

BEHAVIOR OF HIGH-STRENGTH CONCRETE CYLINDERS REPAIRED WITH CFRP SHEETS

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Abstract. This study aims to investigate the behavior of damaged high-strength concrete cylinders repaired using carbon fiber reinforced polymer (CFRP) sheet. The experimental work on CFRP-wrapped concrete cylinders with various pre-damage levels indicated that CFRP can precisely resist the axial aggravated deformation of cylinders caused by damage under uniaxial loading. The findings also revealed that the energy absorption of the damaged specimens confined with CFRP was restored approximately three times more than that of the undamaged specimens without confinement. Therefore, an empirical relationship exists between the pre-damage levels and the uniaxial compressive strength reduction of the concrete cylinders.

Keywords: FRP, concrete, confinement, damage, repair.

Introduction

Since the last decade, interest of researchers in repairing, strengthening, and retrofitting of existing structures with fiber reinforced polymer (FRP) has been increasing (Colalillo, Sheikh 2011; Ferrier *et al.* 2011; Hag-Elsafi *et al.* 2004; Maalej, Leong 2005; Matthys, Taerwe 2006; Panjehpour *et al.* 2011; Taillade *et al.* 2011). Several studies have proven the economical and environmental benefits of the application of FRP in constructions (Cromwell *et al.* 2011; Moy 2001; Sasher 2008). Rehabilitation and repair of concrete structures in light of the degradation of structure members because of aging, increase of structure load capacity, and construction design errors is increasingly needed (Pan, Leung 2007). FRP wrapping is one of the methods for increasing the axial strength, shear strength, and seismic resistance of concrete members.

The column is one of the most critical parts of a structure that is usually loaded axially (Manal K 2011). Numerous studies have focused on the retrofitting and strengthening of concrete columns using FRP sheet with respect to FRP confinement performance (Csuka, Kollár 2011; Gu *et al.* 2012; Jiang, Teng 2012; Naderian *et al.* 2011; Promis, Ferrier 2012). The application of FRP sheets to columns can be classified into three types of wrapping: partial wrapping in the form of continuous spi-

ral straps, partial wrapping in the form of discrete ring straps, and full wrapping (Teng 2002). FRP sheets are wrapped around the column in the circumferential direction parallel to their fiber orientation. The axial strength of the concrete column increases with the triaxial stress condition created by FRP confinement (Lam *et al.* 2006). Moreover, FRP wrapping also prevents the premature spalling failure of the column, particularly for lateral loading that may occur during earthquake (Giuseppe 2006; Lam *et al.* 2006; Sasmal *et al.* 2011).

Previous studies have focused on the issues of ductility and stress–strain curve of FRP-confined concrete cylinders. The present study discusses the preceding issues on pre-damaged concrete cylinders confined with CFRP sheets. The ductility of concrete members such as columns usually decreases because of the unstrengthening caused by damage (FIB 2001). Lateral confinement of the concrete column in the compressive zone is one of the alternative techniques for enhancing the ductile behavior of a column by preventing pre-mature cracking and crushing (Gdoutos *et al.* 2000). The effect of FRP confinement on the ductility of undamaged concrete columns in the compressive zone has been investigated by a number of researchers (Hadi 2007; Jiang, Teng 2007).

Typical stress–strain curves for undamaged FRP-confined concrete cylinders have been proposed by re-

searchers with respect to FRP properties, such as the number of layers and thickness of FRP (FIB 2006; IAEE 1992; Teng 2002). In addition, numerical stress–strain models of FRP-confined concrete cylinders have been recommended (Wei, Wu 2012).

The behavior of damaged concrete members repaired with FRP is highly influenced by sound concrete substrate and proper surface preparation (Lam, Teng 2002). However, the different types and sizes of defects for the damaged concrete members are still undefined in the standards. Moreover, the threshold of critical defects has not yet been sufficiently studied (Lam *et al.* 2011; Panjehpour *et al.* 2011). According to previous studies, far too little attention has been given to the effectiveness of CFRP confinement for different levels of damage on concrete columns.

