

Part One

Introduction to Compliant Mechanisms

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Introduction to Compliant Mechanisms

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1.1 What are Compliant Mechanisms?

If something bends to do what it is meant to do, then it is compliant. If the flexibility that allows it to bend also helps it to accomplish something useful, then it is a compliant mechanism [1]. The idea of using compliant mechanisms in products is catching on, but traditionally when designers need a machine that moves, they commonly use very stiff or rigid parts that are connected with hinges (like a door on its hinge or a wheel on an axle) or sliding joints. But when we look at nature we see an entirely different idea from rigid parts connected at joints – most moving things in nature are very flexible instead of stiff, and the motion comes from bending the flexible parts [2]. For example, consider your heart – it is an amazing compliant mechanism that started working before you were born and will work all day every day for your entire life. Think of bee wings, elephant trunks, eels, sea weed, spines, and the blooming of flowers (Figure 1.1) – all of which are compliant. Even the natural motions that seem to be exceptions to this bending behavior, like your knee or elbow, use cartilage, tendons, and muscles to do their work. We see in nature the possibility of making machines that are very compact – a mosquito (Figure 1.1) is able to fly while carrying its own on-board navigation, control, energy harvesting, and reproduction systems. Would it be possible for us to improve human-designed products if we applied the lessons learned from nature and looked to flexibility to achieve movement?

It is interesting that some early man-made machines were compliant mechanisms. Is that because we were closer to nature then? An example of a compliant mechanism with a multi-millennia history is the bow (Figure 1.2). Ancient bows were made using a composite of bone, wood, and tendon, and they used the flexibility of their limbs to

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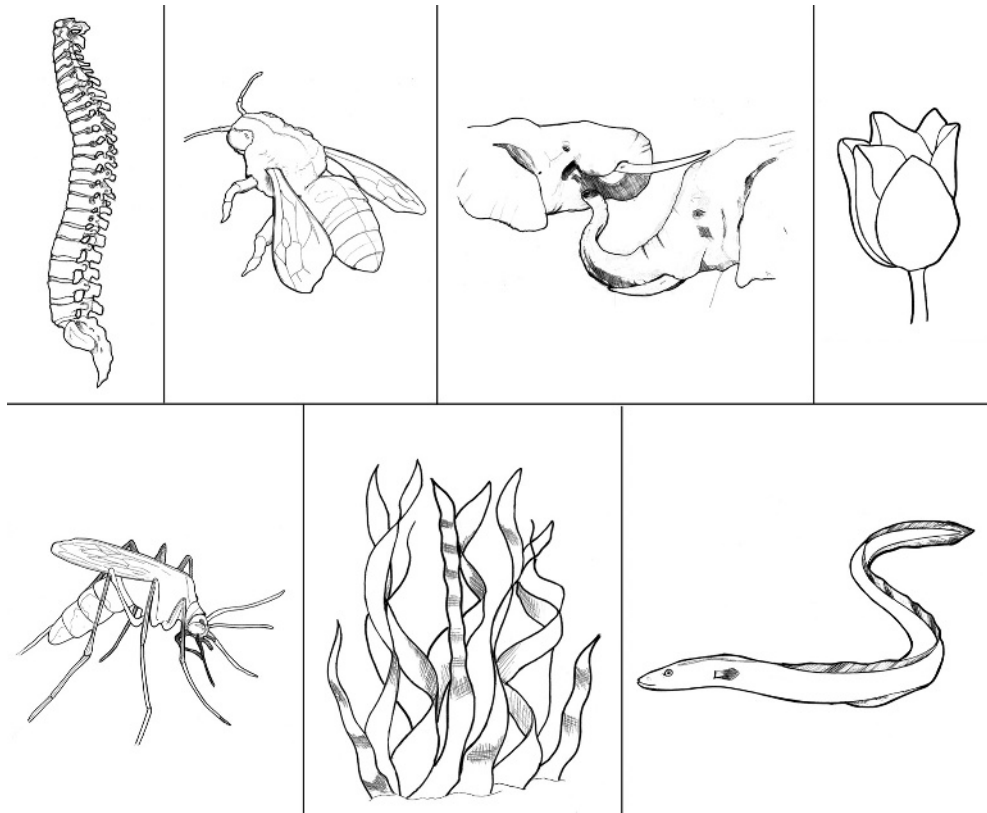


