CE394M: An introduction to plasticity

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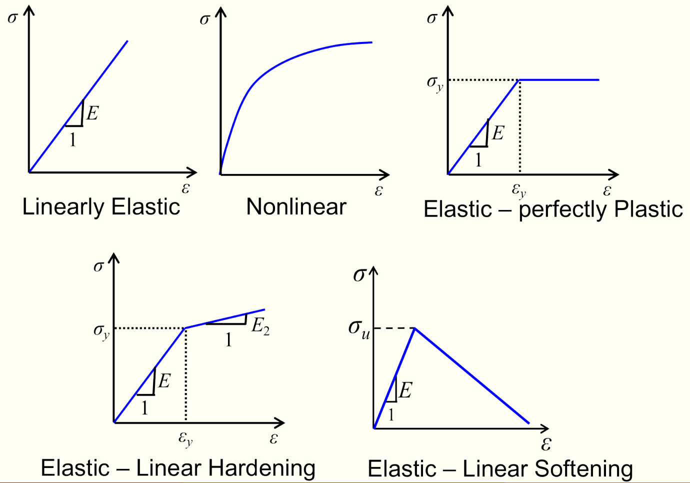
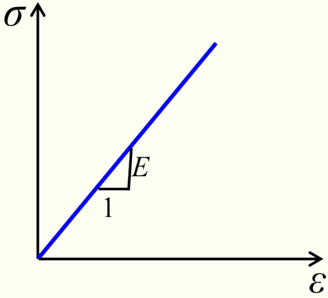
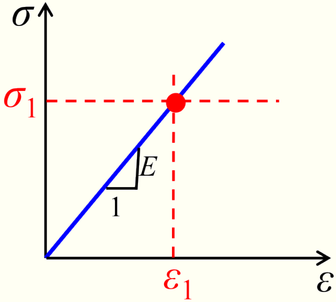
Overview

Constitutive law



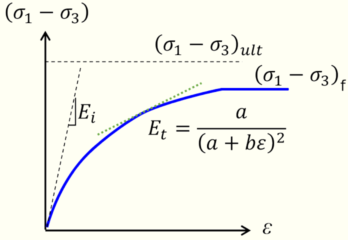
Isotropic linear elasticity



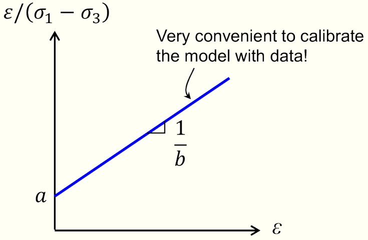


The knowledge of strain alone allows us to obtain the stress value.

Hyperbolic model (Duncan and Chang., 1970)



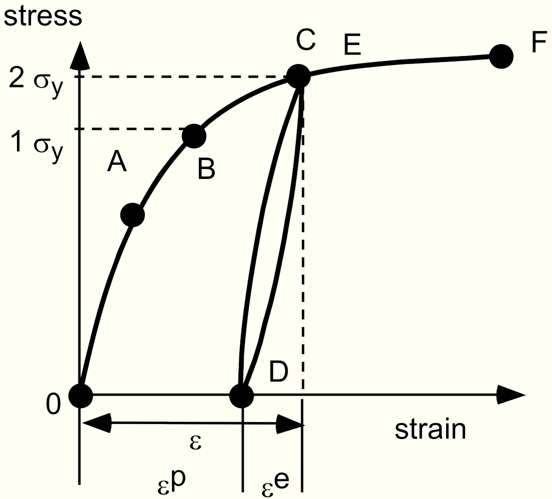
Hyperbolic stress-strain relationship



Transformation of hyperbolic relations

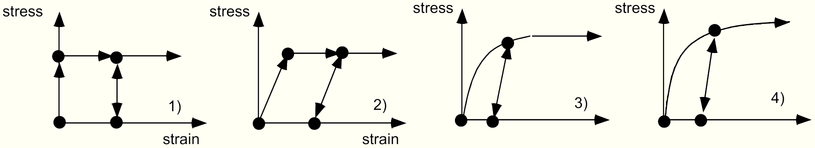
There is no physical meaning to $(\sigma_1 - \sigma_3)_{ult}$. The $(\sigma_1 - \sigma_3)_f$ is determined from the strength criteria $\tau = c + \sigma' \tan \phi'$ (drained) or $\tau = s_u$ (total stress undrained).