The present study aims to investigate the behavior of damaged high-strength concrete cylinders repaired using CFRP sheet. This study is the first research to date that focuses on the effect of damage level on the compressive strength and energy absorption of repaired specimens using one layer of CFRP sheet. In addition, the stress–strain curves and energy absorption of all concrete cylinders comprising unconfined and CFRP-confined control specimens, as well as CFRP-confined pre-damaged specimens, are also compared. The CFRP-confined concrete cylinders with 40%, 55%, 70%, 85%, and 100% pre-damage are tested under uniaxial compressive load to evaluate the efficiency of CFRP confinement in damage status. Moreover, the concrete cylinders with 100% pre-damage, considered as defected specimens, are discussed in separate section in this paper.

1. Experimental program

The experimental program aims to evaluate the effectiveness of FRP confinement for repairing various pre-damage levels of high-strength cylindrical concrete specimens. The experimental specimens were categorized into two groups according to the damage level: cracked specimens and defected specimens. The specimens were tested under four different conditions:

- 1) Three undamaged specimens without any CFRP wrapping as unconfined control specimens;
- 2) Three undamaged specimens with CFRP full wrapping as confined control specimens;
- 3) Twelve specimens comprising four groups with 40%, 55%, 70%, and 85% pre-damage;
- 4) Three defected specimens with 100% pre-damage.

1.1. Material properties

Type I Portland cement, natural sand, gravel, and water were used to form the concrete cylinders according to ASTM C39 (2014). Crushed quartz, with the maximum aggregate size of 12.5 mm and bulk specific gravity of 2.46, were utilized in this batch. Single batch of high-strength concrete was prepared to fabricate 21 cylindrical samples.

In this experiment, 10% silica fume and a w/b ratio of 0.35 were chosen to achieve high-strength concrete.

One layer of unidirectional CFRP, with areal weight of 200 g/m² and thickness of 0.111 mm/ply, and two-part epoxy impregnation resin were utilized for full wrapping of the specimens by wet lay-up system. The typical properties of the CFRP sheet and epoxy resin provided by the manufacturer are illustrated in Table 1. Both CFRP sheet and epoxy resin, with product data sheets of sikadur-330 and sikaWrap-230, respectively, were obtained from Sika Company.

1.2. Casting and curing of specimens

The concrete specimens were demolded at 24 hours after casting, and cured in saturated lime water for 28 days. Afterward, the specimens were allowed to air-dry for the next 28 days in an outdoor environment to resemble the real situation before being damaged at different levels.

1.3. Pre-damaging of specimen

Figure 1 shows the uniaxial compressive tests conducted on the specimens using universal testing machine, which provides stress and displacement as electrical output data. According to the ASTM C39 (2014), cylindrical specimens with the size of 150×300 mm were loaded to determine the ultimate uniaxial compressive strength of unconfined specimens, which was 65.8 Mpa. The other specimens were loaded until they reached 40%, 55%,

Table 1. Typical properties of CFRP sheets and epoxy

Materials	Tensile strength (Mpa)	Tensile modulus of elasticity (Gpa)	Elongation at break	Bond strength (Mpa)
CFRP sheet	3900	230	1.5% (7 days at +23 °C)	–
Epoxy resin	30	4.5	0.9% (7 days at +23 °C)	>4

