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Carbon nanotubes as reinforcement in composites: A review of the analytical, numerical and experimental approaches

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ABSTRACT

This review article is intended to highlight and categorize the most important and novel studies conducted to explore the mechanical behavior of nano-composites reinforced with carbon nanotubes (CNTs). The existing articles cover the mechanical performance of reinforced composites, both theoretically and experimentally, which allows an accurate estimate of the mechanical performance of these nano-structures. It was addressed that the predictive methods can be categorized as: models based on unit cells with a single fiber, models considering a unit cell with a larger number of fibers, and how the fibers are modeled: as a 1D, 2D, or 3D configuration. Furthermore, we review two different experimental methods (destructive and non-destructive) in order to highlight more investigations in this particular field of research. The presented review article includes: (i) a brief outline to CNT reinforced composites; (ii) a review of investigation on analytical, numerical, and experimental modeling; and (iii) a comprehensive conclusion regarding the argued investigations and some thoughts on the potential development.

1. Introduction

There is always an essential need to apply novel materials with improved properties in industry. Carbon nanotubes (CNTs) have attracted significant research attention from various regions of engineering and science due to their outstanding chemical and physical characteristics such as high stiffness, high strength but very low density [1–7]. These hollow cylinder shaped nanostructures are created by hexagonal unit cells which were discovered by Iijima in 1991 [8]. Numerous studies have been conducted in order to estimate and develop the characteristics of CNTs. Determination of tensile strength (of up to 63 GPa), Young's modulus (of about 1 TPa), and vibrational stability of CNTs were of the most significant aims of these research papers [9–14]. The investigations on composite materials reinforced with short fibers started many decades ago before discovering CNTs. These studies can be divided into two distinct aspects of predictive methods (analytical and numerical) and experimental techniques. This review article is prepared as follows: Section 2 presents a review of different modeling approaches of reinforced composites with sub-branches including models based on unit cells with single fibers, models considering unit cells with a larger number of fibers, and how the fibers are modeled: as a 1D, 2D or 3D structure. Fig. 1 illustrates a CNT (3D) and the transition to an effective fiber.

The different modeling approaches for the fibers are schematically shown in Fig. 2: one-dimensional (spring/truss/beam line element), two-dimensional as a hollow cylinder (e.g. surface mesh based on shell elements) and a three-dimensional (solid elements) model in the scope of the finite element (FE) approach.

Fig. 3 illustrates the schematic structure of unit cell models based on single fibers and with a larger number of fibers.

Section 3 presents a review of destructive (e.g. tensile testing up to fracture) and non-destructive (e.g. ultrasound wave propagation and micro CT scanning) experimental investigations, respectively. The final section concludes the presented research and provides an outline on the latest progresses of CNT reinforced composites (CNTRCs). It should be noted that this article covers the investigations concerning both CNT reinforced and carbon fiber reinforced composites because many early results for carbon fibers can be, to a certain extent, transferred to the application of CNTs.

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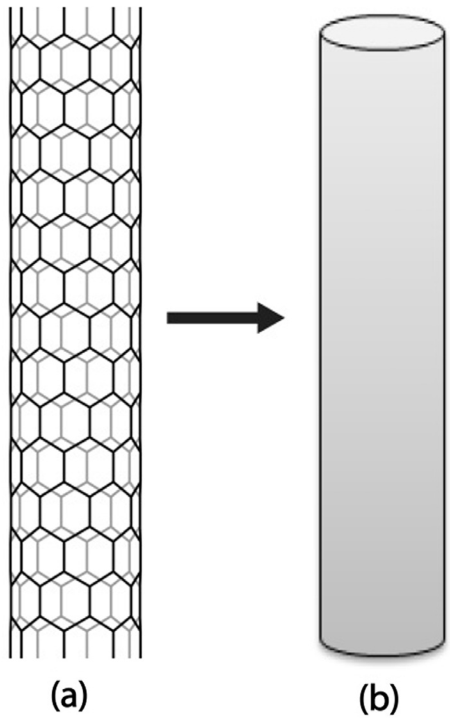

Fig. 1. (a) CNT and (b) effective fiber.

