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Computational local stiffness analysis of biological cell: High aspect ratio single wall carbon nanotube tip

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ABSTRACT

Carbon nanotubes (CNTs) are potentially ideal tips for atomic force microscopy (AFM) due to the robust mechanical properties, nanoscale diameter and also their ability to be functionalized by chemical and biological components at the tip ends. This contribution develops the idea of using CNTs as an AFM tip in computational analysis of the biological cells. The proposed software was ABAQUS 6.13 CAE/CEL provided by Dassault Systems, which is a powerful finite element (FE) tool to perform the numerical analysis and visualize the interactions between proposed tip and membrane of the cell. Finite element analysis employed for each section and displacement of the nodes located in the contact area was monitored by using an output database (ODB). Mooney–Rivlin hyperelastic model of the cell allows the simulation to obtain a new method for estimating the stiffness and spring constant of the cell. Stress and strain curve indicates the yield stress point which defines as a vertical stress and plan stress. Spring constant of the cell and the local stiffness was measured as well as the applied force of CNT-AFM tip on the contact area of the cell. This reliable integration of CNT-AFM tip process provides a new class of high performance nanoprobes for single biological cell analysis.

1. Introduction

Researchers have demonstrated various methods to predict the interaction of the biological cells in bioprocesses which is due to the lack of fundamental measurement approaches in mechanical interactions of the cells. Nowadays, individual cell can be mechanically measured using their structural entities by applying different methods such as: magnetic twisting cytometry [1], ball tonometry [2], micromanipulation [3], micropipette aspiration [4], atomic force microscopy [5], optical tweezers [6], cytoindentation [7], and turgor pressure probe [8]. Among these methods, AFM is playing a significant role in different fields, such as nanotechnology, materials science, surface science and biology [9,10]. AFM has been used to probe a number of properties inherent to microbial cells, mammalian cells and biomolecules including analysis of cellular mechanical strain and elasticity, due to the precise application of low forces to cells with minimal disruption. One of the key parameters to broaden AFM applications is to investigate new probe types which have better lifetime, higher resolution, and higher mechanical property to provide quantitative and accurate analysis of biological cells [11,12].

Researchers have nominated carbon nanotube tips due to the several advantages, including (a) high aspect ratio for imaging deep and narrow features, (b) low tip sample adhesion for gentle imaging, (c) the ability to elastically buckle rather than break when large forces are applied making them highly robust, and (d) the potential to have resolution, 0.5 mm in the case of individual single-wall carbon nanotubes (SWCNTs). Furthermore, the wettability of the CNTs' surface is an important property, governed both by chemical composition and geometrical structure of the contact surface, which can play a key role in the CNTs' performance as an AFM tip. In fact, by using CNTs as an AFM tip, the probed material remains non-reactive [13,14].

The above characteristics make carbon nanotube to be an ideal tip for probing in AFM. First CNT-AFM probe was developed in 1996 by Tans et al. [15] which demonstrated considerable potential in probing mechanism of AFM [16]. In a pioneering study, Lieber group also [17,18] prepared CNT-AFM probes using mechanical assembly. Some other scientist conducted studies on the possibility of carbon nanotubes for force microscopies [19]. Fig. 1 is a SEM image showing a nanotube attached to a conventional micro-fabricated probe.

Previously we had simulated CNTs to find out the variation of mechanical properties of CNTs while immersing Nano-particles on the surface of SWCNTs [21,22]. But in this contribution, a novel finite element analysis of SWCNT-AFM tip is reported to obtain the local stiffness analysis of the cell. Available powerful finite element analysis software

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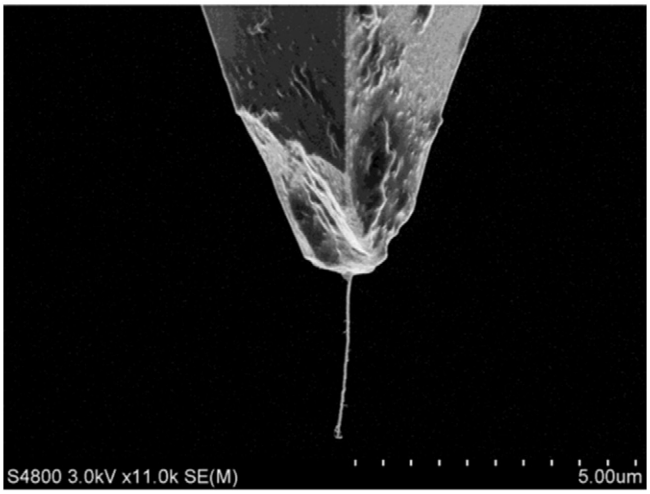

Fig. 1. A carbon nanotube attached to a conventional micro-fabricated probe [20].