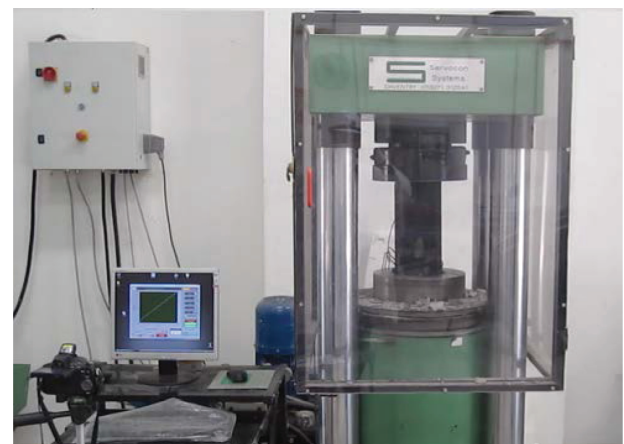


Fig. 1. Test set up

70%, 85%, and 100% of ultimate uniaxial compressive strength to compress to different pre-damage levels. A portable microscope with a resolution of 0.02 mm was used to measure the crack width.

1.4. Repairing of damaged specimens

Excluding three specimens used as unconfined control specimens, the other pre-damaged specimens were fully wrapped with one layer of CFRP sheets. The surface of concrete specimens was rubbed with sand paper to prevent the debonding or delamination of CFRP sheets. In addition, the dusts and particles inside the wide cracks were removed by air compressor. Figure 2 illustrates the specimens with 100% pre-damage, which are considered as defected specimens. The repairing method utilized for these specimens varies from the other pre-damaged specimens. The core of the concrete was observed to be still undamaged for 100% pre-damaged specimens. Hence, only their surface with small parts of defect was needed to be filled and re-shaped using grout, with respect to ASTM C 476-02 (2009) and BS EN 1504 (CS 2009) before CFRP confining. The defected specimens were then remolded, as

illustrated in Figure 3. The grout was poured inside the mould on the vibration table. This part of repairing is the only different part of defected specimens repairing process from the other damaged specimens. The wet lay-up system was utilized to wrap the specimens, and 150 mm overlapping of CFRP sheet was used in the hoop direction.

The hardener and resin (1:4) were mixed for three minutes to prepare the two-part epoxy impregnation resin based on the recommendation of the manufacturer. The hardener and resin were mixed with a spindle attached to a slow-speed electric drill with a maximum rate of 600 rpm until the material became smooth in uniform grey color. Both the pot life and the open time were approximately 30 minutes. Considering the average outdoor environment temperature and curing details provided by the manufacturer of the epoxy resin, all of the CFRP-confined specimens were cured for two days to ensure CFRP–concrete interface bonding. Finally, the whole specimens were tested under uniaxial compressive load to reach their failure load. The average of the results, including stress and strain, was used to draw the curve based on the three specimens for each damage level to

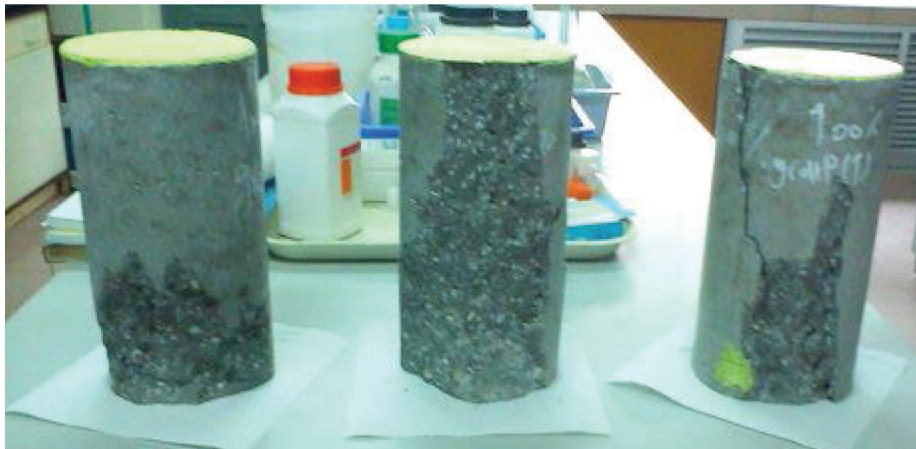


Fig. 2. Defected specimens with level of 100% pre-damage



Fig. 3. Defected specimen (a); remolding of defected specimen (b)

