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Damage-based stress-strain model of RC cylinders wrapped with CFRP composites

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Abstract. In this study, the effects of initial damage of concrete columns on the post-repair performance of reinforced concrete (RC) columns strengthened with carbon-fiber-reinforced polymer (CFRP) composite are investigated experimentally. Four kinds of compression-damaged RC cylinders were reinforced using external CFRP composite wraps, and the stress-strain behavior of the composite/concrete system was investigated. These concrete cylinders were compressed to four pre-damaged states including low -level, medium -level, high -level and total damage states. The percentages of the stress levels of pre-damage were, respectively, 40, 60, 80, and 100% of that of the control RC cylinder. These damaged concrete cylinders simulate bridge piers or building columns subjected to different magnitudes of stress, or at various stages in long-term behavior. Experimental data, as well as a stress-strain model proposed for the behavior of damaged and undamaged concrete strengthened by external CFRP composite sheets are presented. The experimental data shows that external confinement of concrete by CFRP composite wrap significantly improves both compressive strength and ductility of concrete, though the improvement is inversely proportional to the initial degree of damage to the concrete. The failure modes of the composite/damaged concrete systems were examined to evaluate the benefit of this reinforcing methodology. Results predicted by the model showed very good agreement with those of the current experimental program.

Keywords: FRP; confinement; concrete; columns; damage, ductility; strength; model

1. Introduction

Structural concrete is one of the most commonly used construction materials in the world. Many existing concrete structures need rehabilitation or strengthening because of improper design or construction, change or modification in the purpose of use and damage caused by environmental effects or natural hazards. The repair or reinforcement of degraded civil structures with the aid of polymer composites has attracted a great amount of attention due to the economic and environmental benefits of repairing or strengthening of structures compared to demolition and rebuilding. The decision to repair or demolish a building is generally based on economic

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considerations, such as direct costs and time. Typically, the critical factor is time, since the delay in repairing a building could result in serious indirect financial consequences to both owners and insurers. Immediate reinstatement is generally required by the owners to save consequential loss of business due to the delay in the use of the building. One simple and rapid approach to repair consists in applying fiber-reinforced polymers (FRP) wrapping.

In recent years, significant research has been conducted on repairing, strengthening and retrofitting existing concrete structures with fiber-reinforced polymers (Saadatmanesh *et al*. 1994, Mirmiran *et al*. 1998, Shehata *et al*. 2002, Chaallal *et al*. 2003, Campione *et al*. 2004, Matthys *et al*. 2005, Wu *et al*. 2006, Almusallam 2007, Benzaid *et al*. 2008, Rousakis and Karabinis 2008, Benzaid *et al*. 2010, Piekarczyk *et al*. 2011, Dan 2012, Chikh *et al*. 2012, Punurai et al. 2013, Ji *et al*. 2013, Micelli and Modarelli 2013, Wu and Jiang 2013, Benzaid and Mesbah 2013, Choi *et al.* 2014, Colajanni *et al*. 2014, Benzaid and Mesbah 2014, among others). However, to date, very limited research has been conducted to investigate the repair of pre-damaged reinforced concrete using FRP wraps (Demers and Neale 1999, Ilki and Kumbasar 2002, Guoqiang *et al*. 2003, Liu *et al*. 2004, Peled 2007, Yaqub and Bailey 2011, Ma *et al.* 2012, Rousakis 2014, Rabehi *et al.* 2014, Rousakis 2016, Guo *et al.* 2016).

Usually, for the most part of concrete structures, the in-service components generally work with damage cracks. Therefore, the study on the mechanical properties of pre-damaged concrete strengthened with FRP composites closed to the actual state of the in-service components has more reference value. Ilki and Kumbasar (2002), Peled (2007), Rabehi *et al.* (2014) used FRPs to reinforce concrete columns that had been previously subjected to axial loads to create a given level of damage, and it was determined that FRP strengthening could recover the compressive strength of the concrete columns. Based on a series of compressive tests, Liu *et al.* (2004) and Ma *et al.* (2012) found that the level of damage has a slight effect on the strength of FRP confined damaged columns. Guo *et al.* (2016) showed that for small amounts of CFRP reinforcement, the pre-existing damage had a significant effect on the compressive performance of normal strength concrete (NSC) confined with CFRP composite but a smaller effect on that of CFRP-confined high strength concrete (HSC). They confirm that, greater amounts of CFRP considerably improved the ultimate strength and axial strain of the specimens and eliminated the effect of the pre-existing concrete damage. In these works, Roussakis (2014) examines low concrete strength columns in three levels of rope confinement, subjected to monotonic or cyclic loading. The effectiveness of the rope composite reinforcements is assessed by the resulting axial stress versus axial and lateral strain behavior. The elaboration also includes the stress and strain values both at 3% axial strain and at ultimate strain. Suitable fiber rope confinement may improve plain concrete strength by a factor higher than 6.6 and provide an axial strain ductility higher than 40. Thereafter Roussakis (2016) showed in an interesting study that the cylinders wrapped with basalt fiber tape presented gradual fibre fracture and ductile load drop after maximum bearing load. Vinylon fibre ropes and ultra-high molecular weight polyethylene (UHMWPE) or basalt or aramid fibre tapes show interesting resilience features as they can reach high portion of their confining efficiency even after their fracture initiation. In addition, the study presents the test results of severely damaged reinforced concrete column, repaired with high strength mortar and externally wrapped with hybrid basalt-polypropylene confinement. The retrofitted column fully restored the original ever-increasing stress-strain behavior, revealing remarkable energy dissipation under cyclic loading.

In the present study, experimental results highlighting the effectiveness of using CFRP wrap for repairing pre-damaged RC cylinders are presented. The increase in bearing and deformation capacities produced by CFRP jackets on tested specimens was particularly important.

Table 1 Concrete mix proportions

Mixture	Proportions
Compressive cylinder strength at the time of testing, f'_{co} (MPa)	27*
Cement (kg/m^3)	280**
Water (kg/m^3)	180
Crushed gravel (kg/m^3)	
Ø 4/6	122.90
Ø 6/12	258.20
Ø 12/20	769.50
Sand Ø 0/4 (kg/m^3)	729.10
Air content (%)	2.30
W/C	0.64
Slump-test (cm)	8

*The compressive strength value is the average of four plain concrete specimens: f'_{co}=(26.91+27.85+26.35+27.51)/4=27.15 MPa

**Portland cement: CEM II R 32.5 MPa

2. Research significance

Many analytical models are presented in the literature, which are generally empirical and based on tests either on plain concrete specimens or reinforced concrete columns. This paper presents a stress-strain model suitable for monotonic compressive loading capable of predicting FRP's effect on reinforced-concrete columns. The model was inspired by two concrete laws: one based on damage mechanics (damage concept introduced by Kachanov 1958 (Comby 2006) and developed to be applied to concrete by Mazars (1984)); the other on extensive experimental investigation (Fahmy and Wu 2010). A damage-based stress-strain model is proposed for predicting the compressive behavior of damaged and undamaged concrete columns strengthened with CFRP composite sheets. The model is based on the degree of initial damage in concrete before repair and strengthening with external confinement using CFRP composite sheets.

