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Research paper

Pullout Tests on Near-Surface-Mounted CFRP Rods with and Without Lateral Grooves

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Abstract

An assortment of retrofitting strategies are utilized to redesign existing structures. Fiber Fortified Polymer (FRP) materials have been utilized to reinforce numerous basic segments. One of the promising strategies for reinforcing solid individuals in flexure is the close surface-mounted (NSM) FRP strategy. The greater part of the occasions, holding is the basic factor that controls the structure of this method. In this examination, pullout tests were performed to explore the holding conduct of NSM-CFRP poles. The parameters were the span of the CFRP bars and the notch geometry. The goal of this investigation was to acquire a pullout limit that is in any event half of the CFRP rigidity. Three diverse pole sizes were utilized, and an aggregate of six pullout examples were tried. The outcomes demonstrated that utilizing parallel scores essentially expanded the pullout quality. Without horizontal depressions, the most extreme pullout quality for the littlest bar estimate was under half of the CFRP rigidity. The outcomes additionally demonstrated that the security quality is exceedingly influenced by the distance across of the CFRP bars.

Keywords: *Bond; concrete; NSM-CFRP; pullout; strengthening*

1. Introduction

FRP materials have been utilized to reinforce numerous auxiliary segments in a wide range of shapes and types. FRP coats, FRP Strips, and FRP bars are the most widely recognized sorts used to restore the current auxiliary segments. The fundamental advantages of utilizing FRP are that it is lightweight, super solid in strain, and simple to apply. Among the numerous uses of utilizing FRP, NSM-FRP is a promising system of reinforcing solid individuals. In any case, de-holding issues must be defeated to make this procedure more compelling and solid. The procedure of NSM-FRP includes squeezing the FRP pole into a cut that is pre-made in the solid front of the fortified parts. The FRP bars are joined to the solid by epoxy glue. Notch measure, glue, solid, poles properties are the fundamental factors that control the proficiency of NSM-FRP strategy.

Numerous examinations have been done in the ongoing years to explore the pullout quality of NSM-FRP bars [1– 4]. De Lorenzis et al. [5] performed exploratory tests on the bond between the NSM poles and solid that had a compressive quality of 28 MPa. Bond length, the breadth of the pole, material sorts of FRP, surface treatment, and the extent of the depression were the fundamental factors. Four diverse fortified lengths were picked: 6, 12, 18, and multiple times the pole breadth (db). Carbon FRP (CFRP) and glass FRP (GFRP) bars (10 mm and 13 mm) were examined. The CFRP poles had two surface designs: disfigured and sand covered. Three distinct sizes of notch were tried. The test was performed on an altered T-pillar where the pressure confront was reinforced with the NSM method. It was seen that the examples with distorted bars flopped by part the epoxy glue and splitting the solid, encompassing the depression. In any case, the pullout marvel was overwhelming in the examples retrofitted with sandblasted bars. It was likewise seen that the notch estimate significantly affected expanding the holding quality. As the furrow thickness expanded, the quality of the epoxy past expanded and the disappointment moved from the epoxy to the encompassing cement. The bond length additionally affected the bond conduct. By expanding the bond length, the pressure was dispersed over the inserted length of the CFRP poles with the goal that it kept the early de-holding in the epoxy-bar interface. It was additionally announced that the ideal score measure for 10-mm and 13-mm bar width poles was 19-mm and 25-mm, individually.