Figure 1.1 A few examples of compliance in nature: a spine, bee wings, elephant trunks, blooming flowers, a mosquito, sea weed, and eels

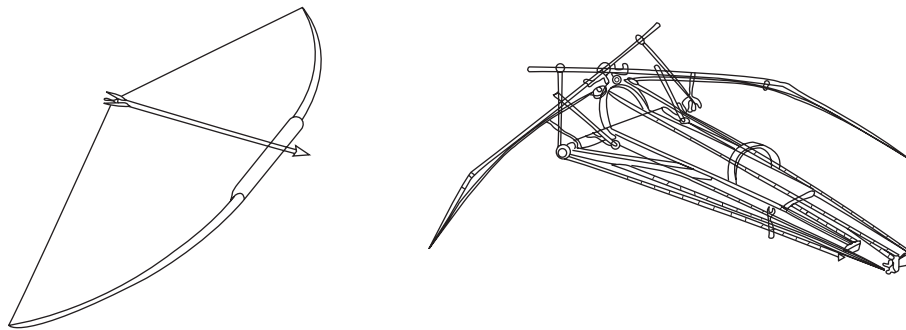


Figure 1.2 Early compliant mechanism designs include the ancient bow and many compliant mechanism designs by Leonardo da Vinci

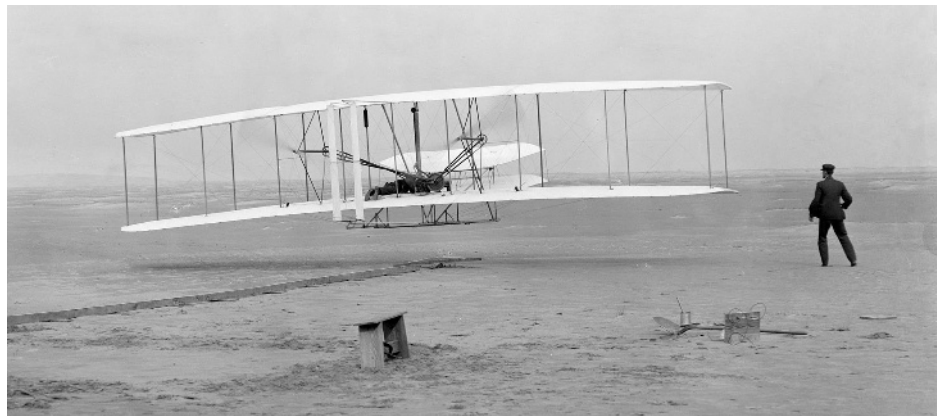


Figure 1.3 The Wright brothers used wing warping to achieve control of their aircraft for sustained human flight

store energy that would be released into propelling the arrow. It is interesting to see the sketches of Leonardo da Vinci [3] and see many compliant mechanisms (see Figure 1.2 for an example). Even one of the great achievements of engineering – sustained human flight – began with a compliant mechanism when the Wright brothers (Figure 1.3) used wing warping to achieve control of their early aircraft [4].

This may all sound good, but it turns out that compliant mechanisms can be difficult to design. Nature has done it, but nature employed very different design methods from those we mortals use. Great strides were made in the design of machines when compliance was left to nature and we moved to the much easier-to-design realm of rigid parts connected at hinges. For example, the too-sophisticated-for-its-time wing warping of the Wright Flier was eventually replaced by the much-easier-to-work-with control surfaces provided by an aileron pivoting on a hinge.

However, over the past few decades our knowledge has advanced. We have developed new materials, increased our computational capabilities and expanded the ability to design more sophisticated devices. At the same time, society has developed new needs that cannot be easily addressed using traditional mechanisms. This means that there is an increased ability to create compliant mechanisms, and an increased motivation for doing so. As an example, reconsider the example of aircraft control. The Wright Flier started out with wing warping for its control surfaces, but other aircraft quickly moved to approaches using traditional mechanisms. But with the increased computational power available and improved materials that have been developed, researchers are returning to the idea of wing warping to get the advantages, such as reduced weight, that would come from the approach.

