UNIVERZITET U ZENICI

Mašinski fakultet

katedra za Automatizaciju i Metrologiju

PART II:

Testing polymeric materials and products

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TESTING PRODUCT CHARACTERISTICS

About polymeric materials and products

Large organic molecule formed by combining many smaller molecules (monomers) in a regular pattern

Thermoplastic resins - when heated during processing, soften and flow as viscous liquids; when cooled, they solidify. The heating/cooling cycle can be repeated many times with little loss in properties.

Thermosetting resins - liquefy when heated and solidify with continued heating; the polymer undergoes permanent cross-linking and retains its shape during subsequent cooling/heating cycles.

About polymeric materials and products

Major benefits:

- Low production and maintenance costs
- Low weight (=easy transport)
- Very good hydraulic characteristics
- Chemicaly resistant (=do not corrode)
- Relatively small modulus of elasticity (=flexibility) with high ductility (deformations up to 20% without loss of bearing capacity)

Properties and Standard Methods of Measurements[1)]

Property	ASTM method	ISO method
Physical properties		
Density, g/mL	D792	1183
Flammability	UL94[e]	
Oxygen index (LOI), %	D2863	4589
Refractive index	D542	489
Yellowness index (YI)	D1925	
Water absorption (24 h, 23°C)		
Electrical properties		
Dielectric constant (1 MHz)	D150	
Dielectric strength (1 mm), kV/mm	D149	
Dissipation factor (1 kHz)	D150	
Volume resistivity (23°C, dry), Ω·cm	D150	

[1)] Encyclopedia of Polymer Science and Technology

Thermal properties		
Glass-transition temperature (T_g), °C		
Melting temperature (T_m), °C		
Heat-deflection temperature (HDT) at 0.45 or 1.8 MPa, °C	D648	75
Specific heat capacity J/(kg·K)		
Thermal conductivity (23°C), W/(m·K)	C177	
Thermal expansion coefficient, K^{-1}	D696	
Upper working temperature, °C		
Mechanical properties		
Elastic modulus, GPa[b]	D638	527
Tensile strength, MPa[c]	D638	527
Flexural modulus, GPa[b]	D790	178
Flexural strength, MPa[c]	D790	178
Compressive strength, MPa[c]	D638	527
Elongation at break, %	D638	527
Notched Izod impact resistance (3.2 mm), J/m[d]	D256	180
Hardness (Rockwell M or R)	D785	2039
Friction coefficient	D1894	8295
Rheological properties		
Intrinsic viscosity, Pa·s		
Melt-flow index, g/10 min	D1238	1133

NDT methods - classes[1)]

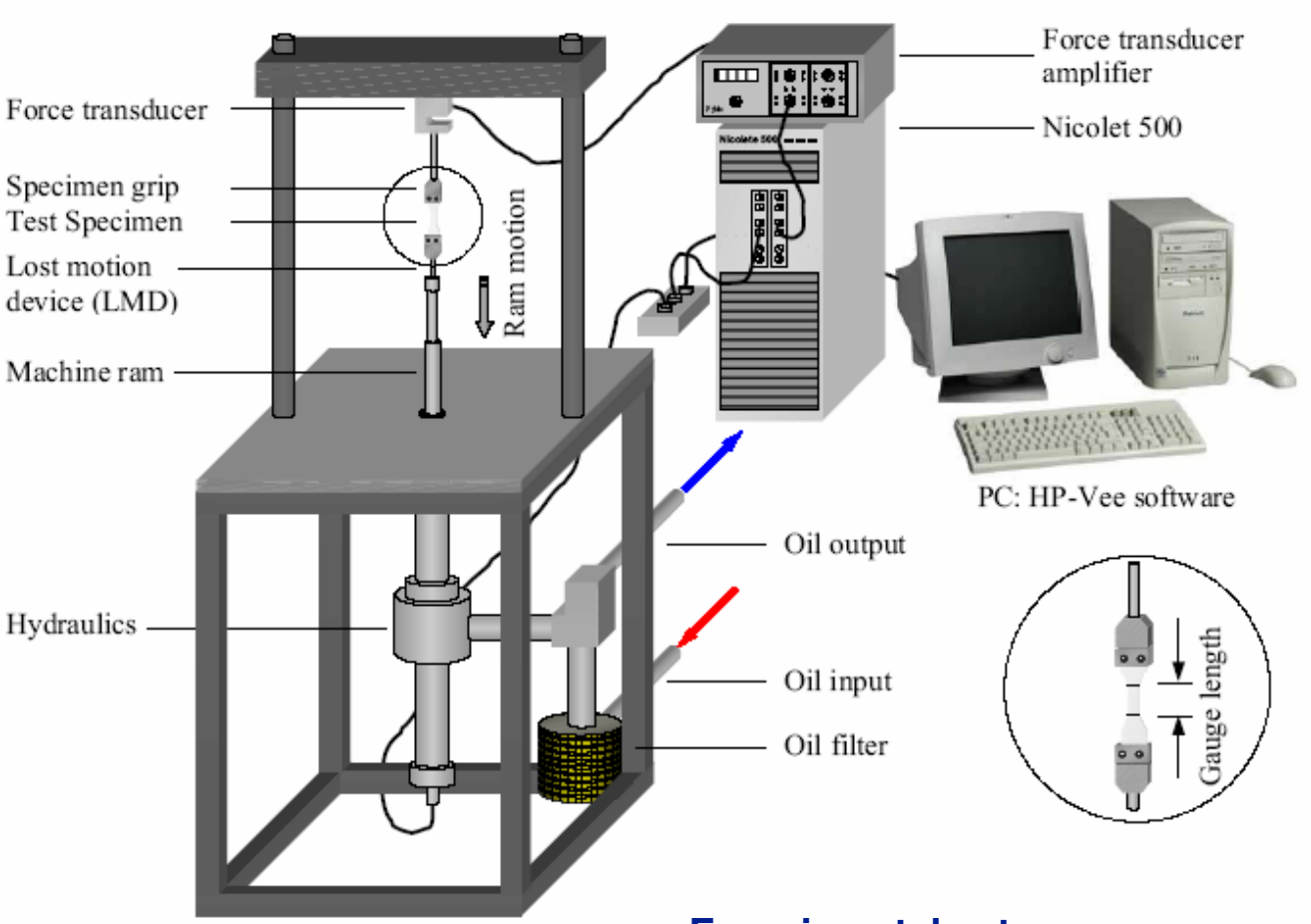
Class	Methods (examples)	Remarks
Mechanical	E-modulus measurement Vibration analysis Modal analysis Scanning probe microscopy	Mostly indirect indications of defects
Optical	Visual inspection Optical microscopy Brillouin scattering Photoelasticity Projection moiré Shearography Optical holography	Using visible part of electromagnetic spectrum (wavelength roughly between 400 and 700 nm)
Penetrating radiation	X-ray radiography X-ray tomography γ-ray radiography Neutron radiography Neutron scattering Electron microscopy	Electromagnetic (wavelengths below about 1 nm) and particle radiation

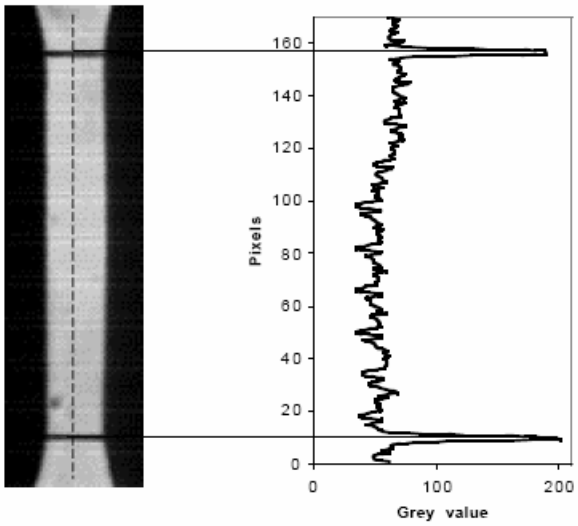
Electromagnetic	Dielectric spectroscopy Resistance measurement Eddy-current testing	X-ray and γ-ray classified among penetrating radiation
Sonic/ultrasonic	Tap testing Acoustic emission Acousto-ultrasonics Ultrasonics Acoustic microscopy	
Thermal/infrared	Thermography	Infrared spectrometry is classified among chemical/analytical
Chemical/analytical	Infrared spectrometry Raman spectrometry Ultraviolet spectrometry X-ray spectrometry Magnetic resonance imaging	

Mechanical testing

- Tensile tests (steady-state, high strain-rate, …)
- Compression tests
- Impact tests (impact resistance)
- ……..
- ……..

Mechanical testing

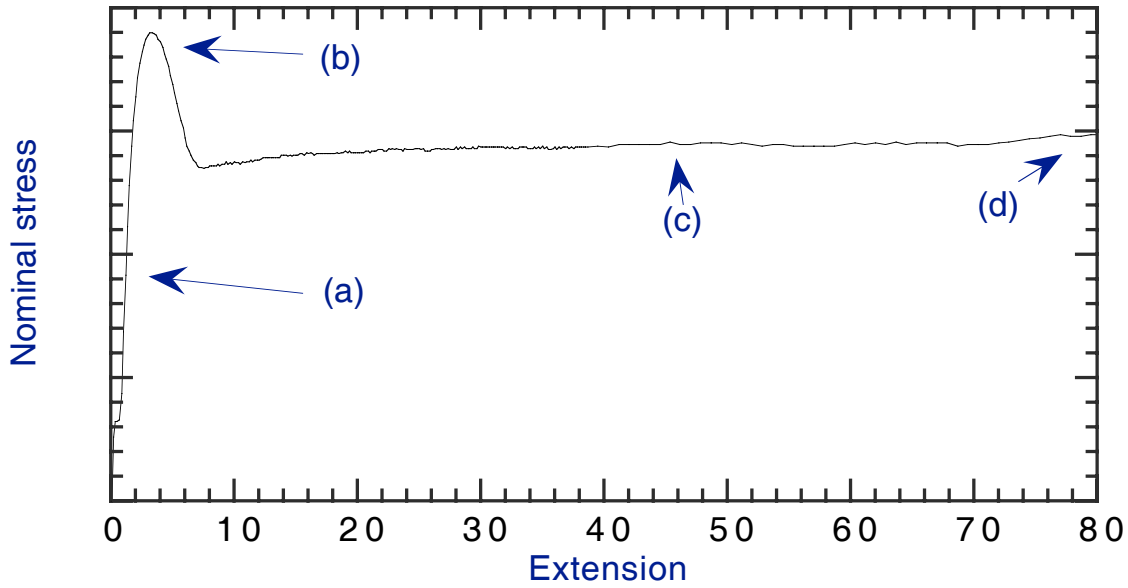


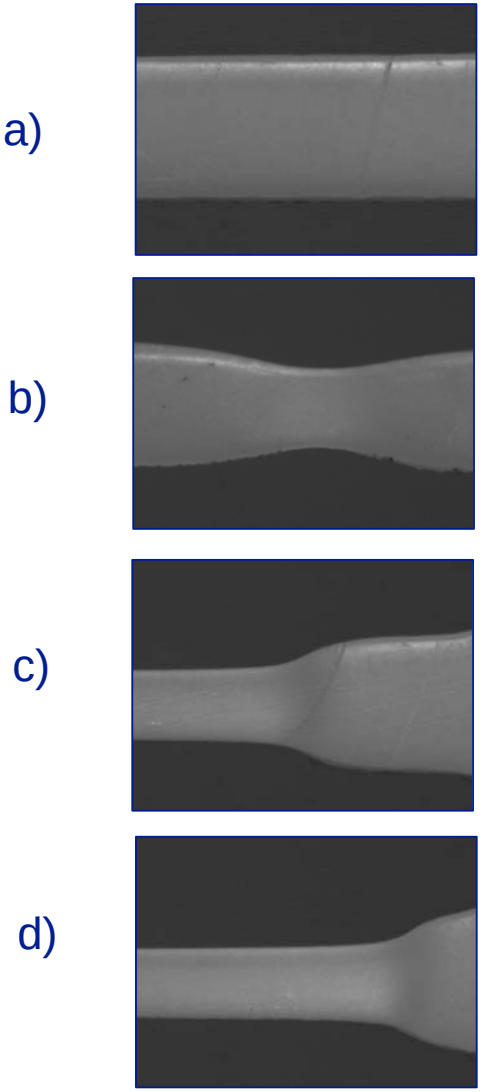


Experiemntal set-up

Mechanical testing

Tensile tests[2)]



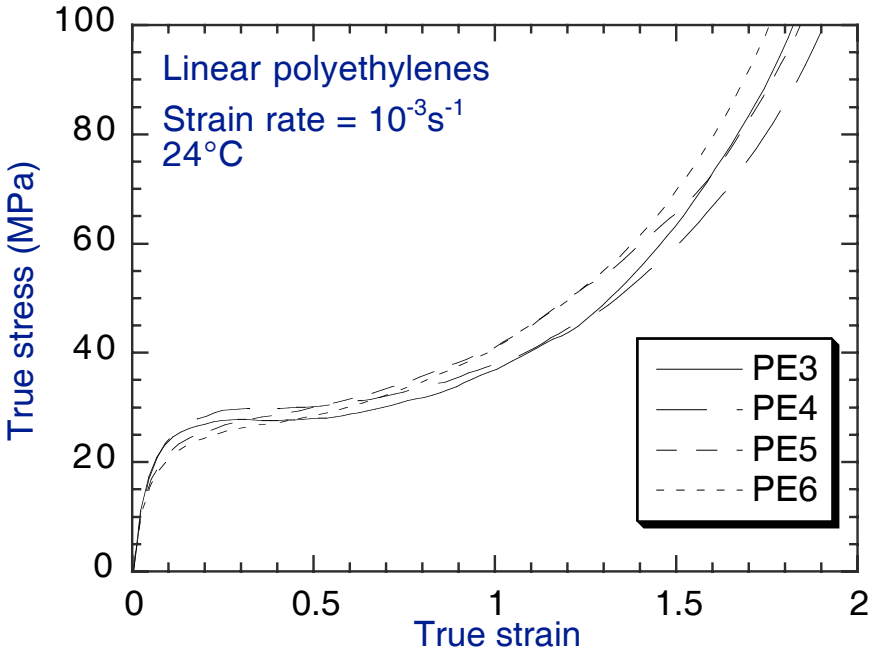


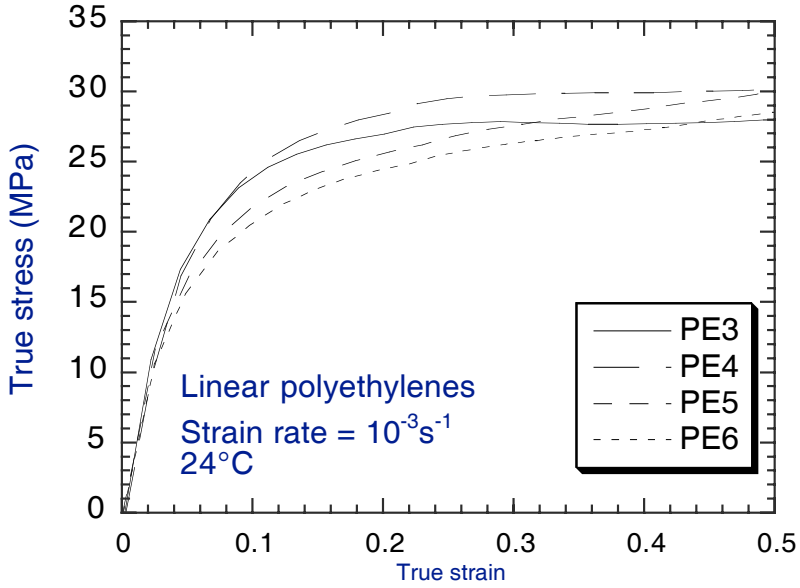
Engineering curve

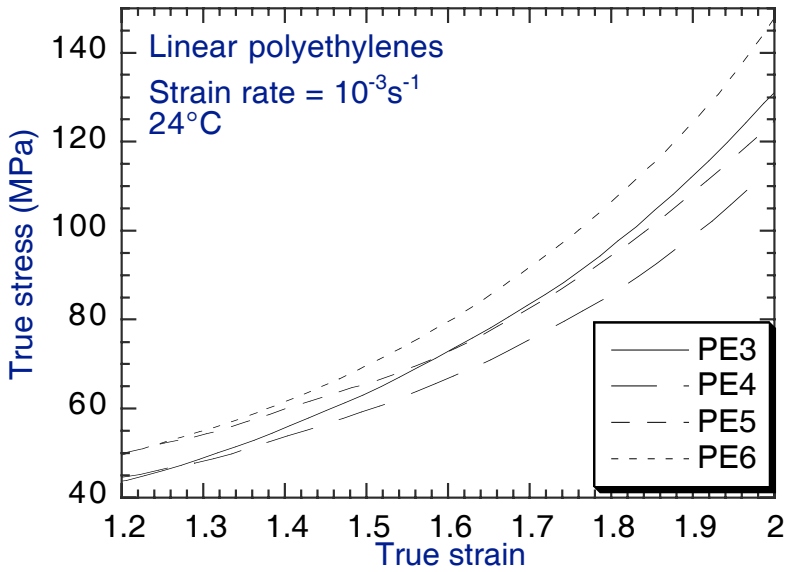
[2)]Hillmansen S., Large strain bulk deformation and brittle-tough transitions in polyethylene, PhD, 2001

Mechanical testing

Tensile tests[2)]



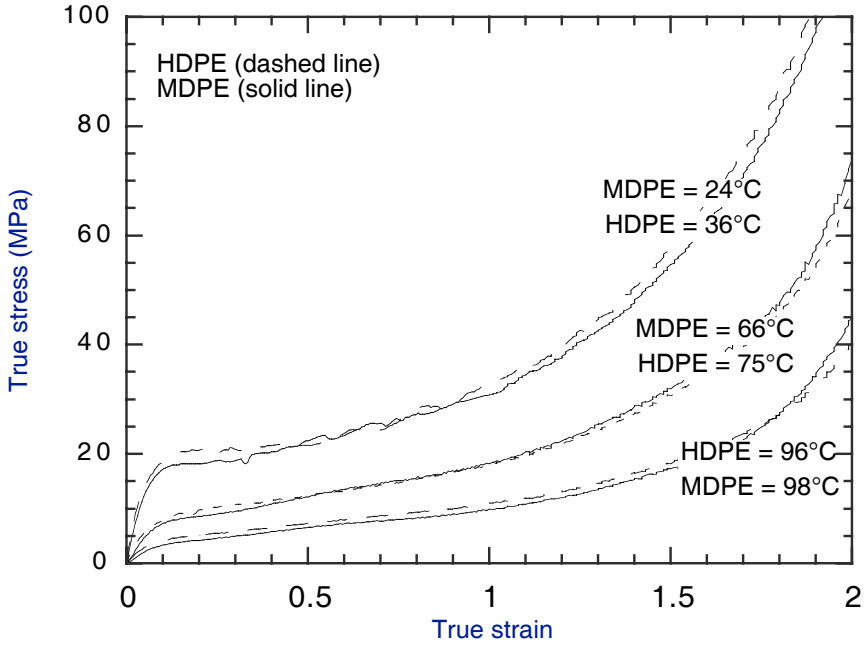


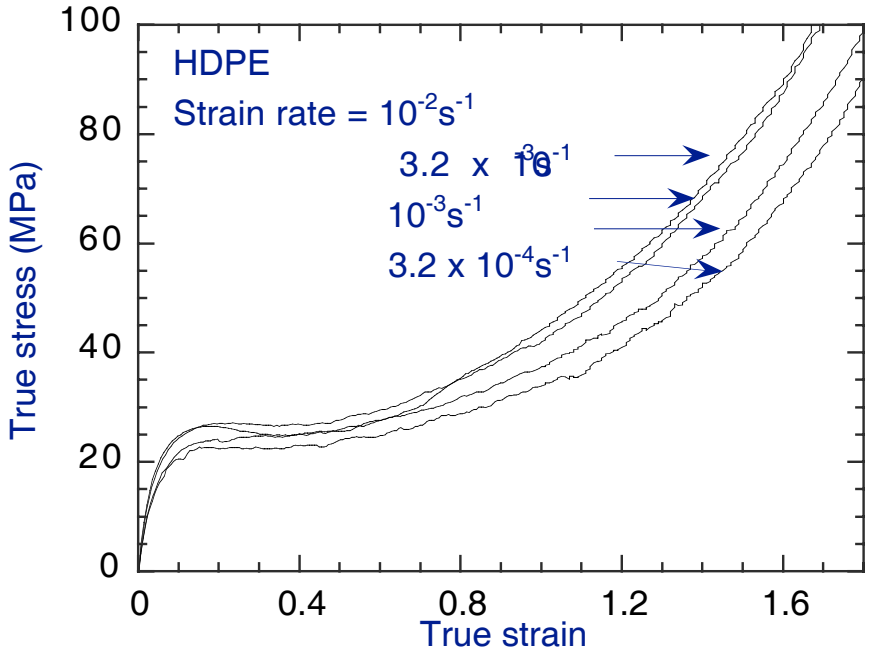


True-stress-true strain curve

Mechanical testing

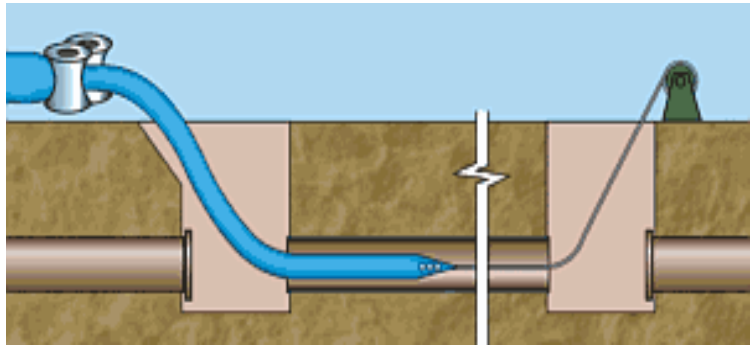
Tensile tests[2)]



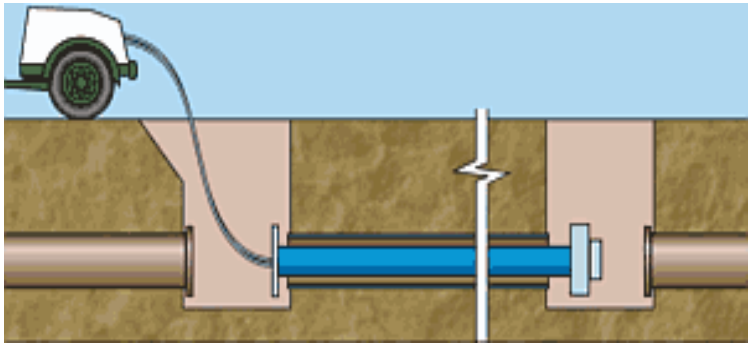


Temperature and stran-rate effects

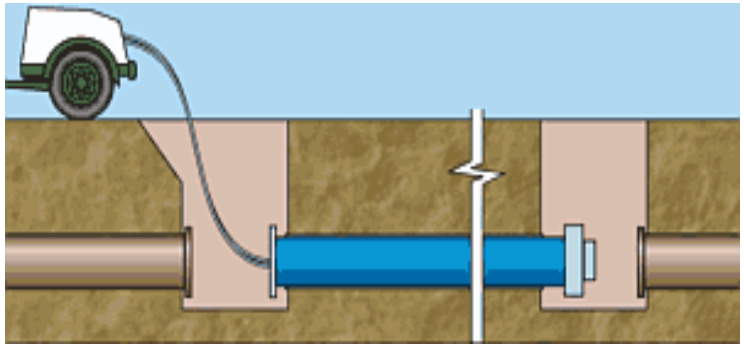
Roll-down process



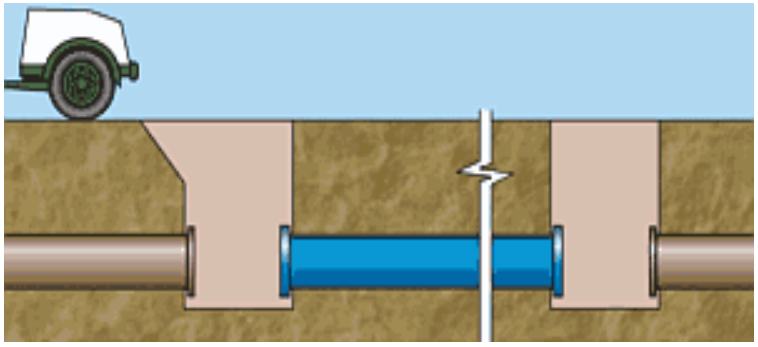
(a)



(b)



