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Review

Mechanical and structural behaviors of ultra-high-performance fiber-reinforced concrete subjected to impact and blast

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HIGHLIGHTS

- UHPFRC dissipates much higher energy by impact than ordinary FRC.
- Fiber orientation significantly influences the impact resistance of UHPFRC.
- Long straight steel fiber is effective in improving the impact resistance of UHPFRC.
- Using high-strength steel in UHPFRC is efficient in enhancing the blast resistance.
- Adopting seismic detailing in UHPFRC columns improves the blast resistance.

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ABSTRACT

This study comprehensively investigates impact and blast resistances of ultra-high-performance fiber-reinforced concrete (UHPFRC) by considering various influential factors. At a material level, rate-dependent fiber pullout behavior, dynamic compressive behavior, and impact tensile and flexural behaviors were examined in detail, and the benefits of using UHPFRC to improve the impact resistance of ordinary concrete were discussed. It was obvious that (1) UHPFRC is able to dissipate much higher energy by impact than ordinary concrete with and without fibers, (2) the use of long straight steel fiber is effective in improving the impact resistance of UHPFRC compared to that of deformed steel fibers at high volume fractions, (3) fiber orientation significantly influences the impact resistance of UHPFRC: when more fibers are aligned in the tensile load direction, better impact resistance is achieved, and (4) size effect on the dynamic increase factor versus strain-rate relationship is insignificant. Impact and blast resistances of UHPFRC beams, slabs, columns, and composite structures were also examined at structural level, and several useful conclusions were drawn. (1) UHPFRC is favored for impact- or blast-resistant structures as compared with ordinary concrete due to its much better impact and blast resistance at identical dimensions, reinforcement configuration, and load magnitude, (2) the use of high-strength steel rebar provides the better blast resistance of UHPFRC beams or slabs as compared with that of normal-strength steel rebar, and (3) seismic detailing applied in UHPFRC columns leads to better blast resistance than is seen for columns without seismic detailing. Further research is suggested to address the remaining complicated problems or conflicts and to inspire proper design of structural UHPFRC members in an attempt to increase the use of UHPFRC.

Contents

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1. Introduction

In recent years, the threat of global terrorism has increased. In order to protect civilian lives from terrorist attacks, buildings and civil infrastructure should provide resistance to extreme loads such as impact and blasts. Ordinary concrete, which is one of the most widely used construction materials, is well-known to be weak under such extreme loadings because of its poor energy absorption capacity and brittle nature. Various methods to overcome the drawbacks of ordinary concrete have been introduced by many researchers, including addition of discontinuous fibers [1–3], use of continuous textile reinforcements [4,5], and external strengthening with fiber-reinforced polymer (FRP) [6]. Among these techniques, discontinuous fibers have been most broadly used for concrete since it is easy to include these fibers in the concrete mixture, and they effectively improve the energy absorption capacity under impact or blast due to a crack bridging effect.

Ultra-high-performance fiber-reinforced concrete (UHPFRC), which was first introduced by Richard and Cheyrezy [7] in the mid-1990s, exhibits excellent mechanical properties in terms of strengths (i.e., its compressive strength is higher than 150 MPa and the design tensile strength is 8 MPa), energy absorption capacity (i.e., fracture energies up to 40 kJ/m^2), durability, and fatigue resistance. These excellent mechanical properties have been achieved by using a low water-to-binder ratio of approximately 0.2, very fine admixtures (silica fume and silica flour), steam curing with heat (90 °C), and the addition of a high volume content of micro steel fibers. However, since UHPFRC is much more expensive than ordinary concrete and requires the above special heat curing process, this material needs to be properly applied for special buildings or infrastructures. First, since UHPFRC has excellent performance with regard to durability as compared with ordinary concrete, it can be applied for the structures near the shore. In addition, it can be effectively used with FRP bars, caused by the fact that, due to its strain-hardening property, the large deflection of ordinary FRP bar-reinforced concrete beams at serviceability limit state, which is one of the most significant drawbacks, can be overcome [8]. Lastly, it can be applied for the structures subjected to extreme loads such as impacts and blasts, because it exhibits much better impact and blast resistance compared to ordinary concrete with and without fibers [9–14]. Therefore, UHPFRC has attracted attention from researchers and engineers for use as a construction material for impact- and blast-resistant structures.

However, the impact and blast resistance of reinforced or non-reinforced UHPFRC elements is affected by numerous factors, including rate of loading (strain-rate effect), fiber properties (shape, aspect ratio, and strength), fiber orientation, specimen size, size and hardness of coarse aggregate, etc. In order to properly design UHPFRC mixtures and structural members, the effects of the various factors on the resulting mechanical and structural properties under impact and blast need to be comprehensively examined. Since UHPFRC exhibits very different post-cracking behavior than ordinary concrete, a novel numerical method is also required. However, to the best of our knowledge, there is no published study that summarizes the overall behaviors of UHPFRC elements subjected to impact and blast. As such, a state-of-the-art review paper focusing on the loading rate effect in various types of UHPFRCs is required.

Therefore, to help researcher's broad understanding on the recent research trends, we comprehensively investigated the present state of knowledge of the mechanical and structural properties of UHPFRC subjected to impact and blast loads. Our attention was focused on (1) the rate-dependent pullout behavior of different fibers in ultra-high-performance concrete (UHPC); (2) mechanical properties (compression, tension, and flexure) of UHPFRC under impact considering various influential factors; (3) impact and blast resistance of reinforced UHPFRC beams, slabs, columns, and composite structures; and (4) numerical modeling for UHPFRC elements under impact and blast loads. We also highlighted several issues that should be addressed in future work and included critical review comments and our insightful opinion on the impact and blast resistance of UHPFRC. Thus, the readers can broadly comprehend the recent research trends on the impact and blast resistance of UHPFRC at both material and structural levels and effectively design their future experimental variables.

2. Material level

2.1. Rate-dependent fiber pullout behavior

In order to understand the impact and blast resistance of UHPFRC elements, the dynamic fiber pullout behavior must first be examined. This is caused by the fact that since UHPFRC exhibits strain- or deflection-hardening behavior, showing a higher load carrying capacity after matrix cracking strength, the ultimate strength is dependent more on fiber pullout capacity than the matrix cracking. The tensile or flexural behavior and even structural behavior of UHPFRC composites can be predicted based on the fiber pullout properties, called micromechanics-based analysis, [15,16], so information of the rate-dependent fiber pullout behavior is very important for further development of micromechanics-based analytical technique considering the strain-rate effect. Tai et al. [17] recently investigated the pullout resistance of three different high-strength steel fibers (twisted, straight, and hooked fibers) embedded in UHPC under various loading rates from 0.018 mm/s (quasi-static level) to 1800 mm/s (impact level). As shown in Fig. 1, the straight steel fibers exhibited the highest dynamic increase factor (DIF) for the bond strength (DIF of 2.1) at a loading rate of 1800 mm/s (impact), followed by the twisted fibers (DIF of 2.0) and hooked fibers (DIF of 1.6) at the same rate of impact load. In particular, the observed strain-rate sensitivity of straight steel fibers was inconsistent with the findings from Gokoz and Naaman [18]. They showed that pullout of straight steel fiber in a cement matrix is not strain rate sensitive because the pullout process is non-destructive in nature. However, in UHPC, damage did occur in the cement