Dynamic analysis

Dynamics is the part of structural geology that involves energy, force, stress, and strength.

It's very important to distinguish dynamic concepts from kinematic ones. Many mistakes have been made in structural geology by people who have tried to do dynamic analysis without first understanding how things have moved (kinematics). Although words like *stress* and *strain* have very similar meanings in everyday life, their scientific meanings are very different. *Stress* is a dynamic term whereas *strain* is purely kinematic.

However, even in everyday life, it's difficult to measure a force or stress directly. For example, when you stand on a bathroom scale, you are deforming a spring (strain!). It is only because the spring has very precisely known dynamic properties that we can use that strain to infer something about your weight.

1. Force and stress

Units of force

Force is measured in Newtons where 1 N is the force necessary to accelerate a mass of 1 kg by 1 m/s^2

Units of stress

In structural geology we are almost always interested in what a force does to some part of the Earth's crust, so we need a measure of *force concentration* or *force per unit area.* This is **stress.**

(Note: some textbooks define two different terms: **traction** is the force per unit area on a single plane, a vector quantity; **stress** is the total of forces acting on all possible planes that pass through a point in the Earth's crust, a tensor quantity. At this level we refer to both concepts as 'stress'; the sense is almost always clear from the context.)

The **unit of stress** is 1 N/m^2 or 1 Pa (**Pascal**)

1 Pascal isn't enough to do detectable damage to any kind of rock. More useful units are

1000 Pa = 1 kPa

10^6 Pa = 1 MPa

10^9 Pa = 1 GPa

1 GPa is roughly the pressure at the base of the crust, about 30 km down.

An older unit of stress is the **bar.**

1 bar = 10^5 Pa or, more usefully 10 kbar = 1GPa

There are other units out there. You may encounter the **atmosphere (atm),** and the **pound per square inch (psi)**

1 atm = 1.01 bar = 10100 Pa

1 psi = 690 Pa

All these units can be used to describe **pressure. Pressure** is the state of stress in a stationary fluid, like water. In fact, pressure is also known as **hydrostatic stress.**

Hydrostatic stress is the type of stress experienced by a submerged submarine. Each m^2 of the skin of the submarine experiences the same force, acting perpendicular to that surface.

2. Stress on a plane

In solids, the situation is more complex. Each surface of a mineral grain within the Earth experiences a different force per unit area depending on its orientation. Also, some surfaces experience forces that are not perpendicular to the surface.

In fact, we can resolve the force per unit area (a vector) on any surface into two components. **Normal stress σ_n** is the part of that stress that acts *perpendicular* to the surface. **Shear stress σ_s** is the part that acts *parallel* to the surface.

Because most normal stresses within the Earth act inward, geologists represent compressive normal stress as positive, and use negative numbers for tensile stresses. Engineers often use the opposite convention.

3. State of stress at a point

For any given orientation (strike and dip) of surface passing through a given point in the crust, there is a different value of normal and shear stress. At first sight this is a bewildering mess of forces, all acting in different directions at the same point, but there are some relationships between the various forces that simplify things.

First, if we represent all the stresses acting on all the surfaces as vectors, drawn as arrows, the tails of those arrows make an ellipse (in 2D) or an ellipsoid (in 3D). The ellipsoid is called the **stress ellipsoid.**

Second, it's possible to prove that there are always three mutually perpendicular planes that experience no shear stress. These are **principal planes of stress.** The normal stresses they experience are the maximum, minimum, and an intermediate value of normal stress. We call them **principal stresses** and label them, in order:

$$\sigma_1 > \sigma_2 > \sigma_3$$

The directions of the principal stresses are called the **stress axes.**

You may have noticed that there are close analogies between stress and strain. Be careful not to confuse them!

Hydrostatic and Lithostatic stress

Hydrostatic stress is the special case where $\sigma_1 = \sigma_2 = \sigma_3$ and is equivalent to 'pressure' in a fluid. Where the pressure is due to overlying rock, not fluid, the term **lithostatic stress** is sometimes used**.**

Non-hydrostatic and differential stress

In much of the Earth's crust, the state of stress is **non-hydrostatic.** However, pressure is still a useful concept. What we mean by pressure under those circumstances is **mean stress.** The mean stress is the average of the three principal stresses

$$\sigma_m = (\sigma_1 + \sigma_2 + \sigma_3) / 3$$

The mean stress is the part of the stress that acts to change volume. It's most important to metamorphic petrologists, because high mean stress tends to produce dense minerals like garnet and glaucophane.

What about the rest of the stress? If we subtract the mean stress from each of the principal stresses, we get a 'left over' stress system called the **deviatoric stress** defined by principal values

$$\sigma_1 - \sigma_m, \quad \sigma_2 - \sigma_m, \quad \sigma_2 - \sigma_m$$

The deviatoric stress is the part of the stress that tends to change shape, and is the part of greatest interest to structural geologists.