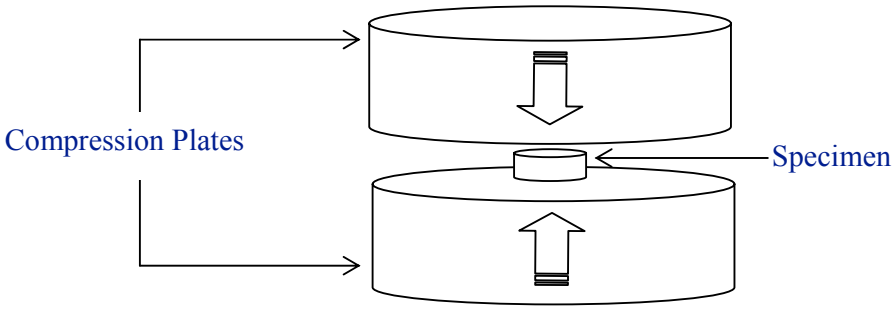
(c)

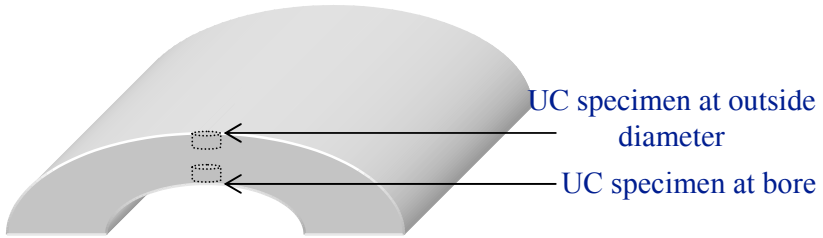


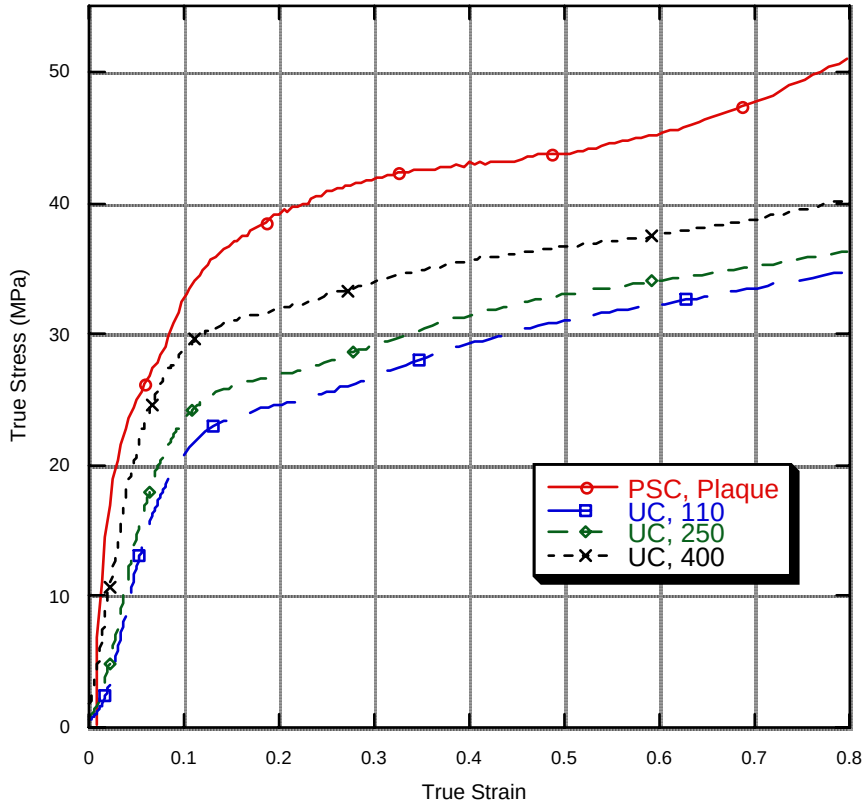
(d)

Mechanical testing

(Uniaxial) compression tests[3)]



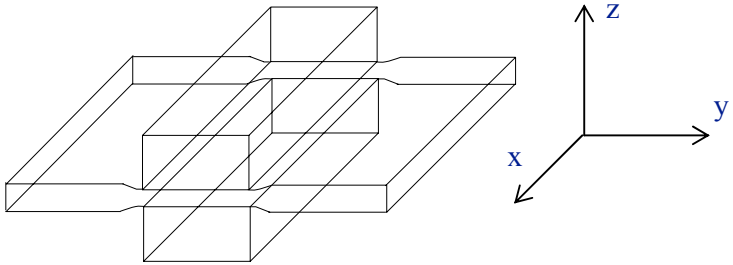




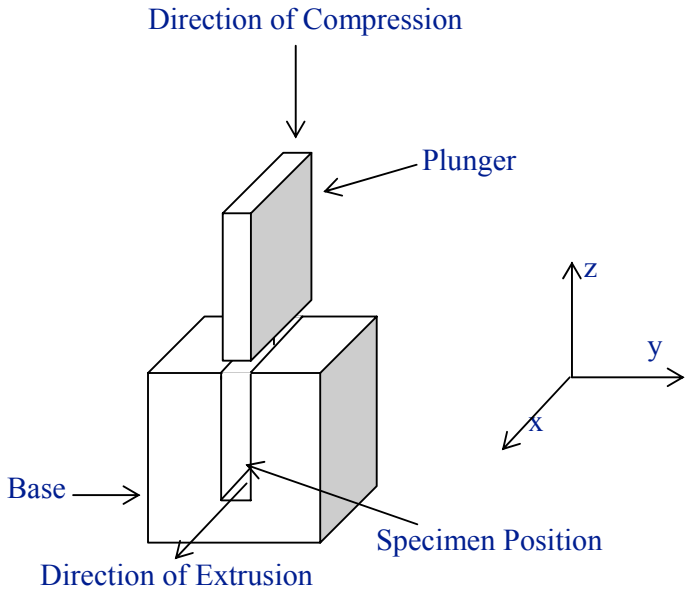
[3)] Paizis A., Orientation and Strain Cycle Effects on the RCP Resistance of Polyethylene Resins, PhD, 2003

Mechanical testing

Plain-strain compression tests[3)]



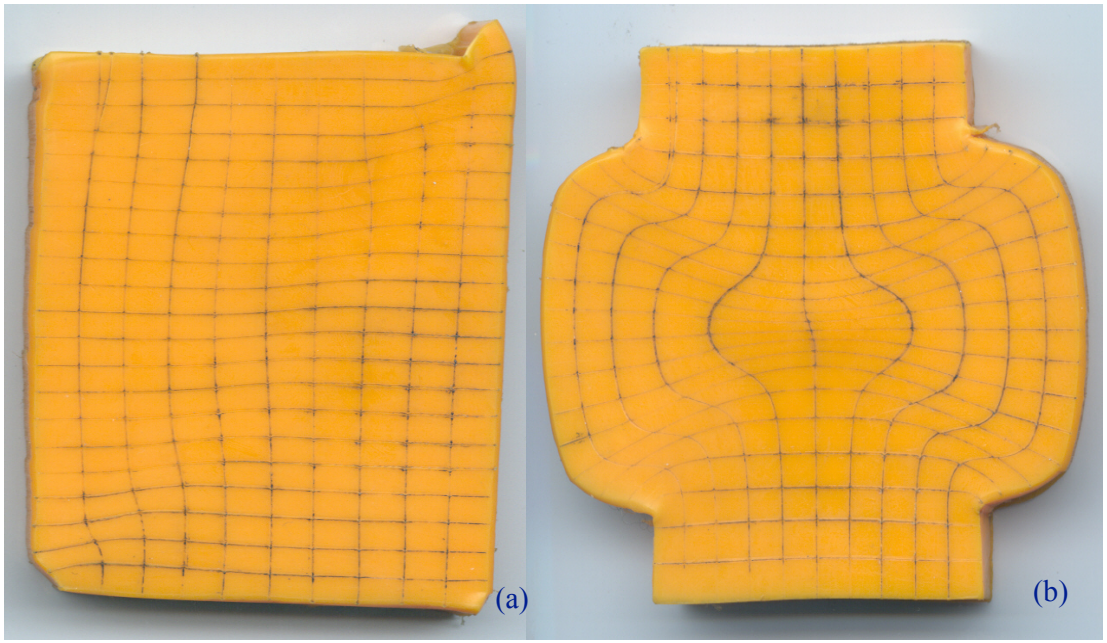
Plane strain compression rig employed by Williams

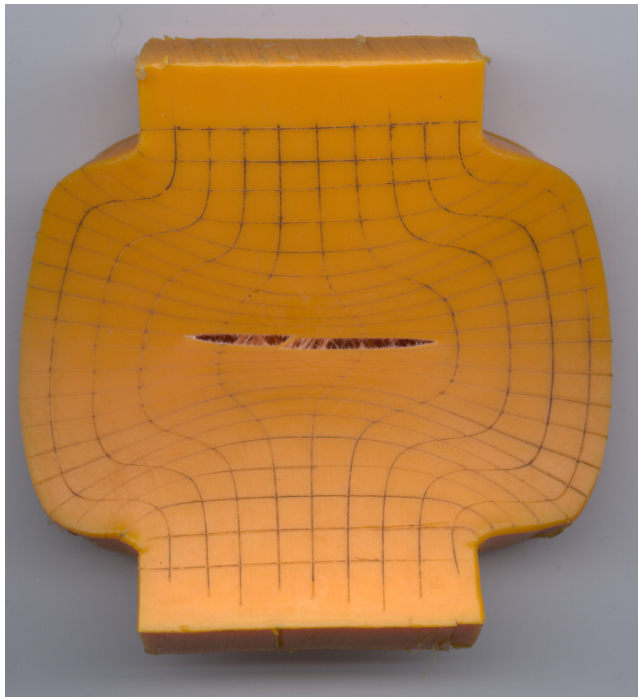


Experimental set-up of the channel die (plane strain) compression rig

Mechanical testing

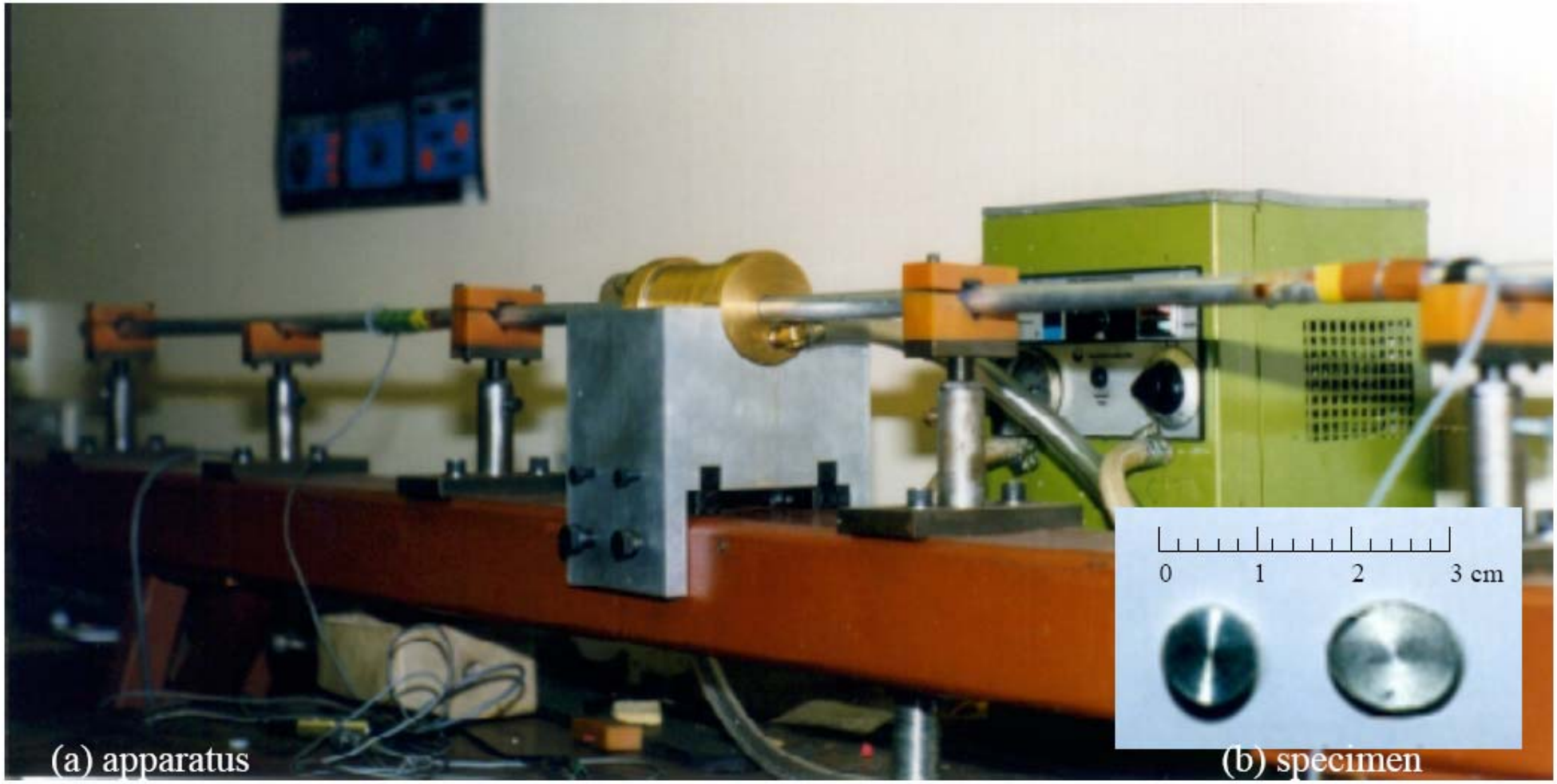
Plain-strain compression tests[3)]





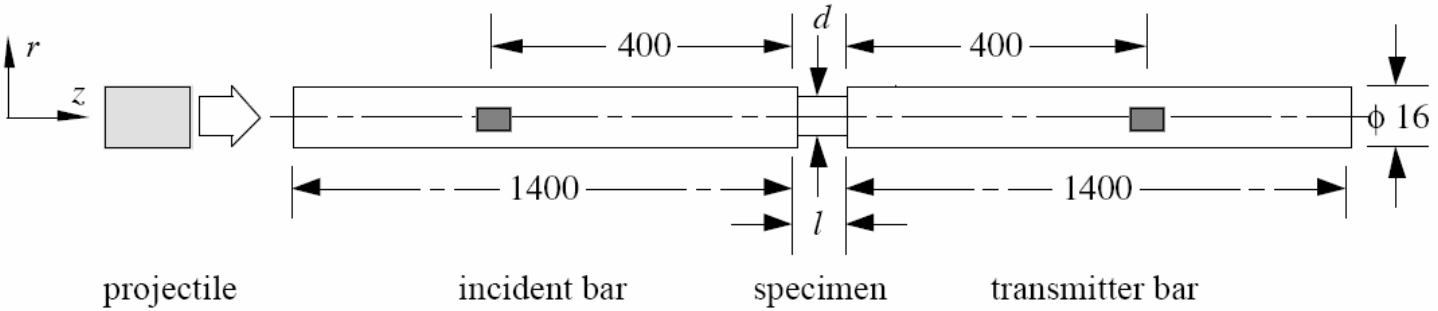
Mechanical testing – high strain-rate tests[4)]

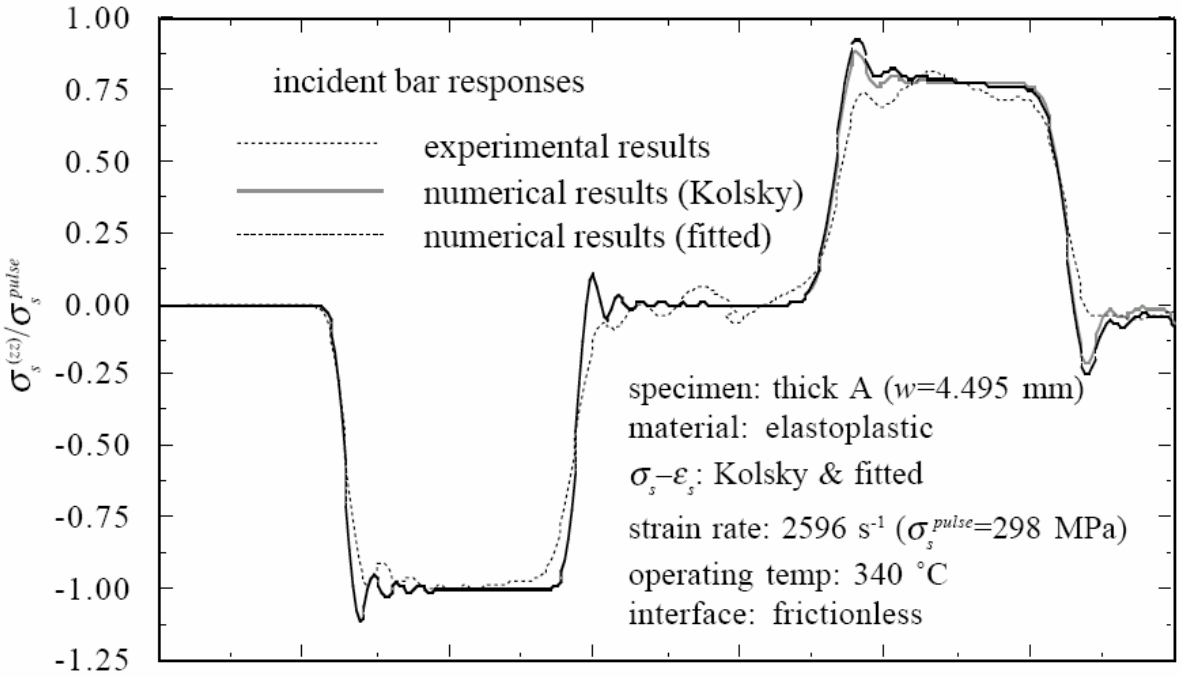
Split – Hopkinson pressure bar at ICL



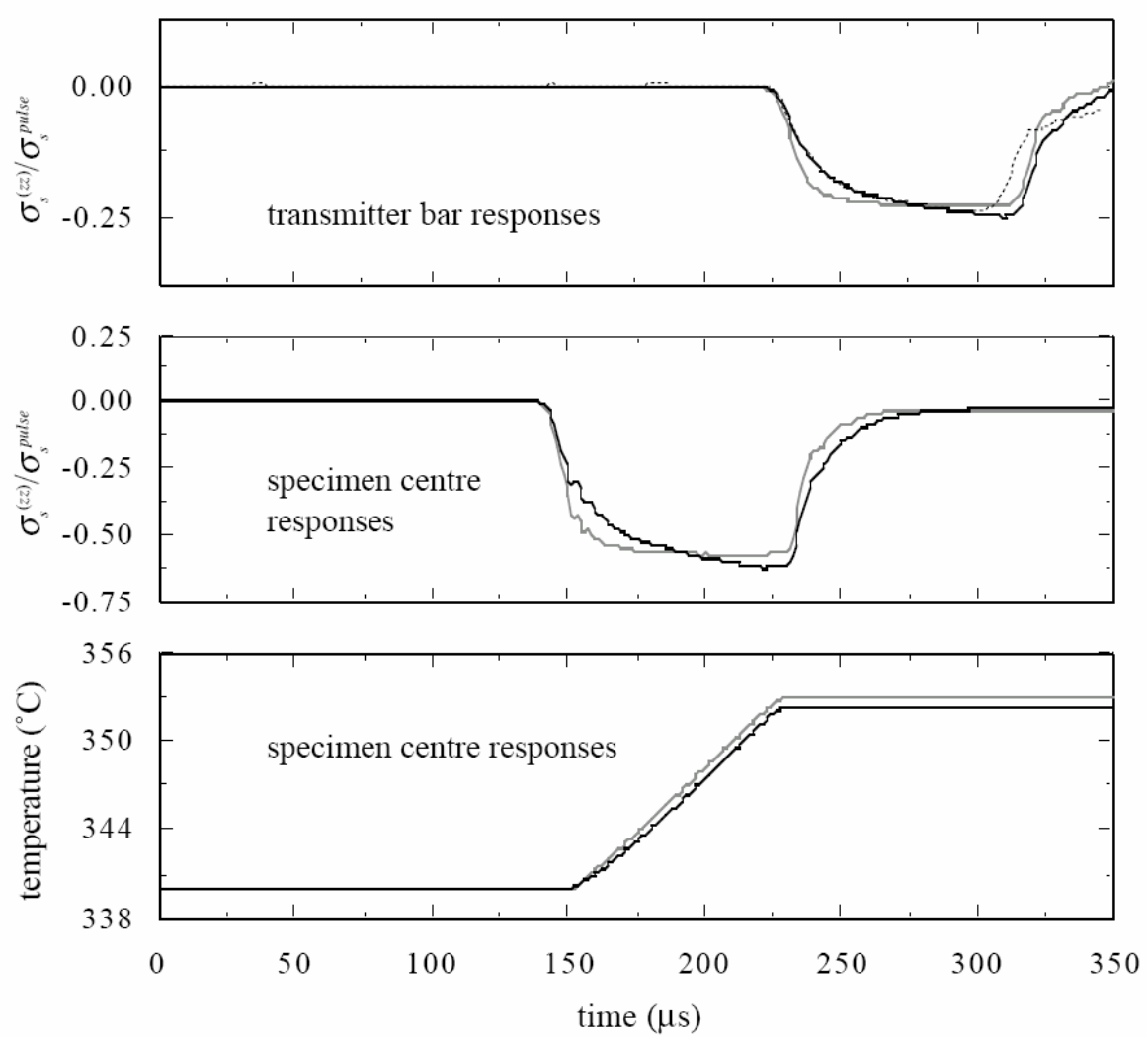
[4)] Maneeratana K.., Development of the finite volume method for non-linear structural applications, PhD, 2000

Mechanical testing – high strain-rate tests (SHPB)[4)]





Mechanical testing – high strain-rate tests (SHPB)[4)]



Impact resistance[1)]

Impact resistance is a measure of the ability of a material, specimen, or structure to withstand a sudden load without failure.

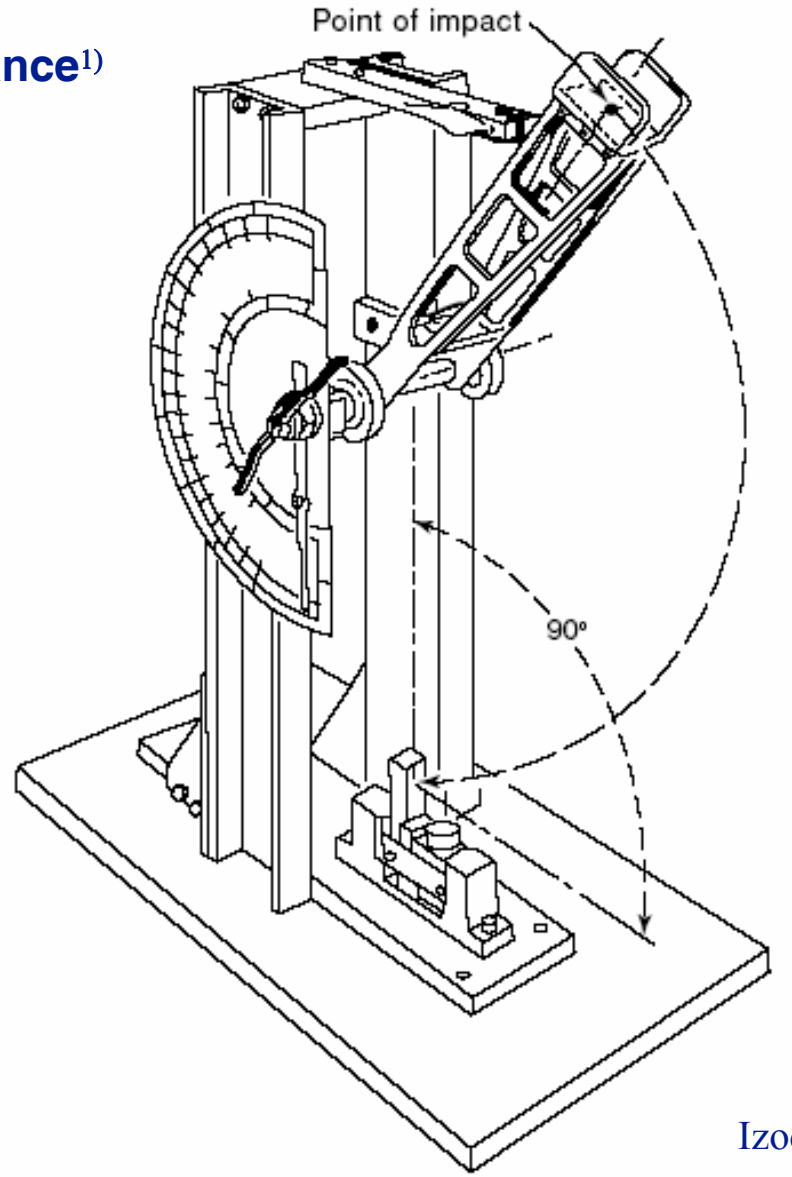
Standard tests

Test	Designation	Description
Brittleness temperature	ASTM D746	The temperature is determined at which plastics and elastomers exhibit brittle failure under impact.
Falling weight	ASTM D3029	Impact resistance indicated by energy to break or crack rigid plastics by means of a falling weight (tup); constant drop height and variable weight (tup)[b] are recommended.
Falling weight	ASTM D1709	Similar to D3029 but for measuring impact resistance of polyethylene film by free-falling round-headed dart.
Falling weight	ASTM D2444	For impact resistance of thermoplastic pipe and fittings by falling weight (tup).[b]

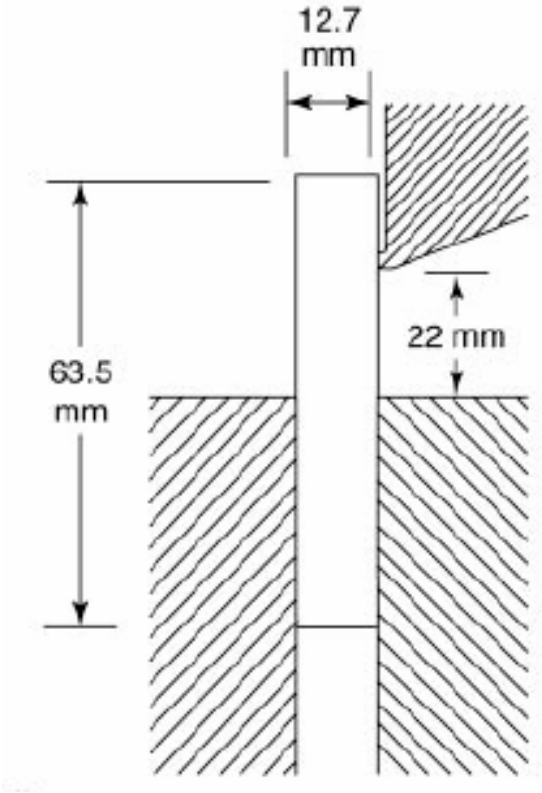
Impact resistance[1)]

Fracture toughness	ASTM D5045	For plane-strain fracture toughness.
High rate stress/ strain (tension)	ASTM D2289	Area under stress–strain curve measures impact resistance at testing speeds up to 254 m/min.
Izod impact	ASTM D256[c]	Energy to break a notched cantilever beam specimen upon impact by a pendulum. Notch tends to promote brittle failure. Unnotched impact strength is obtained by reversing the notched specimen in the vise. Notch sensitivity can be determined by using Method D.
Charpy impact	ASTM D6110 (also, Research Report D20-1034)	Similar to Izod impact test. Notched specimen is supported on two ends and struck by a pendulum in the middle, a three-point-bend setting.
Tensile impact	ASTM D1822	Recommended for plastic materials too flexible, too thin, or too rigid to be tested by ASTM D256. Measures energy to break by "shock in tension" imparted by a swinging pendulum.