One of the things that make traditional design of mechanical components compelling is that designers can separate different functions to be done by different parts, and each part is assigned to do that one function. The blessing and curse of compliant mechanisms is that they integrate different functions into fewer parts. Compliant mechanisms may be able to accomplish complex tasks with very few parts, but they can be much more difficult to design.

1.2 What are the Advantages of Compliant Mechanisms?

The integration of functions into fewer parts leads to compelling advantages for compliant mechanisms. For one, there is a potential for significantly lower costs. This comes from reduced assembly, fewer components to stock, and the possibility of simplified manufacturing (such as fabricating a mechanism from a single mold).

Another advantage is the potential for increased performance. This includes high precision [5,6] due to reduced wear and reduced or eliminated backlash. The low weight of compliant mechanisms can be useful for shipping and for weight-sensitive applications such as spacecraft. Eliminating the need for lubrication at joints is also a useful performance improvement that is helpful in many applications and environments.

Another category of advantages lies in the ability to miniaturize compliant mechanisms. Microelectromechanical systems (MEMS) for example, are often fabricated from planar layers and compliant mechanisms offer a way to achieve motion with the extreme constraints caused by the resulting geometry (Figure 1.4) [7,8]. Compliant mechanisms will likely be central to the creation of nanoscale machines.

1.3 What Challenges do Compliant Mechanisms Introduce?

While the advantages of compliant mechanisms are amazing, they also have some challenges that have to be carefully considered in their design. For example, the

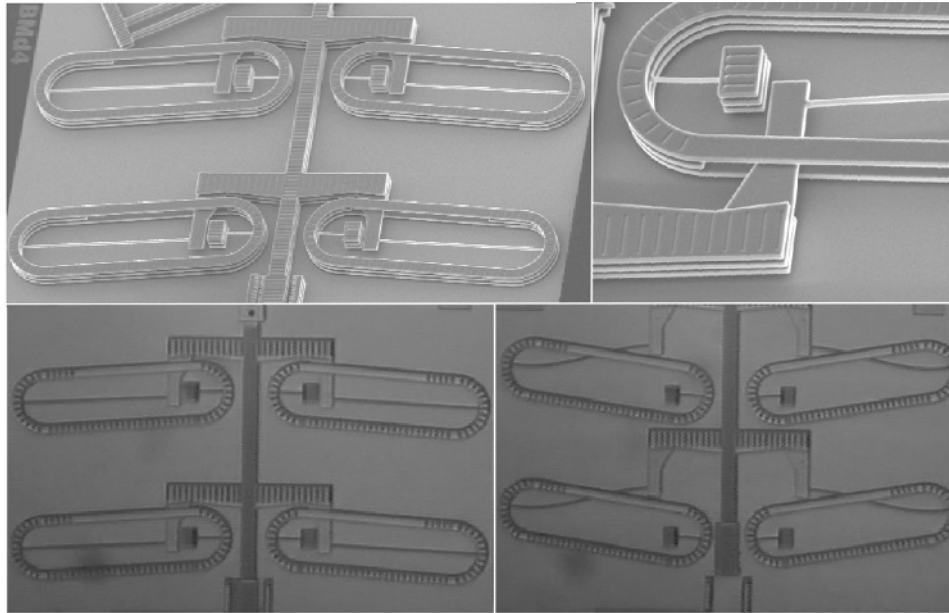


Figure 1.4 A multi-layer compliant microelectromechanical system (MEMS). A scanning electron micrograph of the device (top left) with a close up of compliant segments (top right), and the device shown in two stable equilibrium positions (bottom)

integration of different functions into fewer parts offers advantages, but it also requires the simultaneous design for motion and force behavior. This difficulty is increased further by the fact that the deflections are often well into the nonlinear range and simplified linear equations are not adequate to define their motion.

Fatigue life needs to be addressed for most compliant mechanisms. Because their motion comes from bending of flexible parts, compliant mechanisms experience stress at those locations. When that motion is repeated during its life, fatigue loads are present and the fatigue life must exceed the expected life of the mechanism. Fortunately, methods for analyzing and testing fatigue life are available to help design compliant mechanisms for their needed fatigue life (see Chapter 2), but it requires special attention and effort to ensure that the mechanism has the life required.

