Evaluation of Bond Strength of Joints in Hybrid UHPC and SCC Members

Author(s) & Affiliation:

Megan Voss – Graduate Research Assistant, 365 Weil Hall, University of Florida, Gainesville, FL 32611 USA, Phone: 920-809-4476, Email: mvoss1@ufl.edu
Eduardo Torres* – Graduate Research Assistant, 365 Weil Hall, University of Florida, Gainesville, FL 32611 USA, Phone: 352-872-1082, Email: edu1291@ufl.edu
Raid S. Alrashidi – Graduate Research Assistant, 365 Weil Hall, University of Florida, Gainesville, FL 32611 USA, Phone: 352-278-6730, Email: raidalsaif@ufl.edu
Kyle Riding, Ph.D., P.E. – Associate Professor, 365 Weil Hall, PO Box 116580, University of Florida, Gainesville, FL 32611 USA, Phone: 352-294-1628, Email: kyle.riding@essie.ufl.edu
Trey Hamilton, Ph.D., P.E. – Professor, 365 Weil Hall, University of Florida, Gainesville, FL 32611 USA, Phone: 352-294-7797, Email: hrh@ce.ufl.edu

Abstract:

One of the major barriers to the use of UHPC (ultra-high performance concrete) in the precast industry is the high cost relative to conventional concrete. Often, the properties of UHPC are not fully utilized throughout a member. One solution is to create a hybrid member with UHPC in zones of high or unpredictable stresses while filling the rest of the section with a conventional concrete. Constructing such a member will require innovative techniques to achieve a successful bond between the two different materials. This paper is unique in that it investigates the bond behavior when both materials are in the fresh state. Several specimens of 2 × 2 × 17 inches (50x50x431 mm) were fabricated for direct tension tests. These specimens were fabricated with half UHPC and half SCC (self-consolidating concrete). The interface between the two types of concrete was perpendicular to the tensile force so that the bond was in direct tension. All materials were placed immediately after mixing and were separated by a removable barrier. Time dependency of the bond strength was controlled by removing the barrier at different times after placing. The quality of the bond strength between fresh UHPC and fresh SCC was compared to the tensile strength of the SCC. The results were used to determine a maximum allowable time by which both concretes can be combined while maintaining an acceptable bond strength.

Keywords: bond, girder, UHPC, SCC, direct tension

1. Introduction

Because of the high expense of UHPC, its applications are mostly limited to joints and other niche applications in the United States. In particular, the precast industry has been limited to the properties of conventional concrete. Therefore, introducing a new material with enhanced properties such as UHPC can serve for the improvement of structures or members, such as prestressed bridge girders. This study offers an innovative alternative by combining both self-consolidating concrete (SCC) and UHPC in a girder as shown in Figure 1.

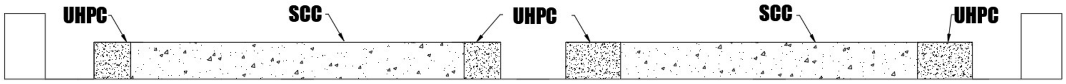


Figure 1. Layout of hybrid girders in precast bed

The mechanical properties of UHPC have the potential to prevent end-region cracking, reduce development length, and allow for increased prestressing capacity. With these improvements, longer spans may be possible. Using SCC for the majority of the member's volume will keep this alternative cost effective. The construction technique used to fabricate this type of girder in a precast yard is currently under development. Part of this process involves the evaluation of the bond strength between conventional SCC and UHPC.

The purpose of this study was to investigate the bond behavior of UHPC and SCC using the Direct Tension Test (DTT). During this project, the authors focused on placing both UHPC and SCC at similar times, in order to create a bond in the concrete before setting and not when either concrete had hardened.

2. Background

It is known that UHPC bonds well to hardened, normal concrete when the surface has been properly prepared (Graybeal). Muñoz et al. showed that bond between UHPC and normal strength concrete (NSC) was stronger than normal strength concrete when the NSC was properly saturated prior to placement (Carbonell Muñoz et al.). Bond can be further improved by sandblasting or creating an exposed aggregate surface, as well as by applying a bonding agent (Graybeal). For hybrid precast member fabrication, it is not economical to allow time for the SCC portion to cure before UHPC placement because this would result in extended construction time. This research will seek to determine the quality of bond that can be produced when plastic UHPC and plastic self-consolidating normal concrete (SCC) are placed together. Ideally, these two materials would be placed at similar times, but when casting a large member in the field, it will likely take several minutes between pours to bring in new truckloads of material. It is known that soon after placement, UHPC quickly forms a layer of "elephant skin" on the exposed surface that is dry and tough (Binard). Therefore, the amount of time between the placement of UHPC and the placement of SCC is likely to make a difference in the failure strength and location.

