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The role of strain rate in the dynamic response of materials

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***Abstract*— We start with the response of ductile materials. To understand the response of these materials to fast dynamic loadings, we introduce two approaches to dynamic viscoplasticity. These are the flowstress approach and the overstress approach, and strain rate has different roles with these two approaches. At very high loading rates the flowstress approach implies very high strength, which is hard to explain by microscale considerations, while the overstress approach does not.We then demonstrate the advantage of using the overstress approach by applying the two approaches to the elastic precursor decay problem.**

Next use the overstress approach to treat the following problems: 1) the 4th power law response in steady flow of ductile materials; 2) high rate stress upturn (HRSU) of ductile materials; and 3) HRSU of brittle materials. With these examples we demonstrate the advantage of using the overstress approach over the flowstress approach. It follows that HRSU means High (strain) Rate Stress Upturn and not High Rate Strength Upturn, as would follow from using the flowstress approach.

***Keywords*— strain rate, ductile materials, HRSU.**

I. INTRODUCTION

We start with the response of ductile materials. To understand and clarify the role of strain rate in the dynamic response of ductile materials,it helps to accept first that there are two approaches to dynamic response of materials, namely: the **flowstress** approach and the **overstress** approach. The flowstress approach is the one that's commonly recognized and used, and it appears as user subroutines in most or all commercial and non-commercial hydrocodes and finite element codes. It seems to us that the flowstress approach became common knowledge and practice since the work of Wilkins [1], who introduced it into his own hydrocode together with his radial return scheme. Before that, the common approach to viscoplasticity was more like the overstress approach that we describe later.

With the flowstress approach the flowstress Y (also called yield stress or strength) is given by:

$$Y = Y\left(P, T, \varepsilon^p_{eff}, \dot{\varepsilon}_{eff}\right) \quad (1)$$

where Y= equivalent stressfor plastic flow, P=pressure, T=temperature, ε^p_{eff} =effective plastic strain and $\dot{\varepsilon}^p_{eff}$ =effective plastic strain rate. The main properties of the flowstress approach are: 1) the stress point (in stress space) is either within (elastic response) or on (plastic response) the flow surface (where equivalent stress =Y); 2) the stress point may jump from the elastic range to the flow surface and vice versa, thereby changing the response from elastic (plastic) to plastic (elastic); and3) the transition from elastic response to plastic response and vice versa is instantaneous.

For any plastic deformation the effective plastic strain increases monotonically. It follows that the flow surface becomes larger with loading, and so does the elastic range in stress space. In contrast, the effective strain rate may jump from low to high values and vice versa depending on loading dynamics, and the flow surface would jump with it. For a highly vibrating loading sequence this would cause a material point to oscillate very quickly. Also, for very high loading rates the flow stress would jump to high values unless the dependence on strain rate is limited artificially.

The overstress approach recognizes that elastic-plastic transition is not instantaneous. On the microscale, plastic flow requires creation of dislocations and flow of these dislocations through the crystal lattice with a speed that is less than the sound speed. Therefore, when a material is loaded at a very high rate, like in shock loading, the elastic-plastic transition does not have enough time to come about, and the state point in stress space may go outside the flow surface and still respond elastically, fully

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or partially. When we consider such a response we refer to it asan**overstress** approach.

A simple straightforward way to demonstrate the validity of the overstress approach is through a planar shock loading: an infinite viscoplastic thick plate is shock loaded on its longitudinal end by a stress σ. Using the flowstress approach we get that: 1) as long as $\sigma \le (1-\nu)/(1-2\nu)Y=\beta Y=HEL$ (Hugoniot Elastic Limit), where ν is Poisson's ratio, the response is elastic, and the ingoing shock stress is σ; 2) when σ is above HEL, a precursor elastic wave of stress HEL enters the plate, and the main wave of stressσ follows at a slower velocity. Running a 1D simulation with a hydrocode that uses the flowstress approach, the value of Y that the code calculates depends on the mesh resolution. For a higher resolution the strain rate is higher, and so is the value calculated for the flowstress Y. In Fig. 1 we show an example of such a simulation.

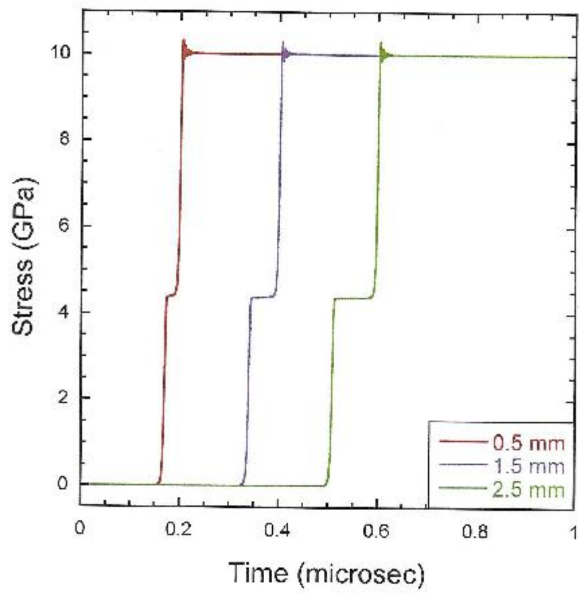

Fig.1: Elastic precursor wave from a simulation with the flowstress approach.

