Shear Behavior of Ultra-High Performance Hybrid Fiber Reinforced Concrete Beams

Author(s) & Affiliation:

Manuel Bermudez and Chung-Chan Hung
Department of Civil Engineering, National Cheng Kung University, Taiwan

Abstract:

Current design codes require a dense array of steel reinforcement for shear-critical structural elements in earthquake-resistant structures, such as columns, walls, coupling beams, and beam-column joints. However, this leads to congested reinforcement in such elements during construction, which could cause extensively prolonged construction and reduced construction quality. This paper aims to investigate the potential of utilizing Ultra-High Performance Concrete (UHPC) with hybrid fibers to reduce shear reinforcement in shear-critical structural elements. A series of UHPC beams reinforced with longitudinal steel bars and various combinations of hybrid fibers were tested in a four-point loading setup. Two different shear span-to-depth ratios were used to evaluate the effect of the hybridization in the shear response of the beam member. The test results showed that the presence of hybrid fibers enhanced the shear cracking stress, ultimate shear stress, and crack width controlled ability of the specimens compared to the beams with monofibers. Due to the synergy of hybrid fibers, a smaller volume fraction of fibers was required for UHPC beams with hybrid fibers to show a shear strength comparable to the UHPC beams with monofibers.

Keywords: *hybrid fibers, synergy, shear strength, beams without shear reinforcement*

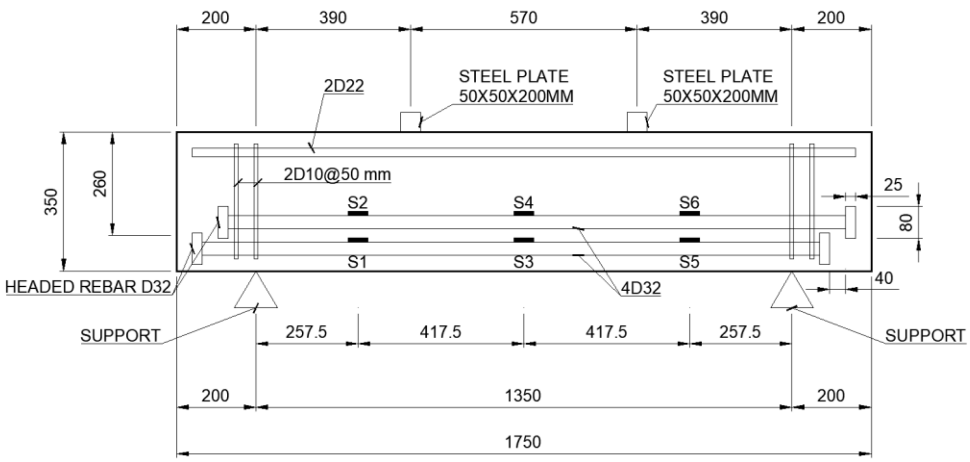
1. Introduction

Ultra-high performance concrete (UHPC), which is a type of high performance fiber reinforced cementitious composites (Naaman and Reinhardt 1996; Li 2012; Hung et al. 2011-2018), has an ultra-high strength in both tension and compression while showing strain-hardening behavior under tension. Banthia et al. (2014), Yoo and Yoon (2016), and Fantilli et al. (2018) investigated the synergy performance of hybrid fibers in UHPC. Juárez et al. (2007), Zakaria et al. (2009), and Rafeeqi and Ayub (2013) indicated that the use of hybrid fibers could increase the tensile strength of the matrix, promote the multiple narrow cracking pattern, and delay the initiation of critical shear cracks. Due to the superior mechanical performance of UHPC, abundant studies have been performed to investigate the applicability of UHPC for new earthquake-resistant structures, structural retrofitting and rehabilitation, and connections of precast members. Nevertheless, while the tensile and compressive behaviors of UHPC have been widely studied, the shear behavior of UHPC remains to be explored. In particular, the shear capacity of UHPC has to be adequately quantified before such an innovative material can be applied to shear-critical members.