De Lorenzis et al. [6] directed a trial work with a changed pullout test expecting to take out any unusualness that would happen in traditional pullout tests. An aggregate of 36 examples were explored. Kind of the FRP pole, sticky material, advancement length, and the furrow measure were the factors of this exploration. CFRP with ribbed and sand covered, and also GFRP, were tried. The filling sticky materials were epoxy-based and bond mortar. The compressive quality of the solid was 22 MPa. The advancement lengths of the pole were changed as 4db, 12db, and24 db, where "db" is the measurement of the poles. At long last, four furrow sizes were sliced in the examples to discover the affectability of the notch estimate on the general holding conduct: 1.25db, 1.5db, 2db, and 2.5db. From the test outcomes, numerous disappointment modes were accounted for: pullout at the solid glue interface; pullout at the pole glue interface; part of the cement's cover with no solid breaking; and pounding the solid encompassing the furrow with the development of a split in the glue's cover. As the depression estimate expanded, the disappointment moved from epoxy-bar interface to solid epoxy interface with commencement of breaks in the encompassing cement. It was additionally announced in this investigation that the epoxy cement gave a superior holding quality than the bond mortar cements, because of its high shear quality. It ought to likewise be noticed that the surface arrangement of the CFRP poles assumed no critical job in the holding practices since the controlling disappointment was at the solid epoxy interface.

Novidis et al. [7] completed an immediate pullout test on twenty-four solid examples with compressive quality of 34.5 MPa. The parametric investigation was the advancement length and the depression estimate. The elements of the solid square were 150 x 150 x 300 mm. The different implanted lengths were 3db, 5db, 7.5db, and 10db, and the depression measurements were either 25 or 20 mm. The end showed that the embraced pullout test gave solid outcomes with a sensible example measure. Two disappointment modes were acquired: haul out of the bar at solid epoxy interface, and pullout of the bar at epoxy-pole interface. As the section measure expanded, the quality of the joint expanded. In a similar way for a given section measure, the holding quality expanded as the advancement length expanded up to a specific length. The non-consistently disseminated pressure happened after a limit increment of advancement length, bringing about a decline in the holding quality.

Bilotta et al. [8] directed exploratory research, looking at the remotely fortified fortification (EBR) to NSM frameworks. For the NSM method, basalt, glass, and carbon FRPs (BFRP, GFRP, and CFRP, individually) were utilized with various geometries. All the pullout tests were performed on crystals that had components of 160 x 200 x 400 mm. The CFRP poles had a breadth of 8 mm with a smooth surface. The scores' width was 1.75db, and the advancement length was 300 mm (37.5db). It was accounted for that the pullout trial of CFRP bar fizzled at 50 KN with de-holding at the epoxy-solid interface, and with the unit of the solid layer as the method of disappointment. It is significant that the solid compressive quality was 19 MPa to reenact the poor existing fortified cement RC parts. As a correlation between the EBR and NSM frameworks, it was reasoned that the NSM framework worked more effectively than the EBR frameworks. For NSM system, the CFRP bar was completely clung to the solid subsurface by the glue. Along these lines, over half of the CFRP's rigidity was accomplished.

Soliman et al. [9] led a broad holding test on 80 examples with compressive quality extending somewhere in the range of 38 and 44 MPa. The creators embraced the altered testing framework proposed by De Lorenzis et al. [6]. The fundamental point of the examination was researching the climate consequences for the securities' conduct. Be that as it may, many bond attributes were examined, for example, FRP type, glass and carbon; installation length: 6db, 12db, 18db, 24db, 36db, and 48db; glue type: epoxy-based and concrete based glue; and depression measure: 1.5db and 2.0db. Two widths of CFRP bars were utilized; 9.5 mm and 12.7 mm, which had a rigidity of 1546 MPa and 1250 MPa separately. The outcomes showed that the molded examples performed less productively than the reference ones. Regarding the glue types, the reference examples with the epoxy based cement had a reliably higher bond quality than the examples with the concrete based cement. It ought to be referenced that expanding the holding length, expanded the quality of the joint. Be that as it may, in the investigation the break of the CFRP and GFRP bars was accounted for the 24db, 36db, and 48db, which gave full proficiency for holding. Shear pressure disappointment of the encompassing cement was the controlling mode disappointment for the reference examples with the epoxy based glue. Be that as it may, for the molded examples, the disappointment was controlled by the epoxy part. The controlling disappointment mode for the reference examples with the concrete based cement was the de-holding in the concrete– cement interface.

