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Overlap length for confinement of carbon and glass FRP-jacketed concrete columns

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ABSTRACT

This paper presents the experimental results of a study on the occurrence of debonding along the overlap length of fiber reinforced polymer (FRP) confined concrete prior to rupture of the FRP jacket. Plain concrete cylinders, twenty-six with 152 mm diameter and 305 mm height, and four with 100 mm diameter and 200 mm height, with cylinder compressive concrete strength 19 MPa, were wrapped with carbon- and glass-FRP jackets and tested under monotonic axial compression. Different overlap configurations and different FRP application methods were investigated. The parameters found to most significantly affect the bond resistance along the overlap zone are the type of the FRP material and the curing age of the resin when dry lay-up application is used.

1. Introduction

The use of fiber reinforced polymer composites (FRP) is a method increasingly more often applied to enhance the structural behavior of concrete members. Strong point of the method is that it does not increase the cross-sectional area. Extensive research on the application of FRP-jackets for the retrofit of existing concrete columns over the past two decades has aimed at understanding of the ultimate performance of the confined concrete [1–11]. More recently, research has been undertaken regarding the potential application of FRP composites in new structures in the form of concrete-filled FRP tubes [12–13], including the use of high strength concrete [14–15]. Alternative non-resin-bonded FRP schemes for confinement have been tested, applying mortar plastering instead of resin [16], or no adhesive on the concrete surface [17–19], aiming at the reduction of material cost.

Considerable research has also been carried out on the important issue that rupture strains measured on FRP-jacketed specimens usually fall substantially lower than those reported from manufacturers, thus reducing the effectiveness of the jacket [20–21]. To account for the reduction of FRP strains Pessiki et al. [22] introduced an efficiency factor for FRP jackets, which has been further investigated by a number of researchers both on FRP jackets [23–26] and on FRP tubes [27–28].

A review of the literature reveals that the FRP jacket overlap length has been essentially investigated in relation to how it affects ultimate state [24–30], or the strain concentration at lap edges [31–33]. Few studies to-date have examined the effect of overlap location and continuity on the activation of the FRP [24,25,28], or attempted to analytically predict the minimum required overlap length [33–34]. In the available experimental studies the overlap length of the FRP jackets or tubes is generally over-dimensioned, occasionally after preliminary tests [10,35]. However, when FRP jackets are applied for large-scale retrofit of columns in a structure the use of shorter overlap lengths may result in considerable cost reduction. The factor of the minimum required overlap length has not been yet experimentally investigated to the best knowledge of the authors.

To this end, this paper presents the results of an experimental study on the factors that affect the minimum overlap length required to avoid debonding of FRP jackets. The influence of different overlap schemes, overlap lengths, and application methods on the effectiveness and the compressive behavior of carbon-, glass-, and hybrid-FRP confined cylinders is examined and discussed. Experimental evidence for the onset of the debonding procedure is provided.

2. Experimental program

2.1. General characteristics of test specimens

Plain concrete cylinders, twenty six of 152 mm diameter by 305 mm height (152/305 mm) and four of 100 mm diameter by 200 mm height (100/200 mm), wrapped with one or two layers of carbon- and glass-FRP (CFRP and GFRP, respectively), and also with both CFRP and GFRP (hybrid), were manufactured and tested under monotonically increasing axial compression. Different overlap lengths, FRP materials, application methods, and jacket configurations were investigated. One specimen was tested for each configuration in general with the intention to test as many different schemes as possible. Dry lay-up

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Table 1
Test results.

