ACCEPTANCE CRITERIA FOR COMPOSITE ULTRA-HIGH PERFORMANCE CONCRETE (UHPC) PANEL SYSTEMS TO SHOW COMPLIANCE WITH THE BUILDING CODES IN THE USA

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Abstract: Currently, all fifty states and Washington, DC in the USA have adopted the International Building Code (IBC) as the model building code. However, the IBC does not include requirements addressing testing and determination of structural capacities, reliability, durability, and serviceability for composite, ultra-high performance concrete (UHPC) panel systems. IBC Section 104.11 states that supporting data, where necessary to assist in the approval of materials or assemblies not specifically provided for in the code, must consist of valid research reports from approved sources. Therefore, Acceptance Criteria for Composite, Ultra-High Performance Concrete (UHPC) Panel Systems (AC493) was published to provide requirements to qualify use of UHPC composite panels under the building codes in the USA, including structural strength and compatibility, fire safety, and material durability. The UHPC panels considered under AC493 are factory-fabricated, composite UHPC panels that are mechanically attached to the wall framing or sub-frame assembly with post-installed connectors that are either undercut anchors, or mechanical fasteners through the face of the panel. This paper explains how composite UHPC panel systems are qualified under AC493 as being in compliance with the IBC.

Keywords: Building code compliance, International Building Code, UHPC, façade panels, interior wall panel.

1. Introduction

Ultra-High Performance Concrete (UHPC) offers new capabilities for structural and aesthetic concrete architectural applications in building design. UHPC derives its high performance from a carefully calibrated ratio of engineered ingredients and a mixing sequence that packs molecules closely together to create very tight bonds. The high packing density yields excellent flexural and compressive strength, while significantly minimizing the capillary pores that may cause degradation (such as freeze-thaw durability) in other cement-based products. The distinct material properties of UHPC provide opportunities for greater spans, thinner profiles, and more complex geometries, with advantageous installation costs, while providing higher performance in durability.

In the United States, where the power to regulate construction is vested in local authorities, a system of model building codes is used to regulate construction. The International Building Code (IBC) is a model building code that was published to establish the minimum requirements for new building construction. Currently, the IBC has been adopted in all 50 states, the District of Columbia, Puerto Rico and the U.S. Virgin Islands. It has also been adopted by the Department of Defense, Department of State, and Department of Commerce, along with several other countries. The IBC allows the integration of new construction products, systems, and technologies not specifically described in the code itself, permitting manufacturers to demonstrate the code compliance of these products. To this end, Section 104.11 of the IBC allows the use of alternative materials, design and methods of construction provided that these alternatives are evaluated to verify their compliance with the code. This evaluation is typically accomplished through product testing in accordance with the established and peer-reviewed acceptance criteria. The acceptance criteria outline specific product sampling, testing and quality requirements that must be fulfilled in order to obtain code-compliance verification. The results of evaluation and testing are summarized in a research report made available to code officials, as set forth in Section 104.11.1 of the IBC. These research reports are typically issued by certification bodies that are accredited as complying with ISO standard 17065.

Currently, the IBC does not include requirements for testing and determination of structural capacities, reliability, and durability for composite UHPC panel systems. Chapter 19 of the IBC refers to ACI 318 for building design of reinforced concrete; however, ACI 318 does not address composite UHPC panel systems. Therefore, an acceptance criteria for Composite, Ultra-high Performance Concrete (UHPC) Panel Systems (AC493) was published by ICC-ES in June 2018 to provide the requirements to qualify the use of composite UHPC while meeting the fundamental objectives of the building codes, including structural strength and compatibility, fire safety, and durability, under Section 104.11.1 of the IBC.

2. Background

Architectural precast concrete cladding and façade elements were in use at the end of the 1950s in Europe to satisfy the increasing demand for affordable housing. For a long time, standard steel reinforced concrete (RC) elements dominated the pre-cast market for cement-based concrete building envelopes. From the 1960s to the 1980s, they dominated the architectural landscape in many urban areas all around the world (Mueller et al., 2015). The disadvantage of RC for architectural applications is the thickness of elements, which is due to the concrete cover required to protect the steel reinforcement from corrosion. This makes the elements particularly heavy and thick. Over the last 20 years, new concrete materials emerged on the market, enabling builders to drastically reduce the thickness and weight of cladding elements by removing the standard steel rebar and steel meshes in favor of other reinforcement alternatives. Two of those new materials are ultra-high-performance concrete (UHPC) – also called reactive powder concrete (RPC) - reinforced with inorganic/organic discrete fibers and textile reinforced concrete (TRC). Originally conceptualized by Bache in 1964 for structural applications (Buitelaar, 2004), ultra-high performance concrete (UHPC) has been in development for the last three decades – and today remains primarily a material used in specialized civil engineering/infrastructure.

