Demonstrating and Measuring the Flexure of a Masonry Wall

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A number of researchers and teachers[1] have commented on the conceptual difficulties that students encounter visualizing Newton's third law for contact forces. Because the actual mechanics of this situation relies on invisible properties of solid matter (microscopic distortion and flexure), students lack observable concrete phenomena to anchor their learning. A number of strategies for making these invisible flexures explicit have been created by Minstrell[2] (using a mirror on a table and a laser), Clement and Camp[3] (metersticks cantilevered from both ends), and most recently Chabay and Sherwood[4] (who base an entire engineering physics curriculum on the spring-and-ball molecular model of solid matter).

In particular, attentive students want to know what the mechanism is behind Newton's third law for contact forces such as the normal force — How does the upward push of the table exactly balance the downward weight of several different books? How does a tree apparently "know" to pull back on a rope tied to it with exactly the same amount of force applied by a person pulling on the other end of the rope? Clement and Camp's work contains a sequence of bridging analogies that include examining a book resting first on a foam pad, next on a thin flexible board, then extrapolating to a book on a mattress and a book on a ball-and-spring model of a crystalline solid. The bottom line is that to justify Newton's third law for contact forces we must provide evidence for microscopic flexures of apparently motionless surfaces.

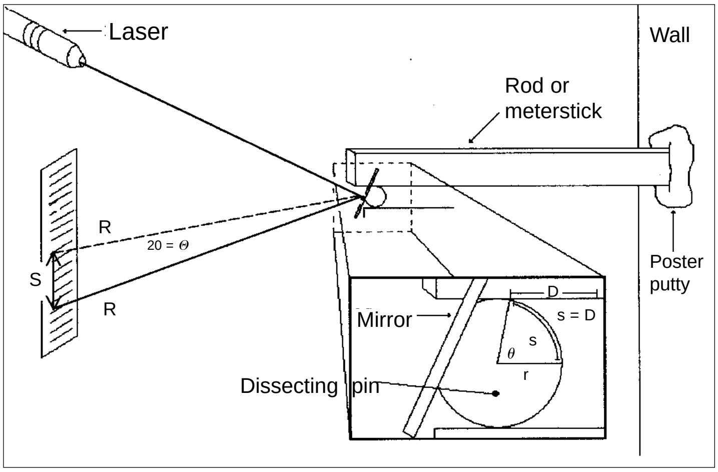

Fig. 1. Apparatus for measuring the distance the wall is flexed.

Apparatus Setup

We have been delighted with recent PHYS-L[5] discussions that describe a simple, low-cost optical apparatus that magnifies microscopic wall flexure by 10^4 times, making Newton's third law flexures in solid walls dramatically apparent. The apparatus (Figs. 1-3) consists of four basic parts: a laser pointer and holder, a small mirror, a stand to raise the apparatus off the floor, and a sturdy meterstick, ring-stand bar, or aluminum rod. The mirror (we use a chip from a broken CD) is glued to a standard 2-in T-shaped biological dissecting pin.[6] Set a sturdy stand or stool approximately 60 cm from the wall you intend to flex. On top of the stand place a flat, smooth surface (we use a textbook). Upon the smooth surface place the pin-and-mirror assembly, ensuring it can rotate freely. With some adhesive putty (we use the type for hanging posters), attach the butt of the rod to the flexing wall. The other end of the rod should rest freely on top of the pin and mirror, such that as the wall flexes the rod will move back and forth and roll the pin and mirror. Mount the laser pointer such that its beam is reflected off the mirror and onto a meterstick located somewhere opposite the flexing wall. Pushing on the flexing wall will roll the pin and visibly deflect the laser spot on the scale (see Fig. 2.)

The distance from the mirror to the target scale magnifies the slight movement of the mirror; therefore a greater distance will provide a more dramatic deflection. In our tests, we could readily flex a solid brick (covering cinderblock over steel I-beam) building pillar about 0.18 μm. Bouncing on the wall clearly deflected the spot 7.0 m away by well over a centimeter. With the inside classroom (plaster over cinderblock) walls, deflections of 5.4 μm were dramatically visible, but this certainly included floor deflection. It is quite difficult to exclude floor deflection with this apparatus (we managed with an outside wall by putting the apparatus on one large concrete slab and standing on and pushing the wall from an adjacent slab). In the classroom, simply walking up to the apparatus in a second-floor lecture theater produced a series of ever-lower dips of the laser spot.

Quantitative Analysis

The mathematical analysis for this apparatus is simple: using the arc length formula twice, it is possible to measure the distance the wall is flexed (see Fig. 1). Here uppercase symbols refer to the angular displacement of the laser beam, and lowercase symbols to the angular motion of the pin.

The first step is to find the angular displacement of the laser spot reflected from the mirror, according to

$$S = R\Theta,$$

where Θ is the angular displacement of the laser beam measured in radians, S is the linear distance the laser spot moves on a scale, and R is the distance from the mirror to the scale. This angular displacement of the laser beam, Θ, is actually twice the angular displacement of the mirror and attached pin which we call θ in radians. The rotation of a planar mirror through an angle rotates the reflection of a stationary beam of light through twice this angle.[7] For the pin,

$$s = r\theta,$$

where

$$\theta = \Theta/2.$$

Hence,

Fig. 2. Michael Nordstrand, Flagstaff physics and mathematics teacher, flexing the NAU Physical Sciences Building wall.

Fig. 3. Laser beam reflected from mirror.

$$s = r\theta = r\frac{\Theta}{2} = \frac{rS}{2R},$$

where s is the linear distance of wall flexure and the arclength subtended by the pin rotation, and r is the pin radius (0.50 mm).

For a very solid exterior brick building pillar, the pin was 0.50 mm in radius, the spot deflected 0.50 cm, and the mirror was 7.1 m from the scale, so the wall flexed 0.18 μm:

$$s = \frac{rS}{2R} = \frac{(0.50 \times 10^{-3}\ \mathrm{m})(0.50 \times 10^{-2}\mathrm{m})}{2(7.1\ \mathrm{m})}$$

$$= 0.18\ \mu m$$

For a more typical interior lecture theater wall (plaster over cinderblock), the pin was again 0.50 mm in radius, the spot deflected 15 cm, and the mirror was 7.0 m from the scale, so the wall flexed 5.4 μm:

$$s = \frac{rS}{2R} = \frac{(0.50 \times 10^{-3}\ \mathrm{m})(15 \times 10^{-2}\mathrm{m})}{2(7.0\ \mathrm{m})}$$

$$= 5.4\ \mu m$$

Comment

We live in a world of contact-force interactions dominated by microscopic flexure of seeming solid and inflexible objects. The conceptual cues provided by this demonstration are particularly valuable because it makes some of these invisible phenomena explicit and approachable for our students.

We are still unaware of the original source of this demonstration and welcome readers' historical information. We also are looking for insightful ways of teaching Newton's third law for noncontact forces, and welcome any suggestions on this topic.

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References

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