Validation and verification methodology to calibrate the dynamic properties of soft materials using Dynamic Indentation and Taylor tests

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OUTLINE

- Introduction
- Research problem
- Methodology
- Results
- Conclusions

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INTRODUCTION

Body-armor ballistic test

- NIJ 0101-06 Standard "Ballistic Resistance of Body Armor"
  - Roma Plastilina No.1 (RP) clay must be used as backing material.
- Performance of body-armor systems:
  - No perforation
  - Indentation in RP less than 44 mm depth

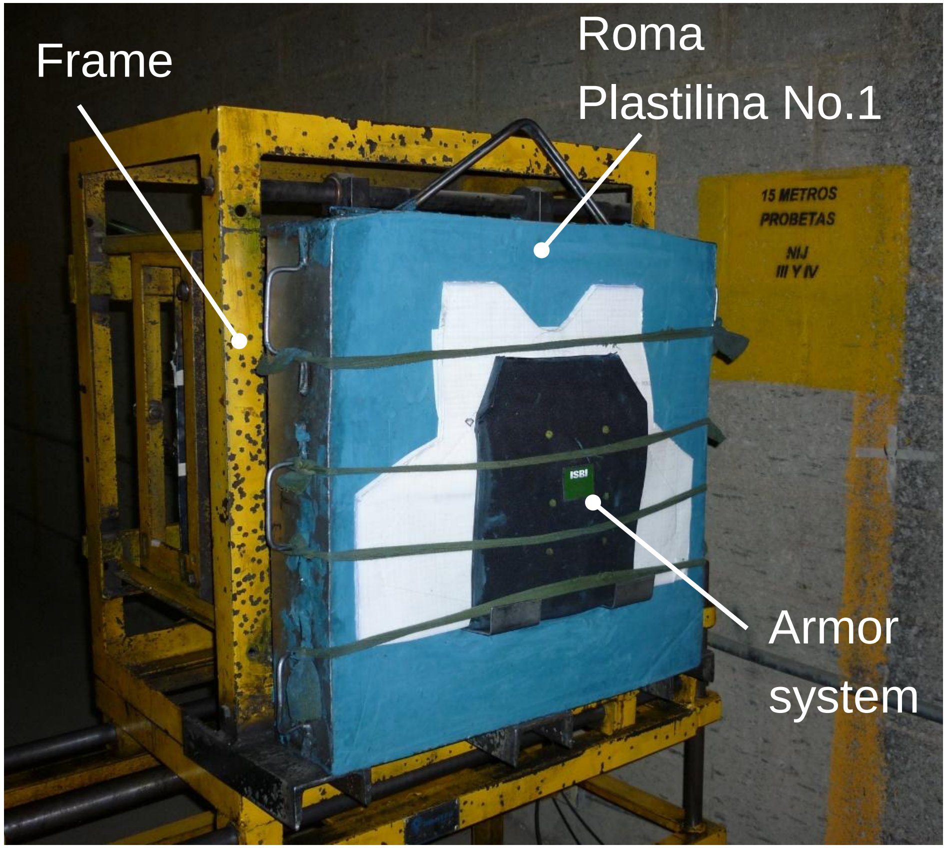

Fig.1. Configuration of the body-armor ballistic test.

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- High-velocity ballistic impact produces:
  - Dynamic deformation of involved materials
  - High strain-rates behavior
  - Plastic and shock waves
  - Final indentation on the Roma Plastilina No.1.

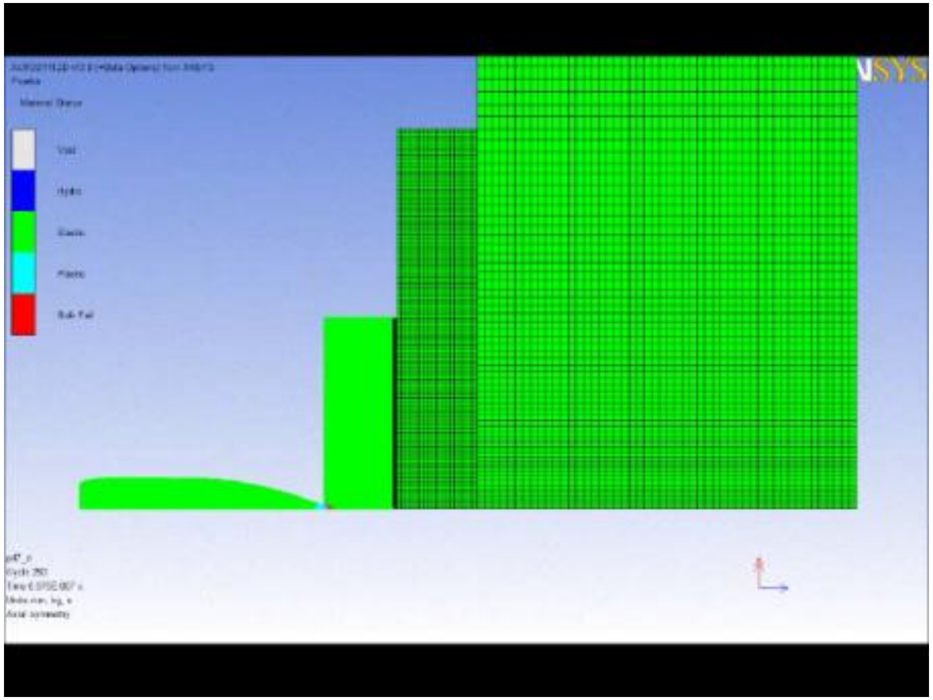

Fig.2. FE simulation of the body-armor ballistic test (Buchely, 2012).

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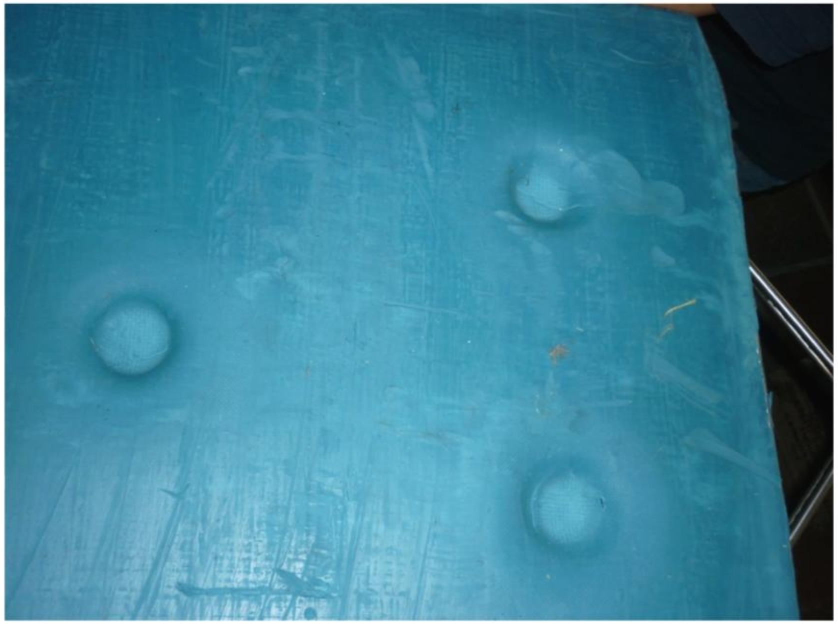

Fig.3. Results of body-armor ballistic test: (a) Armor system after test, and (b) Indentation on the Roma Plastilina No.1 after test.

