# Experimental Study of Shear behavior of UHPC Considering Axial Load Effects

**Abdulrahman Salah** – Graduate Research Assistant, University of Houston, Civil & Environmental Engineering, Houston, TX, USA, Email aasalah@cougarnet.uh.edu

**Noran Shahin** – Graduate Research Assistant, University of Houston, Department of Civil & Environmental Engineering, Houston, TX, USA, Email: nhshahin@cougarnet.uh.edu

**Dimitrios Kalliontzis, Ph.D.** (corresponding author) – Assistant Professor, University of Houston, Department of Civil & Environmental Engineering, Houston, TX, USA, Email: dkallion@central.uh.edu

**Abstract**

To prevent brittle failures of Ultra-High-Performance Concrete (UHPC) members due to diagonal shear cracks, it is crucial to better understand the shear-dominated mechanisms of UHPC. These mechanisms can be affected by the tension and compression fields developed in UHPC, which is investigated in this study through experiments of combined shear and axial loading. The experimental work is carried out with the Universal Panel Tester (UPT) at the University of Houston, where three unreinforced UHPC panel elements are tested, representing elements cut out from full-scale UHPC structures. Via UPT, characterization of the state of stress within one element is used to understand the shear behavior of the full structure. The key variable in the three tests is the level of compressive axial load applied to the panel elements, while upcoming tests will examine the effect of tensile loads. Future work will synthesize the test results to inform the development of shear design equations with consideration to axial load effects.

**Keywords:** Shear behavior; Ultra-High-Performance Concrete (UHPC); Axial load effects; Biaxial loading; UHPC panels; Universal panel tester (UPT).

## 1. Introduction

Ultra-High-Performance Concrete (UHPC) is a new class of concrete that relies on a highly refined microstructure and fiber reinforcement to achieve superior performance, including high compressive strength, post-cracking tensile resistance, high ductility, enhanced durability (Graybeal 2005) and low permeability (Charron et al. 2007). UHPC is a sustainable material (Racky 2004), ideal for various applications including bridge decks, precast structures, and architectural façades. UHPC has been commercially available in North America since 2000 (ACI 239R 2018). However, experiments to understand the effect of axial loading on the shear behavior of UHPC are lacking. Axial loading to UHPC members can be introduced, for example, in the form of prestressing (compression) or via reverse-cyclic frame action (compression and tension). Therefore, an experimental investigation into the axial load effects on UHPC shear is crucial to develop appropriate analysis and design approaches for UHPC structures subjected to axial loads.

Previous studies have investigated the shear behavior of UHPC members considering the effects of fiber geometry and fiber content, and the ability to resist the shear forces in absence of transverse reinforcement (Bae et al. 2021; Crane 2010; Graybeal 2006; Hegger and Bertram 2008; Yang et al. 2022; Yavaş et al. 2019; Yavas and Goker 2020). Some studies considered the variation of the prestressing level (Baby et al. 2013; El-Helou and Graybeal 2022; Metje and Leutbecher 2021). In addition to UHPC beam tests, Yap (2021) tested UHPC panels under pure shear with the variables being the amount of shear reinforcement and the reinforcement direction in the panels. Test results of the above-referenced experimental studies showed that the shear response of UHPC is influenced by its constitutive tensile behavior, featuring strain hardening and significant post-cracking tensile resistance. Shear responses of UHPC beams were associated with multiple closely spaced shear cracks developed by means of fiber reinforcement. It was also shown that increasing the fiber content can increase the shear strength of UHPC beams.

