Civil engineering structures are usually designed to remain as they are built, where they are built. Thus a bridge becomes a fixed crossing of a river, and a tall building a familiar beacon in a skyline. There are exceptions, of course, as when the bascule span of London’s Tower Bridge opens to allow tall ships to pass, or when the brise soleil of the new addition to the Milwaukee Art Museum unfolds to shade its atrium from the sun. Such exceptions fall into the category of deployable structures, those that have more than a single appropriate configuration: open and closed, folded and unfolded, stored and deployed.

In fact, there are many deployable structures, throughout all branches of engineering and in diverse applications. These range from retractable automobile antennas to grocery bags to corrugated boxes to tents to folding-wing airplanes to observatory telescopes to the gigantic movable roofs that cover sports arenas during inclement weather. Among the most convenient and familiar deployable structures is the umbrella that can open at the push of a button. And when the rain stops, the umbrella can be restored to a compact state for carrying in a briefcase or purse.

The Measure of Deployment
Deployable structures are especially desirable when something is awkwardly large to transport in the configuration in which it is used. Thus, since carpenters often have need for a ruler longer than their toolbox, the folding ruler is a familiar accessory. But I have always found folding rulers awkward to deploy—the zig-zag motion requires a dexterity and coordination I do not seem to possess, at least not in combination with speed—and too easily broken. The invention and development of a self-straightening and retractable steel measuring tape, which was introduced in the 1920s, was a boon to carpenters, and I find the device extremely user-friendly.

The Volz rule was operated very much like the retractable tape measure—also made by Stanley—that I have had in my toolbox for three decades. My handy tape has seen considerable use and shows some wear, but it still functions quite well. This flexible metal rule is coated with a plastic film, which is noticeable mainly because it is peeling away in places, and carries U.S. Patent No. 3,121,957, which was issued in 1964 to William G. Brown for a “coilable metal rule.” The principal focus of Brown’s patent is on the plastic film, which provides no direct structural advantage but does protect the rule proper and makes it easier to operate.

According to Brown’s patent, the surface of uncoated deployable metal rules was subject to corrosion and abrasion, which obliterated the numerals and other markings and thus reduced the usefulness of the device. Because of this, a protective coating of lacquer was often employed, but this only aggravated another important failing of the extensible and retractable tape—it increased the surface friction that interfered with easy deployment and retraction. (I remember using some earlier metal rules that had to be coaxed to retract fully into their case.) To protect his rule’s surface while at the same time reducing friction during coiling and uncoiling, Brown came up with a means of encasing the tape in a plastic coating. The coating he preferred was made of a “linear polyester film, specifically polyethylene terephthalate, which has proven particularly suitable for this application.” Brown was right; my tape measure still works like a charm.

Reducing friction and seeking smooth operation can obviously be important objectives in designing and storing a structure for remote deployment not only at the construction site but also in space, where many deployable structures have been employed to great advantage, as the successful Mars rovers have demonstrated. Many early satellite and space missions were hampered by trouble with solar panels or antennas, which were susceptible to getting stuck in a closed or a partially deployed position. But easy and reliable deployment was only one requirement; the deployed structure also had to have the stiffness and stability to maintain the configuration demanded...
to perform its function, whether collecting solar energy or transmitting signals. Smoothness of operation is always desirable, whether for high- or low-tech devices.

An important feature of a deployed steel measuring tape is that it retain a degree of rigidity for some distance from its housing, while remaining flexible enough to be manipulated into corners and to absorb shock without breaking. These qualities allow both the professional and do-it-yourselfer to measure to and from unreachable ceilings and along pieces of lumber or across large spaces without a helper. I have watched carpenters and flooring contractors lay down the end of a steel rule at one side of a great room and deploy it while walking to the other—and get an accurate measurement without once leaving a standing position. When finished, the measuring tape can be retracted into its case—although sometimes too fast, producing a dangerous whipping action—and easily stored in a pocket or clipped to a belt.

Rigidity from Curves
The retractable steel tape works as it does because when deployed it is transversely curved—like a shallow gutter. It possesses “a concavo-convex cross section,” in Volz’s patent terminology. This transverse curvature all along its length—which is created during the manufacturing process by heat-treating spring steel while held in a concavo-convex shape—gives the deployed tape a longitudinal structural stiffness that enables it to maintain the straightness so important for measuring lengths and distances. The phenomenon is not unfamiliar: When picking up a triangular slice of warm pizza, it is helpful to crease it from tip to crust to stiffen it. Otherwise, the end of the pizza slice droops, dripping oil and melted cheese, and makes the slice awkward to eat without contorting the head even more than when eating a taco.