In the simulation that produced Fig. 1 the plate is stainless steel, the ingoing shock stress is 10GPa, the mesh resolution is 100 cells/mm and the flowstress dependence on strain rate is by the usual logarithmic relation as in Eq. (2).

$$Y = Y_0\left(1 + C_r \ell n \frac{\dot{\varepsilon}}{\dot{\varepsilon}_{ref}}\right) \tag{2}$$

To get a strong dependence we used in the simulation $C_r=0.1$.

We see from Fig. 1 that: 1) The elastic precursor wave is much stronger than the quasistatic HEL (4.5GPa versus 1.5GPa); and 2) the elastic precursor wave stays constant (is not decaying) as it progresses into the plate.

But it has been known for years [2,3] that in tests we don't get a constant level elastic precursor, but rather a decaying elastic precursor wave, which is reproduced when using the overstress approach, as we demonstrated in [4].

With the overstress approach we define the effective plastic strain rate as function of the overstress (equivalent stress minus quasistatic stress):

$$d^p_{eff} = \dot{\varepsilon}^p_{eff} = f\left(s_{eq} - Y_{qs}\right) \tag{3}$$

wheres_{eq} is the equivalent stress and Y_{qs} is the quasistatic yield stress.We refer to the function f as the **flow curve** of the considered material. In [5] we've shown that by using for f the function:

$$d^p_{eff} = d_0\left(\frac{s_{eq} - Y_{qs}}{Y_0}\right)^{\alpha} \tag{4}$$

with just one calibration parameter (d_0), and with α=2.4, we can reproduce Grady's 4th power law relation[6]. The coefficient d_0 may of course depend on pressure, temperature and the effective plastic strain. Implementing the overstress approach in a hydrocode, we use Eq. (4) together with the Prandtel-Rauss equation ($d^p_{ij}=\lambda s_{ij}$). The significance of Eq. (4) is that: 1) the plastic strain rate increases exponentially with stress; 2) for a given total strain rate, the elastic strain rate, and therefore also the stress rate, decrease with stress until the stress rate is zero; and 3) the elastic strain rate is the difference between the total strain rate (as given by the problem dynamics) and the plastic strain rate (as given by Eq. (4)). The stress rate is therefore positive or negative, according to the sign of this difference.

Duval [8] derived in the 1960s the following approximate equation for the rate of change of the elastic precursor in a planar shock loading:

$$\frac{\partial\sigma}{\partial h} \cong -\frac{G}{c_L} d^p \tag{5}$$

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where h=Lagrangian longitudinal coordinate, G=shear modulus and c_L=longitudinal sound speed. Using a1D strain flow curve similar to Eq. (4) we get:

$$\frac{\partial\sigma}{\partial h} \cong -\frac{G}{c_L} d_0 \left(\sigma - \beta Y\right)^{\alpha} \qquad (6)$$

and we see from Eq. (6) that for $\sigma>\beta Y$, $\sigma(h)$ is a decreasing function, as obtained in tests. Eq. (6) is of course an approximation, and the exact $\sigma(h)$ curve can be evaluated numerically using a hydrocode. In Fig. 2 we show the result of a hydrocode simulation using the viscoplastic overstress approach for the same impact problem as in Fig. 1.

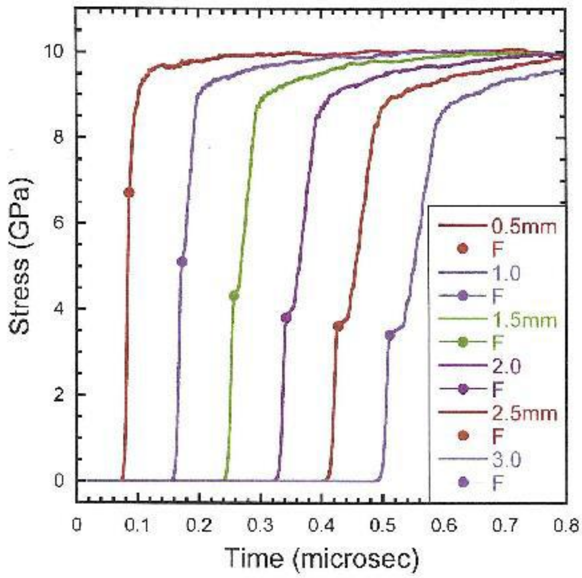

Fig.2: Elastic precursor wave from a simulation with the overstress approach.

We see from Fig. 2 that the elastic precursor wave decays as it propagates, as observed in tests.