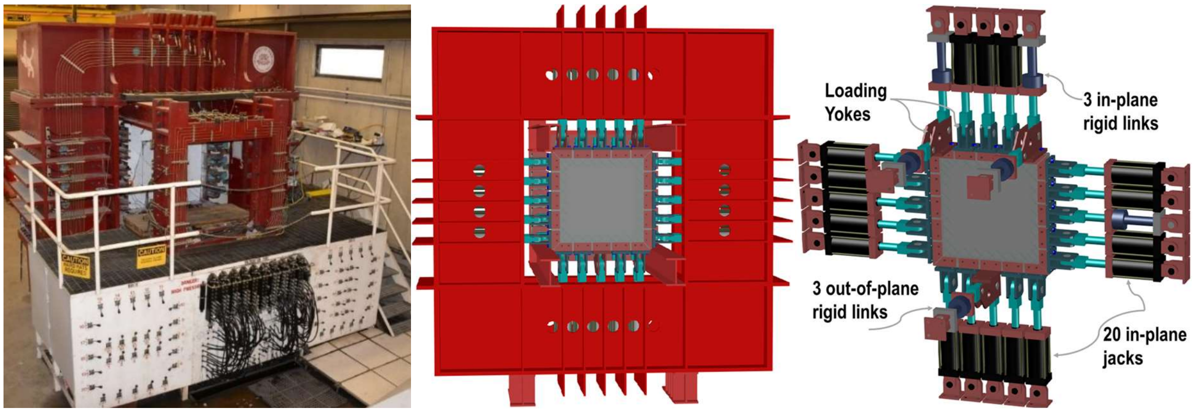
Considering different steel fiber lengths and fiber contents, Voo et al. (2010) conducted shear tests on eight UHPC prestressed girders without the use of transverse reinforcement. They observed that providing enough fiber content in the UHPC mix produced a tensile strain-hardening behavior after the first shear crack. Furthermore, they observed that the shear behavior of UHPC girders is associated with a reduced aggregate interlock action due to the absence of coarse particles in the UHPC mix. Shear tests of eleven UHPC beams by Metje and Leutbecher (2021) showed that increasing the prestressing force induced a proportional increase in the shear cracking load. Based on shear tests of six pretensioned bulb-tee UHPC bridge girders, El-Helou and Graybeal (2022) confirmed that the shear behavior of UHPC girders is a function of UHPC's tensile constitutive behavior and dependent on the associated crack localization strain.

In view of the current state of knowledge on UHPC shear, our research program at the University of Houston utilizes the unique capabilities of the Universal Panel Tester (UPT) to evaluate the behavior of UHPC under shear combined with compression and tension loads. This paper discusses the tests of three unreinforced UHPC panels subjected to pure shear and shear combined with compression loads with two axial load ratios of 5% and 10% in the principal compressive stress direction.

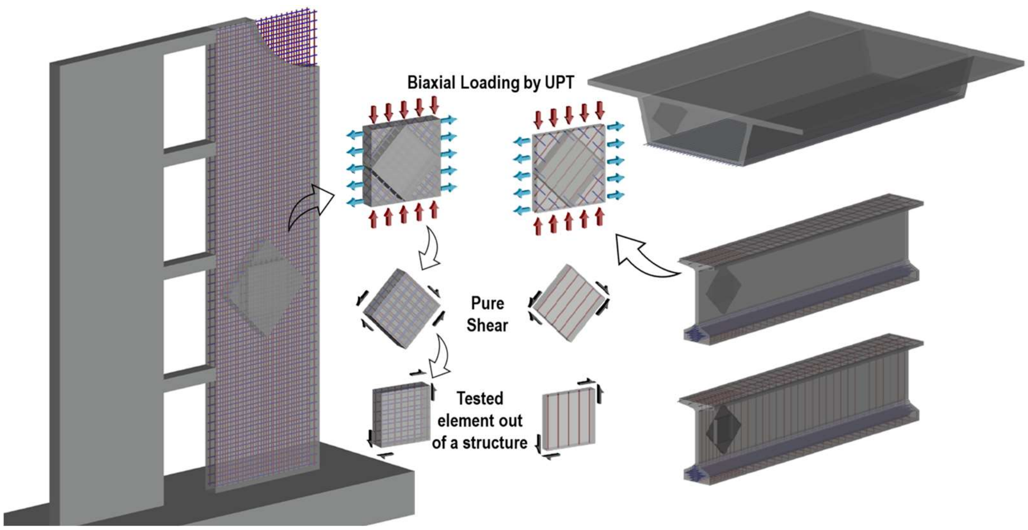
## 2. Universal Panel Tester (UPT)

The UHPC panels were tested using the UPT, which was established at the University of Houston. The UPT can generate various combinations of in-plane and out-of-plane loading conditions (shear, bending, torsion, and combinations thereof) on panels representing cut-off elements of full-scale structures (**Figure 1d**). Originally designed for load control testing, the UPT was later enhanced with a closed-loop servo-control system (Hsu et al. 1995) to enable displacement control testing, for simulating post-peak responses of panel elements. Recently, the UPT research team has received additional funding to upgrade UPT with a multi-channel servo-control system to expand its testing capabilities and enable cyber-physical testing.

