Rate dependent shear failure and the scaling effect in long rod penetration

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Abstract. Long rod penetration tests show a scaling effect that cannot be explained by rate dependent strength. We propose here that this scaling effect may be explained by rate dependent failure. We start by revisiting the well known result that long rod penetration efficiency depends on strain to failure of both projectile and target materials. We then make the strain to failure depend on strain rate, using the overstress concept. In this way the effective strain to failure increases with strain rate. As strain rate increases with decreasing scale, we get that penetration efficiency decreases with decreasing scale, as observed in tests. In the paper we show results of hydrocode runs that demonstrate the relation between strain rate sensitivity of strain to failure and the scaling effect in long rod penetration.

1. Introduction
Long rod penetration tests show a scaling effect, as demonstrated by Magness and Leonard in [1]. They compared the penetration efficiency of WHA rods and DU rods into RHA steel targets of 1:4 scale with 1:1 scale, and found that 1:4 scale rods were less efficient by about 20%. Anderson et al. [2] made computer simulations to check whether the scaling effect could be explained by rate dependent strength. Using literature data for rate dependence of the flow stress of the materials involved they found that the effect of flow stress rate dependence is within the scatter of experimentally determined penetration efficiency. Anderson et al. also suggest in [2] that the scaling effect may be explained by rate dependent failure.

Recalling that long rod penetration efficiency depends on strain to failure in compression (shear failure) of the materials involved [3]; we check here whether a rate dependent strain to failure can explain the scaling effect in long rod penetration.

To do this we run computer simulations of L/D=10 rods, with an impact velocity of 1.5 km/s, penetrating steel targets. We introduce rate dependent strain to failure by the overstress approach. In a dynamic situation (like long rod penetration), the failure process may be to slow to happen right away when the effective plastic strain exceeds the quasi static strain to failure at some computational cell. Therefore, the state point may go beyond the quasi static strain to failure without loosing strength, and the flow stress Y decreases only with time.
2. Rate dependent strain to failure

Let \( \varepsilon_{qs} \) be the strain to failure under quasi static compressive loading. This means that for any computational cell under quasi static loading we have:

\[
\begin{align*}
Y &= Y_0 & \varepsilon_{eff}^p &\leq \varepsilon_{qs} \\
Y &= 0 & \varepsilon_{eff}^p &> \varepsilon_{qs}
\end{align*}
\]

(1)

where \( Y_0 \) is the initial flow stress, and \( \varepsilon_{eff}^p \) is the effective plastic strain. In a dynamic situation (like long rod penetration we are dealing with here), the failure process may be too slow to happen right away when the effective plastic strain exceeds the quasi static strain to failure at some computational cell. To model such a situation we let the material keep its strength, and provide for a time dependent relaxation of the flow stress. This is an example of the **overstress approach**. According to this approach, whenever a mechanical system has a threshold surface for a set of variables in a quasi static situation, the state point may cross this surface in a dynamic situation, but would then relax back towards it at a rate that increases with the amount of overstress. Accordingly, the failure equations that we use are:

\[
\begin{align*}
Y &= Y_{qs} & \varepsilon_{eff}^p &\leq \varepsilon_{qs} \\
\dot{Y} &= -A_f Y & \varepsilon_{eff}^p &> \varepsilon_{qs}
\end{align*}
\]

(2)

where the parameter \( A_f \) expresses the rate dependence of the failure process. For large \( A_f \) the failure process is fast, and vice versa.

3. Simulations

The example we run is of a WHA tungsten L/D=10 projectile penetrating a RHA steel thick target. The projectile length is 100 mm, its diameter 10 mm, and its impact velocity is 1.5 km/s. We use the Euler processor of the old commercial code 2D-PISCES. The material parameters we use for RHA steel are:

\[
\begin{align*}
\rho_0 &= 7.85 \text{gr/cc} & C_0 &= 4.61 \text{km/s} & S &= 1.73 \\
\Gamma_0 &= 1.67 & \rho \Gamma &= \text{Const.} & G &= 80 \text{GPa} \\
Y_{qs} &= 1.0 \text{GPa} & P_{min} &= -3.2 \text{GPa} & \varepsilon_{qs} &= 0.5
\end{align*}
\]

(3)

and the material parameters we use for the tungsten alloy are:

\[
\begin{align*}
\rho_0 &= 17.2 \text{gr/cc} & C_0 &= 3.99 \text{km/s} & S &= 1.24 \\
\Gamma_0 &= 1.5 & \rho \Gamma &= \text{Const.} & G &= 160 \text{GPa} \\
Y_{qs} &= 1.5 \text{GPa} & P_{min} &= -3.2 \text{GPa} & \varepsilon_{qs} &= 0.5
\end{align*}
\]

(4)

where \( \rho \) is density, \( C_0 \), \( S \) are the parameters of the Hugoniot curve, \( \Gamma \) is the Gruneisen coefficient, \( G \) is the shear modulus, and \( P_{min} \) is the spall strength. We use for both materials in this example a quasi static strain to failure of 0.5.