3. Testing Methods

The experiment was designed to evaluate the bond strength between UHPC and SCC in the fresh state. Table 1 lists the time of placement and the type of concrete used per beam type. The naming convention used in the experiment program was XX – YY, where XX indicates the second concrete that was placed in the beam and YY is the time that elapsed since the first concrete was placed. Two separate mixtures of SCC and UHPC were prepared to meet the specified placement types. Table 2 shows each mixture's proportions.

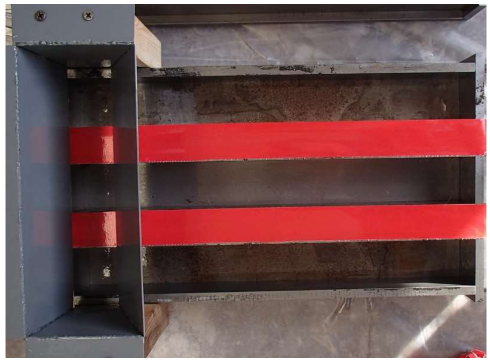
Table 1. Specimen Test Matrix

Classification	Beam Composition	Barrier Type	Placement Order	Delay (min)
UHPC	UHPC	-	-	-
SCC	SCC	-	-	-
SCC -10	UHPC-SCC	Plate	UHPC, SCC	10
SCC - 20	UHPC-SCC	Plate	UHPC, SCC	20
SCC - 40	UHPC-SCC	Plate	UHPC, SCC	40
UHPC - 10	UHPC-SCC	Plate	SCC, UHPC	10
SCC - 0	UHPC-SCC	Plate	simultaneous	0
Mesh - 0	UHPC-SCC	Mesh	simultaneous	0

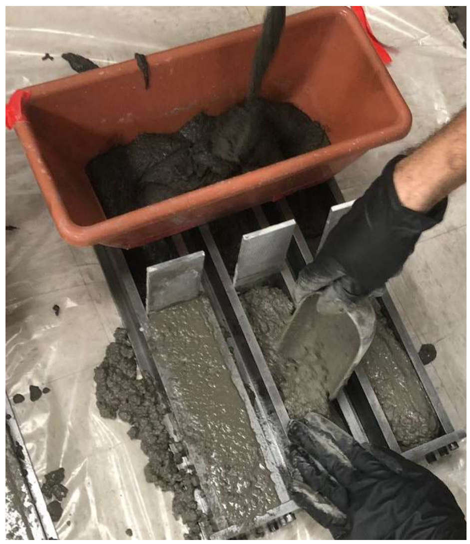
Table 2. Mix Proportions

Materials	UHPC, lbs/yd^3 (kg/m^3)	Materials	SCC, lbs/yd^3 (kg/m^3)
Dry Mix	3530 (2094)	Cement	735 (436)
Water	345 (204)	Fly Ash	165 (98)
Superplasticizer	53 (31.4)	Coarse Aggregate	1370 (812)
Steel Fibers	230 (136)	Sand	1265 (750)
		Water	279 (165)
		HRWR (Oz)	46 (27)

Direct tension specimens were prepared with the following procedures: UHPC was placed using a funnel at the end of the beam (Figure 2a), allowing the UHPC to flow and fill voids using its self-weight. SCC was placed using scoops and allowing the concrete to flow to fill the voids. To create the interface between concretes, an aluminum plate was placed in the middle of the beam. Then, the respective concrete was placed to fill the first half of the mold. At the prescribed delay time, the second type of concrete was placed, and the plate was removed. Figure 2b shows the casting of three specimens from the SCC - 0 class. In that picture, SCC and UHPC were cast at the same time on opposite sides of the aluminum plates. Specimens in the UHPC and SCC classes were cast using one placement with no barriers to find the strength of each material in tension. For specimens in the "Mesh - 0" classification, a polypropylene mesh with ¼ in. (6.35mm) grid opening generally known as "grout stop" was used to divide the specimens (Figure 2 and Figure 3c). This mesh was used because it is being considered by precast plants for use in the production of large-scale girders. It is advantageous because prestressing strands will be able to be threaded through the mesh before the casting. After casting, the mesh can remain inside the member.



