Mechanics and mechanisms of puncture of elastomer membranes

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Regardless of their importance, the intrinsic material parameters controlling the puncture resistance of elastomer membranes are still unknown. Various investigations have been performed on specific cases involving different materials. However, the reported investigations are either qualitative, and do not provide a fundamental understanding of the mechanisms controlling puncture, or are not applicable to the highly elastic elastomer membranes. The puncture resistance of protective gloves to surgical needles was studied in [1, 2]. In these works, 19 commercially available surgical glove liners were qualitatively ranked according to a measurement of the puncture force, in order to compare these materials in terms of puncture protection with respect to the single latex glove. The puncture behavior of rigid plaques such as polycarbonates and acrylics is reported in [3, 4]. In these works, the energy required to perforate the plaque and the peak load recorded in the puncture tests were used to characterize puncture performance. However, the thickness was not taken into account, and no quantitative analysis of the results was performed. More fundamental investigations on puncture have been carried out on rubber blocks by fracture mechanics [5]. With a cylindrical indentor, it was shown that a starter crack initiates as a ring on the rubber-block surface before puncture occurs. Using fracture mechanics, a method has been developed to calculate the fracture energy in puncture. However, this situation is not applicable to thin elastomer membranes. In fact, a quantitative characterization of puncture resistance has been developed for geotextiles and geomembranes. Considering a loading state of pure axisymmetric tension, a correlation was found between the puncture force and the tensile strength for probes greater than 20 mm in diameter [6–9]. However, the results are only applicable in the case of linearly elastic deformation. Thin rubber membranes are for their part hyperelastic, and highly non-linear.

To evaluate puncture resistance, the ASTM F1342 standard test is currently the most commonly used method. Using a conical puncture probe, the test is designed for any type of protective clothing, including coated fabrics, laminates, textiles, plastics, elastomeric films, or flexible materials. This test method determines the puncture resistance of a material by measuring the maximum force required for a conical puncture probe to penetrate through a specimen clamped between two plates with chamfered holes not less than 10 mm in diameter. In a previous investigation, it was found that the probe tip geometry strongly affects the results in puncture characterization. The maximum puncture force depends on the contact surface between the elastomer membrane and the probe tip. The indentation force was calculated for elastomer membranes with large deformations in the absence of friction, using the Mooney strain-energy function. The puncture strengths of elastomer membranes were found to be much lower than their tensile and biaxial strengths. It was also found that the puncture of rubber membranes is controlled by a local equibiaxial deformation on the probe tip, which is independent of the indentor geometry. To find the intrinsic parameters controlling puncture performance, accurate measurements of the equibiaxial deformation on the surface of the probe tip, at the onset of puncture, must be performed. Since the conical probe used in the ASTM F1342 standard is also very costly to produce, it is interesting to find an alternative, simpler, and quantitative measurement not requiring any major modifications of this standard. Since the previous result suggested that there would be a unique relationship between the puncture force and the probe-tip angle, the focus of this work is concentrated on the puncture mechanisms of elastomer membranes by cylindrical probes with both flat and rounded tips.

Three types of commercial rubbers commonly used for protective gloves, neoprene, nitrile, and natural rubber, were investigated. Neoprene sheets with three different thicknesses, 0.40, 0.75, and 1.57 mm, were obtained from Fairprene Industrial Products. The 0.30 mm thick nitrile samples were cut from Nitrile Gloves manufactured by Ansell Co., and the 1.0 mm thick natural rubber samples were cut from NR Gloves, manufactured by Sandstrahler Co. The puncture tests were carried out on an Instron 1137 universal-testing machine. A pin chuck mounted on the load cell held the puncture probes. The elastomer sample was clamped between two steel plates under pressurized air, as shown in Fig. 1a. The hole of the lower plate was chamfered to avoid stress concentration. The cylindrical probes with flat and rounded tips are shown in Fig. 1b and c.