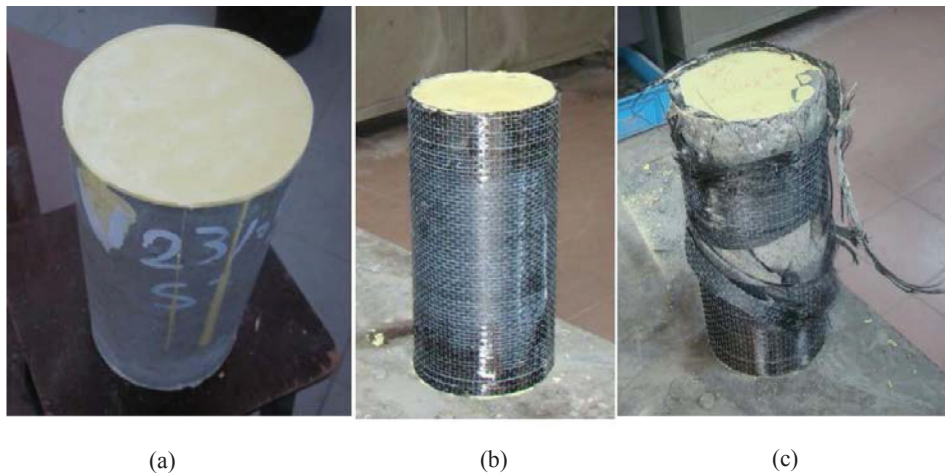


Fig. 4. Unconfined specimen (a); Confined specimen before compressive strength test (b); Confined specimen after compressive strength test (c)

achieve an accurate stress–strain curve. Figure 4 shows the unconfined specimen and CFRP-confined specimens before and after the compressive test.

2. Experimental results and discussions

2.1. Test observations and failure mode

Failures of FRP-wrapped cylindrical concretes occurred with FRP rupture and compressive concrete crushing, as predicted in previous studies (İlki *et al.* 2009). This failure was due to the concrete crumbling and cracking under confinement pressure caused by FRP wrapping.

2.2. Defected specimens

Defected specimens that are 100% pre-damaged in this study can reach up to 68.90% of the compressive strength of the unconfined control specimen after only reshaping with grout based on ASTM C 476-02 (2009) and BS EN 1504 (CS 2009). Using CFRP confinement after reshaping with grout enhanced the compressive strength of the defected concrete cylinders to approximately 84.90% of the compressive strength of the unconfined control specimens. Hence, the effect of one layer of CFRP on the compressive strength of defected specimens after reshaping with grout was approximately 23.22%. This enhancement is approximately 5% lower than the enhancement for control specimens confined with CFRP sheet. The compressive strengths of the unconfined control specimens, defected specimens reshaped with grout, and CFRP-confined defected specimens reshaped with grout are shown in Table 2.

The peak strain of the ultimate compressive strength increased from 0.0090 for CFRP-confined control specimen to 0.0099 (10% increase) for CFRP-confined defected specimen. This increase is due to the defect that causes more ductility than the undamaged specimen. Past studies have recorded that, the axial strain of CFRP-confined cylindrical specimens without any pre-damage related to ultimate compressive stress (ϵ_{cc}) varies from

Table 2. Compressive strength of control and repaired specimens

Specimens status	Uniaxial compressive strength (Mpa)
Unconfined control specimen	65.80
Defected specimen reshaped with grout	45.34
CFRP confined defected specimens after reshaping with grout	55.87

0.106% to 2.516% (Jiang, Teng 2007; Lam, Teng 2002), 0.900% to 2.080% (Jiang, Teng 2007; Lam *et al.* 2006), and 0.691% to 3.700% (Jiang, Teng 2007; Teng *et al.* 2007). In addition, the efficiency of FRP confinement with respect to several relevant models proposed by researchers has been analyzed to find proper equation for estimating the compressive strength of FRP-confined concrete cylindrical specimens (Realfonzo, Napoli 2011). In the present study, the ϵ_{cc} for the defected specimen repaired with CFRP after reshaping with grout is 0.895%. The difference in the ϵ_{cc} obtained by different studies are influenced by some parameters such as type of fiber, including carbon and glass, compressive strength of concrete (f'_{co}), thickness of FRP (t), modulus of elasticity of FRP (E_{FRP}), and type of epoxy.