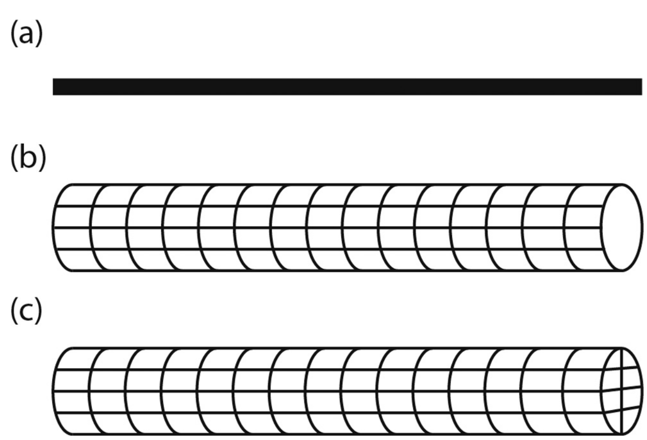

Fig. 2. Different approaches to model the equivalent fiber: (a) 1D line element (b) a hollow cylinder with only a surface mesh, and (c) a solid cylinder.

2. Research work on analytical/numerical modeling

The following sections provide a review on the physical, thermal, and mechanical properties of reinforced composites.

2.1. Unit cell models considering a single inclusion or fiber

2.1.1. Models with a classical inclusion or carbon fiber

In 1969, Amirbayat and Hearle [15] derived an expression for the matrix-fiber load transfer for any type of matrix-fiber bond in the composites, applying the basic theory of elasticity. For no boding, the effect of differences in Poisson's ratios was indicated. They examined the effect of different variables on the system for the special case of no perfect bond in which slippage was inhabited by frictional forces resulting from interfacial pressure. In 1974, Fukuda and Kawata [16] suggested a system of load transfer from the matrix to the fiber in the case of single short fiber models. Then, they predicted Young's modulus of short fiber-reinforced materials provided that the coordination of the fibers follows an specific rule. They eventually compared the mathematical approach with experimental data. They also continued their study calculating the axial stress of a fiber, the shear stress at the fiber-matrix interface and the stress in the matrix of short fiber-reinforced materials under tension [17]. In their proposed model, the matrix and fibers do not overlap at the region corresponding to the fiber. They considered single short fiber models and models of a regular fiber array. In addition, impact of the modulus ratio of the fiber and matrix and the aspect ratio of the fiber were explained in the former case and the effect of the fiber spacing in the latter case. Afterwards in 1984, Tandon and Weng [18] inspected the impact of the aspect ratio on the actual elastic moduli of a transversely isotropic composite. They also assumed the reinforcing inclusion to be spheroidal and unidirectionally aligned. Based on their examinations, in-plane shear modulus and the longitudinal Young's modulus appeared to rise with growing aspect ratio. They applied a combination of Eshelby's and Mori-Tanaka's principles of inclusions in their proposed analysis. After that, Weng [19] conducted an investigation to develop the stress and strain state of stress concentrations at the interface, fundamental phases, and the general moduli and elastic energy of the composite. Both polarization strain and polarization stress were applied in these derivations. The principle was established first for a general composite with oriented inclusions. He finally obtained numerical outputs for stress concentrations at the interphase and at the spherical inclusions and for a 2-phase composite. Later in 2000, Hsueh [20] derived Young's modulus of a discontinuous-fiber composite applying a modified shear-lag model. It was concluded that the shear-lag model was initially enhanced to address the stress-transfer problem between the matrix and the fiber. Cho et al. [21] developed a multi-scale approach combined with molecular

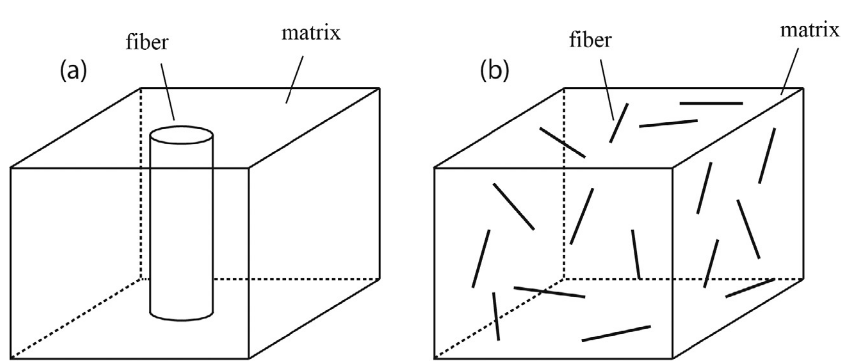

Fig. 3. Models considering (a) unit cell with a single fiber and (b) larger number of fibers.