Although properly designed and tested compliant mechanisms can achieve needed fatigue life, there can still be a consumer perception that flexible components are flimsy or weak. This can be a particular concern where the flexible component is visible to the consumer and it may require special care in the design for adequate life and for its appearance.

The motion of compliant mechanisms is often more limited than for traditional rigid-link mechanisms. For example, a shaft connected to bearings has the ability to undergo continuous revolution, whereas the motion of a flexible component will be limited by the deflection it can undergo before failure.

The fact that strain energy is stored in a deflected beam can be either an advantage or a disadvantage. Advantages include that a compliant element integrates both a spring and hinge function into a single component providing a “home” position where the device will go when unloaded. This integration also allows certain behaviors, such as bistability (the characteristic of having two distinct preferred positions, such as the on-off positions of a light switch) [9]. However, there are times when these qualities are not desired, and the properties become a disadvantage in the device design.

If certain materials are held under stress for long periods of time or at elevated temperatures, they can take on a new shape associated with the stressed position. This is called “stress relaxation.” Some compliant mechanisms have functions where they must maintain positions where they are under stress, and so are subject to stress relaxation conditions. This requires careful design and thoughtful choice of material.

1.4 Why are Compliant Mechanisms Becoming More Common?

Advances in our understanding of compliant mechanisms, combined with general technological developments, have resulted in a rapid growth in compliant mechanism applications (the library portion of this handbook is a testament to that growth). These applications range from high-end, high-precision devices to ultralow-cost packaging; from nanoscale featured components to large-scale machines; from weapons to healthcare products.

We mentioned that many early devices were compliant mechanisms, but then rigid-link devices connected at hinges gained favor because of the simplicity offered for analysis and design. So what is different now and why are there so many more compliant mechanisms than before? The answer lies at least partly in technological

advances that have been made over recent decades. For example, new materials are available that are well suited for compliant mechanisms. There have been dramatic improvements in computational hardware and software available to analyze compliant mechanism motion and stresses. Developers and researchers have also increased our ability to design and analyze compliant mechanisms. Considerable effort has gone into creating methods to facilitate compliant mechanism design (some of the resulting methods are summarized in this handbook). There is also an increased awareness of the advantages of compliant mechanisms. As some commercial applications have been successful, they provide examples and inspiration for other applications to follow. Finally, as society and technology have advanced, new needs have risen, and some of these needs are best addressed by compliant mechanisms. This includes devices at very small size scales, devices with relatively complex motion but must be made at extremely low cost, compact medical implants, and high-precision machines.

1.5 What are the Fundamental Concepts that Help Us Understand Compliance?

There are a few straightforward but counterintuitive concepts that can help us understand the fundamentals of compliant mechanisms.

1.5.1 *Stiffness and Strength are NOT the Same Thing*

Usually when we want something to be strong (meaning that we don't want it to break), we also want it to be stiff (meaning that we don't want it to bend). For example, the floor in the upper story of a building we want to be both stiff and strong. We obviously don't want it to break, but we also don't want it to move around when people walk on it. So it needs to be stiff and strong. The crank shaft in an engine? Stiff and strong. A bridge? Stiff and strong. A desk? Stiff and strong.

We so often design things that need to be both stiff and strong that it is easy for our intuition to begin to tell us that stiffness and strength are the same. But they are NOT the same. Strength relates to resistance to failure, while stiffness relates to resistance to deflection. These are different and are governed by different properties. Consider a piece of steel with a rectangular cross section as shown in Figure 1.5. The steel will withstand a certain stress until it will fail. But its strength is the same whether it is loaded about its thin or thick axis (assuming it is isotropic), while its stiffness is very different for these two conditions.

1.5.2 *It is Possible for Something to be Flexible AND Strong*

Consider examples of things that are both flexible and strong. Flexible endoscopes, such as that shown in Figure 1.6, are used to examine the interior parts of the body. The endoscope must be flexible to undergo the required motion and to minimize any trauma from its use within the body. It must also be strong to withstand the loads that it will undergo during its use. As another example, consider the pulleys on the cables of a ski lift (Figure 1.7). They must be strong enough to reliably lift the skiers to their destination but must be flexible enough to go around the pulleys.

