Construction and Building Materials 123 (2016) 553–564

Contents lists available at ScienceDirect

Construction and Building Materials

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

Bond slip behavior of anchored CFRP strips on concrete surfaces

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HIGHLIGHTS

- The strengthening of RC walls by using CFRP strips was an effective technique.
- The strip configurations were effective on the hysteretic behavior of wall.
- CFRP strips are not effective initial lateral stiffness of the specimens.
- Displacement capacities of specimens have been improved by strengthening technique.
- Strengthened specimens are dissipated much more energy than reference specimen.

ARTICLE INFO

Article history:
Received 23 February 2016
Received in revised form 22 June 2016
Accepted 15 July 2016
Available online 21 July 2016

Keywords:
Bond-slip model
Strain distribution
CFRP
Anchorage

ABSTRACT

In this study, strain distributions and the bond slip behaviors at the carbon fiber reinforced polymer (CFRP) strips and reinforced concrete interface were investigated. 14 concrete specimens with externally bonded CFRP strips were tested. Main variables considered in the experimental study were width of the CFRP strips, bond length of CFRP strips and the number of anchorages. The test results obtained from the experimental study are comparatively presented in terms of strain distributions on CFRP strips with anchorages, stress – displacement behaviors, initial stiffnesses, energy dissipation capacities of test specimens. From the test results it is observed that using anchorages is very effective in terms of ultimate load capacity, strain distribution and energy dissipation capacity. The results of the experimental study are compared with analytical results obtained from several bond strength models available in the literature. A bond slip model was proposed based on the results of the conducted tests. It was observed that bond stress of the CFRP strips increased with increasing number of anchorages.

1. Introduction

Catastrophic damage to structures due to major earthquakes around the world demonstrated seismic vulnerability of many existing buildings. The 1999 Kocaeli- Turkey and 2003 Bam-Iran earthquakes caused loss of a large number of lives due to building collapses while the one that occurred in Taiwan in 1999 caused the collapse of thousands of buildings. In many urban areas around the world, number of buildings designed and constructed using codes that are known to provide poor safety are potential hazards. Therefore, these structurally deficient buildings should be retrofitted to withstand the earthquakes in compliance with modern building design codes. Local retrofitting of poor structural members may be a feasible option to reduce the seismic vulnerability of existing structures. In relation to that retrofitting of deficient reinforced concrete (RC) members using externally bonded carbon fiber reinforced polymers (CFRP) may be a viable option due to the fact that the advanced composite materials such as CFRP are significantly stronger and lighter than structural steel. Many analytical and experimental studies have shown that retrofitting structural elements using CFRP strips or sheets significantly improve their strength and ductility without adding stiffness to the elements [1–4]. The high modulus of elasticity and strength of CFRP makes it suitable for applications as confinement for reinforced concrete columns and beams to improve their strength and ductility. Furthermore, resistance to corrosion and environmental conditions and ease of application are other important properties of CFRP. In relation to these advantages, CFRP has been a widely used material for the retrofitting of RC structures and many kinds and sizes of CFRP are available in the market, suitable for different sorts of retrofitting details. Therefore, experimental studies on the retrofitting of RC elements with CFRP applications and studies on the analytical models investigating the behavior of CFRP have been widely conducted.

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http://dx.doi.org/10.1016/j.conbuildmat.2016.07.060
0950-0618/

From the literature [5–15], it was observed that concrete elements reinforced with CFRP fails in three main modes: (i) debonding of CFRP from concrete, (ii) epoxy failure due to the excessive shear stresses larger than the shear strength of epoxy and (iii) rupture of CFRP under high axial tension loads. However, the rupture of CFRP under tensile axial loads is a very rare failure mode due to the fact that CFRP has very high axial tension strength. In contrary to that, in many cases CFRP debonds from the concrete surface or the adhesive-concrete interface reaches its shear stress capacity and fails before the rupture of CFRP. The most likely failure mode is the debonding of CFRP from the concrete surface. In contrary to that effect of this interfacial slip was neglected in analytical modeling methods which were based on the assumption of "perfect" bond between concrete and CFRP [16–22]. In the study of Napoli et al. [23], it was stated that such models have shown varying degrees of accuracy in the prediction of experimental results, often overestimating the predictions in terms of flexural strength and maximum fiber reinforced polymer (FRP) strain and such discrepancies between experiments and analytical predictions may be attributed to neglecting the concrete - FRP slip which reduces the effectiveness of the strengthening. Consequently, it is clear that the stress distribution between FRP and concrete must be known to accurately estimate the actual capacity of the retrofitted structure. Therefore, studies focused on determining the stress between FRP and the concrete interface became popular in the recent years [13–33]. A recent study [33] showed that many different experimental setups have been used for determining the CFRP to concrete bond strength, but no consensus on a standard test procedure has been reached. The available literature includes experimental studies conducted using single shear tests, double shear tests, and modified beam tests. The existing experimental setups may be classified into five types: (i) double-shear pull tests; (ii) double-shear push tests; (iii) single-shear pull tests; (iv) single-shear push tests; and (v) beam (or bending) tests [33] (Fig. 1). In the study of De Lorenzis et al. [34] it is stated that single shear pull type test specimens offer following advantages: manageable specimen size, possibility to conduct the test in slip-control mode and to measure both loaded-end and free-end slip and visual access to the test zone during loading. Accordingly, a single shear pull type test setup is used (Fig. 1(c)) in this study.

Structures retrofitted using FRP sheets may fail in a brittle mode due to several factors such as; rupture or debonding of FRP sheets and degradation of the mechanical properties of FRP sheets due to harsh environmental conditions. On the other hand, mechanical anchorages may be used to enhance the load resisting capacity of FRP retrofitting and delay the debonding process [35]. Moreover in some cases, properly installed mechanical anchorages may provide a ductile mode of failure instead of sudden brittle failure modes. Conversely, global failure of anchorages or rupture of FRP sheets due to stress concentrations imposed by the presence of anchorages may also trigger a brittle failure mechanism. Thus, it is vital to have a thorough knowledge on the behavior of FRP retrofitting systems enhanced with the anchorages. Accordingly, there are numerous studies focused on the application of anchorages to FRP and RC bond interface to enhance the strength, energy dissipation capacity of the interface and to delay the debonding of FRP from the concrete surface. Furthermore, there are studies focused on the stress distribution between FRP and concrete surface in the presence of cracks [36–37]. Zhang and Smith [38] is one of the studies conducted on the behavior of CFRP strips with anchorages. In the study, results of 30 single shear FRP to concrete joint tests (26 joints includes anchorages) with FRP anchorages of

