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SHEAR PERFORMANCE OF RC BEAMS STRENGTHENED WITH ULTRA-HIGH PERFORMANCE FIBRE REINFORCED CONCRETE (UHPFRC)

Xiangsheng LIU[1], Georgia THERMOU[2]

Abstract: *The damage caused by earthquakes over the years has demonstrated the vulnerability of existing structures to seismic excitations. Most of the reinforced concrete (RC) buildings built before the 1970s have several structural deficiencies mainly related to old-type detailing (e.g. sparse transverse reinforcement, insufficient lap splices and anchorage lengths) and ageing of materials due to aggressive environmental conditions. To increase the resilience of the existing building stock and protect human lives from catastrophic future earthquake events strengthening measures need to be adopted. Recent studies have demonstrated the advanced performance (i.e., high strength, durability, impact resistance and energy absorption) of Ultra-High Performance Fibre Reinforced Concrete (UHPFRC) as strengthening material.*

This study investigates experimentally the performance of shear critical beams strengthened with UHPFRC jackets. One the beams serves as the control specimen whereas two of beams are strengthened with 10 and 20mm UHPFRC jackets. Moreover, a novel hybrid system that comprises Ultra High Tensile Strength Steel (UHTSS) textiles embedded in UHPFRC jackets is applied to the rest of the beams. All beams are subjected to monotonic asymmetric three-point loading using a stiff steel reaction frame. Experimental evidence demonstrates that all strengthening systems are effective and could improve the shear strength. The knowledge gained from this experimental study makes UHPFRC and hybrid jackets a very promising strengthening method of shear critical RC beams.

Keywords: *Shear, Concrete, UHPFRC, strengthening, jacketing*

Introduction

Earthquakes are natural disasters that can cause significant damage to buildings, infrastructure, and loss of human lives. In January 2023, a catastrophic earthquake with a magnitude of 7.8 on the Richter scale struck Turkey and Syria, resulting in devastating consequences (50,399 deaths, 173,000 buildings collapsed, (Support to life, 2023)). Most of the reinforced concrete (RC) buildings constructed before the 1970s have structural deficiencies, mainly related to old-type detailing such as sparse transverse reinforcement, insufficient lap splices, and anchorage lengths, and ageing of materials due to aggressive environmental conditions (Bournas, 2018; Kam, Pampanin, & Elwood, 2011).

In response to the potential risks associated with earthquakes, strengthening measures need to be adopted to increase the resilience of the existing building stock and protect human lives from future earthquake events. Several techniques have been proposed and tested over the years, with Ultra-high Performance Fibre Reinforced Concrete (UHPFRC) emerging as a promising solution (Buttignol, Sousa, & Bittencourt, 2017). UHPFRC is a high-performance composite material that combines the benefits of traditional concrete with the addition of fine and dispersed fibres. It has excellent mechanical properties, including high strength, durability, impact resistance, and energy absorption (Buttignol et al., 2017; Ren, et al., 2021). These properties make UHPFRC an ideal material for strengthening beams as a jacketing device. Recent studies have demonstrated the advanced performance of UHPFRC as a strengthening material (Lampropoulos, et al., 2016; Mansour, Sakr, et al., 2021; Tanarslan, et al., 2017), however further research needs to be carried out.

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[1] PhD Candidate, Civil and Structural Engineering Department, The University of Nottingham, NG7 2RD, Nottingham, UK, evxxl17@nottingham.ac.uk

[2] Assistant Professor, Civil and Structural Engineering Department, The University of Nottingham, NG7 2RD, Nottingham, UK, georgia.thermou@nottingham.ac.uk

This study investigates the shear performance of RC beams strengthened with UHPFRC jackets, in which the concrete cover was removed for the whole length of the critical shear span and completely replaced by UHPFRC system. The experimental program includes in total five beams of the same geometry, with one serving as the control specimen, and the others strengthened using different UHPFRC jacketing configurations. Two beams were strengthened with 10 and 20mm UHPFRC jackets, whereas a hybrid jacket was applied to the other two beams, which comprises UHTSS textiles embedded in 20mm UHPFRC jackets. The UHTSS textiles used have two different densities: 4 cords/in (low density) and 8 cords/in (high density).

The results of the experimental study demonstrate that all strengthening systems are effective and can improve the shear strength of RC beams. The addition of UHTSS textiles further improved the performance of the UHPFRC jackets. The knowledge gained from this experimental study makes UHPFRC and hybrid jackets a very promising strengthening method of shear-critical RC beams and a viable solution for enhancing the seismic performance of existing structures.

Experimental Program

Specimen Details

The experimental investigation involved the testing of a set of five RC beams under three-point bending with a clear span to depth ratio of *a/d* = 2.0. The beams had a rectangular cross-sectional geometry, with a width of 102 mm, a height of 203 mm, and a length of 1677 mm, as illustrated in Figure 1. The effective span of each beam was 1100 mm, while the short shear span (a=350 mm) was designed to have no transverse reinforcement in the critical region to promote shear failure of the beams. A set of 8 mm diameter stirrups were placed at 140 mm intervals in the larger span to control the shear stress distribution. The tensile and compressive longitudinal reinforcement of the beams consisted of 2ø16 and 2ø10 bars, respectively.

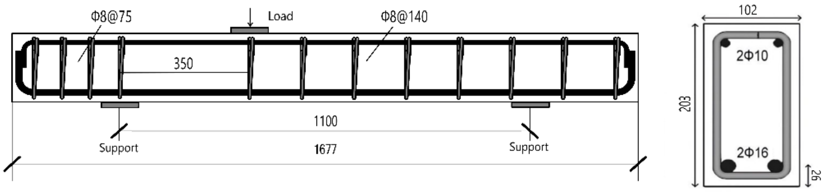

Figure 1. Geometry and reinforcement layout of the tested beams.

Table 1 provides a detailed summary of the tested beams, which were labelled as B-X-Y, in which "B" represents the beam. "X" corresponds to the beam jacketing configuration, where "C" indicates the control beam, "10" represents 10 mm UHPFRC jacketing, and "20" corresponds to 20 mm UHPFRC jacketing. "Y" represents the type of embedded textiles, with "L" and "H" denoting single-layered low- and high-density UHTSS textiles, respectively. For instance, B-20-H indicates a beam with a 20mm UHPFRC jacket embedded with high-density UHTSS textile.

Name	**Jacketing Type**	**Textile Type**
B-C	Control beam	-
B-10	10 mm UHPFRC	No textile
B-20	20 mm UHPFRC	No textile
B-20-L	20 mm UHPFRC	Low-density UHTSS textile
B-20-H	20 mm UHPFRC	High-density UHTSS textile

Table 1. Details of the tested beams.

The RC beams were supported using a pair of steel pedestals on the strong floor and anchored together with threaded rods to prevent span elongation resulting from the second-order horizontal reactions at the beam supports, as shown in Figure 2. Vertical loading was applied to the beams using a 500 kN capacity single-ended actuator with a displacement rate of 0.02 mm/s. The vertical displacement of the beams at the load application position was measured using an external linear.

Figure 2. Three-point bending test set-up.

Materials

The average cube compressive strength of the concrete at 28 days after casting was 22 MPa. The yield stresses for the longitudinal bars with diameters of 16 mm and 10 mm were 538 MPa and 527 MPa, respectively, while the yield stress of the 8 mm-diameter stirrups was 340 MPa.

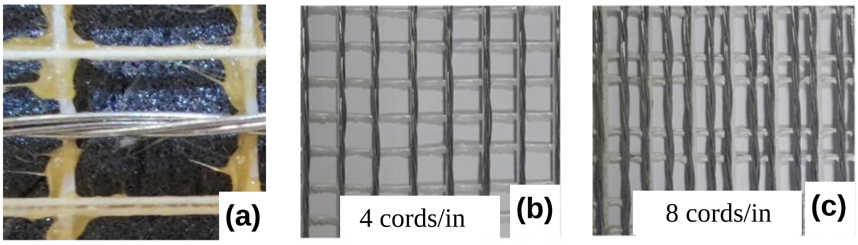

Figure 3. (a) 3x2 Cord; (b) Low-density UHTSS textile; (c) High-density UHTSS textile

