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GAUGE LENGTH DEPENDENT TENSILE AND FLEXURAL BEHAVIOR OF ULTRA-HIGH-PERFORMANCE FIBER REINFORCED CONCRETE

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ABSTRACT

The effects of different gauge lengths on the tensile and flexural behavior of ultra-high-performance fiber reinforced concrete (UHPFRC) were studied. The UHPFRC contained 1% macro twisted and 1% micro smooth steel fibers by volume. The gauge length of direct tensile specimens was 125 and 250 mm for short and long length, while the size of flexural specimens was 50×50×150 and 100×100×300 mm^3 for small and large size, respectively. As the gauge length of tensile specimens increased, there were significant reductions in strain capacity and the number of multiple micro-cracks in a unit length, whereas there was little reduction in post cracking tensile strength of the UHPFRC. However, the flexural strength of the UHPFRC significantly decreased, in addition to decreases of normalized deflection capacity and number of multiple cracks in a unit length, as the size of specimen increased. The reduction in the flexural strength as the size increased could be correlated with the reduced strain capacity as the gauge length of tensile specimen increased.

INTRODUCTION

Ultra-high-performance fiber reinforced concretes (UHPFRCs) have demonstrated their superior mechanical properties, e.g., compressive strength more than 150 MPa, tensile strength more than 15 MPa, strain capacity more than 0.3%, although they only contained a small amount of fiber less than 2.5% by volume [Wille et al. (2011), Park et al. (2012)]. In addition, UHPFRCs have even produced tensile strain hardening behavior accompanied with multiple micro cracks under uniaxial tension. Based on the reported high mechanical properties, the application of UHPFRCs to nuclear power plants (NPPs) is seriously expected to generate highly favorable effects on the resistance of NPPs under high rate loads including seismic, impact and blast loads. For the practical application of UHPFRCs, their size dependent mechanical properties need to be clarified since most of their reported superior mechanical properties have been obtained from small samples in laboratories, not directly from large structural members. Cement-based materials, characterized with their brittle behavior, generally have shown clear size effects on their mechanical properties [Bažant (1984), Bažant and Kazemi (1991), Rossi et al. (1994), Zhou et al. (1998), Kim et al. (2000), Malaikah (2005), Wu et al. (2011), Chandrangsu and Naaman (2003), Lepech and Li (2004), Asano et al. (2010), and Kim et al. (2010)]. Although the ductility of the UHPFRCs was greatly enhanced by adding short discrete fibers, the size dependent mechanical properties of UHPFRCs were discovered [Reineck and Flettlohr (2010), Wille et al. (2012), Kazemi and Lubell (2012), Nguyen et al. (2013)]. However, it is still not clearly understood yet. This motivated this study to focus on the effect of gauge length on tensile (or flexural) stress versus the strain (or normalized deflection) response of UHPFRCs. The specific objectives are to 1) investigate the effect of gauge length on the tensile parameters, including the post cracking strength, the strain capacity, and the multiple cracking behavior of the UHPFRC in tension; 2) investigate the size effect on the flexural parameters, including the flexural strength, the normalized deflection capacity and the multiple cracking behavior of the UHPFRC in flexure; and, 3) to study the correlation between the gauge length dependent tensile behavior and the size dependent flexural behavior of the UHPFRC.

EXPERIMENTAL PROGRAM

Materials and preparation of specimens

The mix composition and compressive strength of ultra high performance concrete (UHPC) are provided in Table 1, while the properties of fibers used are shown in Table 2. Macro twisted fibers are 30 mm long and have an equivalent diameter of 0.3 mm. Micro smooth fibers are 13 mm long and have a diameter of 0.2 mm. The twisted macro steel fiber has a triangle shape cross section and six ribs within its length. The detailed mixing procedure for the UHPFRC was provided by Nguyen et al. (2013).

Table 1 - Composition and compressive strength of UHPC matrix [Park et al. (2008)]

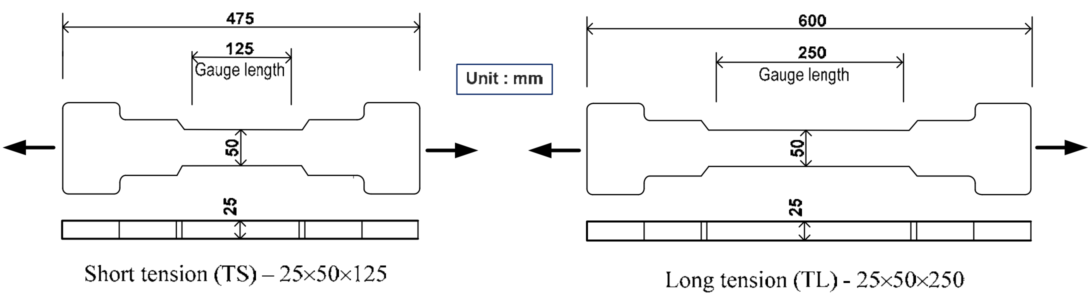
Cement (Type 1)	Silica fume	Silica sand	Glass powder	Super–plasticizer	Water	Compressive strength (MPa)
1.00	0.25	1.10	0.30	0.067	0.2	180