3. Experimental procedures

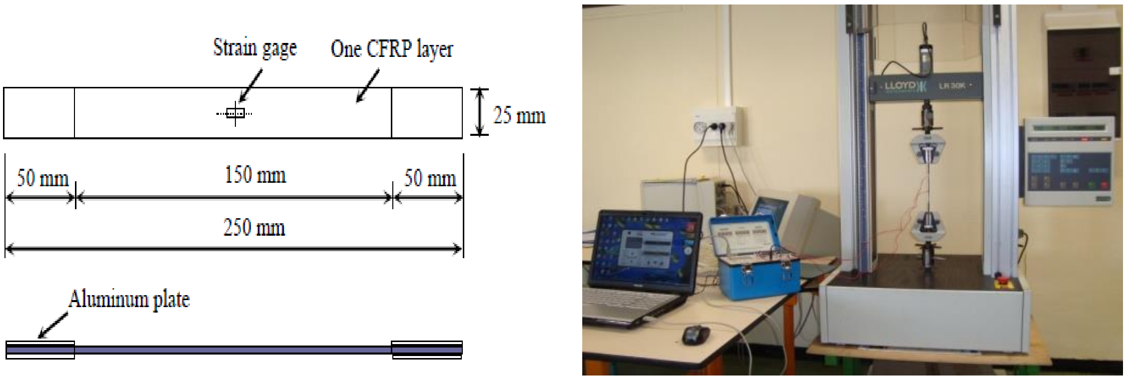
3.1 Materials properties

3.1.1 Concrete mixture

The concrete mix was made up of sand, crushed gravel and Portland cement, as shown in Table 1. The mixture was prepared in the laboratory using a mechanical mixer and was then poured into a cast iron cylindrical mold smeared with a release agent. After 48h of curing in the mold, the concrete cylinder specimens were de-molded and further cured in water at 20°C for 28 days.

3.1.2 CFRP composites

The carbon-fiber fabric used in this study was the SikaWrap-230C/45 product, a unidirectional



(a) Dimensions of CFRP flat coupons (b) CFRP specimen being tested in direct tension

Fig. 1 Flat coupon tensile tests

Table 2 Details of reinforced concrete (RC) cylinders tested

Specimen code	Procedure	f'_{co} (MPa)	CFRP layers	Loading type of initial damage
UN-0%-0L_1	Unconfined	30.82	0	Without prior damage
UN-0%-0L_2	Unconfined	31.18	0	Without prior damage
S-0%-3L_1	S		3	Without prior damage
S-0%-3L_2	S		3	Without prior damage
D.R-40%-0L_1	D.R	30.18	0	C
D.R.S-40%-3L_1	D.R.S		3	C
D.R.S-40%-3L_2	D.R.S		3	C
D.R-60%-0L_1	D.R	28.02	0	C
D.R.S-60%-3L_1	D.R.S		3	C
D.R.S-60%-3L_2	D.R.S		3	C
D.R-80%-0L_1	D.R	24.23	0	C
D.R.S-80%-3L_1	D.R.S		3	C
D.R.S-80%-3L_2	D.R.S		3	C
D.R-100%-0L_1	D.R	23.13	0	M
D.R.S-100%-3L_1	D.R.S		3	M
D.R.S-100%-3L_2	D.R.S		3	M

f'_{co}: compressive strength of RC cylinders at the time of testing, L: Layers of CFRP composite wrap, UN: unconfined with external CFRP, D: damaged, R: repaired, S: strengthened with external CFRP composite, C: 10 loading/unloading cycles, M: monotonic loading until failure

wrap. The manufacturer's guaranteed tensile strength for this carbon fiber is 4000 MPa, with a tensile modulus of 230 GPa, ultimate elongation of 17‰ and a sheet thickness of 0.129 mm. The resin system used to bond the carbon fabrics over the specimens in this work was the epoxy resin made up of two-parts, resin and hardener. The mixing ratio of the two components by weight was 4:1. SikaWrap-230C/45 was field laminated using Sikadur-330 epoxy to form a carbon fiber-reinforced polymer wrap (CFRP) used to strengthen the concrete specimens.

The mechanical properties, including the modulus and the tensile strength of the CFRP

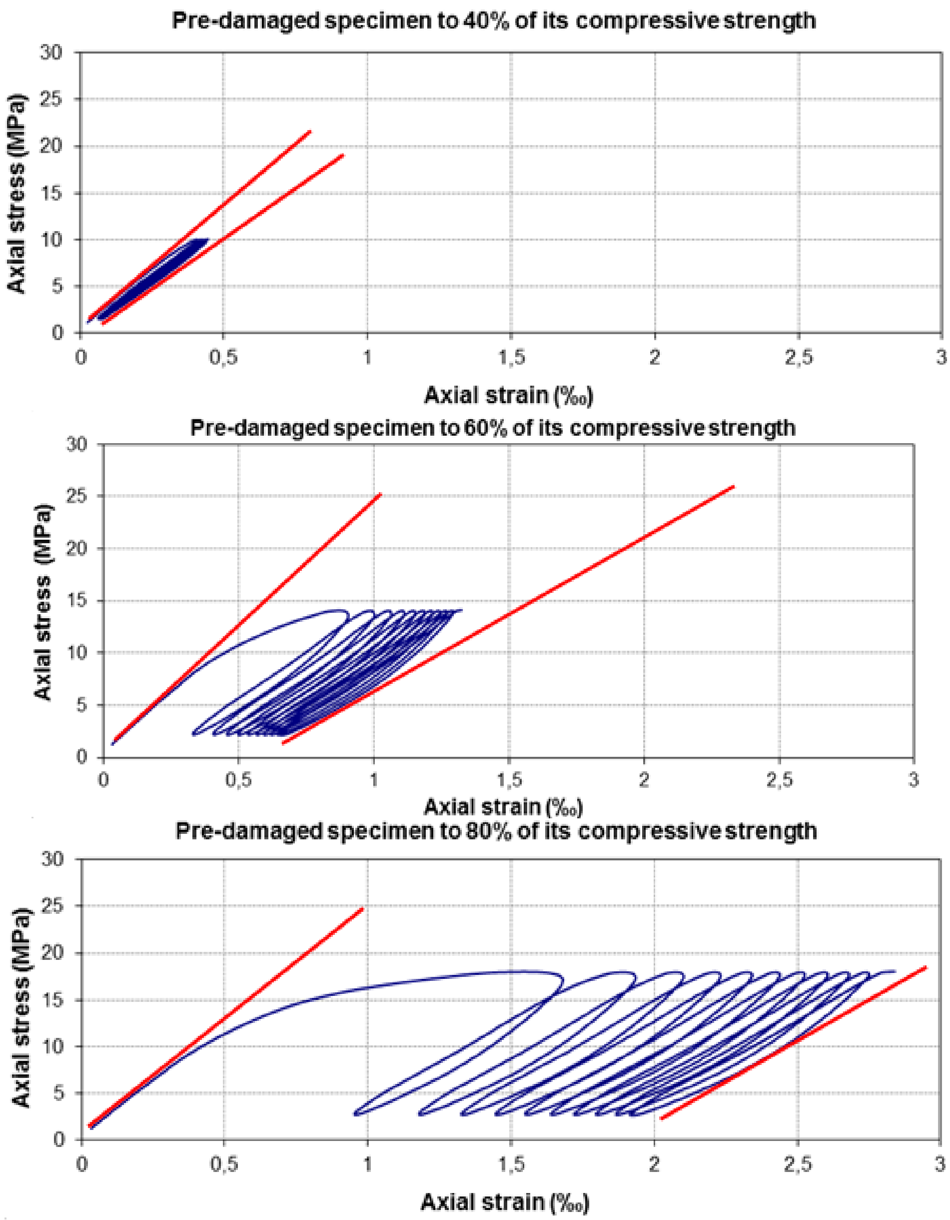


Fig. 2 Various damage situations with repeated compressive loadings (10 loading/unloading cycles)

composite (SikaWrap-230C/45+Sikadur-330 epoxy), were obtained through tensile testing of flat coupons. The tensile tests were conducted essentially following NF EN ISO 527-(1, 2 and 5) recommendations. The configuration of tensile specimens is represented in Fig. 1(a). All of the tests coupons were allowed to cure in a laboratory environment for at least 7 days. Prior to testing, aluminum plates were glued to the ends of the coupons to avoid premature failure of the coupon ends, which were clamped in the jaws of the testing machine. The tests were carried out under displacement control at a rate of 1mm/min. Longitudinal strains were measured using strain gages