Fig. 2 shows the deformations of the elastomer membrane for the cylindrical probes, with rounded and flat tips. It can be seen that in all geometries, the elastomer membrane always adheres to the probe tip over a certain distance with an equibiaxial deformation on the probe-tip surfaces. The effect of probe radius on the maximum

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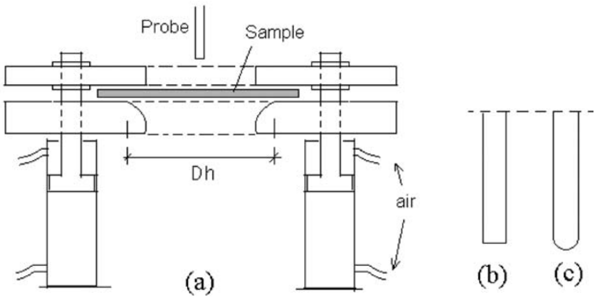

Figure 1 Sketch of sample holder (a); cylindrical probes with flat tip: (b); and cylindrical probes with rounded tip (c).

puncture force is shown in Fig. 3. The results suggest a linear relationship between the maximum puncture forces and the probe radius for the three elastomers tested. Fig. 4 shows the normalized maximum force F/t as a function of the probe diameter for the neoprene sheets of three different thicknesses. It can be seen that the maximum puncture force is proportional to the sheet thickness and the probe diameter.

The results seem to suggest that the puncture behavior of elastomers is controlled by the same material parameter as that of geotextile membranes. The puncture resistance of these materials has been shown to be controlled by their tensile strength, and is given by [6]:

$$T_{\mathrm{f}} = F_{\mathrm{p}}/2\pi r \qquad (1)$$

where T_{f} is the tensile strength per unit width of fabric (kN/m), r is the radius of the probe (m) and F_{p} is the

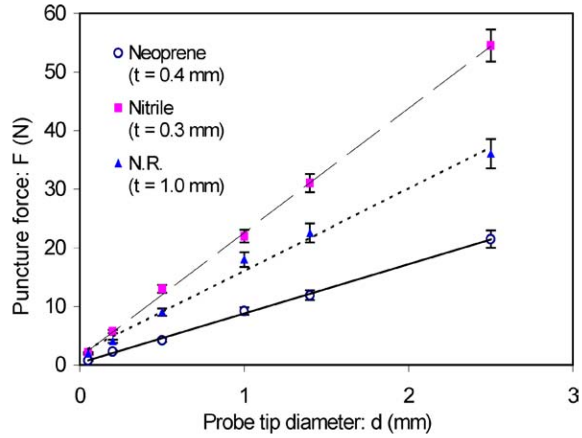

Figure 3 Plots of puncture force versus probe tip diameter for various rubbers.

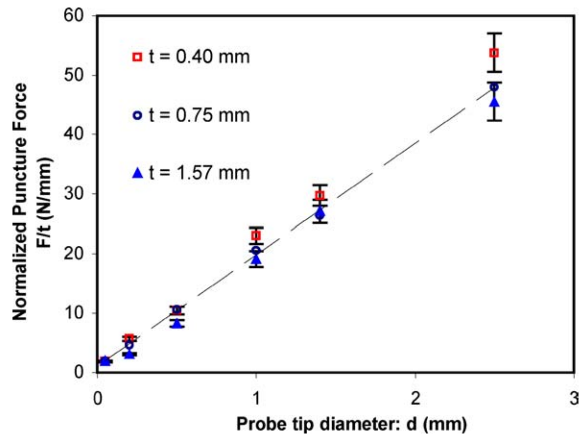

Figure 4 Normalized puncture force as a function of probe tip diameter for Neoprene sheets with different thicknesses.

