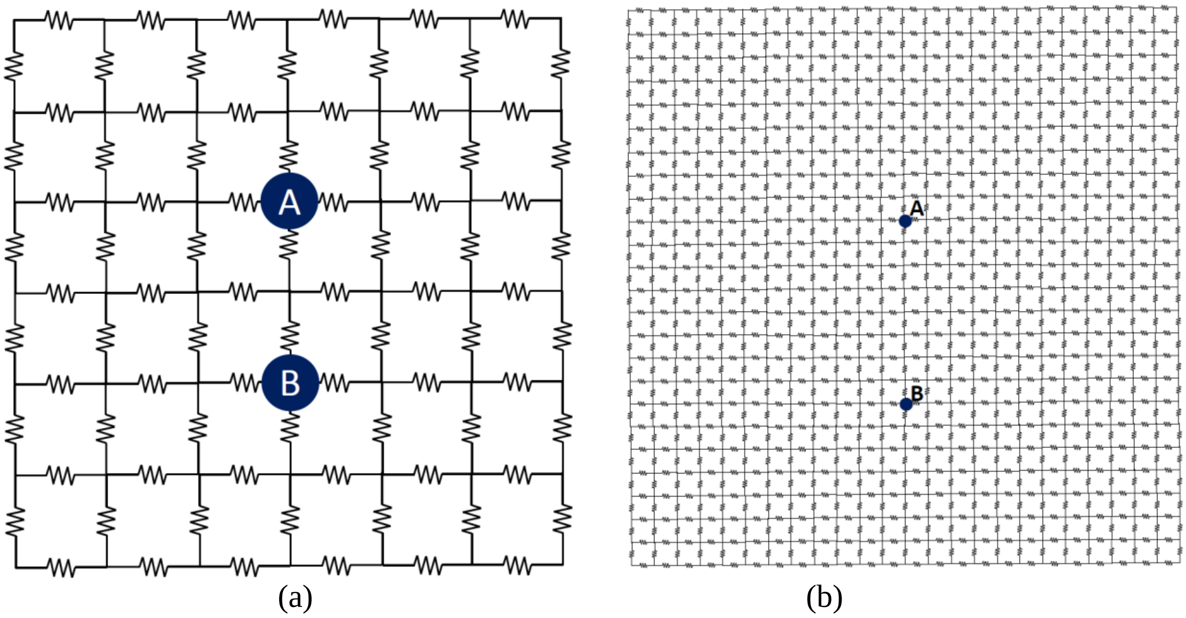


Figure 4: Discretization of the continuous domain- a) Coarse mesh. B) Fine mesh.

The concept of aggregately conductive materials can help to explain the sensitivity for the detection of damages in structures. Examine a very conductive material such as copper or aluminum. One is interested in the electrical conductivity (or electrical resistance) between two points A and B in the structure (figures 4b). If there is a small crack that occurs in the region between A and B (figure 5), whether there is significant change in the resistance between A and B depends on the size of the region between A and B. If the region is small, there may be significant change in the resistance (or conductivity) , but if the region is large, then there may not bẹ signficant change in the electrical conductivity (or resistance) between these two points. The reason is because for a large region, there are many conductive paths between these two points. The occurrence of the damage only disrupts a few of these paths, and electrical current can find many paths to conduct between the two points.

On the other hand, considering a material that is conductive on the aggregate scale (figure 4a). For a region of similar size as that of the metal plate, there is only a discrete number of conductive paths between the two points A and B. If some damage occurs in the region between the two points, a number of these conductive paths will be disrupted. Depending on the number of the conductive paths, the electrical conductivity between the two points may be more affected.

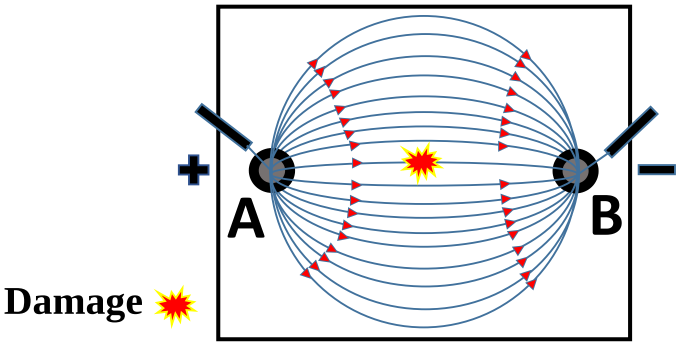


Figure 5: Effect of damage on the conductivity between two pints A and B.