Table 2 - Properties of fibers

Fiber type	L_f(mm)	d_f(mm)	Density (g/cm^3)	Tensile strength (MPa)	Elastic Modulus (GPa)
Macro twisted	30	0.3*	7.9	2428†	200
Micro smooth	13	0.2	7.9	2788	200

* Equivalent diameter, † Tensile strength of the fiber after twisting

Two types of tensile specimens with different gauge length were prepared. That with the shorter gauge length (125 mm) is notated as TS, whereas the other with the longer gauge length (250 mm) is notated as TL as shown in Fig. 1. The larger sized flexural specimen (100×100×300 mm^3) is notated as BL, while the smaller sized specimen (50×50×150 mm^3) is notated as BS. The results of flexural behavior of the UHPFRC were referred to previous research, Nguyen et al. (2013), by the authors. The middle one-third of the span, with a constant internal moment, was considered as the gauge length in flexural specimens. The gauge length of the large specimen was intentionally two times longer than that of the small specimen in both tensile and flexural specimens.

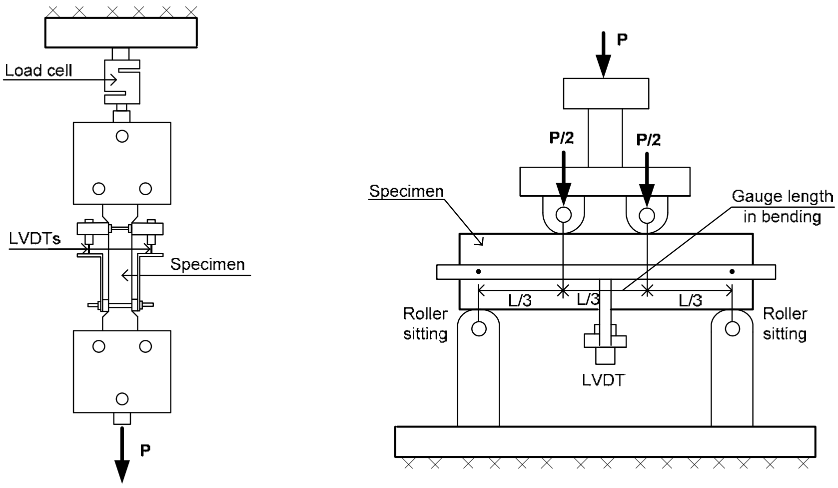


(a) Specimen with shorter gauge length (TS) (b) Specimen with longer gauge length (TL)

Fig. 1 – Geometry of tensile specimens

Test setup and procedure

A universal test machine with displacement control was used, and the applied loading velocity was 1 mm/min. Fig. 2 shows the direct tensile test setup. Two linear variable differential transformers (LVDTs) were attached to the steel frame to measure the elongation of the specimen, while an external load cell of 5 tonf capacity was used to measure the applied load. The frequency of data acquisition was 1 Hz for both tensile and flexural tests.

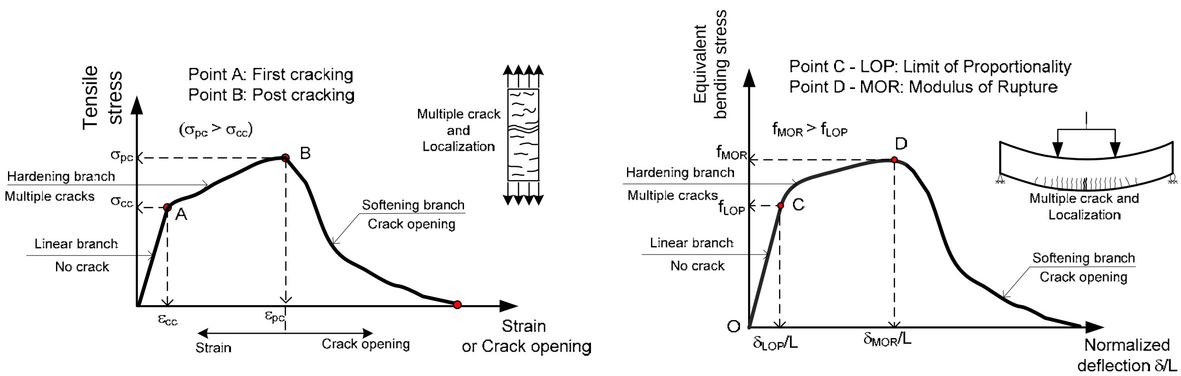


(a) Direct tensile test (b) Flexural test [Nguyen et al. (2013)]