In general, UHPC is defined as having compressive strengths higher than 120 MPa (17 ksi). However, according to the structural definition given by the American Concrete Institute

Committee 239 (ACI 239C minutes, 2017), the minimum compressive strength for UHPC is even higher, at 150 MPa (24.7 ksi). UHPC's high strength comes from a dense microstructure, the result of adding fine particles (increased packing density) and reducing the water/binder ratio to a range of about 0.18 to 0.35. The dense microstructure also increases the resistance against environmental impact (freeze-thaw cycles) and mechanical aggression (impact and wind loads) leading to very durable elements that afford a reduction of the concrete thickness to less than 25.4 mm (1 in.). Another advantage of the dense microstructure created with the use of very fine particles and aggregates (normally lower than 5 mm), is the high-quality surfaces that are obtained, ranging from extremely smooth to intricately textured. It is the combination of architectural UHPC's high strength, durability, and aesthetic range that allows architects to create subtle or dramatic articulated facades and is driving the demand for UHPC in a wide range of architectural applications, from exterior wall cladding and decorative elements to interior finishes.

UHPC formulations can be engineered to achieve the performance characteristics required for specific applications or manufacturing methods such as high compressive strength, tensile strength, rate of strength development and shrinkage to name a few. The very high compressive strength of UHPC is accompanied by a brittle failure mode that necessitates the addition of reinforcements to achieve the ductility required for structural and architectural applications. The typical reinforcements are high carbon steel fibers (load bearing structural application) and in the case of architectural application, organic (poly-propylene and poly-vinyl alcohol) and inorganic fibers (AR-glass). Although steel reinforcements produce the highest strength, they are typically not used in architectural applications for aesthetic reasons.

Since the first application of UHPC as façade material at The Atrium building in 2010 (Dialog, 2012), architects, engineers and specifiers have faced an absence of design standards, codes of practice and/or guideline specifications in North America for implementation of UHPC in architectural or structural applications. Several examples are shown in Figure 1. To overcome the technical challenge at The Atrium, a state of the art mechanical properties evaluation was carried out and the structural analysis of the facade was performed. This analysis utilized a new material constitutive law (stress-strain curve) along with finite element computer models to predict the structural behavior of 20 mm (3 mm ribs, 17 mm nominal) UHPC panels made with organic fibers (PVOH fibers). This structural analysis and design was supported and correlated by implementing laborious and expensive laboratory validation testing. The design and testing results of The Atrium panels were used as a starting point in 2011 for ACI Committee 239, whose mandate is to develop UHPC material design guidelines and specifications suitable for use in North America. Since 2011 ACI Committee 239 has made advances in the testing, design, and specification for the use of UHPC. However, their efforts have been focused on structural applications for bridges (led by the Federal Highway Administration) and primarily UHPC manufactured with metallic fibers and compressive strength higher than 150 MPa. Moreover, ACI 239 is considered a guideline and is not referenced by IBC.

The National Precast Concrete Association (NPCA) made an effort to provide some guidelines for manufacturing architectural precast UHPC elements, releasing a report in 2013 (NPCA, 2013). The purpose of this report was to provide a guide for the manufacture of architectural precast UHPC elements and to educate precasters on the potential opportunities. The report describes the general handling and quality control procedures, including storage of raw materials, forming, batching, curing, and plan requirements of architectural UHPC. However, the NPCA document is also considered a guideline and is not referenced by IBC.

In 2014, some UHPC manufacturers of cladding materials made a joint effort to develop more applicable guidelines for the use of UHPC exterior wall cladding materials, producing an acceptance criteria, AC458 (ICC-ES, 2016), with the purpose of establishing requirements for UHPC used to form exterior thin wall cladding panels and being recognized under the IBC. The goal of these criteria was to provide guidelines for the evaluation of UHPC thin wall cladding (<25.4 mm) panels, since the IBC and documents referenced by the IBC did not specify requirements for the testing and use of UHPC panel products. However, the AC458 acceptance criteria did not include the use of composite UHPC wall panels and elements in which extended deflection (high strain) after the first fracture is produced through the presence of reinforcing 2D textiles such as a mesh.