2.3. Specimens with 40% to 85% pre-damage

Typically, cracks wider than 0.3 mm in concrete members require sealing to prevent the entry of moisture, oxygen, and other materials, in contrast to the cracks narrower than 0.3 mm, which are considered as superficial cracks (Gambhir 2010; Komorowski 2011). Thus, the cracks wider than 0.3 mm are injected with epoxy before wrapping with CFRP sheet in this experiment. The widths of the cracks for the current specimens with 40% pre-damage were not wider than 0.3 mm. Figure 5 illustrates the compressive strength reduction for different pre-damage

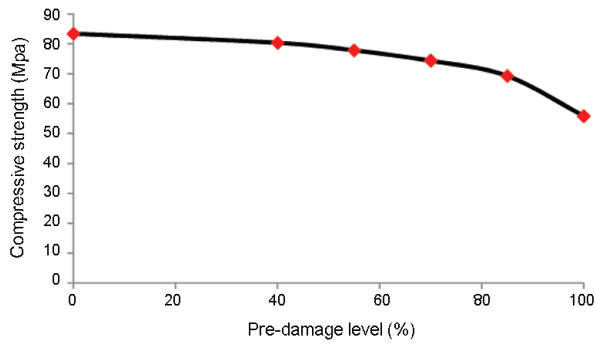


Fig. 5. Uniaxial compressive strength of CFRP-confined pre-damaged specimens

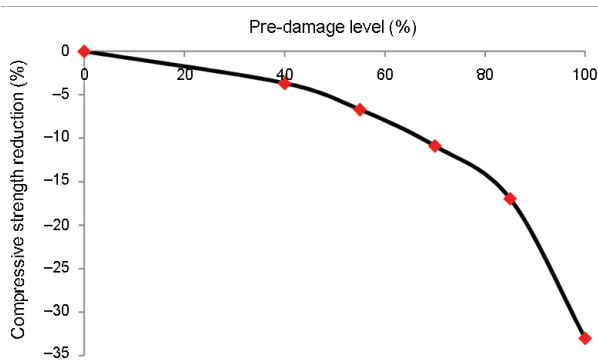


Fig. 6. Compressive strength reduction of pre-damaged specimens confined with CFRP

levels of CFRP-confined pre-damaged specimens. Subsequently, an empirical relationship between the pre-damage levels and reduction of compressive strength of CFRP-confined pre-damaged specimens is indicated in Figure 6. The compressive strength of CFRP control specimens was considered as the reference value to calculate the total compressive strength reduction in this study.

According to the experimental results, a slight compressive strength reduction of about 3.67% occurred in the 40% pre-damaged specimen. This result indicates the significant efficiency of CFRP confinement up to 40% pre-damage because CFRP can enhance the strength of specimen very close to the control specimen, with only approximately 3.67% reduction. The width of the cracks for 55% pre-damage was slightly wider than 0.3 mm in some parts of the concrete specimens. The reduction of compressive strength from 40% to 55% pre-damage was around 3.15%, which may be due to the wider cracks. However, the total reduction of compressive strength in 55% pre-damage specimen was approximately 6.70%. The cracks on 70% pre-damaged specimens became wider than the previous specimens. In some parts of the top and bottom of cylindrical specimens, small pieces of concrete were delaminated, with maximum dimension of approximately 10 mm. In this level of pre-damage, crushing of concrete was not observed.

