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Dynamic strength and ductility of ultra-high performance concrete with flow-induced fiber alignment

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ABSTRACT

The effect of fiber alignment on dynamic strength and ductility of an ultra-high performance concrete has been investigated. A beam was cast to produce a realistic level of flow-induced fiber alignment. Cores were drilled from the beam, and fiber orientation was non-destructively characterized using x-ray computed tomography. Fiber orientations in three orthogonal directions were significantly different at a 95% confidence level, with fibers preferentially aligned in the direction of flow during placement. Cored specimens were then tested in high-strain rate compression using a split-Hopkinson pressure bar. Dynamic compressive strength was independent of fiber orientation for the specimens tested. Ductility, measured by the strain at peak stress, increased with the proportion of fibers oriented perpendicular to the applied load.

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1. Introduction

Ultra-high performance concrete (UHPC) can use fiber reinforcement to increase tensile strength and control cracks. When casting structural elements with fiber-reinforced UHPC, fibers tend to align. Factors affecting alignment include flow of the concrete, use of vibration for consolidation, and wall effects from the formwork [1]. Fiber alignment results in strength anisotropy [2,3], which needs to be accounted for in design. Assuming that fibers are randomly oriented may be unconservative. In previous dynamic tests on UHPC, post-failure inspection indicated that some failures occurred on weak planes where there were few fibers [4]. This work examines the fiber orientation that occurs in a cast UHPC beam, and the effect this orientation has on dynamic compressive strength and ductility.

The split-Hopkinson pressure bar (SHPB) is used to conduct high-strain rate material tests. Developed by Kolsky [5], this technique places a specimen between two long, elastic bars. These bars are instrumented to measure the propagation of stress waves, from which the specimen's response can be determined. A schematic of an SHPB is shown in Fig. 1. An elastic compressive stress wave is produced in the input bar by the impact of a striker rod, typically fired from a compressed-gas cannon. When testing brittle materials, a pulse shaper can be placed on the face of the input bar. The pulse shaper deforms during impact, resulting in a stress wave with a tapered rise [6]. The stress wave propagates along the input bar until reaching the input bar-specimen interface. When the specimen has a lower acoustic impedance than the bar, part of the wave is reflected back into the input bar as a tensile stress wave. The rest of the wave continues into the specimen and is then transmitted into the output bar. This description has ignored wave reflections in the specimen, which must be considered when assessing the uniformity of stress [7].

Data are usually analyzed under the assumptions that wave propagation in the bars can be adequately described by the one-dimensional elastic theory, stress in the specimen is uniform, and the effects of friction and inertia are negligible [7]. Then, the specimen engineering stress (σ_s), engineering strain (ε_s), and engineering strain rate ($\dot{\varepsilon}_s$) can be determined as

$$\sigma_s(t) = \frac{A_b E_b}{2A_s}(\varepsilon_I(t) + \varepsilon_R(t) + \varepsilon_T(t)), \tag{1}$$

$$\varepsilon_s(t) = \int_0^t \dot{\varepsilon}_s(\tau)\, \mathrm{d}\tau, \tag{2}$$

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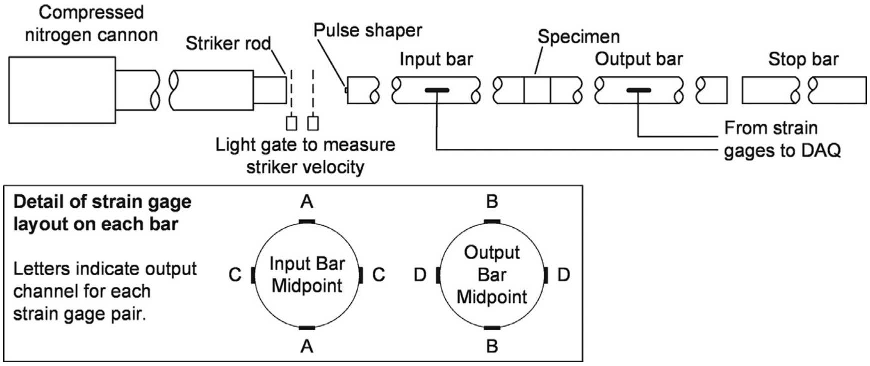

Fig. 1. Schematic of the SHPB.

$$\dot{\varepsilon}_s(t) = \frac{c_{0,b}}{L_s}(\varepsilon_I(t) - \varepsilon_R(t) - \varepsilon_T(t)), \tag{3}$$

where A is cross-sectional area, E is the elastic modulus, $c_0 = (E/\rho)^{1/2}$ is the thin-rod elastic wave speed, ρ is mass density, L is length, and the subscripts b and s refer to the bar and specimen, respectively. Note that stresses and strains are taken as positive in compression throughout this article. The measured strains ε_I, ε_R, and ε_T correspond to the incident, reflected, and transmitted stress waves, respectively. These strains are measured by strain gages bonded to the bars at their midpoints. An example of the strain gage output is shown in Fig. 2.