3. Use of the concept of ACM to understand the effect of defect on electrical conductivity of composites materials containing carbon nanotubes:

In order to investigate the effect of the occurrence of defects on the electrical conductivity of composite plates containing carbon nanotubes, as compared to the behavior of electrical conductivity, two square plates (12 inch × 12 inch), one made of copper purchased from McMaster-Carr , and the other made of glass/epoxy containing 0.30wt% multiwalled carbon nanotubes were made. For the glass/epoxy plate, 0.3wt% carbon nanotubes were mixed inside the epoxy resin using a three roll milling (EXAKT 80E, EXAKT Technologies Inc.), and the modified epoxy was incorporated with glass fabrics (HL.Plasto) by Hand Lay Up. Three layers of glass woven fabric (15oz/yd^2) were hand laid, debulked, vacuum bagged and cured inside an autoclave. Many electrical contacts were deposited at many locations on the surface of the plates. Figure 6 shows the pattern for the contact points, and figure 7 shows the hardware. In figure 6a, the contact points are aligned along the circumferential and radial directions. Along the circumferential direction, there are points at 0°, 45°, 90° and 135° directions. Along the radial direction, there are points at 10 locations, 1 being at a 1 inch (25.4 mm) radius from the center of the plate, and 10 at a 10 inch (254 mm) radius from the plate center. At a particular radial distance, there are 8 pairs of points (figure 6b). Each pair consists of two points, one is for the current flow (connection to the red line) and the other is for the measurement of voltage (connection to the black line). The dotted lines in figure 6b shows the process to measure the resistance between points 1 and point 5. The region between the two points is the region where the resistance is measured. It is also the region where a defect may be created to determine the effect of the occurrence of the defect on the change in electrical resistance between the two points. This type of electrical set up to measure the resistance between two points is following the four-probe method.

The experimental set up is shown in figure 7.

The center of the plate undergoes the following conditions: Virgin (no modification), and hole with different diameters. For each condition, the electrical resistance between pairs of electrical points were measured. Holes of diameters of 1/16 inch (1.59 mm) to 3/8 inch (9.53 mm) were drilled at the center of the plate, and the electrical resistances were measured.

