India's First Long-Span Unbonded Post-Tensioned RC-UHPC Composite I-Beams

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Abstract

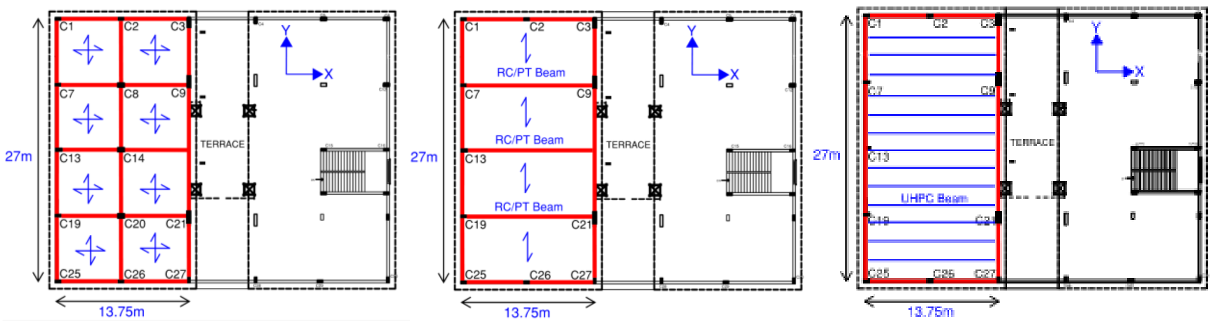
With ultra-high mechanical and durability characteristics, Ultra High-Performance Concrete (UHPC) offers structural solutions that compares well with structural steel. This paper illustrates the application of UHPC in a school building project where the functionality of the floor was altered from a set of classrooms to an auditorium at the top floor during the construction stage. The change required intermediate columns to be eliminated at the top floor of the three-story structure, thus increasing the span length from 6.875 m (22.1 ft) to 13.75 m (45.1 ft). A conventional long-span reinforced concrete (RC) or post-tensioned beam resulted in significant dead weight addition to the peripheral columns while also making them appear bulky Unbonded post-tensioned UHPC I-beams designed as composite with the RC-slab provided an apt solution to the project. The UHPC was prepared on-site using a dry premix and the beams were precast on-site and post-tensioned at the ground level with unbonded strands. The UHPC beams were erected in place using a crane after which the RC slab was cast-in-place. The design resulted in about 30 percent lighter floor system as compared to the original framing with the 6.875 m (22.1 ft) span. This led to a reduction in forces at the peripheral columns of the top floor level. This paper describes the design and construction process of the RC-UHPC composite floor system using India's first long-span UHPC I-beams.

Keywords: UHPC, UHPFRC, Beams, Long-Span, Precast, Unbonded Post-tensioned.

1. Project Overview

The project is a skill development and training institute located 75km (47 miles) north of Mumbai city in India. The structure is a three-story lecture hall complex having a set of classrooms. However, as the construction progressed, the clients realized that a large-sized auditorium at the topmost floor should be accommodated. The original framing plan consisted of a system of Reinforced Concrete (RC) beams, periphery columns, and interior columns as shown in Figure

1(a). Typical interior RC beams were 300 mm (11.8 in.) wide and 750mm (29.5 in.) deep and the RC slab was 175mm (6.89 in.) thick assuming a two-way load distribution



(a) (b) (c)

Figure 1. Topmost floor framing plan (a) Original framing plan with interior columns (b) Floor structural system option with 13.75m (45.1 ft) span RC or PT beams and no interior columns (c) Floor structural system with UHPC beams and no interior columns. (1 m = 3.28 ft)

The change in functionality of the floor system required elimination of the interior columns as shown in Figure 1(b). This led to doubling the span of the RC beams spanning along the X-direction. The easiest solution would be to provide a system of deeper RC beams or post-tensioned (PT) concrete beams with a 250 mm (9.8 in.) thick one-way slab as shown in Figure 1(b). However, this change added significant dead weight to the floor system and the peripheral columns. The additional load on the already constructed periphery columns pushed them outside their safe strength envelope at the ground floor level, thus requiring them to be strengthened by jacketing. However, the same was not acceptable to the clients. The second solution would have been to go with closely spaced open-web steel trusses or joists along with a composite deck slab, which meant adding another agency during construction, while also adding to the project timeline.