Cor-Tuf Baseline, a UHPC developed by the U.S. Army Corps of Engineers [8], has been tested in both unconfined [4] and confined [9] dynamic compression using an SHPB. Cor-Tuf Baseline is rate-sensitive, achieving higher strengths at increasing rates of loading. This strength increase is typically quantified using the dynamic increase factor (DIF), which is the ratio of dynamic strength to the corresponding quasi-static strength. The reduced time for micro-crack propagation at high strain rates is thought to be responsible for strengthening [10]. However, it is also known that confinement in dynamic tests increases the measured strength [10,11]. When an axial compressive load is rapidly applied, a test specimen's radial expansion due to the Poisson effect is opposed by inertia forces. This is equivalent to applying a radial confining stress, which has been determined under the assumption of linear elasticity by Forrestal et al. [12]. However, concrete is a non-linear material. Also, the contribution of inertial confinement to the strength increase in high-strain rate tests can only be assessed indirectly, as the effect of inertia cannot be eliminated. A number of studies (for example, [13–15]) have used numerical simulation to study the effects of inertial confinement on SHPB tests of concrete.

Fibers are most efficient in crack-bridging when oriented perpendicular to a crack. Therefore, when a material is loaded in tension, fibers should be oriented parallel to the tensile stress [16]. Similarly, when a material is loaded in compression, fibers should generally be oriented perpendicular to the compressive stress [2,3].

Fiber orientation can be described using the orientation number, typically η. Traditionally, η has been determined by cutting a cross-section in a specimen and examining the fibers in the cut surface. In this case, η is the ratio of the projected fiber length normal to the surface to the total fiber length [17]. In light of the different effects of orientation in tension and compression, the orientation number can be generalized as follows:

$$\eta_{\parallel} = \frac{1}{N}\sum_{i=1}^{N}\cos(\theta_i), \tag{4}$$

$$\eta_{\perp} = \frac{1}{N}\sum_{i=1}^{N}\sin(\theta_i), \tag{5}$$

where N is the total number of fibers, and θ_i is the angle that the ith fiber makes with the axis of loading. The parallel orientation number, $\eta_{\parallel}$, is the fraction of fiber length that is projected parallel to the applied load. Similarly, the perpendicular orientation number, $\eta_{\perp}$, is the fraction of fiber length that is projected perpendicular to the applied load. Although this definition suggests a simple geometric relationship between the two orientation numbers, it is generally *not* the case that $\eta_{\parallel}^2 + \eta_{\perp}^2 = 1$. This would hold for a single fiber, but

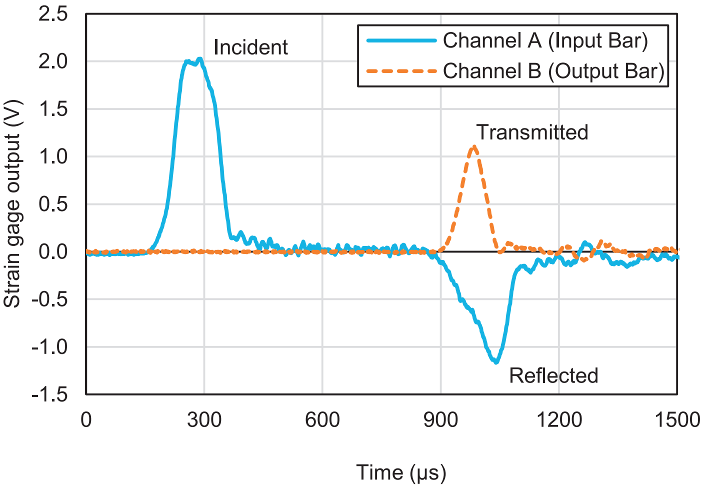

Fig. 2. Strain gage output from test of specimen X-D-2M.