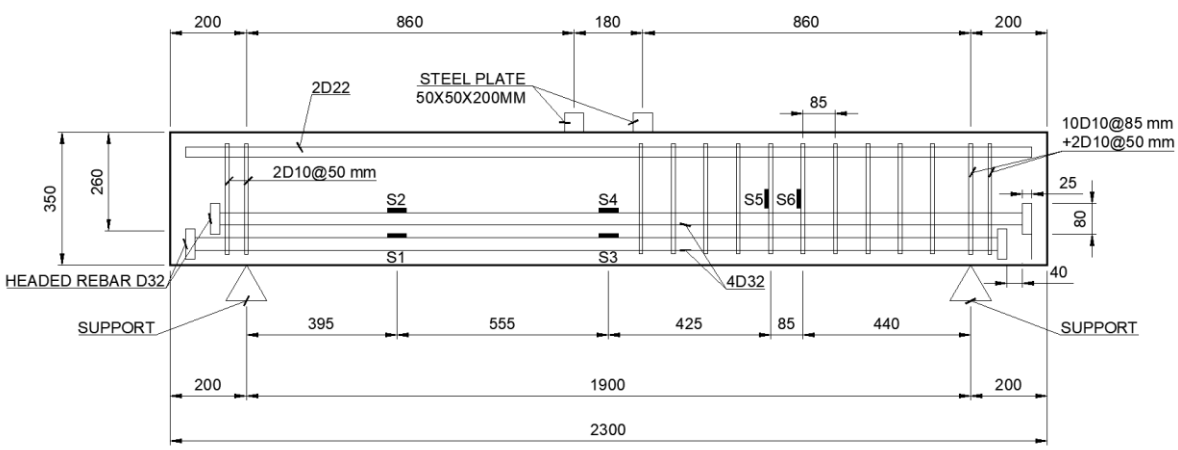
In this research, the shear behavior of UHPC beam members without stirrups was studied. The experimental parameters included the amount and type of fibers and the shear span-to-depth ratio of the beam. The synergy of the mixture with three different types of fibers was studied. In particular, its effect on the shear strength of the beam was investigated.

2. Experimental Program

The beam specimens had cross-sectional dimensions of 165 mm (6.5”) by 350 mm (13.8”). The length of the beam members was 1750 mm (68.9”) or 2300 mm (90.1”). A total of 24 beam specimens, with detailed dimensions shown in Figure 1, were tested in the study. Details of the experimental and design parameters are listed in Table 1. Three different types of fibers were used in this study, i.e., short steel hooked fibers with Ø : 0.38 mm (0.015”) and length: 30 mm (1.2”); long steel hooked fibers with Ø : 0.90 mm (0.035”) and length: 60 mm (2.4”); and PVA fiber with Ø : 0.038 mm (0.0015”) and length: 8 mm (0.3”).



(a) Short Beams with a/d = 1.5



(b) Long Beams with a/d = 3.3

Figure 1. Reinforcement Details of Short and Long Beams (units in mm; 1 inch=25.4 mm)

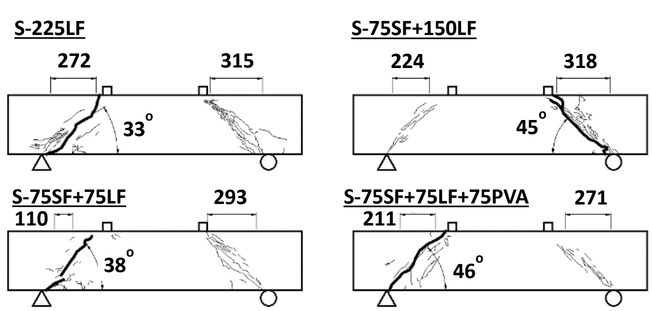
The mix components and weight proportions of the UHPC material were 1.0 of Type I ordinary Portland cement, 0.22 of silica fume, 0.5 of silica sand, 0.39 of quartz powder, and 0.28 of water and polycarboxylate-based superplasticizer. The design water-to-binder ratio was 0.23 but it was slightly adjusted for the mixes with different types and amounts of fibers in order for the fresh UHPC to have an adequate workability. The UHPC compressive and splitting tensile strength were obtained by cylinders, which were prepared according to ASTM C172, fabricated and cured following ASTM C31, and tested following ASTM C39 and ASTM C496. The mean f'_c was 116 MPa (16.6 ksi). The uniaxial tensile strength of UHPC was obtained by direct tension tests on UHPC dogbone-shaped specimens and the average uniaxial tensile strength f'_t was 4.1 MPa (0.59 ksi).