UHPC was just making inroads into India and so a long span post-tensioned UHPC I-girders was proposed as a viable alternative. These beams were suggested to be precast-on-site and erected in place. A set of lightweight UHPC I-beams equally spaced as shown in Figure 1(c) and compositely connected with a 100mm (3.94 in.) thick RC slab helped achieve a 40% and 35% lighter floor system than RC beam and PT beam option, respectively. Moreover, the proposed system with UHPC was 30% lighter than the original floor system with interior columns. The dead weight reduction of the floor system helped in reducing the gravity loads and seismic forces in the structural system bringing them well within the strength envelope. More details on this floor system is discussed in subsequent sections.

2. Structural Design

The 13.75m (45.1 ft) span UHPC beam is analyzed and designed as simply supported at both the ends. Thirteen such UHPC beams were placed at a spacing of 1.875m (6.15 ft) center-to-center. These post-tensioned beams were compositely connected with 100mm (3.94 in.) thick cast-in-place RC Slab. The subsequent sections discuss the design of these unbonded post-tensioned composite beams.

2.1. Design Loads, Reinforcement and Geometry

The UHPC beam is designed to resist flexure and shear demands at the critical sections. The unfactored bending moment at mid-span and the shear force at an effective depth, d_p located at 822mm (32.4 in.) from the center of the support is reported for each load case in Table 1.

Table 1 Bending moment and shear forces at critical locations at service load.

Load type	Bending moment at mid-span kN-m (kip-ft)	Shear force at critical shear section kN (kips)
Girder Self-Weight	73 (53.8)	19 (4.3)
RC Slab	111 (81.9)	28 (6.3)
Superimposed Dead Load (SDL)	66 (48.7)	17 (3.8)
Live Load (LL)	133 (98.1)	34 (7.6)

The proposed UHPC beam section with dimensions is illustrated in Figure 2. The beam has a unit weight of 3.1 kN/m (0.21 kips/ft).and is post-tensioned with three straight unbonded 7-wire strands of 12.7 mm (0.5 in.) diameter placed longitudinally in the bottom flange. The strands are positioned at a center-to-center spacing of 150mm (5.9 in.) and with a minimum clear cover of 35mm (1.38 in.). The beam is also reinforced with 4 reinforcing bars of 12mm (0.47 in.) diameter in the bottom flange. The center-to-center spacing, and minimum clear cover of the rebar is like that of the unbonded strands. The centroid of the strands as well as rebar is located at 53mm from the bottommost fiber of the girder section (Refer Figure 2).

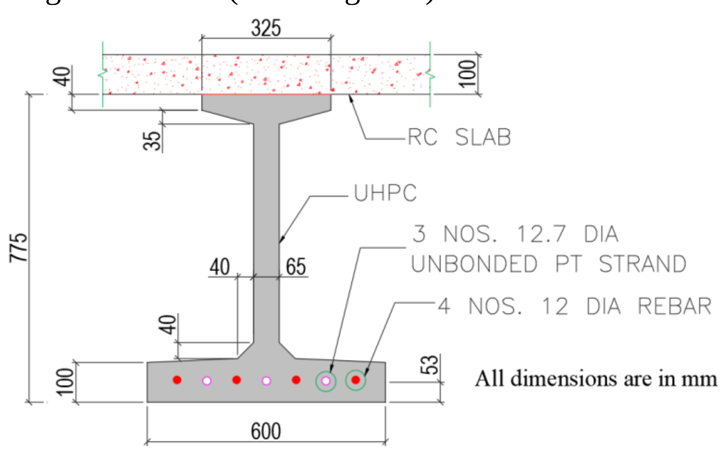


Figure 2 Cross-section geometry of the proposed unbonded post-tensioned UHPC beam section compositely connected with RC deck slab (1 in. = 25.4mm)

2.2. Material Models

2.2.1. UHPC

The characteristic value of compressive strength of UHPC at 28 days is taken as 150 MPa (21.8 ksi) with modulus of elasticity, E_U as 48 GPa (6962 ksi). An elastic-plastic stress strain model as recommended by the French design standard (NF P 18-710, 2016) is adopted to get the design stress-strain response of UHPC in compression (shown in Figure 3(a)). The ultimate compressive strength is factored per guidelines of (NF P 18-710, 2016) to get design compressive strength, f_{cd} as 85 MPa (12.3 ksi). The strain at peak strength is taken as 0.0032.

