Pasta Bending Experiment

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Abstract

This paper describes a simple and fun experiment that demonstrates structural failure in bending. It is very inexpensive, uses ordinary uncooked pasta, and needs minimal instrumentation. It can be done by two or more students. Multiple types of pasta can be used to make comparisons based on the pasta type (e.g., spaghetti vs. linguine) and/or based on pasta diameter (e.g., thick spaghetti vs. thin spaghetti). The lab can be designed to fit into one class period by varying the number of pasta types investigated, the number of pieces of each pasta type that will be tested, and the number of students in each group. While the experiment itself is easy, the analysis can be challenging depending on what the students are required to calculate and report.

Keywords

Pasta, bending, experiment, fracture, structural member, ultimate failure.

Introduction

A great deal of research goes into the production of pasta. This includes measuring its properties both before and after cooking (e.g., [1-3]). Considerable literature exists for measuring the properties of both cooked and uncooked pasta (e.g., 4-6). To the authors' knowledge, the experiment described here is not done by pasta manufacturers to determine any properties. In the uncooked state, pasta is brittle and the thicker the pasta the more brittle it is. Pasta with a rectangular cross section is flexible when bent perpendicular to the longer dimension and relatively inflexible when bent perpendicular to the short dimension.

Pasta is an inexpensive material that can be used to demonstrate ultimate strength in bending which is defined as the maximum strain a material can endure before fracturing. On the significance of this phenomenon, Heisser et al. (2018) write, "Understanding and controlling fracture dynamics remain one of the foremost theoretical and practical challenges in material science and physics" [7]. Bucciarelli (2003) [8] has posted online the directions including the theory for the lab discussed here which has been one of the labs for an Experimental Methods class taught by the lead author at Oral Roberts University (ORU) since 2010. The objective of this paper is to provide more details, sample results, and recommendations for this lab.

Theory

Long, slender, uniform structural members generally fail due to bending. Knowing what strain, as measured by the ratio of the radius of the member to the deformed curvature of its centerline, can be tolerated is essential to controlling and avoiding failure. Euler's 18th century analysis of the large deflections of an elastic lamina (the elastic) provides the basis for a determination of the maximum extensional strain at fracture. The measurements in this lab are a surrogate for making much more expensive measurements on structural steel elements that might be used in bridges and buildings.

An *elastic lamina* is a slender element, uniform in its geometric and physical properties along its length, – e.g., a long rod or beam capable of supporting a compressive or tensile load. When subject to an axial compressive force, if the length is sufficiently long, the lamina will *bend* out of line as shown in Figure 1.

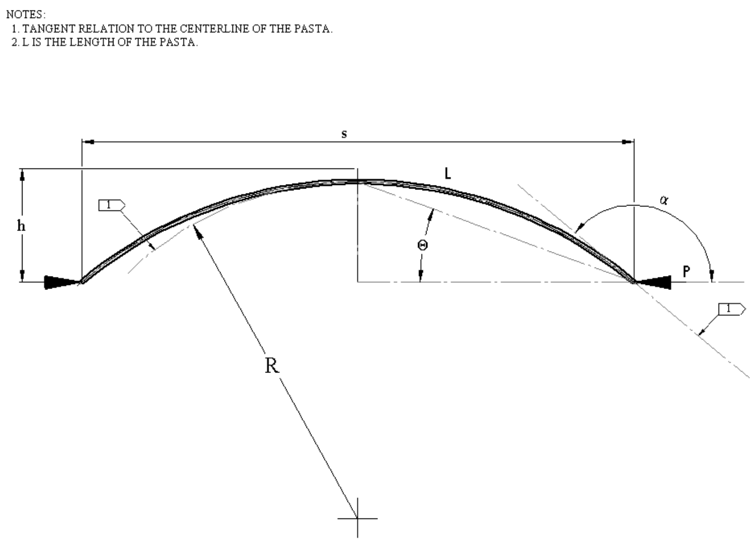

Figure 1. Deformed elastica.