Table 1. Design Details and Material Properties of the Tested Beams (1 MPa=0.143 ksi; 1 cm = 0.39 in)

Beam	d (cm)	a/d	ρ (%)	Volume Fraction and Type of Fiber	V_f %	f'_c (MPa)	f'_t (Split Test) (MPa)	f'_t (Dogbone Test) (MPa)
B1.5-F0-N*[1]	26	1.5	7.6	No Fiber	0	118.6	-	2.5
B1.5-F075-N*[1]	26	1.5	7.6	0.75% SF	0.75	115.3	-	3.2
B1.5-F150-N*[1]	26	1.5	7.6	1.50% SF	1.50	124.1	-	6.3
S - 75PVA	26	1.5	7.6	0.75% PVA	0.75	111.7	5.44	2.1
S - 225PVA	26	1.5	7.6	2.25% PVA	2.25	104.5	8.76	4.3
S - 75LF	26	1.5	7.6	0.75% LF	0.75	126.3	8.68	2.3
S - 150LF	26	1.5	7.6	1.50% LF	1.50	107.4	14.58	4.9
S - 225LF	26	1.5	7.6	2.25% LF	2.25	124.0	12.47	5.6
S - 75SF+75LF	26	1.5	7.6	0.75% SF + 0.75% LF	1.50	122.9	12.18	5.1
S - 150SF+75LF	26	1.5	7.6	1.50% SF + 0.75% LF	2.25	118.7	12.98	7.0
S - 75SF+150LF	26	1.5	7.6	0.75% SF + 1.50% LF	2.25	114.4	16.16	6.0
S - 75SF+75LF+75PVA	26	1.5	7.6	0.75%SF+0.5%LF+0.75%PVA	2.25	97.6	9.82	4.4
B3.3-F0-N*[1]	26	3.3	7.6	No Fiber	0	94.5	-	2.6
B3.3-F075-N*[1]	26	3.3	7.6	0.75% SF	0.75	116.5	-	2.3
B3.3-F150-N*[1]	26	3.3	7.6	1.50% SF	1.50	102.9	-	3.9
L - 75PVA	26	3.3	7.6	0.75% PVA	0.75	115.0	5.77	1.6
L - 225PVA	26	3.3	7.6	2.25% PVA	2.25	94.2	8.96	5.8
L - 75LF	26	3.3	7.6	0.75% LF	0.75	133.7	5.94	1.5
L - 150LF	26	3.3	7.6	1.50% LF	1.50	132.0	9.56	3.8
L - 225LF	26	3.3	7.6	2.25% LF	2.25	116.6	15.41	5.1
L - 75SF+75LF	26	3.3	7.6	0.75% SF + 0.75% LF	1.50	136.0	11.55	3.9
L - 150SF+75LF	26	3.3	7.6	1.50% SF + 0.75% LF	2.25	109.7	11.84	3.7
L - 75SF+150LF	26	3.3	7.6	0.75% SF + 1.50% LF	2.25	124.2	13.10	5.4
L - 75SF+75LF+75PVA	26	3.3	7.6	0.75%SF+0.5%LF+0.75%PVA	2.25	113.0	10.79	4.6

3. Results and Discussion

All beams failed due to the development of localized, diagonal shear cracks before major flexural cracks occurred, except for L-75SF+150LF that failed in flexure. Figure 2 presents the representative failure patterns of the beams. The test results were discussed in this section in terms of the shear strength and the influences of fibers and beam slenderness.



