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Investigating the impact resistance of ultra-high-performance fiber-reinforced concrete using an improved strain energy impact test machine

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HIGHLIGHTS

- Direct tensile stress versus strain responses of UHPFRCs at high strain rates (10–150 s^{-1}) were investigated.
- The speed of impact load was increased by using titanium energy frame in I-SEFIM.
- Equations for predicting strain rate dependent tensile parameters of UHPFRCs are proposed.

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ABSTRACT

The direct tensile stress versus strain responses of ultra-high-performance fiber-reinforced concretes (UHPFRCs) at high strain rates (10–150 s^{-1}) were investigated using an improved strain energy frame impact machine. The high strain rates (>100 s^{-1}) were achieved by increasing the capacity of the hydraulic jack and coupler and changing the diameter and material of the energy frame. The use of a titanium energy frame (diameter of 30 mm) increased the impact speed. As the strain rate was increased from 0.000333 to 170 s^{-1}, the post-cracking strength of the UHPFRCs containing 2% straight steel fibers increased from 16.5 to 47.1 MPa.

1. Introduction

There has been considerable interest in enhancing the impact and blast resistances of the civil and/or military infrastructure owing to the increasing number of terrorist attacks [1,2]. Ultra-high-performance fiber-reinforced concretes (UHPFRCs) have been considered as one of the promising solutions for enhancing the resistance of such structures under high rate loads, including missile or airplane attacks and bombings. This is because UHPFRCs exhibit very high strengths as well as high energy absorption capacities even at high strain rates [3–7]. However, information regarding the tensile stress versus strain responses of UHPFRCs at high strain rates, especially at rates higher than 100 s^{-1}, is still very limited, as listed in Table 1.

There have been only a few studies reporting the direct tensile stress versus strain curves of UHPFRCs at high strain rates. Tran et al. [6] investigated the tensile stress versus strain responses of UHPFRCs containing high-strength steel fibers (straight or twisted) under both static (0.000167 s^{-1}) and dynamic (5–19 s^{-1}) strain rates by using a strain energy frame impact machine (SEFIM) [8]. Although they could determine the tensile responses of the UHPFRCs at relatively high strain rates by using the SEFIM, the range of strain rates investigated was narrow (5–23.7 s^{-1}) for estimating the overall effects of the strain rate on the tensile response. Pyo and El-Tawil [7] applied a modified SEFIM (M-SEFIM) to investigate the tensile behaviors of UHPFRCs at higher strain rates (90–145 s^{-1}) but used small specimens with a sectional area of

Abbreviations: UHPFRC, ultra-high-performance fiber-reinforced concrete; SEFIM, strain energy frame impact machine; M-ISEFIM, modified SEFIM; I-SEFIM, improved SEFIM; UHPC, ultra-high-performance concrete; DIF, dynamic increase factor; CEB, Comité Euro-International du Béton.

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Table 1
Tensile resistances of the various UHPFRCs at high strain rates.

Tensile resistance			Fiber type and volume content	Test method (machine)	Tensile stress versus strain curves	Strain rates (s^{-1})	Reference
Tensile strength (MPa)	Strain capacity (%)	Energy absorption capacity (kJ/m^3)					
61.5–95.1	–	97.7–181.9 (J)	Smooth steel fibers, 6%	Bending (Drop method)[1]	×	–	Bindiganavile et al. [21]
25.2–76.9	–	–	Smooth steel bar, 11%	Bending (Drop method)	×	–	Parant et al. [23]
54–68	–	–	Steel fibers, 6%	Bending (Drop method)	×	1.66	Millard et al. [3]
15–21.5	0.47–0.62	68–112	Smooth steel fibers, 2–3%	Direct tension (Hydraulic machine)	○	0.0001–0.1	Wille et al. (2011)
14.6–15.5	0.55–0.61	83.1–89.3	Smooth steel fibers, 1–2%	Direct tension (Hydraulic machine)	○	0.0001– 0.1	Pyo et al. [11]
8.31–24.1	0.19–0.79	33.5–186	Twisted steel fibers, 1–3%				
11.4–16.0	–	–	Polyvinyl-alcohol fibers, 2.5% or steel fibers, 2.5%	Direct tension (M-SHPB)[2]	×	50–200	Cadoni et al. [22]
41.7–45.8	–	–	Smooth steel fibers, 1.5–6%	Direct tension (SHPB)[3]	×	110–137	Millon et al. (2009)
9–37			Smooth steel fibers, 3–4%	Direct tension (SHPB)	×	21–66	Rong and Sun [4]
13.3–30.8	0.68–1.53	48–178	Smooth steel fibers, 1.5%	Direct tension (SEFIM)[4]	○	6.9–23.7	Tran et al. [6]
19.7–34.0	0.49–1.00	53–171	Twisted steel fibers, 1.5%			5.1–13.7	
20–60			Twisted steel fibers, 1–3%	Direct tension (M-SEFIM)[5]	○	90–145	Pyo et al. [11]