a)



b)

c)

Figure 2. Placement Methods

After concrete placement, the beams were cured in a moist room for 7 days. Then, the procedures recommended by Graybeal and Baby (2013) were used to prepare and test the specimens in the Direct Tension Test (DTT) (Graybeal and Baby). First, aluminum plates were attached to the side of the beams using epoxy as shown in Figure 3. The DTT was adapted to our specimen characteristics. For instance, the grip pressure was reduced from 5800psi (40MPa) to 1000psi (7MPa), ensuring that SCC would not crack during gripping. Due to the decrease in grip pressure, the specimens were checked during the test to ensure that the grips did not slip. The test procedure was modified to be load controlled as only the peak strength was of interest for this study. The load rate used generated a stress rate of roughly 0.5ksi/min (3.5MPa/min).

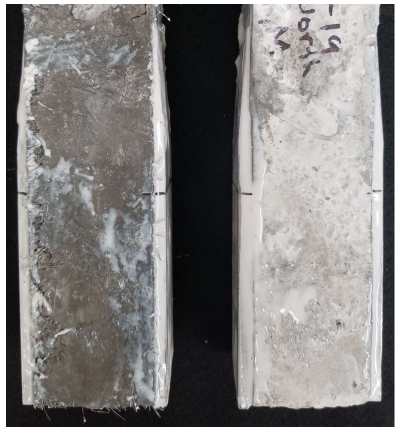


Figure 3. Direct Tension Specimens

After termination of the test, the specimens were removed from the test machine and examined to determine the location of the failure. The crack location was determined to occur either through the SCC, through the UHPC, or at the interface between the two. A failure through the UHPC was thought to be unlikely. It was assumed that longer wait times between SCC and UHPC placements would result in a higher probability of interface failure. Failures that occurred through the SCC would be desirable because it would indicate a high bond strength. When UHPC is placed next to cured normal concrete with proper surface treatment, the specimen will typically fail through the normal concrete (Carbonell Muñoz et al.).

4. Results and Discussion

Results from the experimental program are divided into two points of interest. First is the peak stress at which the fracture occurred. Second is the evaluation of the fracture surface to characterize the location of fracture. Table 3 provides a summary of all the test results. The cross-sectional area was measured at the location of fracture in order to calculate the stress values from the loads. The variability of results within specimens of the same group complicates the evaluation of the fracture. For instance, SCC specimens exhibited a standard deviation of 122 psi (0.84MPa). For the remaining specimens, the standard deviation varied from 39 psi (0.26MPa) to 74 psi (0.51MPa).

Table 3. Average Specimen Strengths

Classification	Concrete Type	Avg. Peak Load, lbs (kg)	Avg. Stress, psi (MPa)	Std. Deviation, psi (MPa)
UHPC	UHPC	5002 (2268)	1241 (8.55)	155 (1.06)
SCC	SCC	691 (313)	164 (1.13)	122 (0.84)
SCC -10	UHPC-SCC	620 (281)	152 (1.04)	48 (0.33)
SCC - 20	UHPC-SCC	585 (265)	143 (0.98)	50 (0.35)
SCC - 40	UHPC-SCC	312 (141)	74 (0.51)	74 (0.51)
UHPC - 10	UHPC-SCC	959 (435)	228 (1.57)	43 (0.29)
SCC - 0	UHPC-SCC	685 (310)	167 (1.15)	39 (0.26)
Mesh - 0	UHPC-SCC	521 (236)	129 (0.88)	42 (0.28)

The effect of placement delay is shown in Figure 4. The trend indicates that bond strength decreases as the time between concrete placements increases. For instance, when both concretes were placed simultaneously, the average bond strength was of 167 psi (1.15MPa), but when the SCC was placed after 40 min, the average bond strength was only 74 psi (0.51MPa). This is mainly attributed to the rapid loss of workability and formation of the UHPC. It was observed that when specimens required UHPC to rest behind the aluminum plate for twenty or forty minutes, the UHPC stiffened and was self-supporting when the aluminum plates were removed. This resulted in a flat surface that provided little mechanical bond. This finding illustrates the importance of minimizing delay between placements, emphasizing the need for new methods to deliver and place UHPC in a timely manner.

