



# Dynamic impact behaviors and constitutive model of super-fine stainless wire reinforced reactive powder concrete

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## HIGHLIGHTS

- Dynamic impact behavior of concrete with super-fine stainless wires was studied.
- A revised visco-elastic model considering damage is proposed for wires/concrete.
- Adding wires can obviously improve impact toughness of reactive powder concrete.
- Dynamic failure of reactive powder concrete is effectively inhibited by wires.
- Inter-anchored surface in bundling wires improves crack resistance of concrete.

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## ABSTRACT

The dynamic impact behavior of super-fine stainless wire (SSW) reinforced reactive powder concrete (RPC) was studied through split hopkinson pressure bar test with the strain rate range from 94/s to 926/s in this paper. The modification mechanisms of SSW to the dynamic impact performance of RPC were revealed via computed tomography and scanning electron microscope analysis. Experimental results showed that the dynamic impact compressive strength of SSW reinforced RPC increases with the strain rate. The dynamic increase factor of compressive strength is decreased and the strain-rate strengthening effect of RPC is weakened by SSW. The maximum dynamic peak strain of SSW reinforced RPC reaches up to 34,070  $\mu\epsilon$  at the strain rate of 305/s. The limit strain of RPC is decreased because of the lateral confinement effect of SSW. The stress-strain curves of SSW reinforced RPC include elastic stage, elastic-plastic stage and descending stage. The addition of SSW leads 43.5% and 58.2% of increase in dynamic impact toughness and impact dissipate energy of RPC, respectively. Increasing SSW volume fraction makes more SSW to inhibit the generation and propagation of cracks in RPC, thus leading to the decrease of destruction degree. The formation of inter-anchored interface among bundling SSW increases the resistance of RPC to crack development. The dynamic impact constitutive model established on the basis of revised visco-elastic and damage theory can well describe the stress-strain relationship of SSW reinforced RPC at different strain rates, in which the strain threshold is governed by strain rate and SSW volume fraction simultaneously.

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## 1. Introduction

There are more and more severe challenges for modern concrete material due to the construction of large-scale and complicated infrastructures, extreme service environments and multi-factor coupling actions [1,2]. High-performance and

smart/multifunctional concrete is one way to implement the sustainable development of concrete structures [3,4]. This new concrete composite has excellent workability, mechanical properties and durability as well as self-sensing, self-healing and self-compacting functions [5–8]. However, most of large-scale concrete structures not only bear static load but also inevitably bear dynamic load (e.g., seismic load, impact load, and blast load). The impact and blast load with rapidly changing characteristic must be considered in the design of nuclear power protection structure and military defensive project. Therefore, investigations of the

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dynamic mechanical behavior of concrete are important and essential to provide valuable information for the structural design.

The strain rate caused by impact or blast load is  $10^2$ – $10^4$ /s or higher [9]. Meanwhile, the corresponding strain rate characteristic of concrete is commonly explored using split hopkinson pressure bar (SHPB) test in the existing studies. Wang et al. [10] found that the addition of steel fiber with a diameter of 0.16 mm and a length of 13 mm (its volume fraction is 1% and 2%) reduces the sensibility of RPC dynamic compressive strength to strain rate (the maximum strain rate is 154/s). They pointed out that the destruction pulverization degree of RPC specimen decreases due to the bridging and inhibition effect of steel fiber on cracks as the strain rate is larger than 100/s. Wang et al. [11] studied the dynamic compressive behavior of concrete containing 3% and 6% ultra-short steel fiber with a diameter of 0.175 mm and a length of 6 mm by using the SHPB device at the strain rate up to 100/s. It was concluded that the dynamic compressive strength of concrete increases with steel fiber volume fraction and strain rate. Meanwhile, the stress-strain curve of concrete with 6% ultra-short steel fiber possesses slow descending stage at the low strain rate, representing the improvement of dynamic impact toughness. Tai [12] performed SHPB compressive test on RPC with different steel fiber volume fractions (the length and diameter of steel fiber were 12 mm and 0.175 mm respectively) at strain rate of 78.5/s–1235/s. The results demonstrated that the RPC is strain rate dependent, and the absorption energy of RPC reinforced by 3% steel fiber can reach 42.4 J/cm<sup>3</sup> at the strain rate of 1235/s. Both fiber volume fraction and strain rate exert significant enhancing effect on the impact toughness and energy absorption of RPC, while the improvement effect of steel fiber cannot be demonstrated at low-speed impact due to the limitation of distortion and destruction of RPC. Wang et al. [13] found that the failure mode of concrete with 3.0% steel fiber (the diameter and length were 0.2 mm and 13 mm respectively) changes from fragile to ductile under SHPB test. Meanwhile, the fibrous concrete can resist repeated impact load and the damage softening of concrete with high volume fraction of steel fiber can be offset by strain-rate strengthening effect. Hao et al. [14] conducted a series of SHPB tests to explore the dynamic compressive property of spiral fiber reinforced concrete at high strain rate. It was found that the dynamic compressive strength of concrete shows increasing sensitivity to strain rate with the increase of fiber volume fraction. The energy absorption ability of concrete is significantly affected by steel fiber volume fraction as the strain rate is higher than 100/s. The experimental results of Sun et al. [15] indicated that the strain-rate strengthening effect of concrete is reduced with the increase of steel fiber volume fraction. The energy absorption of concrete with 3% steel fiber can reach 2.25 MJ/m<sup>3</sup> at strain rate of 147/s. Meanwhile, the damage evolution of concrete is effectively inhibited by steel fiber. Hou et al. [16] investigated the dynamic compressive behavior of RPC with 2% and 5% steel fiber (the diameter and the length were 0.22 mm and 13 mm respectively) at the strain rate range from 75/s to 274/s. It was concluded that the dynamic elastic modulus of concrete is sensitive to both steel fiber volume fraction and strain rate. The energy absorption of RPC with 2% steel fiber is 5.0 MJ/m<sup>3</sup> at the strain rate of 274/s, which continuously increases with the increase of strain rate and steel fiber volume fraction.