Therefore, per Section 104.11.1 of the IBC, Acceptance Criteria for Composite, Ultra-high Performance Concrete (UHPC) Panel Systems (AC493) was published by ICC-ES in June 2018. In accordance with the scope of AC493, a composite UHPC panel is a panel formed by UHPC, and one or two layers of embedded continuous alkali-resistant glass mesh reinforcement. Panels can have a base thickness range of ½ in. to 1-in. (12.7 mm to 25.4 mm), and panel nominal dimensions may come in various widths and lengths. Panels are either smooth faced or manufactured with optional raised surface textures or patterns of an overall average thickness, calculated by volume, not to exceed 1.5 times the base thickness. Base thickness is defined as the panel thickness (not less than ½ in. (12.7mm)) except of the surface textures and patterns.

AC493 provides material properties, panel properties and connection properties, and requires that the composite UHPC panel design loads and deflection requirements be established by a registered design professional based on the properties provided by AC493, taking into consideration the stiffness compatibility of the substrate wall systems with the composite UHPC panels to ensure additional stresses to the panels are not introduced. Also, AC493 states that the use of composite UHPC Panel connectors (anchors and visible fasteners) in structures assigned to Seismic Design Categories of C through F has not been evaluated and is outside the scope of this acceptance criteria.

3. Summary of Acceptance Criteria Testing Methods

3.1. UHPC Material Testing

AC493 requires material test specimens to include all component materials of UHPC (excluding glass mesh reinforcement), and testing be conducted for each combination of concrete mix proportions, fiber type, fiber length/denier and fiber dosage, fiber slenderness ratio, placement method, curing/treatment method, for which recognition is sought.

3.1.1. Compressive Strength of UHPC Material

AC493 requires compressive strength of UHPC material to be tested in accordance ASTM C109. A minimum of five replicate specimens from standard mix design must be tested on specimens with 2-inch (51mm) cubes. Tests must be stored and cured in accordance with ASTM C31. AC493 requires average 28-day compressive strength to be reported with a maximum Coefficient of Variation (COV) of 10 percent and used for quality control purposes by the manufacturer for consistent production under AC493.

3.1.2. Splitting Tensile Strength test of UHPC Material

AC493 requires a minimum of five replicate specimens to be tested in accordance with ASTM C496. The required sample dimensions are 3-in. (76.2 mm) in diameter cylinders with 1.5-in. (38.1 mm) thickness (2:1 ratio) from each standard mix design. AC493 requires average 28-day splitting strength to be reported with maximum Coefficient of Variation (COV) of 15 percent and used for quality control purposes by the manufacturer for consistent production under AC493.

Figure 1 – Examples of UHPC Facades in the USA: (a) 860 Washington, New York City (b) University of Cincinnati, Lindner College of Business.

(a) (b)

3.1.3. Water Absorption of UHPC Material

AC493 requires a minimum of five replicate prism specimens from the standard mix design to be tested in accordance with ASTM C642. Because of presence of fibers, the test must be modified so that the boiling temperature is 90^{o} C ± 2^{o} C (194^{o} F ± 4^{o} F). The average absorption after immersion and boiling must be less than 8 percent.

3.1.4. Freeze Thaw Resistance of UHPC Material

AC493 requires a minimum of three replicate prism specimens from the standard mix design with dimensions of 1.5 inches by 1.5 inches by 6.25 inches (38mm x 38mm x 159mm) tested in accordance with ASTM C666 Procedure A with 600 cycles of freezing and thawing. The minimum Average Durability Factor in accordance with ASTM C666 must be more than 90.

3.1.5 Linear Coefficient of Thermal Expansion of UHPC Material

AC493 requires a minimum of three specimens from the standard mix design tested for linear coefficient of thermal expansion in accordance with ASTM C531 with modifications in FHWA HRT 06-103 Section 3.9 and AASHTO TP60-00. The average linear coefficient must be reported.

3.1.6. Alkali-silica reactivity of UHPC Material

AC493 requires a minimum of six replicate mortar bars to be cast and tested for alkali-silica reactivity of the fine aggregate in accordance with ASTM C1260 and/or ASTM C1567. The result of the ASTM C1260 test must indicate that the 28-day expansion values of all specimens are less than 0.10 percent. If the criterion is not met, the result of six replicate mortar bars tested in accordance with ASTM C1567 using the same mixture as that of the ASTM C1260 specimens must indicate that the expansion of each test specimen is less than 0.10 percent at 28 days.

