

BREAKING SPAGHETTI

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Formulation of the problem:

Find the conditions under which dry spaghetti falling on a hard floor does not break.

Introduction:

Behavior of dry spaghetti as a brittle rod and its mechanical properties was the subject of many researches. But goals of the most part of these researches are investigations of behavior of spaghetti in cases of static deformations. The goal of my research is to describe the processes which occur during dynamic deformation. Dynamic deformation is not the same kind of deformation as static deformation because the causes of breaking of spaghetti during impact with some surface are waves. The kind of wave which breaks spaghetti (the kind of wave which dominates in exact case) depends of conditions of an impact of spaghetti with the surface. That's why we must find out what kind of wave occurs in spaghetti to understand the main cause of breaking and, finally find the conditions under which dry spaghetti falling on a floor does not break.

The goal of my research is to determine the most important kind of wave what breaks spaghetti, estimate parameters of this wave, determine the point of maximum curvature and investigate the conditions under what probability of breaking is the least.

Theoretical model:

To begin with, we should consider three different variants for spaghetti to hit the floor: 1) horizontally, 2) vertically, 3) at some angle between 0° and 90° . The cause of breaking in the first case is compressive strain. But we need enormous amount of energy to compress spaghetti so much. Moreover, it is hard to make such experiments and this kind of impact is not very interesting. The third variant of hitting demands very complicated mathematical model. That's why I investigated only vertical falling of spaghetti.

And now let's explain what exactly happens with spaghetti during the impact. It was mentioned before that the cause of breaking of spaghetti is some kind of wave. There are 4 basic kinds of waves: longitudinal, transverse, torsional, bending waves. Torsional waves don't take place during the impact because spaghetti isn't twisted very much. Transverse waves usually occur in continuous medium, not in rods. Longitudinal waves take place during every impact of solids. Nevertheless, from the point of view of energy necessary for breaking of spaghetti, the energy necessary for breaking with bending is less than without bending. The influence of longitudinal waves is negligible. Therefore, spaghetti is



Figure 1: bending of spaghetti at the moment of impact

more likely to break because of curving. Thus, deformation of whole spaghetti is a combination of 2 deformations – some layers of spaghetti are stretched, some are compressed. Using a high-speed camera, I have taken videos of impact. I took some frames (Figure 1) of these videos and in that way proved the theory about bending waves: we can see that spaghetti really bends.

Now, understanding the nature of processes what occur in spaghetti, we can determine velocity of bending wave in spaghetti (c_b).

$$c_b = \sqrt{\frac{2\sqrt{2\pi} \cdot R}{T}} \cdot \sqrt{\frac{E}{\rho}}$$

E – Young modulus of spaghetti, T – period of wave, ρ – density of spaghetti, R – section radius of spaghetti.

I approximated the dependence of reaction force of surface on time as sinusoid and estimated period of wave. The shape of bend of the spaghetti is sinusoid too.

$$T \approx 2t \approx 0,004s$$

t – time of the impact, found with the help of high-speed camera (1000 frames/s).

Also I found Young modulus of spaghetti: $E \approx 2,3 \cdot 10^7 Pa$.

Now it is possible to estimate the velocity of propagation of bending wave: $c_b \approx 16,6 m/s$.

As a consequence of these estimations, I can calculate the wave-length (λ):

$$\lambda \approx c_b \cdot T \approx 6cm$$

Bending wave dies out very quickly, that's why not the whole of spaghetti bends. After watching slowed videos of impact I noticed that approximately 3 cm of spaghetti (from the bottom of spaghetti) bend. Further propagation of bending wave does not take place because of energy loss as a result of plastic deformation in spaghetti. Thus, all the energy of bending wave is spent on deformation and, consequently breaking. After breaking there is almost no energy left. Therefore spaghetti usually breaks only 1 time and only in 1 point.

How can we find this point? Spaghetti breaks at the distance $l \approx \lambda/4 \approx \underline{1,5 cm}$ from the bottom because of maximum curvature exactly in this point. The length of broke off pieces of spaghetti was around 1,5 cm in all the experiments. It perfectly proves my theory about bending waves as the main cause of breaking of spaghetti.