Lastly, the specimens were loaded up to 85% pre-damage. The cracks became wider than the previous specimens, and some parts of the concrete were delaminated. Crushing of the concrete occurred at the top and the bottom regions of the specimens; however, defected parts of concrete on the specimen bodies were not observed. The reduction of compressive strength from 70% to 85% pre-damage was approximately 6.81%, greater than the previous specimens. This reduction was due to the high pre-damage level that caused wide cracks and small parts of defect. The total compressive strength reduction of CFRP-confined specimens with 85% pre-damage was 16.96%. This result indicates the efficiency of CFRP confinement, which can compensate the reduction effect of damage upon the compressive strength of cylindrical specimens. CFRP sheet is dormant until the ultimate strength of the corresponding unconfined pre-damaged specimens is reached. This is because of higher transverse Poisson's ratio and lower axial stiffness of FRP than those of concrete.

Figures 5 and 6 illustrate the comparisons of the uniaxial compressive strength of the defected specimens with the other specimens. Crucially, defected specimens were reshaped with simple grout before confining with CFRP. The compressive strength reduction of CFRP-confined defected specimens was approximately 19.32% more than those of the 85% pre-damaged specimens. Hence, CFRP-confined defected specimens can reach up to about 84.90% of the strength of unconfined control specimens.

2.4. Relationship between pre-damage levels and compressive strength reduction

Types of concrete column damages that comprise cracking, crushing, and defecting can be roughly determined by observation. Figure 7 illustrates an empirical relationship between pre-damage levels and uniaxial compressive strength reduction of high-strength concrete cylindrical specimens. This relationship was derived from the experimental results within the scope of the present research. In future studies, this relationship can

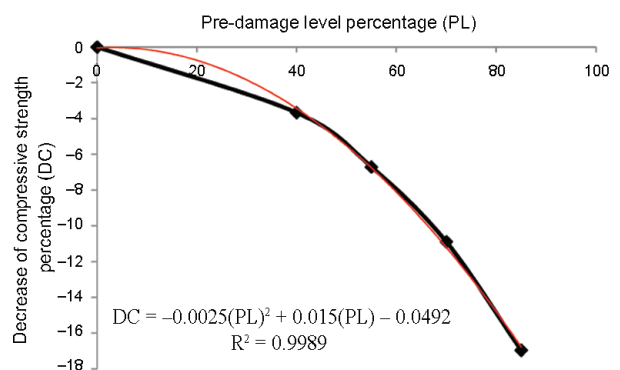


Fig. 7. Relationship between pre-damage level and decrease of compressive strength

be further calibrated with considering grade of concrete, number of the layers, thickness, and modulus of elasticity of CFRP. Nevertheless, the relationship reveals a schematic diagram to clarify how the reduction of uniaxial compressive strength of concrete cylinders varies with the damage levels. According to this relationship, similar to the parabolic curve, the uniaxial compressive strength reduction for CFRP-confined cylindrical specimens can be predicted based on the pre-damage level. Thus, the uniaxial compressive strength reduction of the CFRP-confined cylindrical specimen pertinent to 50% pre-damage may be about 5.54%.

2.5. Ductility

The ductility of concrete members such as column decreases because of the unstrengthening caused by damage (FIB 2001). Lateral confinement of the concrete column in the compressive zone is one of the alternative techniques that can be utilized to enhance the ductility of a column (Gdoutos *et al.* 2000). The area under the load-deformation curve for all specimens comprising the unconfined and CFRP-confined control specimens, as well as the CFRP-confined pre-damaged and defected specimens, was calculated using Simpson's rule. The amount of this area represents the energy absorption of the specimens, as illustrated in Figure 8. Numerous studies have shown a consistent positive correlation between energy absorption and ductility of concrete cylinders. Crucially, the initial small part of the stress-strain curve is likely to represent initial settlements of the specimen within the testing rig. However, the effect of this part of curves upon the accuracy of calculation for the area under load-axial deflection curves is not the major concern of this study.

