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Discrete modeling of ultra-high-performance concrete with application to projectile penetration

Jovanca Smith[a], Gianluca Cusatis[b,*], Daniele Pelessone[c], Eric Landis[d], James O'Daniel[e], James Baylot[e]

[a] *Department of Civil and Environmental Engineering, Northwestern University, Tech Building Room A323, Evanston, IL 60208, USA*
[b] *Department of Civil and Environmental Engineering, Northwestern University, Tech Building Room A125, Evanston, IL 60208, USA*
[c] *ES3, San Diego, CA 92101, USA*
[d] *Department of Civil and Environmental Engineering, University of Maine, 303 Boardman Hall, Orono, ME 04469, USA*
[e] *Geotechnical and Structures Laboratory, U.S. Army Engineer Research and Development Center, Vicksburg, MS 39180, USA*

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ABSTRACT

In this paper, the Lattice Discrete Particle Model for fiber reinforced concrete (LDPM-F) is calibrated and validated with reference to a new high-strength, ultra-high-performance concrete (UHPC) named CORTUF and applied to the simulation of projectile penetration. LDPM-F is a three-dimensional model that simulates concrete at the length scale of coarse aggregate pieces (meso-scale) through the adoption of a discrete modeling framework for both fiber reinforcement and embedding matrix heterogeneity. In this study, CORTUF parameter identification is performed using basic laboratory fiber pull-out experiments and experiments relevant to a CORTUF mix without fiber reinforcement. Extensive comparisons of the numerical predictions against experimental data that were not used during the calibration phase (relevant to both plain CORTUF and CORTUF with fiber reinforcement) are used to validate the calibrated model and to provide solid evidence of its predictive capabilities. Simulations are then carried out to investigate the behavior of protective CORTUF panels subjected to projectile penetration, and the numerical results are discussed with reference to available experimental data obtained at the Engineering Research and Development Center (ERDC).

1. Introduction

The design flexibility and natural durability of concrete help to make it the most used man-made material in the world. As opposed to other building materials, such as brick and stone, concrete has revolutionized previous construction methods with its intrinsic versatility and high compressive strength. Within the last century, a tremendous effort has been made to increase concrete strength. Over time, each new generation of the material became stronger and more durable, birthing the title we know today as ultra-high-performance concrete (UHPC). The material is sought for many uses including its adoption in high-rise structures, long-span bridges, offshore structures, and structural rehabilitation [1,2].

There are various methods used today to develop higher compressive strength in cementitious composites. One method is strengthening the interfacial transition zone (ITZ), the weak area surrounding the aggregate particle, which is often accomplished through a reduction of the aggregate size; this enhances homogeneity and reduces stress concentrations between the aggregate and mortar under loading. Another method to enhance the ITZ mechanical properties is reducing the water-to-binder ratio [3]. This process can be counter productive if not balanced, since the high rates of hydration often results in autogeneous shrinkage and can lead to premature cracking during the setting phase [4]. Many high-performance concretes use silica fume, which acts like a microfiller and can also react with calcium hydroxide to increase the final strength of the composite [5]. Other methods reported in the literature that enhance the compressive strength of concrete are particle-size gradation for optimum packing of aggregates [6] and heat treatment [7–10].

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* Corresponding author. McCormick School of Engineering and Applied Science, Northwestern University, Tech Building Room A125, 2145 N Sheridan Rd, Evanston, IL 60208-3109, USA. Tel.: +1 847 491 4027.

E-mail addresses: jsmith2014@u.northwestern.edu (J. Smith), g-cusatis@northwestern.edu (G. Cusatis), peless@es3inc.com (D. Pelessone), landis@maine.edu (E. Landis), James.L.O'Daniel@usace.army.mil (J. O'Daniel), James.T.Baylot@usace.army.mil (J. Baylot).

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Although there are many methods focused on increasing the compressive strength of concrete, techniques to increase tensile resistance and toughness are still in their infancy. One method typically used for this purpose is the addition of fibers in the matrix [5,11–14]. Multi-scale fiber reinforcing, in which fibers of various lengths and cross sectional sizes are used in the same mix, has also been explored in recent times [15]. When fiber reinforcing is used, the type and amount of fibers need to be optimized in order to maximize tensile strength and toughness while preserving workability and efficiency in terms of cost-to-performance ratio.

Enhancement of material toughness is particularly important in the case of the UHPC materials that are being tested to determine their efficiency against blast impact and penetration and for their use in particular areas susceptible to man-made and natural hazards [16,17]. As it pertains to projectile impact testing, many researchers found the penetration depth to increase with increasing impact velocities, and to decrease with increasing compressive strength. The perforation ballistic limit (the minimum velocity at which the bullet completely perforates the specimen) is typically reported to increase with higher compressive strength [18]. Aggregate size also plays an important role in material impact response. Stronger and larger sized aggregate particles improve impact resistance as long as enough workability is maintained [3,12,19]. For UHPC without fiber reinforcing, penetration events cause dynamic propagation of many micro-cracks and often lead to shattering of the target. On the contrary, inclusion of fibers confines cracks in the crater region in both front and rear faces and creates a more localized damage around the crater. However, for increasing fiber volume fraction, a saturation limit seems to exist after which no significant change is observed in both crater area and penetration depth [20–22].