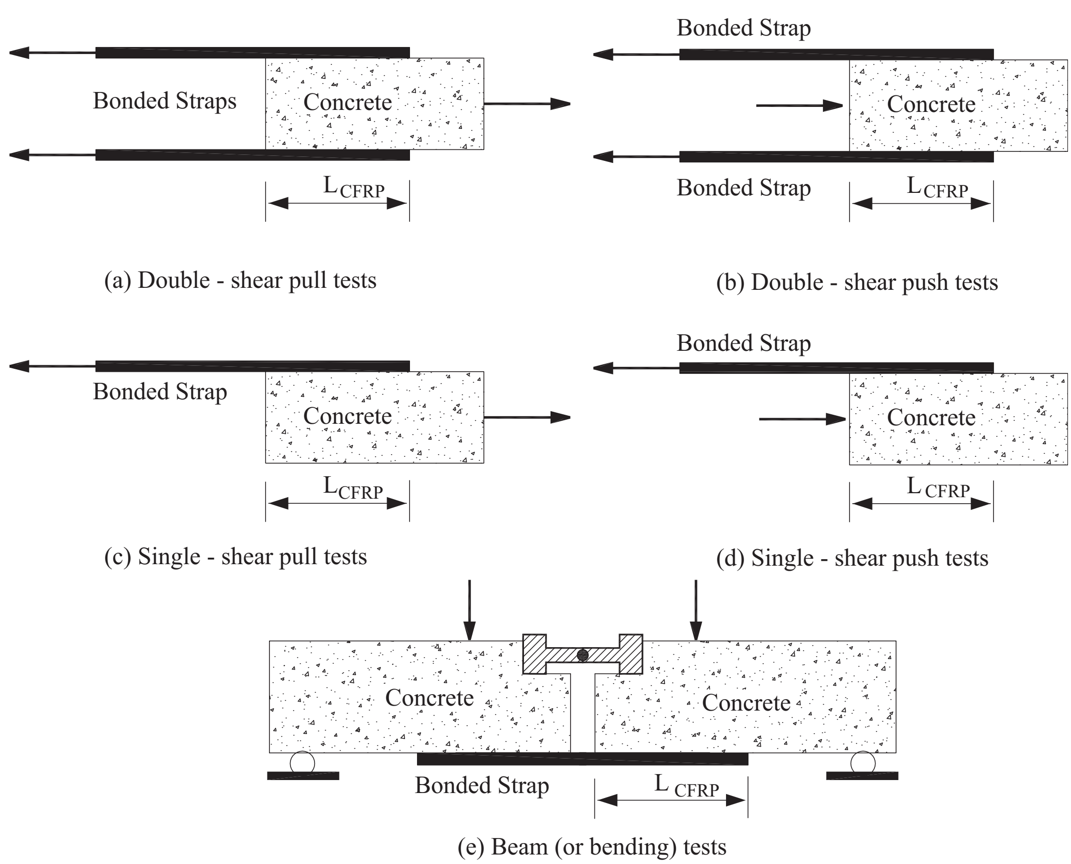


Fig. 1. Classification of experimental setups used for bonding strength tests.

varying geometric configurations (fan configuration and dowel angle) were presented. From the results of the study it was observed that the joint strength was increased up to 160% in comparison unanchored control joints. In addition, the maximum strain resisted by the FRP plates was significantly increased in comparison to unanchored control joints. In the another study of Zhang and Smith [39], tests of 41 FRP-to concrete joints anchored with single as well as multiple FRP anchorages and two unanchored control joints were performed. In the study, locations of the anchorages are investigated in addition to the method of anchorage installation and anchorage type. From the results of the study, it was concluded that the strain capacities of the joints were generally increased at least five fold. Finally, a simple analytical model was also presented. The studies presented above may be stated as the comprehensive experimental studies on the general behavior of CFRP strips with anchors.

However, it may be stated that the research on the behavior of CFRP strips with FRP anchorages are still limited although the increasing use of FRP anchorages in practice. Accordingly, to reduce the lack of experimental knowledge, an experimental study focused on the strain distribution of CFRP bonded to concrete members with FRP anchorages and without anchorages is conducted in this study. In the study, the bond slip behavior of CFRP and concrete interface and strain as well as stress distribution are investigated. In the current study, the width of the CFRP strips, number of anchorages and the CFRP bond length are considered as main variables. The tests are conducted using the displacement controlled test setup specially designed for this experimental study. Finally, using the results of the study, a bond slip model is presented for CFRP strips with anchors.

2. Experimental study

In scope of the experimental study, behaviors of CFRP strips bonded to concrete block surface are investigated. From the test results, strength, stiffness, energy dissipation capacity, load displacement behavior and failure modes of the CFRP strips are obtained together with the stress distributions along the strip length. In the experimental study, the width of the CFRP strips, number of anchorages and the CFRP bond length are considered as main variables. Widths of the CFRP strips are selected as 50 mm and 100 mm and the bond lengths were selected as 200 mm and 280 mm.

2.1. Materials

The average compressive strength of concrete used in the manufacturing of concrete blocks was 25 MPa with a standard deviation of 0.14 MPa. The compressive strength of the concrete is measured using the standard cylindrical concrete samples.

The concrete blocks are retrofitted using uniaxial single layered CFRP strips bonded to the concrete block surface with a two component epoxy resin. The FRP (Sika Wrap Hex-230C) used in the tests was a unidirectional woven carbon fiber (99% of areal weight) fabric equipped with thermoplastic heat set weft fibers (1% of areal weight) with a fiber density of 1.78 g/cm3. It is available in the market in rolls with dimensions of 30 cm × 4500 cm or 60 cm × 4500. Mechanical properties of epoxy resin and CFRP fibers are separately given in Table 1. The mechanical properties of the FRP strips were not measured in laboratory conditions. The properties are provided by the manufacturer.

Table 1
Mechanical properties of the CFRP and epoxy resin.

CFRP properties	
Remarks	Value
Weight	220 gr/m^2
Thickness	0.12 mm
Tension Strength	4100 MPa
Modulus of Elasticity	231 GPa
Ultimate Strain	1.7%
Epoxy Resin	
Density	1.31 kg/lt
Mix Ratio	White/Grey Compound = 4/1
Application Temperature	Min + 10 °C, mac + 35 °C
Tension Strength	30 MPa
Bending Modulus of Elasticity	3800 MPa

2.2. Test specimens

In scope of the experimental study, seven concrete blocks are manufactured. Each concrete block is used two times from two opposite faces. Manufactured test specimens are composed of concrete blocks with the dimensions of 300 mm × 250 mm × 600 mm and CFRP strips bonded to concrete blocks. Test specimens are manufactured with one, two or three anchorages in addition to reference test specimens without any anchorages. The drawings showing the details of test specimens with one, two or three anchorages are given in Fig. 2. Some properties of the manufactured test specimens are given in Table 2. After the manufacturing of concrete blocks, the CFRP strips are bonded to the concrete blocks using epoxy. Prior to applying the epoxy resin, the surfaces of the concrete block in contact with CFRP strips are roughened mechanically to provide the maximum possible bond between the CFRP strips and the block surface. Next, the holes for anchorage dowels are prepared. Then, the roughened surfaces are brushed with moist foam to remove any dust and loose particles. Consequently, the final form of the surfaces in contact with CFRP strips is obtained by drying the roughened and brushed surfaces with pressured air. Next, the epoxy compound is prepared and spread over the surface in contact with the CFRP strips. Then the CFRP strips are placed on the prepared surfaces and tightened by hand along the fiber directions to remove the entrapped air bubbles. Then, the second layer of epoxy resin is spread on the CFRP strips. Finally, the holes of anchorage dowels (Fig. 3) are fulfilled with the epoxy and the anchorage dowels are placed in these holes without harming the CFRP strips bonded to concrete block surface. Finally, the CFRP extensions from the anchorage dowels are bonded to the CFRP strips lying on the concrete surface. The air temperature was constant about 20 °C during all bonding processes. The test specimens are cured at least seven days under laboratory conditions before testing.