A related concept is the **differential stress**. This is just the difference between the largest and the smallest principal stress $\sigma_d = \sigma_1 - \sigma_3$

Effective stress

A final concept to be aware of in dynamic analysis is that of **effective stress**. In porous rock, the pore spaces are typically filled with fluid - often water, but sometimes oil or natural gas. If that fluid is itself under pressure, it partially supports the mineral grains, and reduces the stresses between the solid parts of the rock, making them behave as if they were located at a shallower depth. The **effective stress** is then the true stress minus the fluid pressure.

Orientation of stress axes

The Earth's surface is approximately a plane of zero shear stress (give or take a few ocean currents and wind storms). For this reason, *near the Earth's surface, one of the principal stresses is normally vertical.*

This idea was first promoted by Anderson, and has become known as the Andersonian theory of stress. Anderson distinguished three near-surface tectonic regimes depending on which stress axis was vertical.

σ_1 vertical: **Gravity regime**

σ_2 vertical: **Wrench regime**

σ_3 vertical: **Thrust regime**

In a general way, these three regimes correspond respectively to typical states of stress near the three types of plate boundary: spreading centres, transform faults, and subduction zones.

4. Stress-strain relationships

Experimental vs. geological strain rates

Experimental rigs are used to study the types of stress that are necessary to produce different kinds of strain in rocks. A great deal has been learned from such experiments. However, it's important to realize one major limitation: time. Geological strain rates are of the order of 10^{-12} - 10^{-15} strains per second. In the lab, if we don't want to run our experiments for hundreds of years, it's not feasible to achieve strain rates much below 10^{-8} strains per second. To get geologically meaningful results we have to *extrapolate* experiments to much slower strain rates.

Elastic

When rocks are subjected to small strains at low confining pressure (or mean stress) we find that the stress is proportional to the strain, and the strain is recoverable (ie it goes away when the stress is removed)

This type of stress-strain relationship is called **elastic**. The elastic behaviour or rocks allows them to store strain energy and to transmit seismic waves.

Brittle

As stress, and strain, are increased, eventually most rocks undergo a catastrophic loss of strength, with the release of stored strain energy. In an experiment this is called **brittle fracture** or **brittle failure**. In an experimental rig the result is a loud bang and the sample disintegrates. In the Earth's crust the result is an **earthquake.** There are some characteristic relationships between the orientation of fractures and the stress axes that give us useful information.

Extensional fractures

At low mean stress (or 'confining pressure') the sample is likely to be broken along fractures perpendicular to $\boldsymbol{\sigma_3}$**.** If we catch the sample before it has completely failed, and examine the fractures, we find that they are **extension fractures**: the two sides of the fracture have been pulled apart**.**

Conjugate shear fractures

At higher confining pressure, failure typically occurs along two families of planes, breaking the sample into wedge-shaped fragments. The angle between the two families is about 60°. The planes intersect each other in a line parallel to σ_2. The maximum principal stress σ_1 bisects the acute angle between the planes, and the minimum stress σ_3 bisects the obtuse angle**.**

If we catch the sample before it has completely failed, and examine the fractures, we find that they are **shear fractures**: the two sides of the fracture have slid past each other. The sense of shear is such that the acute angles at the edges of the fragments have been pushed inward. Movement is inwards along the σ_1 direction and outward along σ_3.

Brittle failure is non-recoverable deformation!

Plastic

If the confining pressure is higher still, or the temperature is raised, a different type of behaviour occurs. After an initial phase of elastic deformation, the sample starts to deform in a ductile manner. This deformation is also non-recoverable, but it occurs without loss of strength. The sample shortens in the σ_1 direction, and thickens parallel to σ_3.

In **ideal plastic** behaviour, a sample shows no deformation at all until a certain stress (**yield stress**) is reached. Thereafter, it deforms freely so that however much shortening is imposed by the rig, it's impossible to get the stress to go any higher.

Real rocks are a bit more complicated than the ideal. They typically show some elastic deformation below the yield stress, and with continuing plastic deformation the stress may rise a little or fall a little.

Viscous

At temperatures close to their melting point, some rocks show a much simpler type of flow behaviour without a yield stress. In viscous behaviour, any small amount of stress will cause strain to start. The **strain rate** is proportional to the stress. Viscous behaviour is sometimes also called **Newtonian.** Water, air, magmas, and rock salt may show approximately Newtonian behaviour.

Competence

For each of the above idealized types of behaviour, there is a parameter that measures a rock's strength, or resistance to stress. For elastic deformation it is callled Young's modulus; for brittle behaviour it is the differential stress at failure; for plastic deformation it's the yield stress; and for viscous behaviour it's the viscosity.

Real rocks show complicated mixtures of these behaviour types, making these quantities very hard to measure. Nonetheless, in the field we can often recognize rock types that have undergone more strain, and those that have undergone less, side by side in the same outcrop (where they have presumably had very similar stress histories.) Under these circumstances it's useful to have a general term for resistance for stress. That term is **competence.** For example, if we observe that layers of slate have undergone a lot more strain than interbedded quartzite layers, we might deduce that the quartzite was more **competent.**