A SUPER LIGHTWEIGHT HURRICANE-RESISTANT THIN-WALLED BOX-CELL ROOFING SYSTEM

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Abstract: Roofs are the most vulnerable building components when subjected to extreme wind events such as hurricanes. An innovative wind-resistant composite roof structure is engineered for commercial, industrial, and multistory residential buildings to withstand hurricanes and other windstorms up to 200 miles per hour (322 kilometers per hour). The design is based on the most stringent wind design code provisions in the United States, namely the High Velocity Hurricane Zones (HVHZ) provisions in the Florida Building Code. The new proposed roofing system is made of ultra-high performance concrete (UHPC) reinforced with high-strength steel (HSS). The special feature of the section geometry, enhanced with the material combination made it feasible to design and construct super lightweight (17 lb/ft^2, 83 kg/m^2), low profile (4 in., 10.2 cm), and ultra-thin-walled (3/4 in., 1.9 cm) box-cells units with no shear reinforcement. Test results clearly showed that the proposed roof system successfully meets the strength expectations for a 19.26-ft (5.87 m) long span, under both downward and uplift pressures. This confirms potential for manufacturing and using a super lightweight hurricane-resistant thin-walled roofing system for various types of buildings in the hurricane-prone coastal states.
Keywords: composite roof, wind mitigation, ultra-high performance concrete (UHPC), high-strength steel (HSS)

1 INTRODUCTION

Roofs are the most vulnerable building components when subjected to extreme wind events such as hurricanes. Flat roofs experience high wind suction due to the flow separation taking place at the edges or cornering vortices generated from diagonal winds. As wind blows across the roof, edges and corners are subjected to high suctions which can initiate damages, often leading to cascading failures and causing extensive interior damage and disturbance of services.

Conventional roofs suffer from extensive damages in high windstorm events. These multilayer roofs are composed of several components that are mechanically connected. According to the investigation report on Hurricane Katrina (2005) performed by Roofing Industry Committee on Weather Issues (Ricowi, 2007), “evidence from field reconnaissance indicated that low slope roof failures in hurricane winds are generally system failures associated with the integrity of the composite system and the attachment of the system to the building structure”. This highlight the importance of connections in roofing systems. In general, high wind-induced uplift pressures damage roof covering and components and result in water intrusion, causing interior content loss and service disruption.

2 OBJECTIVE

Limited studies have been performed to develop new roofing systems to mitigate wind related concerns. Mintz et al. (2015) developed a composite roofing system for residential buildings, in order to resist hurricane-induced damage and replicate the shape and color of commonly used barrel tiles. However, the research was limited to residential roofs with only corrugated surfaces. The objective of the present research is to develop a new high-wind resistant flat roofing system for commercial and industrial buildings that addresses the above-mentioned concerns, while incorporating structural performance of the new system.

3 METHODOLOGY

Development of the proposed engineering roofing system involved three interrelated challenges-material selection, shape determination, and specification of manufacturing techniques, which all are described in the next sections. Development initiated with research on composite materials that could potentially be utilized to resolve the concerns addressed in literature, while lending themselves to constructible systems from a manufacturing point of view. It was found ultra-high performance concrete (UHPC) reinforced with high-strength steel (HSS) is the best alternative materials. Subsequently, demand loads and serviceability requirements were determined in accordance with the Florida Building Code (FBC 2010). Finite Element (FE) analyses were utilized to determine the shape and size of the roof section and to help develop a primary design tool. The new system was designed to meet all FBC (2010) requirements. Accordingly, a comprehensive experimental plan was established to verify the design.

4 COMPOSITE MATERIALS

Ultra-high performance concrete (UHPC) is a new class of concrete with exceptional characteristics. UHPC offers high compressive strength in the range of four to eight times the conventional concrete, with minimum tensile-cracking strength of 0.9 to 1.3 ksi (6.2 to 9 MPa), depending on curing treatment (Graybeal, 2006, 2014), as opposed to 0.3 to 0.7 ksi (2.1MPa to 4.8MPa) for conventional concrete. One of the beneficial characteristics of UHPC is that it still carries significant amount of tensile loads after cracking, irrespective of curing treatment (Graybeal 2006). The high tensile strength of UHPC significantly improves its shear capacity as well.