UPT incorporates a servo-control hydraulic system that includes 37 in-plane jacks with a capacity of 250 kips (1112 kN) in compression and 200 kips (890 kN) in tension, and 3 in-plane rigid links. In addition, it has 17 out-of-plane jacks with a capacity of 150 kips (668 kN) in compression and 120 kips (535 kN) in tension, and 3 out-of-plane rigid links. The test panels are mounted to the connector yokes with threaded bolts, and the yokes are connected to the hydraulic jacks with cylindrical pins. The UPT picture and 3D illustrations are shown in **Figure 1a-c**.




**(a) Picture of UPT south face** **(b) UPT 3D illustration** **(c) Panel under in-plane loading**




**(d) The concept of testing cut-off large-scale elements using UPT.**

**Figure 1. The Universal Panel Tester (UPT) at University of Houston**

The largest panel size that can be tested in UPT is 55 in. × 55 in. (1400 mm × 1400 mm) with a thickness of up to 16 in. (406 mm). For the purpose of this research study, a group of 20 in-plane jacks (one face of jack pairs) and 3 out-of-plane rigid links were utilized to test large-scale UHPC panels that are 4 in. (100 mm) thick. This thickness was selected to represent typical design details of UHPC girder webs (e.g., El-Helou and Graybeal 2022; Kodsy and Morcous 2022).

## 3. Experimental Program

The shear behavior of UHPC under axial load effects was examined with three UHPC panels subjected to pure shear and shear combined with compression. The three panels used a thickness of 4 in. (100 mm) and were unreinforced to represent market trends in the development of thin UHPC members without shear reinforcement. The overall UHPC panel dimensions in all three cases were 55 in. × 55 in. × 4 in. (1400 mm × 1400 mm × 100 mm).

### 3.1. Test Matrix

The test matrix included three unreinforced UHPC panels as shown in **Table 1**. Panel#1-PS was subjected to pure shear, while Panel#2-CS5 and Panel#2-CS10 were subjected to shear combined with compression. In the latter two panels, the axial load was imposed at the beginning of the test and followed by shear loading. The compressive loading corresponded to an axial load ratio of 5% for Panel#2-CS5 and a ratio of 10% for Panel#3-CS10. The axial load ratio, $A_r$, was calculated as $A_r = P_c/\left(f_c' A_{panel}\right)$, where $P_c$ is the applied compression force in the principal compressive stress direction, $f_c'$ is the UHPC compressive strength measured with cylinder tests, and $A_{panel}$ is the cross-sectional area of the panel.

**Table 1 UHPC Panel Test Matrix**

| Panel ID | Test conditions | Compressive strength ksi (MPa) | Direct tensile strength ksi (MPa) |
|---|---|---|---|
| PANEL#1-PS | Pure shear | 22.74 (156) | 1.22 (8.4) |
| PANEL#2-CS5 | Shear combined with Compression<br>Target compressive stress = 0.95 ksi<br>(5% of the compressive strength) | 19 (131) | 1.21 (9.0) |
| PANEL#3-CS10 | Shear combined with Compression<br>Target compressive stress = 1.82 ksi<br>(10% of the compressive strength) | 18.2 (125.4) | 0.9 (6.2)* |

*Result based on a limited number of direct tensile tests; more tests are being performed.