The experimental results indicated that a significant increase in the energy absorption of CFRP-confined control specimens occurred compared with the unconfined control specimens. The energy absorptions of the confined and unconfined control specimens, as well as the confined defected specimens, are illustrated in Figure 8. CFRP confinement increases the energy absorption of the undamaged specimen by approximately more than

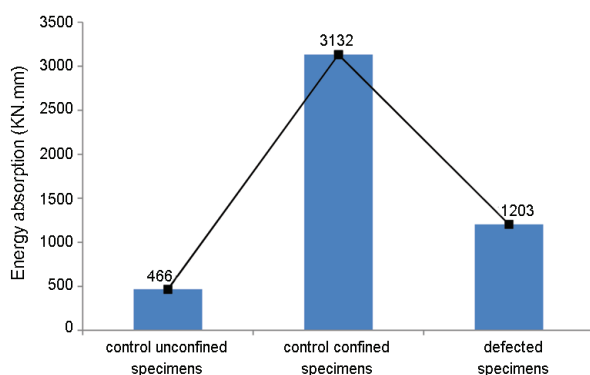


Fig. 8. Energy absorption of specimens

six times. Based on the experimental results, the energy absorption of the CFRP-confined specimens with 40% pre-damage is 1.5 times more than those of the defected specimens, with 100% pre-damage, because the damaged concrete specimens were weaker than the undamaged concrete specimens in absorbing the energy. From another point of view, debonding may be induced by major cracks of the concrete (Pan, Leung 2007). The increase of interfacial bonding stress between the concrete and FRP can enhance the strength and stiffness of the repaired columns (Guoqiang 2006; Li *et al.* 2003). For the repairing of damaged concrete specimens, the FRP is wrapped on the surface of the cracked concrete cylinders that are not as smooth as undamaged concrete cylinders. Thus, only a part of axial load can be transferred to the FRP sheet through interfacial bonding and interfacial friction force. As a result, the degradation of energy absorption from CFRP-confined specimen with 40% pre-damage to the defected specimens may be due to the weakened concrete and debonding of the CFRP-concrete interface. Nevertheless, bonding stress may affect the stiffness and may have minor effect on the compressive strength because the bond does not reduce the ultimate confinement pressure.

Experimental results indicated that CFRP confinement increases energy absorption by approximately three times for specimens with 40% to 85% pre-damage, as well as defected specimens, compared with the unconfined control specimens. This result implies the effectiveness of CFRP confinement for energy absorption of the repaired concrete cylinders, as proven for undamaged concrete columns in previous studies (Hadi 2007; Jiang, Teng 2007).

2.6. Stress-strain curve

In the present study, the behavior of all specimens was observed throughout the load history until the occurrence of FRP material rupture. The stress-strain curve is characterized by two distinct regions for CFRP-confined control specimens. The first region is approximately linear where the CFRP wrapping is dormant, whereas the second region after some fluctuation in the beginning is approximately linear with the lower gradient compared with the first region. The preceding typical stress-strain curve has been proposed by several researchers for undamaged FRP-confined specimens with respect to the FRP properties such as number of layers and thickness of FRP (FIB 2006; Teng 2002). In addition, some researchers also recommend the numerical stress-strain model of concrete for FRP-confined columns (Wei, Wu 2012).

