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Building success out of failure:

Statistics of fatigue & fracture

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UNIQ 2022 - Worksheet

Cyclic Loading & Fatigue

Fatigue is the failure of a material after many repeated load-unload cycles. It occurs at load ranges that are often much lower than those that the material could sustain in a single overload event. Fatigue is a vital consideration when designing and using materials in safety critical applications. In the lecture we talked about some recent cases where fatigue presented challenges.

Almost all engineering structures are subject to loading variations. Some are obvious, for example take-off to landing for aircraft, pistons in a car engine, rotation of wheels and axles. Some are obviously present but less predictable in size, for example loading from waves on boats, or off-shore windfarms, or thermal loading on satellites.

How many cycles?

Loading at different regions of wheels and axles make one cycle from high to low as the wheel makes a complete rotation.

- *Can you make a rough estimate of how many loading cycles occur on a train journey from London to Glasgow?*
- *What about in a week, or a year?*
- *What about load cycles that the track is subjected to? How quickly do they accumulate over time?*
- *What other things might make the loads on wheels/track vary?*

Fatigue Failure

It is very likely that you will have used fatigue to break something yourself at some point, for example to get into some packaging. A classic example is a paperclip. You are unable to apply enough force with your fingers to break it in one go, but if you bend it back a forth it will eventually break.

The fatigue process is often split into a number of stages. Firstly crack nucleation which is difficult to study and can dominate lifetimes especially at low stresses. Next comes crack growth in which the crack advances either after a block of cycles or as it grows longer cycle by cycle leaving striation markings visible on the fracture surface. Eventually the crack becomes large enough that the material breaks rapidly and catastrophically.

Although the size of the maximum loading has an affect especially in the final catastrophic fracture stage, the load range (ie difference between maximum and minimum loading) is much more important in control fatigue lifetime.

Fatigue failures in notable disasters

There have been multiple engineering disasters in which fatigue has played a role. You can try to research some of them:

- *The deHavilland Comet Disaster*
  FAA: https://lessonslearned.faa.gov/ll_main.cfm?TabID=2&LifeCycleID=1
  Aircrash Minority Report: https://youtu.be/2rvx-r2itrE
  Prof Paul Withey (Uni of Birmingham): https://youtu.be/K5HqEwbp4GA
- *McDonnell Douglas D-10 – Sioux City, Iowa*
  FAA: https://lessonslearned.faa.gov/ll_main.cfm?TabID=2&LifeCycleID=1&LLID=17
  Wikipedia: https://en.wikipedia.org/wiki/United_Airlines_Flight_232

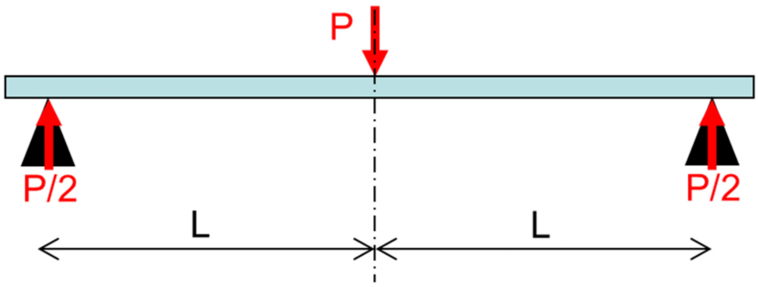
Statistics of Failure

In general the larger the change in forces used the fewer the number of cycles until the material fails. But repeated tests at the same condition give different results - sometime by large factors. This scatter in the fatigue life comes from differences in the details of crystals, phases, and defects present at the microscopic scale, what we call *microstructure.* Samples that look nominally the same are subtly different and somewhere in each of them will be a microstructural feature that acts as the 'weakest link' that will control the failure. In turn the distribution of those 'weakest links' are controlled by how the material was processed.

We can explore how 'weakest links' control failure under static loading with a experiment described on the next page.

Home Experiment:
Pasta Beam Fracture Testing

We can use a three point bending geometry to break some strands of uncooked pasta (or similar) and record the fracture loads. It is called three point bending because we have two points of support under the beam and a third point of loading pushing downwards at the middle of the beam.



A simple way to do this is to fix two supports of equal height on top of a kitchen balance. The supports need to high enough that the beam doesn't contact the surface of the balance before it breaks, and the distance between the supports needs to be fixed for a series of tests. To run the test just put the test piece across the supports and press down with your finger midway between the supports. Try to steadily increase the load keeping an eye on the balance to record the maximum load reached before fracture.

I used some lego to make my supports, but you could use pens/pencils held in place with sticky tape, or try out your own ideas. Record the details of your rig in the methods section. I ran my first set of tests on some linguine but anything that snaps relatively easily and you can find in the kitchen but spaghetti or dry noodles, or bread sticks, or even cornflakes or crisps should work fine - you can be inventive and improvise but ask permission.

Repeat the test for many (~between 10 and 20) nominally identical test pieces, keeping all other conditions the same. Convert the maximum loads (in g) for each test into the correct units (1 kg mass on the scales → ~1 N), and sort into a list from lowest to highest – this is best done on a computer spreadsheet. We can estimate the probability of failure at each ranked position n through the list as being $n/(N+1)$, where N is the total number of tests. The $(N+1)$ comes from the argument that however many samples we test there is always the chance that if we made one more test we could record a load either higher or lower than all our previous tests. Plot your results as probability of failure versus load.