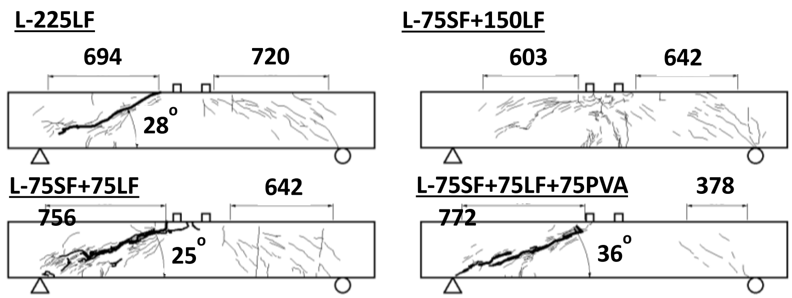


Figure 2. Crack patterns of representative UHPC beams

3.1. Shear Strength

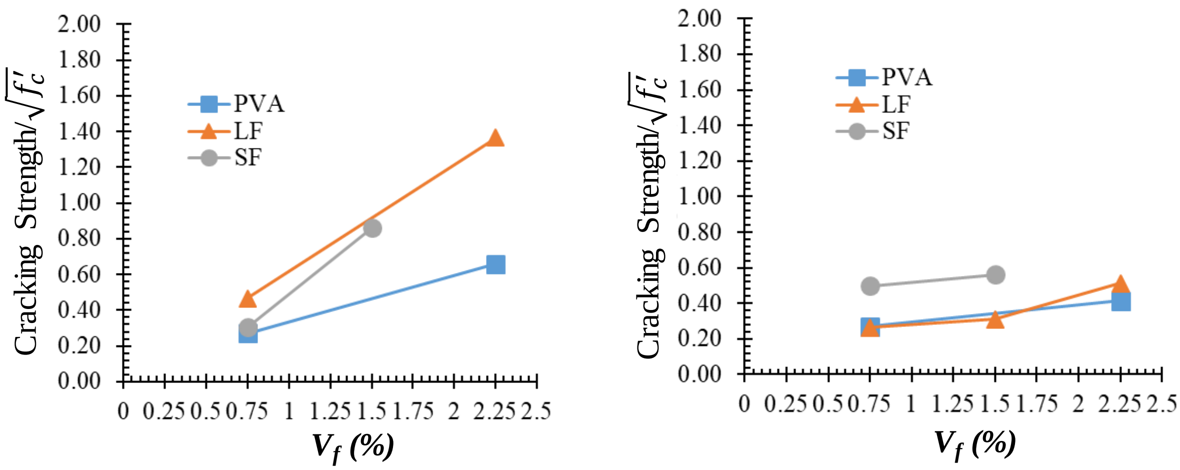
The obtained shear strengths of the beams were summarized in Table 2. The average shear strengths for the short and long UHPC beams were 1.74 $\sqrt{f'c}$ and 0.86$\sqrt{f'c}$ (in MPa units), respectively. These shear strengths were 2.2 and 3.4 times greater than that of the control beams without fibers for short and long beams, respectively. For beams with fibers, the lowest shear strength for the short beam was 0.93$\sqrt{f'c}$ occurring to B1.5-F075-N; and for the long beam was 0.37$\sqrt{f'c}$ occurring to L – 75PVA. Both beams had the lowest volume fraction of fibers among the tested beams with fibers, i.e., 0.75%. It is worth mentioning this level of shear strength was still 1.2 and 1.5 times greater than that of their corresponding control specimens.