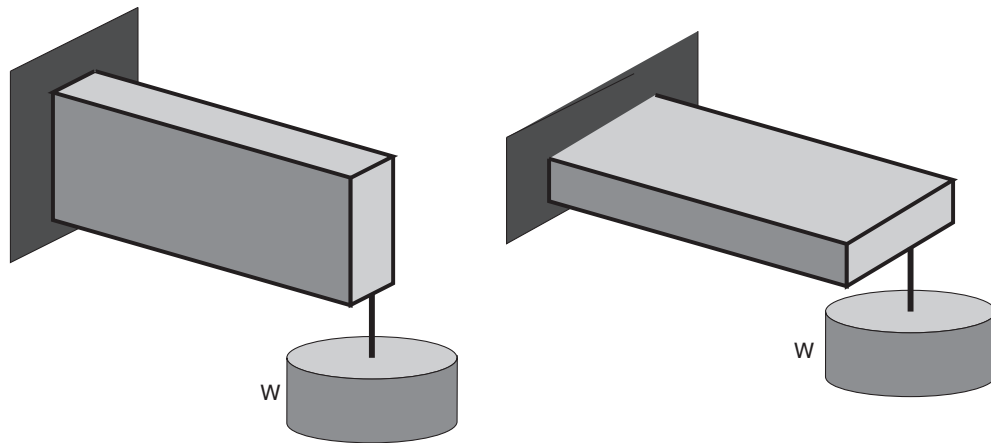


Figure 1.5 The rectangular piece of steel may have the same strength in different directions, but it will have very different stiffness for the two orientations shown

So why is it that many things we want to be stiff and strong, but others we want to be flexible and strong? What is it that determines the difference between these two situations? The answer lies in whether the device needs to hold a force, or if it needs to be deflected (like a cable going around a pulley). A bridge is an example of something that needs to be stiff and strong because we want it to hold the weight of

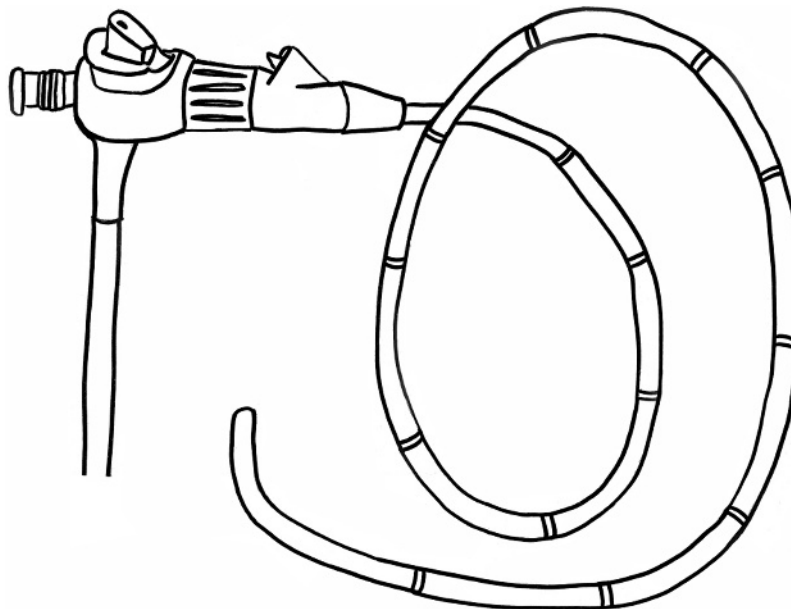


Figure 1.6 A flexible endoscope is an example of a device that needs to be both flexible and strong