Classical plasticity

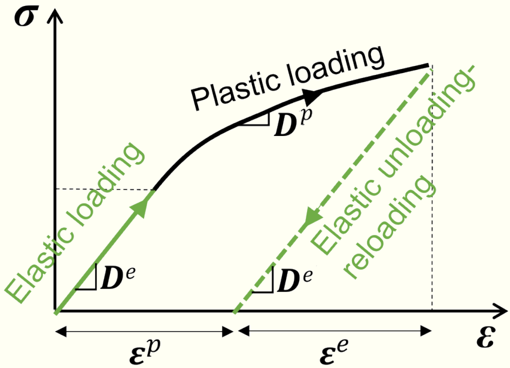


Specimen 1 at point 0 same as specimen 2 at point D, but yield stress of specimen 2 is greater than the yield stress of specimen 1 due to **plastic hardening**.

Classical plasticity



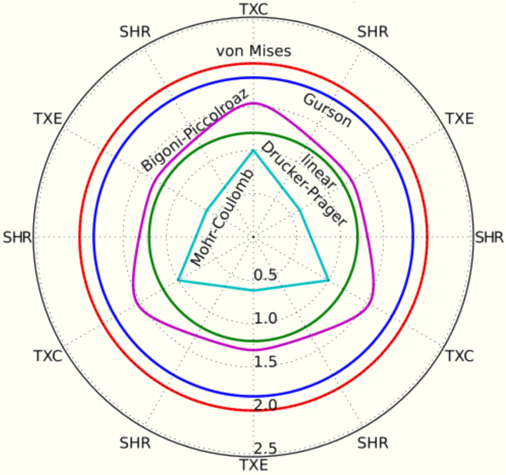
Elasto-plastic materials



Basic concepts of classical plasticity

To formulate an elasto-plastic constitutive model we need:

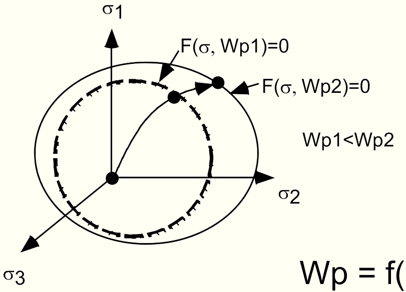
defines when plastic strains occur. If the material is isotropic, we can use the principal stresses to define the stress state.

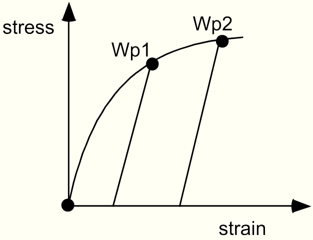


Wikipedia

Hardening law

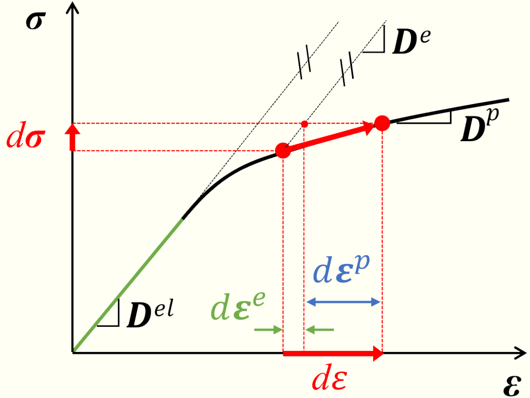
How the threshold of yielding changes with plastic strain or how the yield function changes with plastic strain.