The two approaches to dynamic viscoplasticity lead to different interpretations of dynamic viscoplastic response. According to the flowstress approach, high strain rate loading may increase material strength to high values and even very high values. This should be in accordance with an appropriate microscale mechanism (that would lead for instance to a very high mobile dislocation density). In contrast, by the overstress approach strength does not change much. What may increase to high values is the stress. This is quite legitimate, and does not require special interpretation on the microscale.

In the next three sections we present examples in which we predict literature test data using the overstress approach. In section 2 we reproduce the so called σ^4 law. In section 3 we reproduce the phenomenon of high rate stress upturn in ductile materials for strain rates above 10^4/s, and in section 4 we reproduce high rate stress upturn in brittle materials for strain rates above 10/s. Literature data for such stress upturn are given mainly for concrete.

<u>Predicting the of 4th power law using the overstress approach</u>

Using quite accurate (1 ns resolution) planar impact tests, Grady and others [6] have shown that for steady wave shapes in viscoplastic materials (beyond the elastic precursor decay range) the following relations holds:

$$\dot{\varepsilon}_{max} \propto \left(\Delta\sigma\right)^{\beta} \qquad \beta = 4 \qquad (7)$$

where$\Delta\sigma$ and $d\varepsilon_{max}/dt$ are defined in Fig. 5.

And test results from Barker [7] for aluminum, reproduced in Fig. 3, were the first to demonstrate this relation.

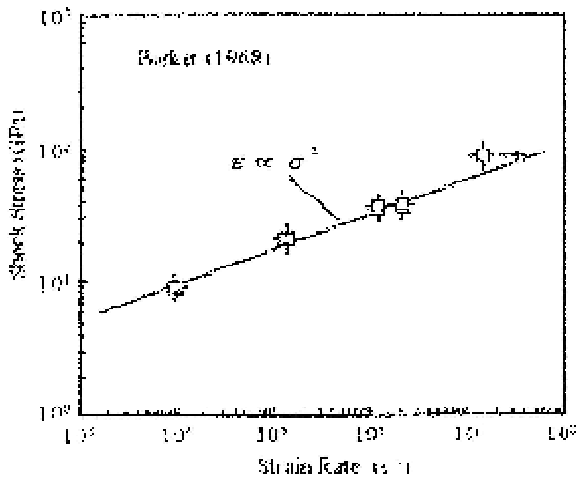

Fig.3: Log-log plot of shock stress (or stress jump) versus longitudinal maximum strain rate. From Barker (1968).

To reproduce the results of Eq. (7) and Fig. 3, we start from the steady planar (1D strain) equations for viscoplastic materials which are [8]:

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$$\dot{\sigma} = \frac{2G}{\left(c_L^2/U^2 - 1\right)} d^p$$
$$\dot{u} = \frac{2G}{\rho_0 U\left(c_L^2/U^2 - 1\right)} d^p \qquad (8)$$
$$\dot{\varepsilon} = \frac{2G}{\rho_0 U^2\left(c_L^2/U^2 - 1\right)} d^p$$

where G=shear modulus, c_L=longitudinal sound speed, U=wave speed, u=particle velocity, ε=longitudinal strain, and $d^p=d^p_{eff}$=longitudinal deformation rate= effective plastic deformation rate.

Eqs. (8) also describe the Rayleigh line. Dividing any two of these equations one by the other yields the Rayleigh line equations derived from the Hugoniot equations. This is in accordance with the well-known result that for a steady viscoplastic wave, the state point moves along the Rayleigh line. Eqs. (8) were developed in the 1960s by Duvall and coworkers[8]. To derive these simple relations he ignored the difference between the Hugoniot and isentrope curves. The derivation is therefore a good approximation only below a stress of about 20 GPa. Here we integrate the system of ODEs (8) using a standard 4th order Runge-Kutta solver. As an example we show in Figs. 4 and 5 histories of stress and strain for ε_{max}=0.05. We use the parameters of aluminum, and for the flow curve exponent we use α=2.

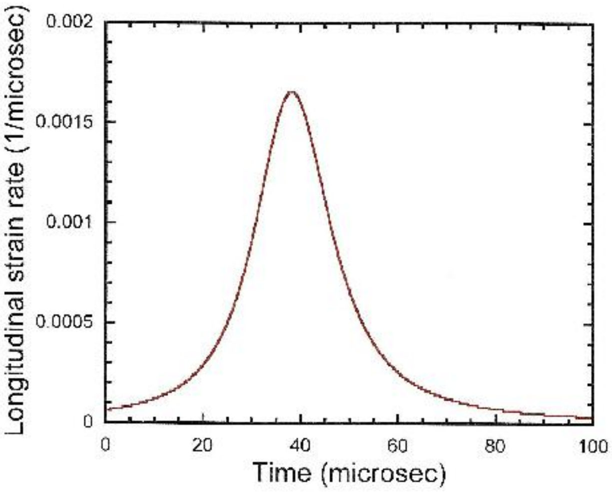

Fig.4: Strain rate history of a steady viscoplastic wave for ε_{max}=0.05.