2.3. Instrumentation and test procedure

Test specimens are placed on a specially designed test setup which is manufactured from steel members. The tensile loads to test specimens are applied using a hydraulic pump until the failure of the CFRP strips or debonding of CFRP strips from the concrete surface. Test setup and instrumentation details are given in Fig. 4. The test specimens are fixed to a steel plate with a thickness of 10 mm to prevent the movement during the test. Used CFRP strips are fixed to steel plates directed along the fiber direction. The loading is applied by pulling these plates by the hydraulic pump with 400 kN loading capacity. The strains of CFRP strips were measured with strain gages uniformly distributed on the bonded part of the CFRP strip surfaces and the force displacement measurements are taken by using a linear variable differential transformer (LVDT) and Load Cell. The slip of test specimens were measured using a properly installed LVDT. The additional deformation of concrete was prevented by attaching a full height thick steel anchorage plate to the loaded face of concrete block. Furthermore, the deformation that may occur in the holding mechanism was prevented by attaching the free end of the FRP sheets to the pulling mechanism by using 16 bolts placed on double wrapped FRP sheets.

3. Experimental results

In this section, the shear load and displacement relationships of test specimens are presented together with the CFRP strain distributions. Furthermore, the peak stresses, the displacements at peak stresses, dissipated energy amounts of the test specimens are comparatively given in Table 3 together with the failure modes of the test specimens. The effect of several parameters on the variation of strengths, stiffnesses, energy dissipation capacities and stress distributions are presented in the following subsections.

3.1. Strengths of the test specimens

The strength and the stiffness of the test specimens are comparatively presented in this section. First, the effect of bond length on the variation of peak stress is considered. From Table 3, it is observed that increasing the bond length of CFRP strips from 200 mm to 280 mm (1,4 times), while keeping the CFRP strip width and number of anchors constant, did not increase the peak stress. Such behavior indicates that the effective bond length is smaller than the bond lengths used in this study. In relation to that it is decided that the bond length is not a critical parameter in this study. Hence, specimens with identical properties (except bond length) may be considered as similar specimens used to contribute the development of the proposed model and verify the results of the conducted tests.

Another observation from Table 3 is that the presence of fan type anchorages increased the observed peak stress of the test specimens.

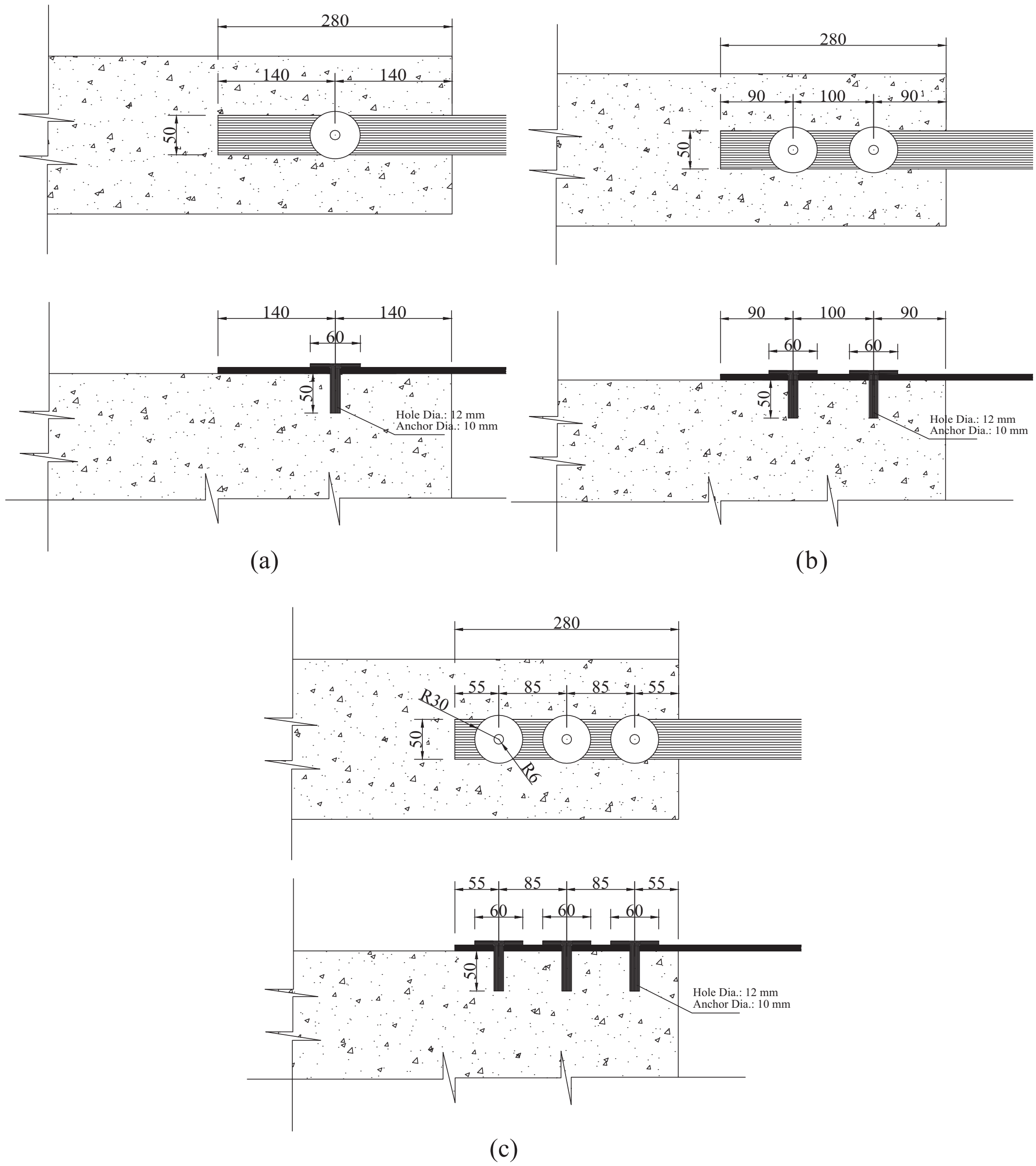


Fig. 2. Plan and side views of test specimens with (a) one anchor, (b) two anchor, (c) three anchor.

Table 2
Properties of test specimens.

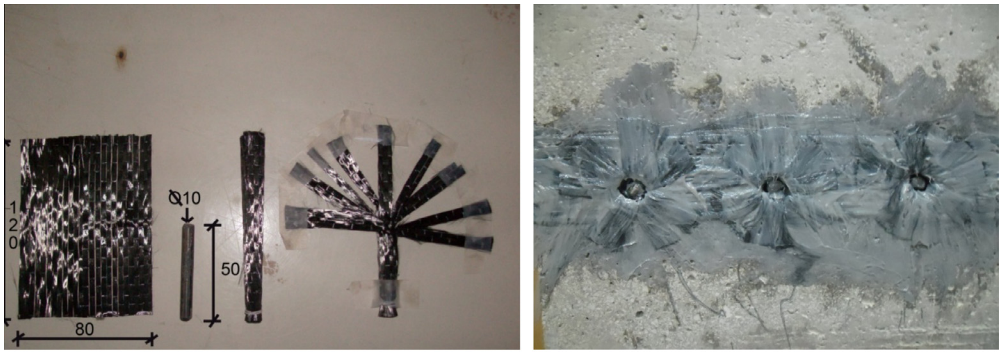
Specimen #	CFRP strip width (mm)	Bond length (mm)	Comp. strength of concrete (MPa)	Anchor #
1	100	200	25	0
2	100	280	25	0
3	50	200	25	0
4	50	280	25	0
5	50	200	25	1
6	50	200	25	2
7	50	280	25	1
8	50	280	25	2
9	100	200	25	1
10	100	200	25	2
11	100	280	25	1
12	100	280	25	2
13	100	280	25	3
14	50	280	25	3

In Fig. 5 effect of number of anchorages on the variation of maximum stresses resisted by the test specimens are given. From Fig. 5 it is observed that using more anchorages increased the peak stresses regardless of the width of the CFRP strips.