Specimen	f'_{cc} (MPa)	f'_{co} (MPa)	Days from FRP lay-up to test	ε_{cu} (‰)	ε_{lu} (‰)	$\varepsilon_{h,max}$ (‰)	$\frac{h_{debond}}{h_{fail,conc}}$	$f_{lu,aver}$ (MPa)	$\tau_{fu,aver}$ (MPa)	$Eff_{c,conf}$
C-s-1–10 cm	34.81	17.60	7	24.6	19.7	15.19	0.49	5.97	2.31	0.482
C-s-2–10 cm	39.69	17.60	8	20.2	18.3	15.19	0.33	6.30	2.92	0.549
C-1–10 cm	36.37	17.60	7	23.1	17.1	14.43	0.67	5.81	2.46	0.503
C-2–10 cm	37.42	17.60	8	18.9	16.3	12.90	0.70	5.19	2.19	0.518
G-s-1–10 cm	26.43	18.30	8	11.4	16.4	16.21	0	2.82	1.12	0.343
G-s-2–10 cm	27.48	18.30	13	10.3	16.7	14.30	0	2.58	1.15	0.356
G-1–10 cm	25.76	18.30	13	12.3	13.4	13.25	0	2.45	1.17	0.334
G-2–10 cm	26.86	18.30	8	13.0	18.4	14.39	0	2.54	1.06	0.348
C-12 cm	41.98	18.85	8	20.2	17.0	15.37	0.67	6.38	2.38	0.524
C-14 cm	42.26	18.85	8	21.3	16.8	15.53	0.43	6.15	1.72	0.511
C-17 cm	41.43	19.30	8	n.a$^{(1)}$	20.0	14.88	0.15	5.93	1.39	0.466
wC-10 cm	39.60	19.70	13	17.7	15.5	13.40	0	5.40	2.35	0.490
wC-17 cm	36.89	19.70	15	16.7	15.3	14.91	0	5.61	1.29	0.407
C-309 g-10 cm	39.66	19.70	28	13.2	15.8	11.43	0	5.79	2.45	0.298
C-309 g-17 cm	38.62	19.30	7	15.8	13.1	10.62	0	5.85	1.34	0.264
C-old-10 cm	41.12	20.00	79	19.6	17.9	14.63	0	5.40	2.05	0.501
G-7.5 cm	27.87	18.85	13	17.1	17.8	15.47	0	2.77	1.60	0.367
G-5 cm	26.65	18.85	8	13.5	16.3	15.55	0	2.70	2.11	0.367
G-3 cm	25.89	19.30	9	11.1	13.5	11.19	0	1.92	2.39	0.362
G-1 cm	26.53	19.30	8	12.6	17.4	18.17	0	2.90	14.78	0.386
CC-17 cm	58.82	19.70	13	25.1	20.2	16.18	0.17	11.29	1.26	0.373
CC-5 cm–10 cm	56.25	19.70	14	28.4	19.9	14.71	0.40	11.02	2.06	0.363
GG-1 cm–6.5 cm	39.14	19.30	8	30.2	18.0	13.00	0	4.57	2.02	0.270
GG-3 cm–5 cm	35.00	19.30	8	14.4	16.7	11.48	0	3.96	2.19	0.240
CG-10 cm–1 cm	48.77	19.70	25	22.3	16.8	17.89	0.83	8.31	8.84	0.323
CG-17 cm–1 cm	50.37	19.70	15	21.9	18.7	16.97	0.10	8.91	9.96	0.313
C-14 cm (10 × 20)	51.88	19.30	8	17.8$^{(2)}$	n.a$^{(1)}$	14.58	1	8.85	1.62	0.360
G-5 cm (10 × 20)	33.66	19.30	9	8.3$^{(2)}$	n.a$^{(1)}$	11.54	0	3.14	1.88	0.284
CG-10 cm–1cm(10 × 20)	65.56	19.70	27	24.0$^{(2)}$	n.a$^{(1)}$	17.72	0.17	13.68	9.56	0.271
GG-1 cm–1cm(10 × 20)	44.34	19.70	27	17.6$^{(2)}$	n.a$^{(1)}$	11.57	0.61	5.77	7.50$^{(3)}$	0.206

Notation: $^{(1)}$ = not available; $^{(2)}$ ε_{cu} from 20-mm-length strain gauge at mid-height of specimen; $^{(3)}$ $\tau_{fu,aver}$ = 25 MPa for the measured L_f = 3 mm of the outer GFRP layer that debonded at mid-height of the specimen.

application was used as a rule because this method is often used in retrofit works in Greece.

2.2. Material characteristics

All concrete cylinders were cast simultaneously from the same batch of commercial ready-mix concrete with 28-days cylinder compressive strength 19 MPa. It is noted that the specimens were tested over a 4-month period because the specimens' jacket characteristics were specified each time according to the previous test results. The unconfined compressive strength of concrete, f_{co}, was determined on plain concrete cylinders 152/305 mm at the period each group of specimens was tested (Table 1).

The FRP materials used are formed from unidirectional carbon or glass fiber tow sheets (CFRP and GFRP, respectively). The basic type of CFRP used has areal weight 235 g/m^2, nominal thickness t_f = 0.129 mm, tensile modulus of elasticity E_f = 230 GPa, and rupture strain ε_{fu} = 17‰. In two specimens an alternative type of CFRP was used with areal weight 309 g/m^2, t_f = 0.171 mm, E_f = 242 GPa, and rupture strain ε_{fu} = 14.3‰. Only one type of GFRP (areal weight of 445 g/m^2) with t_f = 0.172 mm, E_f = 76 GPa, and ε_{fu} = 28‰ was tested.

2.3. Application of the jackets

Before the application of the FRP jacket, the cylinder surface was ground, cleaned with water, allowed to dry, and sprayed with compressed air. Additional CFRP strips (of height 30 mm or 20 mm in cylinders 152/305 and 100/200 mm, respectively) were placed at the top and bottom ends of the cylinders to constrain the location of FRP rupture to the middle section [24,27]. The FRP jackets were allowed to cure in the laboratory environment for at least seven days according to manufacturer's guidelines. The number of days from FRP application to testing is displayed in Table 1.

The composite wrapping was applied by hand lay-up with the fibers of the FRP oriented in the hoop direction. The only difference between dry and wet lay-up process consists that in the latter method the FRP sheets are previously impregnated by epoxy resin before they are placed on the epoxy resin-coated concrete substrate. In general a hard plastic laminating roller was used to smooth out air pockets and irregularities. A soft (s) roller was used alternatively in four specimens. It is noted that in cases the target end position of the FRP was not always met, with observed deviations up to 7 mm.

2.4. Instrumentation and testing

The specimens were tested under monotonic axial compression using a 3000 kN capacity compression testing machine. Lateral and axial (over a 150-mm height) deformations of the 152/305 mm cylinders were measured by linear variable displacement transducers (LVDTs), one in each direction, mounted on a Humboldt metallic testing frame [36]. The lateral strains were recorded at mid-height of the FRP jackets through two to four unidirectional strain gauges placed in the hoop direction. Strain gauges with 20 mm- and with 10 mm-gauge length were used for 152/305 mm, and 100/200 mm cylinders, respectively. The strain gauges were located at the axis of overlap length, L_f, at its diametrically opposite point ("outside L_f") for one FRP layer (Fig. 1a), and at a 15- mm distance from the start/end of L_f (Fig. 1a and b) so that strain measurements do not include possible local strain concentrations at the tips of L_f [32].

2.5. Details and designation of test specimens

The typical specimens are 152/305 mm cylinders with jackets of