In Fig. 6 we show the result obtained for several values of the stress jump $\Delta\sigma=\sigma_1-\sigma_{HEL}$ (see Fig. 5). We see from Fig. 6 that 1) we get a straight line in a log-log plot (as in tests), and the straight line equation is:

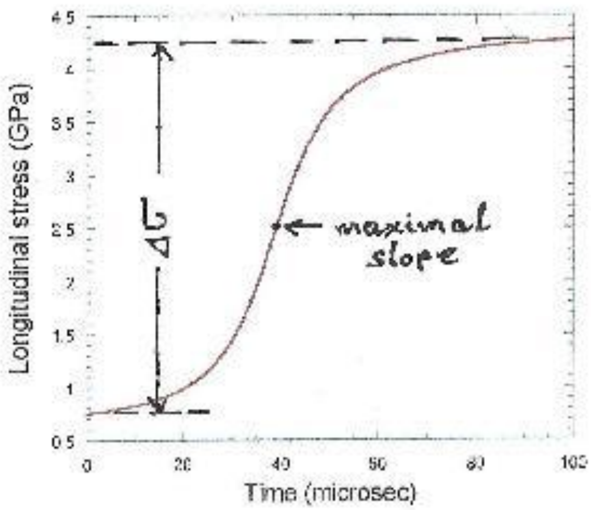

Fig.5: Stress history of a steady viscoplastic wave for ε_{max}=0.05.

$$\dot{\varepsilon}_{max} = B\left(\Delta\sigma\right)^{\beta} \qquad (9)$$

2) the straight line slope (in Fig. 6) is β=1/0.296=3.378<4; and 3) the stress jump is too low compared to Barker's data (Fig. 2), which is easy to verify at the lowest strain rate. To correct for this difference and move the straight line up, we need to decrease the coefficient d_0 of the flow curve equation.

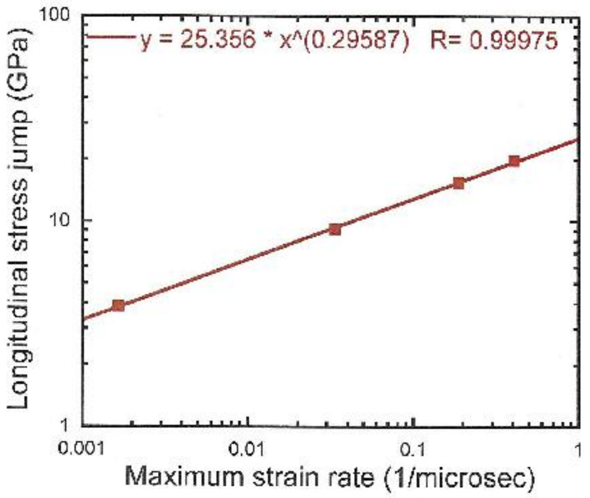

Fig.6: Log-log plot of stress jump versus maximum strain rate for arbitrary parameters of the overstress flow curve.

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To calibrate the exponent α we performed computations with different values of α without changing d_0. From two such computations we evaluateβ by:

$$\beta = \frac{\ell n\left(\dot{\varepsilon}_{max2}/\dot{\varepsilon}_{max1}\right)}{\ell n\left(\Delta\sigma_2/\Delta\sigma_1\right)} \quad (10)$$

We show the results for β(α) in Fig.7.

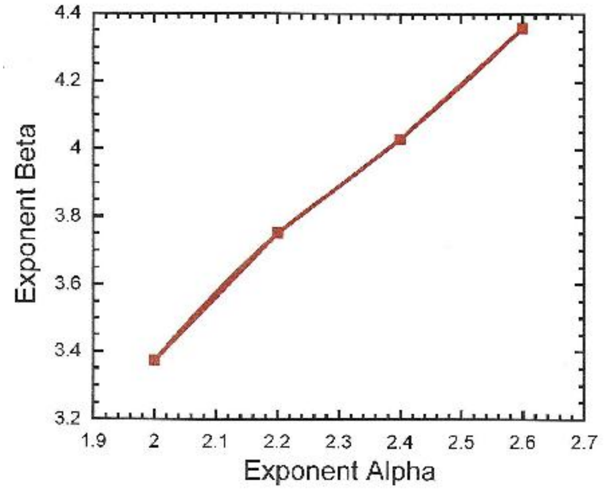

Fig.7: The relation β(α) evaluated from our computations.

We see from Fig. 7 that to get β=4 (as obtained on the average in tests), we need to use α=2.38. We also adjusted the value of d_0 to 1734/s to get agreement with Barker's results (see Fig. 3), and in Fig. 8 we show the agreement obtained.