### 3.2. UHPC Materials

The UHPC mix for Panel#1-PS and Panel#2-CS5 was provided by Steelike and the mix for Panel#3-CS10 was provided by Tindall Corp. Both mixes had a fiber content of 2% by volume of 0.5 in. (13 mm) long straight steel fibers with a diameter of 0.008 in. (0.2 mm) and a tensile strength of 414 ksi (2850 MPa). Companion specimens for material characterization tests were also cast from the same mixes and cured at ambient temperature. Companion tests included (a) compressive testing of cylinders with a diameter of 3 in. (76.2 mm) and height of 6 in. (152.4 mm) and (b) direct tensile testing of prisms with dimensions of 2 in. × 2 in. × 17 in. (50.8 mm × 50.8 mm × 431.8 mm), i.e., width × height × length.

### 3.3. Panel Fabrication

**Figure 2** presents the panel design details. The panels included no reinforcement in the designated test region to simulate the shear behavior of UHPC webs without shear reinforcement. To ensure adequate transfer of the actuator forces into the test region, the panel edges were strengthened with reinforcing bars and confining plates. In the three UHPC panels tested here, the edges were reinforced with twenty weldable rebars of ASTM A706 Grade #4 (13 mm) on each side, which were oriented at a 45-degree angle to the panel edge and overlapping. The rebars were welded to steel inserts with dimensions of 9.5 in. × 3 in. × 0.5 in. (241 mm × 76 mm × 12.7 mm). The inserts were, in turn, welded to end blocks with dimensions of 9.5 in. × 1.5 in × 1.5 in. (241 mm × 38 mm × 38 mm). Two threaded bolts were used to anchor the yokes to the panels.

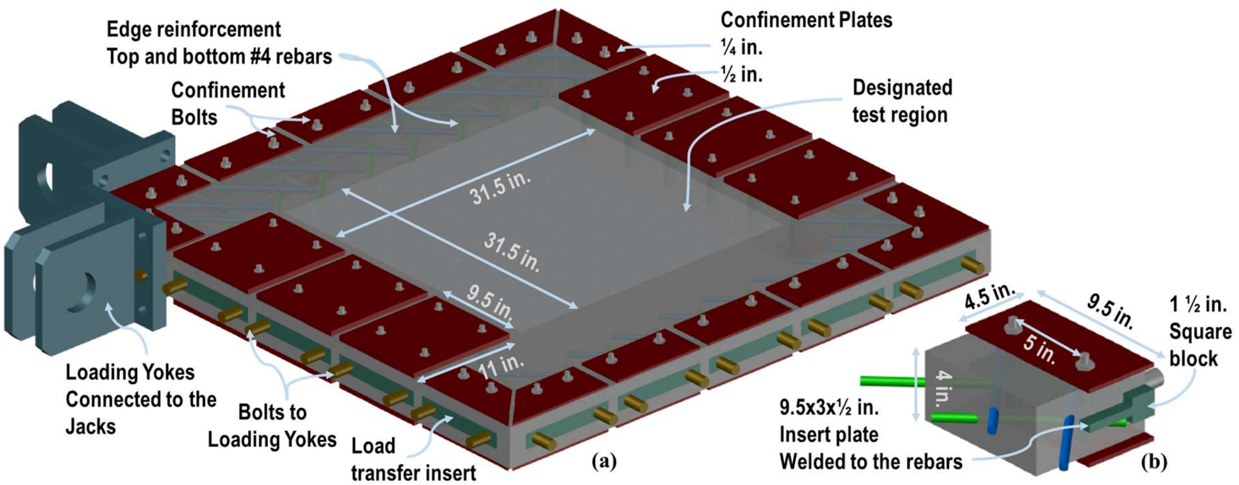



**Figure 2. UHPC Panel details: (a) Full panel details; (b) Enlarged insert details.**

As shown in **Figure 3**, the UHPC was mixed using a rotary mixer and promptly poured toward the centroid of the panel. The mix was able to flow to the edges of the casting bed without the use of vibrators due to its consistent flowability during casting with no signs of non-uniformity, segregation, or fiber balling. After casting, the three panels were cured at ambient temperature.