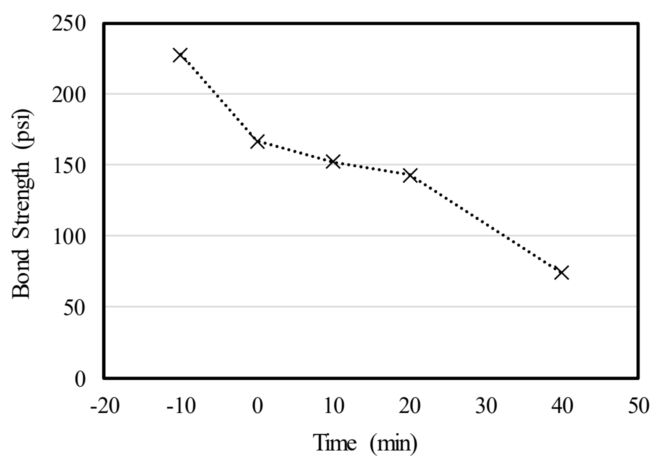


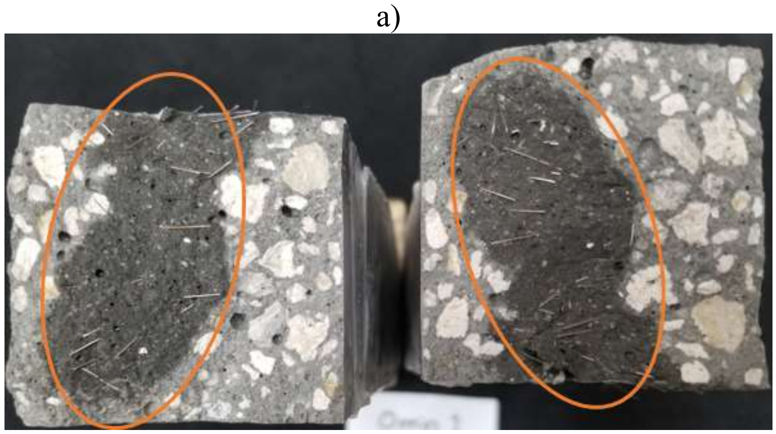
Figure 4. Bond strength vs. placement delay

Figure 4 shows the peak strength results plotted against the time of placement. Figure 4 indicates that the highest bond strength occurred when SCC was placed 10 min. before UHPC. This result may be attributed to the effect that the aluminum plate had on the UHPC during concrete placement. It was hypothesized that the steel fibers would align parallel to the front face of the aluminum plate, which resulted in a flat surface. Because SCC maintains flowability for a longer time than UHPC, it was still able to flow easily after being held back by the aluminum plate for ten minutes.

The specimens that used mesh as a barrier achieved a lower average tensile stress than all those that used an aluminum plate except for the SCC-40 class. Based on visual inspection, it was thought that the lower bond strength for the mesh specimens could have been caused by two factors. One factor was that the mesh had been cut larger than the cross section of the mold. The extra mesh was folded in to the mold, and this extra congestion may have resulted in air voids. This observation suggests that during girder construction, using mechanical vibration may be beneficial to remove air voids. The other possibility is that the tie wires used to hold the mesh in place could have created a weak failure plane for the crack to originate.

In order to characterize the fracture, three categories were defined: SCC, Interface, and UHPC. The fracture was determined to break across SCC if there were visible signs of aggregates on both sides of the fracture, as shown in Figure 5a. To be classified as a UHPC break, the fracture had to go through the UHPC so that there were fibers on both sides, as shown in Figure 5b. The interface failure would have some paste from either SCC, UHPC, or both visible, but no aggregates or fibers would be present, showing that the fracture occurred very close to the boundary of the two materials. An example of this is shown in Figure 5c.

a)



b)

c)

Figure 5: Failure Types: a) SCC Failure, b) UHPC Failure and c) Interface Failure

Each fracture was then classified with an estimated percentage in each of the three categories. For example, the sample shown in Figure 5a was classified as 5% UHPC and 95% SCC. The sample in Figure 5b was described as being 50% UHPC and 50% SCC. Figure 5c was characterized as 10% UHPC and 90% interface failure. All of the interfaces are plotted with their classified failures in Figure 6.