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INTRODUCTION

Fig.4. Measurements of trauma in the Roma Plastilina.

- After the test, indentation on the RP is measured.
- According with NIJ 0101-06 Standard:
  - Maximum indentation depth on the RP after test must be less than 44mm.
- Performance of the personal armor system is related with the indentation on the RP

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- Real tests are time consuming and expensive
- FE models can be used previously to the test
- Dynamic mechanical properties of materials must be known
- Mechanical properties are adjusted to some constitutive models.
- There are not available and reliable models to use.

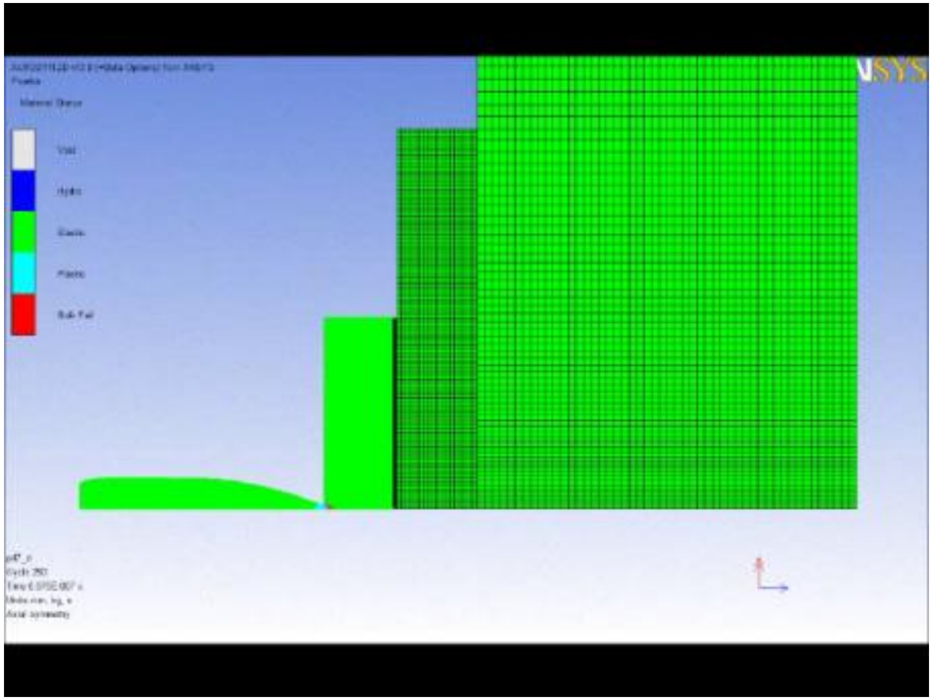

Fig.5. FE simulation of the body-armor ballistic test (Buchely, 2012).

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INTRODUCTION

- Roma Plastilina No.1 (RP)
  - Most researches have characterized RP using quasi-static compression test or ring expansion tests.
  - Plastic behavior or RP can be adjusted to the Cowper-Symonds constitutive model:

$$\sigma_e = Y_0\left(1+\left(\frac{\dot{\varepsilon}_{pl}}{D}\right)^{1/q}\right)$$

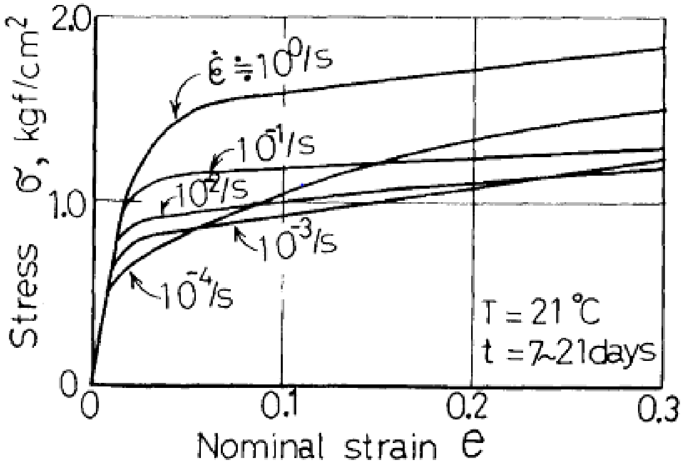

Fig. 6. Dependence of plasticine with strain-rate (Chijiiwa, 1981).

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- Given a sample of Roma Plastilina No.1, conditioned according to NIJ 0101-06 standard, calibrate its Cowper-Symmonds material parameters from Dynamic Indentation test.

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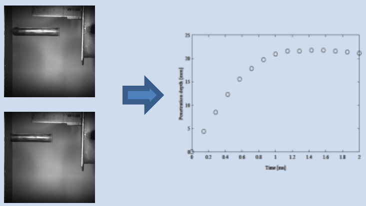
Methodology

Experimental

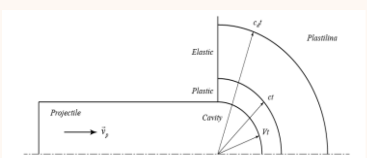
Engineering Model

FEA Model

- Dynamic Indentation test (DI)

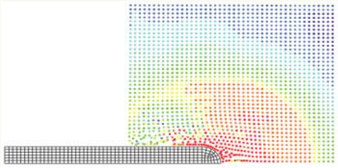


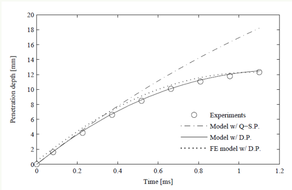
- Engineering penetration model
- Optimization process



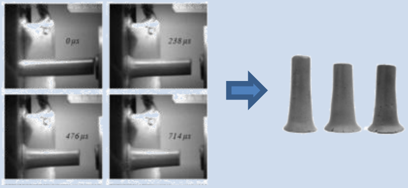
Verification

- FEA model of the DI Test and comparisons

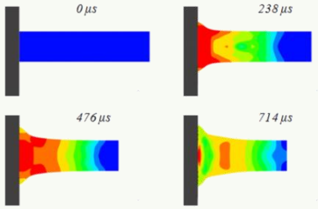




- Taylor test



- FEA model of the Taylor test



Characterization

Validation

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Results

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- **Results**
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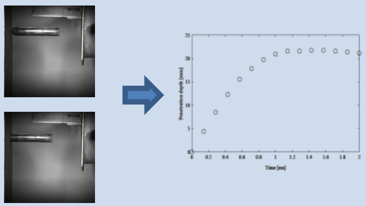
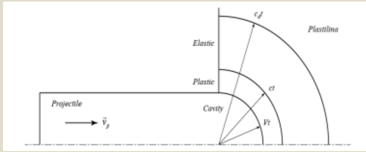


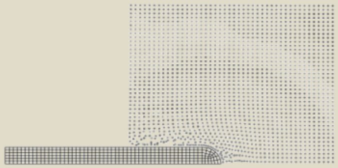
- Engineering penetration model
- Optimization process

