Proceedings of the 7th GACM Colloquium on Computational Mechanics for Young Scientists from Academia and Industry October 11-13, 2017 in Stuttgart, Germany

Numerical fracture studies of ultra-high performance concrete under dynamic loading

Mohammad Reza Khosravani[1]*, Carola Bilgen[1] and Kerstin Weinberg[1]

Micro Abstract
Ultra-high performance concrete (UHPC) is a new class of concrete material. In this contribution, split Hopkinson pressure bar (SHPB) is modified and utilized to conduct series of spalling tests. Dynamic elastic modulus and dynamic tensile strength of the studied UHPC sepcimens are determined. Furthermore, the spalling test is numerically simulated by MATLAB program. Within this context two numerical fracture methods are compared with respect to determination of main parameter like the tensile strength and the specific fracture energy. In order to determine the latter one an inverse analysis is applied. The achieved results showed good agreement between numerical simulations and experimental observations.

[1]Institute of Solid Mechanics, University of Siegen, Siegen, Germany
***Corresponding author**: mohammadreza.khosravani@uni-siegen.de

Introduction

In construction of new engineering structures, optimization of the concrete panels seems to be necessary which leads to new generation of concrete. The successful production of ultra-high performance concrete (UHPC) provided denser cement-based material which shows higher strength properties, more durability, low porosity and improved fatigue behavior. The evolution of concrete into UHPC is a gradual process, but desired properties of UHPC material, converted it to one of the most preferred material for different applications such as engineering and military structures, tall buildings and machine parts. Several researches with various aspects have been conducted on UHPC material [5, 6, 9, 11]. Literature review indicates that investigations on behavior and mechanical properties of concrete under dynamic loading has been topic of interest along the years [1,8,12], but behavior of UHPC material under dynamic loading condition is not well documented. Dynamic properties, such as impact strength, dynamic tensile resistance and failure criteria can hardly be gained under reproducible conditions. However, ongoing researches are filling the knowledge gaps and provide reliable data about behavior and response of UHPC under high rate of loading.

A Split Hopkinson pressure bar (SHPB) test is a common technique to study the behavior and to determine the mechanical properties of materials under dynamic loading conditions. The traditional SHPB consists of an air gun, a striker and incident and transmission bars. Generally, a data acquision system is used to collect the data during the test. A spalling test by means of a SHPB demonstrated in [4] is applied on concrete specimens. The researchers conduct a spalling test to characterize the dynamic strength and the damage of the concrete specimens under dynamic loading conditions. They determine the spall strength of wet and dry concrete by a series of spalling tests. Recently, in [2] a SHPB is used to run the Brazilian test on concrete. The researchers deduce a dynamic splitting tensile test with different loading angles and impact velocities. They determine the dynamic tensile strength of concrete. Furthermore, within the obtained results it is concluded that the impact velocity plays an important role in failure patterns of concrete.

In the current paper, a SHPB is modified and series of spalling tests and also numerical fracture study of UHPC are performed. This paper is organized as follows: Section 1 describes briefly the experimental procedure of spalling tests on UHPC. In the second section, numerical fracture studies of spalling test are demonstrated. Finally, the conclusion is presented.

1 Experimental fracture study of UHPC material

Cylindrical UHPC specimens with length and diameter of 200 mm and 20 mm are produced. In series of spalling tests, specimens are placed on the modified SHPB. An air gun launched the striker which impacts the incident bar. This initial impact produces a compressive stress pulse traveling through the incident bar and reaches the incident bar-specimen interface. One part is reflected back and another part is transmitted through the specimen. At the free end of the specimen, the stress is reflected as tensile pulse. When this tensile pulse exceeds the ultimate tensile strength of the UHPC specimen, a crack starts to occur within the specimens and spall is observed. In characterization of the brittle materials like UHPC, the specimen deformation prior to failure is very small and the specific conditions should be satisfied in a short period of time. In current research, a circular paper pulse shaper is used to satisfy the conditions in all the experiments, [7].
To measure the incoming and passing impulses, strain gauges are mounted in the middle of incident bar and all data are acquired by a HBM GEN7t system. According to the one-dimensional wave theory for SHPB experiments, the stress, strain and strain rate can be calculated. Furthermore, a high speed camera system with capability of clear recording in low-light is employed to record the process from initial impact till specimen failure. Additionally to the spalling tests the dynamic elastic modulus and dynamic tensile strength of the studied UHPC specimens are determined to $E_{dyn} = 51.3 \pm 0.5\,\mathrm{GPa}$ and $\sigma_T = 19.5 \pm 0.93\,\mathrm{MPa}$ respectively.