1 Obtained from flexural load versus deflection curve.
2 Modified split Hopkinson pressure bar.
3 Split Hopkinson pressure bar.
4 Strain energy frame impact machine.
5 Modified strain energy frame impact machine.

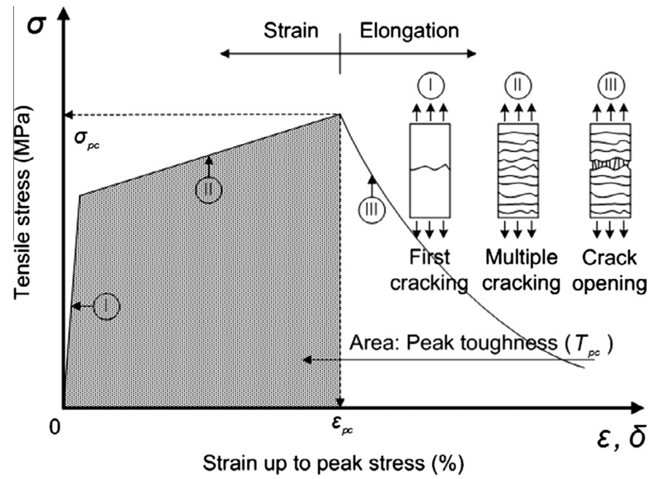

Fig. 1. Tensile parameters of the ultra-high-performance fiber-reinforced concretes (UHPFRCs).

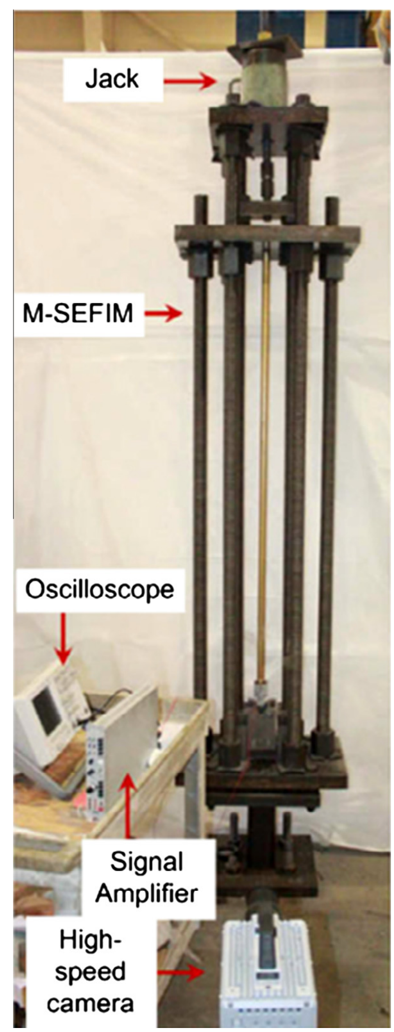

Fig. 2. Modified strain energy frame impact machine (M-SEFIM) (Pyo et al. [11]).

25×25 mm^2. Thus, there is an urgent need for more information regarding the tensile responses of UHPFRCs for a wider range of high strain rates, if one wishes to estimate the effects of the strain rate on the tensile responses of UHPFRCs under both impact and blast conditions.