An analysis of equilibrium and deformation of the lamina, based upon the principles of Solid Mechanics, produces an ordinary, but nonlinear differential equation whose solution describes the geometry of the deformed lamina. Only the essential results of the analysis are presented here. The solution yields expressions for the height h and the span s in terms of two parameters, related to the slope α at the ends:

$k \equiv \sin\left(\frac{\alpha}{2}\right) \equiv \sin\theta$ which is dimensionless, and a second related to the applied force P and the bending stiffness, EI. (2)

E = modulus of elasticity or Young's modulus

I = moment of inertia

$c \equiv (EI/P)^{1/2}$ which has the dimensions of length. (3)

The solution gives:

$$s = 2c \cdot [2F_1(k) - F_2(k)] \quad (4a)$$

$$h = 2ck \quad (4b)$$

$$L = 2cF_2(k) \quad (4c)$$

$R_{min} = c^2 / h = h / (4k\ )$ (4d)

R_{min} is the minimum radius of curvature that occurs at the mid-span. L is the original straight length of the lamina.

In these equations, $F_1(k)$ and $F_2(k)$ are functions of the parameter k alone and are defined by the following two definite, so-called "elliptic integrals". The following is an elliptical integral of the second kind:

$$F_1(k) = \int_0^{\pi/2} \sqrt{1 - k^2 \cdot \sin^2 \theta}\, d\theta \quad (5a)$$

The following is an elliptical integral of the first kind:

$$F_2(k) = \int_0^{\pi/2} \frac{1}{\sqrt{1 - k^2 \cdot \sin^2 \theta}} d\theta \quad (5b)$$

Values of F_1 and F_2 for a range of values of k have been computed and are available elsewhere (e.g., [9]). A curve-fit relation is provided later so these values are not required here.

In this experiment, the maximum strain the lamina can withstand before fracture is to be determined. The strain is a function of the radius of the lamina and the radius of curvature. It is proportional to the former and inversely proportional to the latter. Hence the *maximum strain* occurs where the radius of curvature is a *minimum*, i.e.:

$$\varepsilon_{\max} = r / R_{min} \quad (6)$$

where r = radius of a lamina with a round cross section. In this experiment, the span, s, and the mid-span height, h, are measured at fracture. The original straight length, L, is measured before applying the end loads. From equations (4b) and (4c), c can be eliminated, which remains an unknown, to obtain:

$$k = (h / L)\, F_2(k) \quad (7a)$$

The roots of this expression are available for a range of values of (h/L); where k as a function of h/L. With these values of k for a given ratio (h/L), the above relationship for the radius of curvature may be rewritten, normalizing with respect to L:

$$\frac{R}{L} = \frac{h/L}{4k^2} \quad (7b)$$

So, measuring h and L and calculating h/L fixes k from eq. (7a) and the ratio R/L from eq. (7b); hence the radius of curvature R can be calculated. Having measured the diameter d of the strand, the pasta radius can be calculated ($r = d / 2$) and the maximum strain due to bending can be computed from eq. (6).

From equations (4a) and (4b), an expression can be written for the span, again normalized with respect to L:

$$\frac{s}{L} = \frac{2F_1(k)}{F_2(k)} - 1 \tag{7c}$$

Again, once having a value of k, for some h/L, the definite integrals $F_1(k)$ and $F_2(k)$ could be computed or obtained from tables with elliptic integrals, and so the span can be computed. This will serve as a check since s was independently measured and recorded at fracture.

Plots of (s/L) and (R/L) as a function of (h/L), determined in accord with the above relationships are shown in Figure 2. This plot is used to directly obtain values for the two ratios s/L and R/L, having measured h and L.