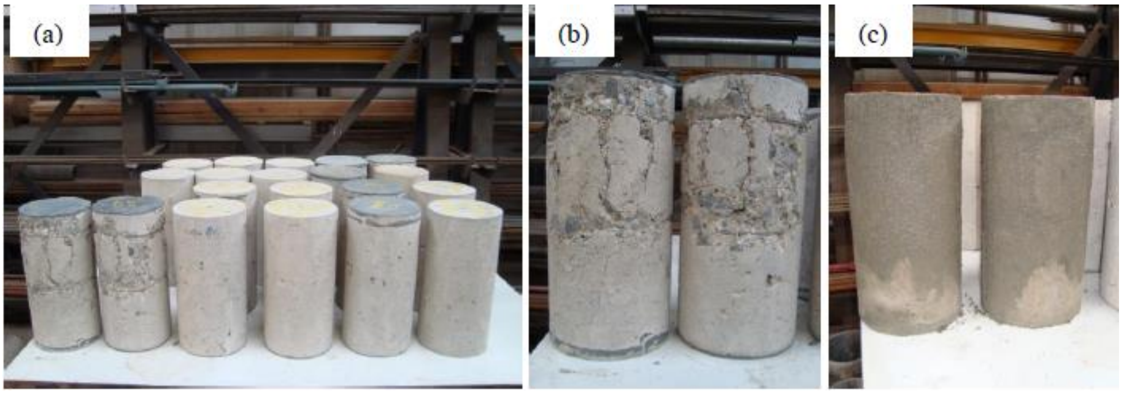


Fig. 3(a) Specimens after initial damage; (b) spalled cylinders; (c) mortar repaired cylinders

at mid-length of the test coupon. The load and strain readings were taken using a data logging system and were stored in a computer (Fig. 1(b)). Main mechanical properties obtained from the average values of the tested coupons are as follows: Thickness (per ply)=1 mm, Modulus E_{frp} = 34.5 GPa, Tensile strength f_{frp} = 500 MPa, Ultimate strain ε_{fu} = 14.5 ‰. Note that the tensile strength was defined based on the cross-sectional area of the coupons, while the elastic modulus was calculated from the stress-strain response.

3.2 Test specimens

The experimental program was carried out on cylindrical specimens with a diameter of 160 mm and a height of 320 mm. A total of 20 specimens were tested, which included 16 reinforced concrete (RC) specimens and 4 plain concrete (PC) specimens. For all RC specimens, the diameter of the main reinforcing bars and link-bars was 12 mm and 8 mm, respectively. The longitudinal steel ratio was constant for all specimens and equal to 2.25% (4HA12 mm), with a yield strength of 500 MPa. Transverse ties were spaced every 140 mm (three ties per specimen), with the yield strength being 235 MPa.

In order to simulate various damage situations of a column in a structure, 16 RC cylinders were used. Nine of these RC cylinders were compressed using 10 loading/unloading cycles to 40, 60, and 80% of their compressive strength, as shown in Fig. 2. Three other specimens were tested until failure, which represents 100% of the compressive strength of an original RC specimen. The remaining 4 specimens were the CFRP confined and unconfined RC cylinders without prior damage. Specimens involved in the experimental work are indicated in Table 2.

3.3 Repair and strengthening technique

For the specimens which spalled, a mortar with the same cement content as the original concrete was used before wrapping with CFRP jackets. The loose concrete was removed with a steel wire brush. The spalled surface of the specimen was cleaned with a brush and sprayed with water to achieve a good bond between the old concrete and the new cement mortar, as shown in Fig. 3. After preparation, the cement mortar was applied to the surface with a steel trowel and was pressed firmly into position. The specimens were kept for curing in the laboratory environment until testing.

Fig. 4(a) application of primer adhesive; (b) application of CFRP wrap; (c) specimens wrapped with CFRP

Fig. 5 Test setup

The CFRP jackets were applied to the specimens using the manual wet lay-up process. The concrete specimens were cleaned and completely dried before the resin was applied. The mixed Sikadur-330 epoxy resin was directly applied onto the substrate at a rate of 0.7 kg/m^2. The fabric was carefully placed into the resin with gloved hands and any irregularities or air pockets were smoothed out using a plastic laminating roller. The roller was continuously used until the resin was reflected on the surface of the fabric, an indication of full wetting. After the application of the first CFRP wrap, a second layer of resin was applied, at a rate of 0.5 kg/m^2, to allow the impregnation of the second layer of the CFRP wrap. The following layer was applied in the same way. Finally, a layer of resin was applied to complete the operation. The last CFRP layer was wrapped around the column with an overlap of ¼ of the perimeter to avoid sliding or debonding of fibers during tests and ensure the development of full composite strength (Benzaid *et al.* 2010). The wrapped specimens were left at room temperature for 1 week in order for the epoxy to harden adequately before testing. Fig. 4 shows samples of the wrapped specimens.

3.4 Test set up and testing procedure

Specimens were loaded under a monotonic uniaxial compression load until failure. The compression testing machine has a capacity of 200 tons. The compressive load was applied at a rate corresponding to 0.24 MPa/s and was recorded with an automatic data acquisition system.

Table 3 Mean-values of experimental results

Specimen code	f'_{cc} (MPa)	f'_{cc}/f'_{co}	ε_{cc} (‰)	$\varepsilon_{cc}/\varepsilon_{co}$	ε_r (‰)	$\varepsilon_r/\varepsilon_{ro}$	$\varepsilon_r/\varepsilon_{cc}$
UN-0%-0L	31.00	1	3.89	1	4.81	1	1.23
S-0%-3L	74.50	2.40	21.45	5.51	13.23	2.75	0.61
D.R.S-40%-3L	74.42 (-0.10%)	2.40	20.15 (-6.06%)	5.17	13.92 (+5.21%)	2.89	0.69
D.R.S-60%-3L	73.20 (-1.74%)	2.36	22.45 (+4.66%)	5.77	13.13 (-0.75%)	2.72	0.58
D.R.S-80%-3L	72.93 (-2.10%)	2.35	26.27 (+22.47%)	6.75	13.94 (+5.36%)	2.89	0.53
D.R.S-100%-3L	70.44 (-5.44%)	2.27	26.38 (+22.98%)	6.78	14.07 (+6.34%)	2.92	0.53

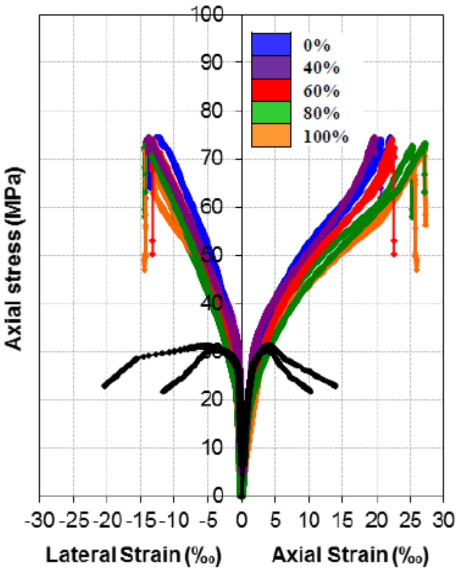


Fig. 6 Axial stress-axial and lateral strain curves for CFRP jacketed pre-damaged RC cylinders

Axial and lateral strains were measured using an appreciable extensometer. The instrumentation included one radial linear variable differential transducer (LVDT) placed in the form of a hoop at mid-height of the specimens. Measurement devices also included three vertical LVDTs to measure the average axial strains. Prior to testing, all CFRP-wrapped specimens were capped with sulfur mortar at both ends to ensure parallel surfaces and distribute the load uniformly before testing. The test setup is shown in Fig. 5.