In the UHPFRC system, steel fibres were incorporated into the Ultra-High Performance Concrete (UHPC) with a volume fraction of 1.66%. For the hybrid jackets, Ultra-High Tensile Strength Steel (UHTSS) textiles were utilised, consisting of galvanized unidirectional high strength steel 3×2 cords affixed to a fibreglass micromesh for effortless installation (see Figure 3a). Each cord was comprised of five twisted wires, three of which were straight filaments wrapped with two filaments at a high twist angle. The fibreglass micromesh holds the cords in place without adding strength to the composite system (Thermou et al., 2019). Two densities of 1.57 (4 cords/in: low density) and 3.14 (8 cords/in: high density) cords/cm were used in this experimental study (see Figures 3b and c). The geometric and mechanical properties of UHPC are detailed in Table 2, while Table 3 summarises the properties of the UHTSS textiles, with all data sourced directly from the manufacturers.

	Mixture Density (kg/cm3)	f_{cm} **(MPa)**	f_f **(MPa)**	f_b **(MPa)**	E_f **(GPa)**
UHP	2270	110	14	2	34

Table 2. Properties of the UHPC used according to the manufacturer.

Textile	t_f **(mm)**	**Weigh (g/m2)**	A_c **(mm2)**	**Density (cords/in)**	f_{fu} **(MPa)**	E_f **(GPa)**	ε_{fu} **(%)**
Low density	0.084	670	0.538	4	3000	190	1.5
High density	0.169	1200	0.538	8	3000	190	1.5

Table 3. Properties of the UHTSS used according to the manufacturer.

Strengthening Procedure

All the beams except the control one were strengthened in the shear critical zone (a=350 mm). The cross-sectional details of the retrofitted beams are illustrated in Figure 4. Grooves with a depth equal to the cover thickness (10 mm) in the shear critical area of the retrofitted beams were created. The grooved surface was then roughened, cleaned, and water-saturated before the application of UHPFRC. In the case of hybrid jackets, two strips of UHTSS textile with a width of 300 mm and 50 mm were utilised for each layer, as the textile roll had a width of 300 mm. The UHTSS textiles were pre-bent to facilitate the jacketing process and placed directly on the surface of the beams within the critical zone. Next, the jacket's mould was out in place in the critical zone and the UHPFRC was poured. The mould was removed after two days, and the beams were covered with plastic film and cured until the time of testing. Figure 5 presents the basic steps of the hybrid jacketing application.

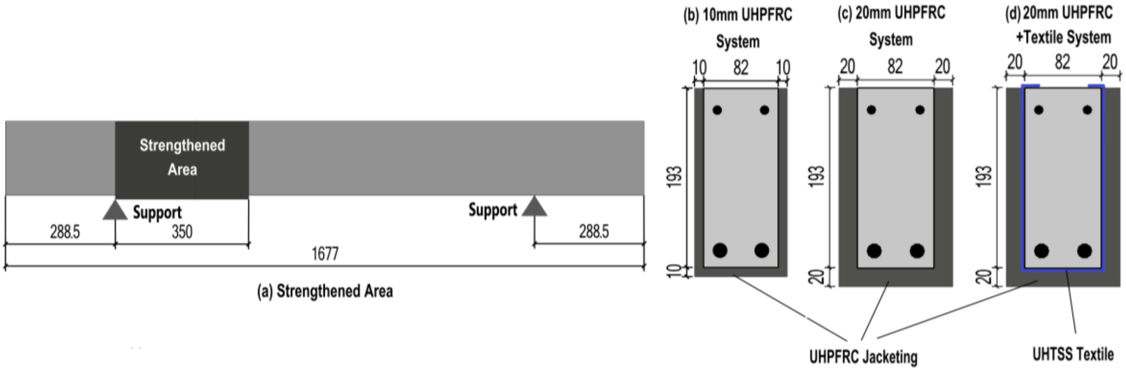

Figure 4. Strengthened area and jacketing configuration: (a) strengthened area; (b) B-10-P; (c) B-20-P; (d) B-20-L and B-20-H.

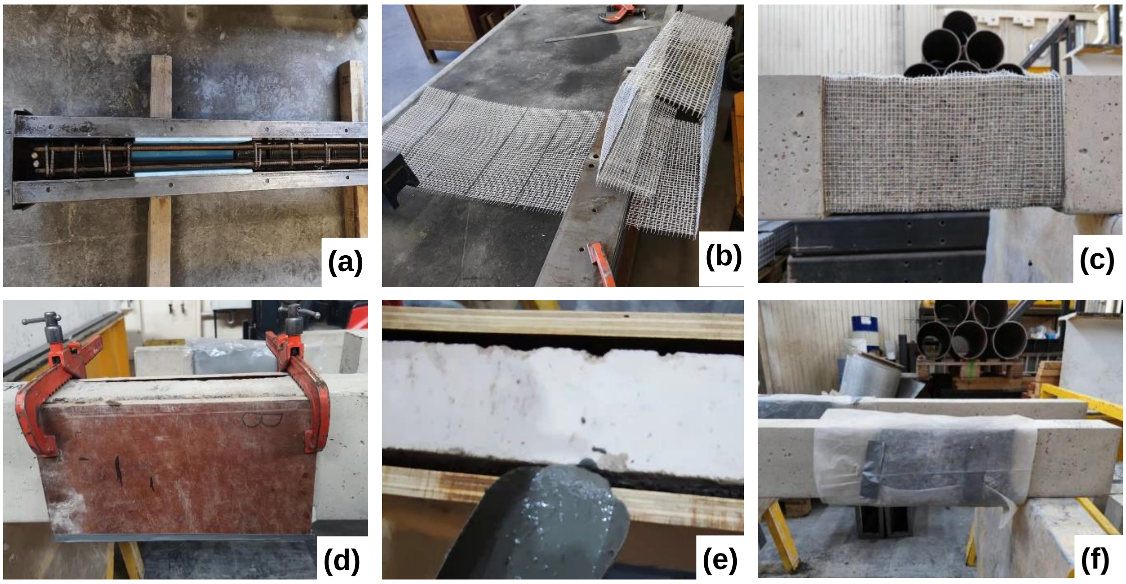

Figure 5. Steps of the hybrid jacketing application: (a) create a grooved beam; (b) prebend textiles; (c) roughen the surface in strengthened area and place the textiles; (d) fix the jacketing mould; (e) pour UHPFRC; (f) curing.

Experimental Results & Discussion

Table 4 presents a summary of the test results, which includes the concrete compressive strength of all beams on the test day (f_c), the peak load (P_{max}), the corresponding displacement (δ_{max}), the strength increase of the retrofitted beams ($\Delta P_{\max}$), the ultimate load (80% P_{max}=P_u) and the corresponding displacement (δ_u), and the failure mode (FM). Two failure modes were observed: shear failure (S) and shear-detachment failure (S-D). The shear failure is primarily caused by diagonal tension and fibre rupture, whereas the shear-detachment failure occurs due to detachment between the composite and beam substrate or within the jacket layer.

The experimental results revealed that the retrofitting system, consisting of UHPFRC and hybrid systems, can enhance the shear capacity of RC beams. Moreover, the introduction of UHTSS can further improve the shear performance of beams.

Beam	f_c **(MPa)**	P_{max} **(kN)**	ΔP_{max} **(%)**	P_u **(kN)**	δ_{max} **(mm)**	δ_u **(mm)**	**FM**
B-C	26.4	51.34	-	41.1	2.50	3.96	S
B-10	30.6	113.73	122	91.0	4.93	6.30	S-D
B-20	26.6	80.09	56	64.08	3.89	7.22	S-D
B-20-L	21.9	121.38	136	97.11	4.43	5.27	S-D
B-20-H	22.4	135.93	165	108.74	5.17	5.42	S-D

Table 4. Summary of test results.

