

This requirement has stretched previous approaches to their limit, but several innovations currently demonstrated by Someya's team mean that the present approach is readily capable of such performance. First, the ultralong nanotubes, which are stronger and less tedious to process than the micrometre-long tubes used in previous experiments, will allow us to make elastic conductors at an industrial scale using cheap materials. Second, successfully integrating this material as wires and

interconnects in a printed organic transistor circuit means that more complex electronics can be made in the same way in the future. Further optimization of the ingredients of this composite may lead to even better conducting, stretchable materials.

Although the electrical conductivity achieved by Someya's team is impressive, it is still a long way from existing circuits and high-performance electronic capabilities. Nevertheless, without a doubt, improving the conductivity of the rubber composite

by two orders of magnitude and integrating them into an active flexible circuit brings us yet another step closer to the conveniences of future macro-electronics.

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NANOMATERIALS

Nanotubes reveal their true strength

The mechanical properties of carbon nanotubes have not matched theoretical predictions in the past. New measurements have now confirmed that nanotubes are indeed as strong as theory suggests.

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Humankind has made continuous efforts to improve the mechanical performance of materials, with different eras of history being named after specific developments in metallurgical technology such as the Bronze Age and the Iron Age. Since their discovery¹ in the early 1990s, carbon nanotubes have attracted extraordinary attention as potentially revolutionary mechanical elements: they are inherently light and stiff², and have been predicted to be extraordinarily strong³. However, experimental values of various mechanical properties have always been much lower than theoretical predictions. On page 626 of this issue Horacio Espinosa and co-workers⁴ at Northwestern University and the Argonne National Laboratory report experimental results that, for the first time, show that multi-walled carbon nanotubes can have failure strengths and strains near those that have been predicted by quantum mechanical simulations. Moreover, they report that creating controlled mechanical linkages between the different walls of a nanotube can increase the maximum load that can be supported, offering the promise of even greater utility.

For bulk materials, the primary method for measuring mechanical properties is a simple uniaxial tensile test. A carefully

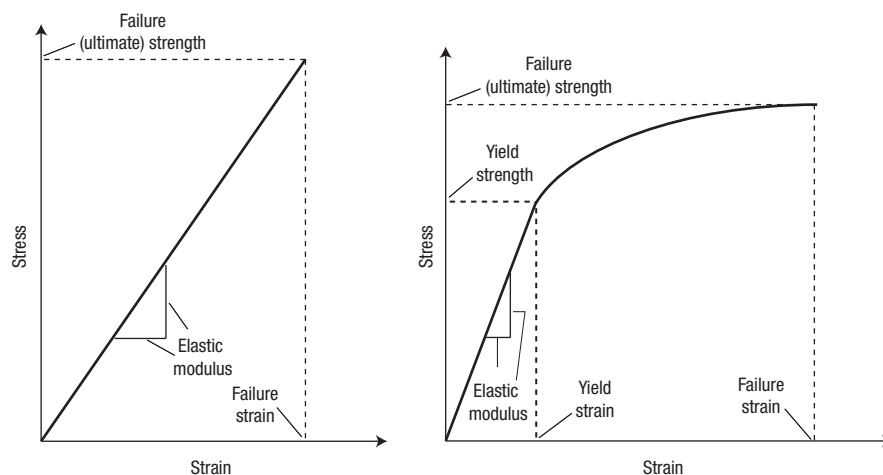


Figure 1 Schematic stress–strain curves for a brittle material (left) and a plastic material (right) showing how the elastic modulus and other mechanical properties of a material can be determined. Experiments measure the displacement caused by an applied load, and these two quantities are then converted into strain and stress respectively via simple relations. Plastic materials (such as metals) start to deform at the yield stress or strain, before eventually failing at higher values of stress/strain, whereas brittle materials (like ceramics) fail without going through a deformation phase. The experiments of Espinosa and co-workers suggest that nanotubes behave like brittle materials, although in many calculations they display some plastic-like behaviour.

shaped sample is loaded into a machine that measures the load required to obtain a fixed rate of displacement, and the resulting stress–strain curve can be used to determine properties such as elastic modulus, yield strength and failure strength (Fig. 1). For nanotubes, however, the question is: how do you

perform such a test on an object that is so extraordinarily small?