4. Experimental results and discussion

4.1 Overall behavior

In the following section, test results are presented, including the different stress-strain

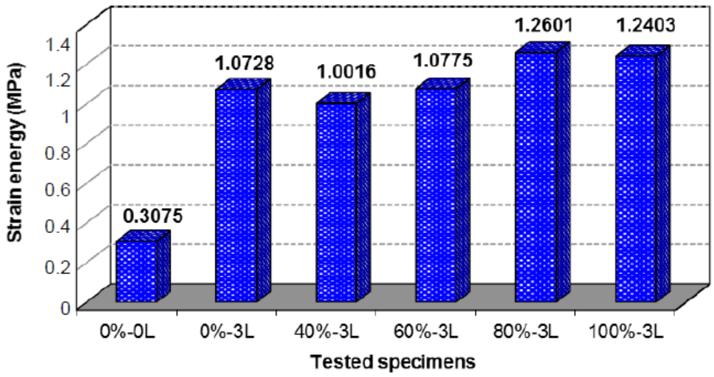


Fig. 7 Area under axial stress-strain curves, (MPa)

responses of tested specimens.

As seen in Table 3, the increase in bearing and deformation capacities produced by CFRP jackets on tested pre-damaged specimens was particularly important. Table 3 presents the average values of experimental results. It shows that if the rate of initial damage exceeds 60% of the unconfined concrete strength (f'_{co}), it slightly affects the compressive strengths (f'_{cc}) of the repaired specimens. In contrast to compressive strengths, axial (ε_{cc}) and radial (ε_r) deformations are generally improved compared to the control specimen. This result confirms that the confining pressure exerted by the composite jacket limits the radial expansion of the pre-damaged concrete specimen in the same way as the strengthened undamaged specimen.

The compressive strength and the axial and radial deformations for the control specimen (S-0%-3L) are respectively 74.50 MPa, 21.45‰ and 13.23‰. These values are very close to those recorded for similar specimens pre-damaged at the rate of 40%, 60%, 80% and 100% of their unconfined concrete strength (f'_{co}), see Table 3. This indicates that the investigated strengthening technique is effective on strength and deformability enhancement and can also be used for strengthening of pre-damaged concrete member after repair.

4.2 Stress-strain response

Fig. 6 shows that all the columns specimens behaved similarly during the initial part of loading, indicating that the passive confinement action due to the dual confinement (transverse steel reinforcement and CFRP composite) does not play a role at this stage.

Fig. 6 also indicates that, for both pre-damaged and undamaged strengthened specimens, the stress-strain relationships change significantly in a positive manner. As shown in this Figure, all CFRP strengthened specimens showed a typical bilinear trend with a transition zone. Pre-damaged specimens, after being repaired and strengthened with CFRP composite sheets, behaved in almost the same way as the strengthened undamaged specimens. What is remarkable is that the pre-damaged concrete specimens, after being repaired and strengthened, recovered their strength and ductility.

4.3 Strain energy

Table 4 shows a quantitative comparison of the strain energy of tested specimens. Strain energy

Fig. 8 Typical failure modes for some pre-damaged and undamaged strengthened specimens

Table 4 Comparison of energy dissipation

Percentage of the initial damage	Specimen code	Area under axial stress-axial strain curves (MPa)	Mean values (MPa)
0% f'_{co}	UN-0%-0L_1	0.2553	0.3075
	UN-0%-0L_2	0.3597	
0% f'_{co}	S-0%-3L_1	1.0068	1.0728
	S-0%-3L_2	1.1387	
40% f'_{co}	D.R.S-40%-3L_1	1.0332	1.0016
	D.R.S-40%-3L_2	0.9699	
60% f'_{co}	D.R.S-60%-3L_1	1.0850	1.0775
	D.R.S-60%-3L_2	1.0700	
80% f'_{co}	D.R.S-80%-3L_1	1.2280	1.2601
	D.R.S-80%-3L_2	1.2921	
100% f'_{co}	D.R.S-100%-3L_1	1.2903	1.2403
	D.R.S-100%-3L_2	1.1904	

is a good indicator of ductility, which is calculated by considering the area under the axial stress-axial strain curves. The average strain energy for the unconfined specimens (UN-0%-0L) was about 0.3 MPa. Therefore, as seen in Table 4, this strain energy was improved by approximately 3 to 4 times for three layers of CFRP composite wrap, when compared with unconfined concrete specimens. The calculated strain energy values are presented in Fig. 7. As seen in this figure, the increase in strain energy is very significant for external CFRP composite confined specimens of pre-damaged and undamaged RC specimens. It should be noted that, the increase in strain energy obtained for pre-damaged RC specimens is similar (sometimes better) than undamaged RC specimens.

In the case of cylindrical specimens, the initial damage is at least more uniform, giving rise to a new material cracked with decreasing resistance as a function of increasing the rate of damage. This explains the improvement of the strain energy provided by the composite jacket for the most damaged specimens (D.R.S-80%-3L and D.R.S-100%-3L). It can be concluded that the effect on strength and ductility capacities decreases with an increase in initial concrete strength (in our case the reduction in concrete strength is due to the initial damage).

4.4 Failure mode

All the CFRP-strengthened cylinders (pre-damaged or undamaged) failed by rupture of the FRP jacket due to hoop tension. The CFRP-confined specimens failed in a sudden manner at a level of axial strain ranging from 21.45‰ to 26.38‰ and were preceded by some snapping sounds. Tis behaviour occur because more energy is accumulated before failure. Hence, many hoop sections formed as the CFRP ruptured. These hoops were either concentrated in the central zone of the specimen or distributed over the entire height (Fig. 8), indicating that the pre-existing damage had no significant effect on the failure mode of CFRP confined pre-damaged specimens. For all specimens, delamination was not observed at the overlap location of the CFRP-jacket, which confirmed the adequate stress transfer over the splice.

On the other hand, it can be observed that the behaviour of RC columns, pre-damaged and strengthened with external CFRP wrap, were almost identical to the control specimens. This similarity is probably due to the redistribution of damage accumulation (Rousakis 2016). This phenomenon can be explained by the fact that dual confinement of circular concrete columns consisting of CFRP sheets and steel ties can provide stronger confinement to the concrete core. knowing that at the end of testing of specimens D.R.S-100%-3L and D.R.S-80%-3L, a slight expansion of the concrete cover was observed at the CFRP rupture zone (Fig. 8) which may be due to buckling of the longitudinal steels bars.

