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Bjarne Haugstad
Director of Research

EVERYTHING YOU WANTED TO KNOW ABOUT MATERIAL TESTING BUT WERE AFRAID TO ASK

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8) ABSTRACT

The theory behind various methods of material testing is reviewed. We look in detail at static triaxial testing with a GREAC cell and dynamic testing with the Split Hopkinson Bar and Flyer plate. In particular, we discuss the testing of concrete using these methods.

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CONTENTS

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1 INTRODUCTION

To give accurate predictions about dynamic processes involving specific materials, it is necessary to know how the relevant materials behave under various circumstances. A way of finding this out, is by performing material tests, in which the material is subjected to different types of loading. On the basis of the test results, a mathematical model describing the material can be constructed. Unfortunately, real materials turn out to behave in a very complicated fashion, strongly dependent on how the external forces are applied. As a consequence, it is very difficult to create a complete material model that is valid for every type of loading. Instead, one aims at constructing a model that reflects the behaviour of the material under loadings that are relevant for the particular process under study.

Several different methods for testing a material have been developed over the years. In this report we take a close look at the most important ones, describing the theory behind them and their strengths and weaknesses.

The tests can roughly be divided into two groups, namely static and dynamic tests. As the name indicates, in static tests the load on the material is applied very slowly, while in dynamic tests the material is loaded very quickly.

The following tests are covered in the report:

- GREAC cell
- Split Hopkinson Bar
- Flyer Plate

In the report we first emphasize the mathematical description of the "ideal tests", i.e. we momentarily ignore practical problems that will arise when the tests are performed. Having completed this, we try to examine the practical problems, whether they are important, how they can be avoided and ways to live with them.

2 PRELIMINARY THEORY FOR STATIC TESTING

We will start by describing static concrete testing in detail. However, before developing the mathematical theory, it will be useful to examine material behaviour under states of uniaxial stress and uniaxial strain.

In Teland (1) mathematical expressions for these cases of loading were given in cartesian coordinates for a rectangular specimen. Here we present the expressions in cylindrical coordinates for a cylindrical specimen. They are seen to be very similar.

2.1 Uniaxial stress

Ideally the specimen is under uniaxial stress during a standard compressive test. The elastic stress and strain behaviour of the material is given by:

$$\sigma_r = \sigma_\theta = 0 \quad , \quad \sigma_z = E\epsilon_z \tag{2.1}$$

$$\epsilon_r = \epsilon_\theta = -\nu\epsilon_z \tag{2.2}$$

Consequently we have:

$$\sigma_{vm} = \sqrt{3J_2} = |\sigma_z| \quad , \quad p = \frac{\sigma_z}{3} \tag{2.3}$$

where J_2 is the second stress invariant. When the yield limit is reached, the material turns plastic. During plasticity, the following condition must be satisfied:

$$\sigma_{vm} = Y(p) \tag{2.4}$$

Since $\sigma_r = \sigma_\theta$ also during plasticity, Equation (2.3) still holds and on inserting into Equation (2.4) is seen to produce only one equation for one unknown quantity, σ_z. The equation then has a unique solution, and can only be satisfied for one value of σ_z and thus one value of p. Consequently we can not detemine the yield stress as a function of pressure with this test, since it becomes impossible to increase the pressure further once yielding has been achieved (although the strain can be increased indefinitely). A uniaxial stress test therefore only provides us with with one single point on the yield curve.

2.2 Uniaxial strain

If the material is unable to expand laterally while being compressed axially, it is said to be in a state of uniaxial strain. The elastic behaviour is then as follows:

$$\sigma_r = \sigma_\theta = \left(\frac{E\nu}{(1+\nu)(1-2\nu)}\right)\epsilon_z \quad , \quad \sigma_z = \left(\frac{E(1-\nu)}{(1+\nu)(1-2\nu)}\right)\epsilon_z \tag{2.5}$$

$$\epsilon_r = \epsilon_\theta = 0 \tag{2.6}$$

We then have:

$$\sigma_{vm} = \sqrt{3J_2} = |\sigma_z - \sigma_r| = \left(\frac{E}{1+\nu}\right)\epsilon_z = 2G\epsilon_z \tag{2.7}$$

$$p = \frac{2\sigma_r + \sigma_z}{3} = \frac{E}{3(1-2\nu)}\epsilon_z = K\epsilon_z \tag{2.8}$$

Combining Equations (2.7) and (2.8) gives us:

$$\sigma_{vm} = 3\left(\frac{1-2\nu}{1+\nu}\right)p \tag{2.9}$$

During plasticity, the following conditions must be satisfied:

$$\sigma_{vm} = |\sigma_z - \sigma_r| = Y(p) \tag{2.10}$$

$$p = \frac{2\sigma_r + \sigma_z}{3} \tag{2.11}$$

Since σ_r is not identically zero in this case, we see that Equation (2.10) is one equation with two unknowns. Thus, neither σ_r nor σ_z are fixed, which means that the pressure can be varied during plastic flow. A uniaxial strain test can therefore be used to determine part of the yield curve *Y(p)*. This is done by recording the relationship between σ_{vm} and p during plastic flow.