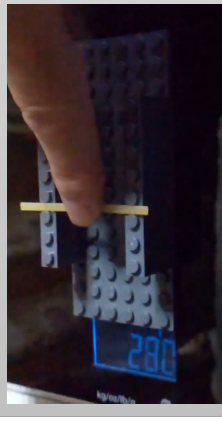
Angus J Wilkinson July 2022

Fracture Testing Experiment

Experimenter: AJW Date: 27/6/2021

Experimental Method

- two supports built using lego and placed on kitchen balance (5kg capacity - digital display to ±1g)
- inner edges of supports 32 mm apart
- test material DeCecco Linguine Nº 7 (~3mm wide, ~1mm high)
- pasta beam pressed down at centre of span with finger - trying to increase load steadily until fracture
- used phone to video load readout - check to get max load after test

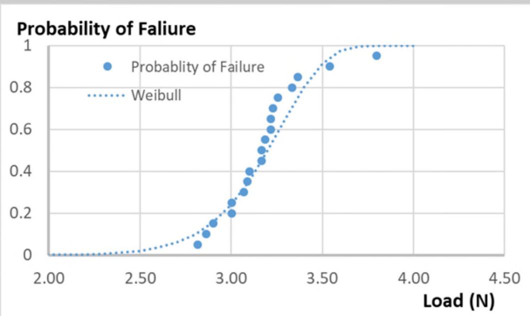


Results - fracture sudden giving clean break always close to centre point

Test Nº.	Load (g)	Test Nº.	Load (g)	Test Nº.	Load (g)	Test Nº.	Load (g)
1	315	6	313	11	343	16	323
2	306	7	306	12	387	17	296
3	332	8	287	13	340	18	292
4	323	9	328	14	328	19	325
5	316	10	361	15	329	20	—

Table gives max. load in each test

Analysis



median (50%) 3.17N
mean 3.18N
5% - 95% range: 2.86 - 3.57N

load (g)	Load (N)	Rank Position	Probability of Failure	Probability of Survival	Ln(Load)	Ln(-Ln(Ps))
287	2.82	1	0.05	0.95	1.04	-2.97
292	2.86	2	0.1	0.9	1.05	-2.25
296	2.90	3	0.15	0.85	1.07	-1.82
306	3.00	4	0.2	0.8	1.10	-1.50
306	3.00	5	0.25	0.75	1.10	-1.25
313	3.07	6	0.3	0.7	1.12	-1.03
315	3.09	7	0.35	0.65	1.13	-0.84
316	3.10	8	0.4	0.6	1.13	-0.67
323	3.17	9	0.45	0.55	1.15	-0.51
323	3.17	10	0.5	0.5	1.15	-0.37
325	3.19	11	0.55	0.45	1.16	-0.23
328	3.22	12	0.6	0.4	1.17	-0.09
328	3.22	13	0.65	0.35	1.17	0.05
329	3.23	14	0.7	0.3	1.17	0.19
332	3.26	15	0.75	0.25	1.18	0.33
340	3.34	16	0.8	0.2	1.20	0.48
343	3.36	17	0.85	0.15	1.21	0.64
361	3.54	18	0.9	0.1	1.26	0.83
387	3.80	19	0.95	0.05	1.33	1.10

Fracture Testing Experiment

Experimenter: Date:

Experimental Method

Results

Test Nº.	Load (g)	Test Nº.	Load (g)	Test Nº.	Load (g)	Test Nº.	Load (g)
1		6		11		16	
2		7		12		17	
3		8		13		18	
4		9		14		19	
5		10		15		20	

Analysis (use a spreadsheet!)

More Testing…

If you'd like to and have time you could run similar test on pasta from different suppliers, or maybe compare normal and wholegrain pasta.

You could look at what difference it makes if you change the distance between the two supports… Share your result and/or questions with us via @OMG_Oxford on twitter.

Things to think about?

- *What load could you apply and expect 90% of test pieces to survive? What if you needed a 99.9% survival rate?*
- *How might an engineer use this sort of data (not on pasta, obvs) to design a safe structure? What probability of failure might be tolerated? How might that be achieved?*
- *Is the average strength (or fatigue life) or the scatter in strength (or fatigue life) more important?*
- *Are there structural features (microstructure) in your test material that are likely controlling the strength?*

Materials Science

Materials Science is a fascinating subject area that bridges between physics, chemistry and engineering to make a distinct field examining the links between how we make or processes materials and their properties often by understanding their structures and defects within them. This generally spans multiple length scales from large engineering structure down to crystals and atomic arrangements within them.

Materials Science is key to many of the technological changes are happening in the world right now, for example making better batteries for cars, and providing clean electricity from solar cells or nuclear fusion, improving the efficiency and safety of our transport systems. Materials Science is crucial to so many of the challenges the world faces.

You can find out more from the following sources:

- www.materials.ox.ac.uk/admissions/schools.html
- http://www.discovermaterials.uk/
- www.iom3.org/careers-learning/schools-outreach.html