The shear load and displacement relationships of the test specimens are plotted in Fig. 6. From the figure, it is observed that specimens manufactured with anchorages gained significant residual strength capacity together with enhanced stress and displacement capacity. In contrary to that, the elements without any anchorages had no residual load capacity. Effect of presence of anchorages on the variation of load displacement relationships are also illustrated in Fig. 7. As observed from the figure, presence of anchorages significantly enhances the load displacement relationship of the element.

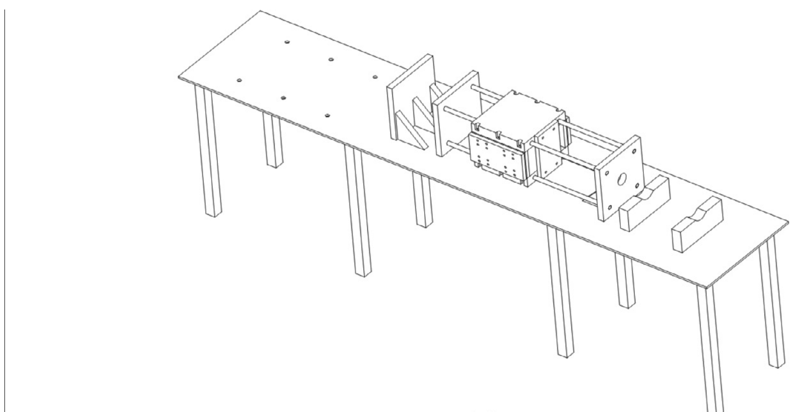
3.2. Energy dissipation capacities of specimens

In this section, effects of several factors on the variation of energy dissipation capacities of test samples are considered. From the experimental results (Table 3), it is observed that, generally, the energy dissipation capacities of the test specimens increase linearly with the anchorage numbers, while keeping other

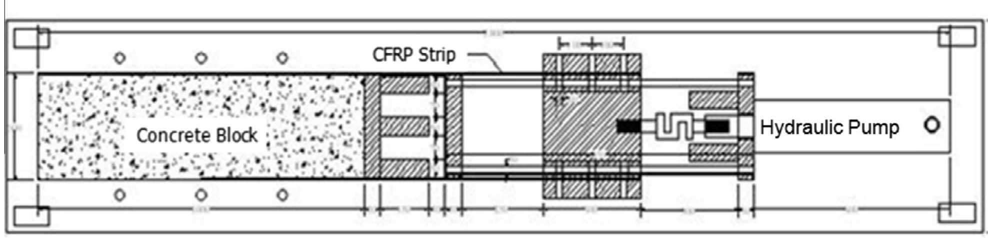


(a) (b)

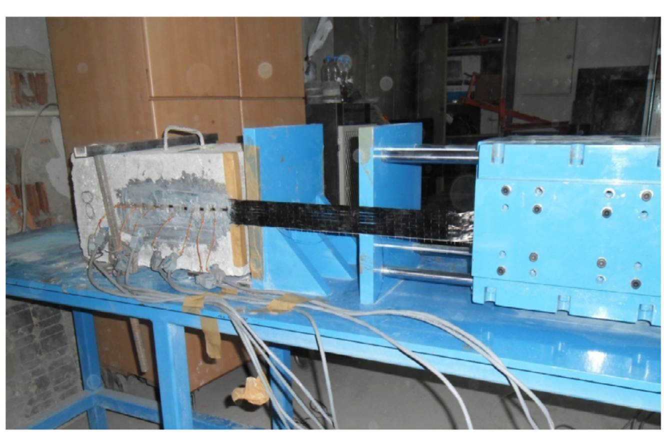
Fig. 3. Fan type anchorages used in the retrofitting procedure (a) before application, (b) after application.



(a)



(b)



(c)

Fig. 4. Typical test setup; (a) perspective (b) plan view, (c) photo.

Table 3
Test results.

Specimen #	CFRP strip width (mm)	Bond length (mm)	Anchorage number	Peak stress (MPa)	Displacement at peak stress (mm)	Dissipated energy (kN-mm)	Stiffness (kN/mm)	Failure mode
1	100	200	0	1.0	4.5	105	4.5	1*
2	100	280	0	0.9	7.4	134	3.3	1*
3	50	200	0	1.3	6.7	70	1.9	1*
4	50	280	0	1.0	6.1	66	2.3	1*
5	50	200	1	1.4	6.8	117	2.0	2*
6	50	200	2	1.5	7.8	115	1.9	2*
7	50	280	1	1.2	8.5	140	1.9	2*
8	50	280	2	1.3	9.0	141	2.0	2*
9	100	200	1	1.3	9.5	275	2.8	2*
10	100	200	2	1.5	9.9	271	2.9	2*
11	100	280	1	1.3	7.8	342	4.6	2*
12	100	280	2	1.6	8.1	353	5.4	2*
13	100	280	3	1.8	9.5	481	5.3	2*
14	50	280	3	1.7	5.5	178	4.3	2*

1*: Debonding.
2*: FRP Rupture.

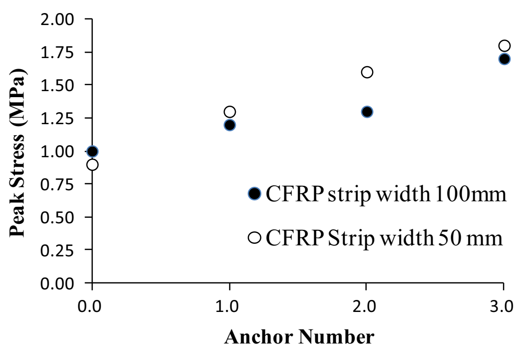


Fig. 5. Effect of anchorages on the variation of peak stress.

parameters constant. A similar conclusion is also valid for the effect of bond length and CFRP strip width on the variation of energy dissipation capacities of test specimens.

3.3. Strain distributions in CFRP strips

In this section the CFRP strain distributions of test specimens and several factors effecting the distribution of CFRP strip strains are considered. As stated before, the strain distributions of CFRP strips at the ultimate stresses are given in Fig. 8. The vertical axes of the plots given in Fig. 8 (ε_0) represent the normalized strains of the CFRP strips with respect to the CFRP strip strain capacity. From the first four plots of Fig. 8 (test specimens without any anchorages) it is observed that the CFRP strip parts far from the loaded end did not deformed until the failure which indicates that the un-deformed parts of the CFRP strips are ineffective during the loading. It is anticipated that the use of anchorages may help to have a more uniform strain distribution along the CFRP strip length which indicates that the more length of the CFRP strips are effective during the loading. In Fig. 9, the strain distributions of CFRP strips in test specimens 1, 9 and 10 (specimens with same bond length and strip width) are plotted together to observe the effect of anchorages on the strain distribution. From the figure it is observed that the strain distribution gets more uniform with increasing number of anchors.

