The mechanical property of single-walled carbon nanotube (SWCNT) ropes mainly comes from intratube C–C bonds and intertube binding; the former is 0.2 eV/at, and the latter is 15 meV/at.1,2 Therefore, it is anticipated that stress can be fully transferred onto C–C characters rather than intertube junctions. In practice, load is mostly undertaken by intertube binding, and tube-tube sliding leads to a material fracture. This is evident by the fact that the strength of individual SWCNTs reaches terapascal, whereas SWCNT ropes fracture. This is evident by the fact that the strength of individual SWCNTs reaches terapascal, whereas SWCNT ropes fall in the range of 0.3–10 GPa.3–5 In addition, the effective area (EA) of load dispersion is essentially low along the bundle axis which also limits the contribution of C–C bonds to the rope strength (blue, Fig. 1). For example, EA for nanotubes packed in a hexagonal geometry can be calculated using,

\[
EA(\%) = \frac{2\pi(R^2 - r^2)}{[3\pi/2(2R + d)^2].}
\]  

Based on a report,6 we set parameters as \( R = 0.85 \text{ nm} \), \( r = 0.26 \text{ nm} \), and \( d = 1.4 \text{ nm} \), and EA appears to be 6.6%, a value which is very small. In fact, an efficient load transfer can be achieved if (a) tube-tube sliding is prohibited or (b) internanotube binding is promoted to a value comparable with C–C bond energy. Point (a) has been carried out via a chemical modification of nanotubes and a polymer blending process,7–9 and point (b), however, remains to be established. This work shows that winding of SWCNT ropes to a certain degree can significantly increase the tube-tube binding, and the material strength is therefore enhanced.

SWCNTs were produced by pyrolysis of ferrocene at 1200 °C (Ref. 10), and filmlike pristine materials were spun into long bundles [Figs. 2(a)–2(c)] via a lab-made nozzle device. Bundle dimension is approximately 15 μm in diameter and 8 cm in length, and the winding is roughly 10 turns/cm measured by a scanning electron microscope (SEM) [inset, Fig. 2(c)]. Three bundles were combined and fixed between clamps separated by 7 cm. The top clamp was rotated by an electrical motor, while the lower one remained still, so combined bundles were again twisted and the resultant structure is here defined as SWCNT ropes. The rope winding has been controlled at 10, 30, 50, and 70 [Fig. 3(a)], and the revolving direction is clockwise, same as bundles. We find that length of SWCNT ropes slightly decreases as winding increases and length shortening does not correlate linearly with the revolving number. For example, ropes are shortened by approximately 1% for 30 turns and by approximately 5%–7% for 70 turns. Nevertheless, general trends are found as follows. Firstly, regular twists become obvious along the rope axis in high winding samples [e.g., 70 turns, Fig. 3(a)], and secondly, SWCNTs protrude from rope surfaces when winding increases [Fig. 3(a)]. This reveals that SWCNTs are truly packed closely by winding, and shorter tubes are somewhat “squeezed out.”

The strength of single-walled carbon nanotube ropes is enhanced by a factor of 6 via a winding procedure. A stepwise structure seen at a load-strain profile is explained based on an intermittent fracture mechanism. © 2007 American Institute of Physics. [DOI: 10.1063/1.2714282]
larger tubles are less rigid along the c axis, so carbon lattices significantly deform upon winding.\(^1\)

The enhancement of the intertube force by rope winding can be further characterized using friction formula \(F_r = \mu N\), where \(F_r\), \(\mu\), and \(N\) are the resistive force of friction, friction coefficient, and bold force to the object surface, respectively. For nanotube bundles, the \(F_r\) approximates \(1.4 \times 10^{-7}\) N m\(^{-2}\) (corresponding to 0.35 GPa)\(^1\) and \(\mu\) is 0.1 based on the graphite-graphite friction along 001 basal planes,\(^1\) which yields \(N = 1.4 \times 10^{-3}\) N (3.5 GPa). The \(F_r\) and \(N\) can be regarded as the tensile strength along the rope axis and intertube binding because tube-tube sliding (friction) is determined by the magnitude of both;\(^1\) in other words, rope winding would also enhance the \(F_r\) and \(N\). According to Figs. 3(b) and 3(c), the rope strength enhanced by twisting is sixfold, corresponding to \(F_r = 0.35 \times 6 = 1.5\) GPa and \(N = 3.5 \times 6 = 21\) GPa; the former is in good agreement with the value seen at 70 turns [1.2 GPa, Fig. 3(c)] and the latter is now comparable with the strength of individual SWCNTs.\(^4\)