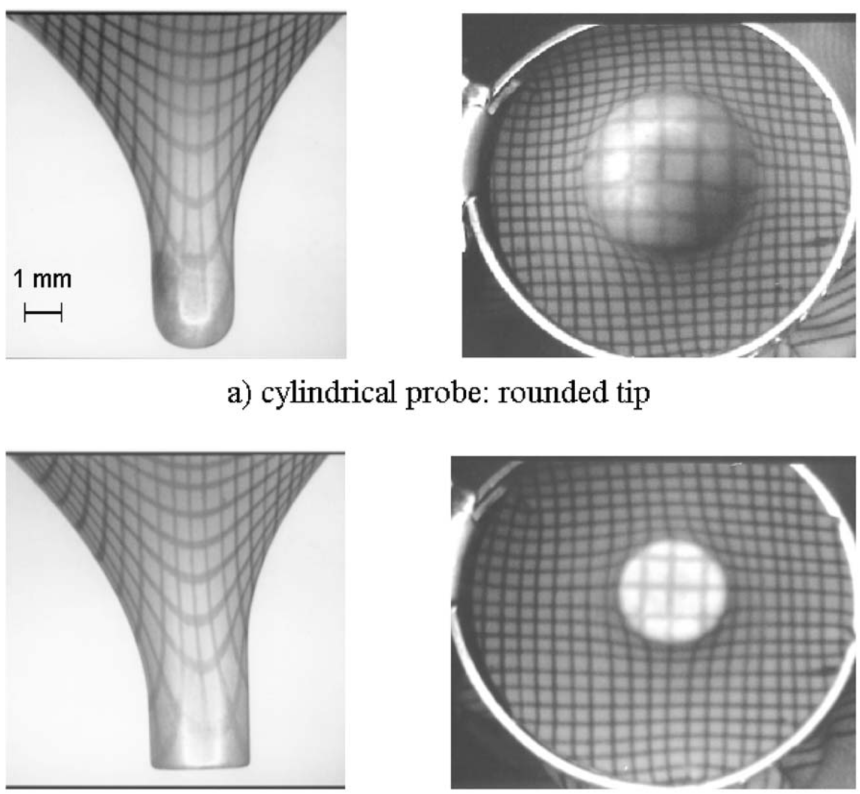

Figure 2 Deformations of the elastomer membrane for the cylindrical probes: (a) rounded tip and (b) flat tip.

TABLE I Failure engineering stress and true stress of tensile and puncture tests (in parenthesis: SD)

Material	Nitrile	Neoprene	N.R.
Failure engineering stress (MPa)			
Tensile	41 (4)	15 (2)	30 (3)
Puncture	55 (7)	18 (2)	25 (3)
Failure true stress (MPa)			
Tensile	210 (22)	71 (7)	325 (31)
Puncture	128 (18)	45 (7)	104 (11)

TABLE II Relations between probe tip diameter and cut-out disk diameter

Material	Nitrile			Neoprene		N.R.
d (mm)	1.0	1.4	2.5	1.4	2.5	2.5
d_f (mm)	0.43	0.60	1.10	0.55	1.05	0.60
d/d_f	2.32	2.33	2.30	2.54	2.40	4.16
e_r	1.32	1.33	1.30	1.54	1.40	3.16
ε_r	0.84	0.85	0.83	0.93	0.88	1.43

puncture force (kN). Table I shows the comparison between the measured tensile and puncture strengths of different elastomers, suggesting that unlike in the case of geotextile membranes, the puncture strength is much smaller than the tensile strength, thus refuting the criterion controlling the puncture resistance of geotextile membranes.

With the cylindrical probes, it is interesting to note that after puncture, a hole in the membrane having a specific diameter is always observed, and a small disk is cut out from the rubber membrane as shown in Fig. 5. The diameter of the cut-out disks, d_f, depends on the probe diameter d, and is always smaller than that of the probe ($d_f < d$). From the deformation observed in Fig. 2, it is reasonable to consider that puncture would take place around the circumferential edge of the cylindrical probe. The diameter of the cut-out disk at the onset of puncture (at maximum equibiaxial deformation) would correspond to the diameter of the probe. Since the deformation is axisymmetrical, the radial strain ε_r and the tangential strain ε_t of the cut-out disk can be calculated. The extension ratios λ_r, λ_t at the radial and tangential directions are, respectively:

$$\lambda_r = d/d_f \tag{2a}$$

$$\lambda_t = \frac{\text{Circumference of cutout disk at puncture}}{\text{Circumference of cutout disk at undeformed state}} = \frac{\pi d}{\pi d_f} = \frac{d}{d_f}. \tag{2b}$$

The corresponding engineering strains and true strains are therefore, respectively:

$$e_r = e_t = \lambda_t - 1 = d/d_f - 1 \tag{3a}$$

$$\varepsilon_r = \varepsilon_t = \mathrm{Ln}(\lambda_t) = \mathrm{Ln}(d/d_f). \tag{3b}$$