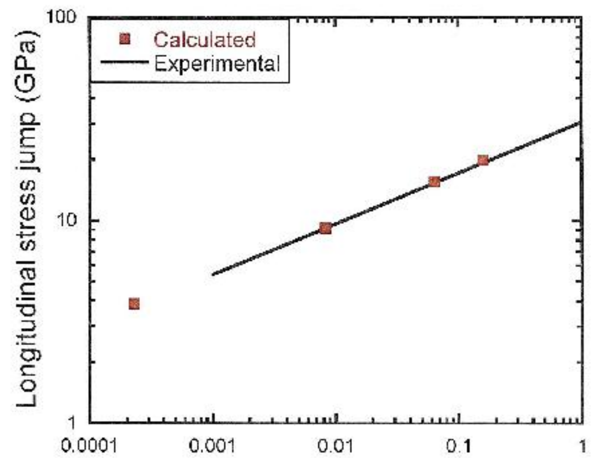

Fig.8: Reproduction of Barker's test results for aluminum with the calibrated values of α and d_0.

In summary: from planar impact (1D strain) tests with many viscoplastic materials one gets after some distance into the target a power law relation, as in Eq. (9), with β=4 (to a good approximation). This result is known as the 4th power law of dynamic viscoplasticity. It would make sense for researchers to look for an overall explanation of the 4th power law. But we don't see such an explanation in the literature. Also, it would make sense for computational modelers to try reproduce the 4th power response with a hydrocode that uses the flowstress approach to viscoplasticity. But we don't find such trials in the literature. It seems to us that such trials were unsuccessful, for one or both of two reasons. Either the results were obscured by artificial viscosity, or the flowstress approach to viscoplasticity is not appropriate, similar to the elastic precursor decay phenomenon described in the introduction.

Here we reproduce the 4th power law using the overstress approach to dynamic viscoplasticity, integrating directly the time dependent ODEs describing a steady viscoplastic plane wave. In this way we're able to evaluate a steady viscoplastic wave with minimal effort and to a desired precision. Our overstress approach flow curve includes two free parameters: 1) the exponent α that determines the slope β of the test results(we find α=2.38); and 2) the flow curve coefficient d_0 that moves the test results line up and down. We find that to reproduce Barker's data we need to use d_0=1734/s.

It turns out that we can calibrate the flow curve parameters directly from 4th power low data.

II. HIGH RATE STRESS UPTURN IN DUCTILE MATERIALS

Ductile materials (mainly metals) have been observed to exhibit HRSU (High Rate Stress Upturn) at strain rates between 10^3 and 10^4/s. Such a HRSU is quite important to consider when dealing with fast dynamic loadings. An example of HRSU of copper, taken from the literature [9] is shown in Fig. 9. Another example is from the work of Couque [10] (not reproduced here) on six metals. From this example we can see that all six metals have a similar HRSU response.

The S in HRSU may be interpreted either as STRESS or as STRENGTH. For those using the flowstress approach S stands for strength, because with this approach stremgth goes along with stress upon loading in the plastic range. But accepting strength upturn is hard to justify on the microscale (dislocation mechanics). On the other hand, for those using the overstress approach, S stands for stress, which does not impose any problem. As most workers in the field use the flowstress approach, the HRSU phenomenon has led to a controversy. Some [9, 10] believe that HRSU is a real and important phenomenon, and others [11] claim that it doesn't exist.

Here we propose a way out of the controversy. Using the overstress approach we show that: 1) S in HRSU means stress, and there's no need to come up with microscale models to justify very high values of strength; and 2) HRSU responses of many metals are quite similar, as they represent their flow curves. And we've shown in section 2 that flow curves of different materials are quite similar.

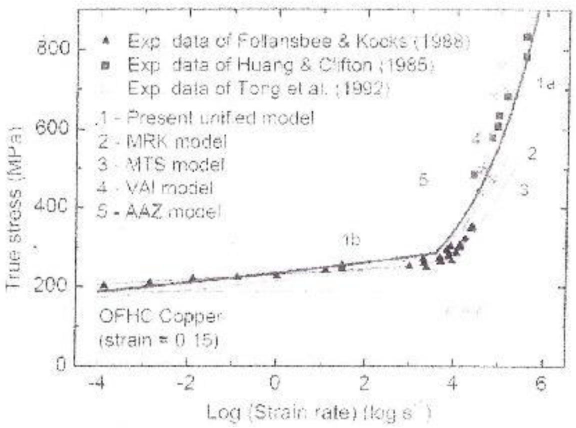

Fig.9: Test data of HRSU for copper from several sources.

Next we use the flow curve that we calibrated in section 2 for aluminum to predict its HRSU response. Inverting the flow curve equation we get:

$$s_{eq} = Y_0\left[\left(\frac{\dot{\varepsilon}_{eff}}{\dot{\varepsilon}_0}\right)^{1/\alpha} + 1\right] = Y_0\left[\left(\frac{d^p_{eff}}{d_0}\right)^{1/\alpha} + 1\right] \tag{11}$$

Using α=2.38 and d_0=1.734/s for aluminum from the previous section we get from Eq. (11) the HRSU curve shown in Fig. 10 together with Couque's data. From Fig. 10 we see that: 1) the computed curve has the right shape, similar to the curves in Fig. 9; and 2) agreement with Couque's data is quite good.In Fig. 11 we show that by increasing the coefficient d_0, we can move the upturn curve to the right.