Impact resistance[1)]

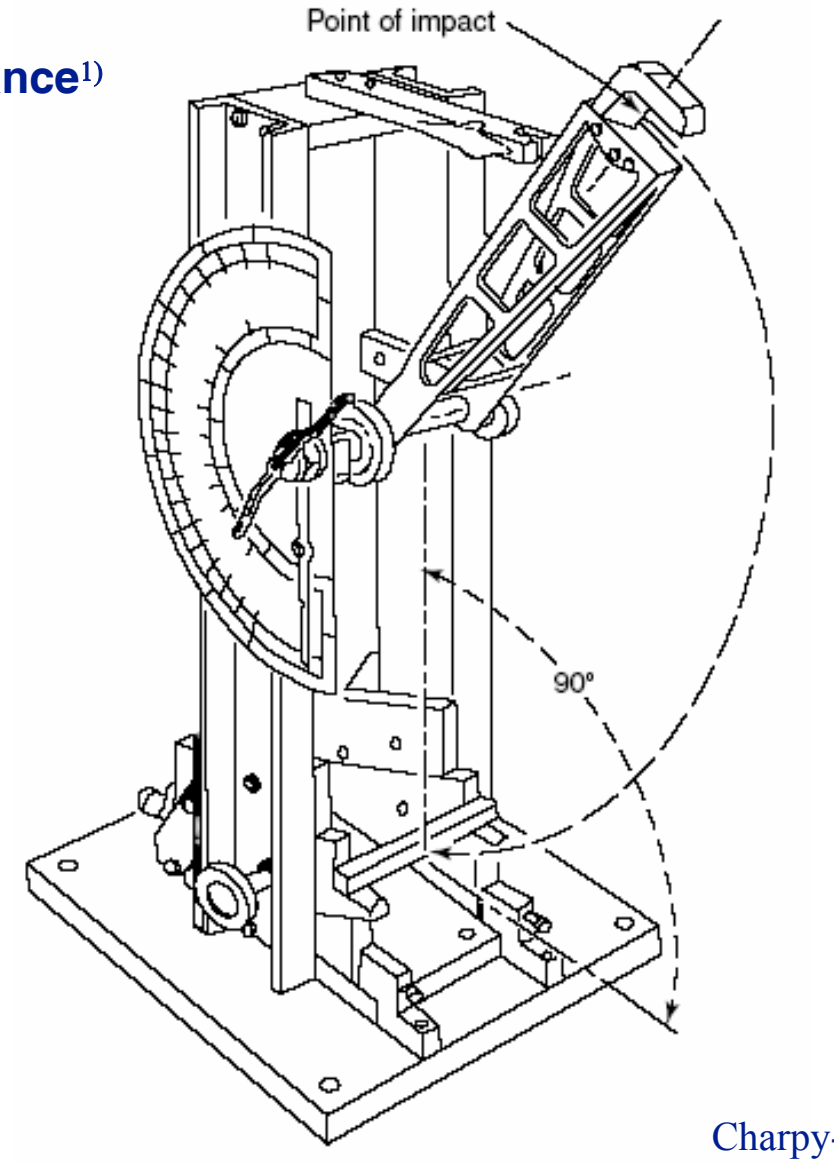


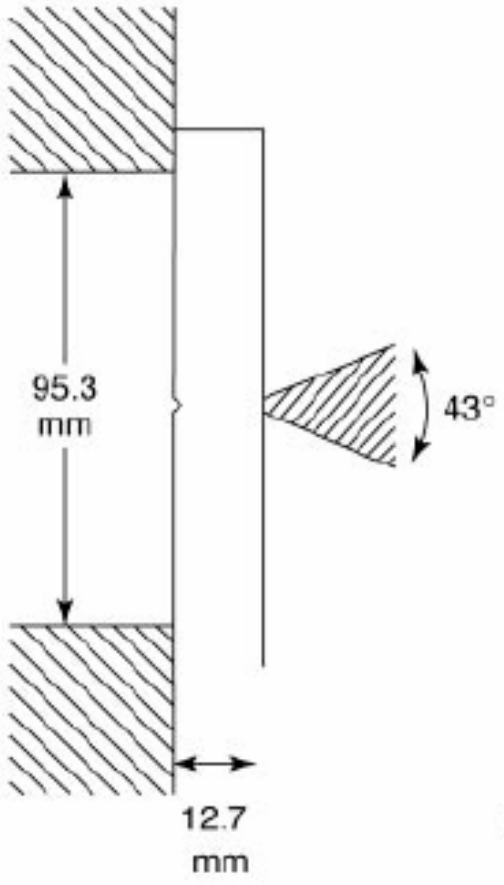
$$E_S = E_I - E_R - E_F - E_w$$



Izod-type pendulum impact machine, ASTM D256

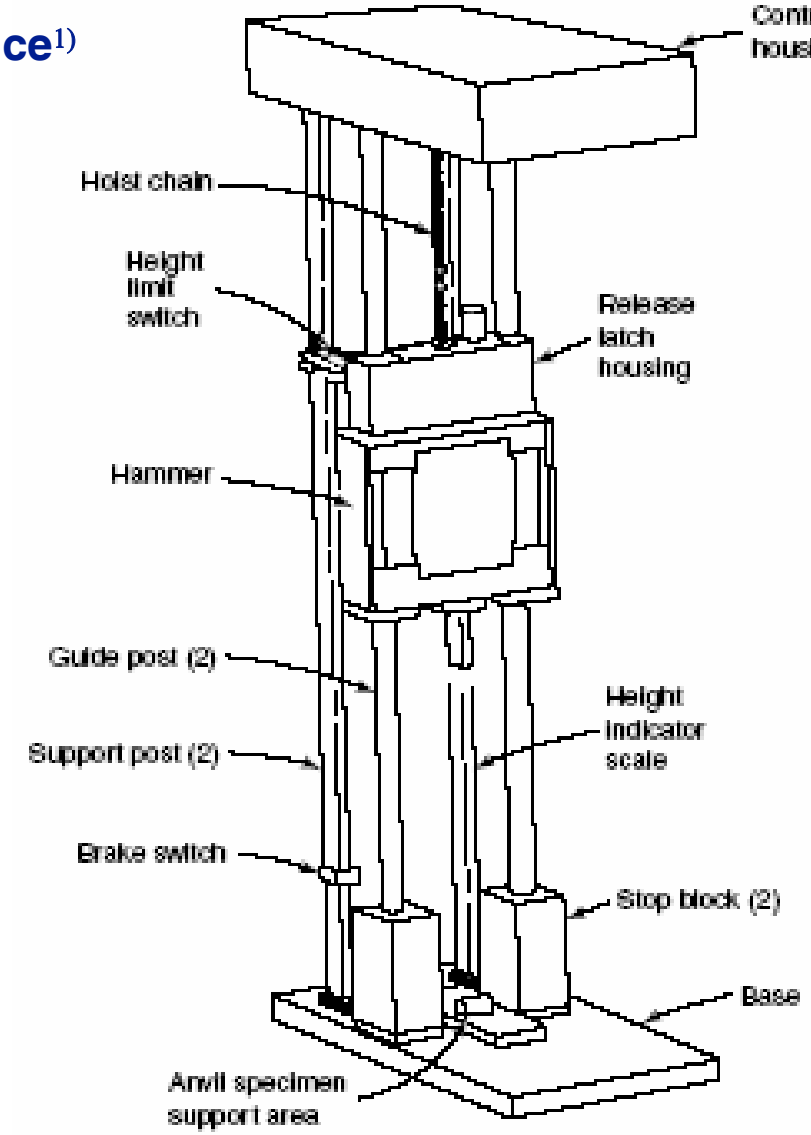
Impact resistance[1)]





Charpy-type pendulum impact machine, ASTM D256

Impact resistance[1)]

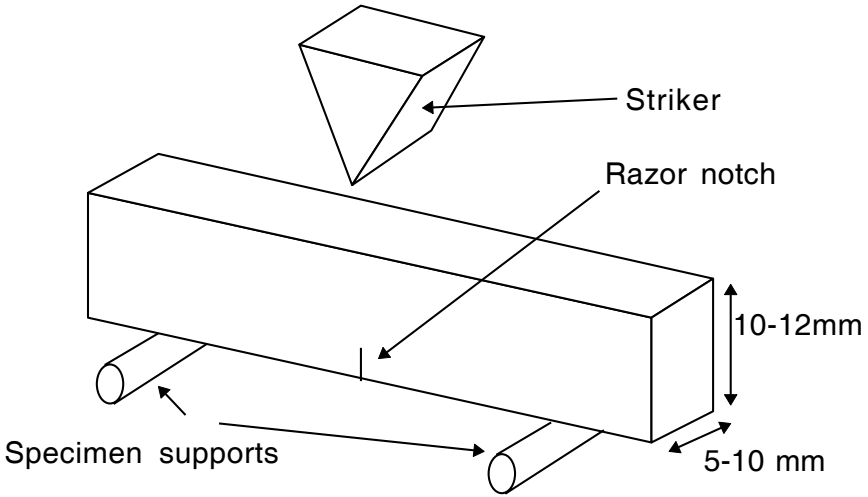


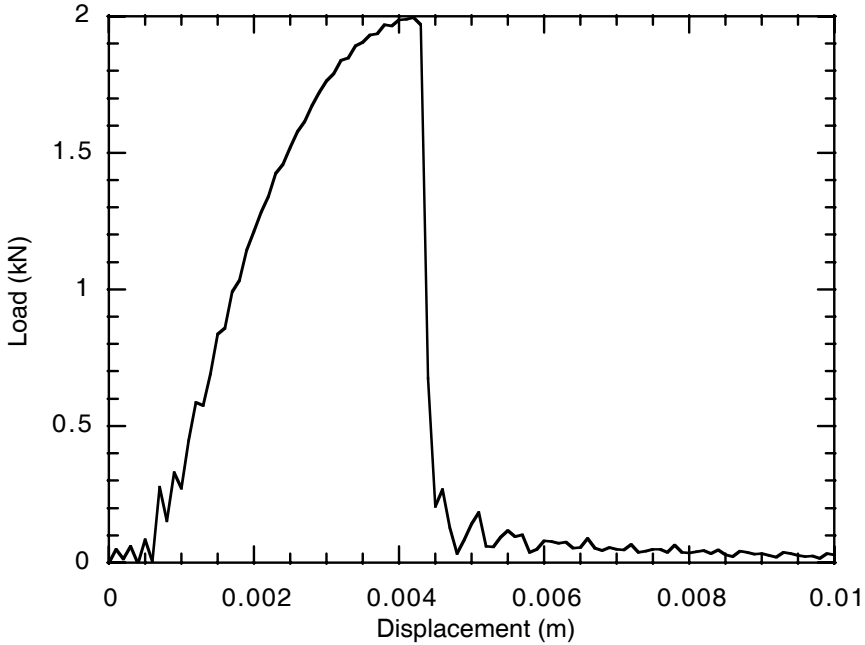
Typical drop-weight testing machine

Three-point-bend testing[2)]

$$G_C = \frac{U}{BD\phi(\frac{a}{W})}$$

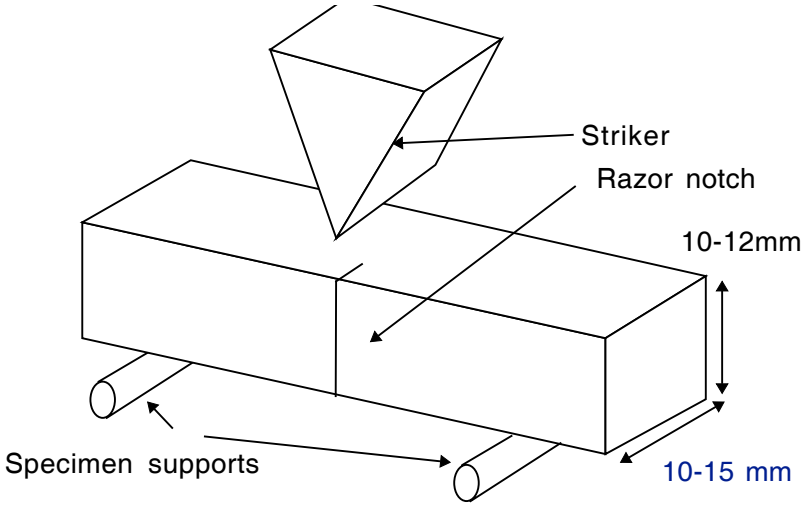
Conventional Charpy test

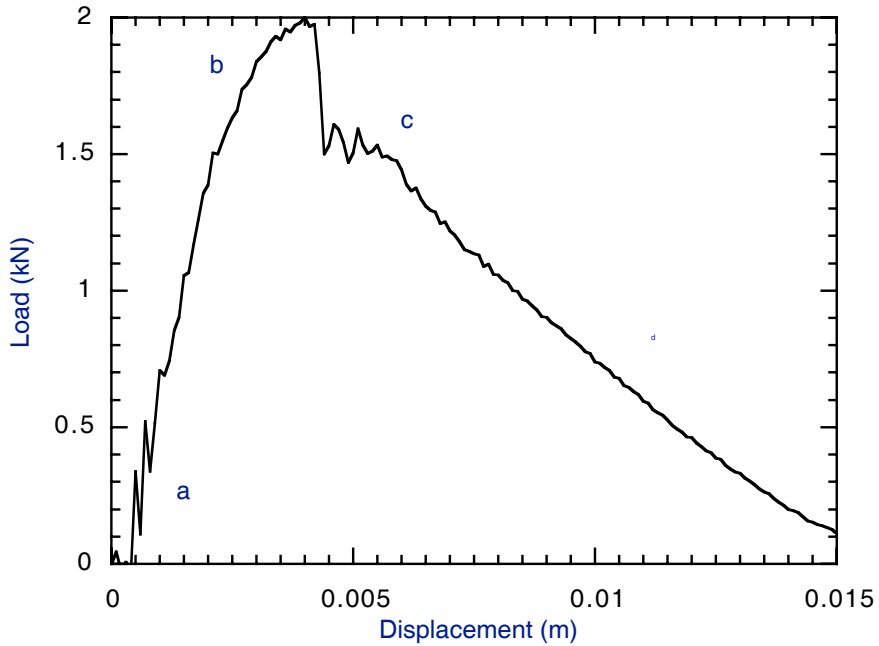




Three-point-bend testing[2)]

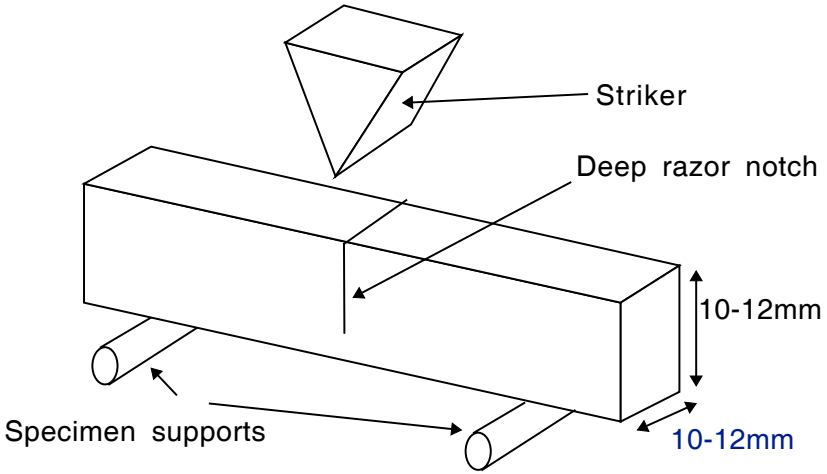
Side-notched Charpy test

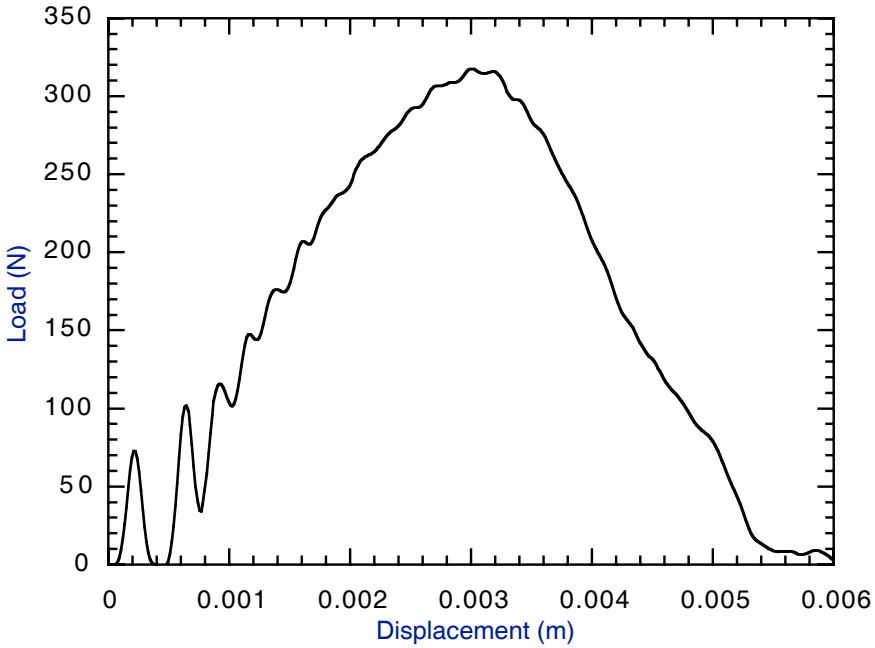




Three-point-bend testing[2)]

Inverted Charpy test

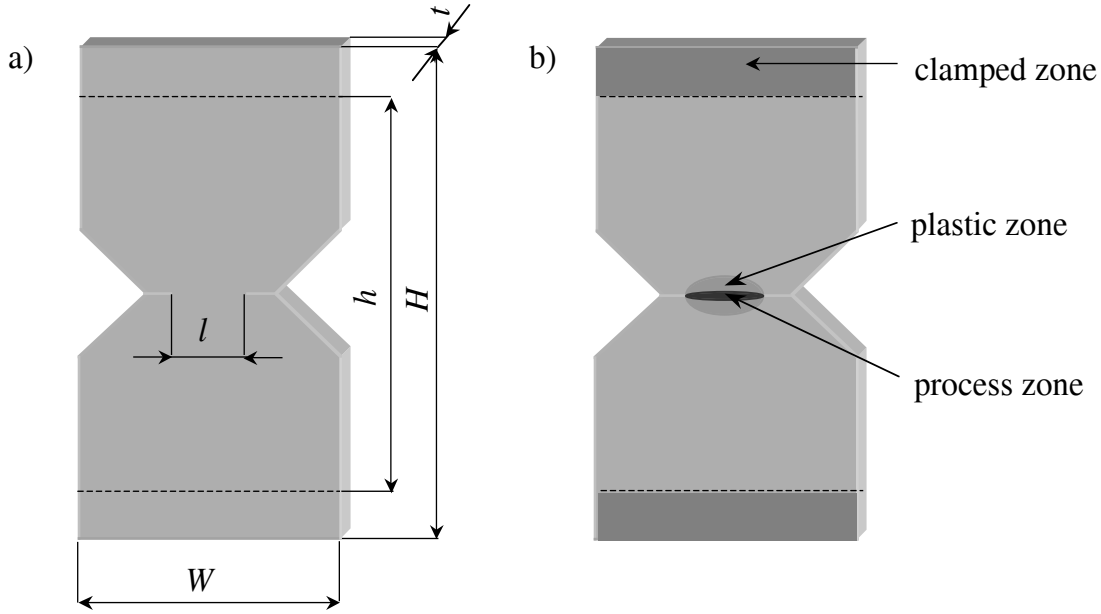




Measuring fracture toughness for thin plastic sheets

Concept of Essential Work of Fracture (EWF) method

Specimen

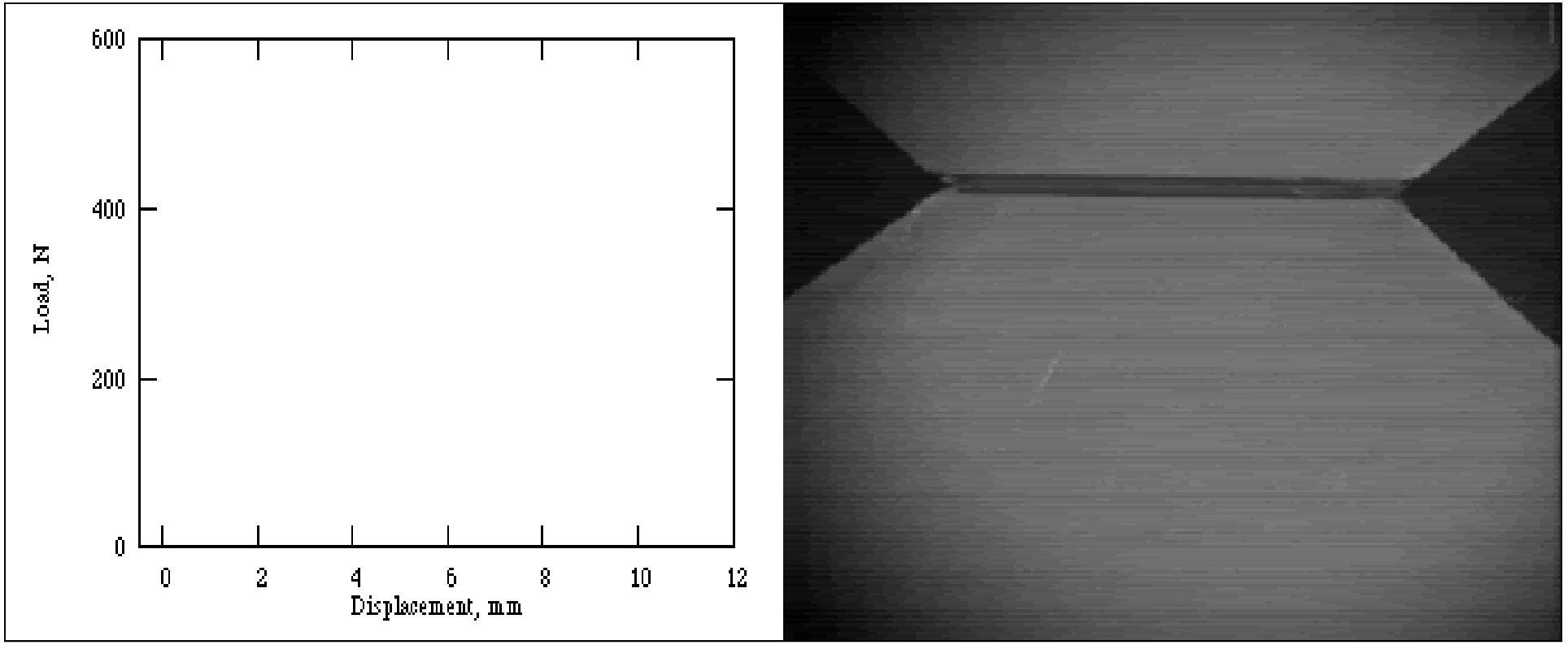


Basic equations

$$W_f = w_e lt + w_p \beta l^2 t$$

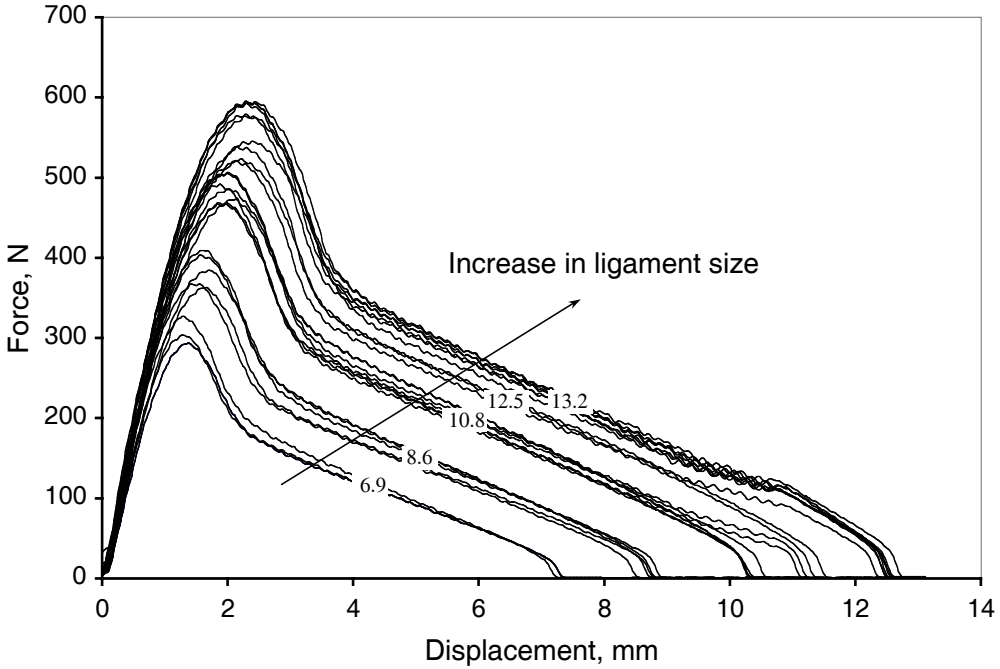
$$w_f = \left(\frac{W_f}{lt} \right) = w_e + w_p \beta l$$