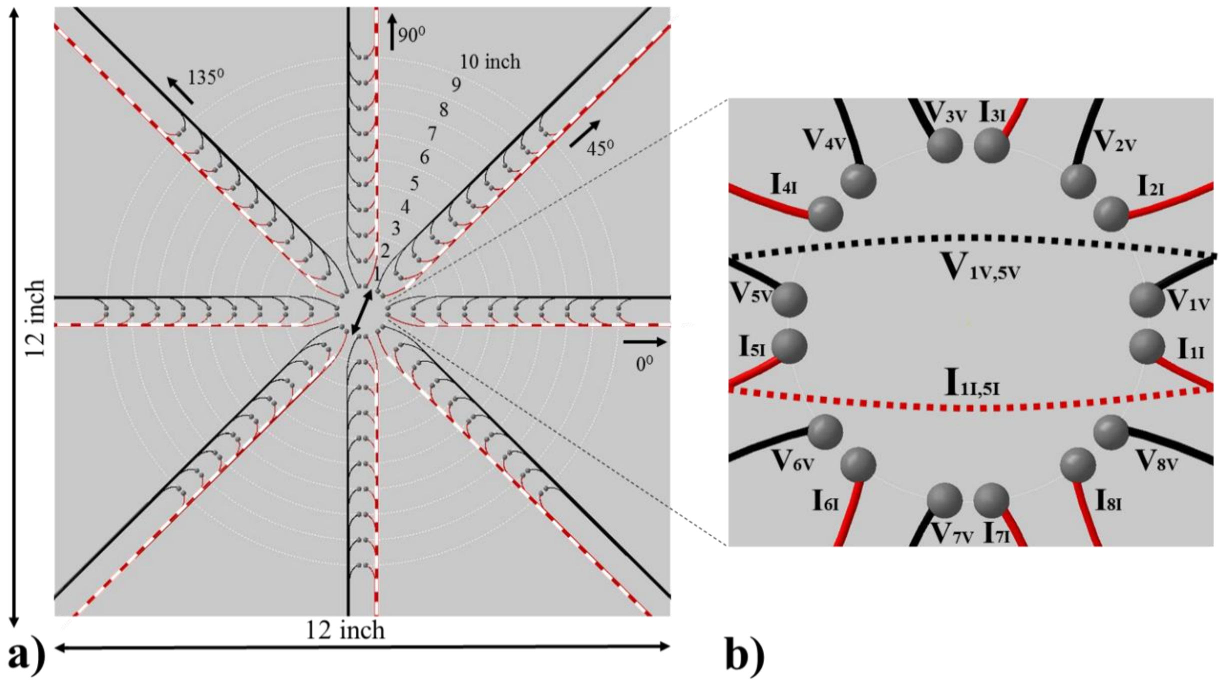


Figure 6: Pattern of contact points on the surface of the plate

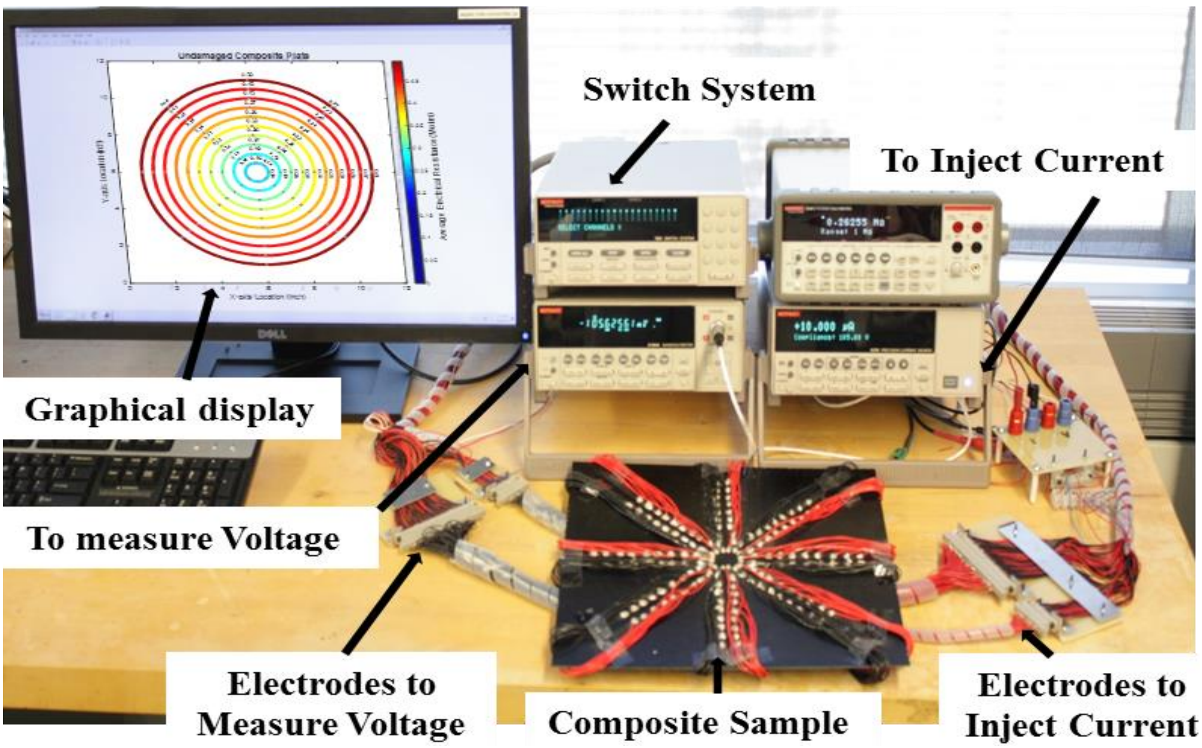
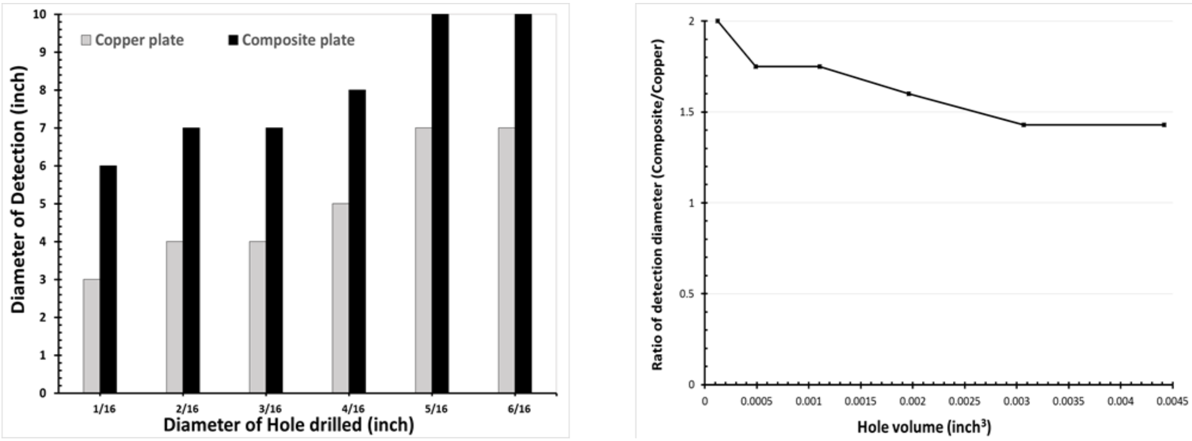


Figure 7: Experimental set up.