In summary, we show here that the HRSU of ductile materials follows directly from the overstress approach to dynamic viscoplasticity. It turns out that the HRSU curve is just an inverse representation of the material flow curve.

In the previous section we've shown that many materials have the same flow curve exponent α=2.38, and that their flow curves are therefore similar. We conclude that this is why the HRSU curves of many materials are similar, as shown experimentally by Couque [10].

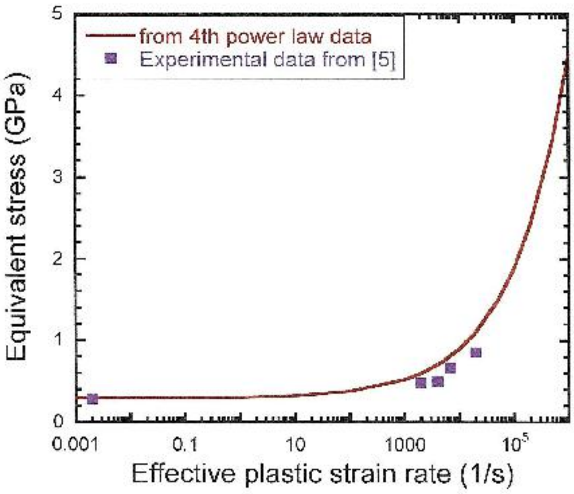

Fig.10: Inverted flow curve representing the HRSU curve compared with Couque's data for aluminum.

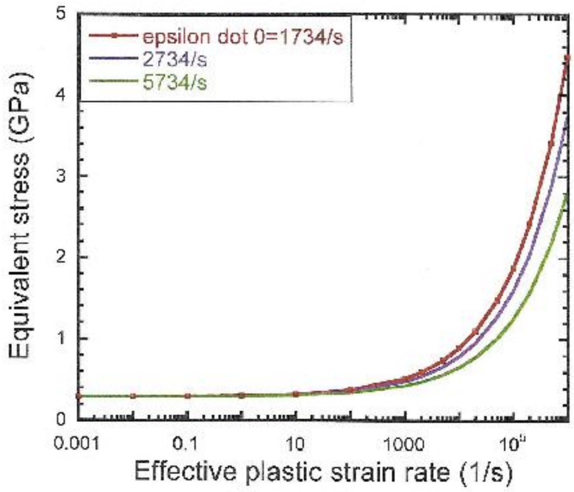

Fig.11: Influence of the coefficient d_0 on the upturn strain rate.

III. HIGH RATE STRESS UPTURN IN BRITTLE MATERIALS

It turns out that brittle materials also exhibit HRSU, but for different reasons. There are many kinds of brittle materials like ceramics, glasses and different types of rocks. But most data on HRSU of brittle materials by far is for concrete. We show an example of such data in Fig. 12.

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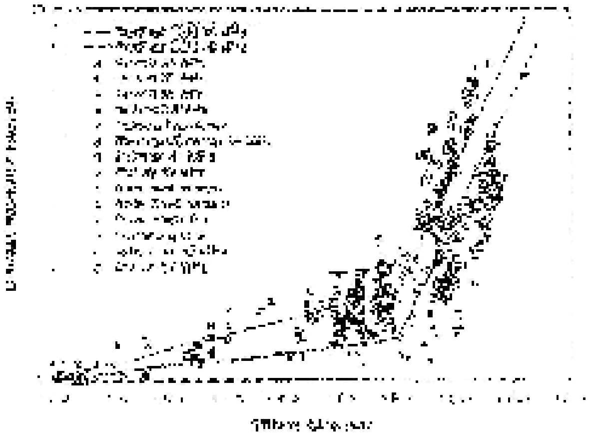

Fig.12: Dynamic increase factor as function of strain rate in concrete samples in tension. From many sources. Taken from [12].

As is well known, the dynamic response of brittle materials is quite different from that of ductile materials. In spite of that, the dynamic response of concrete to high rate loading is quite similar to that of ductile materials. The main difference is that high rate stress upturn of concrete occurs at a lower strain rate of about 100/s in compression and 1/s in tension. As the quasistatic strength of concrete varies with small changes of production details, it is customary to describe dynamic changes of strength or stress in terms of the dynamic factor DIF (DIF=Dynamic Increase Factor), relative to the quasistatic strength. From the example in Fig. 12 we see that although there's a lot of spread in the data, the general trend is obvious, brittle materials (or at least concrete) do exhibit a HRSU response similar to ductile materials.

To model the HRSU of brittle materials we use our brittle materials dynamic response model (BMDRM), which we developed previously. With our BMDRM we assume that a brittle material has three damage threshold curves in the SP (shear pressure) plane. These curves are shown in Fig. 13. The main threshold curve, denoted by A_i is the shear fracture threshold, which increases with pressure. The two others are damage threshold curves in tension (T_i) and in compression (P_i). In what follows we deal only with the shear threshold.