However, experimental results show that the lateral strains were around 13.13‰ and 13.94‰, with the exception of specimens D.R.S-100%-3L, where the lateral strain was about 14.07‰ (Table 3). Therefore, failure generally occurs prematurely and the circumferential failure strain was lower than the ultimate strain obtained from standard tensile testing of the FRP composite (ε_{fu} = 14.5‰). This reduction in the strain of the FRP composites can be attributed to several causes as reported in related literature (Ilki and Kumbasar 2002, Lam and Teng 2003, De Lorenzis and Tepfers (2003), Matthys *et al*. 2005, Rousakis *et al*. 2008, Benzaid *et al*. 2010):

- The curved shape of the composite wrap or misalignment of fibers may reduce FRP axial strength;
- Concrete is initially cracked for pre-damaged specimens, after which uneven distribution of lateral strain occurs as a consequence of uneven distribution of damage.

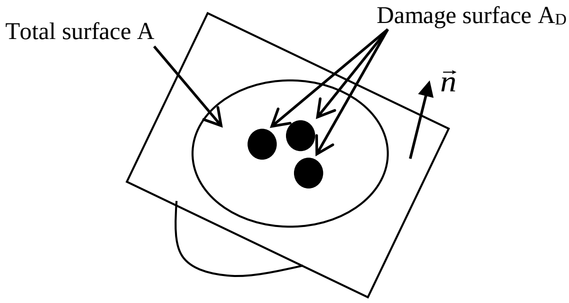


Fig. 9 Definition of damage (Comby 2006)

- Whereas for undamaged confined specimens near failure, the concrete is internally cracked resulting in non-homogeneous deformations.

Due to these non-homogeneous deformations and high loads applied on the cracked concrete, local stress concentrations may occur in the FRP reinforcement.

5. Definition of damage and calculation hypothesis

The term "damage" refers to the progressive reduction of the mechanical properties of material due to initiation, growth and coalescence of microscopic cracks and/or microvoids. These internal changes lead to a reduction in the available capacities in load-resisting area that contributes to the degradation of mechanical properties of the material. A simple means of describing the state of damage consists in its geometric quantification and dates back to Kachanov 1958 (Comby 2006).

In a cross-section of damaged body, we therefore consider an area element $\boldsymbol{A}$ (initial area of the undamaged section) with unit normal vector $\vec{n}$ (Fig. 9) and $\boldsymbol{A_D}$ the damaged surface (the area of the defects in this section). $\tilde{\boldsymbol{A}}$ denotes the effective resistant surface ($\tilde{A} < A$) and takes into account voids and cracks.

$$\tilde{A} = A - A_D \tag{1}$$

The amount of damage can then be characterized by the area fraction

$$D_n = A_D / A = (A - \tilde{A})/A \tag{2}$$

An assumption frequently encountered consists in assuming isotropic damage. If the defects distribution does not display preferred directions, damage is isotropic (D_n does not depend on $\vec{n}$) and the state of damage can be characterized by a scalar

$$D_n = D \quad \text{with} \quad 0 \leq D_n \leq 1 \tag{3}$$

Where $D_n = 0$ corresponds to the undamaged material and $D_n = 1$ describes the totally damaged material. The amount of damage D can be determined by measuring the effective Young's modulus of the damaged material

$$\tilde{E} = E\,(1 - D) \tag{4}$$

$\tilde{E}$ and E are respectively the effective Young modulus of damaged material and the initial Young modulus of undamaged material.

Table 5 Degree of damage of RC cylinders

Initial damage	Specimen code	E_c (MPa)	$\tilde{E}_c$ (MPa)	$D=1-(\tilde{E}_c/E_c)$	D (average)
0% f'_{co}	S-0%-3L$_1$	25753	25753	0	0
	S-0%-3L$_2$	25447	25447	0	
40% f'_{co}	D.R.S-40%-3L$_1$	25610	21700	0.152	0.15
	D.R.S-40%-3L$_2$	25420	21510	0.153	
60% f'_{co}	D.R.S-60%-3L$_1$	25062	17075	0.318	0.32
	D.R.S-60%-3L$_2$	23566	15821	0.328	
80% f'_{co}	D.R.S-80%-3L$_1$	24346	14793	0.392	0.38
	D.R.S-80%-3L$_2$	24228	14945	0.383	
100% f'_{co}	D.R.S-100%-3L$_1$	24253	11500	0.525	0.52
	D.R.S-100%-3L$_2$	23648	11257	0.523	

The damage concept introduced by Kachanov has been successfully applied to concrete by Mazars (1984). From Eq. (4), the degree of damage D of reinforced concrete specimens of the present study is estimated as follows

$$D = 1 - (\tilde{E}_c / E_c) \tag{5}$$

With:

E_c: the initial Young modulus of undamaged reinforced concrete specimen.

$\tilde{E}_c$: the effective Young modulus of damaged reinforced concrete specimen.

D: the degree of damage of the specimen before being repaired with the CFRP composites.

Table 5 shows the degree of damage D of reinforced concrete (RC) cylinders (Ø160×320 mm).

6. Fahmy and Wu model

Based on the experimental results of 257 cylindrical concrete specimens confined with different types of composite material collected from the existing literature, an analytical model has been developed by Fahmy and Wu (2010) to predict the stress-strain responses of FRP-confined concrete columns with strain hardening performance. This model is characterized by the fact that the definitions of parameters of the stress-strain relationship are interrelated and reflect the impact of FRP confining material throughout the provided lateral stiffness, rather than the ultimate lateral pressure, which is only considered responsible for the definition of the endpoint of this relationship. For FRP-confined concrete, Fahmy and Wu (2010) assumed that the stress-strain curve is bilinear. The first ascending branch is described as follows

$$\sigma_c = E_c \varepsilon_c - \frac{(E_c - E_2)^2}{4 f_o} \varepsilon_c^2 \tag{6}$$

Where, ε_c and σ_c are the axial strain and concrete stress, E_c and E_2 define the elastic modulus of unconfined concrete and the second slope of the stress-strain relationship of FRP-confined concrete, and finally f_o is the reference plastic stress, which represents the intersection of the second slope of the stress-strain relationship with the stress axis and is taken as the compressive

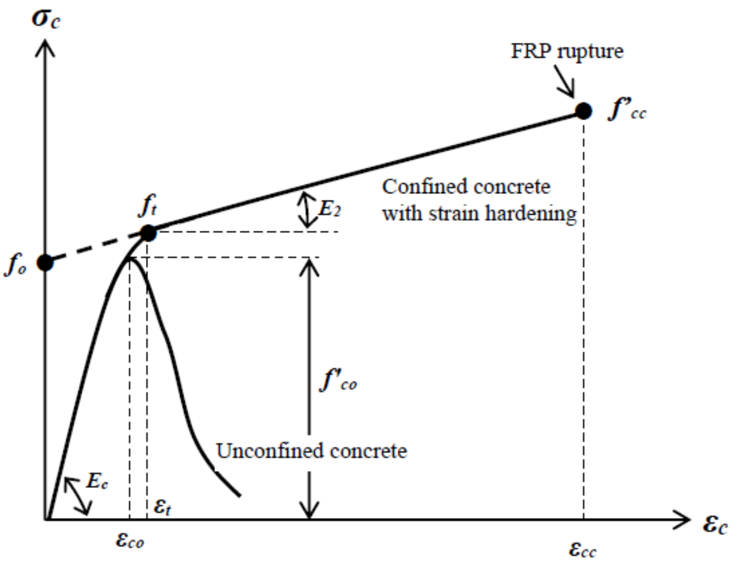


Fig. 10 Typical stress-strain responses and model parameters (Fahmy and Wu 2010)

strength of unconfined concrete f'_{co}. Fig. 10 shows the various parameters involved.

