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Shear performance of prestressed ultra high strength concrete encased steel beams

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HIGHLIGHTS

- Encasing structural steel improves the shear performance of PUHC beam significantly.
- The height of diagonal cracks is restricted to the upper flange of structural steel.
- The post-cracking stiffness decreases slightly due to structural steel contribution.
- Structural steel prevent the instantaneous failure and keep load descending stably.
- The shear ductility is efficiently improved to an average increase of 2.13 times.

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ABSTRACT

Due to the high compressive strength and durability properties of ultra high strength concrete, prestressed ultra high strength concrete beam was used extensively in bridge engineering, but it possessed obvious brittle behavior. Encasing structural steel into it was a good way for alleviating the problem of brittleness. The purpose of this study was to investigate shear performance of prestressed ultra high strength concrete encased steel beams. A total of fifteen prestressed ultra high strength concrete encased steel beams and seven prestressed ultra high strength concrete beams were tested to shear failure under simply supported three-point loading conditions. The primary variables of this investigation included the presence or not of structural steel, shear span-depth ratio, degree of prestress, ratio of stirrup and thickness of web. The shear performance was evaluated based on cracking pattern, load–deflection behavior and shear ductility. Test results showed that prestressed ultra high strength concrete encased steel beams had higher residual shear capacity and post-cracking stiffness as well as by far better shear ductility than prestressed ultra high strength concrete beams. In addition, influence of experimental parameters on the shear performance of prestressed ultra high strength concrete encased steel beams and prestressed ultra high strength concrete beams also was discussed and compared, respectively.

1. Introduction

Prestressed concrete (PC) members have been used in building structures and infrastructure facilities since the 1960s because of their various advantages such as high quality, durable aesthetics, reduced time span of construction and economic efficiency. In particular, prestressed concrete technology has been advanced by the technical growth of ultra high strength concrete manufacture from the development of various admixture agencies. In general, it defines ultra high strength concrete with 28-day uniaxial compressive strength as determined by a standard 150 mm × 150 mm test specimens in excess of 100 MPa [1]. In comparison to ordinary strength concrete, ultra high strength concrete exhibits superior compressive and tensile mechanical behaviors, as well as exceptional durability properties [2]. Hence, the use of ultra high strength concrete has become in prestressed cross-sea bridge and prestressed concrete offshore platforms. Up to now, there also are a few studies about flexural and shear performance of prestressed ultra high strength concrete (PUHC) beams [3–5]. Furthermore, studies showed that PUHC beams had higher strength and smaller crack width than prestressed ordinary strength concrete beams. Studies also reported that PUHC beams exhibited higher stiffness, due to ultra high strength concrete having much greater elastic modulus. However, Yao et al. [6] found that PUHC beams had obvious brittle behavior in shear test. The lack of shear ductility results in sudden failure without warning in severe earthquakes, which is a serious drawback [7–9]. Thus, it is very necessary to improve the shear ductility of PUHC beams.

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One type of the structural members in the composite construction is the concrete encased structural steel, referred to as “steel-reinforced concrete (SRC) construction.” This type of composite member has been used in Japan for more than 4 decades [10], and has become increasingly popular in building constructions in Taiwan since the Ji-Ji earthquake in 1999 [11]. Because the encasement of structural steel in concrete columns or beams can greatly increase the strength, stiffness and energy absorption capacity of composite members, it has been a common way to improve the ductility of concrete members in seismic zone [12–20]. Therefore, encasing structural steel into PUHC beam could be also a way to alleviate the problem of brittleness on PUHC beams, due to the lack of shear ductility. Unfortunately, according to the literature search, no research results related to shear performance of prestressed ultra high strength concrete encased steel (PUHCES) beams. Hence, it is necessary that the test systematically investigates shear performance of PUHCES beams.

The experimental program described in this paper has two objectives: (1) present the results of an investigation comparing the shear performance of PUHCES beams to that of PUHC beams; (2) further investigate the influence of test variables on shear performance of PUHCES beams. To achieve two objectives, twenty-two test beams were tested in this study. Fifteen of test beams were PUHCES beams and the rest were PUHC beams. The experimental parameters included in the study were the presence or not of structural steel, shear span-depth ratio a/d, degree of prestress λ_p, ratio of stirrup ρ_{sv} and thickness of web t_w.

2. Experimental programs

2.1. Design of the test beams

Twenty-two test beams were made in this study. Fifteen of test beams were PUHCES beams, while the others were PUHC beams. The main experimental parameters considered in the study included the presence or not of structural steel, shear span–depth ratio a/d (1.5, 2.0 and 2.5), degree of prestress λ_p (0, 0.34 and 0.42), ratio of stirrup ρ_{sv} (0.22%, 0.32% and 0.42%) and thickness of web t_w (3.0 mm and 8.0 mm). All test beams with a dimension of B (width) × H (depth) × L (length) were 160 mm × 340 mm × (1200, 1400 and 1600) mm, were tested on a span of l_s 840 mm, 1120 mm and 1400 mm. The compressive strength of concrete was 108.2 MPa, which was determined by compression tests on 9 cubic specimens with each side dimension of 150 mm. Each beam had three longitudinal tensile bars of D 20 (diameter 20 mm) and two longitudinal compressive bars of D 18 (diameter 18 mm). Longitudinal tensile bars had 90° hooks at the test beam end to ensure adequate anchorage. The stirrups were symmetrically placed and stirrup of D 6.5 (diameter 6.5 mm). Two different cross section areas of prestressing strand, 139 mm^2 and 98.7 mm^2 were used. In order to reduce the prestress loss due to the short length of test beam, low shrinkage anchor and a technique of double jacking with the same prestressing forces were used (details of this technique were published in the literature [21]) in this study. The PUHCES beams had three different types of structural steel. To avoid the possible shear splitting failure along the interface between upper flange of structural steel and ultrahigh strength concrete, shear studs of 10 mm diameter × 55 mm height were welded on upper flange of structural steel. Table 1 shows the details of test beams. Fig. 1 shows the cross section of structural steel. Fig. 2 shows the cross section of test beams.

