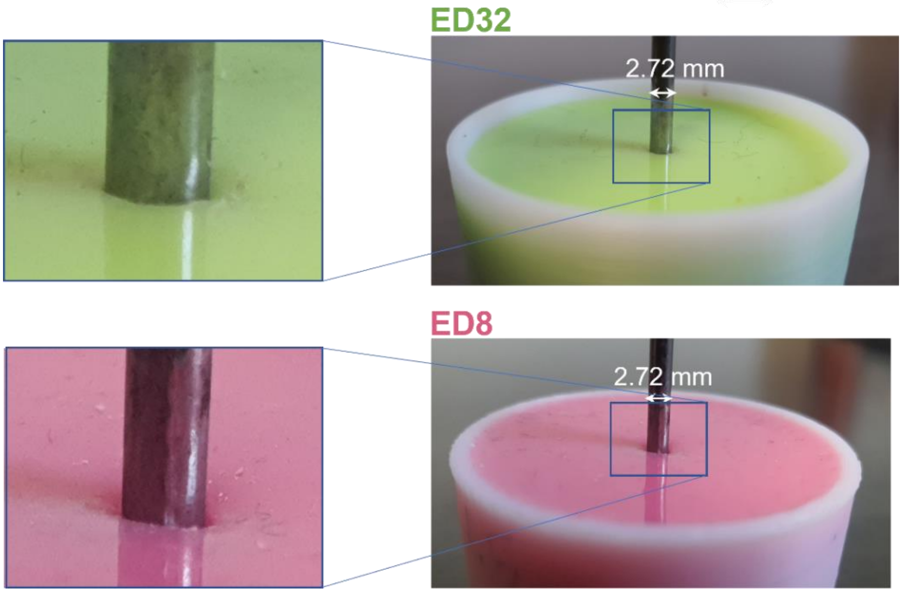
Electronic Supplementary Material (ESI) for Soft Matter.

Electronic Supplementary information for:

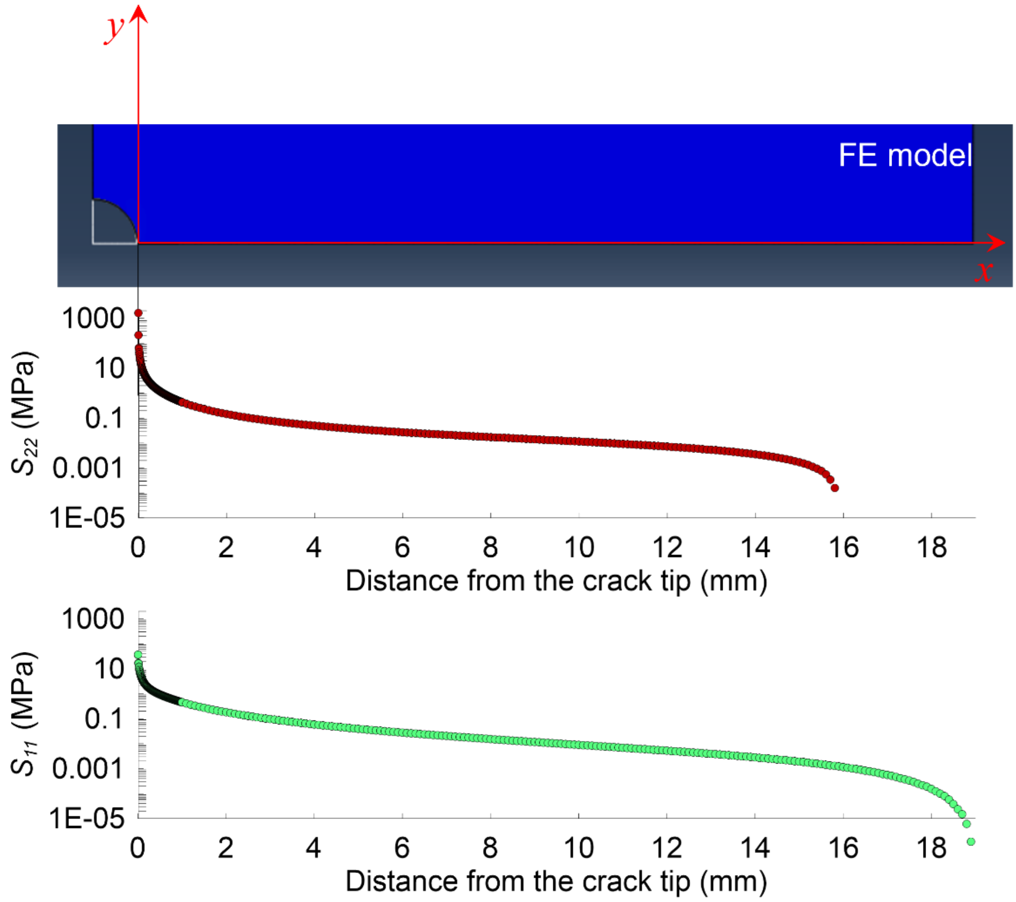
Puncturing of soft tissues: experimental and fracture mechanics-based study