Our first two runs of the penetration event are aimed at measuring (from the simulation results) the influence of strain to failure on penetration efficiency. To this end we compare penetration history from the run with the parameters above, to a similar run where we turned off the strain to failure (used a large number for it) in both projectile and target. We show this comparison in figure 1. The influence of rate dependent strain to failure can only be as large as the difference between the results of these two runs.

From figure 1 we see that the penetration efficiency increases when strain to failure in both projectile and target decreases. In this example the influence of strain to failure on the total penetration
is about 20%. We therefore anticipate that the effect of rate dependent strain to failure would be some part of these 20%.

**Figure 1.** Penetration depth histories without rate dependent failure. Full line: with the quasi static strain to failure. Broken line: with no strain to failure.

**Figure 2.** Penetration depth histories for different values of (rate independent) strain to failure in the projectile. Quasi static strain to failure in the target.

**Figure 3.** Penetration depth histories for different values of (rate independent) strain to failure in the target. Quasi static strain to failure in the projectile.

**Figure 4.** Penetration depth histories with rate dependent strain to failure. Full and broken lines: rate independent strain to failure curves from figure 1. Dotted line: rate dependent strain to failure with $A_f=0.1/\mu s$.

In figures 2 and 3 we show the influence of changing strain to failure in the projectile and in the target separately. Figure 2 is for the projectile, and figure 3 is for the target. We see from figures 2 and 3 that the influence of strain to failure in the projectile and in the target is about the same. Also,
comparing to figure 1 we see that the two influences add up. It is easy to understand why an increase of strain to failure in the target decreases penetration efficiency. Increase of strain to failure in the target strengthens the target, and it is more difficult to penetrate it. But the influence of strain to failure in the projectile, which is similar to that of the target, is counter intuitive. The explanation, as we have shown in [3] by computer simulations, is as follows. Increasing strain to failure in the projectile makes it harder for the projectile head to flow plastically backwards (relative to the projectile/target interface) in the narrow penetration crater. The incoming projectile reaching the crater bottom needs therefore, at least partially, to penetrate itself, and this decreases penetration efficiency. In [3] we called this mechanism penetration flow effect. The penetration flow effect would hold over the whole range of strain to failure, and its magnitude is enhanced for high values of the flow stress.

In figure 4 we show the curves from figure 1 together with the penetration history curve from an additional run, with rate dependent strain to failure in both projectile and target, and with \(A_f=0.1/\mu s\). We see from figure 4 that, as expected, using rate dependent strain to failure moves the penetration history curve from the rate independent curve towards the no failure curve.

We made two more runs with different values of the parameters \(A_f\), and we show the results in figure 5. We see from figure 5 that as expected, by increasing the rate dependence parameter \(A_f\), the penetration history curve approaches the rate independent curve, and by decreasing it, the penetration history curve approaches the no strain to failure curve.

Finally we made an additional run with a 1:5 scale, to see how rate dependent strain to failure reproduces the scaling effect. We used \(A_f=0.5/\mu s\), and we show the results in figure 6. We see from figure 6 that, as expected, the relative penetration efficiency is lower for the 1:5 scale run. This is in the same direction as the tests, and the difference is about 8%. We expect this difference to increase for higher aspect ratio projectiles.

4. Summary
From tests we know that there is a scaling effect in long rod penetration into thick targets. This means that the penetration process may be rate dependent. Anderson et al. checked whether this scaling effect can be explained by rate dependence of the flow stress, as determined from other tests. They found
that rate dependence of the flow stress is too small to explain the scaling effect. Here we check by computer simulations whether rate dependent strain to failure can explain the scaling effect. We propose a rate dependent strain to failure using the overstress approach, and our model includes just a single material parameter to be calibrated from tests. We show that rate dependent strain to failure is capable of explaining (and after appropriate calibration also of predicting) the scaling effect of long rod penetration. Our simulations are for the special case of a tungsten alloy projectile penetrating a steel target. This should work for other projectile-target combinations, but the magnitude of the effect needs to be checked for each case separately.

5. References
[1] Magness L S and Leonard W 1993 Scaling Issues for Kinetic Energy Penetrators 14th International Symposium on Ballistics, Quebec 281-289
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[3] Partom Y 1995 Projectile Flow Effect in Long Rod Penetration 15th International Symposium on Ballistics, Jerusalem 107-113