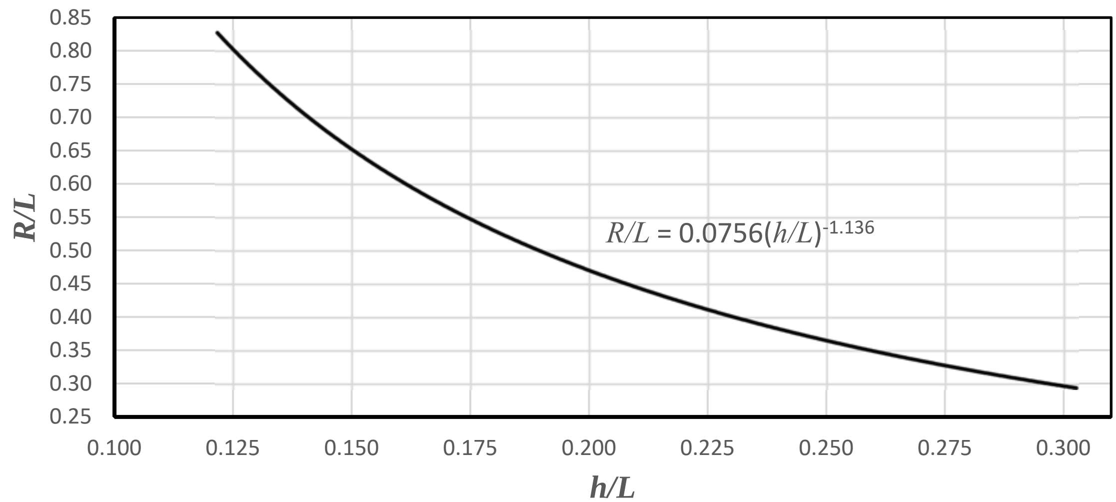

Figure 2. *R/L* vs. *h/L* plot.

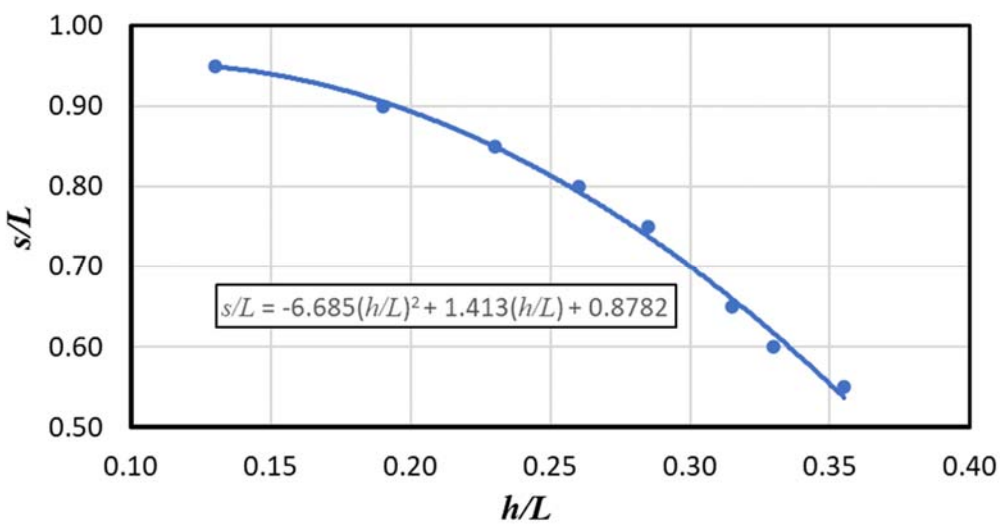

Figure 3. *s/L* vs. *h/L* plot.

Materials

The materials required for this lab are as follows:

- graph paper with dimensions (at least 1 for each team)
- At least (2) packages of different types of pasta (see Figure 4 which shows 4 types) with enough pieces for all teams with lots of extra pieces in case some of the pieces break into more than 2 pieces (discussed later)

Figure 4. Four types of pasta: fettuccine, spaghetti, thin spaghetti, and thick spaghetti.

- Some type of marking device such as a pen or pencil to determine the height of the breaking point and to record data.