Experiment:

First of all, let's clarify the way of characterizing probability of breaking of spaghetti. Let it be p – frequency of breaking of spaghetti. N – number of spaghetti which broke, N_o – number of all falling spaghetti

$$p = \frac{N}{N_o} \cdot 100\%$$

Secondly, let's determine the most important factor what has influence on probability of breaking. We can say that this factor is quantity of energy what spaghetti has just before the impact with the surface. If we carry out experiments with the identical spaghettis, this quantity of energy depends only on the height of falling.

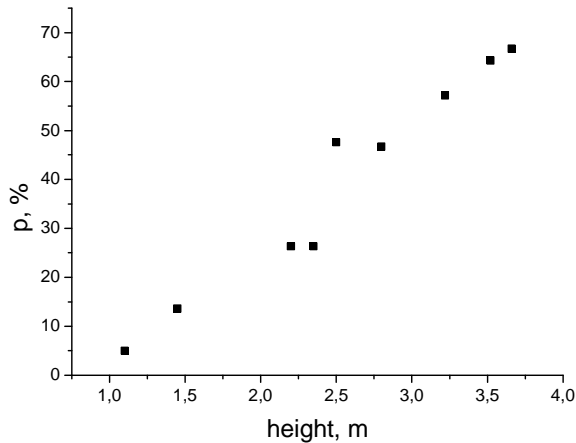


Figure 2: Frequency of breaking vs. height of falling

We have run some experiments, so, you can see the experimental dependence of frequency of breaking on height of falling (figure 2). So, the higher is the kinetic energy of spaghetti, the higher is possibility, that spaghetti bends very much and break.

But there are a some other ways of changing kinetic energy: we can change mass of spaghetti by changing length of spaghettis, cutting them (certainly, not changing the diameter). You can see the experimental dependence of frequency of breaking on length of spaghetti (figure 3). We run this experiment keeping the same height of falling. So, we change reaction force of surface by changing kinetic energy of spaghetti