3.1.7. Fiber compatibility Used in UHPC Material

AC493 requires that the testing of fiber compatibility with the UHPC be conducted in accordance with the ICC-ES Acceptance Criteria for Concrete with Synthetic Fibers (AC32), Section 4.6, with the conditions of acceptance shown therein.

3.1.8. Glass Mesh Material Specification

AC493 requires testing of glass fiber mesh for fingerprinting purposes. Evidence of compliance is required to show that the alkali-resistant (AR) glass mesh specification and properties comply with ASTM C1666. Test results must be submitted for tension breaking and elongation determined in accordance with ASTM D5035 with modifications as given in AC493.

3.2. Composite UHPC Panel Testing

The reason AC493 requires the tests described in this section is to form the basis of determining engineering values to be used by registered design professional. Test specimens include all component materials of composite UHPC panels including continuous glass fiber mesh reinforcement (if applicable), and testing is required to be conducted for each combination of concrete mix proportions, fiber type, fiber length/denier and fiber dosage, and fiber slenderness ratio. The mesh placement methods and the curing/treatment method must be from actual panel production methods.

3.2.1. Flexural Strength (Modulus of Rupture-MoR) of Composite UHPC Panel

AC493 requires a minimum of eight replicate specimens to be selected, half in warp direction and half in weft direction. Specimen size must be 6 inches by 12 inches by the panel base thickness (152 mm x 305 mm x panel thickness). Equilibrium-conditioning (73 ± 4°F (23 ± 2°C) and 50 ± 5% relative humidity) and wet-conditioning (soaked in water at 73 ± 7°F (23 ± 4°C)) for a period of minimum 48 hours) of test specimens are required. Flexural strength testing must be conducted in accordance with ASTM C1185, Section 5 for both wet and dry (equilibrium) specimens utilizing three-point loading with modifications given in AC493. The test span must be 10 in. (254 mm) and the load line and support must be parallel. AC493 requires that the average flexural strength of the specimen must be the arithmetic mean value obtained in the two directions (warp and weft directions). The allowable flexural strength must be determined by dividing the lowest of the average flexural strength from the warp and weft directions by a safety factor of 3.0. The following acceptance conditions referring to Figure 2 also apply: a) Minimum individual P_p over P_1 must be 1.5, and minimum average P_p over P_1 must be 2. b) Minimum individual δ_p over δ_1 must be 20, and minimum average δ_p over δ_1 must be 40. c) The coefficient of variation for the test sets must not exceed 15 percent.

3.2.2. Water Tightness of Composite UHPC Panels

AC493 requires test specimens with dimensions of minimum 24 in. by 20 in. (610 by 508 mm) to be obtained from at least three manufactured panels. Water tightness testing is to be conducted in accordance with ASTM C1185, Section 11, with exceptions given in AC493. Criteria require that no trace of moisture on the underside of the UHPC composite panel is visible and there is no formation of water drops.