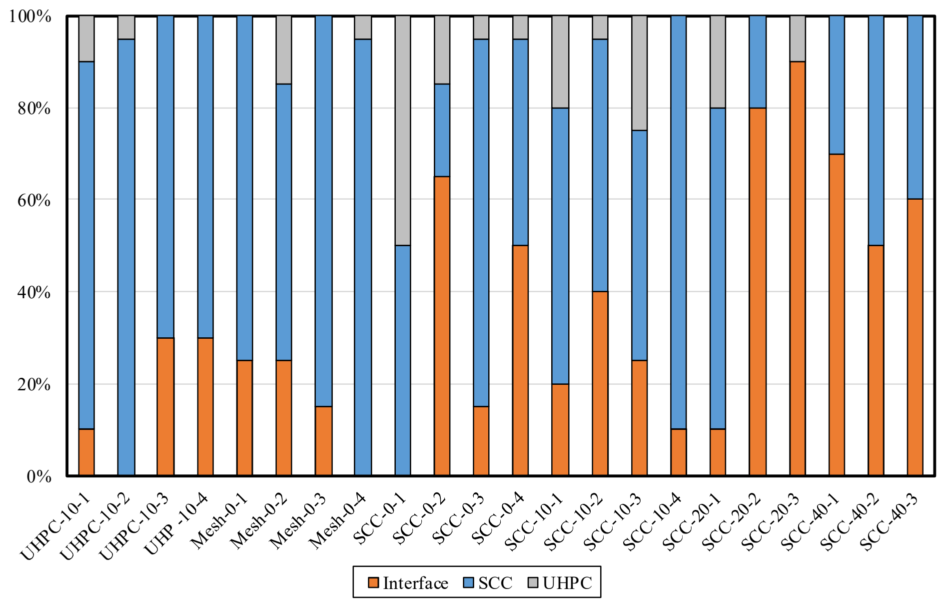


Figure 6: Fracture Location Classification

Table4 shows the averages of the fracture classifications. If there is good bond between the two materials, the specimen is expected to fail through the SCC. While UHPC failures were unexpected, many failures did have a proportion of their fracture through UHPC. It is likely that this occurred because the plates used to separate the regions during placement may have caused fibers to align parallel to the interface. Interface failures indicate that there is a weak plane between the two materials, and the goal is to minimize this. While the large-scale specimen will have prestressing strands perpendicular to the interface, it is important to keep this area watertight as well as uniform for aesthetic reasons. It can be seen that when UHPC was left to sit for 20 or 40 minutes before the addition of SCC, the interface became much weaker. If possible, it is preferred to pour the SCC prior to the UHPC or to wait no more than ten minutes between pours. The specimens that used mesh instead of a plate in the interface typically had an interface that stayed more intact than specimens that used the plate. This is likely because the plate created a very flat surface, but the mesh could both bend and let small amounts of material through to create a rougher bond. However, it should be noted that the use of mesh lowered the overall strength of the bond. This is likely due to the interfaces created between the concrete and the mesh or the wires used to hold it in place.

Table 4: Average Failure Modes

Time Delay (min)	Interface (%)	SCC (%)	UHPC (%)
Neg. Ten	17.5	78.75	3.75
Mesh	16.25	78.75	5
Zero	32.5	48.75	18.75
Ten	23.75	63.75	12.5
Twenty	60	30	10
Forty	60	40	0

5. Conclusions

This study evaluated the bond strength of the joint formed when UHPC and conventional SCC were used to fabricate a single structural element. The following conclusions have been drawn from the results of this study, relating to UHPC and SCC placed in the fresh state with a specified time delay:

1. When UHPC was placed before SCC, bond strength decreased as delay time increased. This is thought to have been caused by the rapid stiffening typical in UHPC mixtures. A delay time of 40 minutes resulted in a bond strength reduction of more than 50% compared to specimens with a delay time of 0 minutes.
2. When SCC was placed before UHPC, bond strength increased by about 35% compared to when both were placed at the same time. Overall, the best performance for both strength and crack location was measured when SCC was placed first.
3. The use of the polyethylene mesh resulted in strengths that were 23% lower than specimens that used a removable aluminum plate as the interface. However, when the mesh was used, the failure occurred mainly through the SCC.
4. For specimens with a delay time of twenty or forty minutes, the majority of the failure occurred at the interface between the two materials.

6. References

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