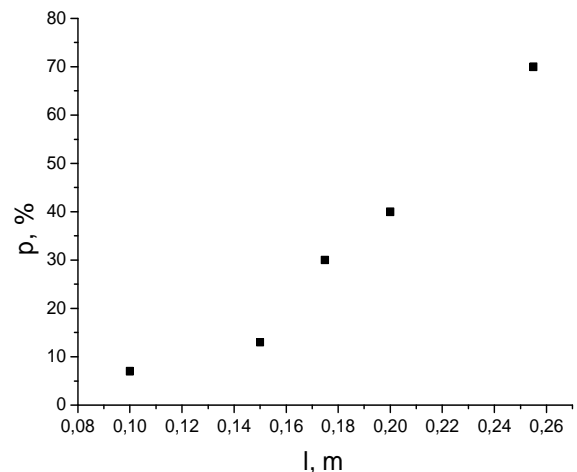


Figure 3: Frequency of breaking vs. length of spaghetti

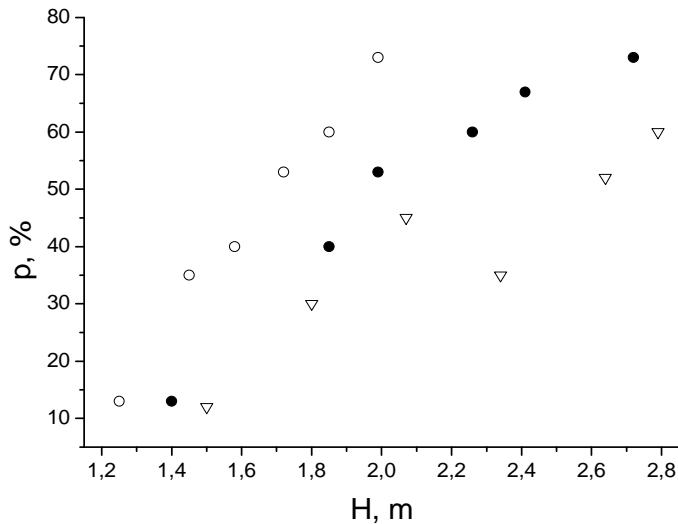


Figure 4. Frequency of breaking vs. height of falling. It is just hard to believe that we need the same force to bend spaghetti. It is just hard to believe that we need the same force to bend empty circles for $d=1.4$ mm, full – $d=1.7$ mm, triangles – $d=2$ spaghetti with diameters of 1,45 and 2 mm. It goes without saying that there is some critical curvature for breaking for spaghetti of certain dimensions. Thus, changing of critical curvature is the most important cause of decreasing of frequency of breaking with increasing of diameter of spaghetti.

There are a lot of different interesting parameters what can have influence on frequency of breaking, but within the limits of IYPT report we cannot investigate all of them. Therefore, we must understand which parameters are the most relevant and which haven't so much physical meaning for us because of too much complicated mathematical formulation of certain parameter. There are 3 the most relevant parameters: 1) height of falling, 2) length of spaghetti, 3) diameter of spaghetti. These parameters influence kinetic energy of spaghetti to the utmost: All of these 3 parameters were investigated in my research.

But there is one more parameter what I would like to investigate. It is nature of the surface. I run an

experiment with 3 different surfaces (figure 5). It is really hard to explain it numerically because different surfaces have a lot of different properties. breaking is higher when spaghetti hits plastic than granite or metal. It is really hard to explain it numerically because different surfaces have a lot of different properties.

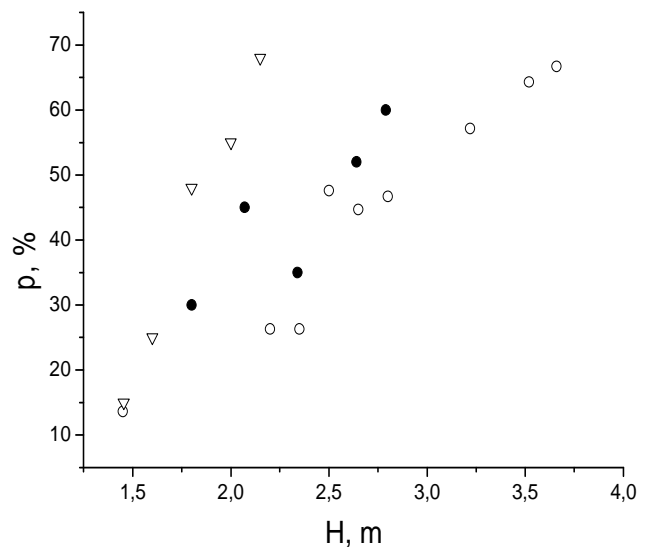


Figure 5. Frequency of breaking vs. height of falling: empty circles for metal, full – granite, triangles – plastic

But also we have the third way of changing kinetic energy of spaghetti. We can run 3 experiments with spaghetti with 3 different diameters and the same length. And what do we see on figure 4? Increasing kinetic energy by changing of spaghetti we does not increase frequency of breaking. But what is the reason of such a contradiction? Let's solve this ambiguity: we should notice that when we

Nevertheless, during experiments I noticed that when spaghetti hits metal it jumps up very high, when it hits granite – jumps up a bit lower, and when it hits plastic – spaghetti almost doesn't jump. Thus, I can make a conclusion that during the impact with metal a great part of kinetic energy is lost and less quantity of energy is spent on deformation. It is the simplest explanation of this surprising effect.

Conclusion:

In summary, there is no exact answer to the question “find the conditions under which dry spaghetti falling on a hard floor does not break” because it is really hard to describe the influence of all the parameters numerically. We can discuss only the frequency of breaking in experimental research and the quantity of energy required for breaking of ideal spaghetti in theoretical computation. But, summing up all the research, we can suppose that the frequency of breaking of an average spaghetti will be low if it falls from a low height (approximately lower than 1,5 m), has a big diameter and has not very big length.