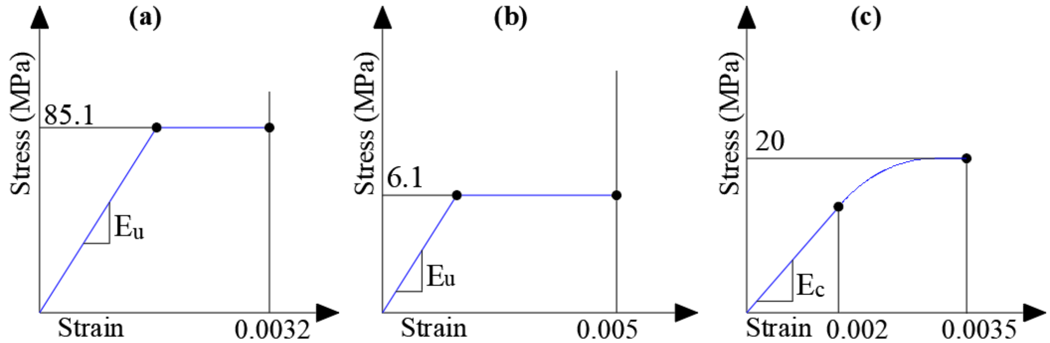


Figure 3 Stress-strain design curve for (a) UHPC in compression, (b) UHPC in tension, and (c) RC slab concrete in compression (1 MPa = 0.145 ksi)

The design value of elastic and ultimate tensile strength of UHPC at 28 days is taken as 6.1 MPa (0.89 ksi) with a crack localization strain of 0.005 (Refer SIA 2052, 2016) shown in Figure 3(b). The UHPC creep coefficient, $\varphi_u(t, t_0)$ at t^{th} day due to a load applied at time, t_0 and shrinkage strain value, $\varepsilon_u(t)$ at t^{th} day for UHPC is calculated using provisions from the Swiss design standard (SIA 2052, 2016). The ultimate shrinkage strain value is taken as 0.075%. The Figure 4 shows creep coefficient and shrinkage strain for UHPC at 4th, 28th, and 1825th day. The elastic moduli, E_U for UHPC at 4th, 28th, and 1825th day is taken as 35, 45, and 48 GPa (5076, 6527, and 6962 ksi).

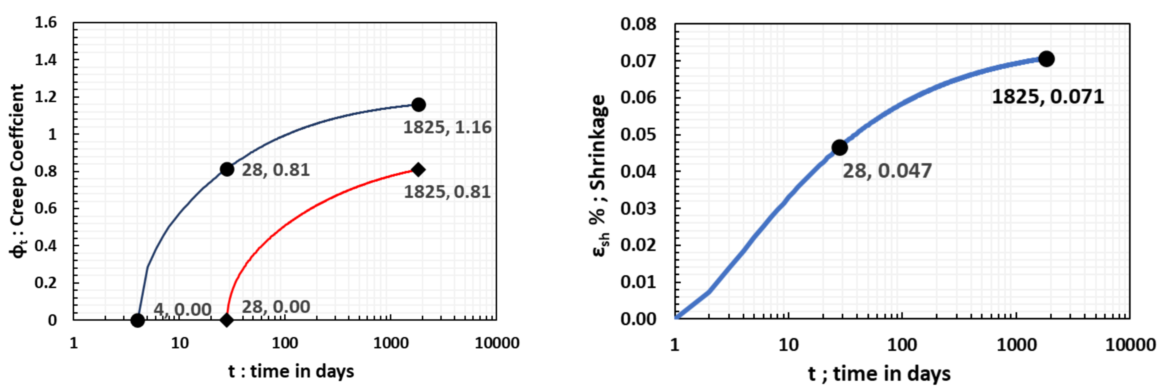


Figure 4 Creep and Shrinkage curve for UHPC as per Swiss recommendations (2016)