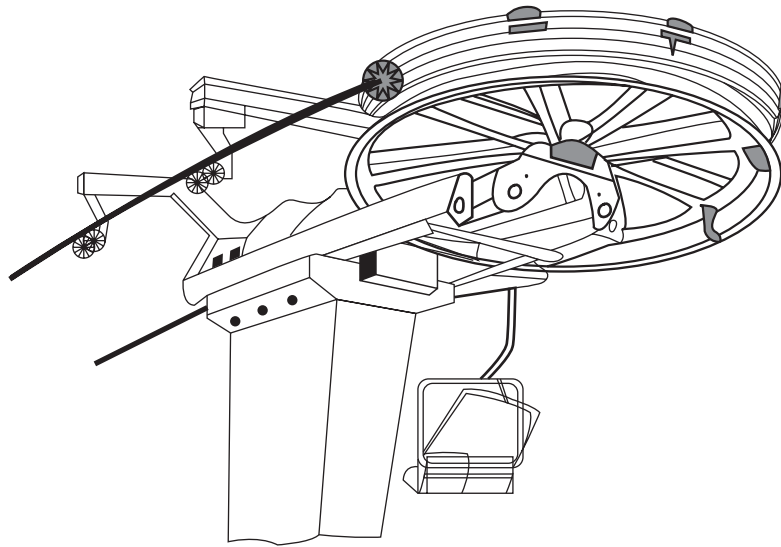


Figure 1.7 A ski lift cable must be flexible enough to go around the pulley and strong enough to carry the loads

traffic going across them without moving. The endoscope and the pulley cable are both examples of things that need to bend to perform their function. If they were too stiff, they would be overstressed and would break when they were forced to undergo the needed motion. So if something needs to hold a weight or other force, it should be stiff and strong; if it needs to go through a certain deflection, it should be flexible and strong.

1.5.3 The Basics of Creating Flexibility

There are three primary ways that we can influence flexibility. These are

1. material properties (what it is made of);
2. geometry (its shape and size);
3. loading and boundary conditions (how is it held and loaded).

Each of these is described below.

1.5.3.1 Materials Properties

Different materials have different stiffnesses as measured by the material's Young's modulus (or modulus of elasticity). Consider the three rods in Figure 1.8. Each rod has identical size and shape and each has the same size weight hanging from it, but they are each made of a different material: steel, aluminum, and polypropylene. The Young's modulus of steel (207 GPa) is about three times that of aluminum (72 GPa), so for the same geometry and same weight, the aluminum rod will deflect three times

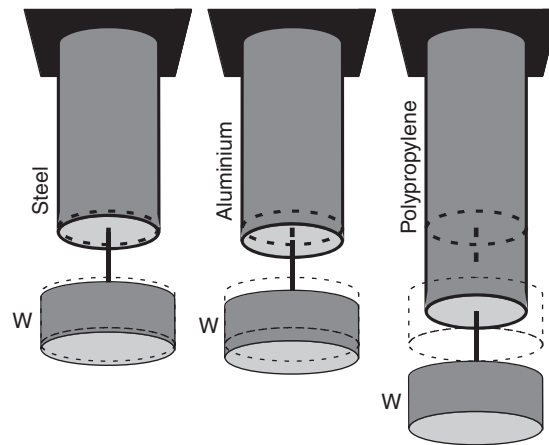


Figure 1.8 Material properties contribute to stiffness. These three rods all have the same geometry but they experience different deflections even with the same size weight hanging from them

as much as the steel. But polypropylene's Young's modulus (1.4 GPa), is about one fiftieth that of aluminum, so it deflects much farther than either aluminum or steel for the same applied load.

Because we want something both flexible and strong when we are designing compliant mechanisms, we look for materials with a high strength and a low Young's modulus. One way to compare different materials for use in a compliant mechanism is to compare the ratio of strength to Young's modulus, with a higher ratio being better. A similar approach is to compare the "resilience" of materials, where the modulus of resilience is one-half the yield strength squared divided by the Young's modulus. The modulus of resilience is a measure of how much energy per unit volume the material can withstand without a permanent change. Table 1.1 lists some materials and their ratio of strength to modulus and their resilience.