$$Wp = f(\varepsilon^p)$$

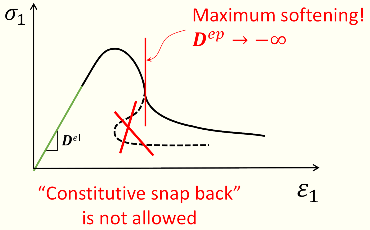
Equations of elasto-plasticity: 1. Stress-strain relation



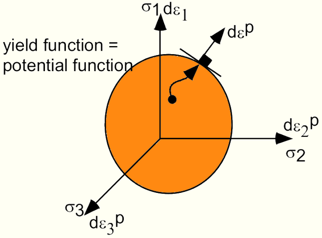
Equations of elasto-plasticity: 2. Flow rule

Drucker's postulate

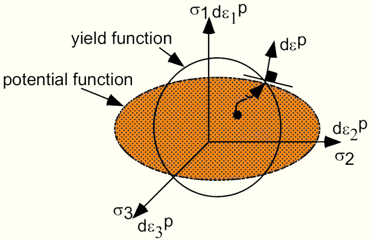
Drucker (1952) established that for a stable inelastic material in a closed stress cycle, a positive work must be done.



Associated and non-associated plasticity

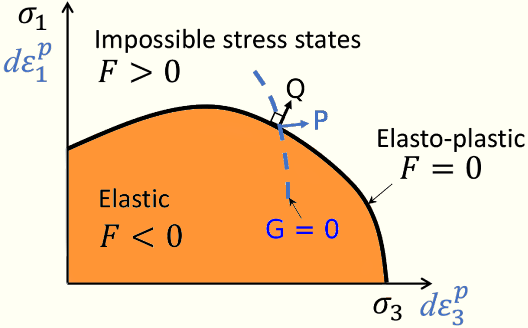


Associated flow rule



Non-associated flow rule

Equations of elasto-plasticity: 3. Consistency condition



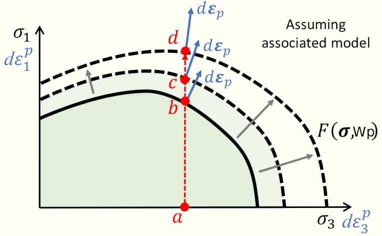
Equations of elasto-plasticity: 3. Consistency condition

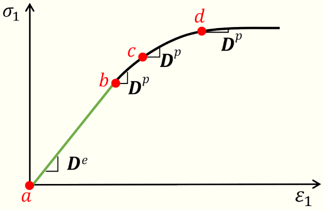
The consistency condition can be written as:

$$
\begin{aligned}
dF &= \left(\frac{\partial F}{\partial \sigma}\right)^T \cdot d\sigma + \frac{\partial F}{\partial Wp} \cdot dWp && = 0 \\
&= \left(\frac{\partial F}{\partial \sigma}\right)^T \cdot d\sigma + \left(\frac{\partial F}{\partial Wp}\right) \cdot \left(\frac{\partial Wp}{\partial \varepsilon^p}\right)^T \cdot d\varepsilon^p && = 0 \\
&= \left(\frac{\partial F}{\partial \sigma}\right)^T \cdot d\sigma + \left(\frac{\partial F}{\partial Wp}\right) \left(\frac{\partial Wp}{\partial \varepsilon^p}\right)^T \cdot \frac{\partial G}{\partial \sigma} d\lambda && = 0 \\
dF &= \left(\frac{\partial F}{\partial \sigma}\right)^T \cdot d\sigma - H d\lambda && = 0.
\end{aligned}
$$

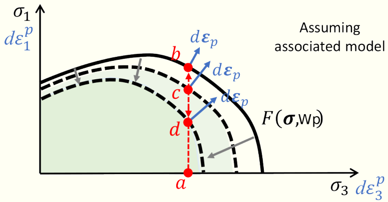
if $H > 0$: Hardening, if $H = 0$: perfect plasticity, if $H < 0$: softening.