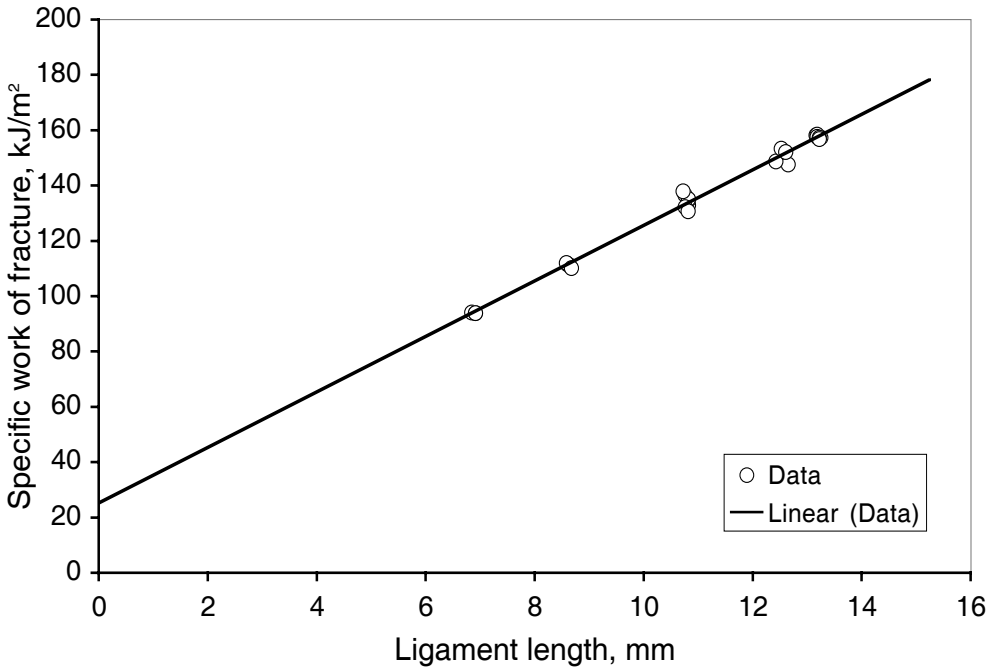
HM5411EA – test speed 1 mm/s



HM5411EA –test speed mm/s

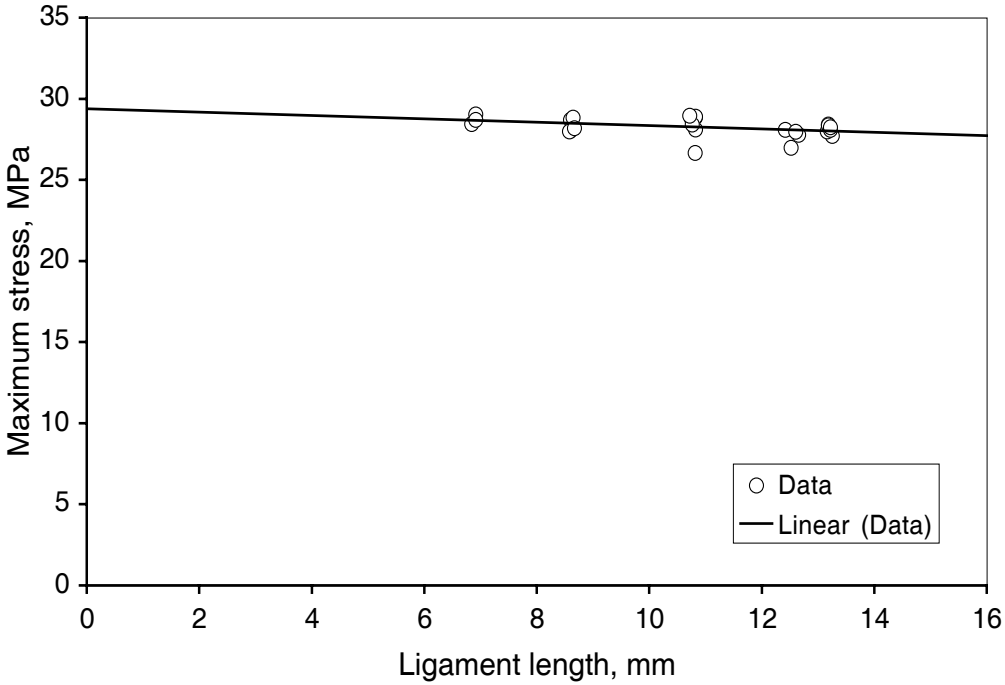
Determination of fracture toughness

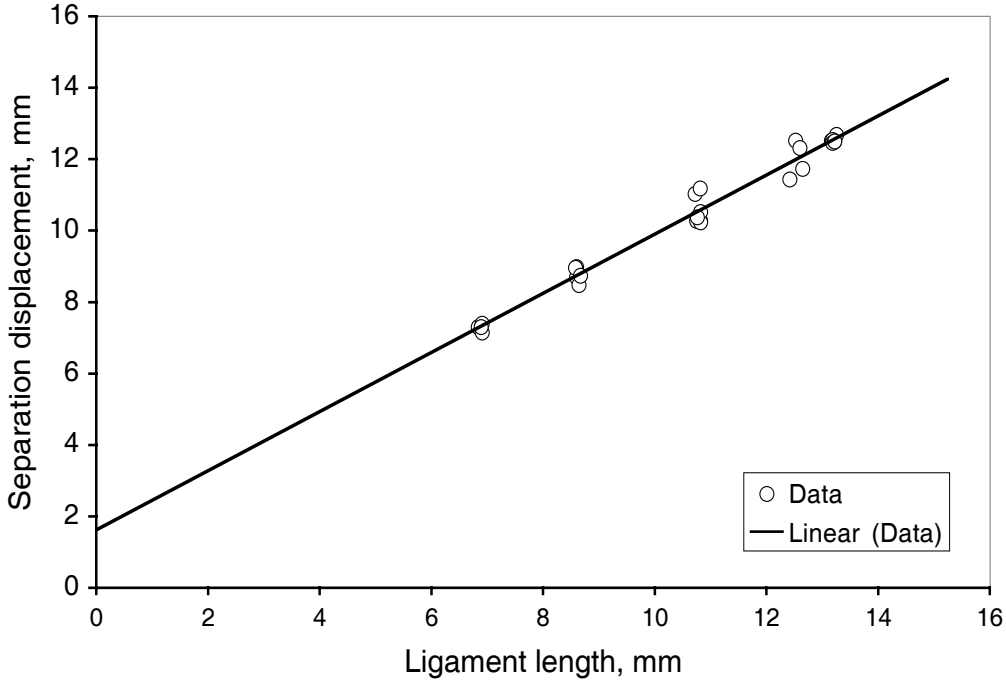




HM5411EA – test speed 1 mm/s

Determination of Cohesive Zone parameters – maximum displacement method

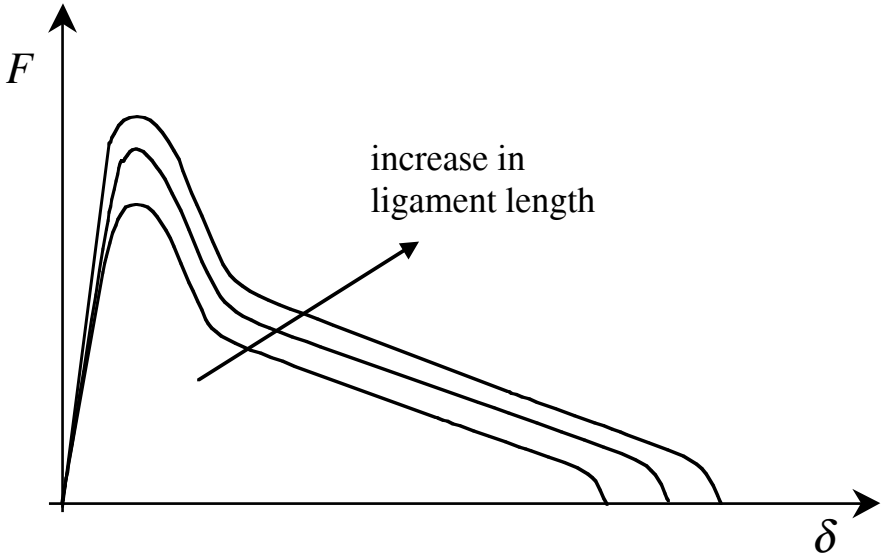


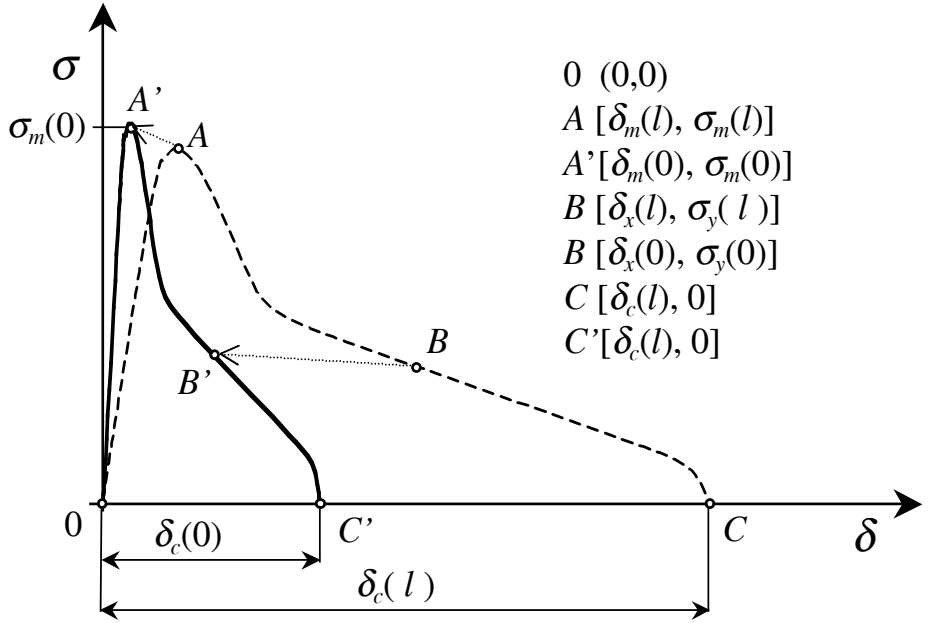


HM5411EA – test speed 1 mm/s

Determination of Cohesive Zone parameters – maximum displacement method

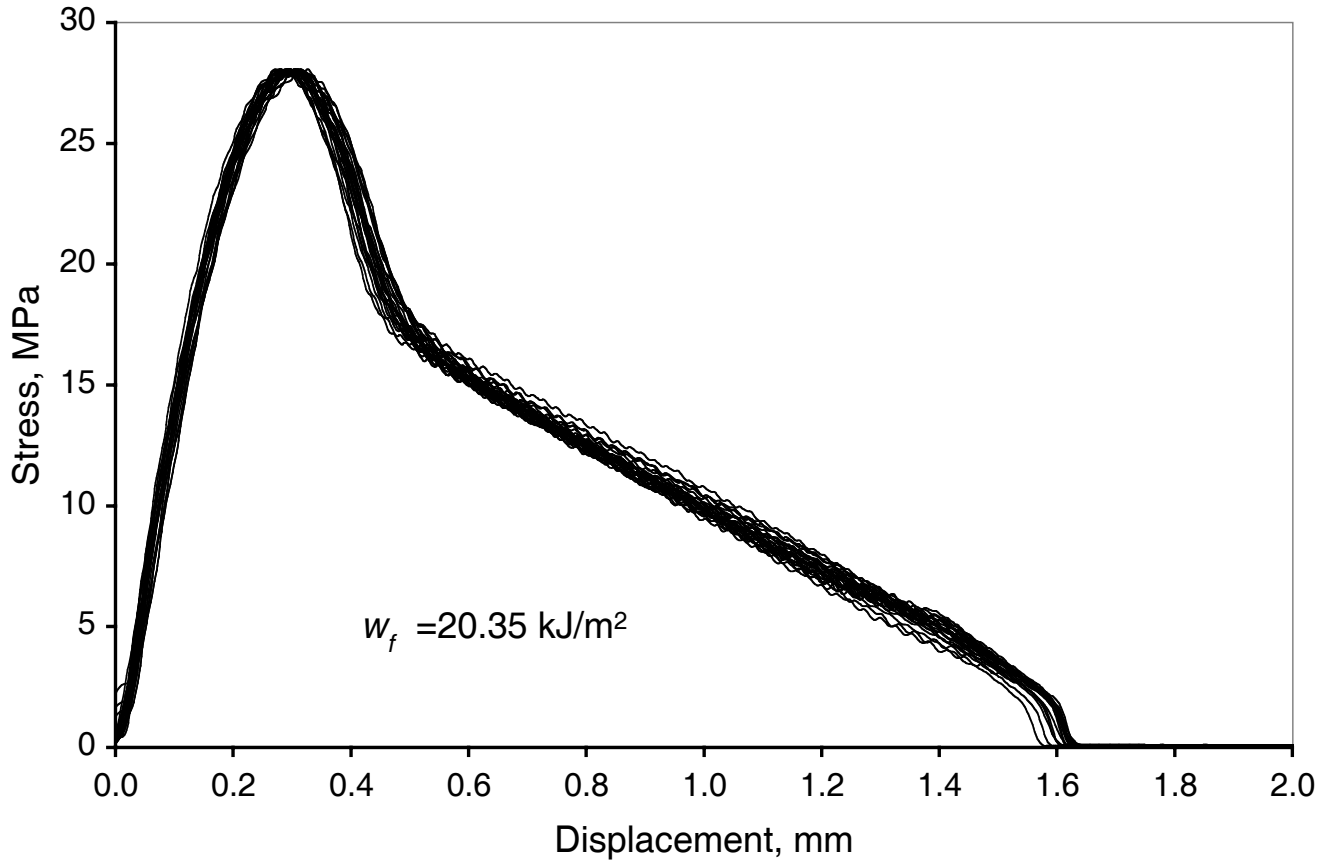
$$\sigma_y(0) = \sigma_y(l)\left[\frac{\sigma_m(0)}{\sigma_m(l)}\right] \qquad \delta_x(0) = \delta_x(l)\left[\frac{\delta_c(0)}{\delta_c(l)}\right]$$



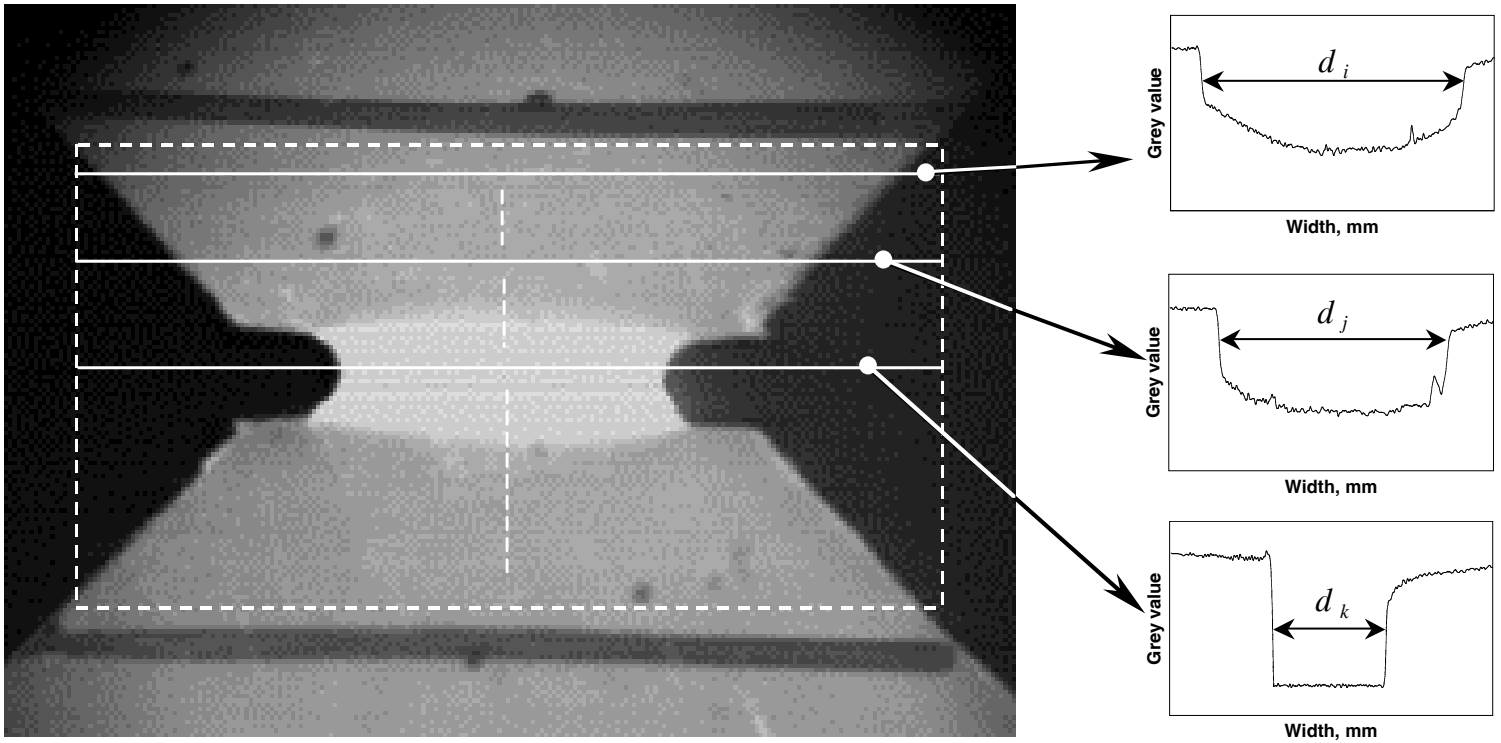


HM5411EA – test speed 1 mm/s

Determination of Cohesive Zone parameters – maximum displacement method

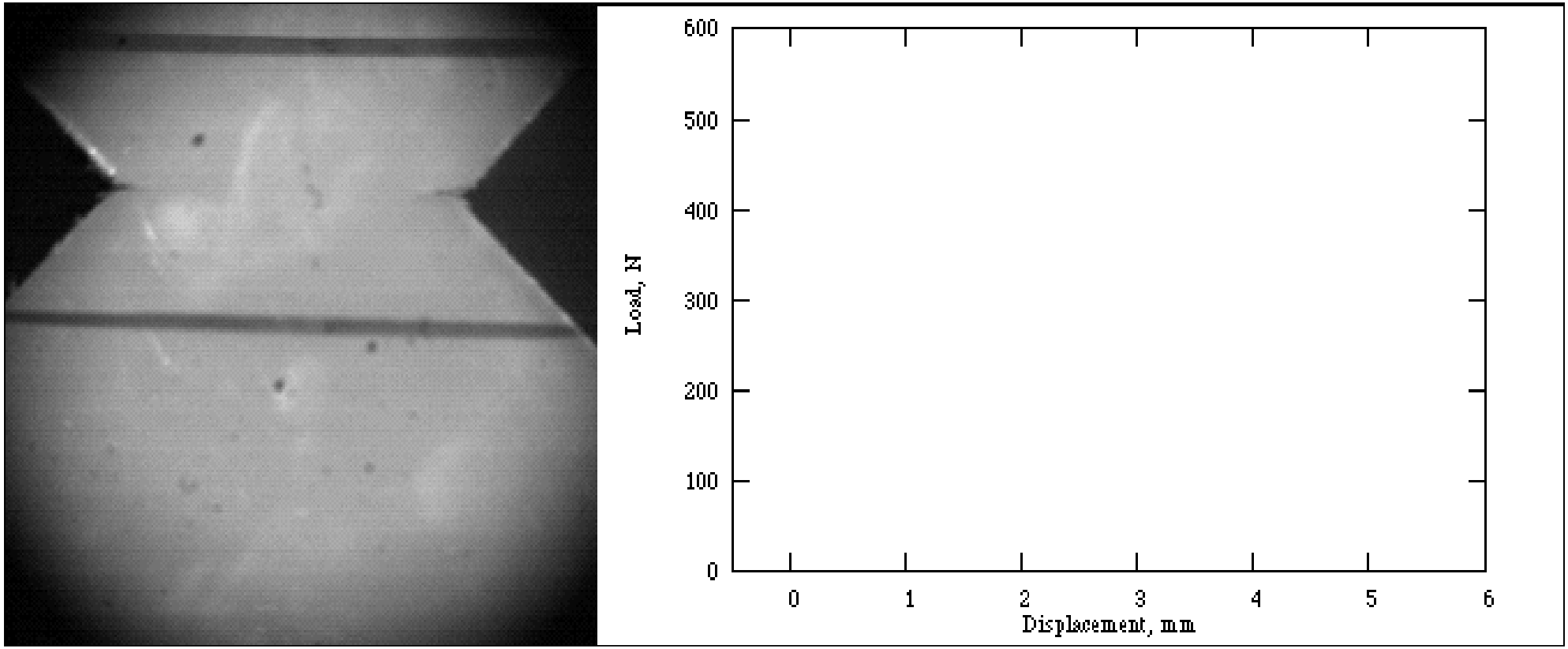


Profile analysis of deformation zone

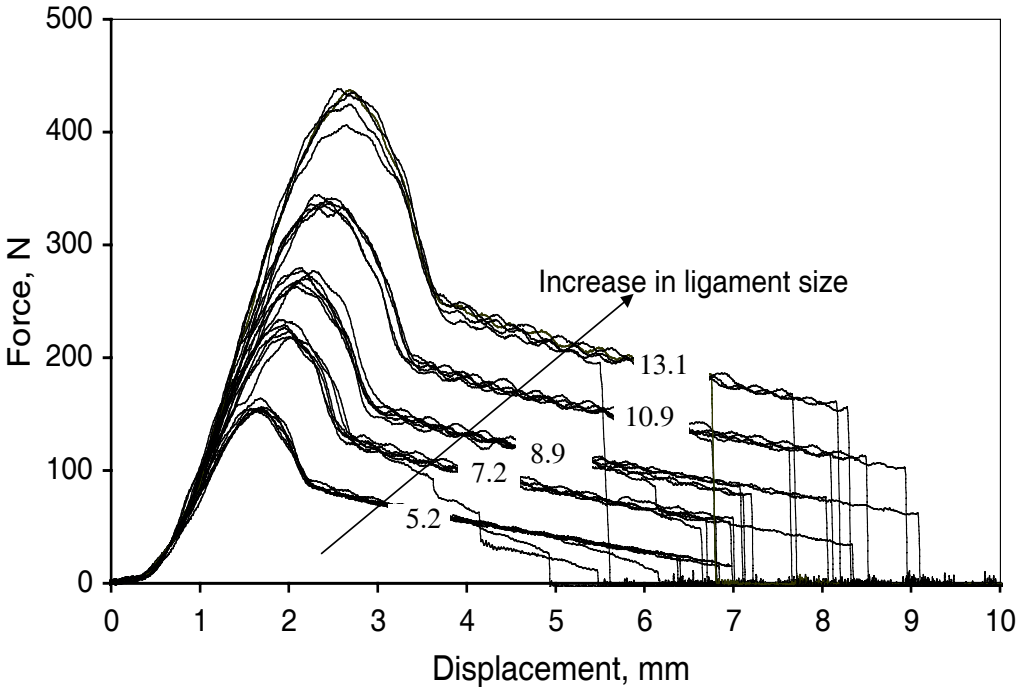


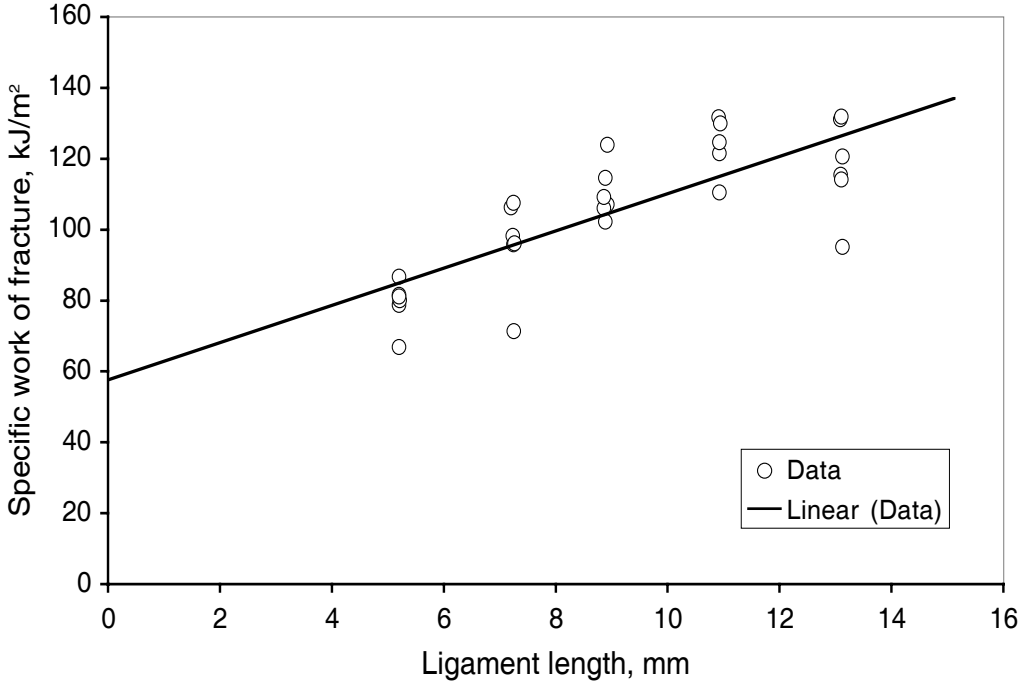
minimum width = min (d_i), i – line index in a ROI