According to Richard and Cheyrezy (1995) "[the] damage phase of the material, i.e., micro-cracking of the matrix with gradual and controlled opening of cracks, limits the risk of sudden failure". Therefore, this ductility behavior of UHPC provides the new roof with higher safety against sudden failure. Also, its high tensile strength as well as strain-hardening properties improve serviceability performance through increased stiffness, reduced deflection and postponement of "formation of localized macro-cracks" (Habel, Denarié et al. 2007), as compared to conventional concrete. All these features are the governing factors that greatly benefit the design of the new roof and result in less material use, which in turn leads to a super lightweight, high-strength low profile section, in contrast to conventional reinforced concrete.

Corrosion is another problematic issue with most conventional roofs. However, UHPC has superior low porosity (Perry and Seibert 2008), which protect reinforcing bars from corrosion. UHPC provides the proposed roofing system significantly high resistance to corrosive environments, much longer life span and subsequently lower maintenance costs.

Additionally, steel fibers content in UHPC provide non-brittle behavior (AFGC 2002), bond at micro level (Harris and Roberts-Wollmann 2005), control crack width and increase tensile strength, which all are beneficial to the performance of the roof system. Fibers "act as micro-reinforcement similar to mild steel reinforcement in conventional reinforced concrete on the macro level" (Perry, 2003; Harris and Roberts-Wollmann, 2005), which enables a design with lower reinforcement ratio. The need for less "passive reinforcing steel provides significant flexibility for designing innovative, more refined shapes and eliminates the basic weakness with reinforced concrete decks that eventually leads to failure of the deck" (Perry and Seibert, 2008). As a result, it is feasible to design thin-walled flexural elements with little or no ordinary reinforcement.

UHPC has been used in highway bridge construction in the United States since 2006. With the help of its superior mechanical properties, the motivation for the increased use of UHPC has been used to solve the corrosion problem by eliminating or minimizing the use of mild steel reinforcement in bridge decks (Perry and Seibert 2008). Glass-fiber reinforced plastic (GFRP), carbon-fiber–reinforced plastic (CFRP) and HSS bars were utilized with UHPC in bridge decks (Perry and Seibert, 2008; Ghasemi et al., 2015, 2016; Saleem et al., 2011; Xia et al., 2011) however, Ghasemi et. al. (2015) concluded that HSS provides noticeable higher strength as opposed to CFRP. In this study, Ductal, the commercially available UHPC product of Lafarge, was utilized with high-strength steel bars, namely ChrōmX 9100, product of MMFX® Steel Corporation, as primary reinforcement, with 100 ksi yield strength (689 MPa) and five times corrosion resistance as that of conventional steel.

5 SYSTEM DESIGN

Finite Element model was employed as the analytical tool to engineering an optimal section. The new roofing system is designed to meet all the High Velocity Hurricane Zones (HVHZ) (defined as Miami-Dade and Broward counties) provisions of the Florida Building Code (FBC 2010), the most stringent wind design code provisions in the United States. For wind calculations the FBC (2010) refers to the wind pressures in the American Society of Civil Engineers' 'Minimum Design Loads for Buildings and Other Structures' (ASCE-7). Directional Procedure- Regular Approach for All heights was used to determine the wind pressures on the Main Wind Force Resisting System (MWFRS). A flat roof building with mean roof height of 60 ft. (18.3 m) was considered, as the case study, located in Miami-Dade County with the highest wind velocity of 200 miles per hour (322 kilometers per hour) at 33 ft. (10 m) above an Exposure C ground category. The load combinations were assigned based on FBC (2010) according to its Table 1607.1 and equations (16-3) and (16.6). Design loads are reported in Table 1.

