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Dynamic strength increase of plain concrete from high strain rate plasticity with shear dilation

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A B S T R A C T

An increase in the strength of concrete when loaded dynamically has been noted in the testing literature since the early twentieth century. The origins or mechanisms leading to this increase, despite having been observed in a variety of tests, are not satisfactorily established. Aspects of test setup, specimen design, etc., have been shown to influence the outcome of any given test. More recently, computer representations of concrete have been tasked with analyzing or predicting the dynamic behavior of structures. Computers have also enabled an inward look at the same empirical tests, showing that some strength increase in compression can be captured by implementation of the proper plasticity model. The major factor touted for strength increase is the well known pressure sensitivity of concrete and a mechanism known as 'inertial confinement'. The present work proposes a new mechanism for dynamic strength increase, focusing on the failure mechanism of concrete in compression known as shear faulting. The faulting process and its associated plastic deformation mode is compared using several material models. Adjustments are made to some parameters within these models to study their effect on dynamic and inertial plastic response. Shear dilation, which does little to increase dynamic strength at moderate strain rates, is identified as a key component of a concrete material model subject to high strain rates. Shear dilation's effects can be seen in the range of strain rates that are practically attainable in a laboratory by using the split Hopkinson pressure bar apparatus. They may also have an increasingly important effect on problems featuring even higher strain rates, such as blast, impact, and penetration through concrete slabs.

1. Introduction: impact pulse testing

Two major review works firmly establish the existence of increasing compressive strength in a concrete specimen when an increasingly rapid application of load results in a higher strain rate to failure [2,24]. Both of these review articles contain data obtained using the split Hopkinson pressure bar (SHPB [14,17]) technique. The SHPB method is typically used to fill out the strain rate regime for which reliable and controlled laboratory data for strength is available. The 'high' strain rate regime is considered to be the two decades between 10^1 and 10^3 s^{-1}. At these strain rates, strength at failure increases by a factor of two to three while strain at failure increases a modest 25–40%. Malvar et al. [24] cite the currently available sources of data and note that CEB [3] recommendations call for slightly more dynamic strength increase than the data might support.

Theories seeking to explain the strength increase center around several known explanations: increased microcracking and damage, inertial confinement of a pressure sensitive material, and geometric or frictional confinement effects. Of these, inertial confinement and geometric or frictional confinement effects have received the most amount of study. Furthermore, these two effects are conceptually the easiest to test in a computational study. Some additional references on these two effects will be made in Section 1.1.

The role of microcracking is likely the least well understood and the most difficult to model in a phenomenological manner. The role of cracking and crack branching is studied by Malvern [25–27] without establishing a direct link to strength increase. Experiments did conclude, especially through forensic post-test analysis [25], that specimens from high strain rate experiments exhibit a greater number of micro- and meso-cracks. These microcracks branch more frequently and take a more tortuous route through the matrix material and aggregates. Higher strain rates increase the

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cracking densities, which implies a larger amount of energy was absorbed. The connection to strength is then made by noting time delay phenomena [27] and increased area underneath the stress strain curve. However, it should be noted that increased crack density means increased formation of voids. Therefore, concrete has been observed gaining volume under applied shear, or dilating more under rapid application of load. Some computational material models account for dilation and thereby represent microcracking in a phenomenological sense.

1.1. Specimen slenderness: geometric and boundary condition effects

In any conventional compression test, the specimen will eventually fail by splitting or fracture. This usually occurs along fracture planes or 'shear faults.' When the failure process is slowed down, microscopic cracks have time to coalesce and form in the same corridor, eventually forming a macroscopic crack. Bischoff [2] observed "an axial splitting failure [...] in specimens where frictional end-restraint was minimized, while the presence of end-restraint altered the crack pattern and caused an apparent shear failure, with the formation of cones at the ends of the specimen. Hakalehto [11] observed that, during dynamic testing, rock specimens were able to transmit more energy as the specimen length became shorter and the influence of the confining effect became greater." Other observations made of more squat test cylinders indicate that the failure takes place due to many, slightly inclined longitudinal cracks.

1.1.1. Boundary conditions

A unifying aspect of unconfined testing of brittle materials was mentioned above: the failure mode is always that of faulting on a cone of material confined on one side by the test apparatus. The angle made at the top of the cone depends on the frictional properties of the material and its interface with the test apparatus. Extraordinary steps are almost never taken to minimize friction in a dynamic test. Even if friction was eliminated, the test transitions to one more akin to a dynamic Brazilian test [32] (used for establishing the dynamic tensile strength) where a single crack splits the specimen in half lengthwise. Failure based on shear faulting, which results in two cones protruding from the test apparatus, is a hallmark of an unconfined compression test.

