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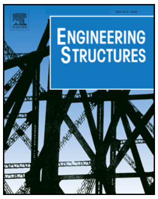

Feasibility of using ultra-high ductility cementitious composites for concrete structures without steel rebar

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ABSTRACT

To verify the feasibility of using the ultra-high ductility cementitious composites (UHDCC) for construction without steel reinforcement, the mechanical properties of UHDCC was experimentally tested at material, structural member and structure levels. The tensile strength of UHDCC was from 5 MPa to 20 MPa, the average tensile strain capacity was 8% with the maximum value up to 12%. Four-point bending tests demonstrated that the plain UHDCC beams can match the loading capacity of conventional reinforced concrete beams with the steel reinforcement ratio of 0.5–1.5%. The deflection-span ratio of all the plain UHDCC beams exceeded 1/50 at the peak load. The eccentric compressive loading tests showed that the loading capacity of plain UHDCC column was close to that of RC column with a steel ratio of 0.8%. Additionally, shaking table tests were implemented on a RC frame (steel reinforcement ratios of columns were about 2.0%) and a plain UHDCC frame. The UHDCC frame survived 3 kinds of earthquakes with the peak ground acceleration from 0.105 g to 1.178 g, and exhibited excellent inter-story drift control under extremely strong earthquakes. The performance of the UHDCC frame fulfilled the requirements of various seismic codes. The feasibility of non-steel reinforced UHDCC structure was preliminarily confirmed by this study.

1. Introduction

Concrete is known as a brittle material with strong compressive strength but weak tensile strength. Cracks develop whenever the tensile stress, induced by loads, restrained shrinkage, or temperature changes exceeds the tensile strength of the concrete. Therefore concrete, in most cases, has to collaborate with steel reinforcement in practical engineering. Due to the high strength and excellent tensile ductility of the steel reinforcement, well-designed RC structures are expected of sufficient reliability in their service lives. Nevertheless, the brittle failures of concrete infrastructures still occurred under extreme loadings, such as earthquakes, explosions and sustained vibrations. Apart from the safety concerns, there are also economic and environmental considerations associated with concrete infrastructure deterioration under normal service conditions [1]. The current practice of repeatedly repairing concrete structures due to cracks, surface spalling and steel corrosion is definitely costly and unsustainable. How to effectively enhance the performance of concrete used in infrastructure constructions has become a great challenge for the engineers all over the world.

Furthermore, there is an increasing demand for more ductile concrete in the perspective of future construction. Due to the global ageing population, the shortage of labor force is becoming an urgent issue to construction industries. Numerous researchers tried to solve the problem by developing the so called “automated construction”, e.g. building 3D printing [2]. In recent years, 3D printing has been adopted by construction industries as an additive construction [2]. Due to its low price, controllable fluidity and good compressive strength, the cementitious mortar (concrete) is widely used as a printable material. However, the natural brittleness of concrete disqualified it to be an ideal material for structure without steel reinforcement. Therefore, after printing, workers have to install steel reinforcements into the printed cavities and fill it with normal concrete for the sake of structural safety, as shown in Fig. 1. To some extent, the application of automated construction is limited due to the absence of appropriate material.

The above-mentioned problems may be solved if the brittleness of concrete is overcome. It is envisaged that once concrete has the “steel like” tensile ductility, the brittle failures of concrete under extreme loadings may be eliminated, thus enhancing the reliability of RC structures; once plain concrete has sufficient ductility and strength, a true sense of automated concrete construction could be achieved, thus helping to alleviate the shortage of labor, and once steel reinforcement

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a) Contour printing   b) Post-installed steel reinforcements and concrete

Fig. 1. Contour crafting technology at present.

Table 1
Mixture proportions for producing different UHDCCs (kg/m^3).

Mixture ID	Silicon Sand	Cement	Fly ash-1	Fly ash-2	GGBFS	SF	Tap water	HRWR
UHDCC-A (UA)	601	936	201	–	–	–	361	4.2
UHDCC-B (UB)	474	592		711			413	5.0
UHDCC-C (UC)	700	500	–		650	150	230	25

is excluded from concrete, the global puzzle “steel corrosion” should never be a problem, thus the durability and sustainability of concrete structure will be significantly improved.