Fig. 2 – Test setup

TEST RESULT AND DISCUSSION

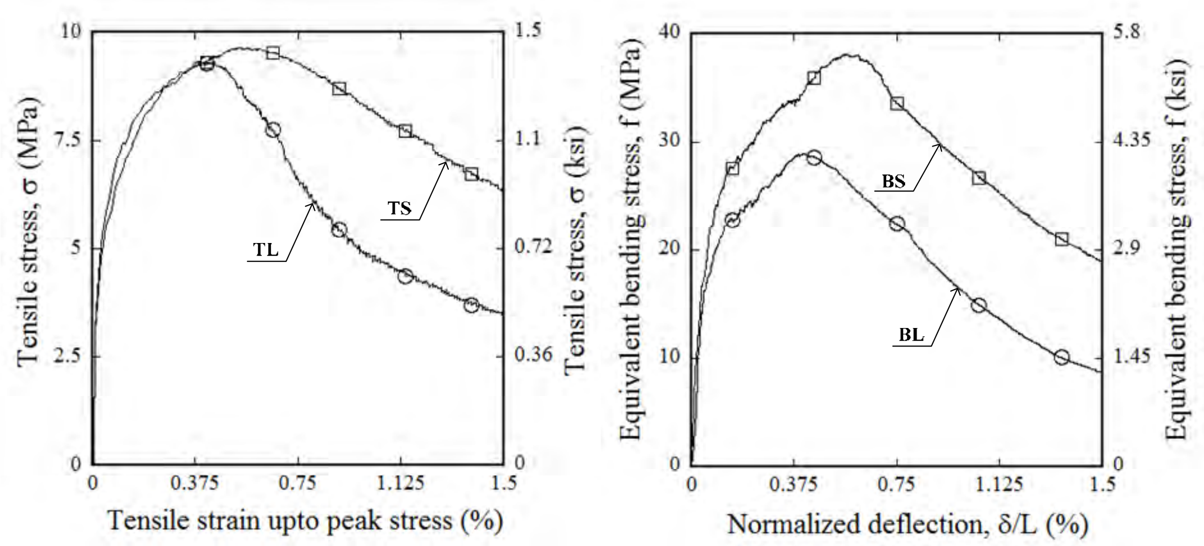
To quantify the effect of gauge length on the tensile and flexural behavior of UHPFRC, several parameters describing the behaviors were analyzed. The parameters are illustrated in Fig. 3, the definitions of them were explained in Park et al. (2012) and Nguyen et al. (2013).



(a) Tensile parameters [Naaman and Reinhardt (1996)] (b) Flexural parameters [Kim et al. (2011)]

Fig. 3 – Mechanical parameters of UHPFRC

The tensile stress (σ) versus strain (ε) curves of UHPFRC according to different gauge lengths are comparatively shown in Fig. 4a, while the equivalent bending stress (f) versus normalized deflection (δ/L) curves of UHPFRC with different sizes are given in Fig. 4b. Each curve was averaged from at least three specimens. All the specimens with different gauge lengths produced both tensile strain hardening and flexural deflection hardening behavior; however, their performance was clearly affected by the gauge length as shown in Fig. 4. To quantitatively investigate the effect of gauge length on the tensile and flexural behavior of UHPFRC, the tensile and flexural parameters, illustrated in Fig. 3, were averaged and summarized in Table 3.



(a) Tensile behavior (b) Flexural behavior [Nguyen et al. (2013)]

Fig. 4 – Effects of gauge length on the tensile and flexural behavior of UHPFRC

Fig. 4a and Table 3a clearly demonstrated that the post cracking strength (σ_{pc}) of UHPFRC was not much influenced by increasing gauge length, whereas its strain capacity (ε_{pc}) was significantly reduced. As the gauge length increased from 125 to 250 mm, σ_{pc} slightly decreased from 9.77 to 9.43 MPa (3.5%), whereas ε_{pc} decreased from 0.56 to 0.44% (22.9%). However, the averaged crack spacing (S_c) increased from 6.25 to 8.62 mm (37.9%).

The effect of gauge length on the flexural behavior of UHPFRC is shown in Fig. 4b, while the flexural parameters depending on different sizes of specimens are provided in Table 3b. Unlike the effects of gauge length on the tensile parameters, all flexural parameters were significantly affected by the size (gauge length) of the specimen. As the gauge length in the flexural specimen increased from 50 to 100 mm, the equivalent flexural strength (f_{MOR}) significantly decreased from 38.91 to 29.10 MPa (25.2%), the normalized deflection capacity (δ_{MOR}/L) decreased from 0.59% to 0.42% (28.7%), and the averaged crack spacing (S_c) increased from 3.85 to 4.55 mm (18.2%).