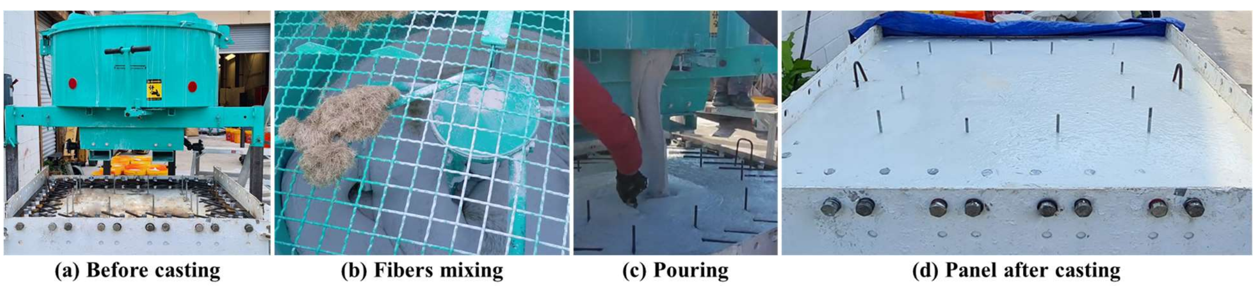



**Figure 3. Photos of UHPC panel casting procedure.**

## 3.4. Loading protocol

Using the UPT in-plane hydraulic jacks (see **Figure 1**), the panels were loaded monotonically, producing a state of pure shear or shear combined with compression. In Panel#2-CS5 and Panel#3-CS10 (see **Table 1**), the compression was applied in the beginning of the test and was followed by shear loading.

## 3.5. Instrumentation Plan

Linear Variable Displacement Transducers (LVDTs) were mounted on both panel faces to record the displacements in different directions. The instrumentation plan incorporated 14 LVDTs mounted on the north panel face and 8 LVDTs mounted on the south panel face. Each LVDT was labeled with a three-letter code indicating the side, direction, and LVDT ordering number. The north panel side was equipped with 12 LVDTs: two displacement-controlling LVDTS aligned horizontally in the tension direction, two LVDTs in the compression direction, four in the vertical and four in the horizontal directions, and two in the diagonal direction. The south side of the panel included eight LVDTs: four in the horizontal and four in the vertical directions.

## 4. Experimental Results

Error! Reference source not found. compares the results of the shear and principal tensile stress-strain responses of the three panels. For Panel#1-PS, the maximum shear strength was measured to be 0.8 ksi (5.5 MPa) at a shear strain value of 0.0013. For Panel#2-CS5, a higher shear strength of 1.2 ksi (8.27 MPa) was measured at a shear strain of 0.0032. Panel#3-CS10 reached a shear capacity of 1.62 ksi (11.16 MPa) at a shear strain of 0.0012.

Furthermore, it was found that the shear stress-strain responses of the three panels were similar to the associated principal tensile stress-strain responses, corroborating aforementioned experimental observations that the shear behavior of UHPC is a function of its tensile constitutive behavior. The principal tensile strength at maximum shear strength was 0.73 ksi (5 MPa), 0.81 ksi (5.6 MPa), and 0.75 ksi (5.2 MPa), respectively, with associated tensile strains of 0.001, 0.0027 and 0.0016.