The failure process, as such, becomes subject to a number of geometric and frictional variations. The above quote acknowledges that more energy may be transmitted if the specimen length is shorter than its diameter and frictional confinement from the apparatus increases. Making the specimen more slender decreases the friction constraint with the apparatus while increasing the distance between shear cones. At extreme slenderness ratios, the failure mechanism transitions to a single angled shear failure 'chopping' the specimen in half.

1.1.2. Inertial confinement and previous computational models

Inertial confinement refers to the elastic process whereby rapid radial expansion due to the Poisson effect applies an inward force to the core of the compressed material. The effect also delivers a small increase in axial stress related solely to the specimen's elastic properties and geometry. Forrestal [8] completes an in-depth mathematical treatment of radial inertia in the linear elastic regime. He concludes from the complete solution, as Kolsky [17] did using an energy approach, that the additional axial stress alone cannot fully explain the observed strength increase. Several authors, e.g. [2,19,29] inter alios, report that the separate but related phenomenon of rate induced, radial confining stress could potentially account for the observed strength increase. The inertial confinement phenomenon is quantitatively assessed in the exact elasticity solution, which shows an increase in rate induced, radial confining stress that is maximum at the core and decreases to zero at the boundary. However, unlike actual concrete specimens, the elasticity solution does not have a material strength limitation.

While the analyses within the linear elastic framework have provided a good basis for identifying some of the causes of strain-rate effects, they provide only a limited understanding of the strength increases observed experimentally. The key assumptions must encompass the entire range of material response—viz., through a framework where yielding is allowed and flow stress is pressure-dependent—since the notion of a stress state that applies specimen-wide is no longer descriptive when rapidly occurring plastic deformation accumulates locally. The admission of plasticity, and the subsequent lack of an exact solution, makes computational methods an attractive means to develop insight into the specimen's response during the complicated evolution from a uniaxial stress state to a multi-axial stress state, e.g. [19,29].

In the realm of computational simulation, Georgin et al. [9] apply a visco-plasic Drucker–Prager model to the compressive SHPB problem. This study does not model the apparatus and employs an axisymmetric model. There is no friction study as in [19], but the work considers fully fixed and frictionless end-restraint conditions. They produce results comparable to the testing literature by assuming that the true response lies between the two extremes. One unique contribution is a plot of the hardening variable for the fixed-end test, showing the formation of shear cones and a plastic localization zone at the core of the specimen. For the case of frictionless boundaries, the specimen deformation is badly non-uniform with respect to its length [29]. The deformation is indicative of a non-uniform stress state, which would violate the SHPB assumptions, but nevertheless may exist in experiments.

Specimen strength gain occurs in the laboratory regardless of whether it is a function of pointwise (material) strength gain or specimen level (mechanical) enhancements. Results and assertions that center on the question of material versus mechanical strength gain can be found in various literature focused on computation [18,19,31,34]. More recently Kim [16] compares J-2 plasticity and a pressure dependant material in a simulated SHPB and concludes that rate dependence is entirely due to pressure sensitivity. Attribution of strength gain to inertial confinement persists in its Poisson-ratio-like form in many of the cited works, despite acknowledged axial non-uniformity of the plastic specimen deformation above the transition strain rate ($1–3\ s^{-1}$). Zhou's [35] model of aggregate at the mesoscale shows increased crack density, accompanied with strength gain, for higher strain rates. The natural treatment of dilation possessed by a mesoscale model that includes aggregate is further commented upon in Section 3.9. The 'natural' causes of strain rate strengthening effects, and their limits, are acknowledged in a research note from Magallanes [21]. The note advocates using only the strain rate curve multiplier in the portion before the transition strain rate mentioned in Section 1.2 and letting pressure sensitivity handle the strength increase at moderate strain rates. Previous simulation and modeling work has indicated a connection between pressure sensitivity, plastic flow and strength increase without a clear indication of the unifying mechanism.

1.2. Previous investigations on the role of dilation

Janach [15] studied the role of bulking in the brittle failure of rocks. His experiments were not based on the typical SHPB and may have attained much higher strain rates than studied in this work for