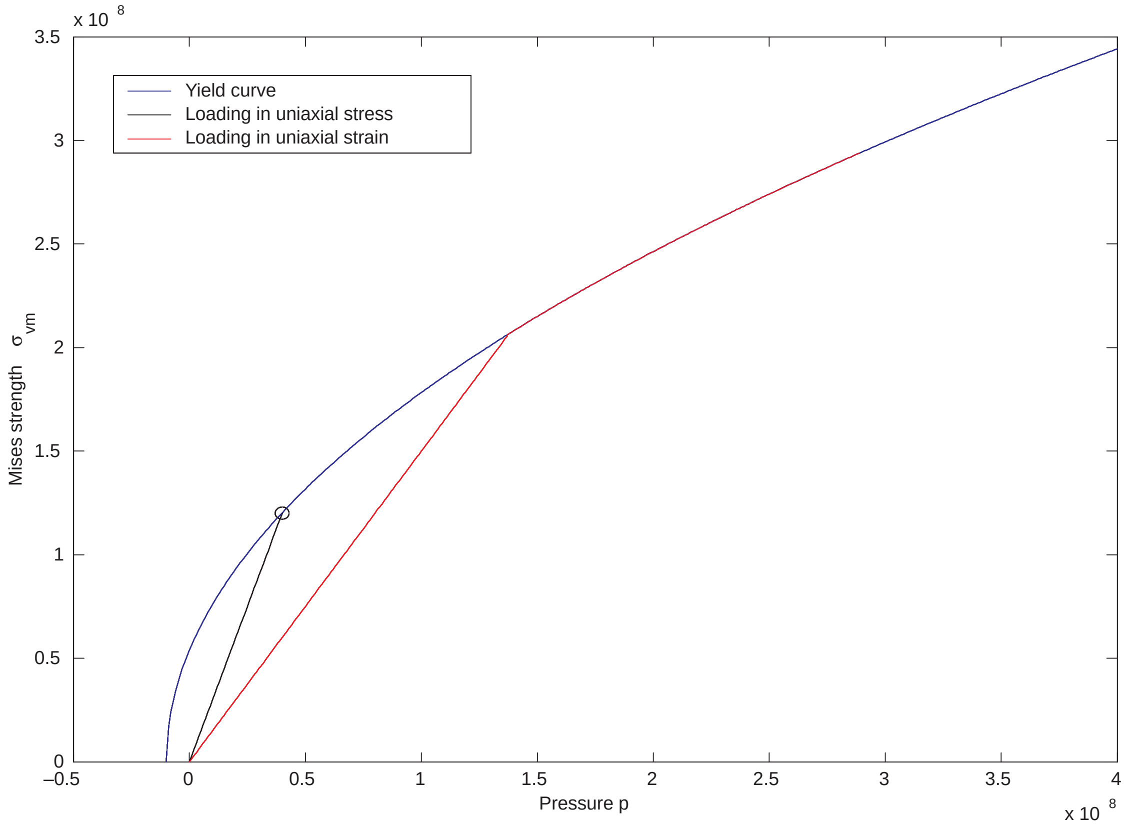


Figure 3.2: Loading paths in stress space for uniaxial stress and strain tests. Unlike the uniaxial strain test, the uniaxial stress test does not move along the yield curve and can therefore only be used for determining a single point on this curve.

In Figure 3.2 we have illustrated the situation for loading under uniaxial stress and strain. We notice that on using the uniaxial strain loading, we miss out on information about the yield curve for low pressures. Performing a uniaxial stress test in addition, enables us to find one additional point lower on the yield curve.

Similarly, by combining the pressure and density we can obtain the equation of state (EOS). In this ideal case, the EOS is easily seen to be linear, but for real materials like concrete it will be more complicated.

2.3 More complicated loading

An interesting question is now the following: Does the yield curve only depend on the pressure (as indicated in the above chapters) or is it a function of other parameters as well?

The answer is that it depends on which material we are studying. For some materials (metals) the yield curve is even independent of pressure and is, in effect, a yield limit, while for other materials it depends on the pressure only. Further, for materials such as concrete things are even more complicated.

For concrete, a stress state where $\sigma_z > \sigma_r = \sigma_\theta$ will not give the same yield stress as a state where $\sigma_z < \sigma_r = \sigma_\theta$ even when the value of $\sqrt{J_2}$ is identical. Thus, for concrete, yielding is defined by a yield surface in some kind of stress space instead of a yield curve or yield limit. We will briefly see this in Chapter 4.5 where we examine the output from a so–called GREAC cell test. For more details, the reader should consult Riedel (4) and references therein.