Deploying a concavo-convex Stanley tape like mine horizontally from its casing turns the tape into a slender cantilever beam. Up to about a foot of extension, there is only a barely noticeable deflection of its hooked tip. Extending it beyond the one-foot mark introduces an increasingly obvious curve along the length of the deployed tape—a curve known as the *elastica*, the analytical determination of which was a subject of great interest among 18th-century mathematicians and mechanicians. The elastica formed by my Stanley rule becomes much more pronounced as the tape is deployed beyond two feet; as a three-foot extension is approached, the tape becomes difficult to hold steady either horizontally or vertically, as it sways and bounces at the slightest movement of the casing. (Steadying the casing on the edge on a table and deploying the tape very carefully, I can extend it to 3 feet 6 inches, at which point its tip is about 2 feet below the tabletop.) Without extra care, at just a bit beyond three feet of extension, the tape buckles and then oscillates like a pendulum for a few cycles before coming to equilibrium in an almost vertical position. At the root of the drooping tape, a neat circular bend has been formed, which has a radius of curvature characteristic of this particular model of rule.
Curving or folding a structure—whether it be a spring-steel measuring tape or a slice of pepperoni pizza—always stiffens it. This is why corrugated boxes are made the way they are, why old tin roof panels were often rippled and why unpressurized tin cans have circumferential ridges beneath the label. Complex curvatures in automobile panels not only make them more stylish but also impart greater stiffness, thus enabling a thinner steel sheet to be used in their manufacture. Decorative ridges on computer and appliance housings similarly are designed to add stiffness as well as styling. If the retractable steel tape were perfectly flat, it would droop like a wet noodle whenever deployed more than a few inches. It would also have virtually no resistance to buckling when pushed against a wall.

A more subtle mechanical characteristic of the bent tape is that its longitudinal curvature around the hairpin curve is constant, regardless of the angle of the bend, and appears to match exactly the transverse curvature that gives the tape its stiffness. This coincidence was first noted in the 1920s, “when those coiled-up self-straightening steel measuring ribbons were novelties.” In an incident described in an obituary of the legendary elastician A. E. H. Love, he was challenged to come up with a rational explanation for this behavior, but he evidently never did. An explanation was offered decades after Love’s death by F. P. J. Rimrott, a pioneer in deployable structures used in space. Rimrott’s work was the basis for the elegant solution given in 1988 by Chris Calladine, in his remarkable Love Centenary Lecture delivered before the Institution of Mechanical Engineers. By analyzing the energy stored in the bent tape, Calladine demonstrated that it takes on a minimum value when the radius of curvature of the bend matches that of the transverse curvature of the tape blade.

When released from the clutches of gravity or the experimenter’s hand, the tape unbends and returns under its own energy to the straight configuration, with no permanent damage having been done to it. It is this property that I saw exploited with great success last summer at the Deployable Structures Laboratory in the Department of Engineering at Cambridge University.

**Deployable Structures Laboratory**

The laboratory is directed by Sergio Pellegrino, who for some years has been developing the technology of deployable structures, and most recently of components termed “tape-spring hinges,” with his graduate student Keith Seffen, now also a researcher at Cambridge, and others. Tape-spring hinges can be made simply by cutting sections from an ordinary retractable steel tape measure. Freed of the housing and left to their own devices, the inches-long sections lie straight. They can be attached with the appropriate fasteners to a pair of solar panels, say, laid next to each other like the covers of an open book. With very little effort, the panels can then be folded together—as if to form a closed book—with the tape sections being bent into a closed hinge-like configuration. Additional panels can also be attached with more tape-spring hinges, and all the panels can then be folded on top of each other and latched together, making a package compact enough to fit easily into, say, a satellite launch vehicle.

When a satellite so equipped is inserted into orbit, its stored solar panels can be deployed remotely simply by activating the latch mechanism. Without the latch restraining the opening...
of the tape hinges, they will spring out into a straight configuration—just as a tape measure does when it is free to do so—and open up the solar panels to their full operating expanse, with the locked-open springs providing rigidity. (Sometimes two hinges are used face-to-face, thus providing even greater locking action.) The operation takes no more energy than that required to release the latch, since the unfolding energy is already stored in the tape-spring hinges themselves.

Such attractive features were what made the class of Storable Tubular Extendible Members—known as STEMs and pioneered by Rimrott—so popular in deployable-structure applications beginning in the early 1960s. They helped address the problem of designing a satellite whose launch configuration was compact enough to fit into the nose cone of a rocket but, once in orbit, whose antenna masts and other devices could be deployed to their full operational length. Also deployable were long arms for controlling the attitude of the satellite the way a tight-rope walker uses a long pole for balance.

Whereas an extended measuring tape takes the shape of a long shallow gutter, a deployed STEM assumes the shape of a circular pipe, but one that is not leakproof. Nevertheless, it is a very efficient structural shape for resisting axial and bending loads, although it offers practically no resistance to twisting. Like a tape measure, a STEM is manufactured from a flat ribbon of steel, but rather than being given a slight curvature, it is shaped by heat treatment into an overlapping form (like a rolled-up sheet of paper), thus locking into it the configuration of a more-than-complete tube, albeit a slit one. Once so formed, the STEM can be forced back into a compact flat shape as it is coiled onto a spool, and then held in that configuration until deployed. Because of the energy stored in the forced flattened shape, once released the STEM will deploy into its stable extended form under its own power.