Procedure

1. Select a piece of pasta to be tested and record its length L with a ruler (or could shorten it slightly to use marked graph paper) and either the diameter if it has a round cross section or short width w_1 and long width w_2 if it has a rectangular cross section, using a caliper. Note that if rectangular pasta is used, an equivalent lamina radius must be computed (see equation 8 below):

2. One person holds the left side of the piece fixed against the origin of the graph paper.

3. That same person starts pushing horizontally to the left, along the x-axis, on the right side of the piece, while keeping the left side of the piece fixed at the origin. The piece should start to bend upward (positive y direction). As it is bending, allow the left side of the piece to rotate counterclockwise, while keeping its tip fixed at the origin.

4. As the piece is bending, a second person should follow the peak of the arc with a pencil or pen until the piece breaks (see Figure 5). If the specimen breaks into more than 2 pieces, discard and repeat with a new piece of pasta.

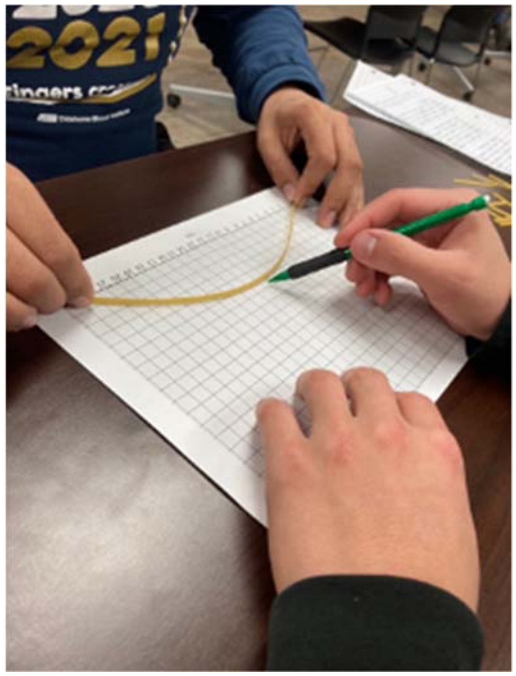

Figure 5. Bending pasta against graph paper.

5. Measure the height h and span s after the break (see Figure 6).

Figure 6. Locating peak just before pasta breaks.

6. Repeat this process using the longer of the two pieces.

Calculations

Calculate an effective radius for any rectangular pasta:

$$r_{\text{eff}} = \sqrt{\frac{w_1 w_2}{\pi}} \tag{8}$$

Calculate the following values:

1. *h/L*
2. Use Figure 2 to determine *R/L* (or the equation in a spreadsheet)
3. Calculate *R* from #2 using the measured *L*
4. Calculate $\varepsilon_{\max}$ using eq. (6)

Include a histogram showing the frequency distribution of strain for each different kind of pasta with two sets of bars (1 for the long pieces and 1 for the short pieces) on the same graph. Include a graph comparing the average strain rate with error bars for all types of pasta tested. Include another graph of average strain rate vs. effective pasta diameter with error bars for all the same type of pasta (e.g., only regular while excluding whole wheat). Consider other comparisons as appropriate such as average strain for round pasta vs. rectangular pasta and/or average strain for regular pasta compared to whole wheat pasta.

Sample Results

This section describes representative results from a pasta bending experiment. Figure 7 shows the frequency vs. strain for the long and short pieces for four different types of pasta (thin spaghetti, spaghetti, thick spaghetti, and fettuccine). The graphs show that the shorter pieces can withstand more strain before fracturing compared to the longer pieces.