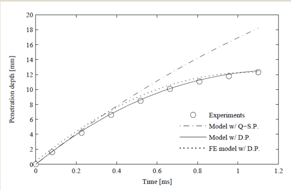


Characterization

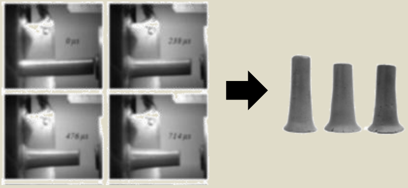
Verification

- FEA model of the DI Test and comparisons

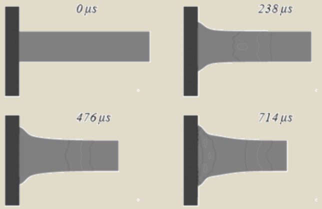




- Taylor test



- FEA model of the Taylor test



Validation

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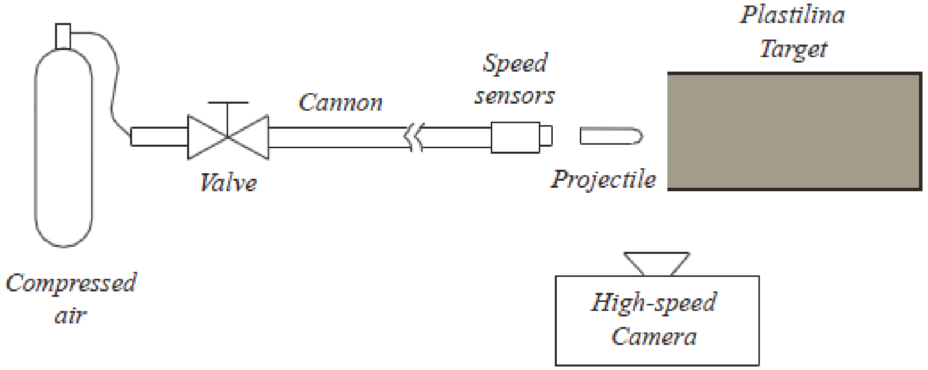
Results: Experimental, DI Test

- Based on: Tirupataiah, 1991.
- Compressed air cannon
  - Velocities range = 5 m/s to 160 m/s.
- Rigid projectile
  - Spherical Nose
  - Aluminum 6061-T4
  - Mass 6.61g
- High-speed camera
  - Range = 1000 fps to 10000 fps



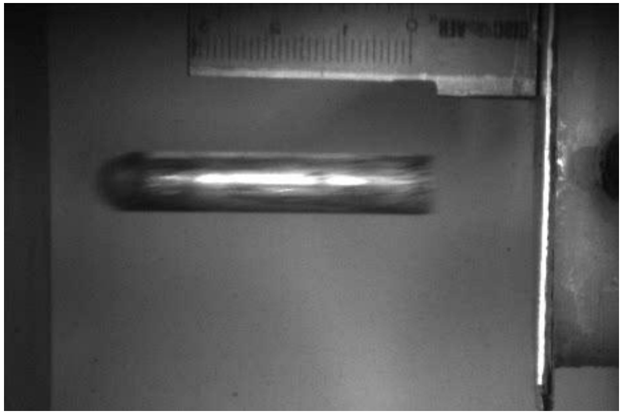


Fig. 8. Dynamical indentation test, and Sequence of a projectile impacting plasticine at 40.84 m/s. Images taken at 5468 fps.

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Results: Experimental, DI Test

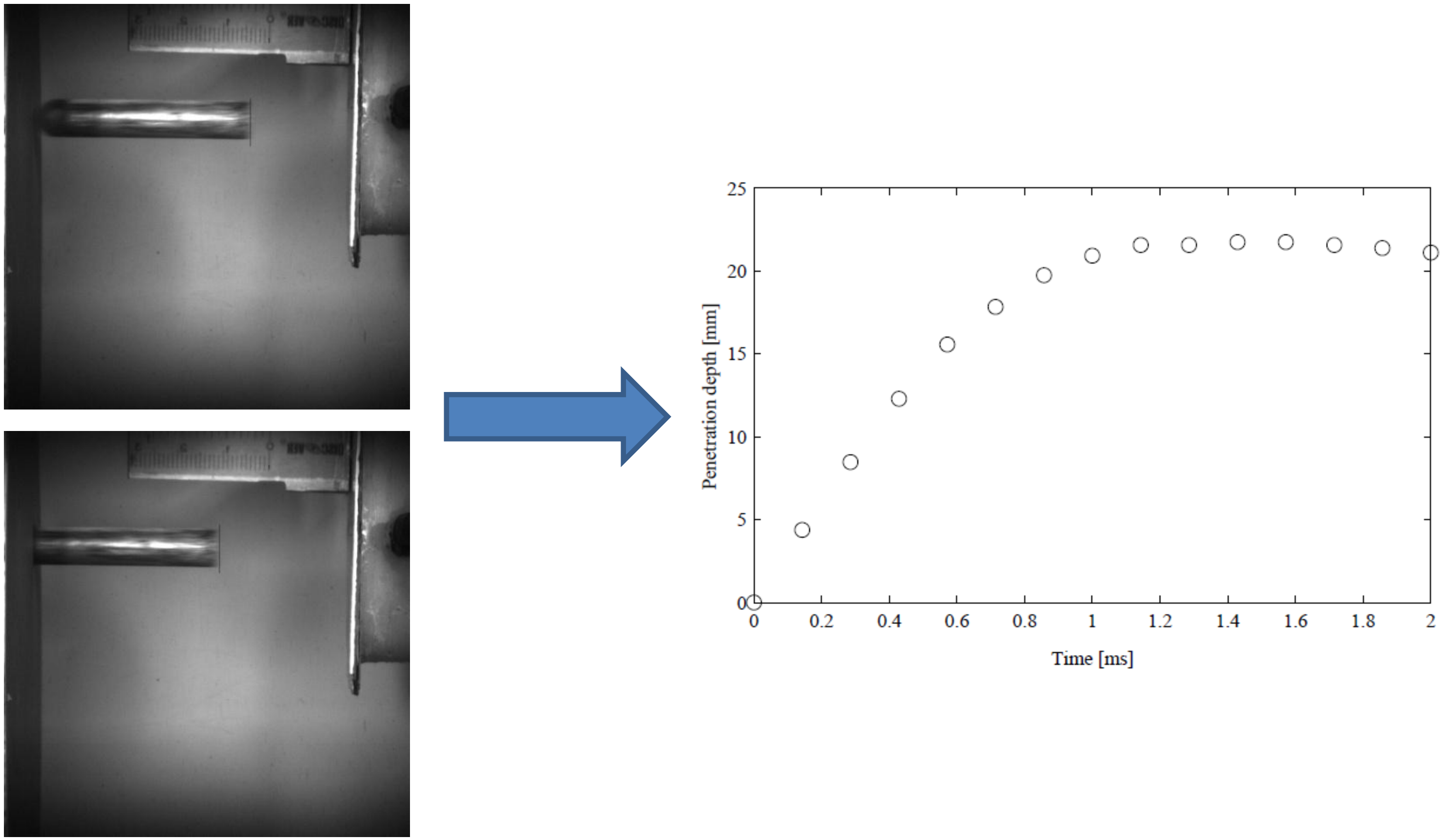

Fig. 9. Extraction of the projectile profile data from the DI test.