Table 1. Summary of test results

Specimen	Design load (lb/ft^2)	Average 28-day UHPC compressive strength (ksi)	Peak load (kips)	Midspan deflection (in.)	Peak moment (kip-ft)	Reduced momen* (kip-ft)	Potential span (ft.)
SC-P	77.9	20.2	4.35	1.27	7.06	5.65	19.67
SC-N	121.2	21.8	6.48	3.67	10.54	8.43	19.26

*Obtained by muliplying experimental moment by a reduction factor of 0.8

In accordance with FBC (2010), roofs shall be designed to have adequate strength as well as stiffness to limit deflection to the permitted range specified by the ceiling types. For the current study the conservative case, the roofs supporting plaster ceiling, was considered, although, it is not common in commercial and industrial buildings. The deflection must be limited to the span length divided by 360 under live load as well as wind load. Also it shall not exceed span length divided by 240 under combination of live and dead load as well. In this regard, a 20-ft. (6.1 m) roof span was considered for the purpose of design and case study. Also the FBC (2010) requires the roofs to be designed for a point load of 300 lb. (136.1 kg) over a 2 ½ ft. (76 cm) square area, where it produces maximum load effect. The wind loads, load combinations, allowable stresses or strength limit state and serviceability requirements used here can be adjusted in accordance with the intended building codes.

In the next step, the most appropriate design geometry was identified, on the basis of the design loads specified earlier. The roof shall be designed to resist positive and negative loadings of 77.93 and 121.20 lb/ft^2 (380.5 and 591.8 kg/m^2) respectively. Thus, the cross section should resist negative loading about twice the positive loading. The trapezoidal thin-walled cross section was found to be the proper geometry for the present work. The trapezoidal structural geometry, called box-cell in this study, offers great structural performance and efficiency, while reducing weight by elimination of superfluous material consumption (e.g. UHPC) in the center of the cross section, where UHPC has a minor contribution on section strength. The top and bottom of section remain solid, where high stresses occur. In principle, the section is effectively functional with respect to the positive and negative loading. Moreover, it has efficient load distribution in transverse direction, and the two webs provide wide and strong upper flange, which support significant quantity of loads, as well as act as roof deck.

As depicted in the 3D schematic in Figure 1, the proposed roof is a panel composed of a series of box-cells with transverse ribs at intermediate locations with the purpose of developing a uniform distribution of imposed loads. It is monolithic prefabricated deck panel made of reinforced UHPC with HSS, as opposed to conventional multi-layered roof systems prone to damage under high wind-induced uplift.

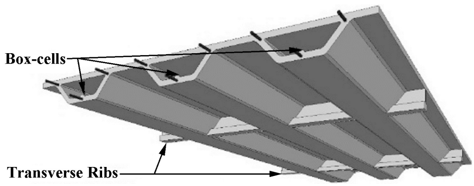


Figure 1. Schematics of the proposed UHPC roofing system

The new roof system was designed as a one-way slab, which spans the roof in one direction along the shorter length between supporting beams or walls. Based on the one-way slab action, it is reasonable to consider the entire panel's action as series of beams, herein box-cell. Subsequently, based upon this concept, box-cell units were accordingly engineered upon beam analogy. Finite Element (FE) analyses were performed on a series of 20 ft. (6.1 m) -box-cells with the purpose of sizing the roof unit while maximizing strength and stiffness, and minimizing the weight. FE models resulted in an optimal balanced and strong super lightweight (17 lb/ft^2, 83 kg/m^2), low profile (4 in., 10.2 cm), and ultra-thin-walled (3/4 in., 1.9 cm) box-cell unit as depicted in Figure 2.

