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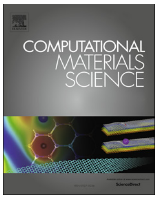

Load sharing inside multi-layered graphene nanosheets under bending and tension

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ABSTRACT

Graphene nanosheets show unique material properties and are highly anisotropic in stiffness and strength. These materials are non-continuum in micro-structures. The mechanisms of load transfer from outside into the inner layers depend on the shear stress in the interphase between layers. In this work, the stress distribution in the layers and the interphases are investigated by using a modified shear-lag method, and the finite element results are also employed for comparison purpose. The loads examined include bending and tension. The effect of layer number and the equivalent shear modulus of the interphase are studied. The simulation results show that the length for saturated stress is around 20 nm for the case of 10 layers and an interphase shear modulus of 4.2 GPa. The shear modulus is sensitive to the load sharing efficiency. This work also reveals that the saturation length increases with an increase in the number of sheets in graphene nanosheets. This length increases from 5 nm to 60 nm when the sheet number changes from 5 to 20. The stresses are drastically varied and the interlayer shear stresses are the highest near the edge where the load is applied.

1. Introduction

Nowadays, single and multi-layer graphene materials have been widely studied owing to their unique and exceptional properties in thermal, electrical and mechanical behavior [1–5]. The Young's modulus of a single graphene with carbon atoms bonded together through the in-plane sp^2 bonding was found to be around 1.04 TPa [6], making it an ideal reinforcement for composite materials [7–10]. Multi-layer graphene nanosheets (GNSs), in which individual sheets are interacted by van der Waals force, can be excellent candidates for flexible medical sensors, mechanical resonators, gas detectors [11–14].

When GNSs are used in composites, the major loads on them are bending and tension. Hence pristine graphenes and graphene-reinforced composites subjected to these loadings have been widely studied [15–22]. Wang [15] studied the rigidity of graphene against bending using molecular mechanics simulations. The rigidity was found to be dependent on the size and shape of GNSs. Moreover, the dependence of the rigidity on the deflection applied to a GNS was revealed. Liu et al. [16] presented a study on bending of multi-layer nanostrips made of graphene for their applications as resonators, sensors and actuators. By using molecular dynamics simulations, it was found that the interlayer shear has apparent impacts on the mechanical deformation, vibration and energy dissipation processes therein. Based on a nonlocal plate model, nonlinear bending behavior of a bilayer graphene in thermal environment was investigated by Xu et al. [17]. The numerical results show that the stacking sequence has a moderate effect, whereas the temperature change as well as the aspect ratio has a significant effect on the nonlinear bending behavior of the bilayer graphene. The deformation of a single-layer circular GNS subjected to a central point load was reported by molecular mechanics [18]. It was found that the nonlinear bending and stretching behaviors of single-layer GNSs can be well described by the von Kármán plate theory. Poot and van der Zant [19] examined mechanical properties of GNSs that were suspended over circular holes by using an AFM. Their findings suggested that GNSs sustain very large bending and stretching prior to the occurrence of fracture.

In addition to efforts on physical and mechanical behaviors of pristine graphenes, investigations on graphene reinforced composite materials have been also studied extensively, especially the load transfer among every sheet of a graphene panel and the matrix [23–25]. Gong et al. [23] have demonstrated

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unambiguously that stress transfer takes place from the polymer matrix to monolayer graphene, showing that the graphene acts as a reinforcing phase. The stress transfer efficiency and the breakdown of the graphene/polymer interface were also included. The load transfer and mechanical properties of a chemically derived single and multilayer graphene as reinforcements in poly (dimethyl) siloxane composites subjected to tension and compression were also studied [26] by Raman and Scanning Electron Microscopy (SEM). It was concluded that the single-layer graphene in poly (dimethyl) siloxane composites displays a more enhanced load transfer, mechanical strength, damping capability, strain energy sensitivity and elastic modulus compared to their graphene counterparts. Kuo et al. [9] studied deformation of a GNS/epoxy composite and used an SEM and Transmission Electron Microscopy (TEM) to achieve microscopic observations. The micrographs revealed that the folding and wrinkling are the two major modes of deformation.