3.4. Failure mode of test specimens

In Table 3 the failure modes of test specimens are presented. From the table it is observed that specimens without any anchorages failed with the debonding of FRP from concrete surface. However specimens with anchorages failed with the rupture of FRP. Such failure modes illustrated that the used anchorages enhanced the capacity of applied retrofitting by providing the development of full strength and preventing the debonding failure. A photo from selected from the tests is given to show the failure with the rupture of FRP material is presented (Fig. 10). On the other hand the failure with debonding is not identifiable from the test photographs. In relation to that any photograph showing the debonding of CFRP sheets from the concrete surfaces is not presented.

3.5. Analytical study

In this section, the experimental results are compared with the results obtained from the available bond slip models in the literature. Then, a new empirical bond – slip model for elements with anchorages is developed and proposed.

3.6. Comparison of experimental results with selected bond-slip models

In the literature there are many analytical models to estimate the ultimate load capacity of CFRP to concrete surfaces. Some models proposed to estimate bond strength of the bonded CFRP strips to concrete are based on empirical relations while others are based on the fracture mechanics theories. In this study, some of the most conveniently used models [40–47] are selected and results of the experimental study are presented in comparison to these results (Fig. 11). From Fig. 11 it is observed that the analytical models Chen and Teng [40], Sato [41] and Maeda [42] generally overestimated the experimental results at the un-conservative side. In contrary to that the analytical models CNR [43], Khalifa [44] and Tanaka [47] generally underestimate the results in the conservative side. On the other hand, Hiroyuki and Wu [45] and Yang [46] Models estimated the results more accurately than the other models. However, an empirical model which is capable of yielding more accurate results by considering the presence of anchorages may be developed. Accordingly, in this study, an empirical bond slip model accounting for the presence of anchorages is developed and proposed.

3.7. Proposed bond-slip model

In this section, an empirical bond slip model for the CFRP strips bonded to concrete surfaces with anchorages is developed. The maximum shear stresses of the test specimens are estimated by multiplying the maximum shear stress of the test specimens without any anchorages with a coefficient, obtained from curve fitting procedures. The maximum shear stresses of the test specimens ($\tau_{\max}$) were calculated by dividing the maximum load applied to the test specimens to the effective area of the used CFRP strips. The maximum shear stress of the test specimens are normalized to clearly observe the effect of anchorages on the maximum shear stress capacities of the test specimens. In Fig. 12, the average normalized maximum shear stresses of the test specimens (τ_n = maximum shear stress of the system with anchorages/maximum shear stress of the system without anchorages) are plotted in relation to the number of anchorages. From the figure it is observed that the average normalized maximum shear stress of the test specimens increases with the increasing number of anchorages. In relation to that several functions are fitted to the data plotted in Fig. 12. In order to verify the validity and robustness of the fitted functional forms, the coefficients of determinations, R^2, are calculated for each functional form. Then, the functional form with the closest R^2 to the unity is selected as the functional form of the proposed model. The R^2 value of the selected functional form was 0.99 which indicates that 99% of the original normalized average maximum shear stresses are estimated reasonably well by the proposed equation.

$$\tau_{\max\_anchor} = \tau_{\max} e^{0.17N} \tag{1}$$

In Eq. (1), $\tau_{\max}$ designates the ultimate shear stress of the element without any anchorages (in this study it is presumed that this value is calculated with any bond strength (or slip) model in the absence of experimental data), N is the number of anchorages and $\tau_{\max\_anchor}$ is the ultimate shear stress capacity of the system with anchorages.

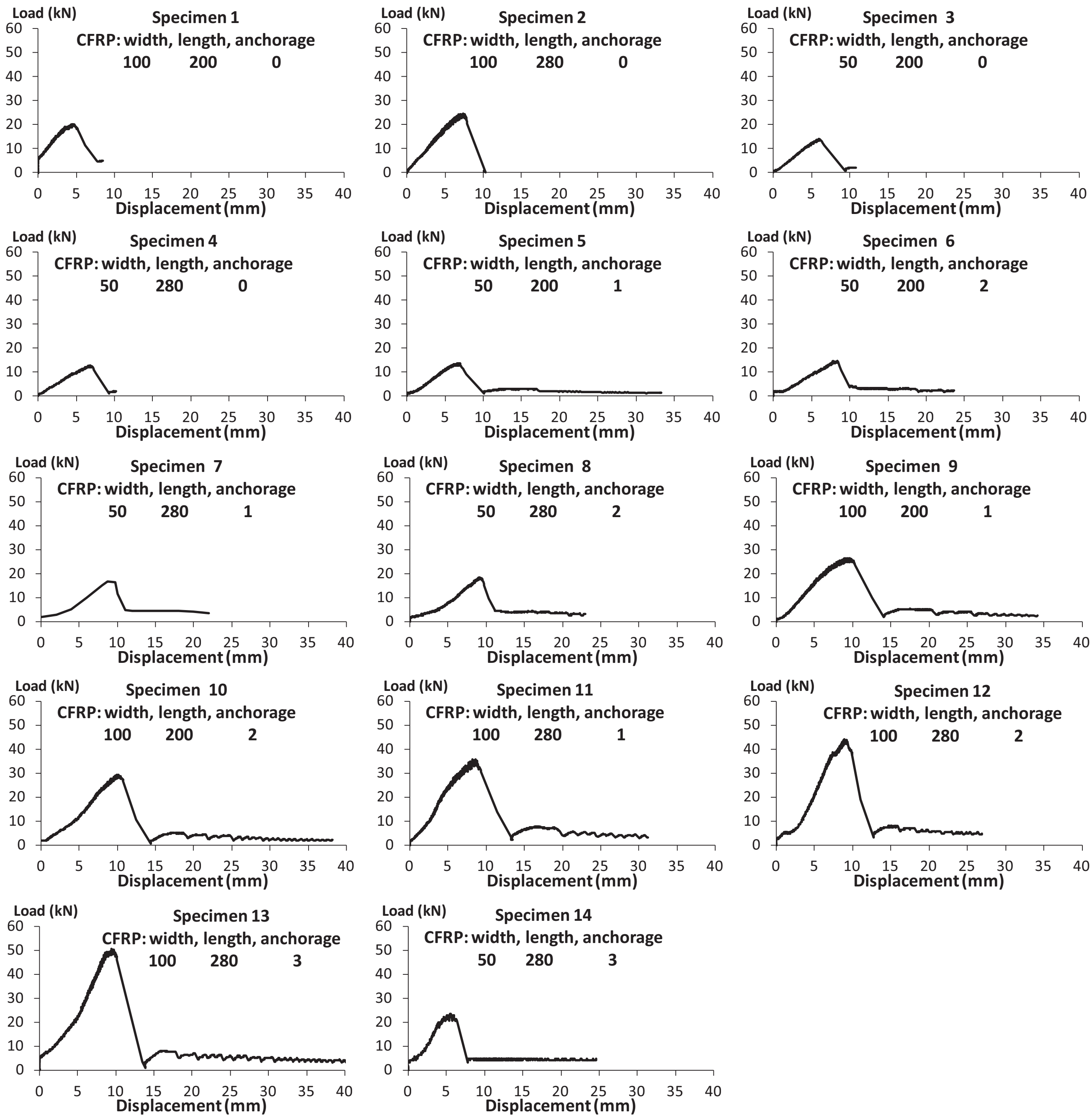


Fig. 6. Shear load – displacement relationships of test specimens.