ABAQUS 6.13 CAE/CEL was used to model and analyze the membrane and CNT tip. With greater understanding of the way in which mechanical properties of SWCNT-AFM, it may easily possible to continuously tune the selectivity and sensitivity of nanotubes in biological applications. Fig. 2 shows the schematic diagram of the proposed idea.

2. Theoretical analysis

Mechanical properties are an important determinant of stress generation in any cell experience molding. To motorize the biomechanics of the cell such as stiffness or spring constant, we have to determine the displacement of the cell by applying load on the model [23]. The stiffness of a cell can be described by the tensile elasticity or Young's modulus (E), which is measured in units of Pa (N/m^{-2}) and represents the ratio between the applied stress on the cell (force per unit area) and the resulting strain (fractional change in length). Spring constant also can be obtained by indenting technic of the cell by CNT-AFM tip [24].

3. Finite element analysis procedure

Finite element is versatile and effective distributed-parameters modeling method, which previously has been used for various modeling regarding the AFM [25–27]. In the pioneering study, ABAQUS 6.13 CAE/CEl finite element toolkit was applied in order to obtain the mechanical behavior of the cell by CNT-AFM tip.

The complete model of the simulation was divided into three parts: 1) CNT-AFM tip, 2) cell and 3) an underlying substrate to hold the sample tightly. Axial displacement of the CNT can be applied by a controllable force during the specific time to monitor the deformation of the cell wall.

4. Finite element analysis of carbon nanotubes

CNTs are extremely tight and stable materials according to their strength sp^2 hybridized covalent C–C bonds. The bonding mechanism in a carbon nanotube system is similar to that of graphite, since CNTs can be thought of as a rolled-up graphene sheet. Considering the high Young's modulus (elastic modulus) and significant density of carbon nanotubes (approximately five times more than steel), they are excellent candidates for AFM probing [28]. Several modeling schemes such as the Tersoff–Brenner potential, an empirical force-constant model,

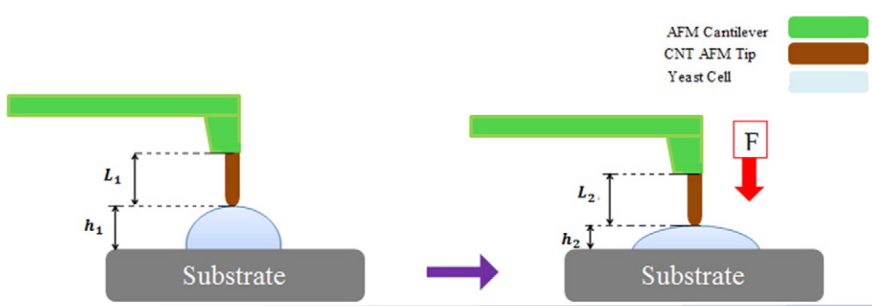

Fig. 2. Schematic diagram of the SWCNT-AFM tip.

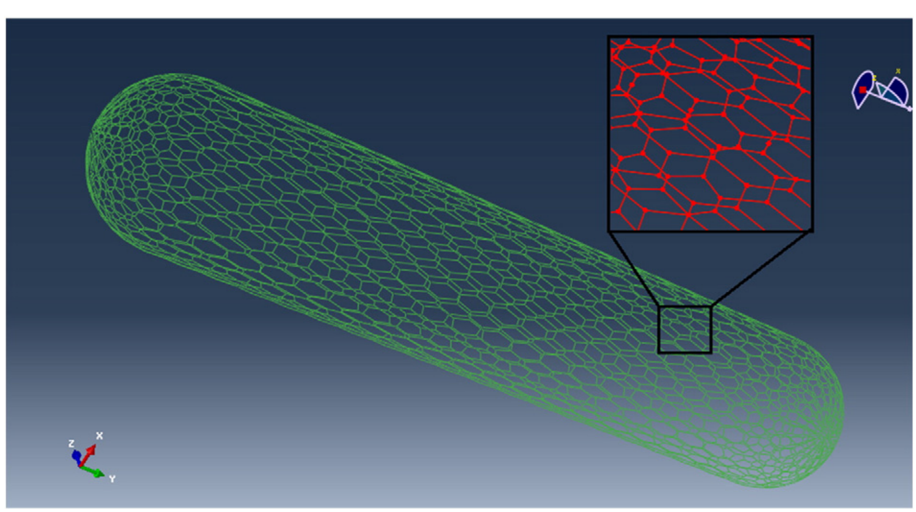

Fig. 3. Meshed model of CNT-tip.