Table 2. Summary of the test results (1 MPa=0.143 ksi)

Beam	$\frac{v_u(MPa)}{\sqrt{f'_c(MPa)}}$	$\gamma_{@v_u}$ (rad)	Beams	$\frac{v_u(MPa)}{\sqrt{f'_c(MPa)}}$	$\gamma_{@v_u}$ (rad)
B1.5-F0-N	0.78	0.0050	B3.3-F0-N	0.25	0.0064
B1.5-F075-N	0.93	0.0062	B3.3-F075-N	0.62	0.0069
B1.5-F150-N	1.41	0.0066	B3.3-F150-N	0.76	0.0068
S - 75PVA	0.97	0.0060	L - 75PVA	0.37	0.0086
S - 225PVA	1.13	0.0054	L - 225PVA	0.62	0.0046
S - 75LF	1.07	0.0032	L - 75LF	0.39	0.0066
S - 150LF	1.26	0.0184	L - 150LF	0.66	0.0062
S - 225LF	1.45	0.0077	L - 225LF	0.75	0.0079
S - 75SF+75LF	1.48	0.0072	L - 75SF+75LF	0.74	0.0079
S - 150SF+75LF	1.74	0.0092	L - 150SF+75LF	0.84	0.0077
S - 75SF+150LF	1.62	0.0094	L - 75SF+150LF	0.86	0.0063
S - 75SF+75LF+75PVA	1.47	0.0070	L - 75SF+75LF+75PVA	0.72	0.0078

3.2. Effects of Fibers

Figure 3 shows the relationship between the shear cracking strength and the volume fraction of fibers for the beams reinforced with monofibers. It can be seen that increasing the amount of fibers considerably enhanced the shear cracking strength for the short beams whereas the effect was relatively minor for long beams.



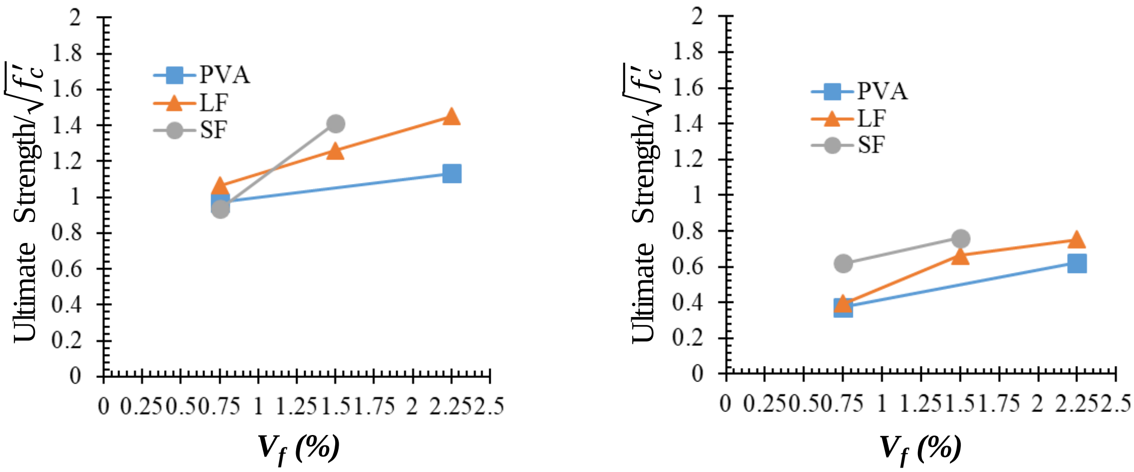
(a) Short Beams **(b) Long Beams**

Figure 3. Relationships between the V_f and the shear cracking strength for the beams with monofibers (in MPa units; 1 MPa=0.143 ksi)

For the short beams with V_f = 0.75%, the shear cracking strengths of the beams were similar for three types of fibers. As V_f was increased, both short and long steel fibers performed better than the PVA ones in terms of the enhancement in the shear cracking strength. In the case of the long beams with V_f = 0.75%, the short steel fibers led to a shear cracking strength twice greater than those of the beams reinforced with long steel fibers and PVA fibers. It is worth mentioning that for the long beams, the short steel fibers at V_f = 1.5% led to a greater cracking strength than that of the long steel fibers at V_f = 2.25%, suggesting the effectiveness of short steel fibers in enhancing the shear cracking strength of UHPC beams. Overall, the beams reinforced PVA fibers had the lowest cracking strength.