2 Numerical fracture study of UHPC material

This section presents numerical fracture simulation methods to determine the appropriate parameter and to prove the experimental approach. In the following the focus is set on two different methods - the cohesive zone model and the phase-field model. An introduction and a detailed comparison of both approaches can be found in [3, 13]. The main aim of spalling experiments is to determine the main parameter which are the tensile strength R_m^t, the critical opening displacement δ_c and the specific fracture energy $\mathcal{G}_c$.

2.1 Simulation of the SHPB-spalling experiment

The simulation part is based on the geometry which is introduced in the experimental part in Section 1. Since the cylindrical specimen is symmetric an axialsymmetric finite element model can be applied which maps a fully three-dimensional material behavior with the reduced effort of a plane mesh. Therefore, extensive parametric studies can be deduced. One of the main tasks is to reproduce the incident and the reflected stress pulses in the specimen. By means of the strain pulse measured in the incident bar and a low amplitude measured in the specimen the shape of the transmitted wave can be stated. On the (left) boundary a pressure impulse is applied which is of the form $\bar{q} = \sigma_{\max} f(t)$ with an appropriate function, cf. [3], and $\sigma_{\max} = -17$ MPa. The average velocity of the specimen before spallation is $v_{\text{spec}} = 6.8\text{m/s}$. The time discretization is based on a special central difference scheme with a weighted displacement field which results in stress pulses that largely correspond to the measured data. Further numerical details can be found in [3, 10].
At first the dynamic tensile resistance of a brittle material R_m^t is presented as one of the main parameter which is usually defined as the maximum tension a material can sustain. There exist different ways to deduce the tensile resistance from the measured data in the experiments. In this contribution the focus is set on quantifying the incident and reflected waves, shifting them to the position of fracture and defining the superposed elastic stress state. Finally, the

dynamic tensile strength is given by the level of tensile stress reached at the location of fracture. Concerning phase-field simulations the fracture energy is the crucial parameter for crack growth. By varying the fracture energy $\mathcal{G}_c$ it can be observed that either the crack does not propagate if $\mathcal{G}_c$ is chosen too high or the cracked zone becomes wider if $\mathcal{G}_c$ is chosen too small. Further studies have been performed to simulate the experiments, cf. [3], and it can be concluded, that for UHPC the tensile strength R_m^t, the critical opening displacement δ_c and the specific fracture energy $\mathcal{G}_c$ are in the following ranges:

$$12 < R_m^t < 18 \quad \text{in [MPa]}\,, \quad 5 < \delta_c \leq 17.5 \qquad \text{in } [\mu\text{m}]\,, \quad 40 \leq \mathcal{G}_c \leq 105 \quad \text{in [N/m]}\,. \tag{1}$$

2.2 Inverse analysis: determination of the $\mathcal{G}_c$

In this section an inverse analysis is considered where the measured data of the experiment are used to determine fracture parameters and the obtained results are applied to simulate the experiment. After spallation two fragments result with the crack located at the position where the stress exceeds the tensile resistance first. The total fracture energy W_c corresponds to the amount of work necessary to form such a new surface. In order to deduce W_c the main idea is to balance the energy before and after crack initiation considering two appropriate times t_1 and t_2. Regarding two fragments with masses $m_{\text{fra},1}$, $m_{\text{fra},2}$ and $m_{\text{spec}} = m_{\text{fra},1} + m_{\text{fra},2}$, cf. Figure 1, the difference of kinetic energy can be formulated as follows:

$$\Delta\mathcal{K} = \frac{1}{2} m_{\text{spec}} \left(v_{\text{spec}}(t_1)\right)^2 - \frac{1}{2} m_{\text{fra},1} \left(v_{\text{fra},1}(t_2)\right)^2 - \frac{1}{2} m_{\text{fra},2} \left(v_{\text{fra},2}(t_2)\right)^2 \tag{2}$$

Since UHPC is assumed to behave linear elastically, it is stated that $\Delta\mathcal{K} = W_c$ is the fracture energy of the specimen. Finally, the specific fracture energy follows as

$$\mathcal{G}_c = \frac{W_c}{A_c}\,. \tag{3}$$

whereby the fractured surface is ideally assumed as $A_c = 2\pi r_{\text{spec}}^2$. Within the inverse analysis a range of input data $\mathcal{G}_c^{\text{inp}}$ is defined, the experiment is simulated and finally the 'measured' value $\mathcal{G}_c^{\text{sim}}$ is deduced.