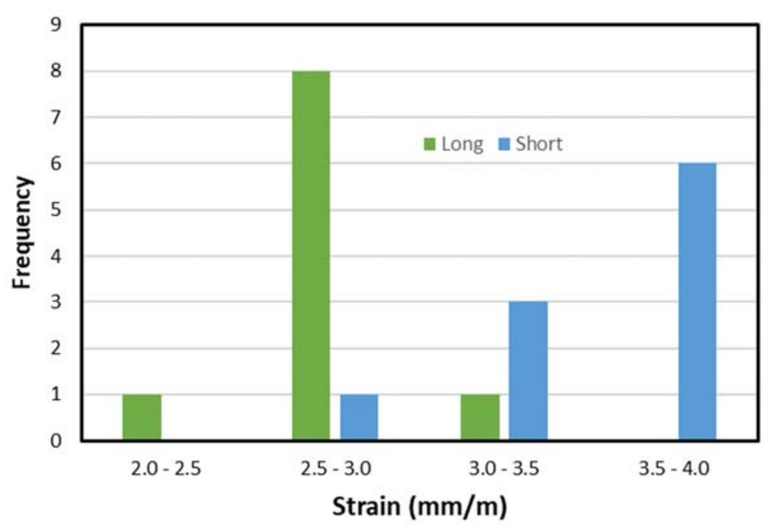

Figure 7a. Frequency (# of pieces) vs. strain for long and short pieces for thin spaghetti.

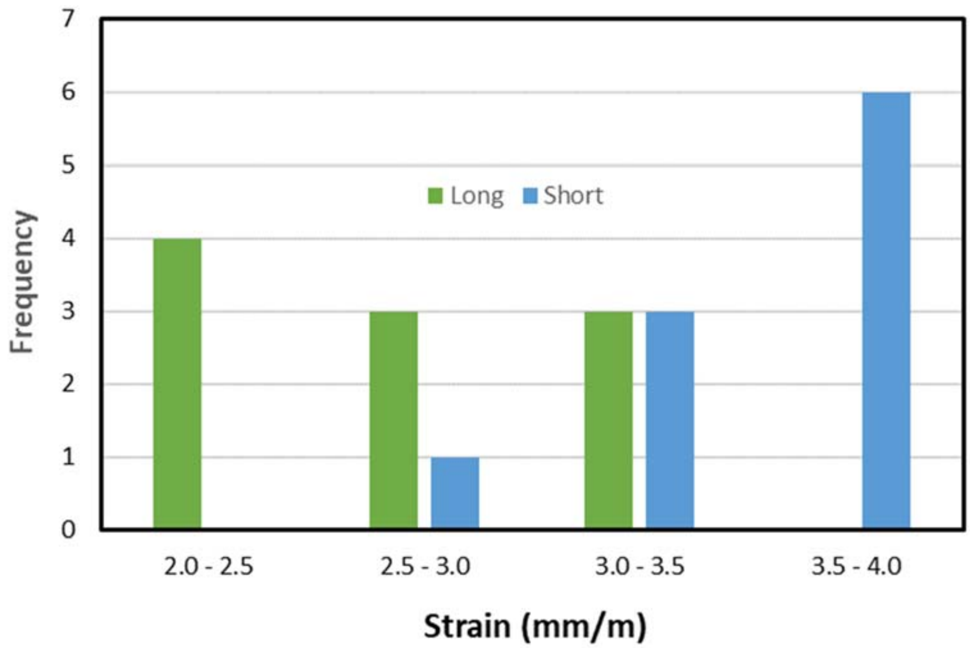

Figure 7b. Frequency (# of pieces) vs. strain for long and short pieces for spaghetti.