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Methodology

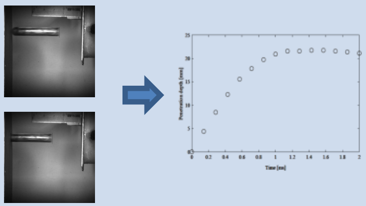
Experimental

Engineering Model

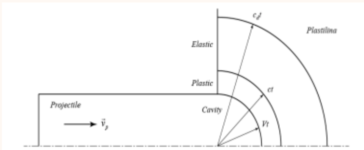
FEA Model

Characterization

- Dynamic Indentation test (DI)

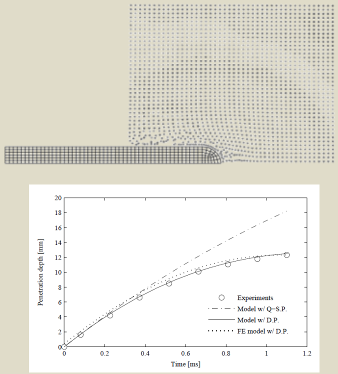


- Engineering penetration model
- Optimization process



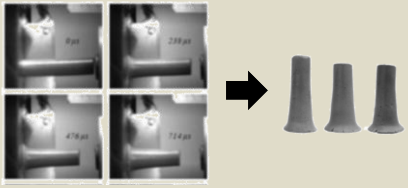
Verification

- FEA model of the DI Test and comparisons

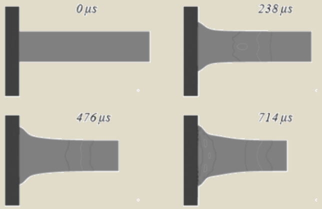


Validation

- Taylor test



- FEA model of the Taylor test



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Spherical Cavity-Expansion

- Uni-dimensional problem: depends on the sphere's radius

$$\frac{\partial \upsilon}{\partial r}+\frac{2\upsilon}{r}=0 \qquad \text{and} \qquad \frac{\partial \sigma_r}{\partial r}+\frac{2(\sigma_r-\sigma_\theta)}{r}=-\rho\left(\frac{\partial \upsilon}{\partial t}+\upsilon\frac{\partial \upsilon}{\partial r}\right)$$

- Elastic region
  - Elastic flow using J2 Mises solid assumptions

- Elasto-plastic Region
  - Cowper-Symonds constitutive model

$$\sigma_e=Y_0\left(1+\left(\frac{\dot{\varepsilon}_{pl}}{D}\right)^{1/q}\right)$$

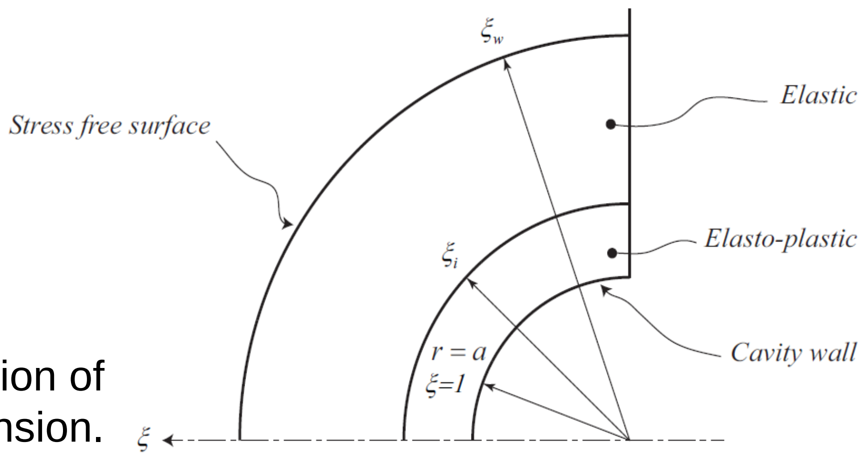

Fig. 11. Schematic representation of material field in spherical cavity expansion.

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Engineering penetration model (Buchely, 2014).

Deceleration Eqs. $$m_p \frac{dV_p}{dt} = m_p \frac{d^2 x_p}{dt^2} = -F_x; \quad \text{where} \quad F_x = 2\pi \int_0^{x_p} P_c \left((a-x) + \mu \sqrt{a^2 - (a-x)^2} \right) dx.$$

Conservation Eqs. $$\frac{\partial \upsilon}{\partial r} + \frac{2\upsilon}{r} = 0, \quad \text{and} \quad \frac{\partial \sigma_r}{\partial r} + \frac{2(\sigma_r - \sigma_\theta)}{r} = -\rho \left(\frac{\partial \upsilon}{\partial t} + \upsilon \frac{\partial \upsilon}{\partial r} \right).$$

Compatibility Eqs. $$\dot{\varepsilon}_r = \frac{\dot{\sigma}_r}{E} - \frac{2\nu \dot{\sigma}_\theta}{E} - \dot{\varepsilon}_{pl} = \frac{d\upsilon}{dr}, \quad \text{and} \quad \dot{\varepsilon}_\theta = -\frac{\nu \dot{\sigma}_r}{E} + \frac{(1-\nu)\dot{\sigma}_\theta}{E} + \frac{\dot{\varepsilon}_{pl}}{2} = \frac{\upsilon}{r}.$$

J2 Mises Solid Eq. $$\sigma_e = \sigma_\theta - \sigma_r \ .$$

Constitutive Eq. $$\sigma_e = Y_0 \left(1 + \left(\frac{\dot{\varepsilon}_{pl}}{D} \right)^{1/q} \right)$$

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Results: Engineering model

- Penetration depth by engineering model:

$$x_p^c = \mathrm{f}\left(a, m_p, \rho, E, Y_0, D, q, \mu, V_p\right)$$

  - Geometrical parameters: a, m_p
  - Material parameters: ρ, E, Y_0, D, q
  - Experimental parameters: μ, V_p

- Optimization model

$$\min \left\| x_p{}^e - x_p{}^c \right\|$$

- $x_p{}^e$: Experimental penetration depth
- $x_p{}^c$: calculated penetration depth