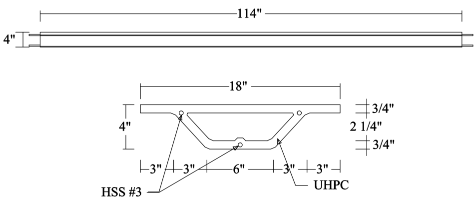


Figure 2. Testing Specimens

6 EXPERIMENTAL DESIGN

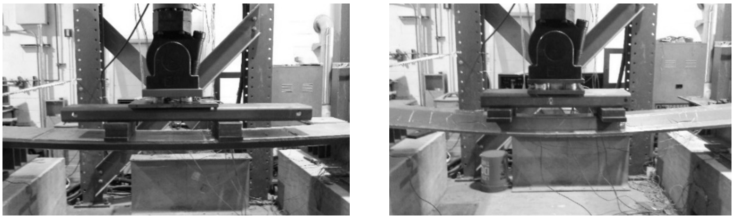
The main objective of the experimental research was to investigate the ultimate strength and serviceability of the proposed roofing system, as well as investigating the flexural behavior. The experimental work was designed in two sequential phases to conduct tests on two sets of specimens. The first phase of testing was performed on two identical simply supported box-cell specimens, representative of panel components, under four-point flexural test, one in positive pressure and another in negative pressure. The same procedure was applied for the second phase of testing on panel specimens. The laboratory constrains governed the test specimen dimensions. The panel specimens consisted of three box-cells with total width of 54 in. (137 cm) by 108 in. (274 cm) length, to maintain the aspect ratio of 2:1 for a one-way slab. Accordingly, box-cell specimens were fabricated with the same length (108 in., 274cm) with additional 3 in. (7.6 cm) at both ends as support setting. During the tests, strains, load and deflections were continuously monitored. This article reports on the experimental results of the first phase of tests of box-cell units, and results are compared at the ultimate limit states.

7 MANUFACTURING TECHNIQUE

Specimens were cast in formwork made of Styrofoam. In practice, the hollow inner core was prepared by suspending a floating foam core in the center of the base platform of Styrofoam, creating a hollow void when removed after UHPC has set. Specimens were cast as single monolithic units, each in one UHPC batch. Mix was fed and the flow was free from one end to let the fibers distribute uniformly and align with specimens' length. All specimens were cured and stored in a temperature controlled room, (68°F, 20°C), covered with plastic sheets for 14 days to avoid moisture content evaporation. Specimens were named "SC-P" and "SC-N", for testing under positive and negative loading, respectively. During the casting cylinder samples were meticulously taken from each batch of UHPC, as it was poured into forms. Three 3×6 in. (7.6× 15.2 cm) compression cylinders were prepared for both specimens. The average 28-day compressive strength are shown in Table 1.

8 INSTRUMENTATION AND TEST SETUP

Both specimens were instrumented with strain gauges attached onto reinforcing bars to measure strain at mid-span of compressive and tensile bars. The deformation was monitored using string potentiometers at mid-span. Specimens were subjected to a displacement-controlled loading, at the average rate of 0.02 inches per minute (0.5 millimeters per minute), using a 235 kips (1045 kN) hydraulic actuator. The load was measured more precisely using four load cells, with 2 kips (8.9 kN) capacity, since the high capacity hydraulic actuator had low precision at its lower loads. Specimens were loaded by two simultaneous equal loads distributed by a steel beam over two 6in×18 in. (15.2cm×45.7 cm) plates, placed at 12 in. (30.5 cm) offset from mid-span with the inner-to-inner spacing of 24 in. (61 cm), as depicted in Figure 3(a) and (b). All tests were performed at the Titan America Structures and Construction Testing Laboratory of the Florida International University (FIU).



(a) (b)

Figure 3. Testing specimens under four-point flexural test (a) Specimen SC-P (b) Specimen SC-N

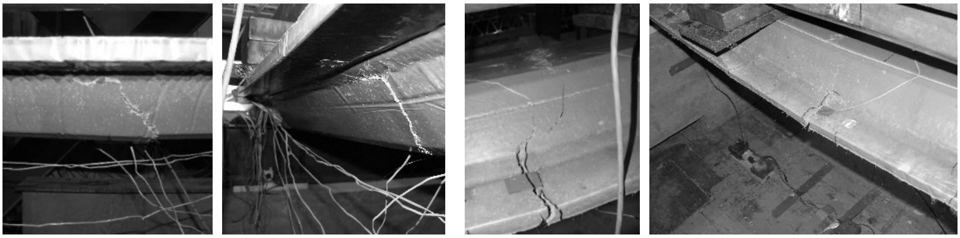
9 TEST RESULTS

During the tests, all stain gauges, string potentiometers and load cells were continuously monitored. Also, the crack propagation and failure modes were noted.