3 STANDARD STATIC CONCRETE TESTS

The previous chapter dealt only with theory, whereas in this chapter we briefly look at the practical application of the theory to standard uniaxial concrete testing.

In the most common material test, only the compressive strength σ_c of the concrete is measured. The test is very simple: One takes a concrete cube (or cylinder) of a specified size and increases the axial stress until the concrete breaks. The corresponding stress is called the compressive strength. Similarly there are standard tensile tests for determining the concrete tensile strength.

All these “engineering tests” have in common that they have not been designed to determine material properties for input into hydrocodes for advanced numerical simulations. Rather they are meant to be standard methods for classification of concrete. Further description of such methods is given in (5) and (6).

Obviously a compression test is relevant for the strength of a bridge beam, but in every construction there will be induced complicated tri–axial stress states. However, compressive strength could still be used as a relevant parameter in empirical calculations since there is an (unknown) relation between uniaxial and triaxial properties.

In this report, our focus will be on tri–axial tests to determine hydrocode data (or similar) and not on the standard “engineering” tests.

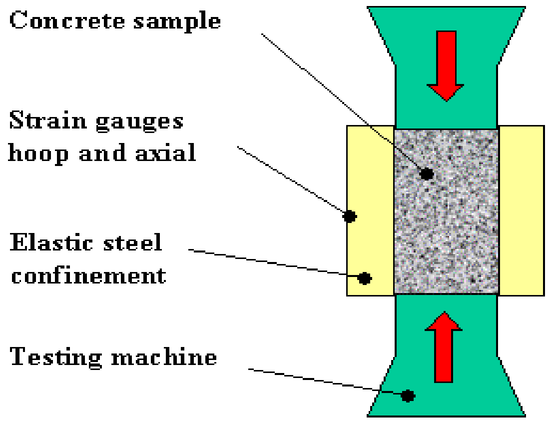
4 GREAC CELL TEST

In this chapter we will discuss the GREAC (Gauged REActive Confinement) cell test method. It is a static triaxial method in which a test specimen is confined inside a cylinder and then loaded axially. A schematic view of the GREAC cell is shown in Figure 3.1. Such an apparatus has been built and used in material testing at FFI.

By measuring the strains on the outside of the cylinder, we shall see that a great deal of information about the material properties of the specimen can be extracted. Of special interest is the yield limit as a function of pressure $Y(p)$ and the equation of state $p(\rho)$.

Unlike in the uniaxial strain case, the steel confinement is not infinitely strong which means that there will be strains in the cylinder. This is actually a good thing because by measuring these strains, we are able to deduce the stress state in the concrete specimen.

To distinguish the quantities in the steel cylinder and the concrete specimen without having indices all over the place, we are going to denote concrete quantities with a "hat", $\hat{\sigma}_{ij}$, and steel cylinder quantities without.



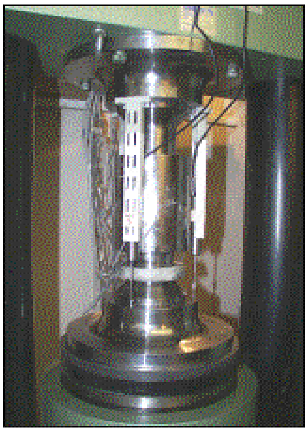


Figure 4.1: GREAC cell

4.1 Experimentally measured quantities

By placing strain gauges on the steel cylinder and by recording the force on the piston, we can perform measurements that eventually enables us to calculate various physical quantities. Although it can be a huge challenge to relate measurements of electrical voltages with strains in the cylinder, we will ignore this problem here, and just assume that the following quantities are measured directly:

- Axial force on the concrete $\hat{F}$
- Axial displacement of the concrete $\hat{u}_z$
- Axial strain on the outside boundary of the confining cylinder $\epsilon_z(b)$
- Angular strain on the outside boundary of the steel cylinder $\epsilon_\theta(b)$

This is all well and good, but as we have seen, expressions for the pressure $\hat{p}$, the density $\hat{\rho}$ and von Mises stress $\hat{\sigma}_{vm}$ in the concrete specimen are what is really needed. Since we are unable to measure any of these directly, it is necessary to figure out a way of calculating them in terms of the quantities given above. To accomplish this, we need to examine the GREAC cell test mathematically.

4.2 Mathematical description of the test

Since $\hat{\sigma}_r = \hat{\sigma}_\theta$ in the specimen (and consequently $\hat{\epsilon}_r = \hat{\epsilon}_\theta$), it becomes slightly easier to calculate $\hat{p}$, $\hat{\rho}$ and $\hat{\sigma}_{vm}$. Using this and assuming all non–diagonal components of the stress tensor to vanish, we have the same relations as for uniaxial strain: