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Hybrid confinement of concrete through use of low and high rupture strain FRP

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ABSTRACT

This study investigates the behavior mechanisms and efficiency of concrete confinement formed with the hybridization of two different types of fiber reinforced polymer (FRP) sheets with the aim of utilizing superior features of these two FRP types. The originality of the study is to combine carbon or glass FRP sheets (CFRP or GFRP) with polyethylene terephthalate FRP sheets (PET-FRP), which have different mechanical features, particularly in terms of deformability. While CFRP and GFRP sheets have relatively high tensile strength and low rupture strain capacity, PET-FRP sheets have low tensile strength but remarkably high rupture strain capacity. Hybridization is performed through external wrapping of two different FRP sheets in a successive way. 24 standard cylinder concrete specimens are tested under compression loading. The test variables of the study are the types and number of layers of the inner and outer FRP constituents of hybrid jacket. Test results show that hybrid confinement of FRP sheets with low and high rupture strain capacities offers an enhanced ductility. Furthermore, it is seen that through the hybridization of FRP sheets with different mechanical properties, stress-strain relationship of FRP confined concrete can be tailored. Several available analytical models developed for stress-strain relationship of the concrete confined with a single type of FRP sheet and one model developed for the hybrid FRP confined concrete are used to predict key stress and strain values of the hybrid confined concrete. Considering the behavior mechanisms of the hybrid confined concrete specimens, several assumptions are made during the application of these models. It is shown that key stress and strain values of hybrid confined concrete can be reasonably predicted.

1. Introduction

A major use of fiber reinforced polymers (FRP) in civil engineering is the external jacketing of the concrete members. Many experimental and analytical studies have been conducted on this subject (e.g. Refs. [1–4]). However, the studies on concrete confinement using combinations of different types of FRP sheets, i.e., hybrid confinement, are limited:

Jing et al. [5] experimentally examined square/rectangular concrete specimens confined by carbon (CFRP) and glass (GFRP) FRPs. They [5] concluded that the hybrid confined specimens had higher deformation capacity than the specimens confined with CFRP or GFRP only under compression loads. Wu et al. [6] conducted an experimental study on standard concrete cylinders confined with hybridized FRP jackets. For this purpose, CFRP, aramid FRP (AFRP), GFRP, and poly-para-phenylene-benzo-bis-oxazole (POB) FRP sheets were used. The authors highlighted that the strength ratio between inner and outer FRP constituents should be high enough to have an efficient hybridization. Based on the experimental data, an axial stress - axial strain model was proposed. According to Bouchelaghem et al. [7], hybrid use of different type of FRP sheets provides a cost benefit with respect to conventional CFRP applications. De Luca et al. [8] examined the behavior of full-scale rectangular column confined with hybrid glass-basalt FRP laminates under axial load. They concluded that the confinement performance of hybrid confined column was similar to that of the column confined with GFRP laminates. Quon et al. [9] studied the efficacy of an alternative FRP jacket manufacturing procedure. Their specimens were confined mainly with a CFRP jacket, and an outer GFRP jacket, which had a special design with an intention of providing an extra deformation capacity. The authors observed a fluctuating stress-strain relationship after the peak load (i.e. slight load drops occur while strain increases) and the enhancements in ductility and energy dissipation. The hybrid confinement of concrete, especially the case of non-bonded interface between inner and outer jacket, was investigated experimentally by Rousakis [10–13] under monotonic or cyclic compression loading in cylinder or full-scale specimens. These studies showed that

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the adopted hybrid confinement configurations raise the strength, strain and energy dissipation capacities of concrete. Padanattil et al. [14] compared the behaviors of hybrid confined concrete specimens, which were formed with sisal reinforced polymer (natural fiber), GFRP and CFRP. The authors inferred that the hybridization of natural and synthetic fibers in concrete confinement can be an appropriate solution for retrofitting applications in place of costly synthetic fibers like carbon.

Considering the need of further understanding the behavior mechanism of hybrid confinement with FRP sheets having total different mechanical features and the limited availability of studies on hybrid FRP confinement, a testing program involving twenty-four standard concrete cylinders is implemented in the current work. The focus is put on the examination of the compression behavior mechanism of concrete confined with hybrid FRP jackets and the efficacy of hybrid FRP confinement. The use of PET-FRP sheet as the outer constituent of the hybrid FRP jacket, which has a very high elongation capacity (ε_{fu} = 10%), constitutes of other original aspect of the current work. The test variables of the study are the constituent FRP sheet type (carbon, glass, or PET) and the number of FRP layers (1, 2, 3, or 6). The test data are analyzed to elucidate the compressive behavior of the hybrid FRP confined specimens by using stress-strain plots, Poisson's ratio variations and energy dissipations. Furthermore, five analytical models (Lam and Teng [2], Ilki and Kumbasar [3], Ilki et al. [15], Teng et al. [16], Wu and Wei [17]), which were proposed for concrete confined with a single type of FRP sheet and one analytical model (Wu et al. [6]) proposed for hybrid FRP confined concrete are used to predict key stress and strain values of specimens. During the application of these models to the hybrid confined specimens, some assumptions are made based on the experimental stress-strain behavior of these specimens.