2.2.2. Conventional Concrete (RC Slab), Prestressing Steel, and Reinforcement Steel

The characteristic compressive strength of conventional concrete, f_{ck} is taken as 45 MPa (6.5 ksi). The allowable stress is 0.45 f_{ck}, which is 20 MPa (2.9 ksi) in compression. The stress-strain curve in compression is shown in Figure 3(c) with crushing strain taken as 0.0035. The creep and shrinkage parameters at each age is determined from Indian standard code (IS 456, 2000). The elastic moduli, E_C for concrete at 4th, 28th, and 1825th day is taken as 20.8, 24.6, and 27.4 GPa (3017, 3568, and 3974 ksi).

The 7-ply steel prestressing strand with ultimate strength, f_{pu} of 1860 MPa (270 ksi). The modulus of elasticity, E_P is 195 GPa (28,282 ksi) and a rupture strain limit of 0.035 (as per IS 1343, 2012). The relaxation coefficient is taken as 0.13 for the strands. An elastic-plastic stress strain model for reinforcement steel (Fe 500) with yield strength, f_{sy} of 500 MPa (72.5 ksi) with a safe value of $0.87\ f_{sy}$, which is 435 MPa (63.1 ksi) is considered with 0.2% proof strain (Refer IS 456, 2000). The modulus of elasticity for reinforcement steel, E_S is taken as 200 GPa (29,000 ksi).

2.3. Service Level Analysis

The UHPC beam is analyzed for service loads in four steps. The load applied and section type at each step is summarized in Table 2. The prestressing force along with the self-weight of girder is applied in the first step on the 4th day. The RC slab dead weight is applied in the second step on the 28th day. The section is assumed to remain non-composite up to the second step. The SDL and LL are applied in the third and fourth step. For the purpose of creep and shrinkage calculations, the third and fourth step are both applied on the 28th day. However, the section is assumed to be composite at these steps. The loading age for long-term deflection is assumed at 1825 days (5 years). The corresponding creep coefficients, shrinkage strain, and elastic modulus at each loading age for all materials are reported in section 2.2 of this paper.

Table 2 Details of each step with associated loads and section type for service analysis

Step #	**Load Applied**	**Section Type**
Step 1	Prestressing Force + Girder Self-Weight	Girder only
Step 2	Prestressing Force + Girder Self-Weight + RC Slab Placement	Girder only
Step 3	Prestressing Force + Girder Self-Weight + RC Slab + SDL	Girder + RC Slab Composite
Step 4	LL only	Girder + RC Slab Composite

The stepwise service load analysis is performed through an in-house developed program on MATLAB®. The program incorporates the instantaneous and time-dependent effects of creep and shrinkage of UHPC, RC Slab, and the relaxation of steel strands. The program also calculates stresses and deflection considering instantaneous and long-term effects at a given step. The calculated stresses at the mid-span section for each step are illustrated in Figure 5. A positive value indicates tensile stress and vice versa. The effective flange width in the composite section is taken as 1665mm (65.6 in.). The tensile stress at the bottommost fiber of the composite section is limited to 4.1 MPa (0.59 ksi) and the compressive stress in the topmost fiber of the RC deck slab is limited to 2.3 MPa (0.33 ksi). The stress diagram at the end section at the prestress force transfer step is also shown. The prestressing force transferred at this step is 75% of the ultimate tensile strength of the strand resulting in a total prestressing force of 410 kN (92.3 kips). The tensile stress at the topmost fiber in UHPC beam is limited to 1.2 MPa (0.17 ksi). The instantaneous and long-term deflections after Step 4 load is limited to 8.9mm (0.35 in.), lower than allowable deflection limit of 20mm (0.79 in.).

