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Article

Estimating the Young's Modulus of spaghetti with a buckling experiment

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SUMMARY

The Young's Modulus of a structural material is a measure of its elasticity and is defined as the ratio of the tensile stress to tensile strain. This study aims to investigate a specific property of the material qualities of pasta through buckling – Young's Modulus. Buckling across three pasta diameters and four different lengths is investigated. A force is applied from the top using a finger until buckling was observed and the weight was measured. The values recorded for applied force and other available values were used to determine the Young's modulus of San Giorgio pasta. The Young's modulus averaged over the different diameters s 5.07 ± 1.7 GPa. It is unknown how broadly these findings apply since other brands, which may use different recipes, may result in different Young's Moduli. Ultimately, our results may assist in quality control during manufacture and serve as useful information for the secondary purpose of educational applications of pasta, where the material is used as structural members in bridges, towers, and other engineered objects.

INTRODUCTION

Man-made and natural structures are commonly subjected to pushing, pulling, bending, and twisting forces. The strength and flexibility of the structures depend on the materials used. For this reason, understanding material properties is essential to the designing and building of any structure.

There are two main reasons why understanding pasta and its material properties can be advantageous: Assisting in quality control and informing learners when used in an educational context. Pasta manufacturing involves mixing, shaping, and drying durum wheat and water during which conditions, such as ambient humidity and temperature, can affect the product (1). To test the quality of the manufactured products, companies conduct material property tests. For example, a bending test can be used to determine the breaking strength of the pasta to predict whether the pasta is likely to break in transit (2). Other applications of this material property include determining the structural integrity of a pasta recipe and developing new pasta recipes based on varying combinations of dry and wet ingredients (3).

Pasta is also useful in an educational context, since it is readily available and a cost-effective building material for early engineering. When used as truss members in model bridge design and builds, spaghetti will theoretically experience two main forces – tension and compression. These forces can cause an object to deform. Tension causes a body to elongate, while compression forces cause a body to shorten. To design a truss effectively, one needs to understand the Young's modulus, which is a key constant that is responsible for determining the maximum compressive force a truss member can support, along with the diameter and length of the truss member. This can be calculated when pasta of know diameter and length are put under varying forces at certain angles to determine its buckling load.

Based on prior data, we hypothesized that the San Giorgio pasta in this experiment will have a Young's modulus between 2.4 to 5.0 GPa. Two notable studies have been done previously on this subject. One study (4) used an Instron 4111 testing machine to test tension in Barilla spaghetti and calculated a value of 5.0 GPa from a stress-strain curve. Another study (5) used bending to test Doria pasta and found the Young's modulus value to be between 2.2 and 2.6 GPa. We noted that the second study used a much thicker pasta (bucatini) by an appropriate experimental method. This motivated us to study relatively thinner forms of pasta using a different approach to calculate the Young's modulus.

Our study aimed to provide additional experimental data on the Young's Modulus of pasta (San Giorgio Spaghetti) to the community, and also proposed a simple and low-cost method that may be used for future studies of determining Young's modulus of other solid, cylindrical pasta.

RESULTS

To determine the Young's Modulus of pasta using buckling, strands of pasta with varying pasta length and diameter were tested using a method that involves pressing down on the vertical pasta on a weighing scale to determine the buckling force required. The experiment was conducted in an environment with constant temperature at 23.0oC and 50% humidity. For pasta that measured 1.7 mm in diameter, the longer the pasta was, the higher the buckling load, ranging from 0.3332 to 1.9208 N (**Table 1**). A similar trend was noticed among the 1.5 mm and 0.9 mm pasta diameters

Pasta Length (m)	0.1	0.15	0.2	0.25
Buckling Load (N)	1.9208	0.882	0.5194	0.3332

Table 1. Pasta Length vs. Buckling Load for Pasta with 1.7 mm diameter

Pasta Length (m)	0.1	0.15	0.2	0.25
Buckling Load (N)	0.5786	0.2844	0.1765	0.1079

Table 2. Pasta Length vs. Buckling Load for Pasta with 1.5 mm diameter

Pasta Length (m)	0.1	0.15	0.2	0.25
Buckling Load (N)	0.1372	0.049	0.00784	0.00098

Table 3. Pasta Length vs. Buckling Load for Pasta with 0.9 mm diameter

ranging from 0.1079to 0.5786 N and ranging from 0.00098 to 0.1372 N respectively (**Table 2,3**) as well with the buckling load values as a whole decreasing with decreasing diameter.