Figure 4 presents the effect of V_f on the ultimate shear strength of the beams with monofibers. When compared to the results of the control specimen without fibers, the ultimate shear strengths of the short beams with V_f = 0.75% were enhanced by at least 20%, regardless of the type of fibers. In the case of long beams, the ultimate shear strengths of the fiber reinforced beams were 1.5 times greater than that of the beams without fibers. For the beams with a short shear span and reinforced with fibers at V_f = 0.75%, the different types of fibers led to similar ultimate shear strengths. When V_f was increased, the short steel fibers with V_f = 1. 5% led to an ultimate shear strength that was essentially the same as the short beam with 2.25% long steel fibers and was 23% greater than that of the short beam with 2.25% PVA fibers.

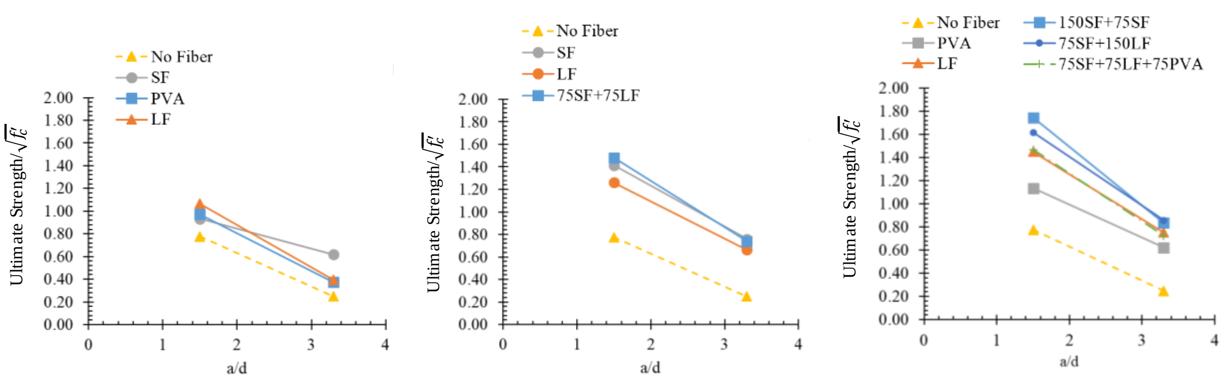
For the long beams with V_f=0.75%, when PVA or long steel fibers were used, the resulting ultimate shear strengths of the beams were essentially the same, whereas the short steel fibers led to an ultimate shear strength that was 19% greater than the other two fibers. Similarly, it can be observed that the addition of 1.5% short steel fibers led to a greater ultimate shear strength than that of the specimens having 2.25% PVA or long steel fibers.



(a) Short Beams **(b) Long Beams**

Figure 4. Relationships between the V_f and the ultimate shear strength for beams with monofibers (in MPa units; 1 MPa=0.143 ksi)

The impacts of V_f and the shear span-to-depth ratio on the ultimate shear strength for beams with hybrid fibers are illustrated in Figure 5. It can be seen that for short and long beams, the ultimate shear strengths of the beams with hybrid fibers were at least 1.8 and 2.8 times greater than that of the control beam specimen having no fibers, respectively. The results also indicated that the combination of short and long steel fibers in the beams achieved the greatest synergy, leading to the largest ultimate shear strengths when compared to other combinations of hybrid fibers.