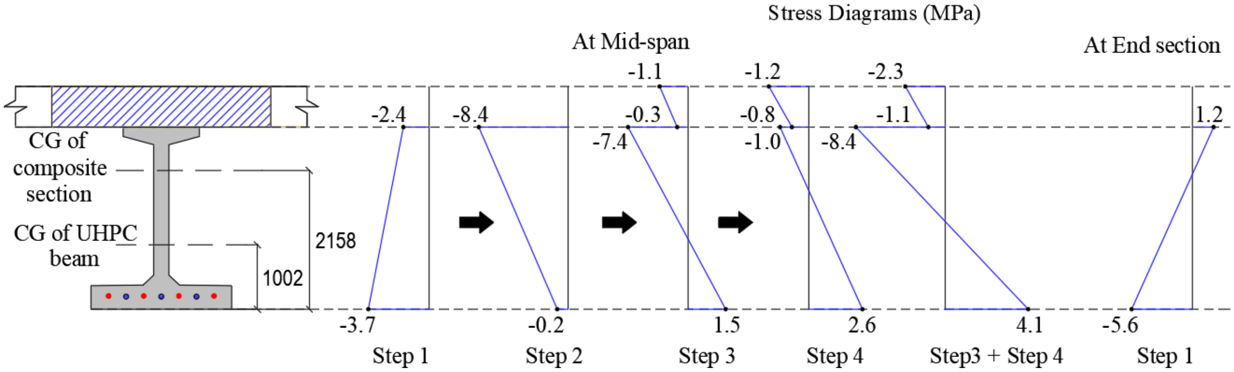


Figure 5 Stress diagram at the mid-span section for service load at each analysis step and at the end section for the first step. All dimensions are in mm. (1 in. = 25.4mm) and (1 MPa = 0.145 ksi)

2.4. Strength Limit State

The total factored bending moment at the mid-span is 575 kN-m (424 kip-ft) calculated using the strength load combination (as per IS 456, 2000). The nominal flexural moment capacity of the UHPC Girder-RC Slab composite is determined through an in-house developed design tool on MATLAB® based on strain compatibility approach. The flexural failure mode assumes that the extreme tension fiber of the UHPC girder reaches the crack localization strain of 0.005. Figure 6 illustrates the strain and stress diagrams for the assumed failure mode. The neutral axis is calculated to be at a depth of 150mm (6 in.) from the extreme compression fiber of the RC Slab. The unbonded strands do not maintain strain compatibility with the surrounding UHPC. The stress in the unbonded strands at limit state is calculated per the ACI 318-14 and is equal to 1290 MPa (187.1 ksi). The resulting ultimate flexural capacity is 975 kN-m (719.1 kip-ft), which is greater than the factored bending moment demand.

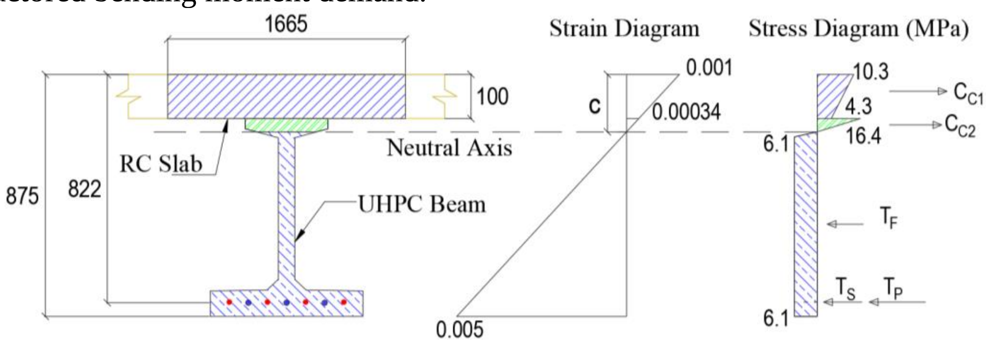


Figure 6 Strain and Stress diagram of the composite section at ultimate state. All dimensions are in mm. (1 in. = 25.4mm) and (1 MPa = 0.145 ksi)

The shear design is based on Swiss design standard (SIA 2052, 2016). This approach is based on the principal tensile stress field caused by diagonal tension force in the web of the girder. The total shear resistance is the superposition of individual contribution of shear resistance of fibrous