HD5502XA – test speed 20 mm/s

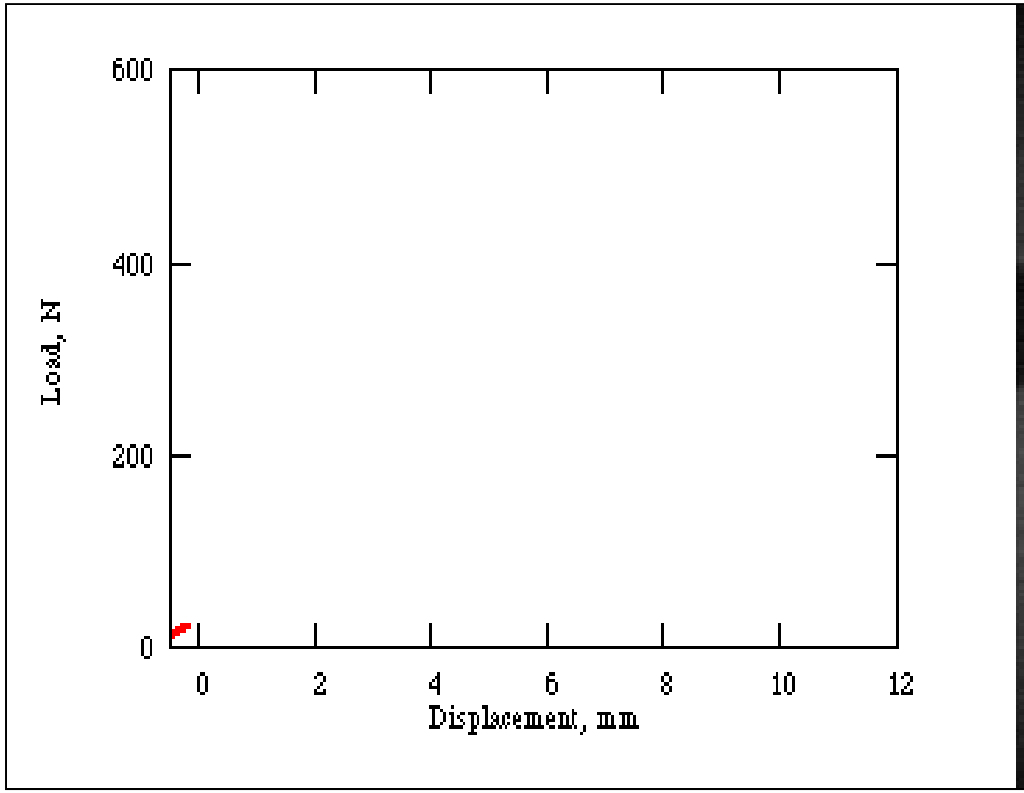


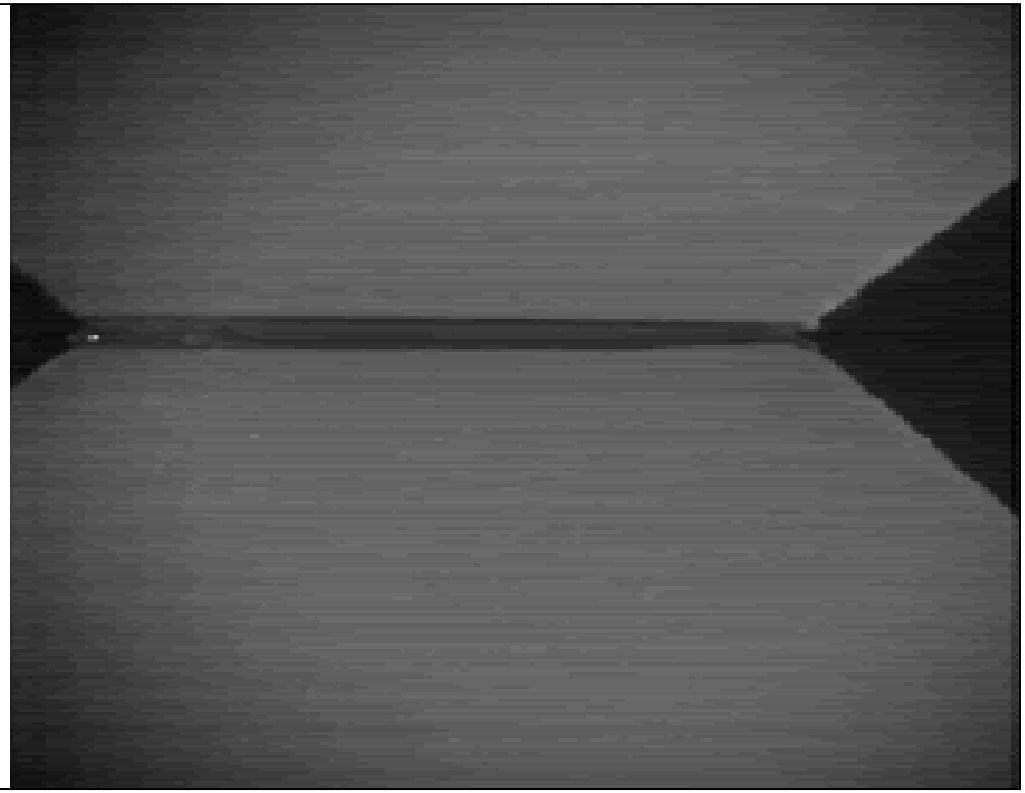
HD5502XA – test speed 20 mm/s





HD5411EA – test speed 1 m/s





Testing plastic pipes

- From sixties intensive use of polymeric materials in pipe production (conveying gases and fluids) in Europe – PE and PVC
- Problems with potential catastrophic accidents
- Use of HDPE and MDPE materials – PE-63, PE-80, PE-100

Testing plastic pipes

Technical programme (ISO): TC 138/SC 5

ISO/DIS(CD) 1167 (1-4)	Resistance to internal pressure
ISO/DIS 2505	Longitudinal reversion
ISO/DIS 7686	Determination of opacity
ISO/CD 11673.2	Determination of the fracture toughness properties
ISO/CD 13477	Determination of resistance to rapid crack propagation
ISO/CD 13478	Determination of resistance to rapid crack propagation (RCP) - Full-scale test (FST)
ISO/AWI 13968	Determination of ring flexibility
ISO/DIS 17454, 17455, 17456	Multilayer pipe systems – various tests

Commonly used standards

ISO 3126:1974, 3127:1994, 11173:1994, 4433:1997, 6259:1997, 7361:1991, 9854:1994, 1167:1996

Testing plastic pipes

Determination of resistance to RCP

- High propagation speed with potential catastrophic consequences
- Type of tests (chronologically)
  - 👎 Full-scale (FT) test – ISO 13478 – British Gas
    - Pipe length up to 20 m, 50 bar
    - First 2 m cooled to -70ºC, the rest 0ºC
    - Crack propagates more than 90%of length, pressure is above critical
    - Extremely slow and expensive testing
  - 👎 Modified Robertson's test – Belgium standard – 1981
  - 👍 S4 test – ISO 13477 – Imperial College London – 1987
    - Possible parametric analysis due to low costs (temperature, pressure, material)
    - Determination of critical pressure and temperature

Testing plastic pipes

Determination of resistance to RCP

Full-scale test

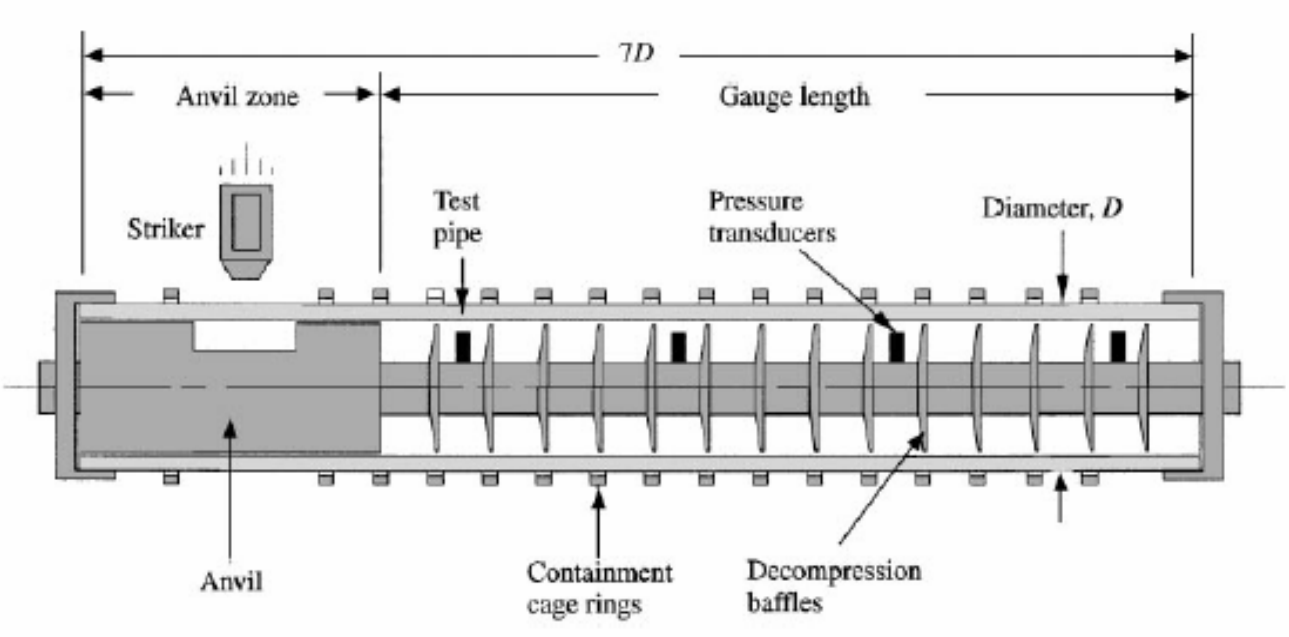
before

during

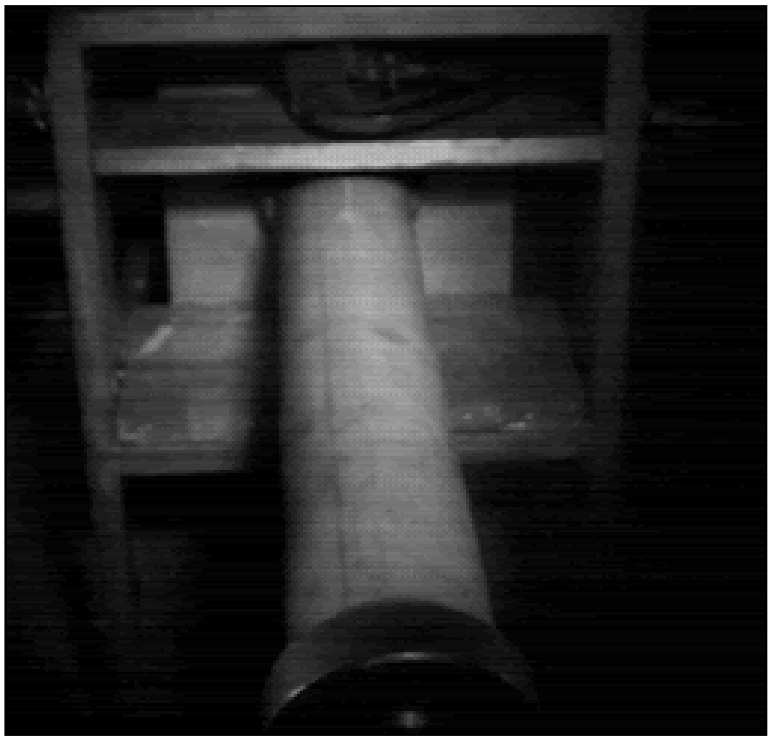
after

Testing plastic pipes

Determination of resistance to RCP



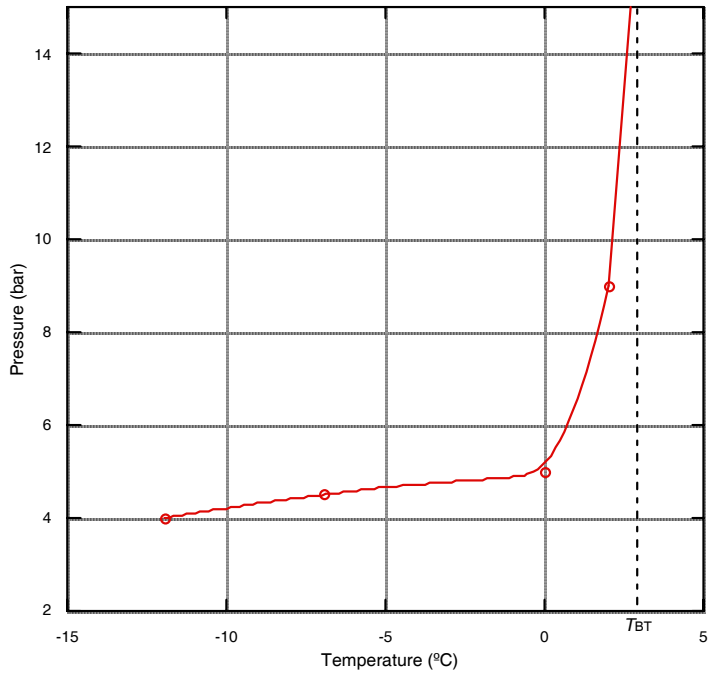
Small-scale steady-state (S4) test

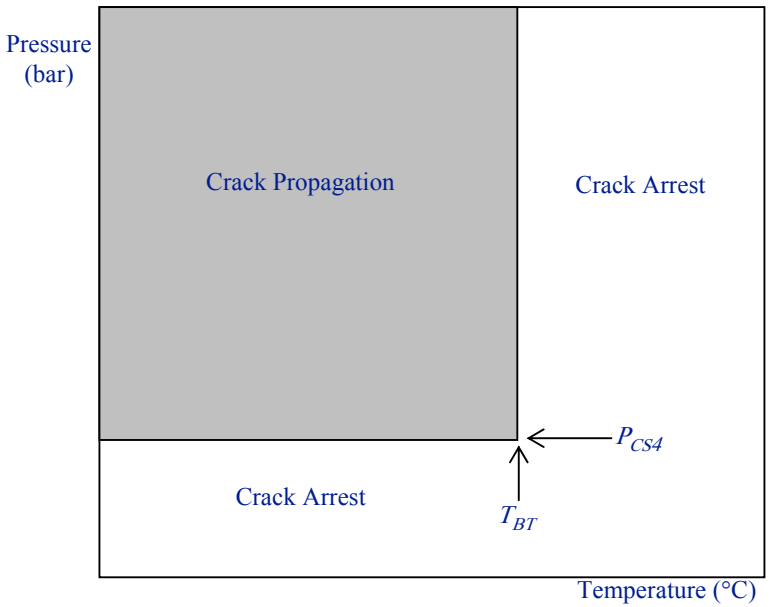


Video: A. Paizis, A. Karac

Testing plastic pipes

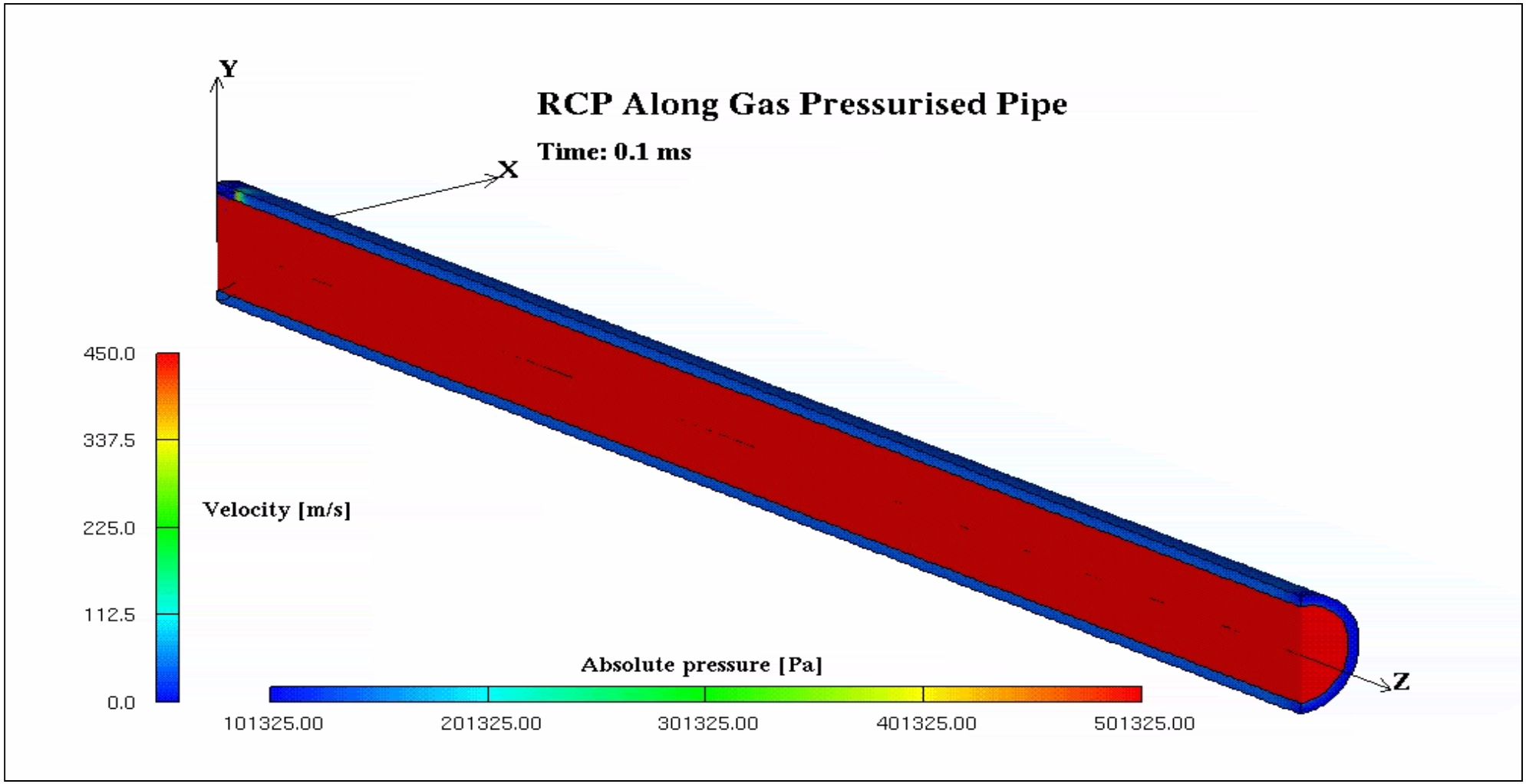
Determination of critical pressure and brittle-to-tough transition temperature