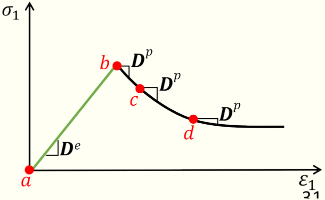
Linear elastic – hardening plastic material $H > 0$





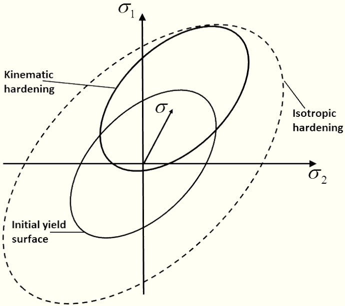
Linear elastic – softening plastic material $H < 0$





Isotropic v kinematic hardening

Two primary types of hardening laws: density and kinematic hardening.



1. **Density hardening**: also referred to as isotropic hardening. $(\sigma_1 - \sigma_3) - 2c(h) = 0$
2. **Kinematic hardening**: typically describing fabric anisotropy. No change in size of yield surface but translating in stress space. $F = (\sigma_1 - \sigma_3) - \alpha(h) - 2c = 0$.

Basic concepts of elasto-plasticity

The response of the material is:

- **elastic**:

- **elasto-plastic**:

Note: When the response is elastic, we have no problem! Knowing the strain, we directly can calculate the stress ($d\sigma = D^e \cdot d\varepsilon$).
The difficulty arises when the material response is elasto-plastic, we need to determine D^p!

Equations of elasto-plasticity

For an elasto-plastic material:

- Input material:
- Results from FE analysis:
- unknowns:
- What we are interested:

1. Stress-strain: $d\sigma = D^e \cdot (d\varepsilon - d\varepsilon^p)$
2. Consistency-condition: $dF = \frac{\partial F}{\partial \sigma}^T \cdot d\sigma - H d\lambda$
3. Flow rule: $d\varepsilon^p = \frac{\partial G}{\partial \sigma} d\lambda$.

Solution procedure:

Equations of elasto-plasticity

Eq 1 and 3 (stress-strain & flow rule) in Eq 2 (consistency condition) for $d\lambda$

$$dF = \left(\frac{\partial F}{\partial \sigma}\right)^T \cdot D^e \cdot \left(d\varepsilon - \frac{\partial G}{\partial \sigma} d\lambda\right) - H d\lambda = 0$$

$$d\lambda = \frac{\left(\frac{\partial F}{\partial \sigma}\right)^T \cdot D^e \cdot d\varepsilon}{\left(\frac{\partial F}{\partial \sigma}\right)^T \cdot D^e \left(\frac{\partial G}{\partial \sigma}\right) + H}$$

$$\left(\frac{\partial F}{\partial \sigma}\right)^T \cdot D^e \frac{\partial G}{\partial \sigma} + H > 0$$

$d\lambda$ in Eq 3 $\rightarrow$ $d\varepsilon^p$

$$d\varepsilon^p = \frac{\partial G}{\partial \sigma} d\lambda = \frac{\partial G}{\partial \sigma} \frac{\left(\frac{\partial F}{\partial \sigma}\right)^T \cdot D^e \cdot d\varepsilon}{\left(\frac{\partial F}{\partial \sigma}\right)^T \cdot D^e \left(\frac{\partial G}{\partial \sigma}\right) + H}$$

