Figure 1: Computer-generated central-axis view of collapsed nanotube.  

2.1 Collapsing Versus Fiber-Forming 

Figure 2: Nannotube Deformations 

2.2 Internal and External Radial Forces 

3.1 Introduction 

4.1 Structural Stability of Carbon Nanotubes
configurations (similarly, of course, many circular cross-section inflated tubes may be in a metastable inflated state).

Do fully collapsed, ribbon-like nanotubes exist? TEM studies\(^2\) have convincingly demonstrated the existence of such tubes. Fig. 2 shows an example of a collapsed nanotube. This particular tube has 9 walls and \( R = 8.0 \) nm for the outermost shell. \( R_{\text{crit}} \) (9) is predicted\(^3\) to be of order 7.5 nm, which implies that the total energy of the collapsed tube in Fig. 2 is at a global (tube) minimum, not just local metastable minimum.

![Figure 2: TEM image of a collapsed nanotube. The arrows identify 180° twists in the tube.](image)

2.2 Nanotube Instabilities Induced by Bending

How did the tube shown in Fig. 2 come to be collapsed? It is possible that it was locally mechanically deformed (perhaps by twisting and/or bending) and "kinked". The "kink" could then propagate along the length of the tube, effectively "zipping" the tube shut into a fully collapsed state.

We have examined the local deformations of carbon nanotubes subjected to severe bending. We observe that if the nanotube parameters are well outside the parameter range for energetically favorable "collapse", the bending does not result in tube collapse, but rather induces unusual instabilities along the inner curve of the bent tube.

The inset of Fig. 3 shows a TEM image of a 16-wall, 20 nm outer diameter tube bent through a 90-degree angle (a larger structure forms the left support for the bent tube). Fig. 3 is a line drawing reproduction of a high resolution TEM image of the bent region of the tube. The inner curve of the tube shows a well-defined periodic ripple, with wavelength 16 nm.

![Figure 3: Line drawing reproduction of HRTEM image of bent region of a nanotube; note the periodic modulation. The inset shows a lower magnification TEM image of the bent tube.](image)

Fig. 4 shows an 8-wall (collapsed) nanotube bent through a severe 90-degree bend. Here no periodic instability is observed; rather the inside curve shows a tortuous folding of the nanotube wall fabric. The high resolution TEM image shows no evidence for tube fabric breakage, despite the small overall radius of curvature of the bend (approximately 20 nm) and the extremely small local radius of curvature at the folds (as small as 0.3 nm). Collapsed nanotubes are extremely flexible and strong.

Collapsed nanotubes are also prone to twisting. The collapsed nanotube shown in Fig. 1 in fact has two distinct 180-degree twists along its length. Nearly all collapsed nanotubes we observe have twists. This feature supports the notion that nanotubes are more flexible in the collapsed state than in the inflated cylindrical state. This distinction could have important implications for mechanical applications. It is also quite possible that the "kink" that nucleates nanotube collapse originates at a partially twisted region in the originally cylindrical tube.
2.3 Nanotube Collapse Induced by Electron-beam Irradiation

We have used 800 keV electrons to selectively weaken carbon bonds in a multi-wall carbon nanotube and induce complete collapse.

Fig. 5 shows schematically the selective bond damage and tube distortion expected from 800 keV electron irradiation. Molecular dynamics studies by Crespi and coworkers\(^4\) demonstrate that knock-on beam damage to the tube is most severe for the regions of tube surface oriented perpendicular to the beam direction. In this representation, the "top" and "bottom" portions of the tube sustain the most damage; the curvature modulus is significantly reduced in the damaged regions. With sufficient reduction in modulus, the tube will collapse into a ribbon form, with the wide part of the ribbon parallel to the electron beam direction.

Fig. 6 shows an experimental realization\(^4\) of such an induced collapse using 800 keV electrons. The dashed line delineates the tube under study from an adjacent tube. After 60s of exposure time, the tube has begun to collapse. After 165s of exposure time (not shown), the multiwalled nanotube is fully collapsed (complete disappearance of the gap in the center of the tube).

Acknowledgments

This work was performed in collaboration with F. Ross, L.X. Benedict, V.H. Crespi, M.L. Cohen, and S.G. Louie. Support is acknowledged from ONR grant N0014-95-F-0099 and DOE grant DE-AC03-76F00098. NGC received support from the Department of Education and AZ received support from the Miller Institute for Basic Research in Science.

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