2. Test program overview

2.1. Test specimens

In this experimental work, 24 concrete cylinder specimens were tested. All specimens had the dimensions of 150-mm diameter and 300-mm height. They were classified as 12 specimens confined with two different types of FRP sheets (hybrid confined specimens), 8 specimens confined with a single type of FRP sheet, and 4 unconfined specimens (control specimens). The hybrid confined specimens were firstly wrapped using FRP sheets with lower elongation capacity (ε_{fu}) (inner FRP sheet). Afterwards, FRP sheet with higher ε_{fu} were wrapped (outer FRP sheet) over the inner constituent FRP sheet. The test program included several hybrid configurations formed with different stiffness of inner and outer FRP jackets. Other than the relative stiffness of the inner and outer FRP layers, deformation capacities of the fibers used in these layers was the other main test variable. The hybridizations were conducted using CFRP & GFRP, CFRP & PET-FRP and GFRP & PET-FRP combinations. The specimens confined with the combination of CFRP & GFRP sheets were prepared to elucidate the hybrid confinement mechanisms with similar ε_{fu}. CFRP & PET-FRP and GFRP & PET-FRP combinations were formed to investigate the efficiency of the hybridization including two types of FRP sheets with significantly different ε_{fu}. The hybrid confined specimens are denoted with the labels which comprise the number of layers of inner FRP sheet, the initial of the inner FRP sheet type (C for CFRP and G for GFRP), the number of layers of outer FRP sheet and the initial of the outer FRP sheet type (G for GFRP and P for PET-FRP). For example, 1C3P specimen is a hybrid confined specimen, which is formed with one layer of CFRP as inner constituent and 3 layers of PET-FRP as outer constituent of hybrid FRP jacket.

The specimens confined with a single type of FRP sheet are symbolized with the number of layers of FRP sheet and the FRP sheet type (1C, 1G, 2G and 6G). These specimens were considered to represent the inner or outer FRP constituents of hybrid jacket, and so these specimens are tested to reveal the individual confinement effect provided by each type of FRP sheet. The specimens confined with only PET-FRP sheets had been tested by Ispir [18] for another project. Those specimens had the same material characteristics and dimensions as the specimens presented in the current paper. Therefore, the details regarding the tests of those specimens were not covered again and only test results were presented in this paper. For each FRP configuration, two identical specimens were tested like many studies in the literature (e.g., Rousakis et al. [11], Ozbakkaloglu and Akın [19]). Although it is more preferable to test three specimens, this could not be possible due to time and budget limitations.

2.2. Material characteristics

Ready mix concrete was used for the production of the cylinder specimens. The ingredients of concrete in kg/m^3 are 156 (cement), 40 (fly ash), 670 (sand), 303 (limestone powder), 988 (aggregate), 1.25 (super-plasticizer) and 101 (water). The average unconfined concrete strength of the standard cylinders was experimentally determined as 17.9 MPa at 28 days. The FRP jackets of the specimens were formed with uniaxial CFRP, GFRP, and PET-FRP sheets. The general characteristics of the fiber sheets are listed in Table 1, as provided by the manufacturers.

2.3. Specimen preparation

After the concrete cylinders were produced, the upper and lower ends of the specimens were capped with a high-strength mortar to facilitate uniform distribution of the applied compression loads. The specimens were then confined externally with FRP sheets via a wet lay-up process. Herein, the hybridization is conducted by wrapping the FRP sheets successively. Firstly, the surface of each specimen was cleaned. A primer material with two constituents was applied the surface to fill air voids, which was then cured for 6 h. Secondly, a layer of epoxy resin was applied to the cured concrete specimen surface. Then, a single continuous fiber sheet (the inner FRP constituent sheet in the case of a hybrid confined specimen) was impregnated with epoxy and bonded to the concrete cylinder surface, with the fibers oriented in the hoop direction. After wrapping, another layer of epoxy resin was applied by a roller to remove air voids and to provide improved resin impregnation. For the hybrid confined specimens, outer FRP constituent sheet was wrapped over the inner FRP sheet using the same technique (Fig. 1a). The overlap lengths were about 150 mm for CFRP and GFRP layers and 150–180 mm for PET-FRP layers. Confined specimens were left to cure for at least one week before the tests.

2.4. Test procedure and instrumentation

The compression tests were performed using a closed-loop Instron test machine with a 5000-kN load capacity. The monotonic compression loads were applied under a displacement control mode at a constant rate of 0.6 mm/min (0.2% vertical strain/min). The axial and lateral deformations were measured using the measurement system that consisted of two linear variable displacement transducers (LVDTs) with 25-mm capacity and two strain gages with 60-mm gage length (Fig. 1b).

Table 1
General characteristics of dry fiber sheets.

Fiber sheet type	Tensile strength f_{fu} (MPa)	Modulus of elasticity E_f (MPa)	Rupture strain ε_{fu} (%)	Effective thickness t_f (mm)
Carbon	4900	230000	2.1	0.166
Glass	1700	80000	2.8	0.230
PET	740	10000	10.0	1.262