In this model, the transition zone is defined respectively by the stress and strain-transition

$$f_t = E_c \varepsilon_t - \frac{(E_c - E_2)^2}{4 f'_{co}} \varepsilon_t^{\,2} \tag{7}$$

$$\varepsilon_t = \frac{2 f'_{co}}{E_c - E_2} \tag{8}$$

While the second ascending branch of the stress-strain relationship is directly defined by the compressive strength of FRP-confined concrete f'_{cc} and the corresponding axial deformation ε_{cc} as follows

$$f'_{cc} = f'_{co} + k_1 f_{lu} \tag{9}$$

$$\varepsilon_{cc} = \frac{f'_{cc} - f_o}{E_2} \tag{10}$$

Where,
$$\begin{cases} k_1 = 4.5 f_{lu}^{\,-0.3} \quad \text{for } f'_{co} \leq 40\text{MPa} \\ E_2 = m_2 \left(245.61 f'^{\,m_1}_{co} + 0.6728 E_l\right) \\ m_1 = 0.5\ ;\ m_2 = 0.83 \quad \text{for } f'_{co} \leq 40\text{MPa} \\ m_1 = 0.2\ ;\ m_2 = 1.73 \quad \text{for } f'_{co} > 40\text{MPa} \\ E_l = \dfrac{2 E_{prf}\ N\ t_{prf}}{d}\text{, the lateral modulus.} \end{cases}$$

For a circular concrete column, E_{prf}, N, t_{prf} and d are, respectively: the elastic modulus of FRP composite, the number of FRP-layers, the thickness of one FRP-layer, and the diameter of the concrete column.

7. Proposed stress-strain model

The simplicity of the described stress-strain response of FRP-confined concrete by Fahmy and Wu (2010), effectively prodded the authors to take up the same assumptions to describe this relation. The originality of the proposed stress-strain model is that it takes into account the initial damage of the concrete. Therefore, it will be applicable to damaged concrete columns repaired with externally applied FRP composite wrap. For this reason, the Fahmy and Wu model has been modified and adapted by introducing the degree of damage of the concrete.

7.1 First ascending branch

The first ascending branch of the stress-strain relationship of this model is generated by the equations summarized in Table 6. The equations proposed by Fahmy and Wu (2010) were modified by introducing the degree of initial damage of the reinforced concrete before being repaired and strengthened using FRP composite wrap. The proposed equations are based on the second slope of the stress-strain relationship of FRP-confined concrete $\tilde{E}_2$, the elastic modulus $\tilde{E}_c$ and the compressive strength $\tilde{f}'_{co}$ of damaged concrete before being repaired and strengthened. The first ascending branch is described as follows

$$\sigma_c = \tilde{E}_c \varepsilon_c - \frac{\left(\tilde{E}_c - \tilde{E}_2\right)^2}{4 f_o} \varepsilon_c^2 \tag{11}$$

The transition zone is defined respectively by the stress and strain-transition

$$f_t = \tilde{E}_c \varepsilon_t \; \frac{\left(\tilde{E}_c - \tilde{E}_2\right)^2}{4 \tilde{f}'_{co}} \varepsilon_t{}^2 \tag{12}$$

$$\varepsilon_t = \frac{2 \tilde{f}'_{co}}{\tilde{E}_c - \tilde{E}_2} \tag{13}$$

For initially undamaged concrete, the reference plastic stress f_o, which represents the intersection of the second slope of the stress-strain relationship with the stress axis, is taken as the compressive strength of unconfined concrete f''_{co}. For pre-damaged concrete, this reference plastic stress is equal to $\tilde{f}'_{co}$, defined as the compressive strength of initially-damaged concrete before being repaired and strengthened with FRP composite wrap.

However, the compressive strength value of initially- damaged concrete $\tilde{f}'_{co}$ is given according to f'_{co} and the damage degree denoted D, by the following equation

$$\tilde{f}'_{co} = f'_{co} \; (1 - D^2) \tag{14}$$

Table 6 Eqs. of the first ascending branch of the proposed model

1st ascending branch equations			
Strength	Reference plastic stress (f_o)	Transition stress (f_t)	Transition strain (ε_t)
Undamaged concrete Fahmy and Wu model (2010):			
$\sigma_c = E_c\varepsilon_c - \frac{(E_c - E_2)^2}{4f_o}\varepsilon_c^2$	f'_{co}	$f_t = E_c\varepsilon_t - \frac{(E_c - E_2)^2}{4f'_{co}}\varepsilon_t^{\,2}$	$\varepsilon_t = \frac{2f'_{co}}{E_c - E_2}$
Initially damaged concrete proposed model:			
$\sigma_c = \tilde{E}_c\varepsilon_c - \frac{(\tilde{E}_c - \tilde{E}_2)^2}{4f_o}\varepsilon_c^2$ $\tilde{f}'_{co} = f'_{co}\ (1 - D^2)$	$\tilde{f}'_{co}$	$f_t = \tilde{E}_c\varepsilon_t - \frac{(\tilde{E}_c - \tilde{E}_2)^2}{4\tilde{f}'_{co}}\varepsilon_t^{\,2}$ $\tilde{E}_c = E_c\ (1 - D)$	$\varepsilon_t = \frac{2\tilde{f}'_{co}}{\tilde{E}_c - \tilde{E}_2}$

This relationship was derived from the experimental results performed on RC cylindrical specimens with different levels of initial damage, while the elastic modulus of damaged concrete before being repaired and strengthened $\tilde{E}_c$ can be obtained depending on the elastic modulus of undamaged unconfined concrete E_c and the damage degree D through Eq. (4).

7.2 Second ascending branch

The second branch of the stress-strain relationship is given using Eqs. (15)-(16) and the second slope of the stress-strain curve is related to the lateral modulus of the FRP-composite jacket, denoted E_l. In Table 7, the given equations reflect the effect of the lateral stiffness of the composite jacket and the compressive strength of initially-damaged concrete $\tilde{f}'_{co}$ on the slope of the second branch $\tilde{E}_2$ of the stress-strain relationship of the FRP-confined concrete.

The peak value of the bilinear ascending stress-strain relationship is defined by the ultimate strength (which coincides with the maximum strength). The confinement effectiveness coefficient k_1 in the equation giving f'_{cc} for undamaged concrete confined with FRP composite was calibrated based on regression of experimental results of the current study. Therefore, k_1 was set to 5.6 instead of 4.5 adopted in the Fahmy and Wu model (2010). The modified compressive strength of FRP-confined concrete f'_{cc} (see Table 7) and the degree of damage of concrete D are used to define the compressive strength of the damaged concrete after being repaired and strengthened with FRP composite wrap $\tilde{f}'_{cc}$, as follows

$$\tilde{f}'_{cc} = f'_{cc}\ (1 - D^4) \tag{15}$$

Secondly, the corresponding deformation of damaged concrete confined with FRP composite is a function of the compressive strength of the damaged concrete repaired and confined with FRP-composite $\tilde{f}'_{cc}$, the compressive strength of the undamaged concrete confined with FRP composite f'_{cc} and the second slope of the stress-strain relationship of the damaged concrete after being