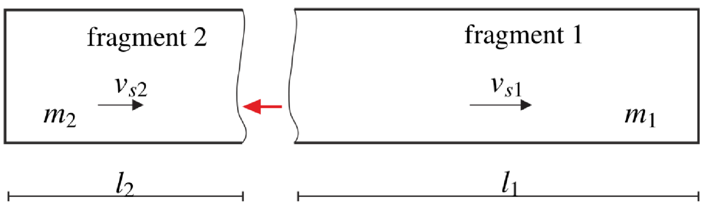

Figure 1. Fragments after spallation

In Figure 2 the computed specific fracture energy $\mathcal{G}_c^{\text{sim}}$ is shown making use of both fracture models - the cohesive zone model and the phase-field model.

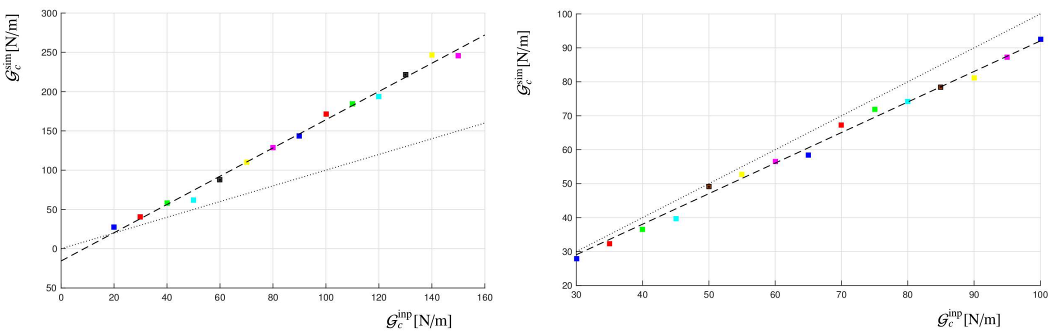

Figure 2. Determination of the specific fracture energy: displayed are the values $\mathcal{G}_c^{\mathsf{sim}}$ derived from the velocity and mass data obtained in the simulation vs. the input parameter $\mathcal{G}_c^{\mathsf{inp}}$ of the experiment. The dotted line marks the identity $\mathcal{G}_c^{\mathsf{sim}} = \mathcal{G}_c^{\mathsf{inp}}$. (a) Cohesive element technique: The dashed line is approximated with $R^2 \approx 0.9928$ and corresponds roughly to $\mathcal{G}_c^{\mathsf{sim}} = 1.5\mathcal{G}_c^{\mathsf{inp}}$. (b) Phase-field fracture approach: The parameters for the simulations are $\epsilon = \frac{5}{2}$ mm, $s(t_1) = 0.8$, $s(t_2) = 0.2$. The dashed line is approximated with $R^2 \approx 0.9969$ and corresponds well to $\mathcal{G}_c^{\mathsf{sim}} = 0.9\mathcal{G}_c^{\mathsf{inp}}$.

Conclusions

Ultra-high performance concrete(UHPC) is a favourable advanced cementitious composite. For further development, in the present study experimental and numerical fracture behavior of UHPC specimens under dynamic loading are performed. In this respect, series of spalling tests in a strain rate of $30\,s^{-1}$ are conducted by a modified split Hopkinson pressure bar (SHPB) setup. The dynamic elastic modulus and dynamic tensile strength of studied UHPC are determined. Furthermore, concerning the numerical study two different fracture methods are investigated and the fracture energy values have been determined. Both models - the cohesive zone model and the phase-field model - allow efficient numerical simulation of crack growth and allow to quantify the related material parameter in an adequate manner.

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