Figure 9 illustrates the stress-strain curves of all specimens comprising confined and unconfined control specimens, as well as confined pre-damaged specimens. These curves are drawn based on the average strain measured using machine displacements, as shown in Figure 1. The former regions of stress-strain curves for all specimens are almost similar, as indicated by the dashed line in Figure 9. The stress-strain curves of the

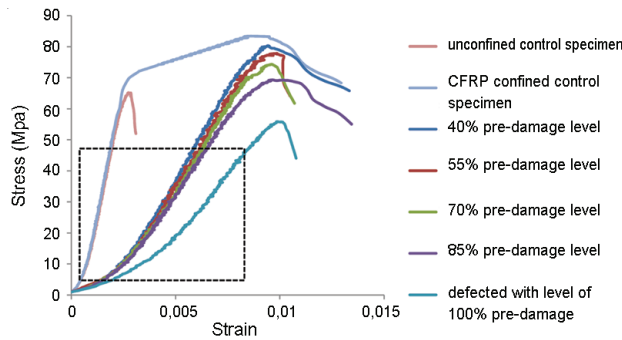


Fig. 9. Stress-strain curve of all specimens

concrete cylinders varied from linear to parabolic from undamaged status to higher damage level. Moreover, the concavities of curves increased from lower to higher pre-damage level, which may be due to increasing void content caused by cracking and crushing. Consequently, the softening of the concrete occurred. The increase of concavity implies that the brittleness index decreases as pre-damage level increases.

Conclusions

This study addresses the repair of high-strength concrete cylinders with CFRP sheet at various pre-damage levels. The uniaxial compressive stress, stress–strain curves, and energy absorption of the pre-damaged concrete cylinders confined with CFRP sheets are compared with CFRP-confined and unconfined specimens without any damage as control specimens. According to the experimental investigation, the following conclusions can be drawn:

1. CFRP confinement can compensate the reduction effect of damage on the compressive strength of the concrete cylindrical specimens. The strength reduction of CFRP-confined concrete cylinders with 85% pre-damage was only about 16.96%, with CFRP-confined control specimen as reference value.
2. Using CFRP confinement after reshaping the concrete cylinders with grout enhances the compressive strength of the defected high-strength concrete cylinders to approximately 84.90% of the compressive strength of unconfined control specimens.
3. An empirical relationship between pre-damage levels and uniaxial compressive strength reduction for concrete cylinders was established in this study. This relationship is approximately similar to a parabolic curve, which roughly shows how uniaxial compressive strength of concrete cylinders reduces with the increase of damage level.
4. Comparing unconfined and CFRP-confined control specimens, the energy absorption increased more than six times using CFRP confinement.
5. CFRP confinement increases the energy absorption for different damage levels of specimens by approximately three times compared with the unconfined control specimens. This result indicates the effective-

ness of CFRP confinement for energy absorption of the repaired concrete cylinders.

6. A degradation of energy absorption of the CFRP-confined pre-damaged concrete cylinders was observed from 42.20% to 61.59%, respectively, for 40% to 100% pre-damage, considering CFRP-confined control specimen as the reference. The degradation may be due to the weaker concrete and lower interfacial bonding stress between the concrete and CFRP caused by cracking at low damage level, crushing at high damage level, and defecting for 100% damage.
7. The stress–strain curves of the concrete cylinders from undamaged status to higher damage level vary from linear to parabolic. In addition, the concavities of the curves increased from lower to higher pre-damage level, which may be due to the increase of void content caused by cracking and crushing. Consequently, softening of the concrete occurred.
8. As implied by the stress–strain curves, utilizing CFRP sheets has slight effect upon the linear part of the stress–strain curves for the confined control specimens. CFRP is dormant in preceding part; however, its effects are considerable in softening plastic region ensuing.
9. CFRP sheet is dormant until the ultimate strength of the corresponding unconfined pre-damaged specimens is reached. This is because of higher transverse Poisson's ratio and lower axial stiffness of CFRP than those of concrete.

In conclusion, CFRP, which resists the axial aggravated deformation due to the damage of concrete cylinders under uniaxial loading, is effective in providing confinement for high-strength concrete cylinders with different damage levels. However, this research can be further explored by considering size effect, different concrete compressive strengths, and FRP properties. In addition, it would be more comprehensive to investigate the relation of Poisson's ratio of CFRP repaired concrete cylinders to Poisson's ratio and stiffness of CFRP.

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