Table 7 Eqs. of the second ascending branch of the proposed model

2nd ascending branch equations		
Ultimate strength	Ultimate strain	Second slope of the stress-strain relationship
Undamaged concrete Fahmy and Wu model (2010) "modified":		
$f'_{cc} = f'_{co} + k_1 f_{lu}$ $k_1 = 5.6 f_{lu}^{-0.3}$, for $f'_{co} \leq$ 40MPa	$\varepsilon_{cc} = \frac{f'_{cc} - f_{co}}{E_2}$	$E_2 = m_2 \left(245.61 f'^{\,m_1}_{co} + 0.6728 E_l\right)$
Initially damaged concrete proposed model:		
$\tilde{f}'_{cc} = f'_{cc} \ (1 - D^4)$	$\tilde{\varepsilon}_{cc} = \frac{\tilde{f}'_{cc} - \tilde{f}'_{co}}{\tilde{E}_2}$	$\tilde{E}_2 = m_2 \left(245.61 \tilde{f}'^{\,m_1}_{co} + 0.6728 E_l\right)$ $m_1 = 0.5$; $m_2 = 0.83$, for $f'_{co} \leq$ 40MPa $E_l = \frac{2E_{prf}\ N\ t_{prf}}{d}$

Table 8 Parameters of the proposed model

Strength of initial damage		0% f'_{co}	40% f'_{co}	60% f'_{co}	80% f'_{co}	100% f'_{co}
Experimental values	f'_{co} (*MPa*)	31.00	30.18	28.02	24.23	23.13
	f'_{cc} (*MPa*)	74.50	74.42	73.20	72.93	70.44
	ε_{co} (‰)	3.89	3.89	3.89	3.89	3.89
	ε_{cc} (‰)	21.45	20.15	22.45	26.27	26.38
	E_c (*MPa*)	25600	25515	24314	24287	23950.50
	$\tilde{E}_c$ (*MPa*)	25600	21605	16448	14869	11378.50
	D	0	0.15	0.32	0.38	0.52
Theoretical values	$\tilde{f}'_{co}$ (*MPa*)	31.00	30.30	27.82	26.52	22.61
	$\tilde{f}'_{cc}$ (*MPa*)	74.58	74.54	73.79	73.02	69.12
	f_t (*MPa*)	35.85	35.93	34.61	33.60	30.42
	f_l (*MPa*)	18.75	18.75	18.75	18.75	18.75
	$\tilde{\varepsilon}_{cc}$ (‰)	23.41	23.98	25.57	26.23	27.48
	ε_t (‰)	2.61	3.05	3.77	3.99	4.62
	E_l (*MPa*)	1293.75	1293.75	1293.75	1293.75	1293.75
	$\tilde{E}_2$ (*MPa*)	1857.48	1844.64	1797.80	1772.34	1691.96
	$\tilde{E}_c$ (*MPa*)	25600	21687.75	16533.52	15057.94	11496.24

repaired and strengthened with FRP composite wrap $\tilde{E}_2$, it is given as follows

$$\tilde{\varepsilon}_{cc} = \frac{\tilde{f}'_{cc} - \tilde{f}'_{co}}{\tilde{E}_2} \tag{16}$$

Table 9 Comparison between experimental and predicted results

Strength of initial damage		$0\% f'_{co}$	$40\% f'_{co}$	$60\% f'_{co}$	$80\% f'_{co}$	$100\% f'_{co}$
Degree of damage *D*		0	0.15	0.32	0.38	0.52
$f'_{cc,theo}$ (*MPa*)		74.58	74.54	73.79	73.02	69.12
$\varepsilon_{cc,theo}$ (‰)		23.41	23.98	25.57	26.23	27.48
$f_{cc,exp}$ (*MPa*)	specimen no.1	74.40	74.20	72.30	72.70	71.90
	specimen no.2	74.60	74.65	74.10	73.17	68.99
$\varepsilon_{cc,exp}$ (‰)	specimen no.1	20.70	20.60	22.60	25.34	27.16
	specimen no.2	22.20	19.70	22.30	27.21	25.61
$f'_{cc,theo}/f'_{cc,exp}$	specimen no.1	1.002	1.004	1.020	1.004	0.961
	specimen no.2	0.999	0.998	0.995	0.997	1.001
	average value	1.000	1.001	1.007	1.000	0.981
$\varepsilon_{cc,theo}/\varepsilon_{cc,exp}$	specimen no.1	1.130	1.164	1.131	1.035	1.011
	specimen no.2	1.054	1.217	1.146	0.963	1.073
	average value	1.092	1.190	1.138	0.999	1.042

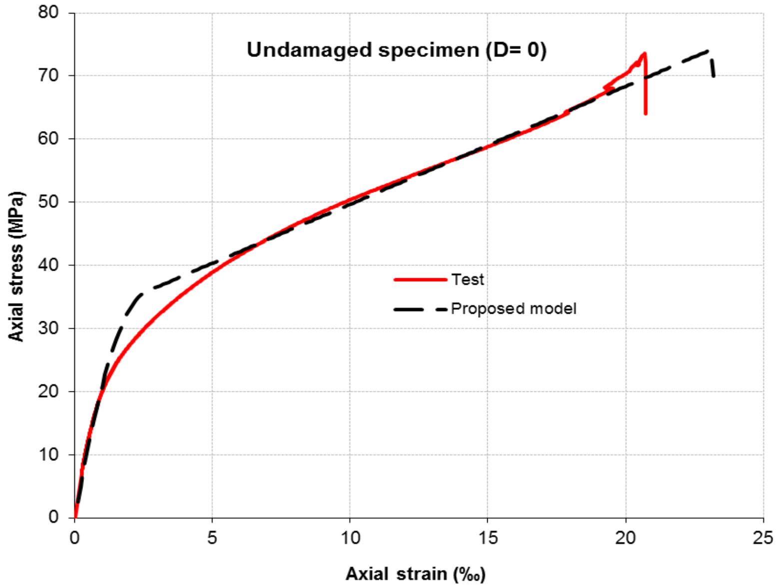


Fig. 11 Comparison of stress-strain curves of specimen S-0%-3L

The model is developed based on the average values of experimental results obtain in this study, whereas the parameters of the proposed model are summarized in Table 8.

7.3 Validation of the proposed model

Using the model provided above, the compressive axial stress-strain curves of pre-damaged concrete repaired and strengthened with FRP composite wrap were predicted, as shown in Figs. 11 to 15 and Table 9, which clearly exhibit excellent agreement between the experimental and