In general, all the mechanical parameters of UHPFRC, except σ_{pc}, were clearly affected by increasing the gauge length. The mechanical resistance of UHPFRC tendentiously decreased as the gauge length increased. The reduced mechanical resistance could be explained using the statistical size effect theory of Weibull (1939, 1951).

Table 3 – Effect of gauge length on the mechanical parameters of UHPFRC

(a) Tensile parameters

Notation	Gauge length (mm)	Post cracking point		Cracking behavior	
		σ_{pc} (MPa)	ε_{pc} (%)	Number of cracks	Crack spacing, S_c (mm)
TS	125	9.77	0.564	20	6.25
TL	250	9.43	0.435	29	8.62

(b) Flexural parameters [Nguyen et al. (2013)]

Notation	Gauge length (mm)	MOR point		Cracking behavior	
		f_{MOR} (MPa)	δ_{MOR} / L (%)	Number of cracks	Crack spacing, S_c (mm)
BS	50	38.91	0.595	13	3.85
BL	100	29.10	0.424	22	4.55

The σ_{pc} of UHPFRC in tension is mainly influenced by the distribution and orientation of short fibers within the specimen [Naaman (1972)]. Thus, if the distribution and orientation of fibers is similar owing to the identical section and mixing procedure, it might not be much different according to different gauge lengths. However, the f_{MOR} of UHPFRC is influenced not only by the fiber distribution but also by the stress distribution at the cross section of the beam. Furthermore, the stress distribution in tensile side strongly depends on the tensile strain capacity (ε_{pc}) of UHPFRC in addition to the tensile strength (σ_{pc}), as illustrated in Fig. 5. Thus, the f_{MOR} was much influenced by the gauge length owing to the different strain capacities of UHPFRC, whereas the σ_{pc} was not. The normalized deflection capacity also depends on the tensile strain at the bottom surface at MOR (ε_{MOR}), i.e, a decrease of ε_{MOR} leads to the reduction of the normalized deflection capacity, as explained and discussed in detail in Nguyen et al. (2013).

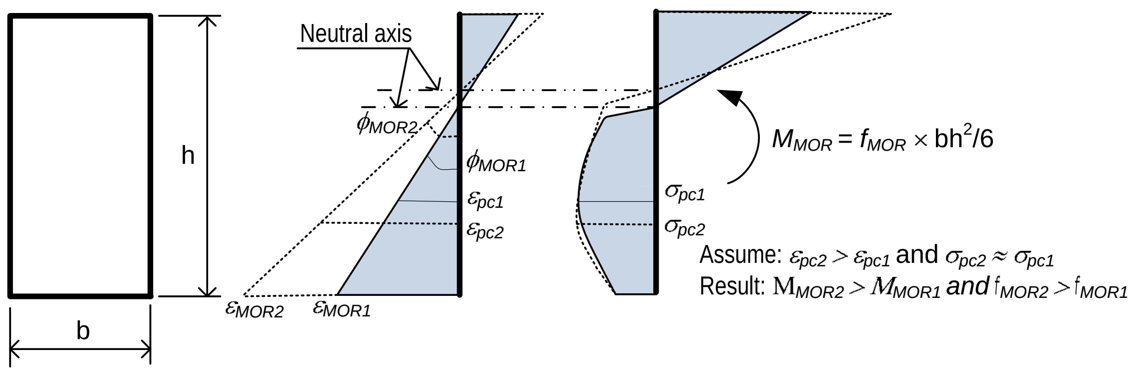


Fig. 5 – Influence of tensile strain capacity (ε_{pc}) of UHPFRC on flexural strength (f_{MOR})

CONCLUSION

This research investigated the effect of different gauge lengths on the tensile and flexural behavior of UHPFRC. The gauge length of the tensile specimens varied between 125 and 250 mm, while that of the flexural specimens differed at between 50 and 100 mm. The UHPFRC investigated contained 1% macro twisted and 1% micro smooth steel fibers by volume. The following conclusions can be drawn from this experimental study:

1) As the gauge length of tensile specimen increased, the tensile strain capacity and crack spacing of UHPFRC was greatly influenced, whereas the post cracking tensile strength of UHPFRC was not.
2) The flexural strength of UHPFRC clearly decreased as the size (gauge length) of the specimen increased whereas the tensile strength was little changed according to the different gauge lengths.
3) The normalized deflection capacity of UHPFRC, as well as cracking behavior, was also significantly influenced by the size (gauge length) of the specimen.
4) The flexural strength depending on the gauge length is correlated with the tensile ductility (strain capacity) of UHPFRC rather than the post cracking tensile strength.

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