As specimen SC-P was loaded, at about 2.7 kips of force (12 kN) and 0.48 in. (1.2 cm) deflection, the concrete cracked on the bottom side of midspan and propagated diagonally into the webs until specimen failed at 4.35 kips of force (19.3 kN) and 1.27 in. (3.2 cm) deflection (Figures 4(a) and 4(b)). Specimen SC-N under negative bending was the same profile as the positive sample, only tested inverted. The first appreciable cracks occurred in about the center bottom at load level of 3.10 kips (13.8 kN) with the respective deflection of 0.8 inches (2 cm). The central failure passed through the webs and into the upper portion of the specimen, as shown in Figure 4(c) and 4(d), until the specimen failed at 6.48 kips of force (28.8 kN) and 3.67 in. (9.3 cm) deflection. A second, thinner crack developed about 12 in. (30.5 cm) from the center, still in the maximum moment region. Figure 3(b) shows specimen SC-N under a high load of 6.06 kips (27 kN) and deformation of 2.51 inches (6.4 cm).

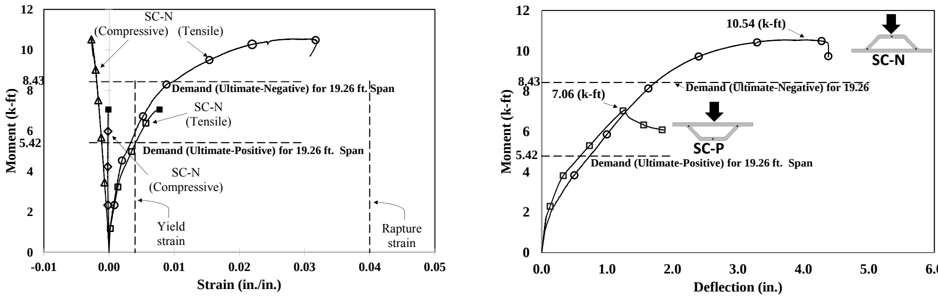
Figure 5(a) illustrates the reinforcement responses. During testing of specimen SC-P, strain gauges attached onto HSS reinforcing bars failed to record data just before peak load. This may be attributed to the damage caused by steel fibers content in UHPC mix. The interrupted data are marked with solid caps at their ends. However, tensile bars on both specimens (SC-P and SC-N) were yielded at 75 and 53% of their ultimate loads, respectively.

Figure 5(b) plots moment-deflection responses of both specimens. Flexural capacity of the given section is constant irrespective of the span length. Therefore, the flexural strength can simply be evaluated for any span length. A safety factor (reduction factor) of 0.8 is applied to ultimate flexure capacity, experimental ultimate moment, to be served as design value (Table 1). Then, accordingly potential span lengths are calculated based on design loads and reduced flexural strength. Table 1 lists experimental results such as peak load and corresponding moment and deflection, and also design loads and design ultimate moment along with potential span length. Potential spans are calculated based on the strength. Both specimens agreed to a span length of 19.26 ft. (5.87 m), which is an identification of perfect optimum design, with only 3.8% discrepancy with original design of 20 feet.



(a) (b) (c) (d)

Figure 4. Failure mode of specimens (a),(b) Specimen SC-P (c),(d) Specimen SC-N



(a) (b)

Figure 5. Test results (a) Reinforcements strain responses (b) Moment-Deflection Responses

10 CONCLUSIONS

The exceptional characteristics of ultra-high performance concrete (UHPC) such as high compressive and tensile strength, reinforced with high strength steel (HSS) with twice yield strength as opposed to mild steel, makes it feasible to develop, design and construct a new super lightweight (17 lb/ft^2, 83 kg/m^2), low profile (4 in., 10.2 cm), ultra-thin-walled (3/4 in., 1.9 cm) composite roofing system with minimal reinforcing bars (No. 3) and no shear reinforcement to withstand high windstorms and hurricanes up to 200 mile per hours (322 kilometers per hour). The 3.8% discrepancy between design and experimental results, verified the design method utilized (FE analyses) and feasibility of the proposed roofing system. Test results clearly showed that the proposed roofing system successfully meet the strength expectations for a 19.26-ft (5.87 m) long span, under both downward and uplift pressures. This confirms potential for manufacturing the proposed roofing system for various types of buildings in the hurricane-prone coastal states.

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