Results:

The results are shown in figure8. For copper plate, with a hole of 1/16 inch (1.59 mm) diameter, the electrical resistances between pairs of points at diameter smaller than 3 inch (76.2 mm) exhibit changes, whereas those between pairs of points at larger diameter do not show any significant changes. On the other hand, for the same hole diameter, for composite plate, the presence of the hole can be detected by pairs of points at diameter of up to 6 inch (152.4 mm). Similar differences can also be seen for holes of larger diameters. Figure 8b shows the ratio of detectable diameters between composite plate and copper plate, for different hole volumes. It can be seen that the composite plate is up to about 2 times more sensitive to the presence of holes than the copper plate.



a) **b)**

Figure 8: Relative sensitivity to defect in copper and composite plate

4. Explanation for the behavior:

The above behavior can be explained using the concept of Aggregately Conductive Materials. The simplest model would be a 1-D model shown in figure 9. In figure 9a, between two points A and B in a certain material domain, there are a number of conductive paths. Each path has a certain electrical resistance R. Assuming that there are N paths of equal electrical resistance, the equivalent resistance between A and B is R/N. If some damage occurs such that one of the resistors is broken, the new resistance between the two points becomes R/(N-1). The relative change (X) is 1/(N-1). A plot of X versus N is shown in figure 9b. It can be seen that the larger is the value of N, the smaller is the relative change. The largest relative change occurs at N = 1 where the change is infinity, since the break of the only resistor would mean an open circuit.

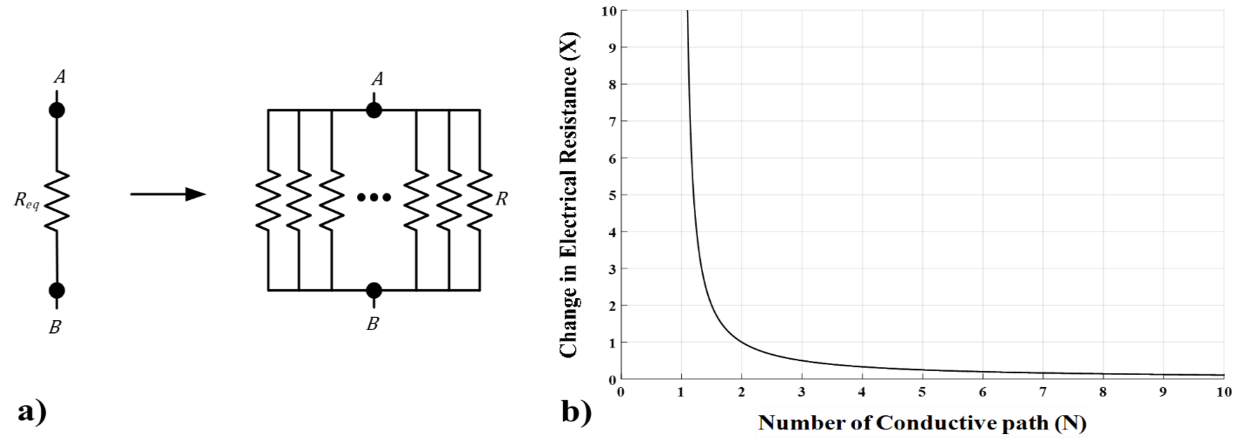


Figure 9: 1D model of Aggregately conductive materials

5. Application in the structural health monitoring of composite structures:

The above behavior can be applied to the detection of defects in composite structures. For any type of health monitoring, one needs to put in contact points and connecting wires. These can add weight and cost. The minimization of these contact points and connecting wires would be essential. The fact that the composite structure is sensitive to the occurrence of defects by probes that are far away from the defect location can translate into less number of contact points and wires.

Conclusion:

It has been shown that the addition of a proper amount of carbon nanotubes into epoxy composites can make these materials to be aggregately conductive. What this means is that the material is conductive, but only on the aggregate scale. This behavior makes the material to be sensitive to the occurrence of defects, by using probes that can be far away from the defect locations. A model has been developed to explain this behavior. This characteristic can be used to advantage in the health monitoring of composite structures.

Acknowledgments

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