Deployment for Sales and Amusement

The ability of structures to store energy has been the basis for some toy-like devices that have been used for advertising and entertainment. One incorporates a bimetallic disk typically about the diameter of a quarter but significantly thinner, and is usually imprinted with the logo of its distributor. In its normal configuration the disk is dished slightly but can be “activated” by first warming it in the hand and then snapping the dished inner portion through to the other side by pushing with the thumb on the disk held against two fingers. The snap through is signaled by a noticeable tactile sensation as well as a dull sound accompanying the buckling. If the disk—whose bimetallic nature gives different expansion factors to each side—is then placed on a surface colder than body temperature, it will soon snap back to its original configuration, which makes the disk appear to jump spontaneously. The simplicity and mystery of operation of this deployable structure make it a curiosity worth keeping, so it continues to display the logo of its provider.

Another amusing device is the so-called “slap bracelet,” a pre-teen fad item from more than a decade ago. Made from a length of spring steel heat treated to take the shape of a section of a wide retractable tape measure, the bracelet has two stable configurations: the familiar one of a straight tape-spring hinge and a fully tubular one similar to what we can imagine a tape measure assumes inside its case—only in reverse. The slap bracelet is often covered with a colorful coating or fabric and is operated by giving someone a gentle tap on the wrist with it, whereupon the steel channel alters its curvature and wraps around the wrist to form a bracelet. Since the bracelet configuration is stable in this configuration, unlike the STEM it does not need a locking mechanism to retain a cylindrical shape. This property makes the device, and more practical ones based on the same principle, potentially desirable for use in more-serious deployable structures.
On the morning I visited the Deployable Structures Laboratory, Sergio Pellegrino was occupied with students and technicians folding a newly hinged device into its transport configuration. Since he was preoccupied, I was shown around the lab by my host at Cambridge, Chris Calladine, who recently had studied deployable engineering structures from the perspective of biological structures. In his paper at the symposium on deployable structures held at Cambridge in 1998, Calladine noted that “all biological structures grow and develop: in that sense they are all deployable.” But he quickly added that studying growth and development in biological structures cannot necessarily be expected to provide useful lessons for deployable engineering structures, for the two processes are not analogous. He also notes that it is not fruitful to look to biological evolution for engineering design guidance, quoting the aphorism that “evolution is blind; technology is mind.”

Where Calladine does see some potential inspiration from biology is at the level of molecular structures, which might “stimulate the constructive thought and imagination of our engineers.” Other students of biological structures see inspiration in the wing folding of insects and the protective curling up of leaves in high winds. Steven Vogel of Duke University has studied this latter phenomenon and has written eloquently about it. Like Calladine, Vogel sees similarities between natural and human-made structures—which, after all, follow the same laws of physics and engineering—but does not believe that copying nature assures superior structures, deployable or otherwise. Nonetheless, inspiration aplenty can be found in nature.

The Deployable Structures Laboratory at Cambridge is full of models of engineered structures, many of which have the beauty of form and operation of a flowering plant. Among these are camera aperture-control devices that might have applications for deployable roof structures to protect sports fans against rain or sunlight. Some are flat and appear to take the form of pressed flowers, whereas others are spherical and suggest the intricate but graceful geometry of pinecones, sunflowers and pineapples. Elsewhere in the laboratory are foldable tensegrity structures, those skeleton-like assemblages of wires in tension and struts in compression that date from the 1960s and that were soon given currency by Buckminster Fuller.

The forms of deployable structures seem virtually endless. Even in common terrestrial applications they include a wide class of inflatable structures, ranging from air mattresses to the giant balloons used in Macy’s Thanksgiving Day parade. Venetian blinds, Murphy beds, sleeper sofas and recliner chairs, and even bureau drawers and common doors are deployable domestic structures. As children we played with Pogo Sticks and Slinkys, and employed the folding kickstands on our bicycles. In the kitchen, we use scissors-operated can openers, ingenious cork-extraction devices, sliding shelves and lettuce baskets daily. In the office or study, we use retractable ball-point pens, mechanical pencils and staplers as a matter of course. Hotel rooms often have retractable clothes lines, collapsible ironing boards and televisions on rotatable bases. Extension ladders are clearly deployable, as are retractable box-cutter knives, and a plethora of gripping and grasping tools. Many cell-phone designs rely on deployable structures for their casings, as do laptop computers. And our automobiles are equipped with air bags, storable cup holders, retractable seat belts, operable sunroofs and a host of other deployable devices. In fact, deployable structures are all around us and have become such common features in our daily lives that we hardly notice them for what they are. Even a book might be said to be a deployable structure, as might the magazine in which this column is printed.

Acknowledgments

I am indebted to Chris Calladine for inviting me to visit Cambridge and for introducing me to Sergio Pellegrino and his Deployable Structures Laboratory. I am grateful to Sergio Pellegrino for a most interesting lunchtime discussion of tape measures and other deployable structures, for presenting me with a copy of the proceedings of the 1998 symposium on the topic and with a model of a retractable roof structure, and for calling my attention to Calladine’s paper on Love.

Bibliography