Matteo MONTANARI, Roberto BRIGHENTI, Michele TERZANO, Andrea SPAGNOLI*
*spagnoli@unipr.it

The constraint effect of the ABS cylinder used in the experiments of puncturing is negligible. This can qualitatively be inferred by looking experimentally at the radial profiles of deformed surface of the target silicone during penetration. For instance, in the pictures below one can appreciate that for the most critical cases of $\mathbf{2R = 2.72\ mm}$ the vertical deflection of the material surface is very localised near the spot of needle penetration.

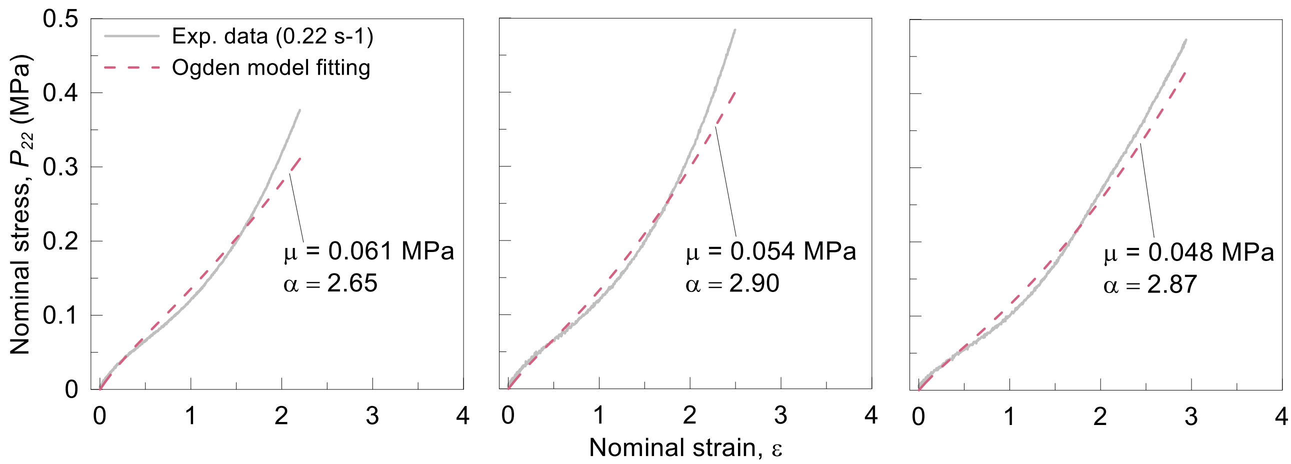


Moreover, selecting the 'worst' case possible in FE simulations ($\boldsymbol{R/a = 1}$, Ogden model with $\boldsymbol{\alpha = 9}$), the stress distributions along the radial direction aligned with the crack plane show a rapidly decreasing trend for both tangential [opening] (S22) and radial (S11) stresses.