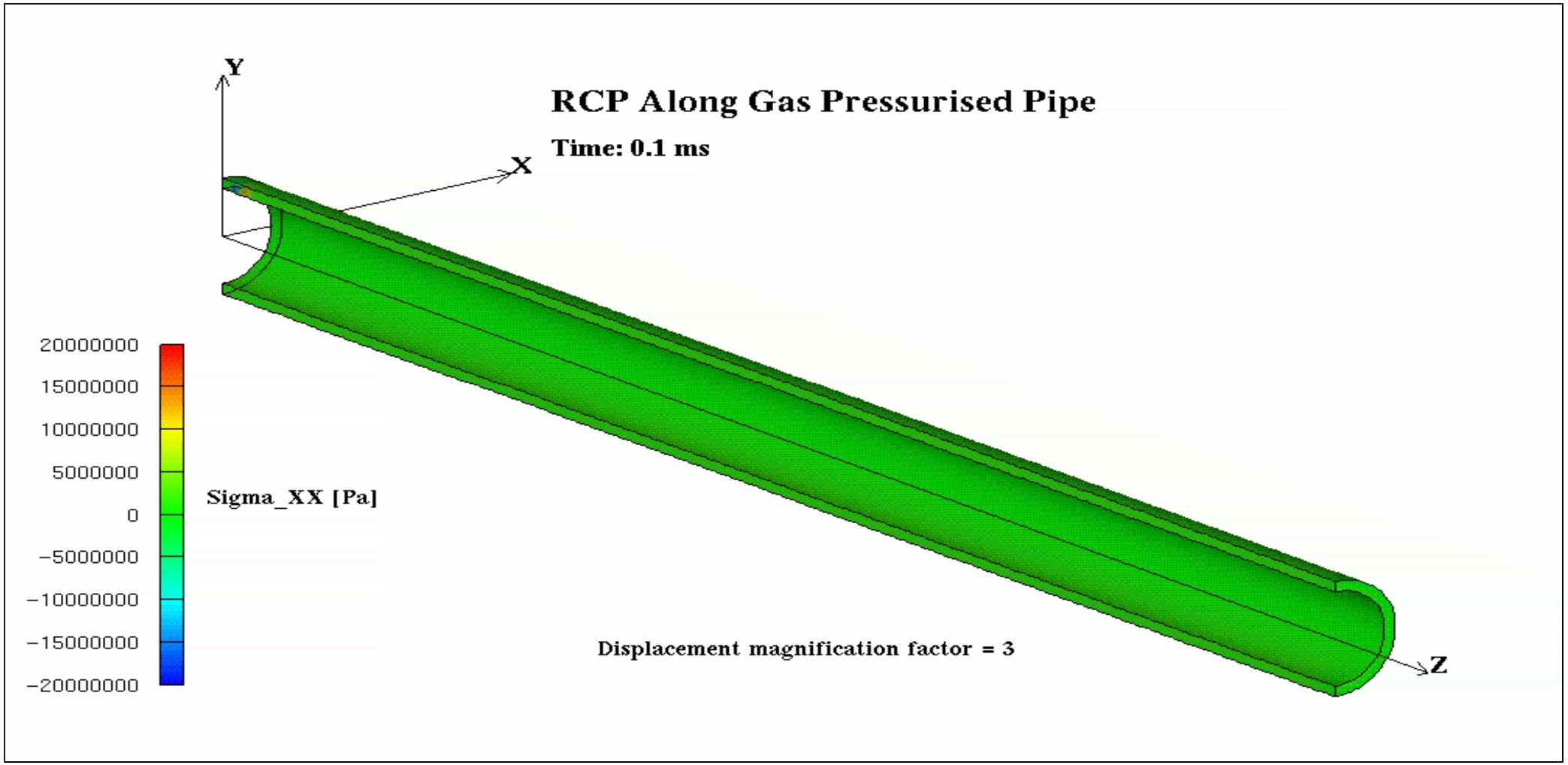
Testing plastic pipes

OpenFOAM simulation



Testing plastic pipes

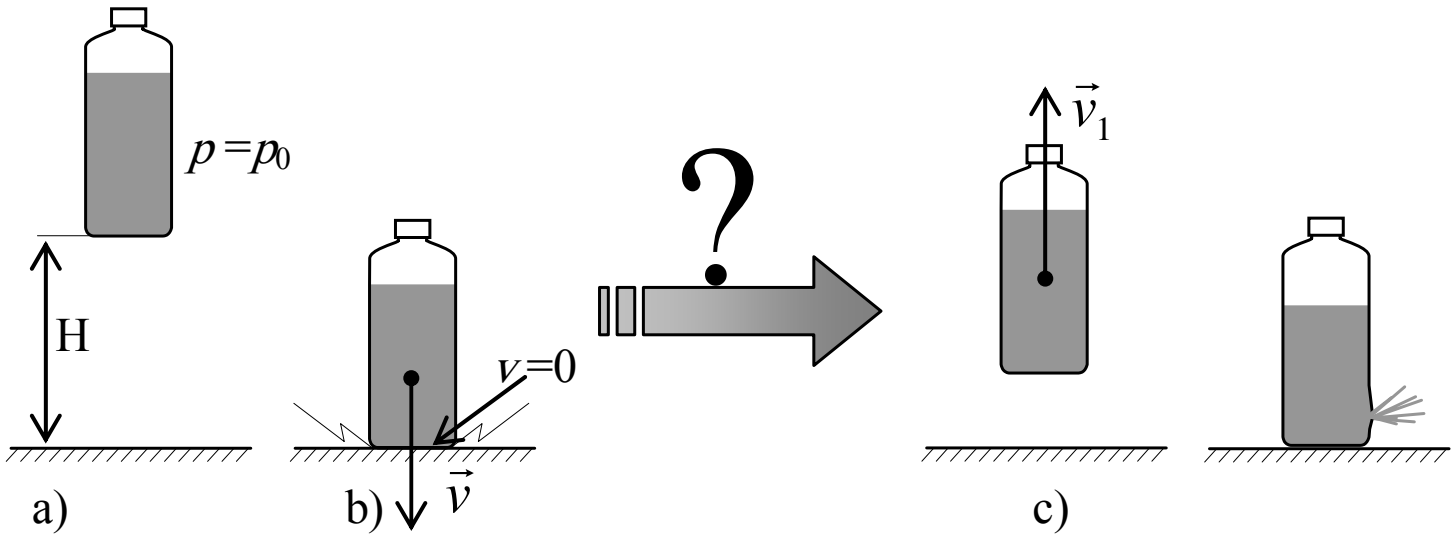
OpenFOAM simulation



Testing plastic bottles

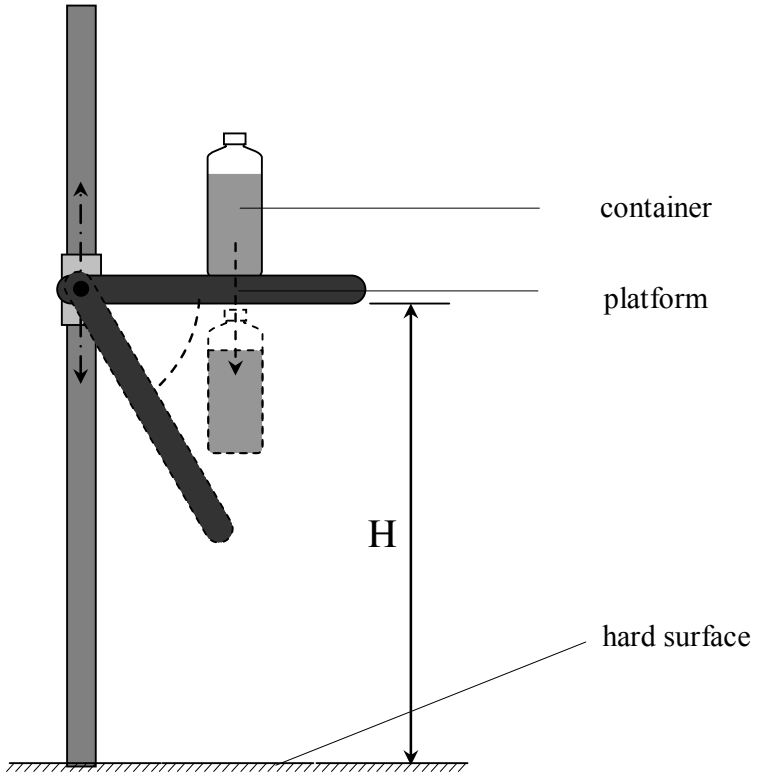
ASTM D2463-95

"Provides measures of the drop impact resistance of blow-moulded thermoplastic containers as a summation of the effects of material, manufacturing conditions, container design, and perhaps other factors."