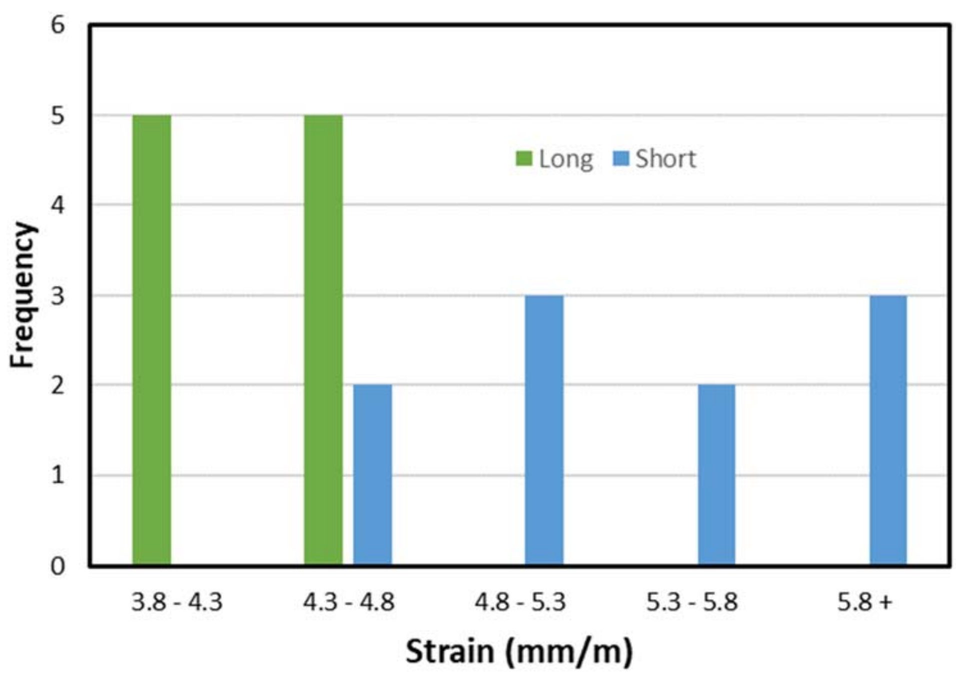

Figure 7c. Frequency (# of pieces) vs. strain for long and short pieces for thick spaghetti.

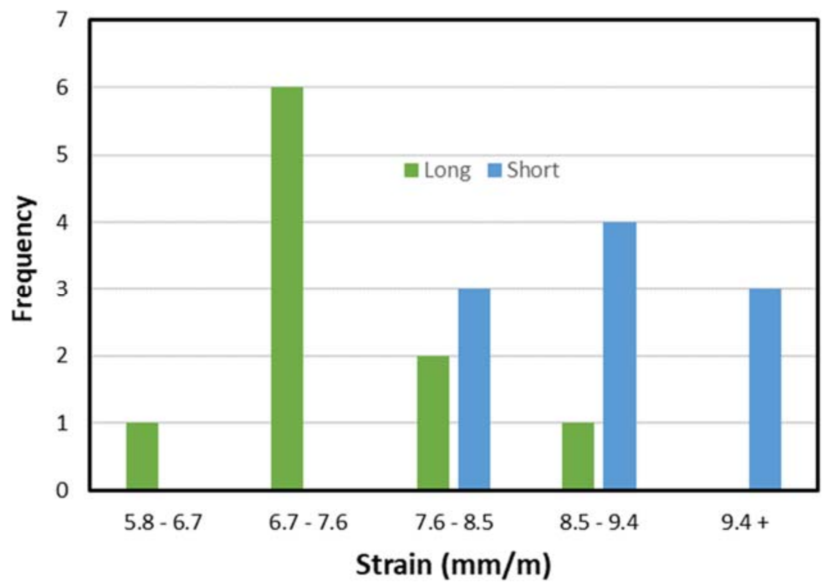

Figure 7d. Frequency (# of pieces) vs. strain for long and short pieces for fettuccine.

Figure 8 shows the average strain values for each type of pasta for both long and short pieces. The graph again shows that short pieces can withstand more strain before fracturing than long pieces. It also shows that fettuccine can withstand much more strain than spaghetti because it is much thicker.