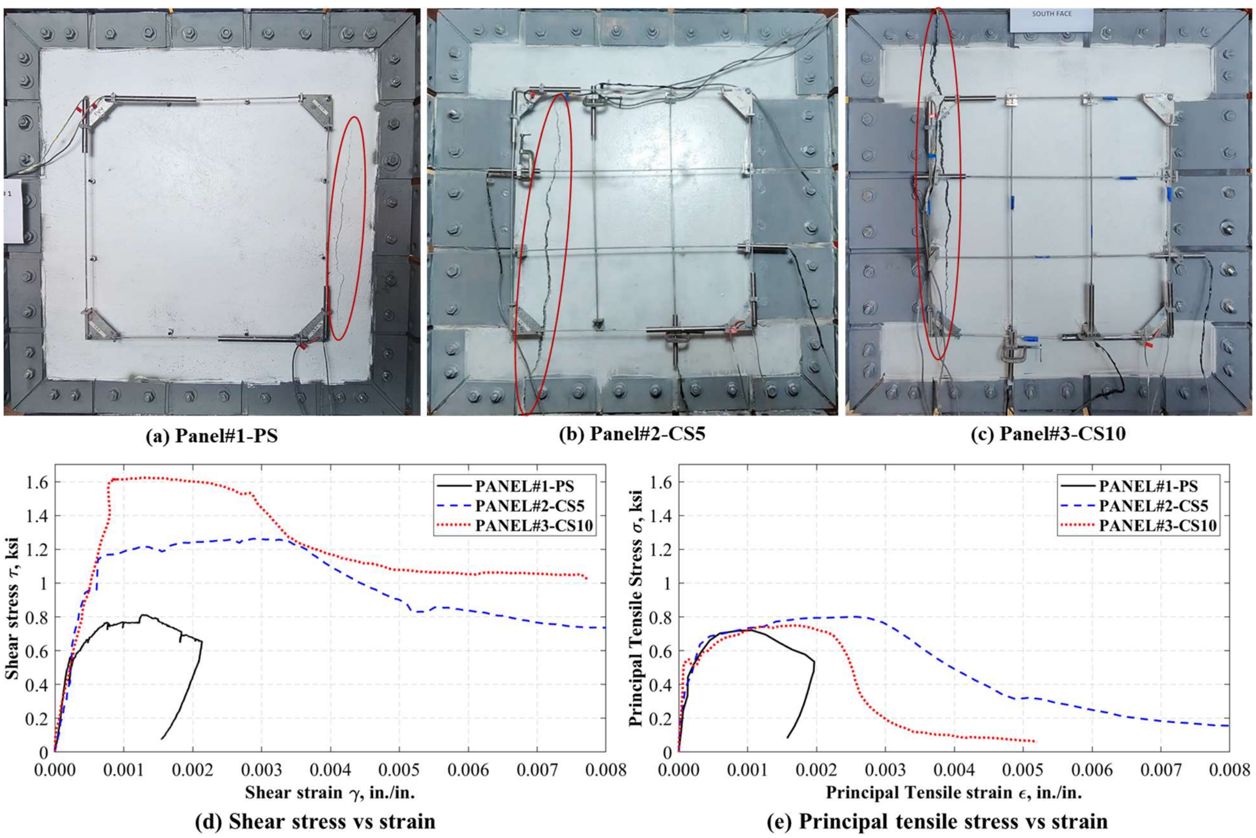



**Figure 4. Test results of UHPC Panels.**

## 5. Summary

As expected, the shear strength of UHPC increased with increasing compression load, as shown in **Figure 4d**. In these tests, the increase in shear strength was about 50% and 100% for axial load ratios of 5% and 10%, respectively. Furthermore, the shear responses of all panels were associated with a tension-dominated behavior. All three panels exhibited a significant post-cracking strain capacity, which was higher in the panels with compression load. For example, Panel#2-CS5 exhibited significant post-cracking ductility with the maximum shear strength occurring at a shear strain of 0.0032, far exceeding the corresponding shear strain of 0.0015 in Panel#1-PS. In Panel#3-SC10, significant descending in the shear stress occurred at a shear strain of 0.0032, with the shear stress being 1.53 ksi (10.54 MPa) or only 5% lower than the panel's peak shear strength.

The compressive strains recorded in all panel tests (not reported here) were small compared to the tensile strains, and remained within the elastic compression response region. Upcoming UHPC panel tests with additional variations in the axial load ratios are expected to complement the test results presented in this paper, and to further enhance our understanding of axial load effects on UHPC shear.

## 6. Acknowledgements

The work presented in this paper was undertaken as part of the ACI Foundation Research Project "Shear Behavior of Ultra-High-Performance Concrete (UHPC) Considering Axial Load Effects" and the PCI Daniel P. Jenny Research Fellowship 2022 "Shear Behavior of PCI-UHPC Members Considering Size Effects". The authors would like to thank Steelike and Tindall Corp. for providing the UHPC mixes. Any opinions, findings, and conclusions, or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of Steelike, Tindall Corp, ACI or PCI Foundation.