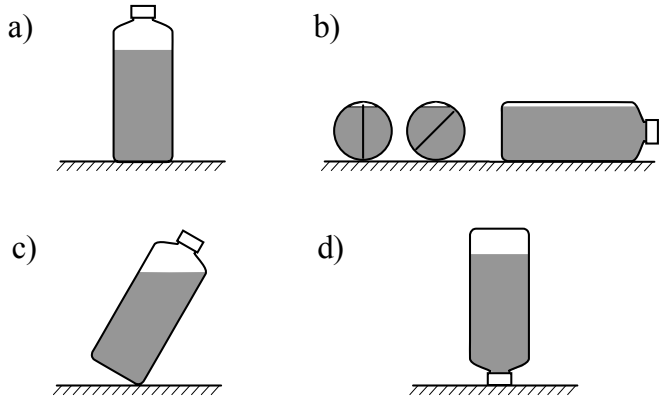


Testing plastic bottles

Standard tests



- Static drop height method
- Bruceton staircase (up-and-down) method

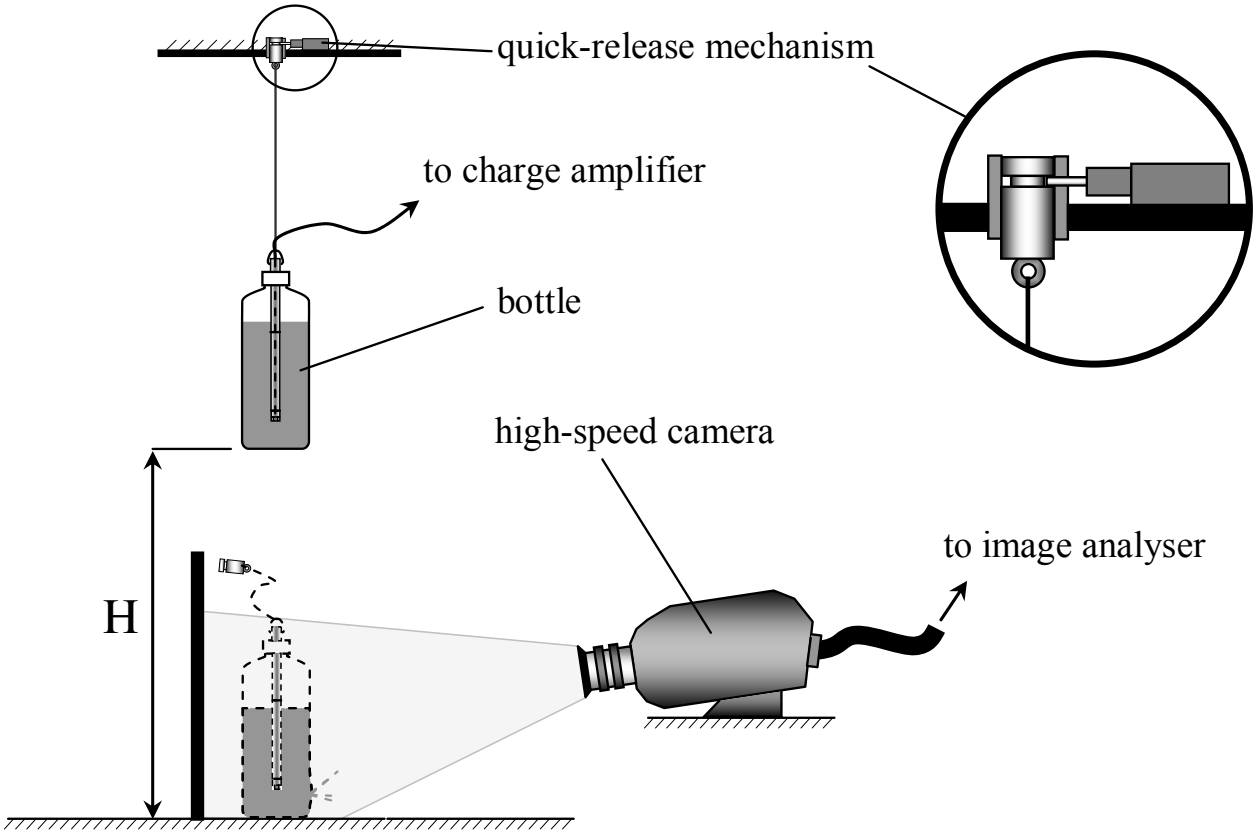


Testing plastic bottles

Standard tests

Testing plastic bottles

Modified standard tests



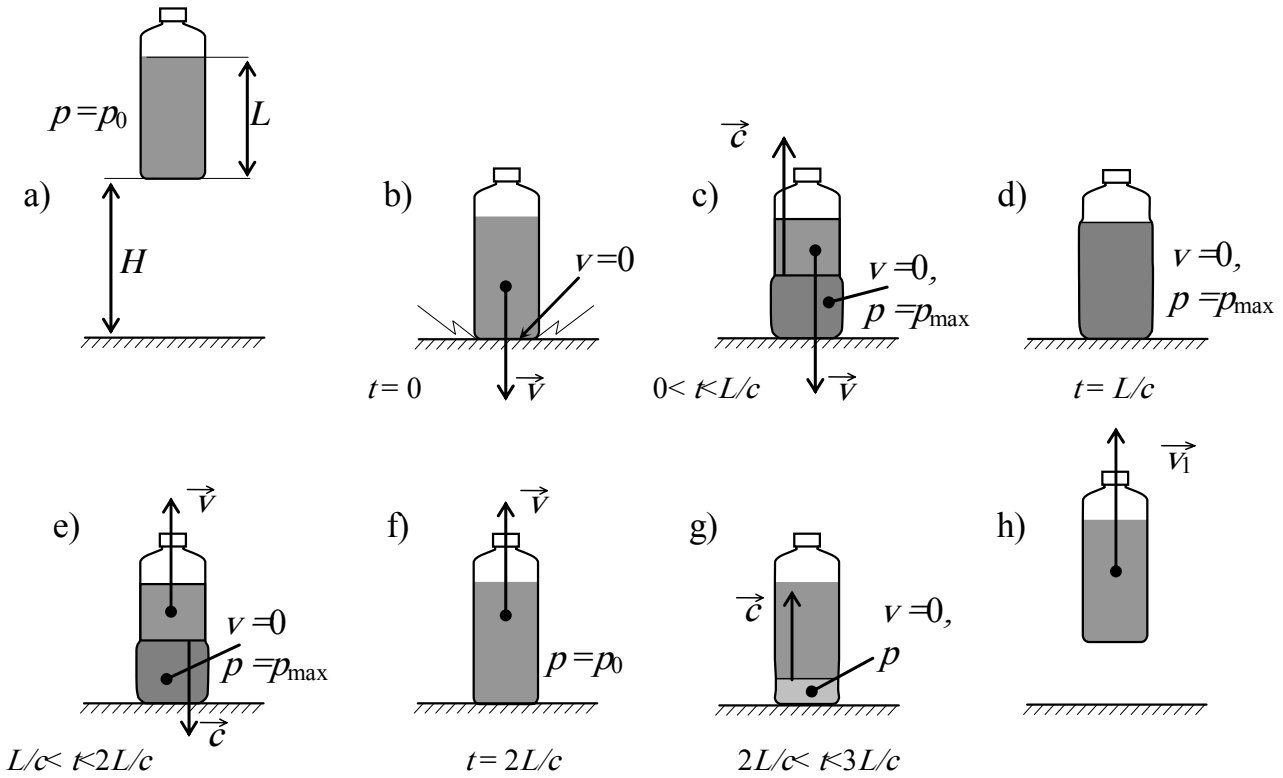
Testing plastic bottles

non-failure

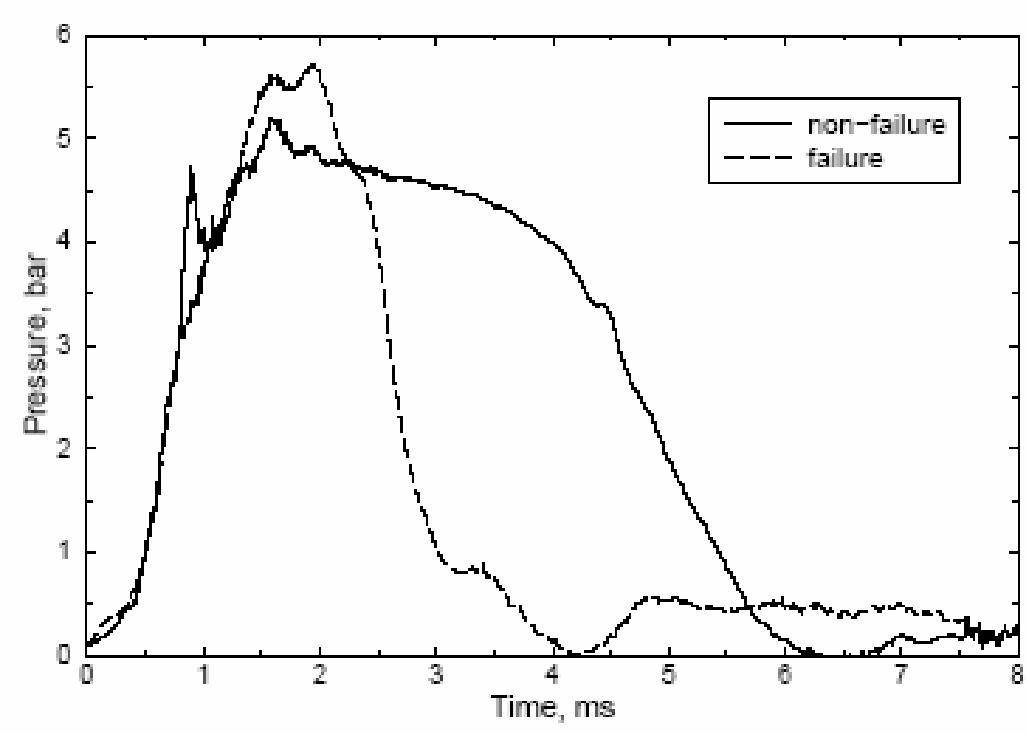
failure

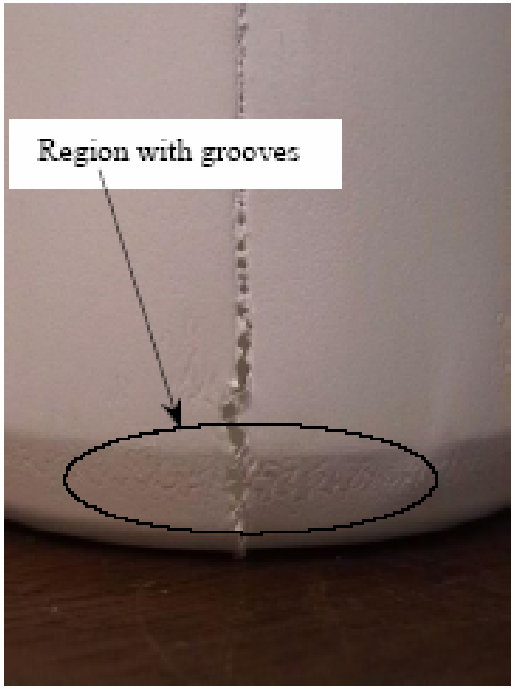
RT6 container

Testing plastic bottles



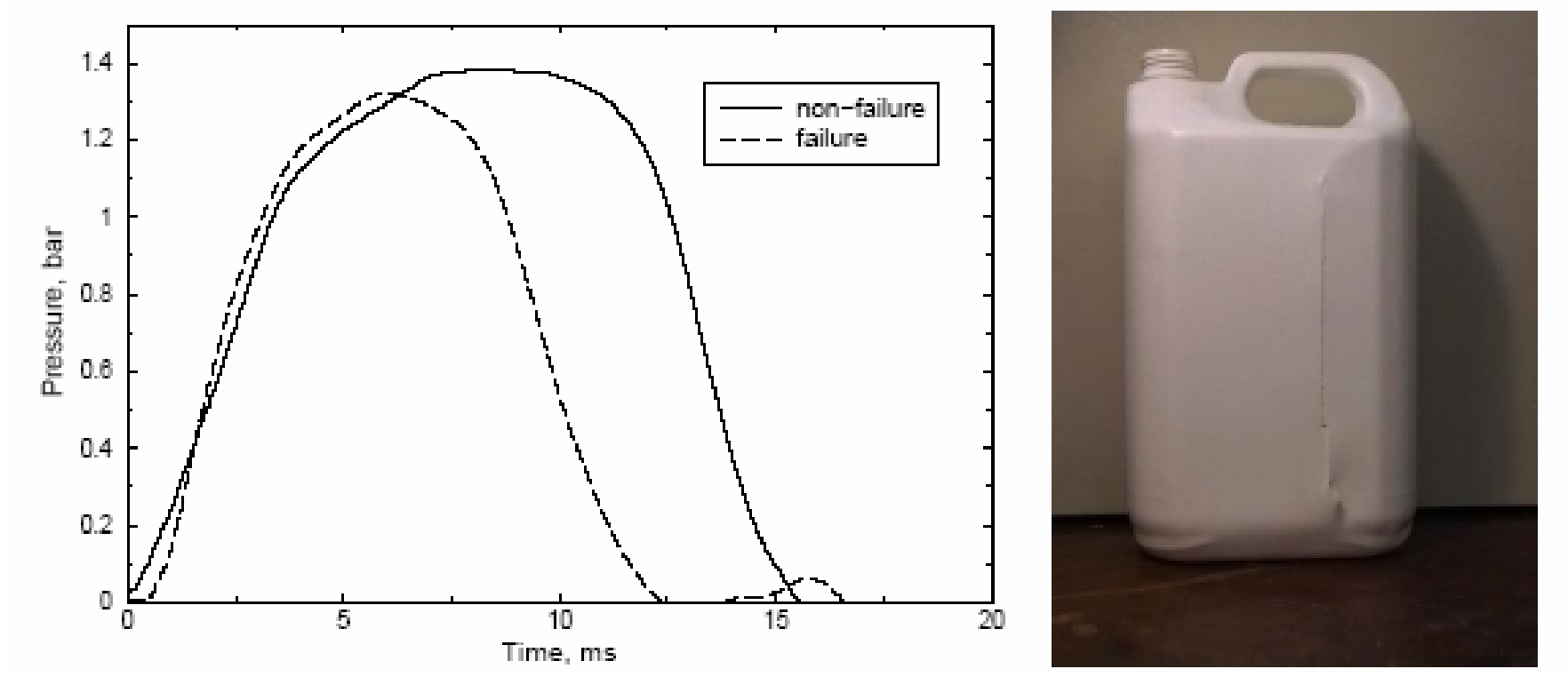
Testing plastic bottles





SR1 container

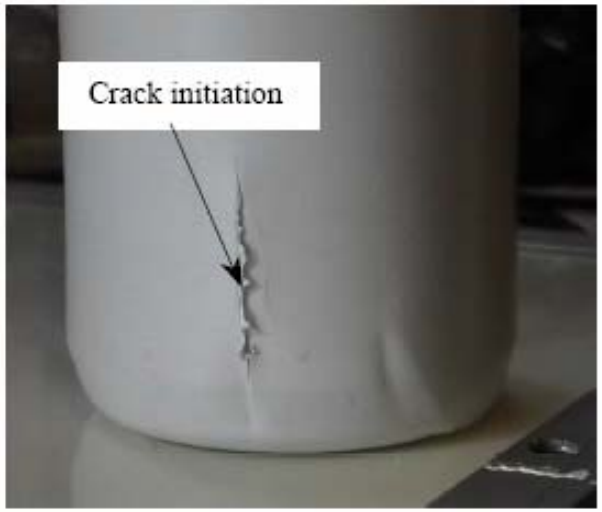
Testing plastic bottles

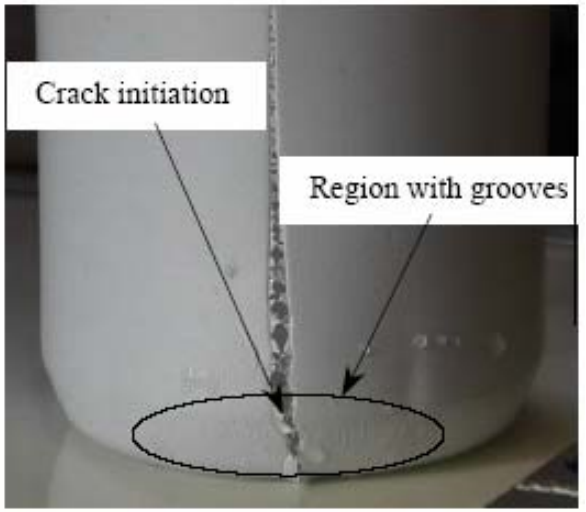


RT6 container

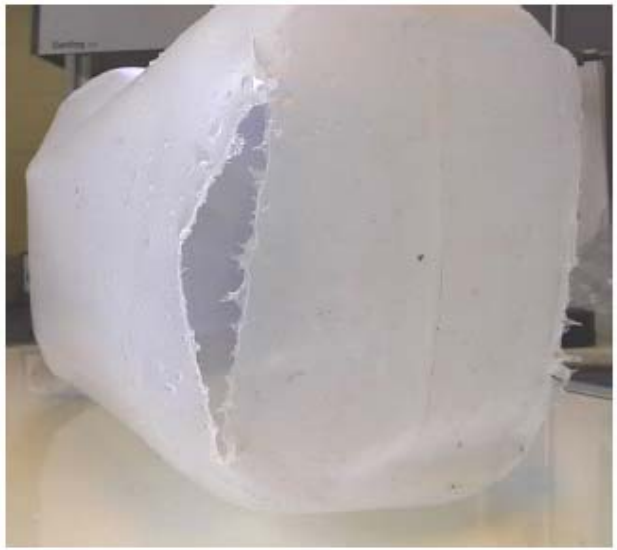
Testing plastic bottles

SR1





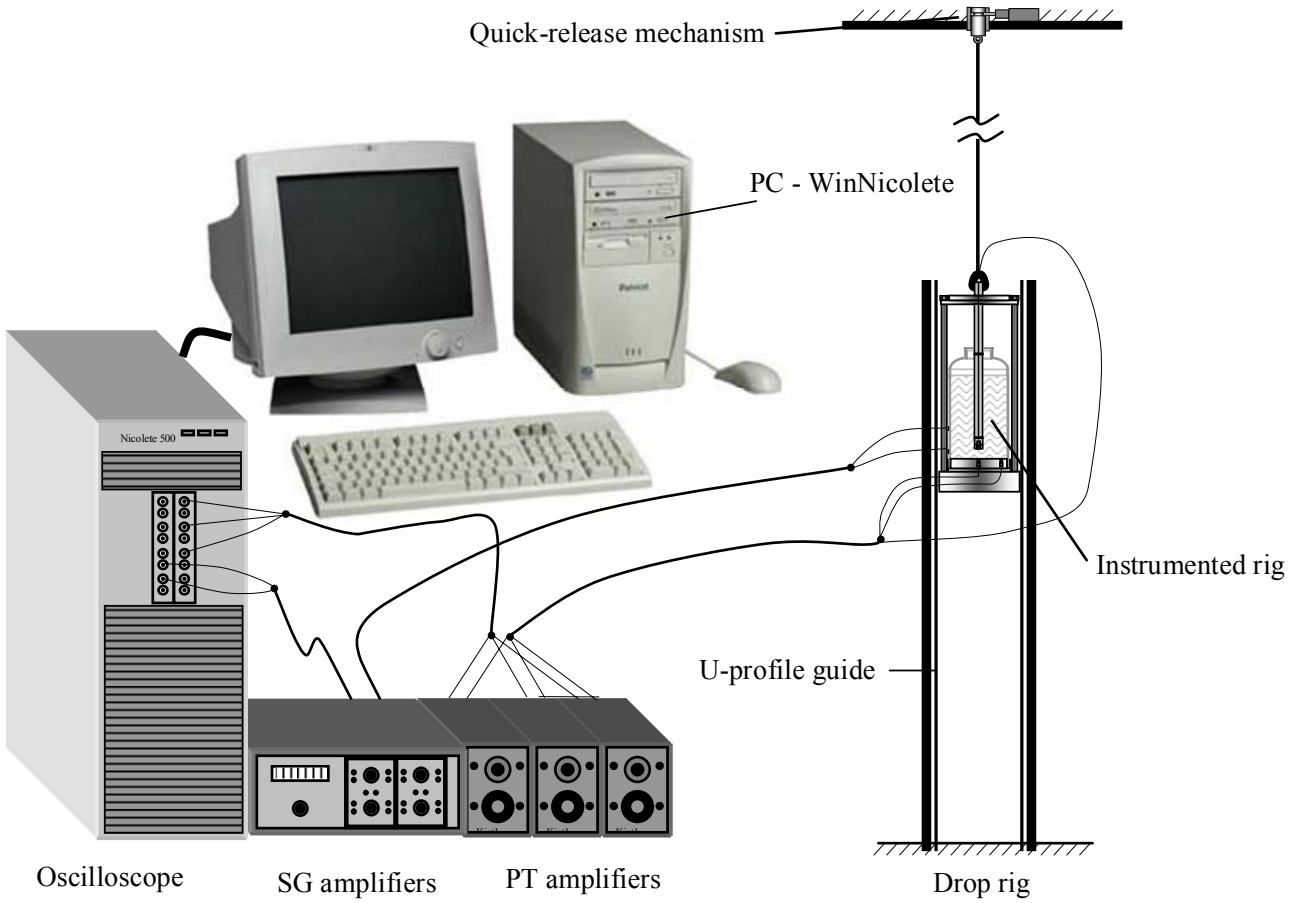
RT6



Fractures containers

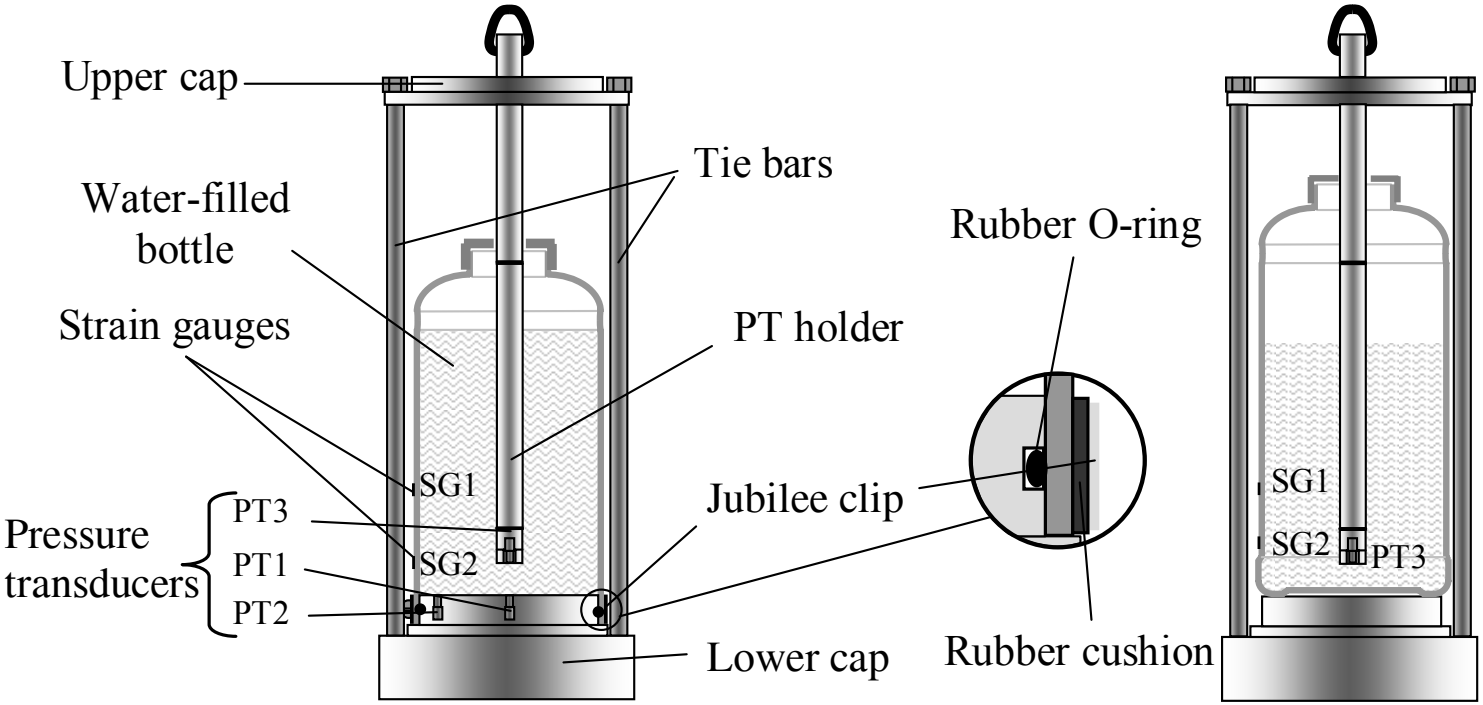
Testing plastic bottles

Experimental set-up



Testing plastic bottles

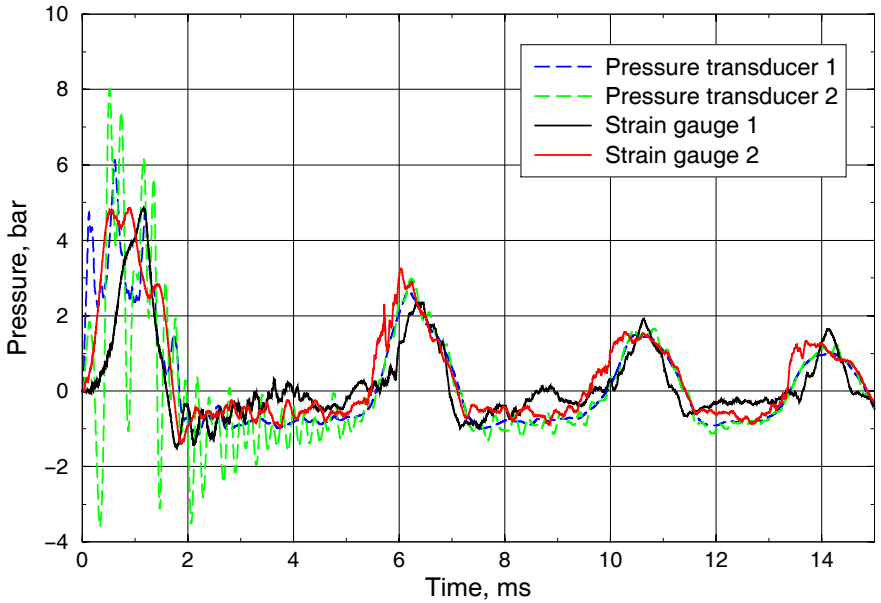
Instrumented rig



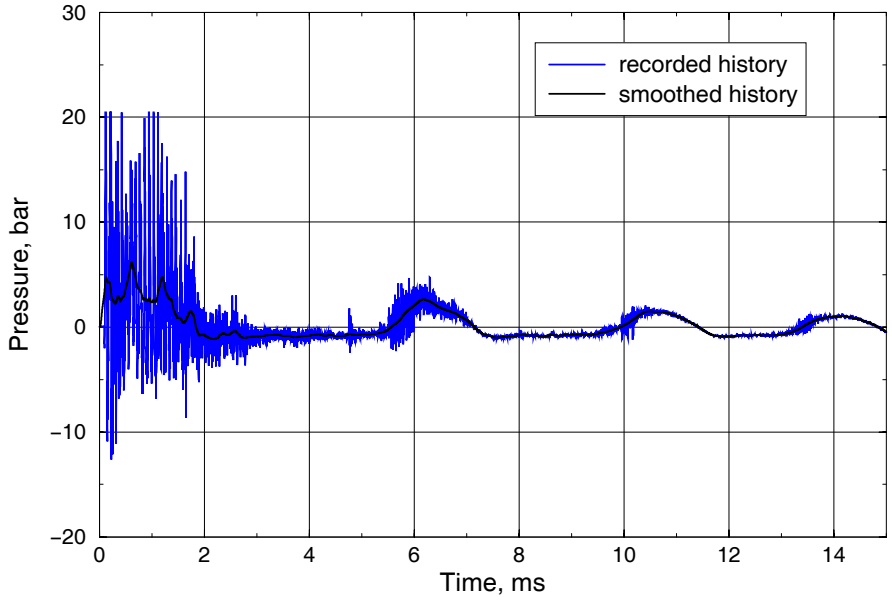
Testing plastic bottles

Pressure histories

All sensors



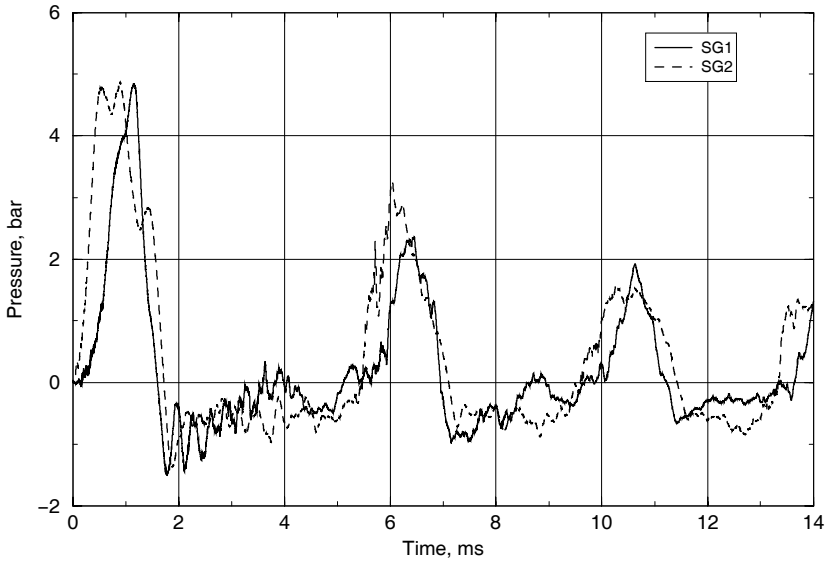
Pressure transducer histories



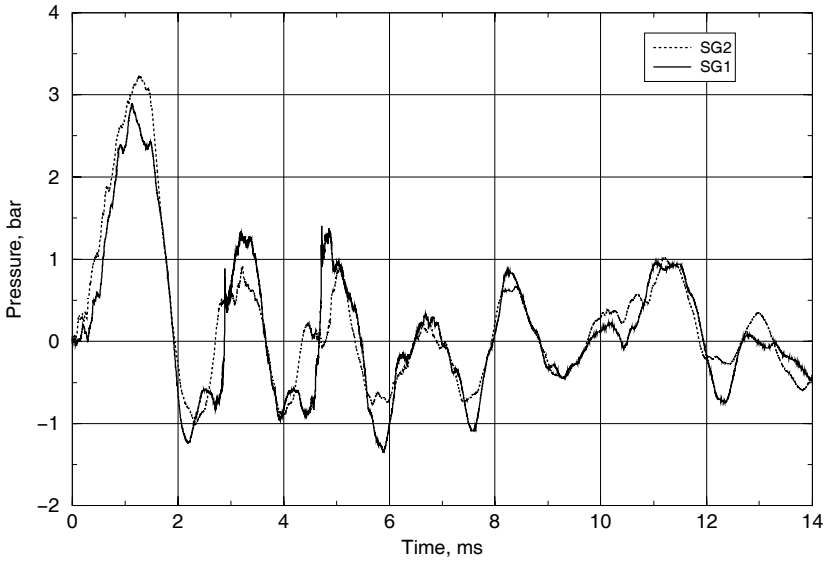
Testing plastic bottles

Strain histories

Bottle without bottom-end



Bottle with original bottom-end

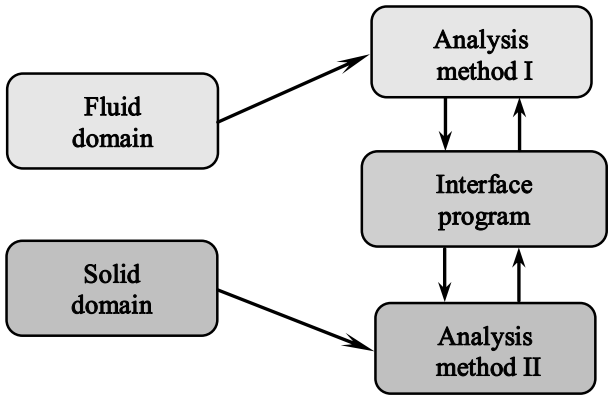


Testing plastic bottles

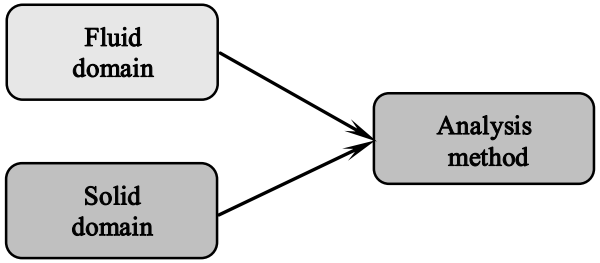
Numerical procedures

Two-system approach:

a)



b)

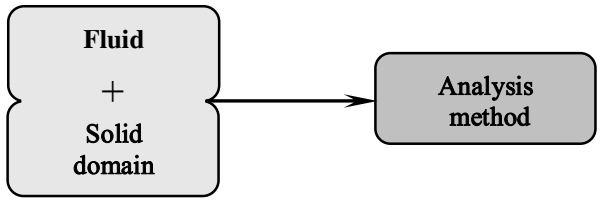


Strongly coupled – interacting

Solids relatively flexible: plastic pipelines, containers, tanks/reservoir sloshing, airbags, cardiovascular flows

One-system approach:

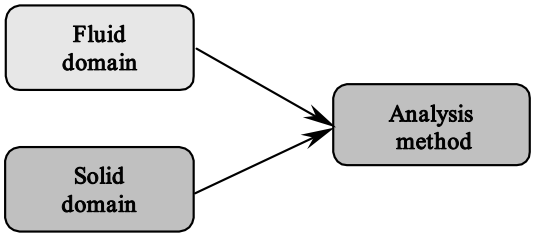
c)



Fully coupled – coupled

Solid-fluid phase transformations: material processing/forming (moulding, casting, extrusion, welding, …)

Testing plastic bottles



Two-system approach:

START OF TIME STEP

1. Solve fluid domain (or 3.)

2. Pass infromation from the fluid to solid domain (or 4.)

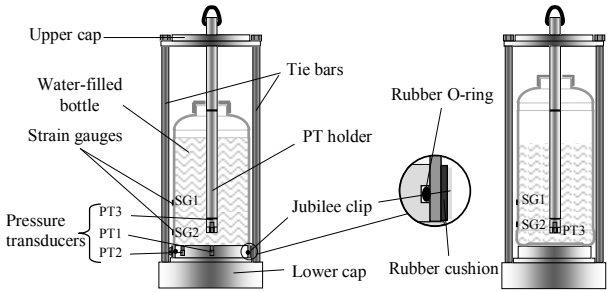
3. Solve structure domain (or 1.)

4. Pass infromation from the solid to fluid domain (or 2.)

END OF TIME STEP

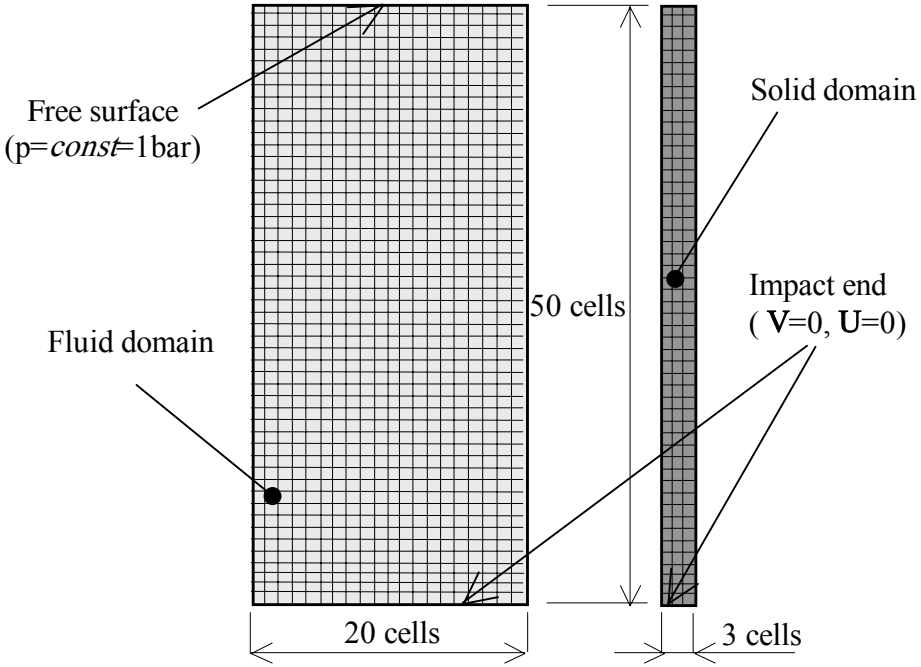
(implicit scheme only)

Testing plastic bottles

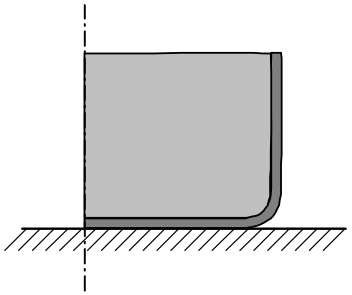


Numerical ‘set-up’