GNSs and multi-walled carbon nanotubes show high similarities in patterns of deformations [27], as both are stacking of GNSs in highly ordered manners. By using the shear-lag model and finite element method in continuum mechanics, studies on load transfer among individual layers of carbon nanotubes as well as transfer between the matrix to carbon nanotubes in the composites under various loadings were extensively conducted [28–31]. Studies on load transfer in single and multi-layer graphene and graphene composites subjected to bending and tension [18,23,26] were also conducted. However, there still lack extensive investigations that are able to clarify the load distribution and transfer efficiency in multi-layer graphene with more than five sheets. Moreover the effects of the length of graphene panels, number of GNSs on the stress distribution and transfer have also been less intensively researched. A comprehensive study on load transfer in graphene with multiple nanosheets will enable to provide (i) a clear understanding on how load shared for each individual layers; (ii) a benchmark on the saturation length of graphene at which a saturated stress occurred; and (iii) a guidance on how to increase the load transfer efficiency in composite applications and the graphene based devices. In this present work, a theoretical work is conducted and developed based on the shear-lag model to study the stress transfer inside GNSs subjected to bending and tension. The obtained results are verified by the finite element approach. Without loss of generality, the GNSs with five to twenty layers are examined.

2. Experimental findings and continuum modeling

2.1. Experimental findings

According to a previous study, GNSs are highly anisotropic in deformation and fracture behaviors [9]. They are very stiff and strong when stretched along the in-plane direction. Without being loaded, GNSs are straight and uniformly stacked. Fig. 1(a) shows a TEM micrograph of the non-deformed part of a GNS. The spacing between GNSs measures 0.34 nm. Near the edge of a GNS, distortion is displayed. A typical example of stretching fracture is shown in Fig. 1(b). The distortion was caused by a sudden release of the tensile stress when the edge is formed. Because of the nature of a membrane with less bending rigidity, GNSs are vulnerable to tearing and virtually resistless to bending. Fig. 1(c) shows a SEM micrograph of a GNS under bending. The bending deformation is non-returnable because a sliding takes place in between the layers.

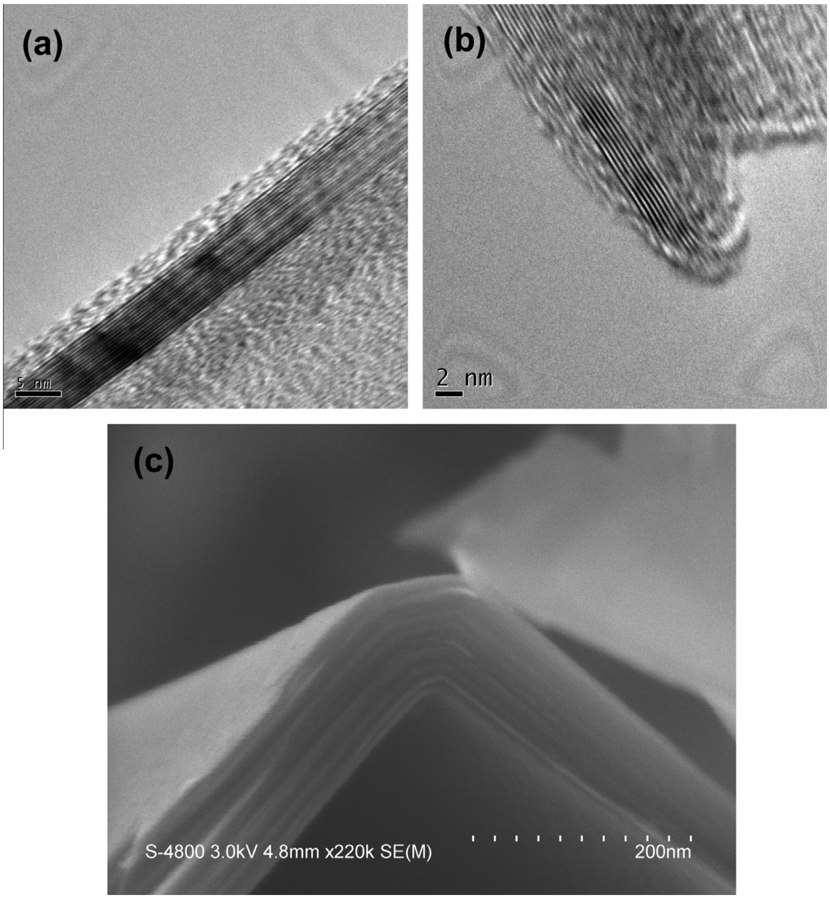

Fig. 1. (a) TEM micrograph of a GNS without deformation, (b) the edge of a fractured GNS, (c) SEM micrograph showing a typical GNS with bending deformation.