- Optimization tool: Matlab - Simulink

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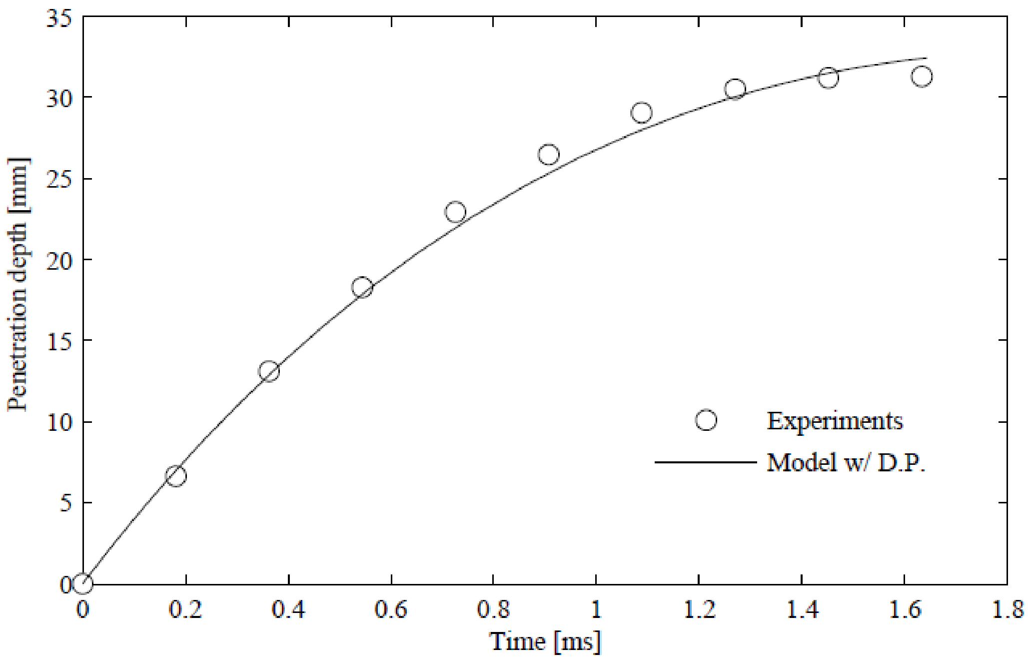
Results: Engineering model



	E [MPa]	Y_0 [MPa]	D [s^{-1}]	q[-]
DP	16.45	0.197	0.2084	13.231

Fig. 12. Parameter calibration of the RP using DI data, Engineering model and Optimization method (Buchely, 2015).

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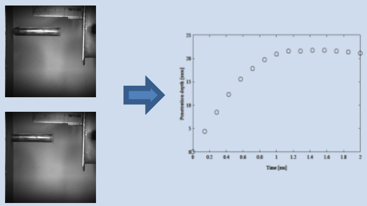
Methodology

Experimental

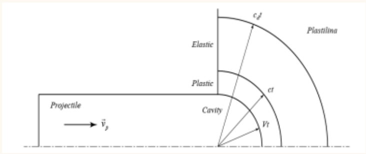
Engineering Model

FEA Model

- Dynamic Indentation test (DI)



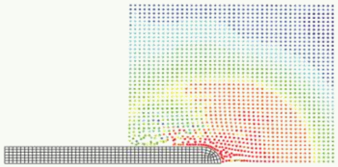
- Engineering penetration model
- Optimization process

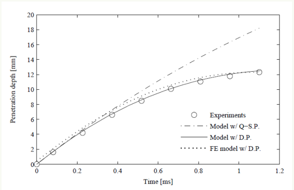


Characterization

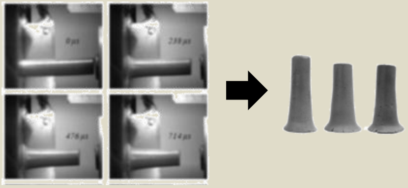
Verification

- FEA model of the DI Test and comparisons

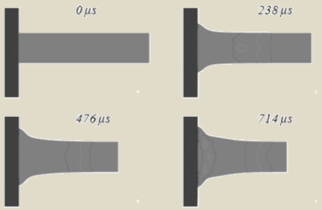




- Taylor test



- FEA model of the Taylor test



Validation

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Results: FEA model

- FEA model
  - ANSYS/AUTODYN v.14
  - Axial symmetry
  - Aluminum
    - Linear – Elastic
  - Plasticine
    - SPH solver
    - Cowper-Symonds constitutive equation

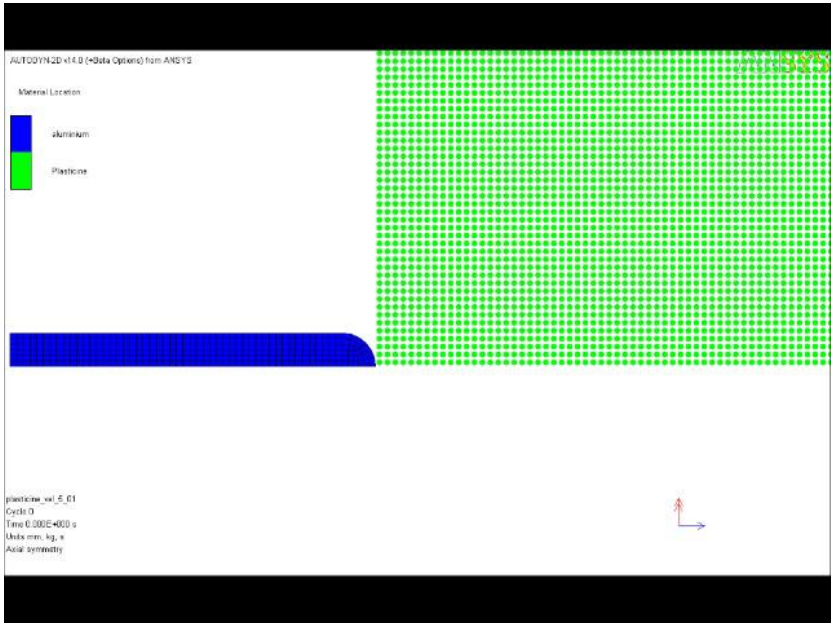

Fig. 11. FEA model of the DI test in ANSYS/UTODYN.

Sequence of the projectile impacting the RP. Color scale represents Von-Mises stress (MPa) into the clay. Projectile at 40.84 m/s.