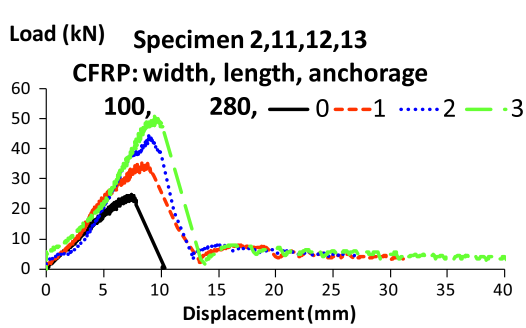


Fig. 7. Effect of anchorages on the variation of load displacement relationships.

In Fig. 13, the results obtained using Eq. (1) are comparatively plotted together with the experimental results. From the comparison, it is observed that, for many cases, the proposed equation yielded accurate results which are in good agreement with the experimental results. However, for some cases slight differences are observed between experimental and analytical results. This discrepancy may be attributed to the variation of the relation of maximum shear stress with number of anchorages observed from the test results of specimens with varying CFRP strip width and bond length. Since the proposed equation was developed using the average values obtained from the test results of these specimens, the stated factor affects the results. Accordingly, to further enhance the proposed equation, in future, experimental studies with more test specimens and more number of anchorages may be conducted.

Next, the stiffnesses of the ascending branches of the stress-displacement relations (S_0) are calculated. The variation of stiffness of the test specimens with number of anchorages are plotted (Fig. 14). From Fig. 14, it is observed that S_0 of the test specimens are not meaningfully correlated with the number of anchorages.

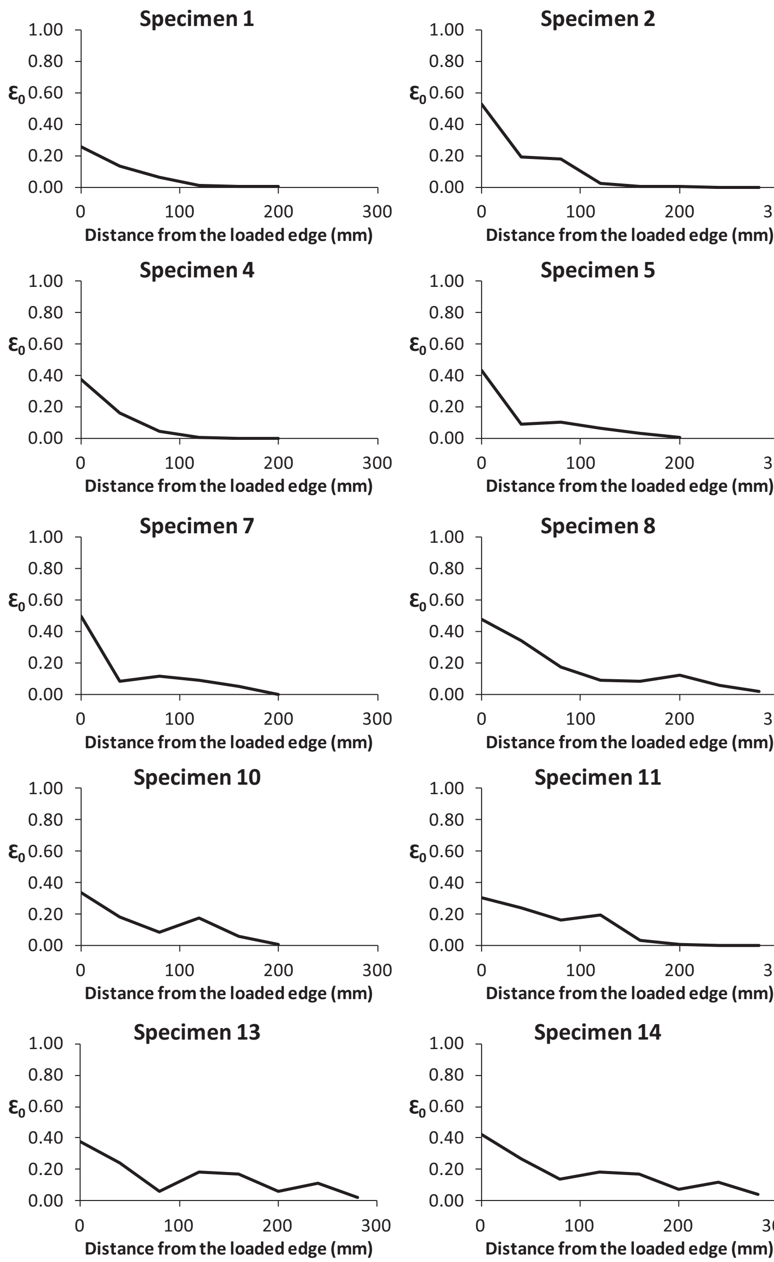


Fig. 8. Strain distributions along the CFRP strips.

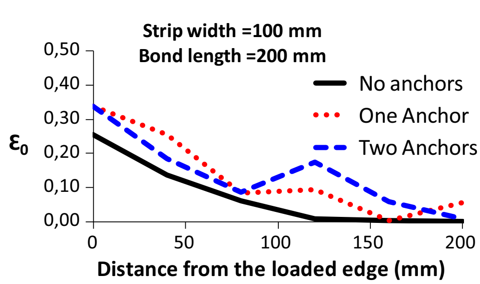


Fig. 9. Strain distributions along the CFRP strips with respect to anchor numbers.

Fig. 10. Failure of a test specimen with the rupture of FRP sheet.