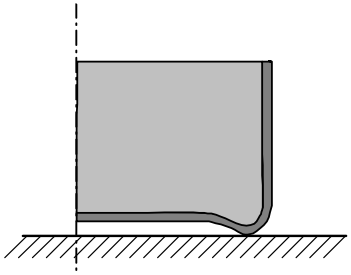
Simple geometry



Flat base

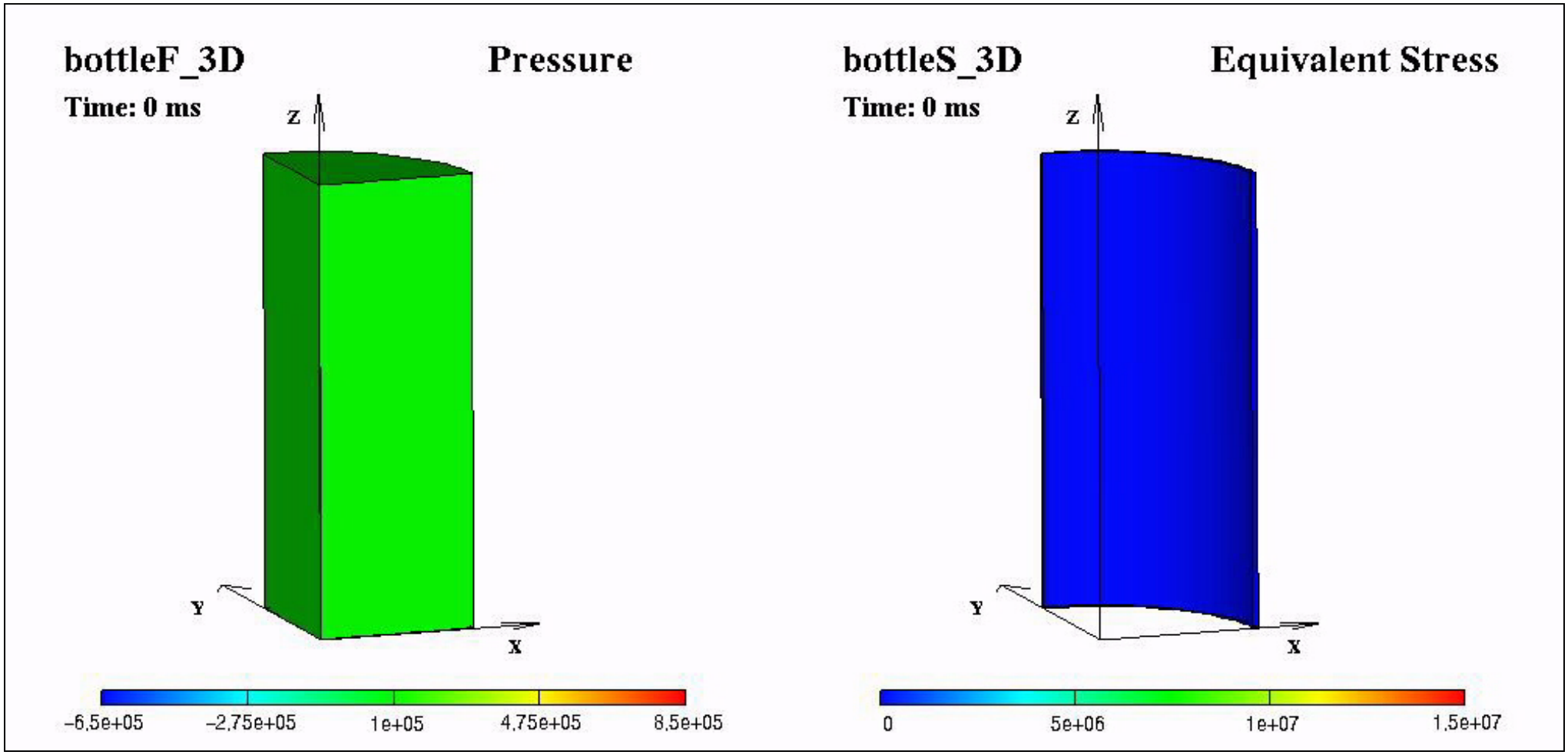


Curved base



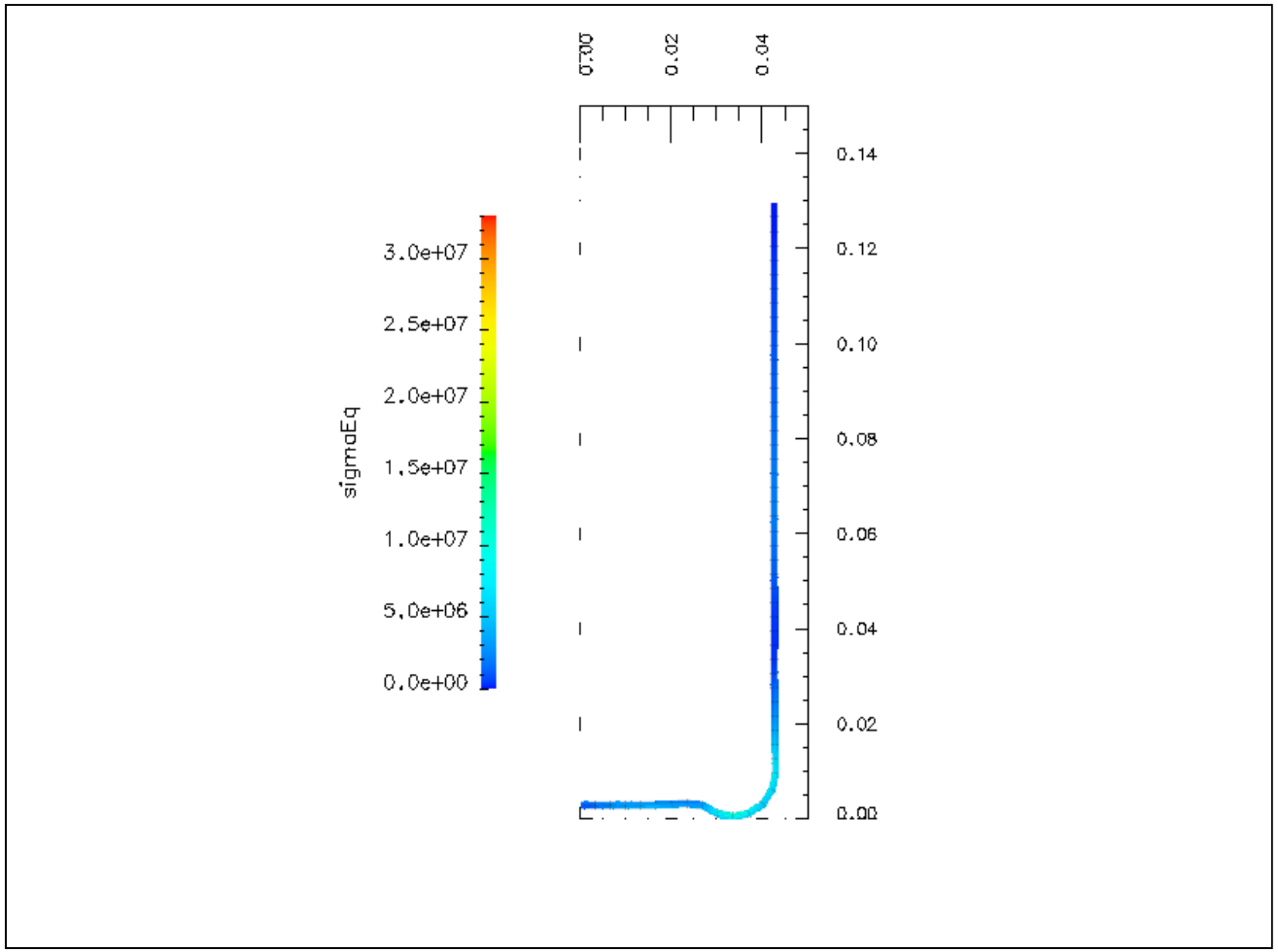
Testing plastic bottles

OpenFOAM simulation – simple geometry

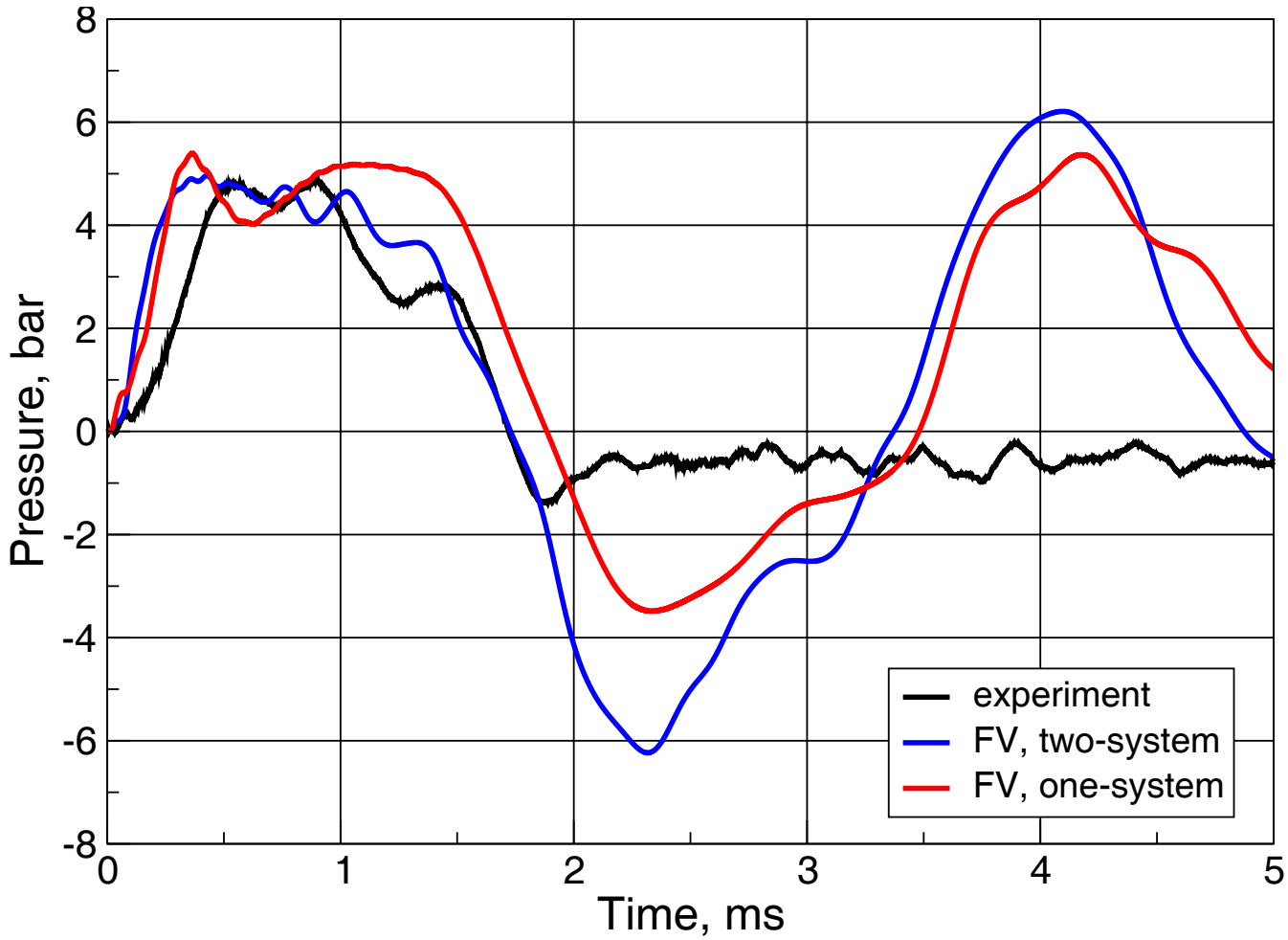


Testing plastic bottles

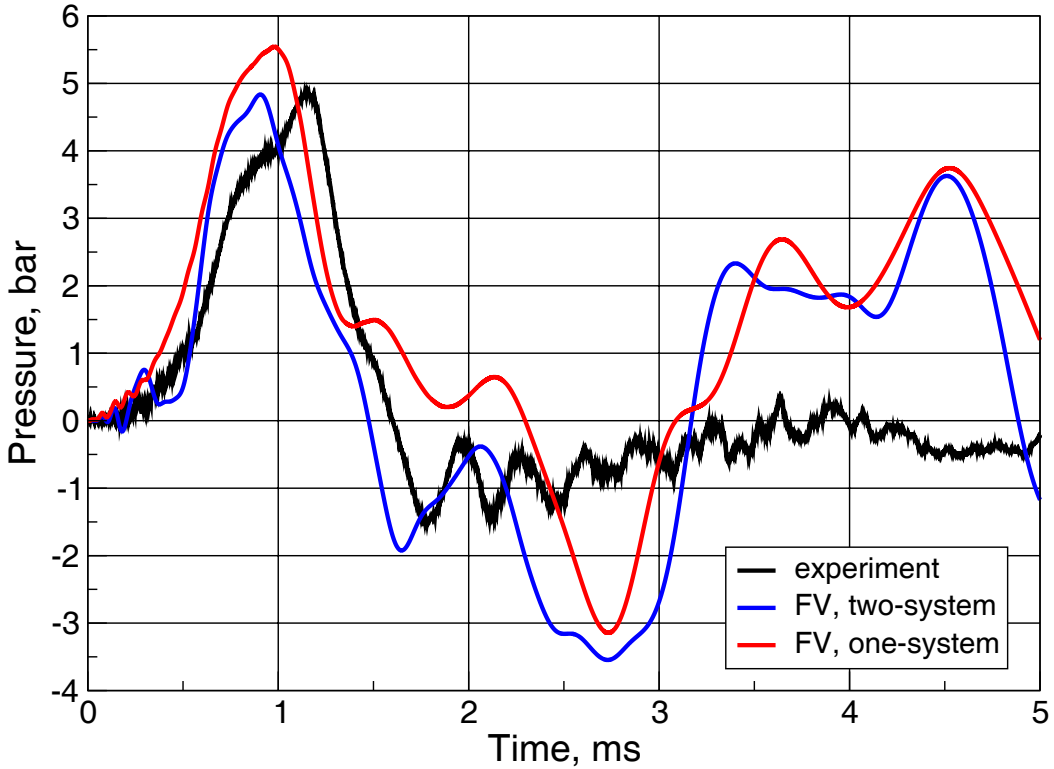
OpenFOAM simulation – base shape effect

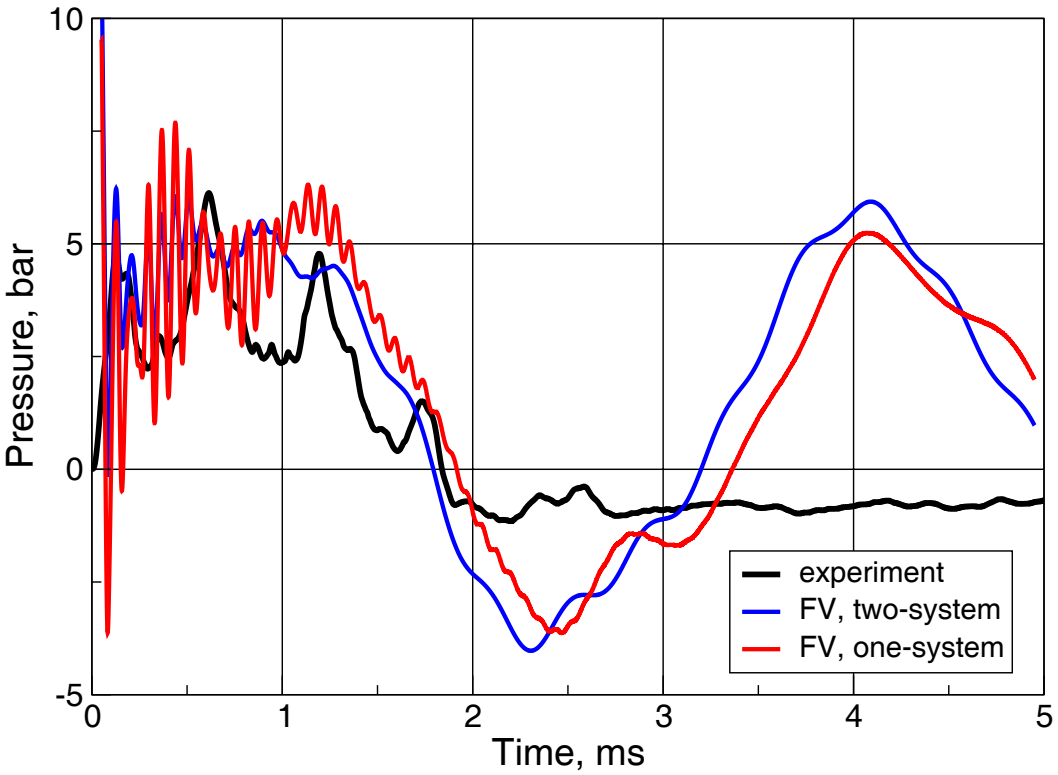


Some quantitative results

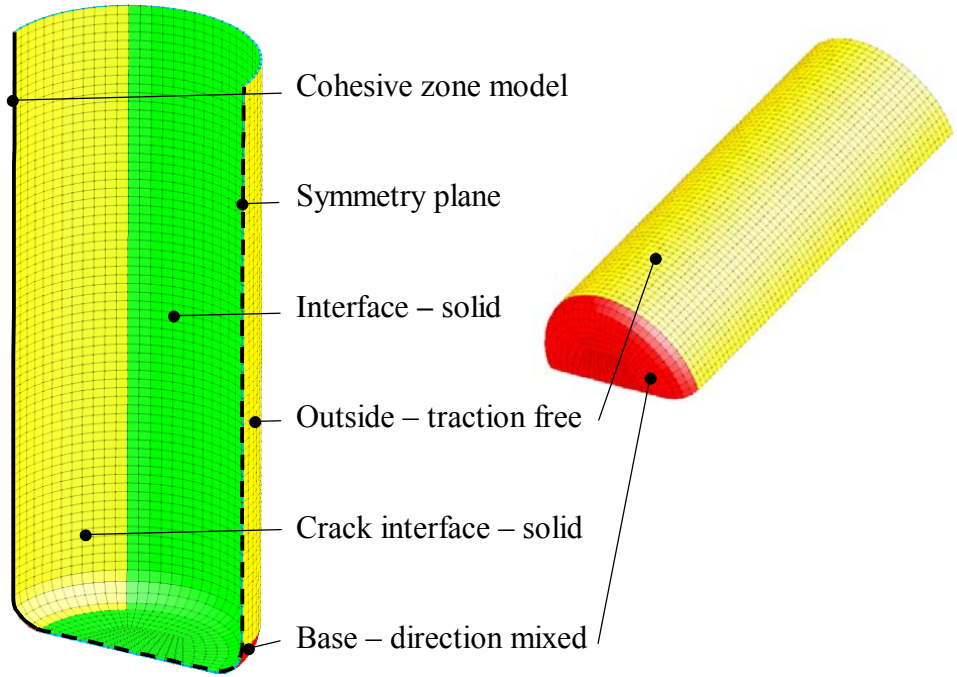


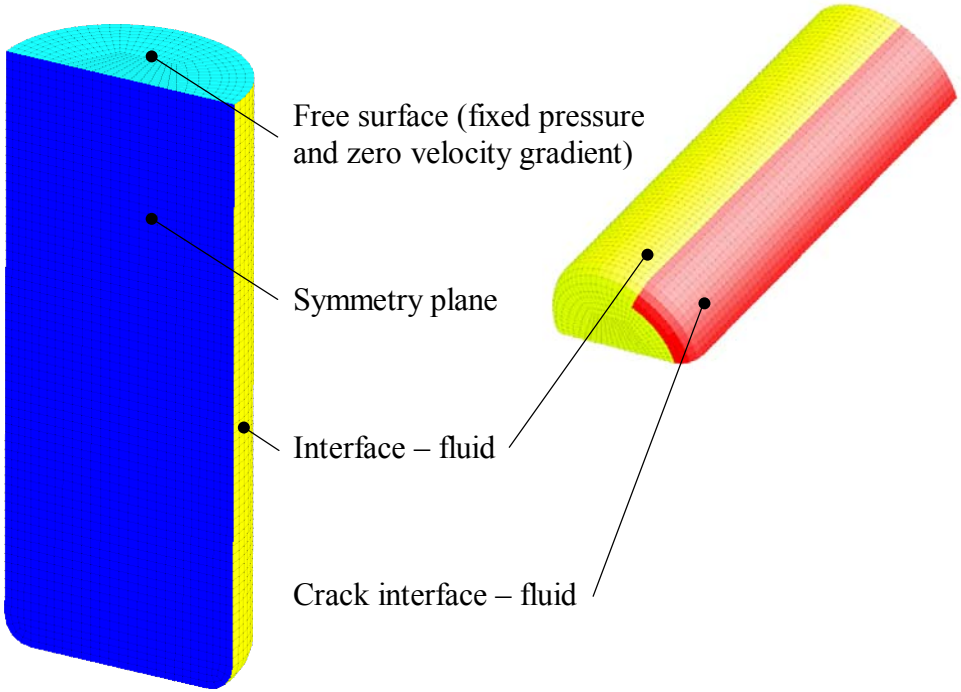
Some quantitative results



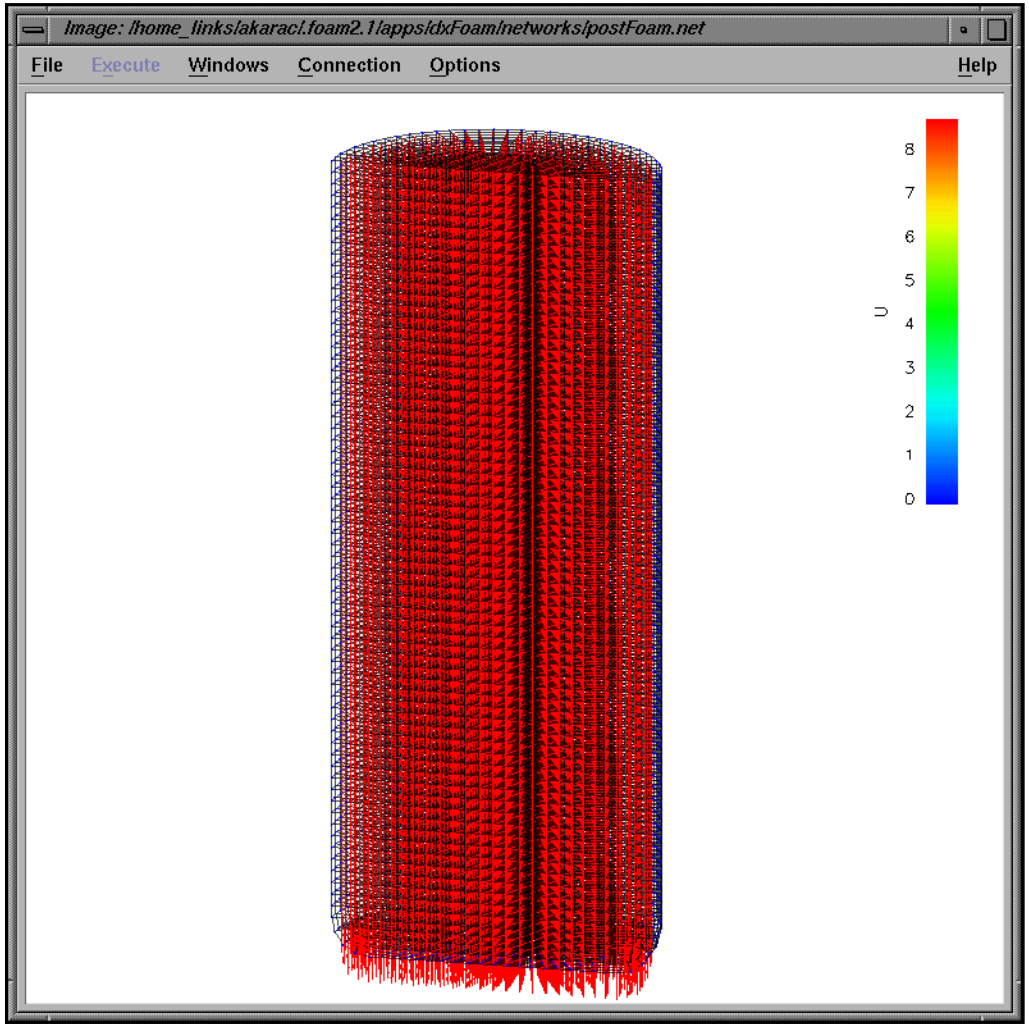


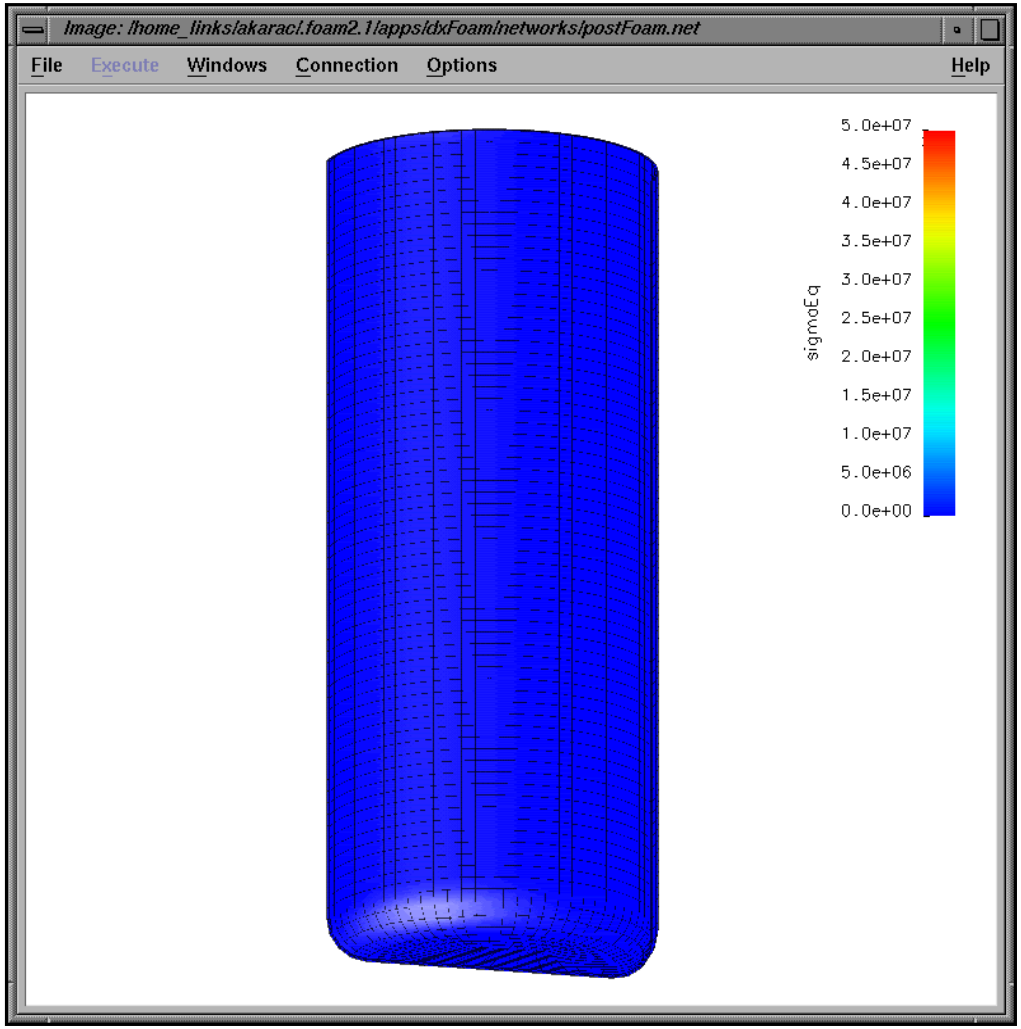
Simulations with fracture – numerical domains





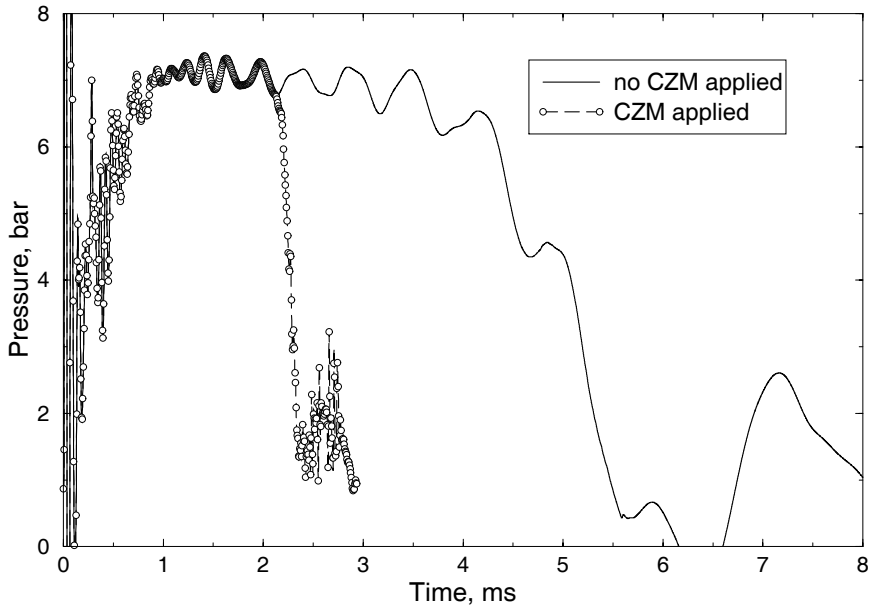
Simulations with fracture – OpenFOAM simulation

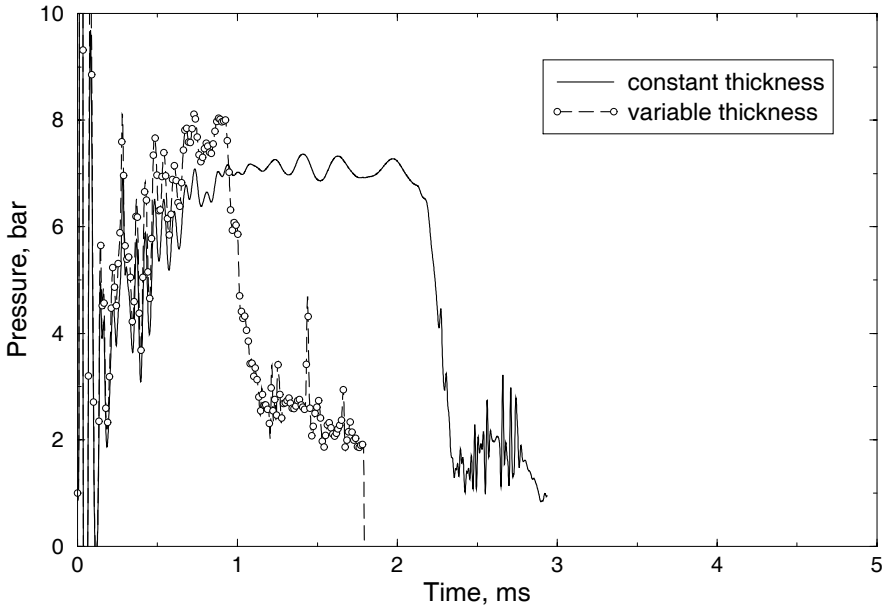




Simulations with fracture – OpenFOAM simulation

Pressure histories





UNIVERZITET U ZENICI
Mašinski fakultet

katedra za Automatizaciju i Metrologiju

PART III:

Testing adhesives and adhesively bonded joints

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