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Results: Comparisons

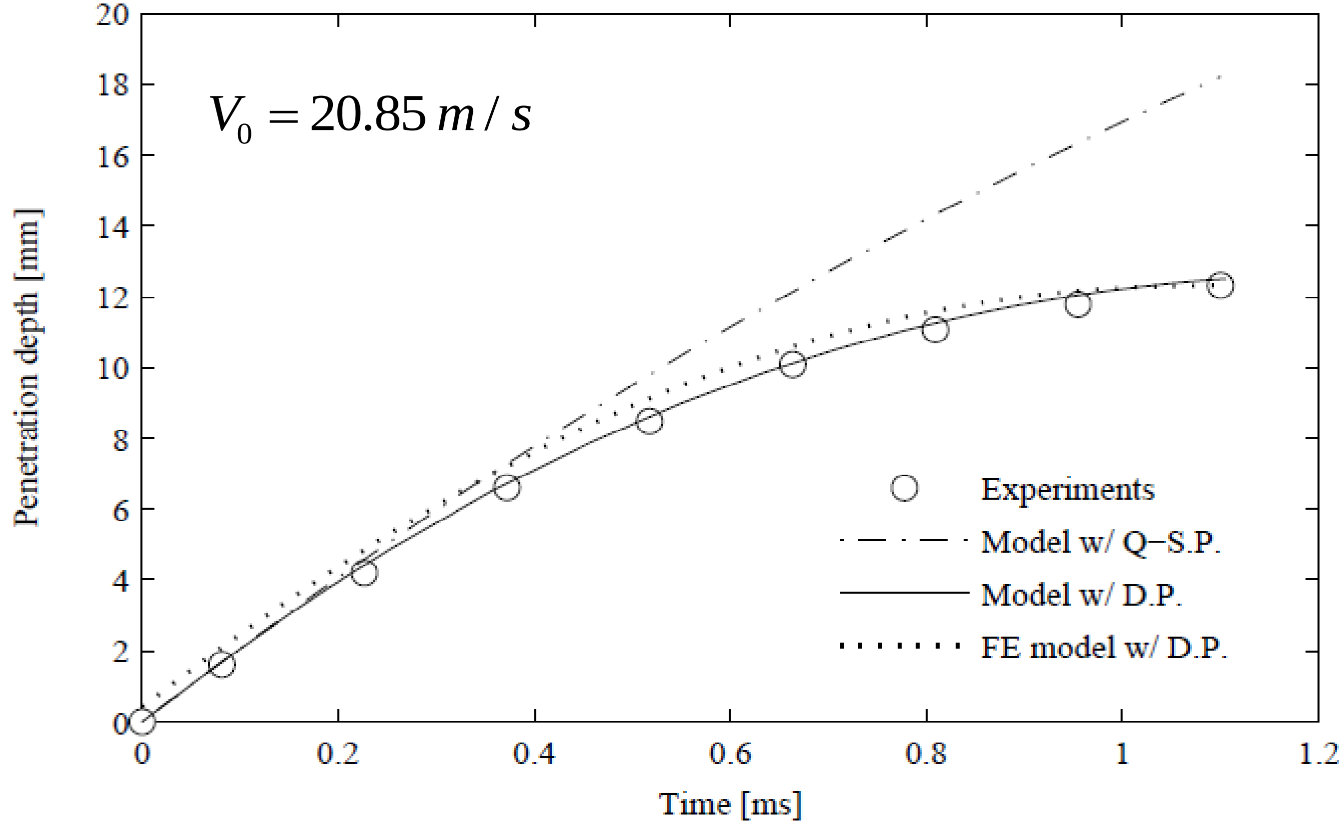

Fig. 13. Comparison among Experimental data, Engineering model and FEA model at different initial velocities of the projectile (Buchely, 2014).

Results: Comparisons

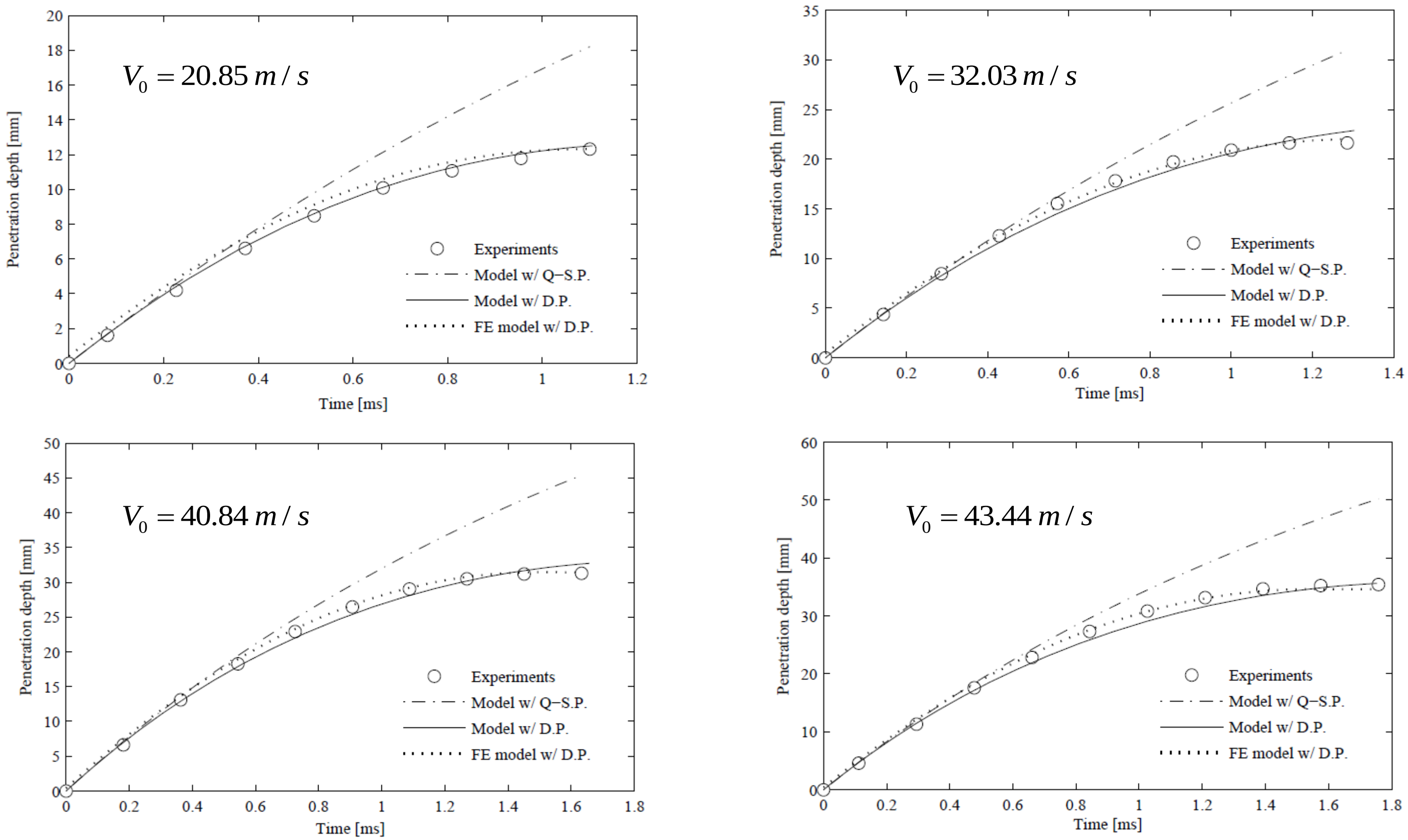

Fig. 13. Comparison among Experimental data, Engineering model and FEA model at different initial velocities of the projectile (Buchely, 2014).

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Methodology

Verification

Experimental

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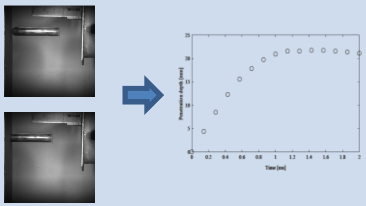
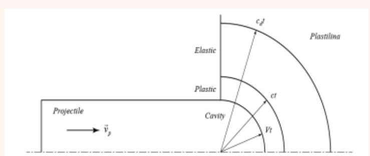


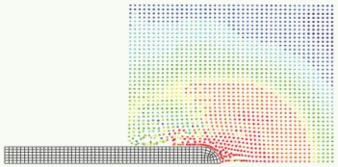
Engineering Model

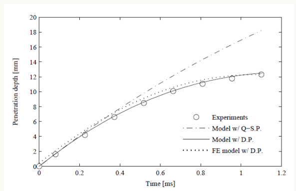
- Engineering penetration model
- Optimization process



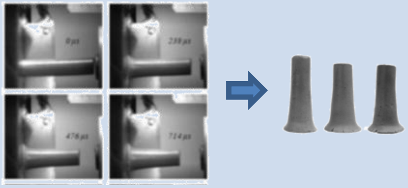
FEA Model

- FEA model of the DI Test and comparisons

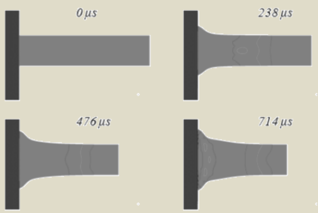




- Taylor test



- FEA model of the Taylor test



Characterization

Validation

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Results: Taylor test

- Based on: Taylor, 1949.
- Taylor specimen
  - Cylindrical shape
  - Blunt Nose
  - Mass 6.61g
- Rigid Surface
  - High-strength steel
- High-speed camera
  - Range = 10000 fps to 20000 fps

