Indentation of a thin film / substrate system

The objective of the session is to illustrate numerically some effects of the configuration of a thin layer / substrate Figure 11) on the indentation curve and the profile of the imprint.

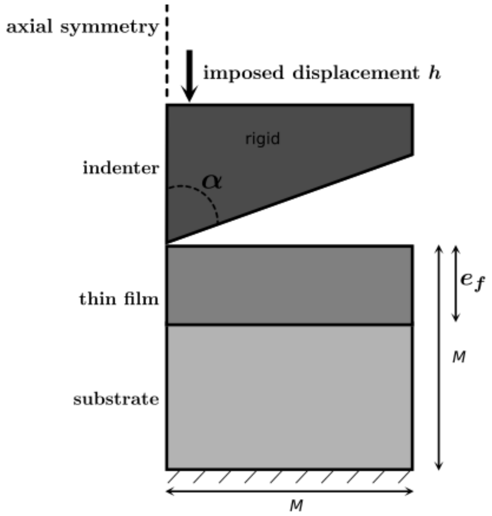

Figure 1 Indentation of the thin layer /substrate system

Two very different elastoplastic materials will be used to illustrate these effects: a soft and a hard one. The isotropic work hardening law used is a power law verifying the von Mises criterion. It is expressed in simple traction in the form of:

$$\begin{aligned} \sigma &= E\varepsilon && pour \quad \sigma < \sigma_y\,, \\ \sigma &= \sigma_y \left(\frac{E}{\sigma_y}\right)^n \varepsilon^n && pour \quad \sigma \geq \sigma_y. \end{aligned} \tag{1}$$

E is the Young's modulus, σ_y is the initial yield stress and n the work hardening coefficient. For the multiaxial formulation, the Poisson's ration is set to $\nu = 0.3$. The parameter values for both materials are summarized in Table 1

Table 1 Elastoplastic properties of the two materials used ($\nu = 0.3$).

	E (GPa)	σ_y(GPa)	n
hard	300	20	0.1
mou	200	2	0.1

After finding some classic results for a homogeneous sample, we will be interested in the effect of a hard layer on a soft substrate, then a soft layer on a hard substrate. In the last part, we will discuss the identifiability of plastic parameters.

The solution of the equations of the model of the indentation test requires is based on the Finite Elements (EF) method. These equations are solved using Ansys software. To simplify the use of APDL (Ansys Parametric Design Language) scripts and address parametric identifiability, MIC2M software (developed in Matlab/Octave script) is used. A specific interface for the workshop also ensures the display of relevant EF results (curves $P(h)$, profiles $Z(X)$, ….).

Other assumptions/remarks (unless otherwise indicated in the question):
- Size of the modelled sample: $M = 40 \times h_{max}$
- Tip: perfect cone, non-deformable, Berkovich equivalent (α =70.3°)
- Coefficient of friction tip/sample: 0.1
- Very coarse EF discretization: (finesse $= 8$: EF size under the tip $= h_{max}/2$) and polynomial approximation (load/unload) of the P-h curves.
- The parametric model of the test is only valid for the values of the statement!

1 Prior

- Download the teaching version of MIC2M integrating the specific module of the Indentation2021 workshop Figure 2 unzip the file and follow the instructions of the tutorial "installation" (file:*MIC2M_indentation2021_start\installation.pdf).*

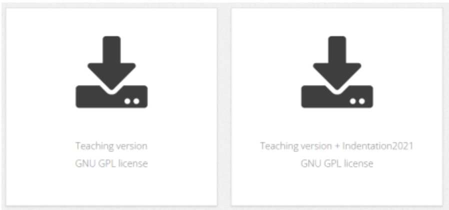

Figure 2: http://mic2m.univ-fcomte.fr (Richard, 2000)> Download

2 Homogeneous samples

- Do the tutorial "simulation" of the workshop to learn how to simulate an indentation test.
  file: *MIC2M_indentation2021_PW_Indentation2021_tuto\simulation_Indentation2021.pdf*

2.1 Indentation curves and profiles of imprints

Q: Plot the curves $P(h)$ and profiles of $Z(X)$ for the two homogeneous samples and the indentation depth $h_{max} = 0.5$ µm.

Q: What do you think of Young's modulus obtained by the Oliver and Pharr method (Oliver and Pharr, 1992)? Quantify $h_{pile-up}/h_{max}$.