In our study, the load-elongation profiles often show stepwise structures at high winding samples [left panel, Fig. 4(a)]. For example, 70 turned ropes exhibit three linear regions (\(E_1\), \(E_2\), and \(E_3\)) interconnected by two yielding points (\(Y_1\) and \(Y_2\)) and corresponding moduli follow \(E_1(=205\) GPa) > \(E_2(=164\) GPa) > \(E_3(=110\) GPa). The elastic modulus is related to the force constant of solid crystals, and various moduli suggest that the cohesion energy per unit length of SWCNT ropes has intermittently changed upon testing. Here, we believe that the stepwise profile is attributed to complex winding structures, and our theory is as follows. The load is initially dispersed onto the entire rope, which produces \(E_1\). When one of the bundles is fractured, the load is continuously taken by remaining aggregates, thus resulting in \(E_2\) and \(E_3\) [right panels, Fig. 4(a)]. This fracture process is supported. Firstly, individual SWCNTs are well contained within the bundle by twisting before merging into ropes, and subsequent rope winding has only tightened the aggregated bundles. In other words, there has no nanotube linkages between adjacent bundles to act as crack propagation paths, and cracking is prohibited at interbundle junctions. This explains the absence of rope snap during tests. Secondly, partial fracture unravels the wound rope [arrow, left, Fig. 4(b)] which, in turn, lowers the intertube binding and cohesion energy (modulus) in the remaining bundles. We...
evaluate the cohesion energy ($E$) per unit length of SWCNT ropes at different elastic regions ($E_1$, $E_2$, and $E_3$) using Eq. (2).\(^1\)

$$E = -2\pi(R - \rho)\gamma - U_0\rho^{1/2} + \pi(\rho^{-1} - R^{-1})C_0,$$

where $U_0$, $\rho$, and $\gamma$ represent the interaction energy per unit length of tube, radius of curvature at the corners, and energy required to separate adjacent tubes, respectively. The first and second terms represent the van der Waals interaction of ropes and the attraction of rounded corners,\(^1\) and the third term is the elastic energy increase due to the enhanced inter-tube interaction by winding. The rope winding also shortens the tube-tube separation. Therefore, one can use the compressibility modulus (which is equivalent to bulk modulus) to evaluate the $U_0$ for different moduli and the equation is expressed below,

$$E_n = 0.66[C_0\rho^{-3} + U_0/(8\pi\rho^{3/2})],$$

where $C_0 = 1.02$ eV.\(^1\) According to SEM images, we set $\rho = 10$ μm. The substitution of $E_1 = 205$ GPa, $E_2 = 164$ GPa, and $E_3 = 110$ GPa into equation yields $U_0 = 0.15$ eV Å$^{-3/2}$ for regions $E_1$, 0.12 eV Å$^{-3/2}$ for $E_2$, and 0.11 meV Å$^{-3/2}$ for $E_3$. Again, the insertion of obtained $U_0$ into Eq. (2) with $\gamma = 7.6$ meV Å$^{-2}$ gives $E = 0.51$ eV Å$^{-2}$ for region $E_1$, 0.4 eV Å$^{-2}$ for region $E_2$, and 0.27 eV Å$^{-2}$ for region $E_3$. The decrease in both $E$ and $U_0$ at regions $E_2$ and $E_3$ supports our theory that the partial bundle fracture has truly loosened the remaining bundles, thus reducing rope strength ($E_2$ and $E_3$). The additional effect is also noticed that fractured bundle has rapidly recovered to film morphology, indicative of strong tubule rigidity [right, Fig. 4(b)].

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\(^1\)J. Tersoff and R. S. Rouff, Phys. Rev. Lett. 73, 676 (1994).

\(^1\)David R. Lide, CRC Handbook of Chemistry and Physics (CRC, Boca Raton, FL, 1994), pp. 15–40.