International Journal of Solids and Structures 90 (2016) 153–166

Contents lists available at ScienceDirect

International Journal of Solids and Structures

journal homepage: www.elsevier.com/locate/ijsolstr

Modeling of concrete spallation with damaged viscoelasticity and retarded damage

Ulrich Häussler-Combe*, Evmorfia Panteki

Institute for Concrete Structures, Technische Universität Dresden, D-01062 Dresden, Germany

ARTICLE INFO

Article history:
Received 3 September 2015
Revised 17 March 2016
Available online 31 March 2016

Keywords:
Strain-rate effect
Concrete
Retarded damage
Damaged viscoelasticity
Dynamic strength increase
Spallation
Modified Split-Hopkinson-Bar
Crack energy

ABSTRACT

A proposal for a triaxial constitutive law is developed to model strain-rate sensitivity of quasi-brittle materials like concrete. It is based on a standard isotropic quasi-static damage law which is extended with damaged viscoelasticity and retarded damage to consider the physical mechanisms of strain-rate sensitivity. Dynamic uniaxial compressive and tensile stress–strain relations are derived as a special case. The material parameters for strain-rate sensitivity are calibrated to reproduce experimental increase factors for uniaxial compressive and tensile strength. A fully triaxial setup is used for modeling of stress wave propagation in cylindrical concrete specimens with spallation of fragments as part of modified Split–Hopkinson–Bar configurations. The validation of the material model is performed with the comparison of computed and experimental pull-back velocities of the specimen's free end. It is shown that the validation is only possible considering both damaged viscoelasticity and retarded damage in the material model. The numerical computations yield stresses far beyond quasi-static strength, but high stresses are maintained only for short periods before material destruction. Furthermore, the computations show that the amount of dissipated energy due to dynamic spallation is much higher compared to quasi-static crack energy.

1. Introduction

Strain-rate dependence of the behavior of inhomogeneous quasi-brittle materials like concrete is still an open field. The influence of strain-rates on the stress–strain relations becomes an issue regarding impact and explosive actions on structures where the strain-rate generally exceeds values of $\approx 1\,\mathrm{s}^{-1}$. Experimental data show a considerable increase of, e.g., absolute values of uniaxial strength compared to quasi-static values for strain-rates $>1\,\mathrm{s}^{-1}$, see Fig. 1.

Strength is the most prominent material property in terms of the strain-rate effect. In a first approach it may be characterized by the dynamic increase factor (DIF), which expresses the ratio between dynamic and static uniaxial concrete strength. Besides strength material characteristics like ultimate failure strain, Young's modulus and fracture energy (Brara and Klepaczko, 2007) are also discussed to be strain-rate dependent assigned with enhancements due to high strain-rates.

A variety of experimental investigations were carried out to study this phenomenon. It was observed for compression (Bischoff and Perry, 1991) as well as for tension (Malvar and Ross, 1998), where it is particularly pronounced. A set up often used for the examination of material properties under high strain-rates is the Split–Hopkinson–Bar, whereby the SHB-theory should adjust the measured data with respect to macroscopic inertia effects. Investigations have been performed in the direct tensile configuration (Weerheijm, 1992; Zheng, 1996; Zielinski, 1982), as well as in the spallation configuration (Birkimer and Lindemann, 1971; Klepaczko and Brara, 2001; McVay, 1988; Schuler et al., 2006), in which higher strain-rates are achieved. Generally the experimental techniques show a large scatter of data resulting in a limited comparability of the results.

Although the strain-rate effect's outcome is generally undisputed, its causes and hence the question whether or not it is a material property remains to be answered. Lateral confinement is frequently discussed as a reason for the strain-rate effect. It arises from the structural system behavior in experimental set-ups (Li and Meng, 2003; Mu et al., 2012; Schwer and Windsor, 2009; Zhou and Hao, 2008). In this regard the strain-rate effect is not a direct material property but comes with lateral confinement of the specimen core caused by the delayed expansion of the outer material layer which first must be accelerated in radial direction. This leads

* Corresponding author. Tel.: +4935146339586.
E-mail addresses: ulrich.haeussler-combe@tu-dresden.de (U. Häussler-Combe), evmorfia.panteki@tu-dresden.de (E. Panteki).

http://dx.doi.org/10.1016/j.ijsolstr.2016.03.022

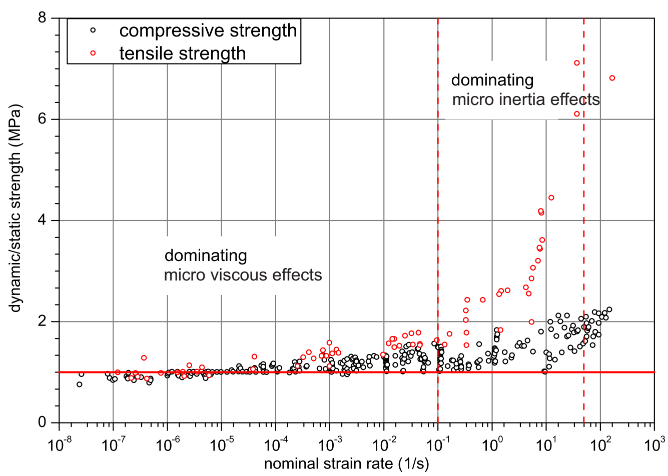

Fig. 1. Dynamic strength increase factor (DIF) for compression (Bischoff and Perry, 1991) and tension (Malvar and Ross, 1998) depending on strain-rate.

to higher hydrostatic stresses, which are in turn associated with strength increase. Another frequently examined factor possibly related to the results of strain-rate experiments is interface friction between the loading device and the specimen itself (Kim et al., 2010; Li and Meng, 2003). Although various studies concluded that a connection exists between lateral confinement, friction influence and the experimental outcome this explanation of the strain-rate effect seems not to be adequate. In particular regarding tension there is strong evidence that the strain-rate effect is connected with intrinsic material mechanisms. This issue is a major topic of the paper.