2.2 Effect of discretization

Q: To study the influence of discretization on the previous results with a finer discretization (finesse $= 4$).

In the rest of the workshop, use finesse $= 8$ to minimize the calculation time.

2.3 Effect of sample size

Q: Study the influence of the modeled sample size by simulating the test with a sample twice as large: $M/h_{max} = 80$

In the rest of the workshop, use $M = 40 \times h_{max}$ to minimize the calculation time.

Remark: The effects of a rounding of the tip, its dimension and its deformability are not studied in the workshop for reasons of calculation time but they can be very important!

2.4 "Self-similarity"

If the numerical model respects the principle of similarity, the same stress and strain fields must be obtained regardless of the indentation depth, with one factor. *P(h)* and *Z(X)* must therefore be similars regardless of the indented depth, with one factor.

- Q: For both materials, simulate an indentation for several depths (0.1, 0.5, 1 and h_{max}µm 2) and verify:

  - the similarity of the curves.$\left(\frac{P}{P_{max}}\right) = f\left(\frac{h^2}{h_{max}^2}\right)$ and $\left(\frac{Z}{h_{max}}\right) = g(\frac{X}{h_{max}})$

  - the proportionality of the load to h^2.

3 Thin film effect

3.1 Hard/Soft

Q: Study the influence of a hard layer of thickness equal to $e_f = 1$ µm on a soft substrate for several depths h_{max} (0.1, 0.5, 1 and 2 µm). What about the similarities of the curves (indentation and profile) and the evolution of the elastic modulus and hardness as a function of h_{max} ?

3.2 Move/Hard

Q: Study the influence of a soft layer of thickness equal to $e_f = 1$ µm on a hard substrate for several depths h_{max} (0.1, 0.5, 1 and 2 µm). What about the similarities of the curves (indentation and profile) and the evolution of the elastic modulus and the hardness as a function of h_{max} ?

4 Identifiability of two plastic parameters

4.1 Introduction to identifiability

When identifying elastoplastic parameters from an indentation curve, a major problem is that of the non-uniqueness of the solution obtained (Cheng and Cheng, 1999). This is the lack of stability of the solution (i.e. its high sensitivity to disturbances P-h) which generates in practice multiples solutions (Phadikar et al., 2013). The I-index (Richard et al., 2013; Richard, 2017) to quantify this problem for a virtual solution without having to perform a FEMU-type optimization procedure, costly in computational time and potentially generating an unstable solution. The lower the I-index, the better the conditioning of the inverse problem that could be posed. If $I > 3$, the parameters are in practice not identifiable (Figure 3).

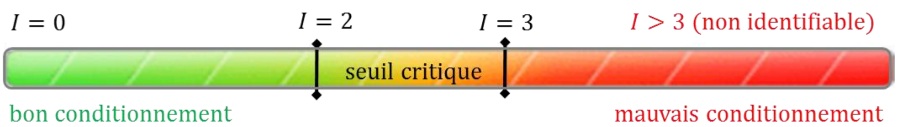

Figure 3: Indicative values I-index / conditioning.

This I-index integrates information on the norms and multi-collinearities of the sensitivity vectors of the observables used *(P(h)* curve, profile $Z(X)$ ...). It can be calculated by finite differences using the model of the test. The MIC2M software automatically calculates this index.

4.2 Homogeneous sample

- Tutorial "identifiability" of the workshop to learn how to calculate the index $I(\sigma_y, n)$ in the case of an homogeneous sample.
  file: *MIC2M_indentation2021_PW_Indentation2021_tuto\identifiabilite_Indentation2021.pdf*

  Q: Compute $I\ (\sigma_y, n)$ for both materials (hard and soft) from *P(h)* and from $Z(X)$.

4.3 Hard/Soft

The behavior of the known soft substrate is assumed.

Q: Calculate the I-index $I(\sigma_y, n)$ in the case of a hard thin film of thickness $e_f = 1$ µm for a depth equal to $h_{max} = e_f$.

4.4 Soft/Hard

The behavior of the known hard substrate is assumed.

Q: Calculate the I-index $I(\sigma_y, n)$ in the case of a soft thin film of thickness $e_f = 1$ µm for a depth equal to $h_{max} = e_f$.

References:

Cheng, Y.-T., Cheng, C.-M., 1999. Can stress–strain relationships be obtained from indentation curves using conical and pyramidal indenters? Journal of Materials Research 14, 3493–3496. https://doi.org/10.1557/JMR.1999.0472

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