We can predict the effect of diameter and length of the pasta on its buckling load (Equation 4). Starting with the effect of the diameter, the diameter d is in the numerator on the right-hand side meaning that the buckling load and the diameter vary directly to the fourth power. Hence from equation 4, it can be concluded that the Buckling load varies directly with the diameter to the fourth power. We observed a direct variation to the 2.6th power (**Figure 1**). With that said, the unexpected result is indicative that more data points with a wider range of diameter (5 or above) are needed for a more representative analysis. The average confidence interval at a 95% confidence level for the buckling load of all three diameters was calculated to be 0.32. The 95% confidence level is a range of values that contains the true mean of the buckling with 95% confidence. The confidence interval of 0.32 was the actual upper and lower bounds of the estimate that is expected to be found at the 95% level of confidence and was a relatively low number given the many uncertainties involved in the experimental setup.

Moving on to the effect of pasta length on Buckling Load, the buckling force, "W", varies as the inverse square

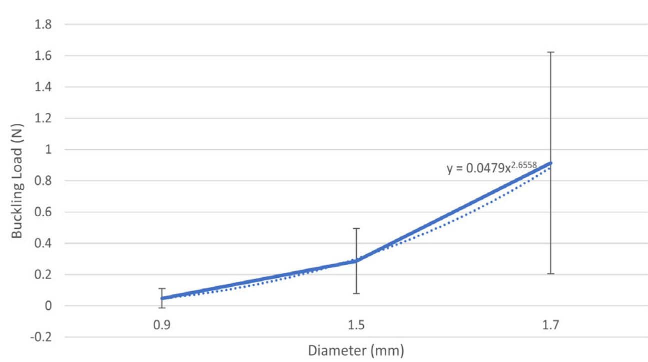

Figure 1. Buckling load (N) increased with diameter of pasta(mm). Buckling load was measured using homemade system for spaghetti-like pasta of three diameters. Data points are fitted with an exponential function and a dotted line of best fit has been shown. Error bars on the y-axis show the standard deviation of the buckling load for each point.

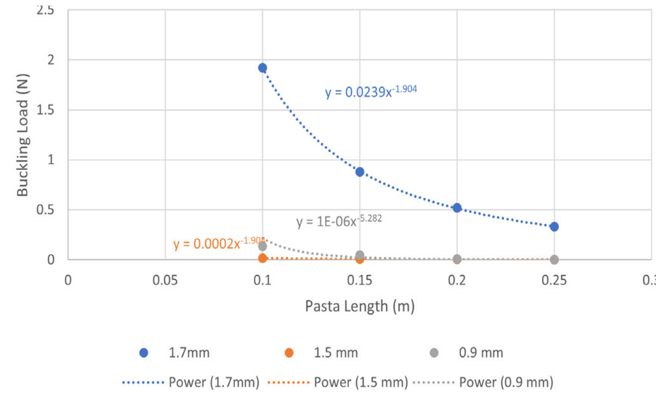

Figure 2. Buckling load (N) decreased with pasta length (m). Buckling load measured using homemade system for spaghetti-like pasta of three diameters for four spaghetti lengths. Data points are fitted with a power function and a line of best fit has been drawn for each diameter (mm).

of the pasta length, L. there was a mostly inverse square relationship, denoted by -1.904 in the power of x (**Figure 2**).

DISCUSSION

We tested the same pasta at different diameters, and we hypothesized that the Young's modulus would remain constant. However, we observed a calculated Young's modulus of 5.07 GPa with a slight standard deviation of 1.7 GPa (**Table 4**). This deviation indicates that there is room for improvement in reducing the inaccuracy. The calculated values for Young's modulus should have been the same because it is not a variable quantity that depends on the geometry of a material, but rather the properties of the material as a whole.

The predicted relationship between diameter and buckling load was a direct relationship with x to the 4th power, but we observed the relationship to be to the 2.6th power (**Figure 1**). This indicates an error in the method of data collection given the sound equations that backed up the prediction. Next, the predicted relationship between pasta length and buckling load was an indirect relationship with x to the 2nd power. This relationship also translates to x to the -2nd power. From the power line of best fits, this relationship stands when ignoring the anomalous 0.9 mm data points (due to it alone showing a power of -5.2) as opposed to the rest which are at -1.9 (**Figure 2**).

Some possible sources of error in this experiment might include the data for 1.5 mm pasta, the accuracy of the digital scale, and the method of breaking pasta. Starting with the data for 1.5 mm pasta, this set was deemed to be anomalous for the pasta length vs. buckling load since the power was inconsistent with the rest of the data (**Figure 2**). Further, the accuracy of the digital scale was not ideal since it was observed that values would sometimes change when the mass was placed at different angles. Additionally, the mass value was expressed in grams and did not include decimal places. The scale's accuracy could have been improved when considering that the value was to be converted to a smaller

Spaghetti (Diameter = 1.7 mm)	Average	Confidence Interval of Average (95% confidence level)	Young's Modulus
Pasta Length (m)	0.175	1	
Buckling Load (N)	0.91385	0.694730044	6.916488894
Vermicelli (Diameter = 1.5 mm)			
Pasta Length (m)	0.175	1	
Buckling Load (N)	0.2868255	0.203455827	3.581452342
Angel Hair (Diameter = 0.9 mm)			
Pasta Length (m)	0.175	1	
Buckling Load (N)	0.048755	0.061406295	4.697378723
	Final Average		5.065106653