Equations of elasto-plasticity

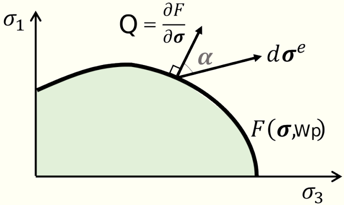
$d\varepsilon^p$ in Eq 1 $\rightarrow d\sigma$

$$d\sigma = D^e \cdot (d\varepsilon - d\varepsilon^p)$$
$$= D^e \cdot \left(d\varepsilon - \frac{\partial G}{\partial \sigma} \frac{\left(\frac{\partial F}{\partial \sigma}\right)^T \cdot D^e \cdot d\varepsilon}{\left(\frac{\partial F}{\partial \sigma}\right)^T \cdot D^e \left(\frac{\partial G}{\partial \sigma}\right) + H} \right)$$

$$\boxed{d\sigma' = \left[D^e - \frac{D^e \left(\frac{\partial G}{\partial \sigma'}\right) \left(\frac{\partial F}{\partial \sigma'}\right)^T D^e}{-\left(\frac{\partial F}{\partial W_p}\right) \left(\frac{\partial W_p}{\partial \varepsilon^p}\right)^T \left(\frac{\partial G}{\partial \sigma'}\right) + \left(\frac{\partial F}{\partial \sigma'}\right)^T D^e \left(\frac{\partial G}{\partial \sigma'}\right)} \right] d\varepsilon}$$

Plastic loading v elastic unloading

Depending on α, we might have three different scenarios:



If $\alpha < 90° \Rightarrow \left(\frac{\partial F}{\partial \boldsymbol{\sigma}}\right)^T \cdot \boldsymbol{D}^e \cdot d\boldsymbol{\varepsilon} > 0$

$\Rightarrow d\Lambda > 0 \Rightarrow d\boldsymbol{\varepsilon}^p > 0$

$\Rightarrow$ **Elastoplastic loading**

$\Rightarrow dF = 0$

If $\alpha = 90° \Rightarrow \left(\frac{\partial F}{\partial \boldsymbol{\sigma}}\right)^T \cdot \boldsymbol{D}^e \cdot d\boldsymbol{\varepsilon} = 0$

$\Rightarrow d\Lambda = 0 \Rightarrow d\boldsymbol{\varepsilon}^p = 0$

$\Rightarrow$ **Neutral loading**

$\Rightarrow dF = 0$

If $\alpha > 90° \Rightarrow \left(\frac{\partial F}{\partial \boldsymbol{\sigma}}\right)^T \cdot \boldsymbol{D}^e \cdot d\boldsymbol{\varepsilon} < 0$

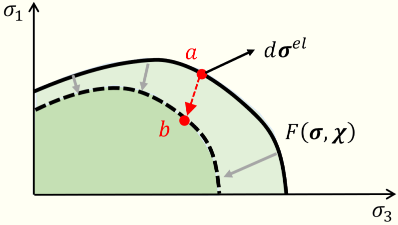
$\Rightarrow \cancel{d\Lambda < 0} \Rightarrow \cancel{d\boldsymbol{\varepsilon}^p = 0}$

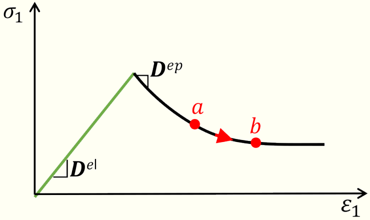
$\Rightarrow$ **Elastic unloading**

$\Rightarrow dF < 0$

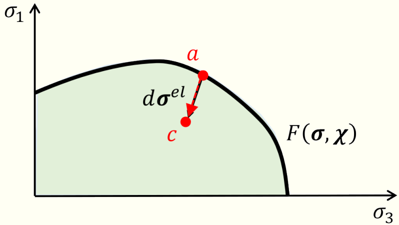
Plastic loading v elastic unloading

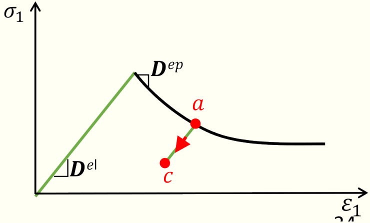
Don't confuse **elastoplastic loading with softenting**...