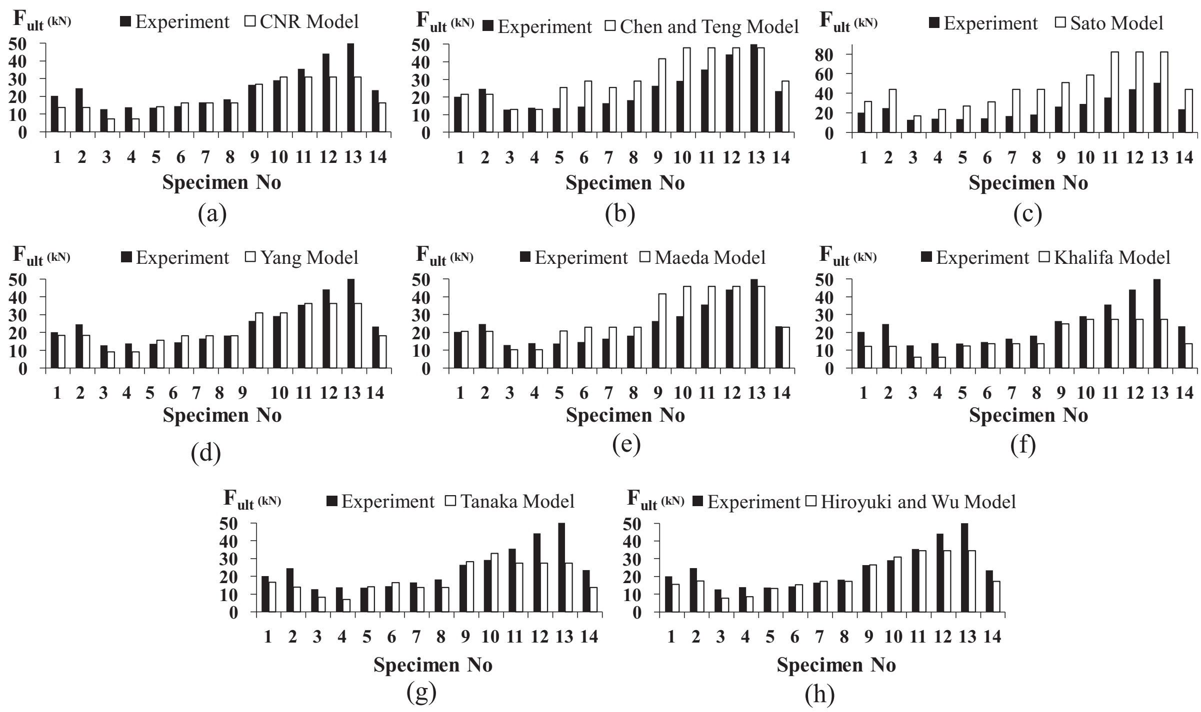


Fig. 11. Comparison of experimental results with the analytical models; (a) CNR Model [33], (b) Cheng and Teng Model [30], (c) Sato Model [31], (d) Yang Model [36], (e) Maeda Model [32], (f) Khalifa Model [34], (g) Tanaka Model [37], (h) Hiroyuki and Wu Model[35].

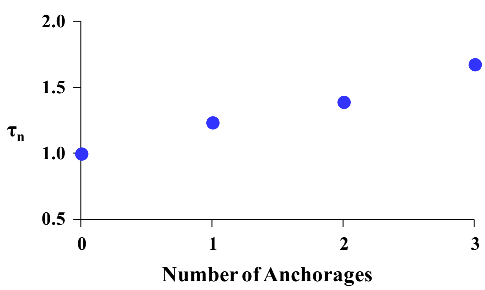


Fig. 12. Effect of number of anchorages on the variation of τ_n (normalized peak stress).

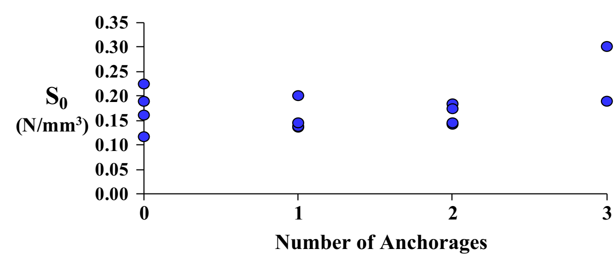


Fig. 14. Relationship of S_0 with number of anchorages.

Consequently, it is assumed that the stiffness of the element without any anchorages (obtained from any valid bond slip model) may be used when plotting the bond slip behavior of an element with anchors.

Then, the residual stress capacity of the test specimens are evaluated in a normalized form (i.e. τ_{res}/τ_{max}). Where τ_{max} is the maximum shear stress of the test specimen, calculated by using Eq. (1), and τ_{res} is the residual load carrying capacity of the test specimens. In Fig. 15, the average residual stress capacity of the test specimens are plotted as a function of number of anchorages. From the figure it is observed that the residual stress capacity slightly decreases with increasing number of anchorages. Based on this observation, it is assumed that the residual stress capacity of an element with any number of anchorages may be conservatively calculated by multiplying the maximum stress capacity of the same element with a factor of 0.2 (Fig. 16).

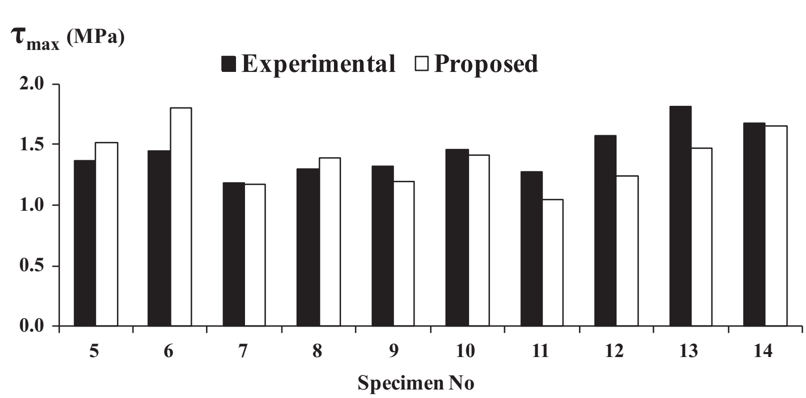


Fig. 13. Comparison of maximum stresses obtained from experiments and proposed method.

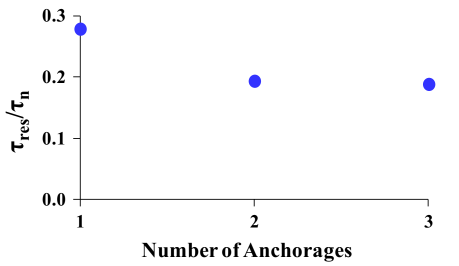


Fig. 15. Relationship of τ_{res}/τ_{max} with number of anchorages.

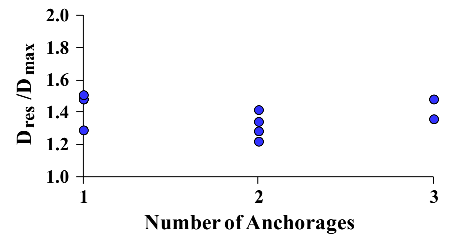


Fig. 17. Relationship of D_{res}/D_{max} with number of anchorages.

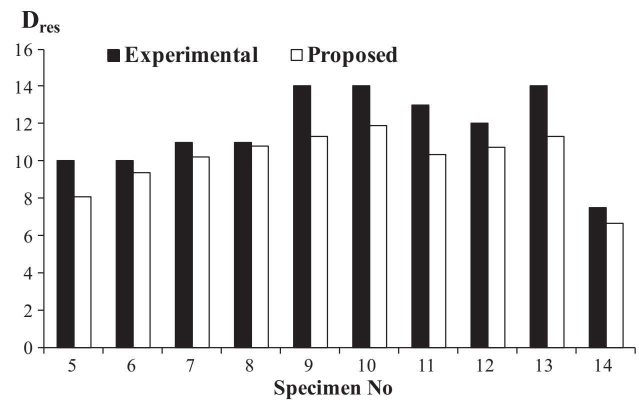


Fig. 18. Comparison of D_{res} obtained from experiments and proposed method.

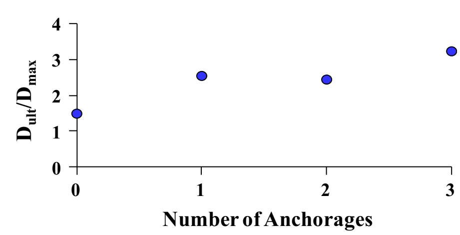


Fig. 19. Relationship of D_{ult}/D_{max} with number of anchorages.