Failure Modes

Figure 6 presents the condition of the beams at the end of the tests, where damage is localised in the shear critical region. The control beam, B-C, exhibited a typical diagonal tension failure in shear span joining the points of load application and support (see Figure 6a). As shown in Figures 6b-c, the UHPFRC-reinforced beams, B-10 and B-20 demonstrated similar failure modes, namely shear detachment failure with several diagonal shear cracks forming in the critical region. In theory, a larger space within a 20mm UHPFRC system can lead to a more uniform distribution of fibres, leading to better adhesion and ultimately improving its shear improving ability. However, despite the potential benefits of the 20mm jacket, early detachment was observed compared to B-10, which may be attributed to possible construction defects of the jacket.

Regarding beams that were strengthened using hybrid jackets (B-20-L and B-20-H), the benefits of a better fibre distribution brought about by the 20mm space were evident. Although both B-20-L and B-20-H exhibited detachment failure, the improved adhesion allowed the jacket to peel off a larger section of the beam's cover layer during detachment. In addition, the insertion of UHTSS textiles changed the stress transfer mechanism, resulting in cracks no longer penetrating the shear critical area on the surface of the UHPFRC jacket (Figure 6d-e). Furthermore, B-20-H showed fewer cracks than B-20-L because the denser textile provided stronger tensile capacity in the transverse direction, thereby helping to prevent the development of transverse damage.

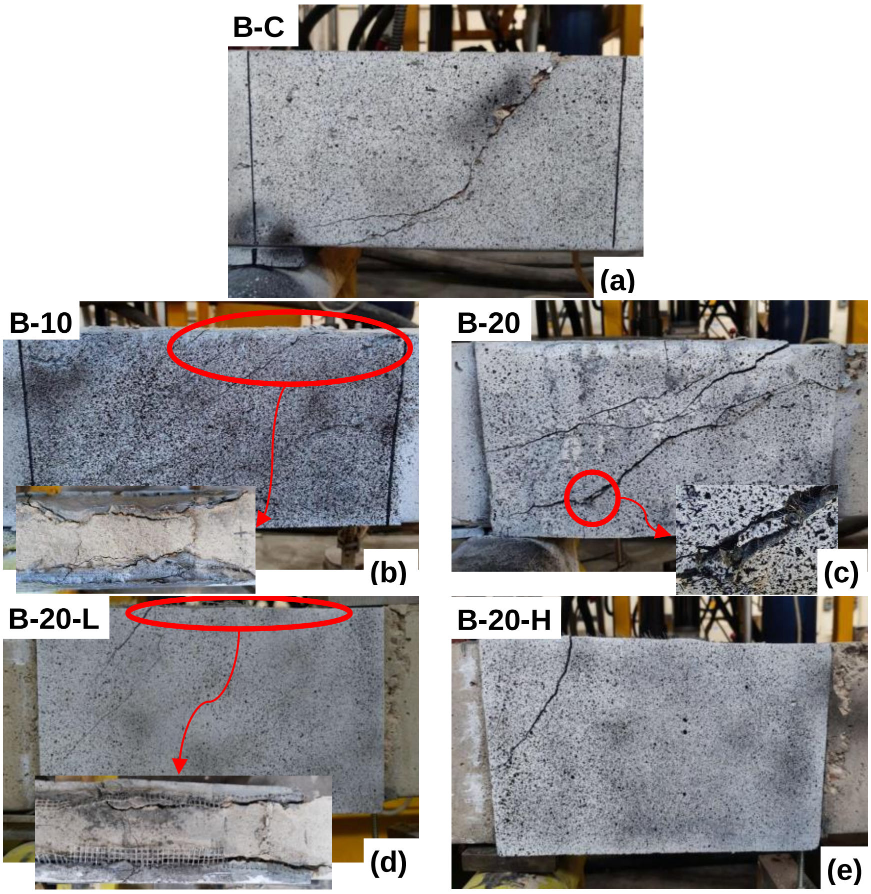

Figure 6. Crack patterns and failure modes.

Load-deflection Curves

Figure 7 displays the load-deflection curves of 5 tested beams all of which failed in shear. The control beam B-C reached a peak load of 51.34 kN with a corresponding displacement of 3.96 mm. Based on the experimental results, it can be concluded that the proposed strengthening systems have significantly improved the behaviour of the RC beams in shear.