Two major ways are available to model to strain-rate effect as a material property. Phenomenological approaches scale strength with a measure of the actual strain-rate, see, e.g., Crawford et al. (2012), Borrvall and Riedel (2011), and Bazant et al. (2000). Involved scaling parameters are calibrated such that a desired course of DIF-values—generally from macroscopically homogeneous uniaxial experiments—is reproduced. It is questionable whether corresponding stress–strain laws can be transferred to multiaxial inhomogeneous conditions. Furthermore such an approach leads to quasi-static strength when strain attains maximum values under high strain-rate conditions which is not reasonable. Physically motivated approaches apply physical models sensitive to rate effects together with quasi-static constitutive laws. Regarding damage as a base, rate of damage is formulated in analogy to the Perzyna-type of viscoplasticity, whereby the yield function of plasticity is replaced by a damage limit function (Cervera et al., 1996; Dube et al., 1996; Gatuingt and Pijaudier-Cabot, 2002; Nemes and Speciel, 1996). Constraints to the rate of damage are directly applied in other formulations (Suffis et al., 2003). As an alternative rheological models are proposed for microcracking including parts covering retarded movement of microcrack surfaces (Eibl and Schmidt-Hurtienne, 1999; Zheng et al., 1999). Numerical models are applicable for the simulation of impact at concrete specimen level, but also for the simulation of the concrete structural dynamic response as experienced with (reinforced) plates and beams under projectile impact (Huang et al., 2005; Irhan et al., 2015; Ozbolt and Sharma, 2011; Tai and Tang, 2006). Particular topics are given with changing crack patterns and increased crack branching under high strain strain-rate conditions compared to quasistatic conditions (Du et al., 2014; Ozbolt and Sharma, 2012; Ozbolt et al., 2011).

Two major physical mechanisms may be regarded as reasons for the strain-rate effect of concrete according to current knowledge. First, water is more or less physically bound in the different capillary systems of a concrete's cement matrix. Its movement in the capillary system is influenced by pressure. A higher pressure is related to a faster movement or higher strain-rates, respectively, due to viscous effects (Rossi, 1991). Viscoelastic and viscoplastic approaches to cover such an effect are proposed for concrete by e.g. Pedersen et al. (2008). Furthermore, strength and stiffness of the cement matrix are strongly influenced by microcracking. Cracking is connected with a movement of crack surfaces relative to its immediate surroundings in the scale of macrocracks as well as in the scale of microcracking. This movement cannot occur arbitrarily fast due to microscopic effects of mass inertia. Thus, if damage is used to describe microcracking its evolution is retarded in case of high strain-rates. The two mechanisms of damaged viscoelasticity and retarded damage were combined in a former proposal of the authors (Häussler-Combe and Kuehn, 2012). The approach basically transforms effects of micro-inertia and micro-viscosity onto the macroscopic scale through integrating them into the macroscopic material model. The current paper works out more details with some modifications and discusses the application to the spallation of concrete.

It is organized as follows: The subsequent section describes the constitutive law with strain-rate sensitivity by viscosity and retarded damage as an extension of a quasi-static scalar damage law. It is implemented as a user-subroutine within the explicit LS-Dyna code for the following numerical investigations. This starts in the third section with the discussion of homogeneous uniaxial compressive and tensile behavior. Experimental results about dynamic strength increase factors (DIF) as shown in Fig. 1 are used to calibrate the particular parameters for the strain-rate sensitivity of the proposed material model. Spallation of concrete exposed to impact is investigated in the following Section 4. Corresponding experimental investigations are usually performed with the Modified Split–Hopkinson–Bar (MSHB). Measured velocities of spalling fragments of specimens are given as immediate results and values of dynamic strength and DIF are derived indirectly on base of simplifying assumptions. This is compared to the results of a fully triaxial simulation model. This concerns first velocities of fragments and stress states within the specimen. Furthermore, the internal energy is evaluated with recoverable elastic and dissipative damage and viscous contributions and compared to the quasi-static crack energy. After all the material model allows to analyze the contribution of the particular mechanisms—viscosity, retarded damage—to strain-rate sensitivity. The discussion is restricted to homogeneous behavior and the MSHB-setup. The application to structures with dynamic crack patterns and increased crack branching are under investigation and have to be presented in following papers.

2. The constitutive law

2.1. Tensile- and compressive states

A strain based formulation is used to describe material behavior. The strain tensor $\boldsymbol{\epsilon}$ has principal values ϵ_1, ϵ_2, ϵ_3 with an ordering (signed!)

$$\epsilon_1 \geq \epsilon_2 \geq \epsilon_3 \tag{1}$$

and with invariants

$$\begin{aligned} \epsilon_m &= \frac{1}{3}(\epsilon_1 + \epsilon_2 + \epsilon_3) \\ I_1 &= \epsilon_1 + \epsilon_2 + \epsilon_3 = 3\epsilon_m \\ J_2 &= \frac{1}{6}\left[(\epsilon_1 - \epsilon_2)^2 + (\epsilon_2 - \epsilon_3)^2 + (\epsilon_3 - \epsilon_1)^2\right] \\ J_3 &= (\epsilon_1 - \epsilon_m)(\epsilon_2 - \epsilon_m)(\epsilon_3 - \epsilon_m) \end{aligned} \tag{2}$$

Herein I_1 is the 1st invariant of strain and J_2,J_3 are the 2nd and 3rd invariant of the strain deviator, see Eq. (11). Another invariant