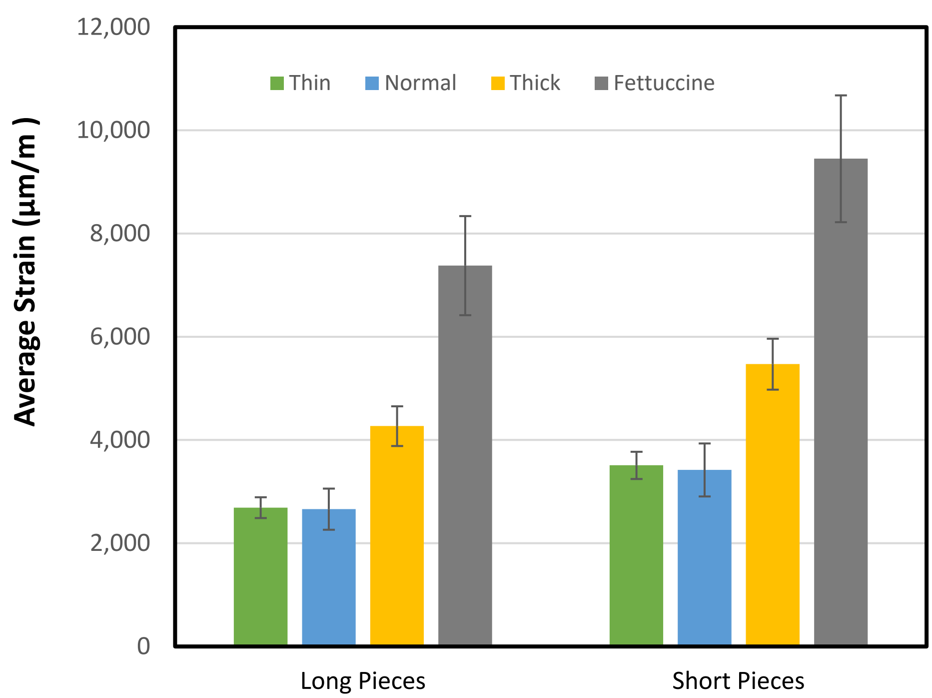

Figure 8. Average strain (µm/m) for long and short pieces as a function of the spaghetti type.

Challenge

The main challenge for this lab is that most pasta does not want to break into only two pieces when bent. Surprisingly, this has been the subject of much interest and research including by the renowned physicist and Nobel prize winner Richard P. Feynman who never actually solved the problem [10]. French researchers Audoly and Neukirch (2005) are generally credited with solving this mystery [11]. Their explanation is that when spaghetti initially breaks, its curvature suddenly relaxes causing a burst of flexural waves which locally increase the curvature causing fragmentation into usually 3 or 4 pieces. Very high-speed photography (250,000 frames/sec) confirms their hypothesis [12]. Using advanced mathematical analyses, Long et al (2021) developed an analytical equation for this phenomenon [13].

Conclusions

A simple and inexpensive experiment is described here to measure the ultimate bending strength of pasta which is a surrogate for measuring the ultimate bending strength of lamina such as beams used in construction. The experiment only requires minimal instrumentation to measure some dimensions and can be scaled according to the time available and the number of students in a class. The results show that shorter and thicker pasta is stronger than longer and thinner pasta. The main challenge of the lab is the propensity for pasta to break into more than two pieces.

Recommendations

Some safety precautions are recommended. Safety glasses could be used as the uncooked pasta sometimes breaks explosively, although there have not been any injuries in the 13 years the lab has been done at ORU. This is likely because the broken pieces tend to fly away from the experimenters. For that reason, it is recommended that teams be spread apart. Make sure students remove any broken pieces that fall on the floor as they can become slip hazards.

At least three different types of pasta are suggested so comparisons can be made for pastas with different diameters (e.g., thin vs. thick spaghetti) and cross sections (e.g., round vs. rectangular). At least two students are needed for each trial. If there are, for example, four students on a team then parallel trials can be conducted to collect more data more quickly. An alternative to having all teams experiment with all pasta types is to have each team work with a single, different pasta type and then to share the data with all the teams. For example, four teams could each work with a single, different type of pasta and the data could be shared so that all four teams would have data for four different types of pasta.

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