Composite Structures 149 (2016) 369–384

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Stress–strain behavior of actively and passively confined concrete under cyclic axial load

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ARTICLE INFO

Article history:
Received 3 February 2016
Revised 31 March 2016
Accepted 18 April 2016
Available online 19 April 2016

Keywords:
Concrete
Active confinement
Passive confinement
Cyclic load
Lateral strain
Fibre-reinforced polymer

ABSTRACT

Monotonic stress–strain relationship of actively-confined concrete has been used as the base model to establish analysis-oriented stress–strain model of fiber reinforced polymer (FRP) confined concrete. This approach is based on the assumption that the axial stress and strain of FRP-confined concrete are the same as those of actively confined concrete under the same confinement pressure and lateral strain. In this study, an experiment was conducted to verify this assumption for concrete subjected to cyclic loading. A total of 31 actively confined and FRP-confined concrete cylinders were tested. The results indicate that this assumption is not applicable to concrete under cyclic loading; a gap was found between the envelop curves of the two types of confined concrete. In addition, the test results also reveal that confinement pressure significantly affects both reloading modulus and plastic strain which are the main factors controlling cyclic behavior of confined concrete.

1. Introduction

The stress–strain behavior of confined concrete has been extensively studied by experimental and analytical investigations [1–14]. Lateral confinement to concrete can be categorized into two types: active confinement, such as by hydraulic pressure and steel stirrups (after steel yielding), and passive confinement such as by fiber reinforced polymer (FRP) jacketing. The monotonic stress–strain relationship of FRP-confined concrete can be established using the stress–strain curves of actively confined concrete in an incremental approach [15–21]. This method is built on the assumption that the axial compressive stress and strain of FRP-confined concrete at a given lateral strain are the same as those of actively confined concrete under a confining pressure equal to that supplied by FRP jacket. The assumption implies that concrete is load path independent in this case. However, this assumption has not been validated for concrete subjected to cyclic loading. Cyclic response of FRP-confined concrete has also been extensively investigated [22–34]. However, most studies have neglected the influence of confinement on key model parameters such as plastic strain. The effect of such simplification has not been determined.

In this experimental study, both FRP-confined and actively-confined concrete cylinders were tested under monotonic or cyclic axial compression to study the influence of load path and pattern on the behavior of confined concrete, to assess the validity of assumption of load path independence. Furthermore effect of active confinement pressure on the cyclic behavior of confined concrete was investigated. Active confinement was applied on concrete cylinders using hydraulic pressure system during the entire loading. Test results indicated that plastic strain and reloading modulus of actively confined concrete are highly dependent on confinement pressure, particularly, at large axial strain.

2. Experimental program

2.1. Specimen design

A total of 31 plain concrete specimens were fabricated and tested under monotonic or cyclic compression. The test specimens were categorized into two series denoted as A and F, to distinguish the difference in confinement; A stands for active confinement and F refers to FRP confinement. The number following A gives the constant confinement pressure in MPa, and the number following F indicates the ply number of carbon FRP (CFRP) sheet. The following letters, M and C, refer to monotonic and cyclic loading, respectively. Two identical specimens were manufactured and tested for each specimen design. Therefore, the last digit 1 and 2 denote

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http://dx.doi.org/10.1016/j.compstruct.2016.04.033
0263-8223/

Table 1
Test results of actively confined concrete specimens.