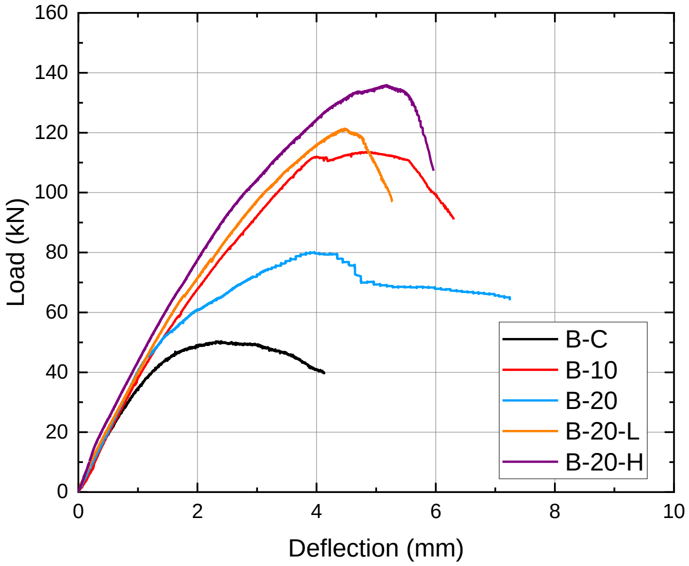

Figure 7. Load-deflection curves.

The 10 mm UHPFRC jacket increased the shear strength by 122%, whereas the 20 mm UHPFRC jacket increased it only by 56% (Table 4). The lower shear strength enhancement observed in B-20 beams may be attributed to defects in the construction of the jacket, which led to early detachment and failure. It is worth noting that although both B-10 and B-20 beams failed in shear, they demonstrated a pseudo-ductile behaviour and managed to maintain the peak load while the beam deformed. This could potentially be attributed to the "bridging effect" of the fibres which delayed crack propagation (Tian et al., 2021).

Regarding the performance of the hybrid system, beams B-20-L and B-20-H showed larger stiffness and shear enhancement capabilities, with 136% and 165% shear strength improvement, respectively. In addition, B-20-H had the best performance due to the introduction of high-density UHTSS textiles. The notable enhancement in hybrid jackets was attributed to the superior properties of the UHTSS textiles and the optimised distribution of the fibres within the 20mm space of the hybrid jackets. Specifically, the fibre distribution in the hybrid jackets enabled better adhesion and stress transfer, reducing the occurrence of diagonal shear cracks in the critical region, and improving overall shear lifting ability.

Conclusions

Due to poor seismic detailing, RC beams are often subjected to shear failure. This study investigated experimentally the effectiveness of UHPFRC and the proposed hybrid jacketing system in improving the performance of shear critical RC beams. The parameters studied included the thickness of the UHPFRC jacket (10 and 20 mm), and the presence or not of UHTSS textiles with density of 4 and 8 cords/in. 5 beams were tested in total, one of which served as the control, and the rest were retrofitted and tested under three-point bending after the application of different UHPFRC jacketing configurations. The main conclusions drawn from this study are as follows:

- All systems were effective in enhancing the strength capacity of shear deficient RC beams. The application of the 10mm UHPFRC jacket increased the strength capacity by 122%. In case of the hybrid UHPFRC jacketing system, when the high-density textile (8 cords/in) was embedded, the shear strength capacity increased by 165%.
- All strengthened beams failed due to shear-detachment. In both B-10 and B-20 diagonal shear cracks formed on the jacket's surface in the shear span. The hybrid jackets, B-20-L and B-20-H showed only minor cracks on one side, and larger parts of the concrete cover

were peeled off when detachment occurred. This was mainly due to the stress transfer and load-displacement response change brought by the addition of the UHTSS textile.

Generally, the research findings suggest that the UHPFRC and hybrid jacketing can be used as promising strengthening techniques for shear-deficient RC beams. Further investigations on the influence of UHPFRC thickness on the shear strength increase need to be carried out.

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