(a) V_f =0.75% **(b) V_f =1.5%** **(c) V_f =2.25%**

Figure 5. Relationships between the V_f and the ultimate shear strength for beams with hybrid fibers (in MPa units; 1 MPa=0.143 ksi)

3.3. Effect of the Beam Slenderness

When V_f=0.75%, it can be observed in Figure 5(a) that different types of fibers led to similar shear strengths of the beams. The influence of fibers on the strength however became more obvious with the increase in the shear span-to-depth ratio; particularly, the use of short steel fibers in conjunction with other types of fibers led to a greater strength. When the V_f was increased to 1.50%, the hybrid fibers with 0.75% short steel fibers in conjunction with 0.75% long steel fibers led to a greater strength than the 1.5% short steel fibers for both cases of a/d ratios. In the case of V_f =2.25%, it can be seen in Figure 5(c) that for the short beams, the presence of more short steel fiber in the hybrid fibers led to a greater ultimate shear strength than the case when more long steel fibers were used. Interestingly, when the shear span was increased, the beneficial effects of long steel fibers became similarly well as the short steel fibers. The results also indicated that when V_f=2.25%, the beams with hybrid fibers had a higher ultimate shear strength than the ones with monofibers. It can be seen in Figure 5(c) that the beam with 0.75% of each type of fibers had a shear strength close to that with 2.25% long steel fibers. Overall, the beams with 2.25% hybrid fibers had an ultimate shear strength that was 1.4-2.2 times and 2.5-3.5 times higher than that of the corresponding ones without fiber for short and slender beams, respectively.

4. Conclusions

The experimental study showed that the shear cracking strength, ultimate shear strength, and critical shear crack width of UHPC beams without stirrups could be considerably improved by using hybrid fibers when compared to the results of beams having monofibers or no fibers. In comparison with the design of conventional reinforced concrete beams that has an upper limit on the design shear strength of $0.83\sqrt{f'_c(MPa)}$ (1MPa=0.143ksi) specified by ACI 318, the study showed that when slender UHPC beams containing hybrid fibers with a V_f larger than 1.5%, it could provide a unit shear strength greater than $0.7\sqrt{f'_c(MPa)}$ (1MPa=0.143ksi) even without the use of stirrups. The result implies that when UHPC is used to replacement conventional concrete materials in shear critical structural members, the amount of shear reinforcement could be fully eliminated or greatly reduced. The study also revealed that the most effective synergy of fibers occurred when the short steel fibers were present. On the other hand, the PVA fibers appeared to have the least enhancement in the shear strength of the UHPC beams when compared to other types of fibers employed in this study. The combination of short and long steel fibers was found to be effective in carrying the loads through localized cracks and delaying the shear failure. Furthermore, the results of the slender beam L-75SF+150LF demonstrated that the proper combination of fibers could significantly enhance the shear strength of the UHPC beam, which ultimately led to a flexurally-dominated behavior even the UHPC beam had no stirrups.

5. References

ACI Committee 318, "Building Code Requirements for Structural Concrete," American Concrete Institute, September. 2014.

Banthia, N., Majdzadeh, F., Wu, J., and Bindiganavile, V., "Fiber Synergy in Hybrid Fiber Reinforced Concrete (HyFRC) in Flexure and Direct Shear," *Cement & Concrete Composites*, 2014, pp. 94-97.

Fantilli, A., Kwon, S., Mihashi, H., and Nishiwaki, T., "Synergy assessment in hybrid Ultra-High Performance Fiber-Reinforced Concrete (UHP-FRC)," *Cement and Concrete Composites*, 2018, pp. 19-29.

Hung, C.-C., Hu, F.-Y., and Yen, C.-H., "Behavior of Slender UHPC Columns under Eccentric Loading," *Engineering Structures*, Vol. 174, 2018, pp.701-711.

Hung, C.-C., and Hu, F.-Y., "Behavior of High-Strength Concrete Slender Columns Strengthened with Steel Fibers under Concentric Axial Loading," *Construction & Building Materials*, Vol. 175, 2018, pp. 422-433.

Hung, C.-C., Su, Y.-F., and Su, Y.-M., "Mechanical Properties and Self-Healing Evaluation of Strain-Hardening Cementitious Composites with High Volumes of Hybrid Pozzolan Materials," *Composites Part B: Engineering*, Vol. 133, 2018, pp. 15-25.