...with **elastic unloading**



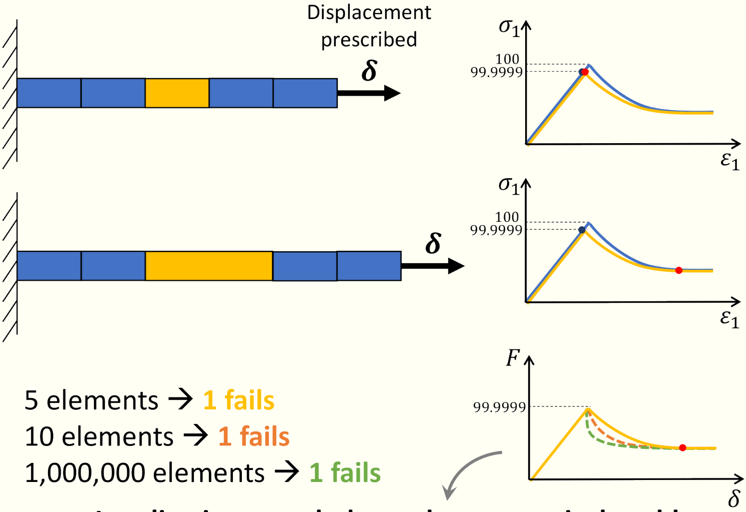


Problems associated to softening

1. The modeling of **strain softening** (i.e. strength decreases from pick to residual conditions) leads to the localization phenomenon.
2. Localization shows up when all deformation is absorbed by one element, while the neighboring elements remain under elastic conditions.
3. The solution depends on the element size, hence the localization is a **mesh dependent numerical problem**.
4. **Solution:** regularization techniques: non-local integration, strain softening models dependent on the element size,...
5. Be careful: Most of the commercial software do not include regularization techniques.

Problems associated to softening

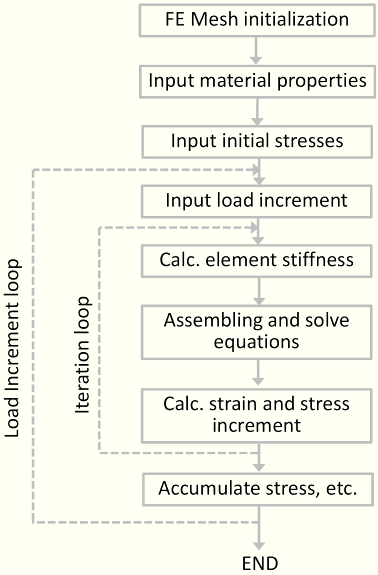
Don't confuse **elastoplastic loading with softenting**...



5 elements → 1 fails
10 elements → 1 fails
1,000,000 elements → 1 fails

Localization =mesh dependent numerical problem

FE workflow



$\boldsymbol{\sigma}$

$\Delta \boldsymbol{f}$

$$K_{ij} \approx \sum_{p}^{n_p} B_i^p D^p B_j^p W_p$$

$\Delta \boldsymbol{u} = \boldsymbol{K}^{-1} \cdot \Delta \boldsymbol{f}$ **Equilibrium eq.**

$\Delta \boldsymbol{\varepsilon} = \boldsymbol{B} \cdot \Delta \boldsymbol{u}$ **Compatibility eq.**

$\Delta \boldsymbol{\sigma} = \boldsymbol{D} \cdot \Delta \boldsymbol{\varepsilon}$ **Constitutive eq.**

$$\boldsymbol{u} = \boldsymbol{u} + \Delta \boldsymbol{u}$$
$$\boldsymbol{\varepsilon} = \boldsymbol{\varepsilon} + \Delta \boldsymbol{\varepsilon}$$
$$\boldsymbol{\sigma} = \boldsymbol{\sigma} + \Delta \boldsymbol{\sigma}$$