To verify the above assumption, the diameters of the cut-out disks were measured with an optical microscope and the results are presented in Table II. Regardless of the probe diameter, the ratio d/d_f is constant for each material, and is very close to the equibiaxial strain measured at the onset of puncture of the elastomer membrane, on the top surface of the probe. In order to verify whether puncture was caused by stress concentration around the circumferential edge of the cylindrical probe with a flat tip, puncture tests using a cylindrical probe with a semi-hemispherical tip were performed. Table III shows the comparisons of the maximum force and deformation at the probe tip between flat and hemispherical tips. It can be seen that the hemispherical geometry of the probe tip gives the same maximum puncture force and equibiaxial strain as the flat tip. It is also interesting to note that the rounded tip probe also produces a hole in the elastomer membrane with a dropout disk of the same diameter as shown in Fig. 6.

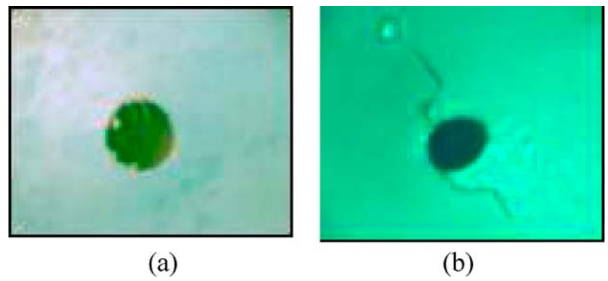

Figure 6 Holes observed in the elastomer membrane after puncture: (a) flat tip and (b) rounded tip.

The result suggests that the puncture in the elastomer membrane is not due to stress concentration around the edge of the flat tip. Within the range of probe diameters investigated in this work (from 0.1 to 2.5 mm), puncture is controlled by an equibiaxial deformation that is independent of the probe diameter and geometry.

The above results are quite interesting for the characterization of the puncture resistance of elastomeric membranes. Indeed, a simpler cylindrical probe can be

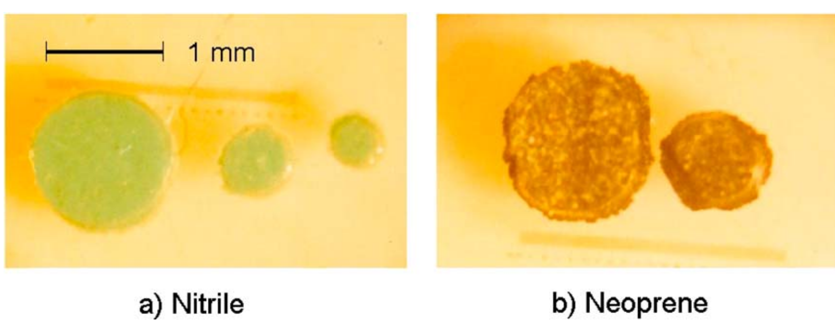

Figure 5 Cut-out disks of easterner samples after puncture (optical microscopy: 20×).

TABLE III Tests results (and their SDs) for two types of puncture probe ($d = 1.0$ mm)

Material	Neoprene		Nitrile		N.R.	
Probe tip type	Flat	Rounded	Flat	Rounded	Flat	Rounded
Puncture force F_p (N)	13.5 ± 0.4	13.6 ± 0.5	21.2 ± 1.4	22.0 ± 0.9	21.0 ± 1.1	20.6 ± 1.6
Max. strain	$1.46 \pm .13$	$1.40 \pm .17$	$1.32 \pm .08$	$1.35 \pm .10$	$3.18 \pm .21$	$3.05 \pm .23$

used in the place of the costly conical probe required by the ASTM Standard and will still provide a quantitative characterization of puncture. Furthermore, the rounded-tip probe gives exactly the same result as that of the flat-tip probe. Since the latter is much easier to produce, the expensive ASTM probe can be replaced by a simple flat-tip cylindrical probe. The cylindrical probe produces a hole with a dropout disk, reflecting the characteristic equibiaxial deformation controlling the puncture resistance of the elastomer membranes. This probe provides a quantitative and much simpler method for the characterization of puncture in these materials.

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