Specimen ID	f_{co} (MPa)	f_{cc} (MPa)	ε_{cc}	ε_l^0	f_l^* (MPa)	Load pattern
A0M1	36.6	35.2	0.0028	–	0	M
A0M2		40.8	0.0028	–	0	M
A0M3		37.4	0.0028	–	0	M
A2.5M1		54.7	0.0069	0.0051	2.5	M
A2.5M2		52.3	0.0070	0.0052	2.5	M
A2.5C1		52.5	0.0063	0.0043	2.5	C
A2.5C2		51.6	0.0078	0.0045	2.5	C
A5M1		61.4	0.0140	0.0090	5	M
A5M2		64.8	0.0114	0.0092	5	M
A5C1		65.5	0.0128	0.0085	5	C
A5C2		64.4	0.0140	0.0083	5	C
A7.5M1		75.5	0.0167	0.0138	7.5	M
A7.5M2		81.5	0.0148	0.0137	7.5	M
A7.5C1		75.5	0.0167	0.0117	7.5	C
A7.5C2		80.6	0.0171	0.0116	7.5	C
A10M1		84.2	0.0223	0.0189	10	M
A10M2		89.3	0.0196	0.0187	10	M
A10C1		89.0	0.0229	0.0170	10	C
A10C2		88.0	0.0223	0.0171	10	C
A15M1		105.7	0.0333	0.0293	15	M
A15M2		108.3	0.0283	0.0295	15	M
A15C1		115.0	0.0278	0.0253	15	C
A15C2		113.9	0.0267	0.0252	15	C
A20M1		131.9	0.0348	0.0373	20	M
A20M2		133.8	0.0411	0.0375	20	M
A20C1		130.9	0.0438	0.0318	20	C
A20C2		136.9	0.0407	0.0317	20	C

Table 2
Test results of FRP confined concrete specimens.

Specimen ID	f_{co} (MPa)	f_{cu} (MPa)	ε_{cu}	$\varepsilon_{h,rup}$	FRP ply no.	Load pattern
F1M1	36.6	131.3	0.0370	−0.0154	1	M
F1M2		124.2	0.0362	−0.0158	1	M
F1C1		121.1	0.0371	−0.0175	1	C
F1C2		132.1	0.0355	−0.0221	1	C

specimen No. 1 and No. 2, respectively, except specimen A0M3 which has three identical plain concrete specimens that were tested for obtaining unconfined concrete strength. The details of twenty-seven actively confined concrete specimens are summarized in Table 1, and details of the other four FRP confined specimens are shown in Table 2. As a large number of tests for FRP confined concrete cylinders are available in the literature, fewer test specimens were designed for FRP confined concrete.

The dimensions of the concrete specimens tested in this study were 54 mm in diameter and 108 mm in height, as determined by the sizes of the Hoek cell. To avoid significant scattering of concrete strength due to the smaller size of specimens, concrete cylinders were extracted from large concrete blocks cast in one batch by a coring machine after 28 days curing in a water tank at a constant temperature of 27 °C. All specimens were ground using a surface grinding machine to remove soft mortar and irregularities on the two surfaces of the specimens, so that axial stress could be applied uniformly.

2.2. Material properties

The design concrete strength of specimens was 35 MPa with a water cement ratio 0.64. The actual concrete strength obtained from 150 mm concrete cylinders at the time of confined specimen test was 36.6 MPa. River sand was used as the fine aggregate and crushed granite stone with a maximum size of 10 mm was used as the coarse aggregate. All aggregates were carefully and completely dried in an oven before mixing to minimize the variation of water content.

After the concrete had been aged for 28 days, unidirectional CFRP was wrapped on the surface of a specimen in the hoop direction in a wet lay-up manner, with an overlap of one third perimeter. The two-part Sikadur-300 epoxy impregnation resin was used as adhesive. The material properties of carbon fiber are summarized in Table 3, including data provided by the manufacturer and obtained in this work from the average value of four flat coupons tested in accordance with ASTM D3039 [35]. All coupons were 50 mm (width) × 300 mm (length) × 0.167 mm (nominal thickness) FRP sheets with one layer carbon fabric.

2.3. Load path of confinement pressure

Constant hydrostatic confining pressure was applied using a Hoek cell [36], as illustrated in Fig. 1. During the test, oil was pumped into the chamber through a bleed valve to provide a uniform lateral pressure on the specimen. Axial load was applied by a compression machine through the steel spherical blocks at the two ends of specimen. In this study, the active lateral pressure was maintained constant during test at design values of 2.5 MPa, 5 MPa, 7.5 MPa, 10 MPa, 15 MPa or 20 MPa.

Table 3
Properties of carbon fiber sheet.

UT70-30 carbon fiber	Thickness t_f (mm)	Tensile strength f_f (MPa)	Ultimate tensile strain ε_f (%)	Elastic modules E_f (GPa)
Manufacturer	0.167	4153	1.72	240
Coupon test	0.167	4338	1.78	242