## 7. References

- ACI Committee 239. (2018). ACI 239R-18 Ultra-High-Performance Concrete: An Emerging Technology Report. In *American Concrete Institute*.
- Baby, Florent, Pierre Marchand, and François Toutlemonde. "Shear behavior of ultrahigh performance fiber-reinforced concrete beams. I: Experimental investigation." *Journal of structural engineering* 140.5 (2014): 04013111.
- Bae, Baek-Il, et al. "Evaluation of the ultimate strength of the ultra-high-performance fiber-reinforced concrete beams." *Applied Sciences* 11.7 (2021): 2951.
- Charron, J-P., E. Denarié, and E. Brühwiler. "Permeability of ultra high performance fiber reinforced concretes (UHPFRC) under high stresses." *Materials and structures* 40 (2007): 269-277.
- Crane, Charles Kennan. *Shear and shear friction of ultra-high performance concrete bridge girders*. Georgia Institute of Technology, 2010.
- El-Helou, Rafic G., and Benjamin A. Graybeal. "Shear behavior of ultrahigh-performance concrete pretensioned bridge girders." *Journal of Structural Engineering* 148.4 (2022): 04022017.
- Graybeal, Benjamin A. *Characterization of the behavior of ultra-high performance concrete*. University of Maryland, College Park, 2005.
- Graybeal, Benjamin A. *Structural behavior of ultra-high performance concrete prestressed I-girders*. No. FHWA-HRT-06-115. United States. Federal Highway Administration. Office of Infrastructure Research and Development, 2006.

- Hegger, Josef, and Guido Bertram. "Shear carrying capacity of ultra-high performance concrete beams." *Tailor Made Concrete Structures* (2008): 341-7.
- HSU, TT C., Abdeldjelil Belarbi, and Xiaobo Pang. "A universal panel tester." *Journal of testing and evaluation* 23.1 (1995): 41-49.
- HSU, TT C., L-X. Zhang, and Tito Gomez. "A servo-control system for the universal panel tester." *Journal of testing and evaluation* 23.6 (1995): 424-430.
- Kalliontzis, Dimitrios, and P. Benson Shing. "Force-Based Frame Element with Axial Force-Flexure-Shear Interaction for Modeling Reinforced Concrete Members." *ACI Structural Journal* 118.3 (2021): 131-146.
- Kodsy, Antony, and George Morcous. "Shear strength of ultra-high-performance concrete (UHPC) beams without transverse reinforcement: Prediction models and test data." *Materials* 15.14 (2022): 4794.
- Kowalsky, Mervyn J., and MJ Nigel Priestley. "Improved analytical model for shear strength of circular reinforced concrete columns in seismic regions." *Structural Journal* 97.3 (2000): 388-396.
- Metje, Kevin, and Torsten Leutbecher. "Experimental investigations on the shear bearing behavior of prestressed ultra-high performance fiber-reinforced concrete beams with compact cross-section." *Structural Concrete* 22.6 (2021): 3746-3762.
- Racky, Peter. "Cost-effectiveness and sustainability of UHPC." *Proceedings of the international symposium on ultra high performance concrete, Kassel, Germany*. 2004.
- Shing, P. B., Kalliontzis, D., Deyglun, L. C., 2021. *Assessment of seismic performance of Coronado Bay Bridge Piles with and without simulated damage and the effectiveness of a retrofit method*, Report No. SSRP 21/02, Department of Structural Engineering, University of California San Diego.
- Voo, Yen Lei, Wai Keat Poon, and Stephen J. Foster. "Shear strength of steel fiber-reinforced ultrahigh-performance concrete beams without stirrups." *Journal of structural engineering* 136.11 (2010): 1393-1400.
- Yang, Jiacheng, et al. "Experimental investigation and prediction of shear capacity for UHPC beams." *Case Studies in Construction Materials* 16 (2022): e01097.
- Yavas, Altug, and Cumali Ogun Goker. "Impact of reinforcement ratio on shear behavior of I-shaped UHPC beams with and without fiber shear reinforcement." *Materials* 13.7 (2020): 1525.
- Yavaş, Altuğ, et al. "Effective fiber type investigation on the shear behavior of ultrahigh-performance fiber-reinforced concrete beams." *Advances in Structural Engineering* 22.7 (2019): 1591-1605.