The degree of prestress λ_p is defined as the ratio of the force carried by the prestressing strand to the force carried by the total reinforcement at ultimate conditions [22], as shown in the following equation:

$$\lambda_p = (A_{ps}f_{ps})/(A_{ps}f_{ps} + A_s f_y) \tag{1}$$

where A_{ps} is the area of prestressing strand; A_s is the area of non-prestressed tensile reinforcement; f_{ps} is the yield stress of prestressing strand; and f_y is the yield stress of non-prestressed tensile reinforcement.

2.2. Material properties

In this test program, the concrete mixture was made with Portland cement type 52.5R, Class-I fly ash, silica fume, water, sand and coarse aggregate. To improve the workability, a polycarboxylic acid–based high-range water-reducing admixture (HRWRA) and D-Gluconic acid sodium salt (D-Gass), were added after extensive trials. Table 2 summarizes the mixture proportions for ultra high strength concrete employed in this test program. The yield stress f_y, ultimate stress f_u and modulus of elasticity E_s of structural steel are given in Table 3. Similarly, Table 4 presents f_y, f_u and E_s values of the longitudinal steel bar, stirrup bar and prestressing strand.

Table 1
Details of test beams.

Beam no.	a/d	t_w (mm)	λ_p	ρ_{sv} (%)	Structural steel	l_s (mm)
PUHCES-01	1.5	5.5	0.42	0.32	B1[a]	840
PUHCES-02	1.5	3.0	0.42	0.32	B2[b]	840
PUHCES-03	1.5	8.0	0.42	0.32	B3[c]	840
PUHCES-04	1.5	5.5	0.34	0.32	B1	840
PUHCES-05	1.5	5.5	0.00	0.32	B1	840
PUHCES-06	1.5	5.5	0.42	0.22	B1	840
PUHCES-07	1.5	5.5	0.42	0.42	B1	840
PUHCES-08	2.0	5.5	0.42	0.32	B1	1120
PUHCES-09	2.0	3.0	0.42	0.32	B2	1120
PUHCES-10	2.0	8.0	0.42	0.32	B3	1120
PUHCES-11	2.0	5.5	0.34	0.32	B1	1120
PUHCES-12	2.0	5.5	0.00	0.32	B1	1120
PUHCES-13	2.0	5.5	0.42	0.22	B1	1120
PUHCES-14	2.0	5.5	0.42	0.42	B1	1120
PUHCES-15	2.5	5.5	0.42	0.32	B1	1400
PUHC-01	1.5	–	0.42	0.22	–	840
PUHC-02	1.5	–	0.42	0.42	–	840
PUHC-03	1.5	–	0.42	0.32	–	840
PUHC-04	1.5	–	0.00	0.32	–	840
PUHC-05	2.0	–	0.42	0.32	–	1120
PUHC-06	2.5	–	0.42	0.32	–	1400
PUHC-07	1.5	–	0.34	0.32	–	840

[a] The dimension of welded steel plate $b \times h$ is 60 mm × 10 mm in lower flange of structural steel (the dimension of structural steel $d_s \times b_f \times t_w \times h_f' \times h_f$ is 140 mm × 80 mm × 5.5 mm × 9.1 mm × 9.1 mm).

[b] The dimension of structural steel $d_s \times b_f \times t_w \times h_f' \times h_f$ is 140 mm × 80 mm × 3.0 mm × 10 mm × 18 mm.

[c] The dimension of structural steel $d_s \times b_f \times t_w \times h_f' \times h_f$ is 140 mm × 80 mm × 8.0 mm × 10 mm × 18 mm.

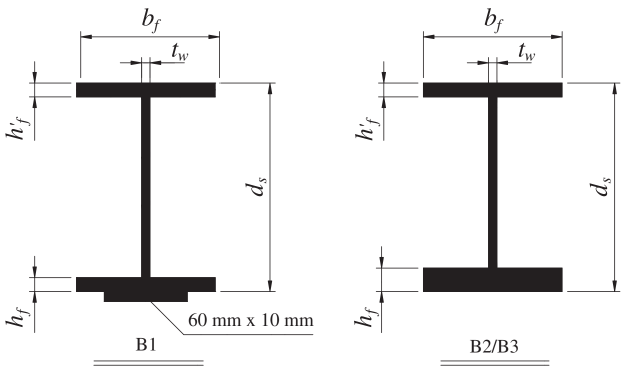

Fig. 1. Cross section of structural steel.

2.3. Measurement and test scheme

Monotonic loading was provided with a 10,000 kN hydraulic servo testing machine. A calibrated load cell was placed between the jack and test beam while linear variable differential transducers (LVDT) were properly installed to measure the displacements at the two supports and mid-span as well as the slip between upper flange of structural steel and ultra high strength concrete during the test, as shown in Fig. 3. Monotonic loading was applied step-by-step up to 85% of the expected ultimate load in a load control manner and then shifted to a displacement control method until the failure of test beam. The combination of the loading methods is to effectively perform the test, while obtaining a full history of failure behavior. The rate of displacement is 0.2 mm/min. An acquisition system automatically monitored load and displacements at pre-selected time intervals throughout the loading history. The test also provided information on the overall behavior of test beams including cracking pattern and crack width.

3. Results and discussions

3.1. Shear resistance of PUCHES beams

In PC beams, the prestressing strand contribution to the shear resistance of beam is generally derived from the dowel action V_{pf} [23,24]. As expressed in Eq. (2), the shear resisting force of PC