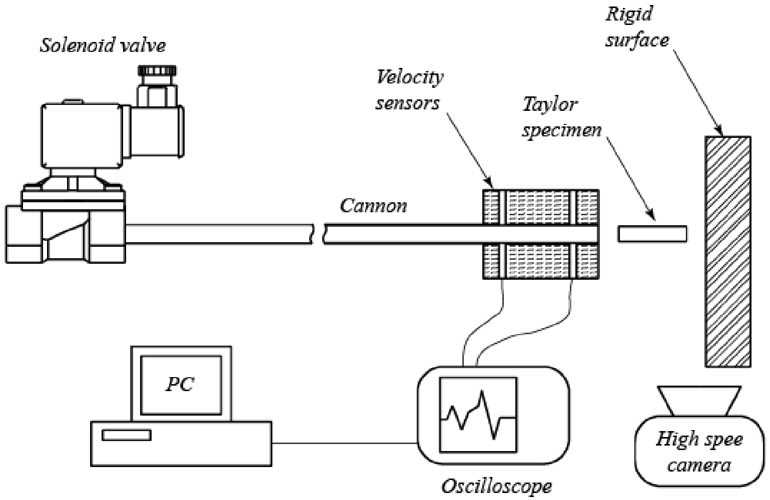


Fig. 14. Taylor Test set-up.

Results: Taylor test

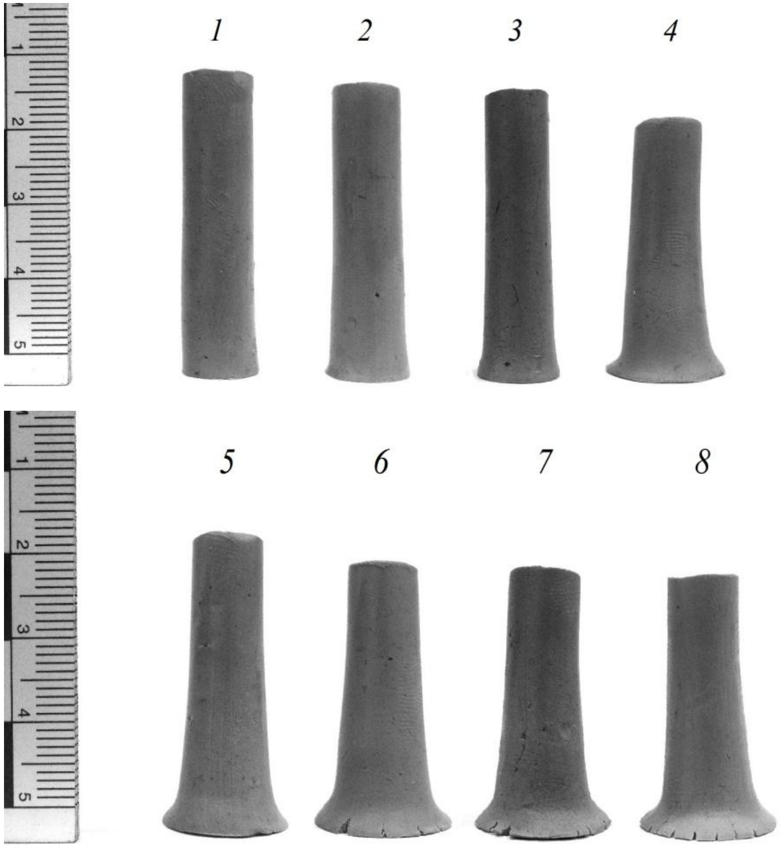
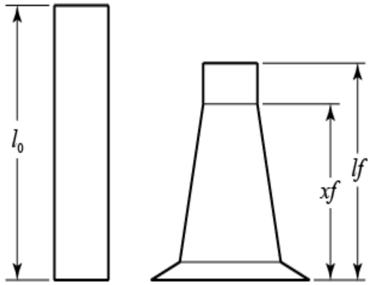


Fig. 15. Taylor test results



$$\dot{\varepsilon}_{prom} = \frac{1}{2}\frac{V_0}{lf - xf}$$

Fig. 16. Scheme of Taylor specimen, and final dimensions (Taylor, 1949).

Table 1. Taylor test results

Specimen No.	V_0 [m/s]	lf_{exp} [mm]	xf_{exp} [mm]	$\dot{\varepsilon}_{prom}$ [s^{-1}]
1	7.30	43.77	10.20	108.72
2	10.70	42.42	20.40	243.05
3	14.00	40.67	24.10	422.45
4	17.65	37.26	31.00	1409.51
5	18.73	36.63	31.20	1725.00
6	19.87	34.23	31.40	3510.16
7	21.58	33.04	31.70	8053.25
8	24.39	31.05	29.80	9756.08

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Methodology

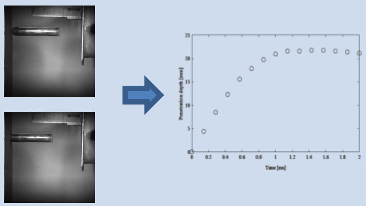
Experimental

Engineering Model

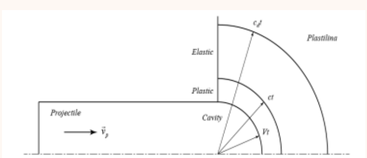
FEA Model

Characterization

- Dynamic Indentation test (DI)

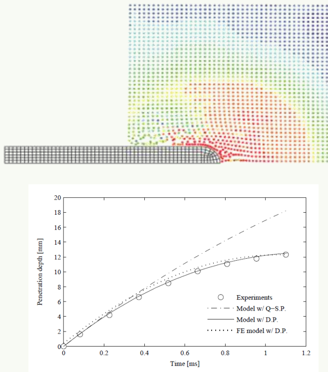


- Engineering penetration model
- Optimization process



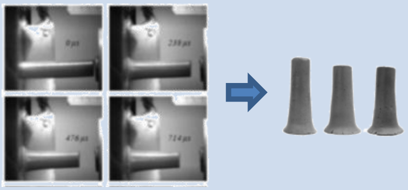
Verification

- FEA model of the DI Test and comparisons

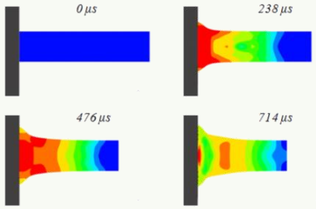


Validation

- Taylor test



- FEA model of the Taylor test



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Results: FEA simulation and Comparisons

