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Experimental investigation and multiscale modeling of ultra-high-performance concrete panels subject to blast loading

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ABSTRACT

Tailored cementitious materials, such as Ultra-High-Performance Concrete (UHPC), may significantly improve the blast resistance of structural panels. To understand and quantify the performance of UHPC panels subject to blast loading, four 1626- by 864- by 51-mm UHPC panels without steel rebar reinforcement were subjected to reflected impulse loads between 0.77 and 2.05 MPa-ms. The UHPC material was composed of a commercially available UHPC premix, high-range water reducing agent, 2% volume fraction of straight, smooth 14-mm-long by 0.185-mm-diameter fibers, and water. Experimental results determined that the UHPC panel fractured at a reflected impulse between 0.97 and 1.47 MPa-ms. These results were used to validate a multiscale model which accounts for structure and phenomena at two length scales: a multiple fiber length scale and a structural length scale. Within the multiscale model, a hand-shaking scheme conveys the energy barrier threshold and dissipated energy density from the model at the multiple fiber length scale to the model at the structural length scale. Together, the models at the two length scales account for energy dissipation through granular flow of the matrix, frictional pullout of the fibers, and friction between the interfaces. The simulated displacement and fracture patterns generated by the multiscale model are compared to experimental observations. This work is significant for three reasons: (1) new experimental data provide an upper and lower bound to the blast resistance of UHPC panels, (2) the multiscale model simulates the experimental results using readily available material properties and information regarding mesostructure attributes at two different length scales, and (3) by incorporating information from multiple length scales, the multiscale model can facilitate the design of UHPC materials to resist blast loading in ways not accessible using single length scale models.

1. Introduction

To protect personnel and infrastructure, the dynamic response of materials and structures subject to blast loads must be understood. This understanding is especially important for new materials such as Ultra-High-Performance Concretes (UHPCs), which have been tailored at the micrometer and millimeter length scales to have compressive strengths exceeding 150 MPa [1] and enhanced fracture energies [2]. Here, a slab is assumed to be a representative structural element with which UHPC materials and their mesostructures will be characterized.

Since the introduction of UHPCs [3], results have been published for five experimental programs that subjected a total of 16 UHPC panels to blast loads at scaled distances ranging from 0.37 to 2.18 m/kg$^{1/3}$ [4]. Of the 16 panels, 13 panels were reinforced with steel rebar, and 3 panels were not reinforced. One of the three non-reinforced panels was 2- by 1- by 0.1-m in dimension and survived a reflected impulse of 1.62 MPa-ms [5]. The maximum and permanent centerline deflections were 13.2 and 4.1 mm, respectively. The two remaining non-reinforced UHPC panels were 3.5- by 1.3- by 0.1-m in dimension with one panel containing 2% volume fraction of fibers and the other panel containing 4% volume fraction of fibers [6]. After being subjected to a reflected impulse of 0.83 MPa-ms, the panels containing 2% and 4% fiber volume fractions permanently deflected 180 and 90 mm, respectively, at their mid-heights. Without testing until failure, the limited experimental

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data provide only a lower limit to the critical load level; the upper bound remains to be established.

The responses of UHPC panels have been simulated by two different computational approaches. Wu et al. [5] used a layered single-degree-of-freedom model to predict the critical energy absorption capacity of UHPC panels with and without steel rebar reinforcement. This approach relies upon an a priori assumption of the elastic–plastic response of the panel [7], which defines a "shape function." Hence, this approach is limited to elastic–plastic responses and cannot model fracture. In contrast to the single-degree-of-freedom approach, Zhou et al. [8] used a coupled damage-plasticity constitutive model that was pressure-sensitive and strain-rate dependent to determine the response of rebar-reinforced UHPC panels. Spall, defined as the ejection of mass on the surface opposite from that of the blast load impingement, was modeled by deleting elements with damage values exceeding 0.22 (on a scale from 0 to 1) during the first 0.5 ms after loading at strain rates greater than 10 s^{-1}. Although it accounts for spall, this approach underestimated the experimentally observed deflection by approximately 40%. Note that neither the layered single-degree-of-freedom model nor the damage-plasticity model included information from length scales smaller than the UHPC structure or steel rebar reinforcement levels; thus, neither approach is suitable for supporting materials design, i.e., tailoring the microstructure to achieve targeted responses or properties.

Gaps in the published literature motivated the objectives of the present study, namely, to experimentally determine the lower and upper bounds of the reflected impulse for a UHPC panel without rebar and to develop a multiscale model of UHPC panels based on the material properties and information regarding mesostructure attributes of the constituents.