In 2000, Ruoff and colleagues⁵ carefully attached nanotube ropes between two atomic force microscope tips using carbon deposition inside a scanning electron microscope, and measured the relative displacement of the tips to determine

both the elastic modulus and failure strength. These experiments were elegantly conceived, but the particular nanotubes used (grown by the arc-discharge method) showed rather poor strength at failure, presumably because of the defective nature of the as-grown structures. Moreover, the inability to observe the internal structure of the tubes during the testing complicated the interpretation of these results.

Now Espinosa and colleagues have performed experiments that border on the heroic. They have made use of a highly sophisticated testing methodology that they have developed over the past six years to measure the mechanical properties of the nanotubes while observing them inside a transmission electron microscope. The testing method uses a specially designed 'microelectromechanical system': this involves electrical signals being used to resistively heat a set of mechanical actuators to apply the load to the nanotube, with on-chip capacitors being used to measure the resulting displacement.

The nanotube is placed on a load frame using a nanoscale positioning robot during simultaneous observation in a scanning electron microscope, and it is then welded in place with local electron-beam-induced carbon deposition. The entire system is then transferred to a specially designed sample holder that can allow the microelectromechanical structures to be

actuated inside the transmission electron microscope. This permits direct, real-time correlations to be made between the load-displacement curves and the structure of the nanotube at the atomic scale (as revealed by electron diffraction). These observations provide correlations between the nanotube chirality (which is the main indicator of structure), the number of walls, the ways in which load is transferred between the walls, and the mechanisms by which failure occurs.

The resulting experiments provide multiple new insights into the mechanical properties of carbon nanotubes. Perhaps most important is the simple confirmation that nanotubes can in fact be as strong as computational studies have predicted. Additionally, Espinosa and colleagues have shown that electron irradiation of the tubes can create mechanical linkages across the individual shells of the tubes, further increasing their capacity to carry load. This suggests that further studies of how to create these interlinks during nanotube production are merited.

Despite these results, much remains to be accomplished before carbon nanotubes are ubiquitous in load-bearing applications. The primary mode in which nanotubes are likely to be used will be as mechanical reinforcement elements in polymer-based composites, providing improvements in both stiffness and strength for little

additional weight. But nanotubes are still relatively expensive, and greater insights into both growth mechanisms and improved growth methods are needed to drive their cost down. Additionally, carbon nanotubes have a strong tendency to bind together, making it difficult to disperse them uniformly in polymeric matrices⁶.

Finally, decades of research have shown that in addition to the properties of the reinforcement, the properties of the interface between the matrix and the reinforcement have an important role in determining, for instance, how load is transferred between the constituents and how cracks propagate in the composite⁷. Thus, increasing our understanding of surface chemistry and interface properties remains crucial. Despite these challenges, the fact that carbon nanotubes can in fact be as stiff and strong as predicted is encouraging and indicates that we might, one day, find ourselves living in the Nanotube Age.

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PROTEIN ENGINEERING

Electrifying cell receptors

Ion channels can be attached to certain types of protein receptors in cells to make a detector-switch pair that could be used in various sensing and screening applications.

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Modifying receptor proteins on the surfaces of cells so that they interact with proteins that are not their natural partners is one way of controlling signalling processes in the cell. Moreover, when isolated from their natural environment, these re-engineered proteins could be used for various sensing

and drug-screening applications. On page 620 of this issue, Michel Vivaudou and co-workers¹ report that two types of proteins — G-protein coupled receptors (GPCRs) and the ion channels that control the voltage gradients across cell membranes — can be combined so that a measurable electrical signal is generated when a molecule such as a potential drug binds to the GPCR. The ability to screen potential drugs that recognize GPCRs with a generic electrical signal in this way could lead to important breakthroughs in nanobiotechnology.

GPCRs are a family of receptors that detect molecules outside the cell: they

help regulate our senses, smell and mood, and are also the target for more than 50% of all modern medicinal drugs^{2,3}. When ligands such as drugs, neurotransmitters, light or odorants bind to these receptors, they change their conformation and this activates G-proteins — a family of proteins that turn on downstream signalling cascades that, in turn, alter cellular function and behaviour⁴. Although this process is well-established, it is becoming clear that GPCR signalling is very complex because it can involve more than one type of G-protein⁵ and can sometimes occur by other pathways that do not require G-proteins⁶. Furthermore,