Table 4. Young's Modulus Calculation using Equation 5 below, and previous data collected (Table 1, 2, and 3)

Newton scale. Furthermore, forces of less than 0.01 N are required to make certain pasta buckle. Finally, the method of breaking pasta was not the most accurate since breaking with fingers at a target point often results in breaking at a slightly higher or lower point than intended, negatively affecting the results of the experiment. The breaking of pasta may have also caused microfractures in the pasta itself and, affecting how it responded to compression when the force was applied. This factor is uncontrollable, being dependent on the production process of the spaghetti which is a mechanized process, and is another downside of using this type of pasta.

San Giorgio brand pasta was used in this experiment. Other pasta brands may be made with different ingredients, so it is unknown how broadly these findings apply. Because this experiment was done in an environment with constant temperature at 23 degrees Celsius and humidity at 50%, it would be interesting to investigate the impact of temperature and humidity on material properties in future studies. This method will require a more sophisticated system where temperature and humidity can be controlled and the method of applying force must be different to prevent any heat transfer between the pasta and human body. Furthermore, testing the effect of change in angle at which force is applied on the Young's modulus will be beneficial in adding to the data in this area.

In conclusion, pasta was tested at three diameters (1.7, 1.5 and 0.9 mm) across different lengths (10, 15, 25 and 30 cm). The Young's modulus averaged over the samples was 5.07 ± 1.7 GPa. This value aligned with the value from the Barilla pasta test in previous literature (4). It must be noted that only one buckling load and length value is required at a particular diameter of pasta to attain a Young's Modulus value. However, this investigation tests various lengths and takes an average to improve the precision of the Young's modulus value. With that said, each test for buckling load for a particular length and diameter has only been conducted once and this is a disadvantage in terms of the precision of the data. Future studies should therefore include a larger number of samples to improve accuracy and precision. Ultimately, these results may assist in quality control in pasta manufacturing and serve as useful information for educational applications of pasta as structural members in bridges, towers, and other engineered structures.

MATERIALS AND METHODS

A small piece of Scotch 3M general purpose masking tape was cut into about 2 cm by 2 cm using a pair of scissors and stuck onto the middle of a US-RA-5000 weighing scale. The diameter of a strand of San Giorgio spaghetti pasta was measured, and then a 25 cm marking on the pasta was made using a standard ruler. Using the fingernails of both thumbs to apply pressure, the pasta was broken at the marking. Then the buckling load was tested by placing the pasta vertically on the weighing scale, fixing it with a piece of tape, and pressing down slowly using an index finger. The weight at which the pasta strand buckles or bends to a side was recorded. When the pasta did not buckle easily, an eraser was used as a cushion between the index finger and the top of the pasta (**Figure 3**). The buckling procedure was repeated using shorter lengths of 20 cm, 15 cm, and 10 cm. Once these were completed, the same process was repeated with the remaining pasta diameters.

In total, the buckling force of pastas of three varying diameters at four separate lengths each were tested. The various graphs for analysis were plotted using the Microsoft Excel 2020 (Version 2109) software and the Graph Options function was used to add equations and lines.

Deriving Young's Modulus

The force exerted on the pasta was measured and the weight is calculated as

$$W = mg \qquad \text{(Equation 1)}$$

Figure 3. Experimental setup of buckling experiment for reference. The setup included masking tape, scissors, a weighing scale, ruler, eraser (to be used as a cushion between the finger and pasta if needed), and spaghetti of different diameters.

where W is the weight exerted, m is the mass of the pasta, eraser and masking tape, and g is the acceleration due to gravity. The mass is measured directly using the digital scale.

The buckling equation that relates the exerted force to the area moment of inertia is

$$W = \frac{\pi^2 IE}{(KL)^2} \quad \text{(Equation 2)}$$

where W is the applied critical force, I is the area moment of inertia, E is the Young's modulus of the material, K is the end condition of the structural member (6), and L is the pasta length (7). The spaghetti, vermicelli, and angel hair pasta all have circular cross-sections, so the area moment of inertia is equal to

$$I = \frac{\pi d^4}{64} \quad \text{(Equation 3)}$$

where d is the diameter of the pasta sample. Substituting Equation 3 into Equation 4 and rearranging terms to separate the deflection variable, we have

$$W = \left(\frac{\pi^3 d^4 E}{64(KL)^2}\right) \quad \text{(Equation 4)}$$

This can be rearranged in terms of E to find the Young's Modulus, giving us

$$E = \left(\frac{64(KL)^2 W}{\pi^3 d^4}\right) \quad \text{(Equation 5)}$$

Where d is the pasta diameter, W is the force applied, K is the end condition, and L is the pasta length.

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