Hung, C.-C., Li, H., and Chen, H.-C., "High-strength Steel Reinforced Squat UHPFRC Shear Walls: Cyclic Behavior and Design Implications," *Engineering Structures*, Vol. 141, 2017, pp.59-74.

Hung, C.-C., Su, Y.-F., and Hung, H.-H., "Impact of Natural Weathering on Medium-Term Self-Healing Performance of Fiber Reinforced Cementitious Composites with Intrinsic Crack-Width Control Capability," *Cement and Concrete Composites*, Vol. 80, 2017, pp.200-209.

Hung, C.-C., and Chueh, C.-Y., "Cyclic Behavior of UHPFRC Flexural Members Reinforced with High-Strength Steel Rebar," *Engineering Structures*, Vol. 122, 2016, pp.108-120.

Hung, C.-C., and Su, Y.-F., "Medium-Term Self-Healing Evaluation of Engineered Cementitious Composites with Varying Amounts of Fly Ash and Exposure Durations," *Construction & Building Materials*, Vol. 118, 2016, pp. 194-203.

Hung, C.-C., and Chen, Y.-S., "Innovative ECC Jacketing for Retrofitting Shear-Deficient RC Members," *Construction & Building Materials*, Vol. 111, 2016, pp. 408-418.

Hung, C.-C., Yen, W.-M., and Yu, K.-H., "Vulnerability and Improvement of Reinforced ECC Flexural Members under Displacement Reversals: Experimental Investigation and Computational Analysis," *Construction & Building Materials*, Vol. 107, 2016, pp.287-298.

Hung, C.-C., Su, Y.-F., and Yu, K.-H., "Modeling the Shear Hysteretic Response for High Performance Fiber Reinforced Cementitious Composites," *Construction and Building Materials*, Vol. 41, 2013, pp.37-48.

Hung, C.-C., and Li, S.-H., "Three-dimensional Model for Analysis of High Performance Fiber Reinforced Cement-based Composites," *Composites Part B: Engineering*, Vol. 45, 2013, pp.1441-1447.

Hung, C.-C., and El-Tawil, S., "Seismic Behavior of a Coupled Wall System with HPFRC Materials in Critical Regions," *ASCE Journal of Structural Engineering*, Vol. 137, No. 12, 2011, pp.1499-1507.

Juárez, C., Valdez, P., and Dura, A., "The diagonal tension behavior of fiber reinforced concrete beams," *Cement & Concrete Composites*, Vol. 29, 2007, pp. 402–408.

Li, V.C., "Tailoring ECC for Special Attributes: A Review," *International Journal of Concrete Structural Materials*, Vol. 6, 2012, pp. 135-144.

Naaman, A.E., and Reinhardt, H.W., "Characterization of High Performance Fiber Reinforced Cement Composites," In: Naaman AE, Reinhardt HW editor. Proceedings of the 2nd International Workshop on High Performance Fiber Reinforced Cement Composites: HPFRCC 2, RILEM, 1996, pp. 1-24.

Rafeeqi, S., and Ayub, T., "Behaviour of Reinforced Concrete Beams Detailed for Shear in compliance with compressive force path method," Ned University Journal of Research - Structural Mechanics, Vol. X, No. 1, 2013, pp. 13-30.

Yoo, D.-Y., and Yoon, Y.-S., "A Review on Structural Behavior, Design, and Application of Ultra-High-Performance Fiber-Reinforced Concrete," *International Journal of Concrete Structures and Materials*, Vol. 10, No. 2, 2016, pp. 125-142.

Zakaria, M., Ueda, T., Wu, Z., and Meng, L., "Experimental Investigation on shear Cracking Behavior in Reinforced Concrete Beams with Shear Reinforcement," *Journal of Advanced Concrete Technology,* Vol. 7, No. 1, 2009, pp. 79-96.

6. Acknowledgements

This study was sponsored in part by the Ministry of Science and Technology, Taiwan, under Grant No. 108-2636-E-006-009. The opinions, findings, and conclusions expressed in this paper are those of the authors, and do not necessarily reflect those of the sponsor.