Then, the displacements of test specimens corresponding to the τ_{res} (D_{res}) are evaluated. From a simple analysis it was observed that the post peak stiffness of the all test specimens were nearly constant regardless of the number of anchorages (Fig. 17). Using this observation, it is assumed that the displacement capacity of an element corresponding to residual stress may be conservatively calculated by multiplying the maximum displacement (displacement at peak stress) of the same element with a factor of 1.2. In Fig. 18, the results obtained from the proposed model are comparatively plotted with the experimental results. From the figure it is observed that proposed model yields acceptable results at the conservative side.

In Fig. 19, the average normalized ultimate displacement values of the test specimens (D_{Nult} = ultimate displacement of the system (D_{ult})/displacement at peak stress (D_{max})) are plotted in relation to the number of anchorages. From the figure it is clear that the average normalized ultimate displacement of the test specimens increases with the increasing number of anchorages. Consequently, several functional forms are fitted to the data plotted in Fig. 19. In order to verify the validity and robustness of the fitted functional forms, the coefficients of determinations, R^2, are calculated for each functional form. Then, the functional form with the closest R^2 to the unity is selected as the functional form of the proposed model. The R^2 value of the selected functional form (Eq. (2)) was 0.85 which indicates that 85% of the original normalized average ultimate displacement values are estimated reasonably well by the proposed equation.

$$D_{ult} = D_{max}(0.51N + 1.68) \qquad (2)$$

In Eq. (2), D_{ult} represent the ultimate displacement of the element, N is the number of anchorages and D_{max} is the displacement at peak stress. It should be noted that D_{max} should be calculated by multiplying τ_{max_anchor} (Eq. (1)) and S_0 of the element. S_0 may be obtained from any accurate bond slip model proposed for systems without any anchorages.

In Fig. 20, results obtained using Eq. (2) are comparatively plotted together with the experimental results. From the comparison, it was observed that the proposed equation yielded accurate results which are in good agreement with the experimental results.

The final form of the proposed model is illustrated in Fig. 21. In the figure the number of equation defining each parameter is given with its equation number and functional form.

It should be noted that the proposed model is only valid for the systems having up to 2 anchorages. Another important issue is the fact the proposed empirical model cannot be verified with any other experimental results due to the lack of experimental studies on the related topic. Also it should be noted that the proposed model is developed using a small number of test data. Such a limitation may limit the validity of the proposed model for structural elements with different geometric or material properties.

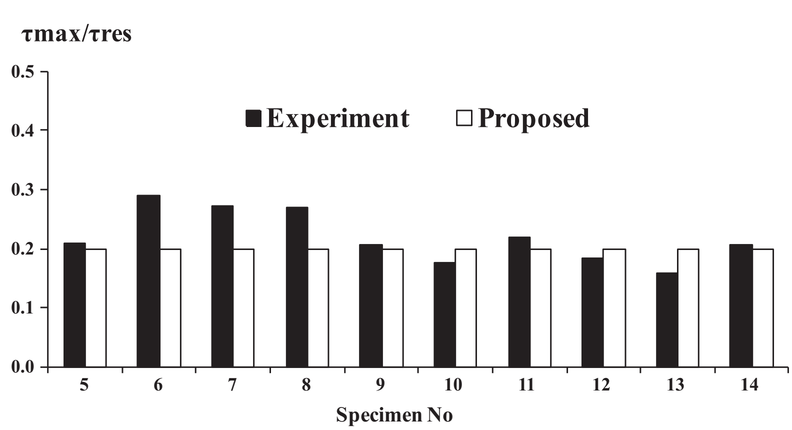


Fig. 16. Comparison of τ_{max}/τ_{res} obtained from experiments and proposed method.

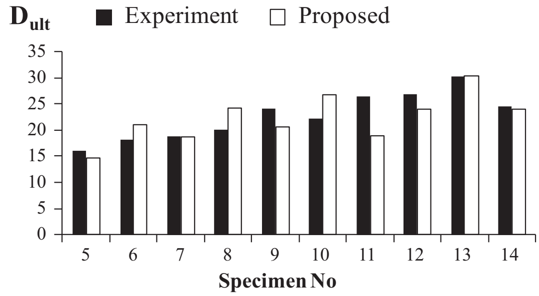
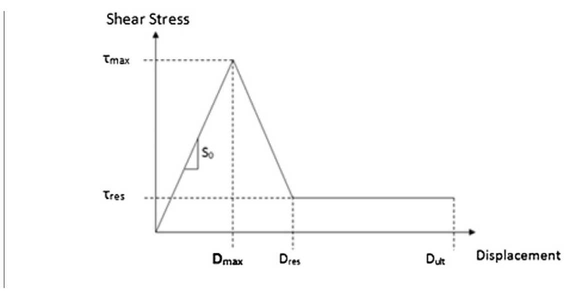


Fig. 20. Comparison of D_{ult} obtained from experiments with proposed method.



τ_{max_anchor} → Calculated using Eq. 1 ($\tau_{max\_anchor} = \tau_{max}\ e^{0.17N}$)

(τ_{max} is calculated from any model proposed for elements without anchorages)

S_0 → (Calculated from any model proposed for elements without anchorages)

τ_{res} → obtained by scaling τ_{max_anchor} by 0.2.

D_{res} → obtained by scaling D_{max} by 1.2.

D_{max} → Calculated by τ_{max_anchor}/S_0

D_{ult} → Calculated using Eq. 2 ($D_{max}(0.51N + 1.68)$)

Fig. 21. Definition of the proposed model.

4. Conclusions

This research study focused on the bond slip behavior of RC elements retrofitted with carbon fiber reinforced polymer (CFRP) strips. In the study, 14 concrete specimens with CFRP strips were tested. Test specimens were strengthened CFRP strips using varying number of anchorages CFRP strip length. Furthermore, reference specimens without any anchorages were tested and the results were compared with those obtained from other specimens. The test results obtained from the experimental study are comparatively presented. Moreover, results of the experimental study are compared with analytical results obtained from several bond slip models. Then, a bond slip model is proposed based on the modification of the results of any valid bond slip model, proposed for the systems without any anchorages, and results of the conducted tests. Following conclusions may be deduced from the conducted study.

- From the results of the study, it was observed that, generally, energy dissipation capacities of the tested specimens increased with increasing CFRP strip width.
- Energy dissipation capacities of the tested specimens also increased with increasing bond length and increasing number of anchorages.
- It is also observed that the initial stiffnesses of the test specimens increased with increasing bond length and CFRP strip width. However, generally this is not true for the increasing number of anchorages.
- The ultimate peak stresses of the test specimens increased with the increasing number of anchorages.
- Finally, it is observed that the proposed bond slip model generally yielded accurate results in terms of ultimate load carrying capacities of the test specimens retrofitted using CFRP strips with anchorages.

Acknowledgements

The authors gratefully acknowledge the financial assistance of the Turkish Academy of Sciences, Young Scientist Award program (GEBIP) and Feyzi AKKAYA Scientific Activates Supporting Fund (FABED) Young Investigator Research Award.

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