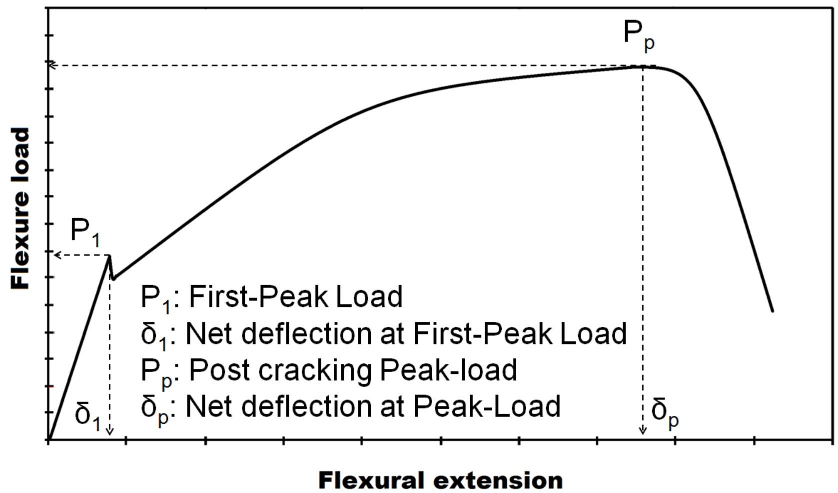

Figure 2 - Characteristic Load-deflection Curve for Composite UHPC Panels

3.2.3. Freeze-Thaw Resistance of Composite UHPC Panels

AC493 requires test specimens be cut from manufactured panels with dimensions of 6 in. by 12 in. (152mm x 305mm), from at least three sampled panel sheets. Freeze-thaw resistance testing (resonant transverse frequency) must be conducted in accordance with ASTM C666, Procedure B with 300 cycles of freezing and thawing. The Durability Factor of all specimens in accordance with ASTM C666 must be a minimum 90 percent for the panel samples. Average MoR of freeze-thaw conditioned specimens must also be at least 90 percent of the average MoR of dry-control specimens.

3.2.4. Temperature Cycling of Composite UHPC Panels

AC493 requires prepration of five panels of minimum base panel thickness and minimum panel dimensions of 60 inches wide x 48 in. (1.5m x 1.2m). Temperature cycling testing must be conducted in accordance with the following conditions with 25 consecutive temperature cycles: one hour of water exposure at room temperature, followed by six hours at minus 40°F (-40°C), followed by two hours at 70°F (21.1°C), followed by 14 hours at 180°F (82°C), and followed by one hour at 70°F (21.1°C). The test panel must be installed vertically with actual anchors used for construction; minimum spacing and minimum edge distance must be considered. After exposure, there must be no cracking, checking, crazing, erosion, or other characteristic which might affect performance as an exterior wall cladding. Additionally, there must be no sign of failure or distress at fastener locations.

3.3 Other Building Code Compliance Requirements of AC493

The following requirements are also a part of AC493 for complete building code compliance:

- Exterior Wall Assembly Fire Propagation Testing (optional): Unless the product is qualified by testing in accordance with NFPA 285, the scope of the evaluation report will be limited under IBC to use in exterior walls of buildings of Type V construction and exterior walls not exceeding 40 feet above grade of buildings of Types I, II, III and IV construction, provided compliance with non-combustibility testing is established.
- Non-combustibility (optional): Non-combustibility testing must be conducted on the UHPC elementary material (without glass mesh) in accordance with ASTM E136 (mix/prism test) when recognition is sought for installation on exterior walls in buildings of Type I, II, III and IV construction in accordance with IBC Section 703.5.1 and composite UHPC panel material must be tested in accordance with IBC Section 703.5.2.
- Interior Non-Load Bearing Wall Finish (optional): For recognition of interior use as a wall finish, panels with minimum concrete thickness over the mesh reinforcement must be tested per ASTM E84, and are required to meet Class A rating.
- Weather Resistive Consideration: A water-resistive barrier complying with Section 1403.2 of the 2018 IBC and Section1404.2 of the 2015 IBC is required.
- Fire-Resistance-Rating (optional): For recognition of composite UHPC panel system use as an integral component of a fire rated assembly, fire-resistance-rating testing must be conducted in accordance with ASTM E119 or UL 263. If the product is not qualified through this testing, the scope of the evaluation report will be limited to use in non-fire-resistance-rated construction.
- Thermal Resistance (optional): Thermal resistance testing of the composite UHPC Panels must be conducted in accordance with ASTM C518, on 1 inch (25.4mm) thick panel samples if an R-value per inch of composite UHPC panel is to be reported.

3.4 Panel Connection Tests

AC493 requires panel connections, either post installed undercut anchors or visible fasteners (mechanical fasteners through pre-drilled holes), to be tested in accordance with Tables 1 and 2 of the criteria AC493, respectively. Post installed anchor tests are based on ICC-ES AC193 and ASTM E488. Visible fastener tests are based on AISI S905 Sections 8 and 9. AC493 requires that the characteristic values of the test results be based on the lesser of the concrete strength, steel strength or connection strength of the tests determined in accordance with ACI 355.2, Appendix A2, and must be reported. The strength reduction factor, ϕ, must be applied in accordance with ACI 318, Section 17.3.3 (Category 1, Condition B).

4. Conclusions

The IBC is the predominant building code in the USA. IBC Section 104.11 allows for alternative materials, design and methods provided that such alternatives have been evaluated to meet code requirements. AC493 provides the required evaluation criteria and data for quantifying the performance characteristics of a composite UHPC wall panel system that satisfies the requirements of the building codes. The resulting research report issued in accordance with AC493 will demonstrates code compliance, as permitted by International Building Code Section 104.11, and is primarily used by code officials and structural engineers.

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