1.5.3.2 Geometry

Shape and size have a large effect on flexibility. Let's start with an obvious example. Consider the two parts shown in Figure 1.9. They are both made of the same material and they both have the same size of weight hanging from them. They are both round but one has a larger diameter than the other, and not surprisingly, the larger part is stiffer and has a smaller deflection than the smaller part. Now reconsider the two rectangular parts shown in Figure 1.5. They are made from the same material and have the same weight hanging from them. They are both the same size, but one is turned a different direction than the other. Even though they have the same size, the orientation of the geometry makes a huge difference in flexibility, with the part loaded on the thinner side being more flexible. Suppose the part were three times as wide as it were thick, then it would actually be nine times more flexible in one direction

Table 1.1 Yield strength to Young's modulus ratio and resilience for several materials

Material	E (GPa)	S_y (MPa)	$(S_y/E) \times 1000$	$(0.5 \times S_y^2/E) \times 0.001$
Steel (1010 hot rolled)	207	179	0.87	77
Steel (4140 Q&T @400)	207	1641	7.9	6500
Aluminum (110 annealed)	71.7	34	0.48	8.1
Aluminum (7075 heat treated)	71.7	503	7.0	1800
Titanium (Ti-35A annealed)	114	207	1.8	190
Titanium (Ti-13 heat treated)	114	1170	10	6000
Nitinol (high-temperature phase)	75	560	7.5	2100
Beryllium copper (CA170)	128	1170	9.2	5300
Polycrystalline silicon	169	930	5.5	2600
Polyethylene (HDPE)	1.4	28	20	280
Nylon (type 66)	2.8	55	20	540
Polypropylene	1.4	34	25	410
Kevlar (82 vol%) in epoxy	86	1517	18	13 000
E-glass (73.3 vol%) in epoxy	56	1640	29	24 000

than the other direction. If the geometry were distributed in other ways, such as in an I-beam shape, then it can be even stiffer for the same volume.

1.5.3.3 Loading and Boundary Conditions

Consider the three parts shown in Figure 1.10. Each part is made from the same material, has the same geometry, and the same size weight is hung from each. But the three parts will deflect differently for the same size weight. How the load is applied, and how the part is held (its boundary conditions), make a difference on its flexibility.

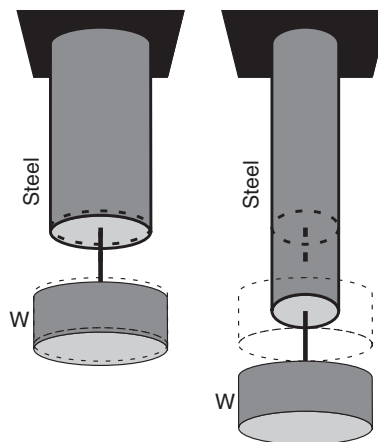


Figure 1.9 These two rods are both made of steel but their different geometries result in their having different deflections even for the same weight hanging from their ends

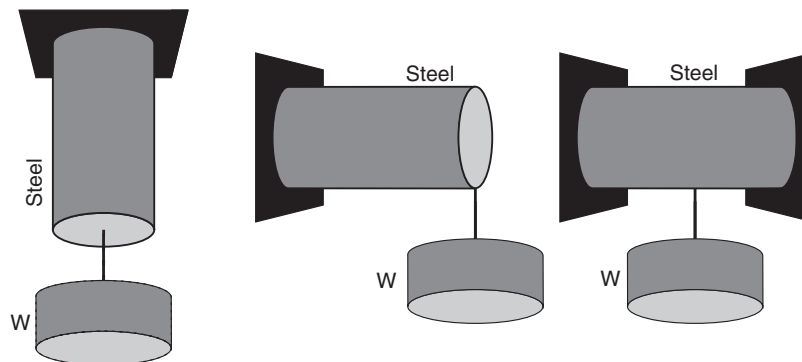


Figure 1.10 Boundary conditions and direction of loading also affect stiffness. The same rod deflects less in tension than in bending

1.6 Conclusion

Compliant mechanisms offer compelling characteristics that make them valuable for implementing in product and system design. Increased performance (e.g. high precision, low weight, compactness, low friction), reduced cost (e.g. reduced assembly, manufacturability), and ability to be miniaturized represent a few of the advantages of compliant mechanisms. The intent of this handbook is to provide information and tools that will be helpful in taking advantage of the possibilities of compliant mechanisms while addressing the challenges of their design.

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