It's important to emphasize that a threshold curve tells us only about the onset of damage when the material is still intact (undamaged) and elastic, and not about the fully damaged material that may flow plastically.

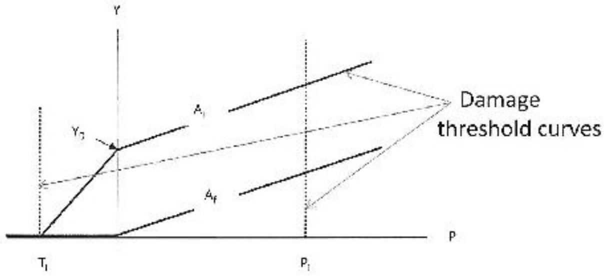

Fig.13: Damage threshold curves shown in the shear-pressure plane.

When a computational cell (or a material control volume) is on a damage threshold curve, it does not fail immediately, but only starts to accumulate damage. When the loading is fast, the state point (in the SP plane) may protrude out of the threshold curve. It follows that our BMDRM is an overstress approach model. As explained in the previous sections, the overstress approach recognizes that threshold crossings (of various kinds) are not instantaneous, but require time. And this is why threshold crossings in response to fast dynamic loadings may lag behind the loading process.

When the state point in the SP plane is beyond the threshold curve, the material in the considered computational cell undergoes various types of fracture, according to the considered material properties. In a macroscopic model (which we consider here) we describe the amount of fracture by means of the macroscopic variable called damage (D). It is customary to define the range of change of D between 0 and 1:

When D=0, the material is intact.

When 0<D<1 the material is partly fractured, but still responds elastically.

When D=1, the material is fractured to such an extent that it may flow plastically, and we define it as failed.

We assume that a failed material responds like a granular material. When loaded it may flow plastically, but because of granular friction, its resistance to flow (or its strength) increases with pressure.

We also assume that when the state point is out of the threshold curve, damage increases. And similar to other overstress approach situations, we assume that the rate of increase of damage goes up as distance of the state point from the threshold curve increases.

In addition we assume, as in the JH models [13], that the threshold curve moves towards the fully failed curve

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(denoted by A_f in Fig. 13), according to the following linear relation:

$$S_D(P) = (1-D)S_i(P) + DS_f(P) \quad (12)$$

For the rate of change of damage we also assume a linear relation (from lack of any specific data):

$$\dot{D} = A_D(S - S_D) \quad (13)$$

Where $S=S_{eq}$ is the equivalent stress, and the coefficient A_D is to be calibrated from tests.

In this way damage rate may increase without limit. But the rate of damage accumulation is limited by the maximum rate of fracture formation and propagation. We therefore limit the rate of damage accumulation by:

$$\dot{D} \leq \dot{D}_{max} \quad (14)$$

It turns out (see later) that such a limitation controls the upturn strain rate.

To demonstrate the HRSU response of concrete we perform computations on a single cell (0D computations). By using different relations between the boundary velocities (u_x and $u_y=u_z$), we get various paths of the state point in the SP plane. For $u_y/u_x>-0.5$ the material is in compression, and otherwise it is in tension. We show such paths in Fig. 14. At the endpoint of each path D=1 and the material is fully damaged.

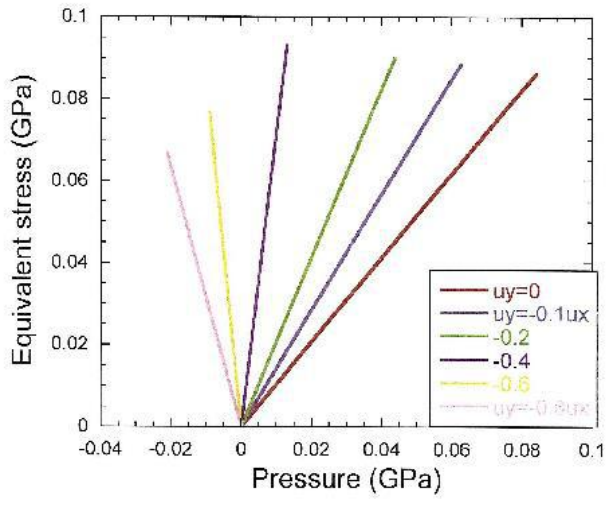

Fig.14: Different paths of material response when changing the ratio u_x/u_y.

Using different values for u_x we compute S and DIF as function of strain rate. From the results of these computations we get curves with an HRSU, similar to what is seen in tests. In Fig. 15 we show two HRSU curves obtained from these computations, one with u_y/u_x=-0.1 (compression), and the other with u_y/u_x=-0.8 (tension).