UHPC and shear resistance of the reinforcement. The distance between extreme compression fiber of the composite section and the centroid of the prestressing strand (effective depth), d_v of the web is 822 mm (32.4 in.), distance between the resultant of compressive and tensile forces (lever arm), z is taken as 740mm (29.1 in.), and web thickness, b_w is 65mm (2.56 in.). The angle of inclination, α of the diagonal compressive stress is taken as 30° (Refer SIA 2052, 2016). The applied ultimate shear force at the critical section is 147 kN (33.1 kips) based on the strength load combination. Considering design elastic tensile strength and ultimate tensile strength of UHPC as 6.1 MPa (0.89 kips), the shear resistance contribution of fibrous UHPC is 508 kN (114.3 kips), which is much greater than the expected shear demand. Also, an additional longitudinal tensile force, F_{tVd} is generated at the effective depth location due to compressive and tensile stress field in the web. This additional force is resisted by the longitudinal reinforcement provided in the bottom flange.

The reinforcement required for shear transfer at the interface of the UHPC beam and RC slab is designed as per the shear friction concept from the PCI design handbook, 2010. The interface design shear force was calculated as 1216 kN (273.5 kips). A roughened surface was assumed at the interface to use shear friction coefficient, μ_e of 1.0. 12mm diameter reinforcement was provided at a spacing of 300mm (11.8 in.) center-to-center to resist the interface shear force throughout the beam length.

3. Construction Methodology

The proprietary UHPC dry premix was transported to the site in jumbo bags. The steel fibers volume was 2% and the fiber size was 0.2mm x 13mm (7.9 mils x 0.51 in.) long having a 2600 MPa (377.1 ksi) ultimate strength. Polypropylene (PP) fibers dosage of 1.8 kg/m^3 was also used. The UHPC dry premix with crushed ice and the fibers were mixed in a high energy planetary mixer on site. The ambient temperatures during the beam casting ranged between 35 to 40 °C (95 to 104 °F). The wet mix UHPC was poured into the steel formwork using buckets. The side plates of the formwork were released after 16 hours from the end of casting. Thereafter, the beam was cured with water for 7 days and wrapped with moist hessian cloth along with polyethene sheets. A single beam was cast each day and a total of six 100 mm cubes were cast each day to get the 28-day compressive strength data. The UHPC produced on-site achieved a median compressive strength of 165.6 (24.0 ksi) MPa and with a standard deviation of 12.6 MPa (1.83 ksi). Figure 7 shows the entire construction process.

The beams were post-tensioned after 15 days from casting the last beam at the ground level prior to erection. The strands were stressed using a mono-strand jack and an average uplift of about 2mm (0.08 in.) was recorded at the beam mid-span immediately after prestressing. The observed strand elongation on-site was at par with the theoretical values. A single stressing pocket was formed during the casting of beam using a suitable pocket former. The anchorage system consisted of cold galvanized mono-strand barrel anchors and steel plates. This helped in preventing immediate rusting of the anchorage system. For further protection after stressing and cutting the strands, the stressing pocket was filled with UHPC which acted as a novel method of encapsulating the anchors. The beams were then lifted to the required height using a 40 MT (44.1 tons) capacity mobile crane. The lifting points were located at one-third points from either end of the beam. It took 6 hours to erect all the beams in place. Thereafter, the RC slab was cast-in-place.

Figure 7 Pictures from site showing the different steps during UHPC beam casting, post-tensioning and erection (With permission from UHPC India Pvt. Ltd., Mumbai (India))

4. Conclusion

This paper presents a way in which use of UHPC brought advantage to clients in accommodating an auditorium at the topmost floor of a building during its construction. The 13.75m (45.1 ft) span RC-UHPC composite beam with unbonded post-tensioning helped in removal of interior columns and reducing the dead weight of the floor system by about 30%. This paper illustrated the design and construction process of India's first commercially produced UHPC beams. These beams were cast-on-site. The wet mix production of UHPC on-site was achieved with superior quality control. The fabrication and erection of UHPC beams was carried out successfully.

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