In the past several decades, significant effort has been expended to improve the properties of concrete. Numerous researchers studied the fiber reinforced concrete (FRC) and proved that adding discontinuous short fibers to cementitious matrix has notable effect on the mechanical properties of concrete, in terms of toughness, ductility and energy absorbing capacity under impact [3,4]. In particular, engineered cementitious composites (ECC, also named as strain hardening cementitious composites) emerged as an improved category of concrete with multiple cracking, strain hardening behavior and high tensile ductility. The normal ECC has a tensile strain capacity (strain at the peak tensile stress) ranging from 3% to 5% and a tensile strength ranging from 3 MPa to 7 MPa [5]. However, despite ECC has a superior tensile strain capacity among all the cementitious materials, its ductility is still insufficient to ensure it a structural material free from steel reinforcement, especially under extreme conditions. According to the ISO code [6], the elongation of steel bar used in the concrete structures (ductility class C) should be more than 7% and 15% corresponding to the peak force and at the fracture point, respectively. Moreover, the tensile strain capacity of steel bar is required to be more than 9% in the codes for seismic design of buildings, e.g., the EN 1998-1:2004 [7]. At present, most of the existing FRCs have the tensile strain capacity far below that of steel reinforcement. Therefore, when a steel reinforced FRC structure is subjected to extreme loadings, steel reinforcement may sustain its contribution, but FRC probably fails in tension.

In recent years, a new kind of ECC with higher tensile ductility is developed, of which the tensile strain capacity ranges from 8% to 12% [8–11], the uniaxial tensile strength ranges from 4 MPa to 20 MPa, and the compressive strength ranges from 20 MPa to 120 MPa. For the first time, a cementitious material has a comparable ductility to steel reinforcement. Considering its excellent ductility, this material was named as the ultra-high ductility cementitious composites (UHDCC).

Theoretically, the ductility and strength of UHDCC promises itself a structural material independent from steel reinforcement. However, the safety of plain UHDCC structure has never been verified before, especially at the structure scale. On the other hand, a variety of standards and codes were issued to specify the mechanical performances from material to structure system to ensure the safety of practical engineering. Therefore, in the following sections, a series of experiments were carried out at three scales, i.e., material scale, structural member scale and structure scale to verify the feasibility of using UHDCC for construction without steel reinforcement. Based on the test results, a comprehensive assessment about the feasibility of non-steel reinforced UHDCC structure is evaluated according to the specific requirements in present standards and codes.

2. Material design

Three mixture proportions were used to produce UHDCCs with different mechanical properties. The detailed mixture proportions are presented in Table 1. Among three composites, UHDCC-A, in short UA, was designed for the normal demands in engineering practice. The high volume fraction of cement and the low volume fraction of fly ash in UA tailored the moderate compressive strength but high tensile ductility. UHDCC-B, in short UB, was used to cast a 1/4 scaled frame for shaking table test. To satisfy the similarity principle in shaking table test, the elastic modulus of UB was reduced to 37% of the prototype material. UB included more fly ash and had a water/binder ratio up to 0.32. In the mixture of UHDCC-C, in short UC, GGBFS and SF took place of fly ash. The water/binder ratio was reduced to 0.18 and water/cement to 0.46. UC was designed to achieve a new type of concrete with both ultra-high strength and ultra-high ductility. High-range water-reducing (HRWR) was used to achieve the proper rheology and ensure the uniformity of fiber dispersion.

Ultra-high molecular weight polyethylene (UHMWPE, PE for short) fibers were used as reinforcement material in all three mixtures. The volume fraction of PE fiber was uniformly 2%. The geometric and mechanical properties of PE fiber provided by manufacture are given in Table 2.

3. Specimen scheme and test methods

The test scheme is listed in Table 3. The tests at material scale included uniaxial tensile test and uniaxial compressive test; the tests at structural member scale included four-point bending tests on plain UHDCC beams and eccentrically loading tests on plain UHDCC columns. In particular, shaking table tests were conducted on a UHDCC frame and an RC frame to comparatively study the seismic performance of plain UHDCC building under extremely strong earthquakes.

Table 2
Properties of PE fiber.

Fiber category	Diameter (μm)	Strength (GPa)	Elastic modulus (GPa)	Rupture elongation (%)	Density (g/cm^3)
PE	24	2.9	116	2.6	0.97