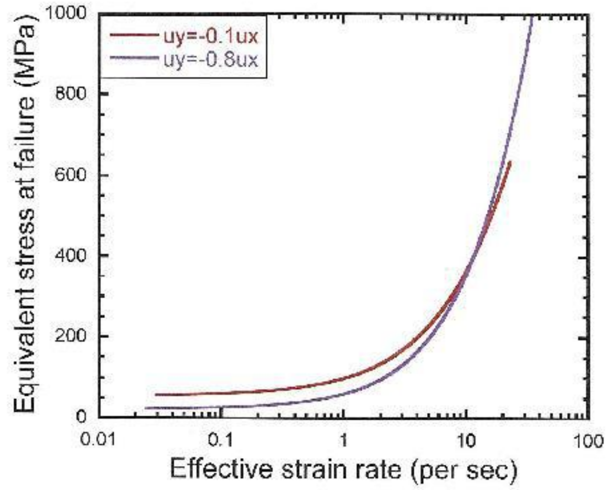

Fig.15: Equivalent stress (S) as function of strain rate for two values of u_y/u_x, one in compression and the other in tension.

We see from Fig. 15 that: 1) for different loading conditions the response is similar but a little different. This may cause some of the spread seen in Fig. 12; 2) the curves upturn at a strain rate of about 1/s, which is consistent with data; and 3) the high strain rate slopes are also consistent with data (stress increases 5 folds for 10 folds increase in strain rate).

In Fig. 16 we show the influence of the maximum damage accumulation rate.

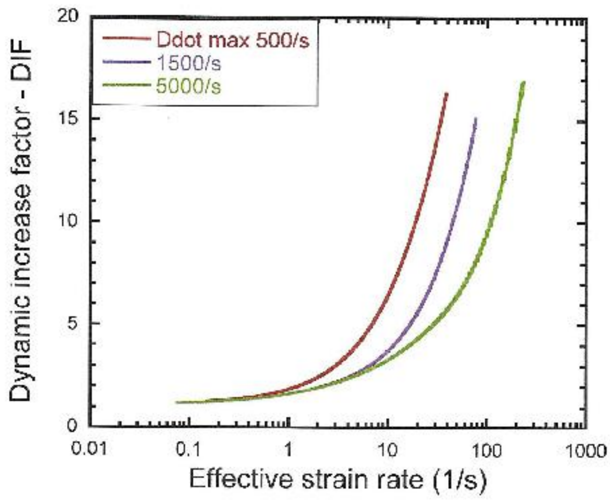

Fig.16: DIF as function of strain rate for different values of the maximum rate of damage accumulation.

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We see from Fig. 16 that by increasing the maximum rate of damage accumulation 10 fold (from 500 to 5000/s), the upturn strain rate increases from about 1/s to about 10/s.

In summary: brittle materials exhibit HRSU similar to ductile materials, although their response to dynamic loading is much different. The main difference of the two types of materials is that the HRSU strain rate of the brittle materials is much lower, between 1 and 10/s.

We compute here the HRSU of concrete. To this end we use our dynamic response model for brittle materials developed previously, which is different from the JH models [13] that are widely accepted. Our brittle material response model is also an overstress approach model. We compute damage accumulation rate as function of overstress relative to a damage threshold curve. We introduce a maximum damage accumulation rate, which controls the upturn strain rate.

IV. SUMMARY

We demonstrate here the power of the so called overstress approach to dynamic response of materials. We start (in the introduction) by describing the two approaches to dynamic viscoplasticity, the flowstress approach and the overstress approach. The flowstress approach is the one that is commonly accepted and practiced. But there are some types of response it does not predict correctly. We demonstrate that with the elastic precursor decay problem. The two approaches to dynamic viscoplasticity differ in the way they treat strain rate. By the flowstress approach strain rate (or rather effective plastic strain rate) is a state variable that strength depends on. When strain rate is very high (like in a shock), strength should be very high too, and it's hard to explain that with microscale considerations. By the overstress approach strength does not depend directly on strain rate, but instead plastic strain rate depends on stress, which can go beyond the quasistatic strength. Using the overstress approach we're able to predict the elastic precursor decay behavior. Duvall [8] did that in the 1960s. He used the overstress approach in a natural way, before the flowstress approach became dominant.

In section 2 we use the overstress approach to dynamic viscoplasticity to predict the 4th power law of steady viscoplastic waves observed in tests with many materials. Using the data we're able to calibrate the two parameters of the flow curve, which expresses the dependence of plastic strain rate on equivalent stress.

In section 3 we use the flow curve calibrated in section 2 to predict the HRSU of viscoplastic materials. With the overstress approach the S in HRSU stands for stress and not for strength, and in this way the controversy over HRSU may be dissolved. It turns out that the HRSU curve is just the overstress approach flow curve with exchanged axes.

The overstress approach applies not just to dynamic viscoplasticity (crossing from elastic to plastic response), but to crossing of a response threshold in general. This is why we're able to apply the overstress approach to predict the HRSU response of brittle materials. In section 4 we outline our brittle materials response model and apply it to predict the HRSU of concrete. Our results are quite similar to available data.

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