In order to modify the dynamic mechanical property of concrete, researches usually used steel fiber with different shape and geometry simultaneously or compositely used steel fiber, organic fiber and nano-particle material. Li et al. [17] found that the ultra-high toughness cementitious composite with 1.5% steel fiber and 2.0% polyvinyl alcohol fiber demonstrates the best dynamic behavior. The volume fraction of steel fiber has no obvious effect on the dynamic compressive strength of composite at high-speed impact (138.8/s–184.8/s). Su et al. [18] observed that the dynamic

behavior of ultra-high performance concrete containing 3% nano material by weight has a strong dependency on the steel fiber. Soufeiani et al. [19] summarized previous researches about the effect of steel fiber shape and volume fraction on the dynamic behavior of concrete. They pointed out that increasing volume fraction of steel fiber has obvious strengthening effect on the dynamic compressive strength of concrete. The ideal shape of steel fiber used to improve the dynamic behavior of concrete is spiral and hooked-end. Al-Masoodi et al. [20] evaluated the effect of W-shaped steel fiber on the dynamic mechanical behavior of concrete. The experimental results showed that the dynamic compressive strength of W-shaped steel fiber reinforced concrete increases by 83.3% and 67.8% under 2 MPa and 3 MPa impact pressures, respectively. The increment of energy absorption can reach up to 162.2% and 146.3%. Su et al. [21] studied the effect of steel fiber (the diameter and the length were 0.12–0.50 mm and 6–30 mm respectively) on the dynamic property of ultra-high performance concrete with 1% nano-CaCO<sub>3</sub> by weight at the strain rate range from 30/s to 100/s. They found that the addition of steel fiber weakens the strain-rate strengthening effect of ultra-high performance concrete. Compared to twisted steel fiber, micro straight fiber has more enhancing effect on the dynamic compressive strength of ultra-high performance concrete. Wu et al. [22] obtained a conclusion that the concrete reinforced with 1.5% long fiber and 0.5% short fiber exhibits the best enhancement to dynamic mechanical behavior. Ren et al. [23] investigated the effect of two types steel fiber on the dynamic behavior of ultra-high performance cementitious composite. It was concluded that the micro straight steel fiber has better effect on increasing the dynamic compressive strength and impact toughness. In conclusion, the previous researches mainly focus on the dynamic mechanical property of concrete with ordinary geometric steel fiber (the diameter and the length are commonly 0.12–0.55 mm and 6–25 mm respectively). Meanwhile, the variation range of strain rate for the existing SHPB test is not wide enough. The research conclusion about the strain rate sensitivity of steel fiber reinforced concrete is inconsistent.

Super-fine stainless wire (SSW), which has excellent mechanical property and similar linear expansion coefficient with concrete, can form three-dimensional modification network in RPC at low volume fraction due to micro diameter. Therefore, super-fine stainless wire (SSW) reinforced reactive powder concrete (RPC) has many outstanding properties such as high strength, good toughness, multifunctional and smart characteristics [24–28]. This new concrete composite is expected to be applied in military field and blast resistance engineering in the future. The investigations on the dynamic characteristic of SSW reinforced RPC is of great significance to understand the mechanic behavior of this composite in extreme condition. However, to the best of our knowledge, there is no any report about the dynamic characteristic of SSW reinforced RPC.

The dynamic mechanical property of SSW reinforced RPC was studied in this paper by using SHPB device at the strain rate range from 94/s to 826/s. The modification mechanisms of SSW to RPC were revealed through computed tomography (CT) and scanning electron microscope (SEM) analysis. Furthermore, the dynamic impact constitutive model of SSW reinforced RPC was established based on revised visco-elastic and continuum damage theory.

## 2. Experimental schemes

### 2.1. Raw materials and mix proportion

The property of raw materials used in this paper such as cement, silica fume, fly ash, and quartz sand was the same as the

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