2. Experimental setup

2.1. Materials

UHPC materials were made from Ductal® BS1000 Grey premix, Chryso® Fluid Primea 150 high-range water reducing agent, 2% volume fraction, V_{fiber}, of steel fibers, and water at a 0.19 nominal water-to-cementitious material ratio. The fibers were 14-mm long with 0.185-mm diameter circular cross-section and were measured to have a 2.16-GPa tensile strength, 210-GPa elastic stiffness, and 7.85-g/cm^3 mass density. The four constituents were mixed in a Nikko high-shear mixer according to the manufacturer's recommendation.

The mixed UHPC slurry was poured into four different rectangular cavities, each having dimensions of 1626-mm long by 864-mm wide by 50.4-mm deep. At the bottom of each cavity, two layers of Hardwire® 3 × 2-4-12-500 brass reinforcement [9] were placed at +45° and −45° from the direction of the 1626-mm length of the cavity. The panels were then cured at 22 °C under wet burlap for 24 h, followed by 2 days in a steam cabinet at 91 °C.

The mechanical properties of UHPC were obtained 14 days after pouring using three 101.6-mm-diameter by 203.2-mm-tall cylinders. The cylinders were poured from the same UHPC slurry and cured using the same protocol as the panels. Test results for the density, ρ_{UHPC}, and quasi-static unconfined compressive strength, $f_c^{'}$, are in Table 1.

Fig. 1 shows a backscatter scanning electron microscope (SEM) image of a representative as-cured UHPC microstructure from Wang, Mattus, and Ren [10]. The black circle represents porosity, the white ellipses represent fibers, the dark grey represents quartz aggregate, and the regions between the previously listed components represent the paste. The magnified view at the right of Fig. 1 shows that the paste is composed of unhydrated clinker (white), quartz powder (dark grey), cracks (black), and hydrated Calcium-Silicate-Hydrate (medium grey). Note that the SEM images were recorded in a vacuum, which implies that the visible cracks in the magnified view may be due to drying during the preparation of the specimen for SEM studies.

Table 1
Density and unconfined compressive strength for cylindrical specimens.

Sample ID	ρ_{UHPC} (kg/m^3)	$f_c^{'}$ (MPa)
125-11DIP#1	2567	200
125-11DIP#2	2566	206
125-11DIP#3	2565	196
Mean	2566	201
Standard deviation	1.0	5.0

2.2. Blast load simulator (BLS)

Panels were tested at the U.S. Army Corps of Engineers (USACE) Engineer Research and Development Center (ERDC) Blast Load Simulator (BLS) located in Vicksburg, MS [11]. As shown in Fig. 2, the BLS is composed of a driver, expansion rings, straight rings, and the target vessel. After the UHPC panel is placed in the target fixture, the target vessel is connected to the straight rings. To initiate the test, a disk between the driver and expansion rings is ruptured, thus releasing the compressed air contained within the driver. The pressure wave travels through the expansion and straight rings before encountering the target located in the target vessel. The BLS produces planar waveforms with peak reflected pressures and impulses of 552 kPa and 11.0 MPa-ms, respectively.

Each UHPC panel was placed in the target fixture at the location indicated in Fig. 2. The target fixture consists of an insert and a cover as shown in Fig. 3a and b, respectively. The insert consists of two 203.2- by 152.4- by 12.7-mm structural steel tubes and two 50.8- by 50.8- by 6.35-mm structural tubes. The panel is placed in the insert with the Hardwire® reinforced surface adjacent to the 50.8- by 50.8- by 6.35-mm steel tubing. The cover keeps the panel in position before and during testing. The target fixture imposes conditions similar to, but not exactly the same as, "simply supported" boundary conditions.

Reflected pressure was recorded by six pressure transducers located at the positions shown as small yellow circles on the target fixture cover in Fig. 3b. Displacement of the distal face of one panel was recorded by an accelerometer and laser measurement system at the positions indicated in Fig. 3b. Video images of the distal faces of all panels were recorded at a rate of 1000 frames per second.

3. Multiscale modeling

The numerical simulations in this study were conducted based on a hierarchical multiscale modeling approach. The finest length scale, the multiple fiber length scale, simulates the fracture of the UHPC matrix and subsequent fiber pullout behavior. The coarsest length scale, the structural length scale, utilizes information from the multiple fiber length scale to simulate the behavior of the UHPC panel.

3.1. Multiple fiber length scale

A two-element Rigid-Body-Spring-Model (RBSM) was adopted at the multiple fiber length scale to define the traction-separation response of an interface bridged by fibers. The RBSM assumes that after the matrix at a given interface cracks, the entire load is carried by the fibers [12]. Here, the RBSM was introduced as part of