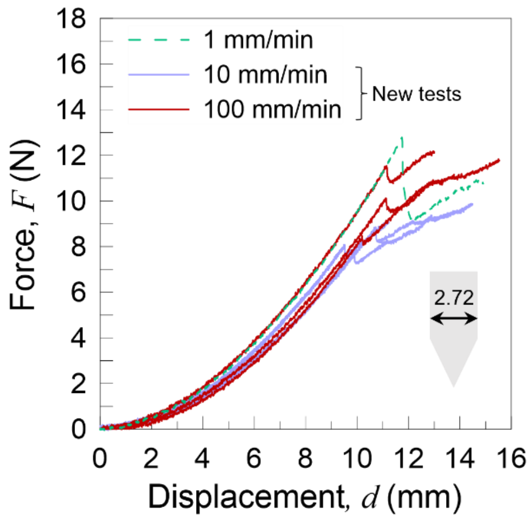


What is indeed evident is the shift of experimental data from theoretical/numerical results when ED8 is considered (see Fig. 9). To this end we performed additional experimental tests in the attempt to clarify the above discrepancy.

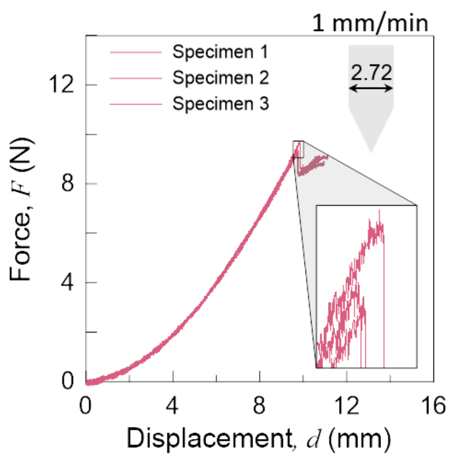
Firstly, as fracture energy has been determined for ED8 by performing pure shear tests at high strain rate ($1\ s^{-1}$), tensile tests at high strain rate ($0.22\ s^{-1}$) were performed with the attempt to explore possible variations in the material's rigidity with respect to that measured at the reference strain rate of $0.001\ s^{-1}$. The experimental results for three coupons are shown below along with the best fitting curves using single-term Ogden function. No significant deviation from the best fitting values obtained with the reference strain rate of $0.001\ s^{-1}$ (μ = 0.061 MPa and α = 2.54, see Fig. 3a) is observed .



Then, the penetration speed for ED8 is experimentally explored using 10 mm/min and 100 mm/min for a $2R = 2.72\ mm$ (note that considering a reference strain $\sigma_0/E^* = 0.5$ - see line before eq. 10, we get a strain rate 0.0083 s^{-1} for a penetration rate of 1 mm/min; consequently a penetration rate of 100 mm/min gives a strain rate of 0.83 s^{-1}). The results are illustrated in the chart below; no clear rate-dependent trend of results is observed.



Finally, to further explore the repeatability of results for penetration tests, the test for ED8 with $2R = 2.72\ mm$ is performed three times at the penetration velocity of 1 mm/min. The plot reported below clearly shows a good consistency in the results.



At this point, it is worth mentioning that the fracture energy for ED8 specimens was calculated by performing pure shear tests under high strain rate to avoid mixed-mode cracking. However, the resulting stress-strain curves exhibited a rather smooth post-peak softening, leading to a degree of uncertainty in the relevant strain energy calculation (to this end, the strain value precisely corresponding to the crack initiation in the experiments should be considered). For the sake of completeness, if fracture energy were calculated by considering the strain energy at full specimen separation (see nominal strain in Fig. 3b at nominal stress equal to zero), the average value of G_c turns out to be equal to 1.348 N/mm instead of 0.754 N/mm. If this newly calculated value of G_c were used in Fig. 9 for ED8, the experimental data points would shift towards the theoretical curves (see light red vs dark red data points for ED8 in the plot below).