When dealing with the effect of dynamic events on concrete structures it is also important to consider the strain-rate dependence of concrete response. Typical experimental observations on regular strength concrete report an increase of macroscopic mechanical properties such as, Young's modulus, compressive strength, tensile strength, and fracture energy, for increasing strain rate (see, among many others, [23–25, 27–32]).

Evidences of strain-rate dependence of UHPC behavior are more scarce and contradictory compared to regular strength concrete. A few studies have been performed on the effect of strain rate on UHPCs that investigated the effect of fiber reinforcement and increasing strain-rate under tensile and compressive loadings. Some researchers found UHPCs with fibers to be less sensitive to strain-rate effects than similar strength unreinforced material [33,34]. Some other researchers [35] found no rate sensitivity for concrete reinforced with hooked steel fibers. Caverzan et al. [36] investigated the effect of temperature on strain rates of high-performance fiber-reinforced concrete (HPFRC) and found an increase in strength for increased strain rate up to a rate of 150 s^{-1} for temperatures up to 200 °C, while material strength decreased for strain-rates above 150 s^{-1} for higher temperatures due to fiber failure.

In most cases, rate effect is quantified through the Dynamic Increase Factor (DIF) defined as the ratio between the dynamic property of interest and the associated quasi-static value. The evolution of DIF with strain-rate is often approximated through a bilinear curve in which the second linear branch, starting for strain-rates around 1–10 s^{-1}, has a much steeper slope than the first branch. In many cases, the DIF curves are obtained by interpolating between experimental data showing huge scatter, especially for high strain-rates. Furthermore, it is common modeling procedure to equip concrete constitutive equations with rate dependence by using the DIF curve as a multiplicative factor for various model parameters. As some authors have shown recently [37–39], this approach is not correct in general because it does not distinguish between "intrinsic" phenomena, which should be included in the constitutive equations, and "apparent" phenomena, which are structural features of the response and should or should not be included in the constitutive equations depending on the spatial and temporal resolution of the adopted numerical model.

At least three intrinsic rate-dependent phenomena can be identified to affect concrete mechanical behavior: 1) creep, 2) Arrhenius-type behavior of fracture processes, and 3) contribution to the load carrying capacity of capillary and adsorbed water.

Concrete creep, the increase in time of deformation under constant applied load, is a complex phenomenon whose fundamental mechanism resides in the cement nano-structure, and it is hypothesized to be the result of shear slips among Calcium Silicate Hydrate (CSH) platelets [40,41]. Since the nano-structure of cement evolves as result of cement hydration and other chemical reactions, creep behavior changes over time: in general, young concrete features a much more pronounced viscous behavior compared to old concrete. In addition, concrete creep is affected by moisture content and temperature and their time rates [42]. In particular, the lower the relative humidity the less concrete creep deformation is typically observed. Wittmann [43] obtained an 87% decrease in creep deformation reducing the relative humidity from 100% to 10%. From the mathematical point of view, concrete creep is typically simulated by aging, temperature, and relative humidity dependent visco-elastic constitutive equations; this naturally leads to a dependence of the stress state on strain-rates.

However, creep cannot fully explain the fracturing behavior of concrete under dynamic loading. For example, creep cannot simulate experimental data on three point bending specimens showing almost instantaneous rehardening when subjected to a sudden increase of loading rate in the softening regime [44]. To model this phenomenon, Bažant analyzed the fracture process within the classical theory of thermally activated processes, and by representing the frequency of bond rupture at the nano-scale with an Arrhenius equation, he derived a dependence of the cohesive stress (stress across a propagating cohesive crack) upon crack opening rate. This formulation was successfully used in Refs. [37,45,46] to simulate the dynamic behavior of concrete under low to moderate strain rates.

Furthermore, concrete is a porous material featuring a complex internal structure characterized by pore sizes spanning various order of magnitudes—from few nanometers to several millimeters. Depending upon the level of relative humidity, water is present in concrete pores in various forms (capillary, absorbed, or hindered) and, according to classical poro-mechanics concepts, it can certainly contribute to the overall carrying capacity. However, under quasi-static loading conditions the amount of load that pore water can carry is negligible because water is much more compressible than the solid skeleton. More complicated scenario arises under high confinement quasi-static triaxial loading because pore collapse occurs and water is squeezed out, even leading to a certain decrease in carrying capacity due to lubrication effects [47]. On the contrary, at high strain rates, water can contribute significantly to concrete strength. As far as tensile loading is concerned, some studies [48] have tried to explain the effect of water at high strain rates through the so-called Steffan effect [49] according to which the force needed to pull apart two parallel rigid plates containing a Newtonian fluid in between is proportional to the relative velocity of the two plates. This approach, although championed by some authors [50,51], has been criticized because its application to absorbed and hindered water (forming the majority of water in real concrete at relative humidity lower that 60–70%) is questionable. For triaxial compressive loading at high strain rates, water has a significant effect because, as pores collapse, water does not have enough time to be released leading to a