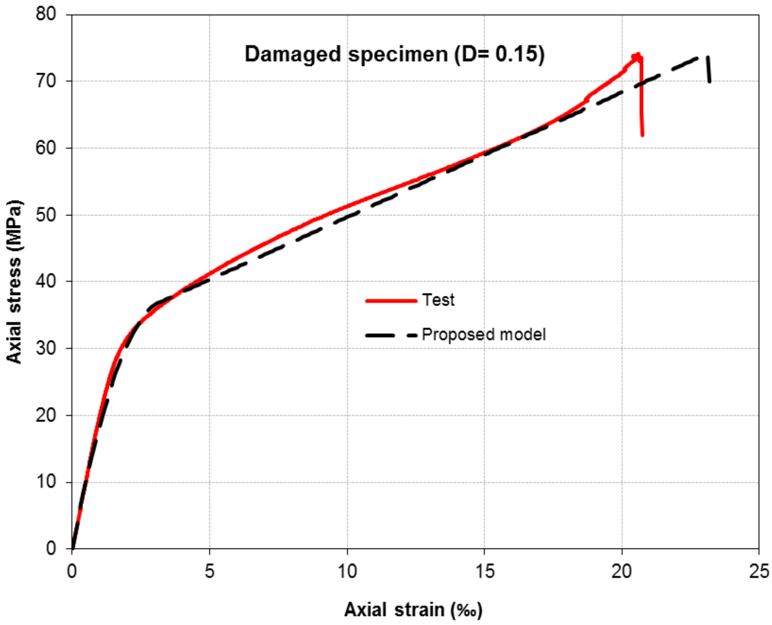


Fig. 12 Comparison of stress-strain curves of specimen D.R.S-40%-3L

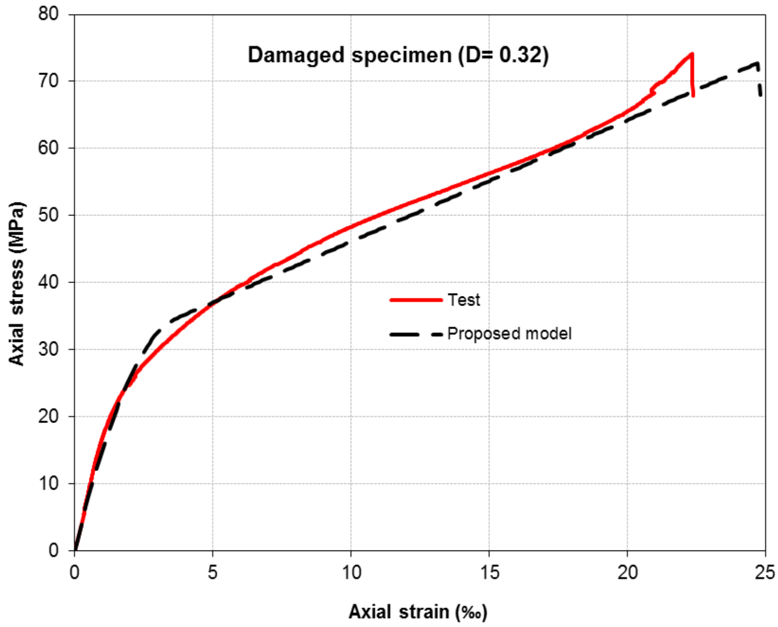


Fig. 13 Comparison of stress-strain curves of specimen D.R.S-60%-3L

predicted curves. This result clearly shows the reliability of the proposed model. We also note that for a small degree of damage (D = 0.15 and 0.32), the curves diverge slightly at the end of loading. In fact, the theoretical equations provide axial strain slightly greater than those recorded in tests (an increase of approximately +19% and +13.8%, respectively), as shown in Table 9.

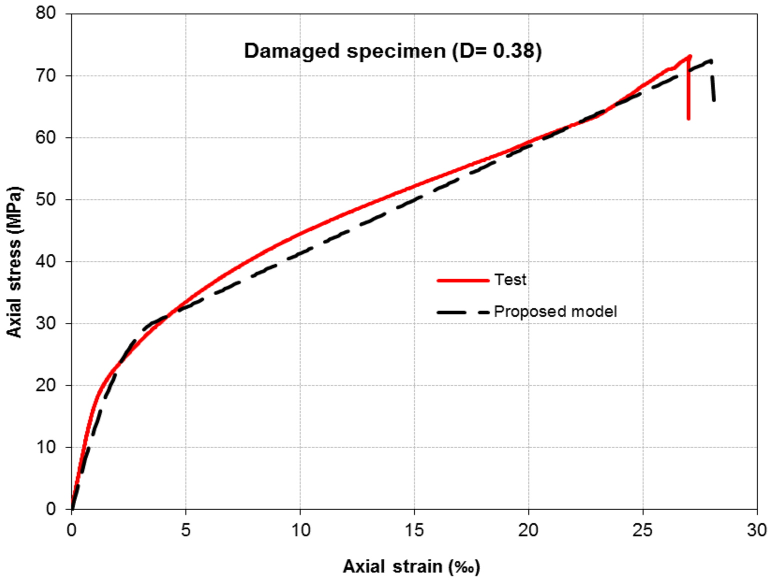


Fig. 14 Comparison of stress-strain curves of specimen D.R.S-80%-3L

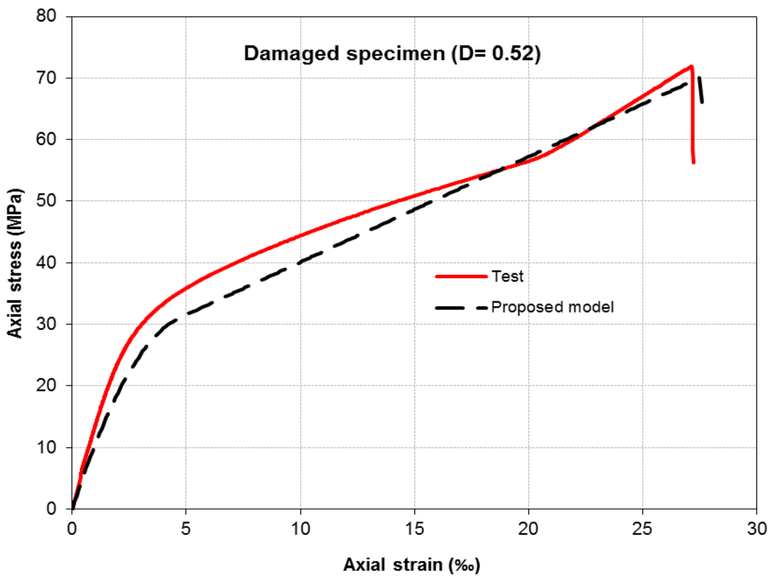


Fig. 15 Comparison of stress-strain curves of specimen D.R.S-100%-3L

8. Conclusions

This work investigates the behavior of pre-damaged and undamaged reinforced-concrete strengthened with CFRP composite sheets. The results obtained showed that application of the investigated strengthening technique to pre-damaged reinforced-concrete members is as effective as application to the undamaged concrete members. A damage-based stress-strain model is proposed for predicting the compressive behavior of pre-damaged and undamaged RC columns strengthened with CFRP composite sheet.

• The pre-damaged specimens, after being repaired and strengthened with CFRP composite sheets, behaved in almost the same way as the strengthened undamaged specimens. This indicates that the repaired and strengthened RC specimens recover their strength, ductility and strain energy characteristics.

• The repair and strengthening of RC members using external CFRP composite sheets is effective on strength and deformability enhancement. Consequently, a significant increase in strain energy is possible, implying an increase in energy dissipation capacity.

• The level of pre-existing damage has a slight effect on the strength and ductility of CFRP confined pre-damaged specimens.

• The level of pre-existing damage had no significant effect on the failure mode of the specimens repaired and strengthened with externally CFRP sheets.

• The behavior of reinforced-concrete columns, pre-damaged and strengthened with external CFRP wrap, were almost identical to the control specimens. This similarity is probably due to the redistribution of damage accumulation. It can be explained by the fact that dual confinement of circular concrete columns consisting of CFRP sheets and steel ties can provide stronger confinement to the concrete core.

• Results predicted by the proposed stress-strain model showed very good agreement with results of the current experimental program. It is believed that the proposed model can provide an acceptable prediction of the stress-strain response of pre-damaged reinforced-concrete repaired and strengthened using CFRP composite sheet.

• Therefore, further work is required to verify the applicability of the proposed model over a wider range of geometric and material parameters to improve its accuracy (particularly that of the axial strain at peak stress) and to place it on a clear mechanical basis. Both additional tests and theoretical investigation are needed to describe the quantitative aspect of the dual confinement consisting of CFRP sheets and steel ties or spirals.

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