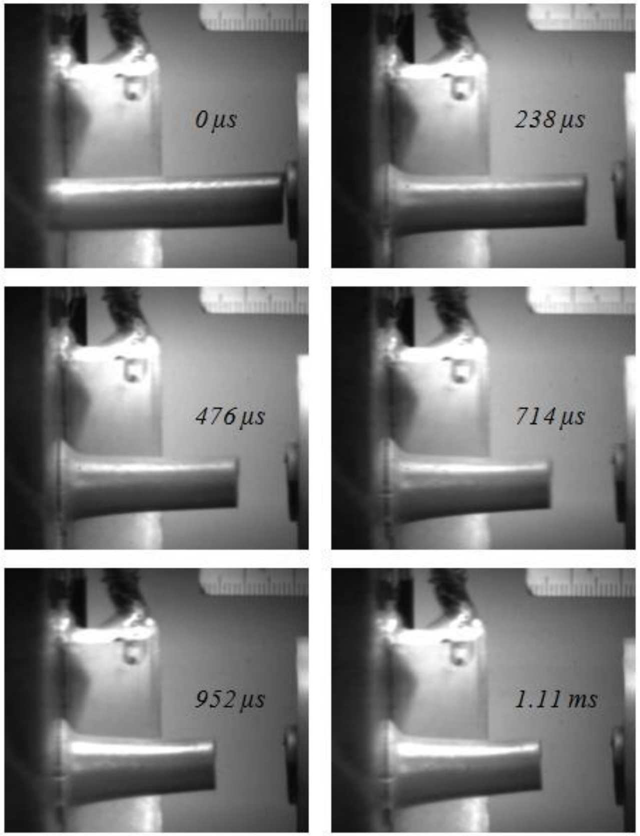

Fig. 12. Sequence of the Taylor test, captured at 12608 fps.

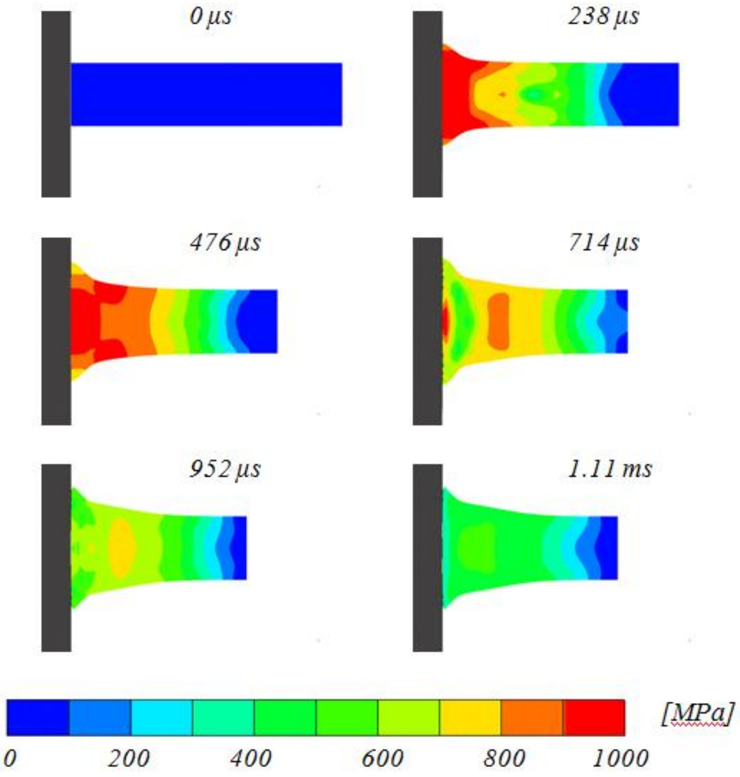

Fig. 13. Sequence of the Taylor test simulation, using AUTODYN.

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Results: FEA simulation and Comparisons

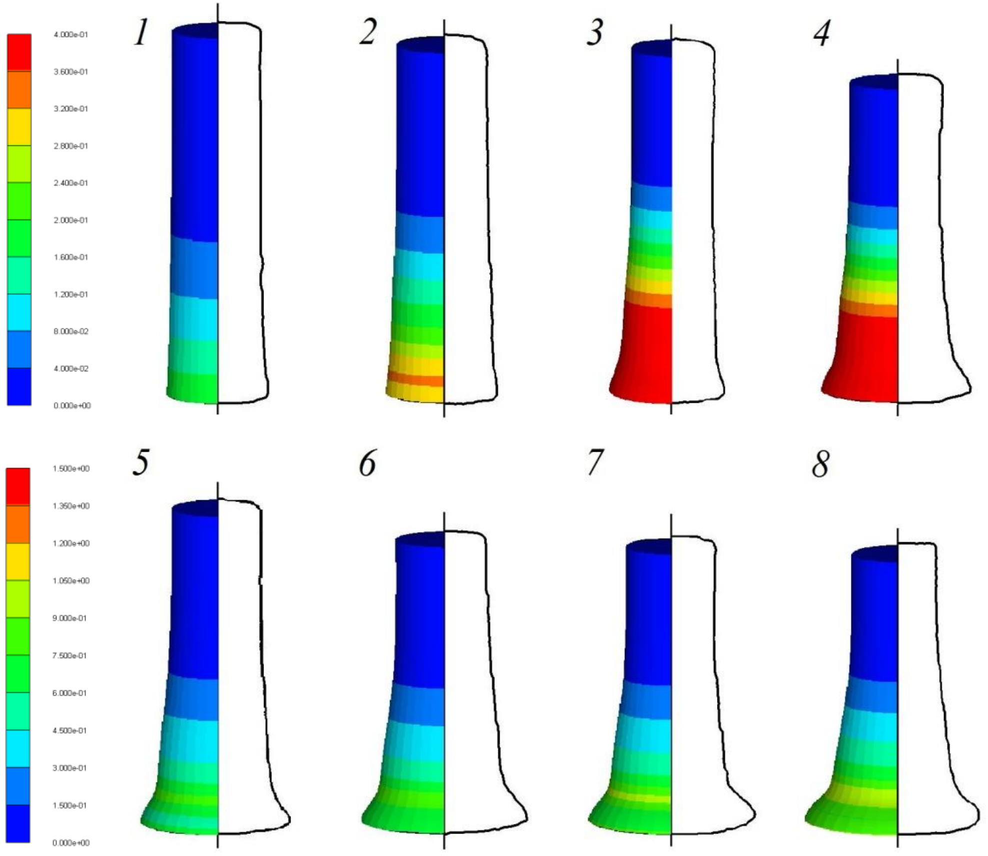

Fig 15. Comparison between experimental Taylor tests (right) and FEA results (left).

Table 2. Comparison between experimental Taylor tests and FEA results.

Specimen No.	lf_{exp} [mm]	lf_{sim} [mm]	%dif [%]
1	43.77	43.21	1,28
2	42.42	41.75	1,58
3	40.67	40.02	1,16
4	37.26	36.57	1,85
5	36.63	35.95	1,86
6	34.23	34.18	0,15
7	33.04	32.46	1,76
8	31.05	30.45	1,93

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OUTLINE

- Introduction
- Problem statement
- Methodology
- Results
- Conclusions

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CONCLUSIONS

- Cowper-Symonds parameters of Roma Plastilina No.1 were calibrating using Dynamic Indentation test.
- Dynamic parameters were validated using and independent test: Taylor test.

Potential work

- Same methodology can be used to find mechanical properties at high strain rates of soft materials.
- Other constitutive model parameters could be calibrated.

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THANK YOU!!!

QUESTIONS???

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