Sharaky et al. [10] examined many bond parameters. The principle qualities that were actualized and examined by utilizing the adjusted pullout test [6] were: groove surface, groove geometry, FRP bar type, bond length, and development points of interest of the furrow. Two CFRP bars were utilized in the tests; 8 mm with smooth surface and 9 mm with surface. The compressive quality of the solid extended somewhere in the range of 35 and 42 MPa. It was accounted for that the score surface had no impacts on the bond limit if the disappointment was at the bar-epoxy interface. As the bond length expanded from 40 mm (5db) to 192 mm (24db) for the CFRP 8-mm pole, the disappointment stack expanded from 13 KN to 37 KN. Expanding the depression measurements from 1.5db to 2db, postponed the bar epoxy interface disappointment. It was likewise detailed that the interlocking expanded the joint limit by 14.8%. It is intriguing to make reference to that the transverse interlocking remarkably affected the exchange stack disappointment and worry from solid epoxy interface to the encompassing cement and improvement of the solid epoxy interface bond.

Up to this time, just a set number of studies were led on tending to the bond properties of the NSM-CFRP bars [11]. Thusly, the point of this examination is to propel the learning of utilizing NSM-CFRP bars in reinforcing and fixing RC pillars. Pullout tests were performed on 6-mm, 10-mm, and 13-mm NSM-CFRP poles. The outcomes were talked about and contrasted with the proposals of the current plan rules [12].

2. Experimental Program

2.1. Materials

The materials used in this project were concrete, CFRP rods, and epoxy. The mechanical properties of CFRP rods and concrete materials were determined experimentally based on ASTM standards [13–16] in the infraStructure Testing and Applied Research (iSTAR) Laboratory and in the South Greenhouse Laboratory at Portland State University.

2.1.1 CFRP tensile properties and anchorage system

FRP materials are moderately feeble the transverse way contrasted with the longitudinal heading. This innate property of the composite materials causes untimely disappointment because of the grumbling activity in the ductile test. Along these lines, ASTM D7205/D7205M – 06 (2016) [13] was embraced in this examination to play out the malleable test appropriately. The pivotal pressure strain conduct of CFRP bars and the modulus of flexibility will be assessed and contrasted and the consequences of the maker. CFRP bars, financially named Aslan™ 200 arrangement, were acquired from Aslan FRP®, Nebraska, USA. Three breadths (6-mm, 10-mm, and 13-mm) with sand covered surfaces, as appeared in Fig. 1, were tried. In view of the producer, the elastic properties are as appeared in Table 1.

Table 1: Mechanical properties of FRP rods based on the manufacturer

Size	Nominal diameter, (mm)	Nominal area, (mm^2)	Guaranteed tensile strength, (MPa)	Modulus of elasticity, (MPa)	Ultimate strain, %
6-mm	6	31.67	2241	124	1.81
10-mm	10	71.26	2172	124	1.73
13-mm	13	126.7	2068	124	1.67

Fig. 1: CFRP rods

Fig. 2: Steel tube

The poles were sliced to a coveted length. A steel tube, the external distance across of which was 32 mm and the internal measurement was 20 mm, was utilized as the stay boundary (Fig. 2). The picked length of the steel tube (inserted length) was 250 mm. The aggregate length of the examples, appeared in Fig. 3, was 760 mm. ASTM D7205/D7205M [13] recommends a filling material (grout) that gives parallel weight between 30 to 50 MPa with an implant length of multiple times the bar's breadth. A financially accessible destruction operator was chosen as the grouting material. In light of the producer, it gives 60 MPa weight following 70 hours of relieving. As trained by the maker, the slurry was blended, and after that poured inside the steel tube, which was stopped with a PVC top from one side as appeared in Fig. 3. At that point, the CFRP pole was embedded inside the steel tube. Following twelve hours of restoring, a similar procedure was rehashed on the opposite side of the bar. At last, the examples were left to solution for something like 70 hours before the malleable tests. This harbor framework was first utilized by Al-Obaidi [17] in fortifying RC pillars and by Saeed and Rad [18] in CFRP prestressed solid application.

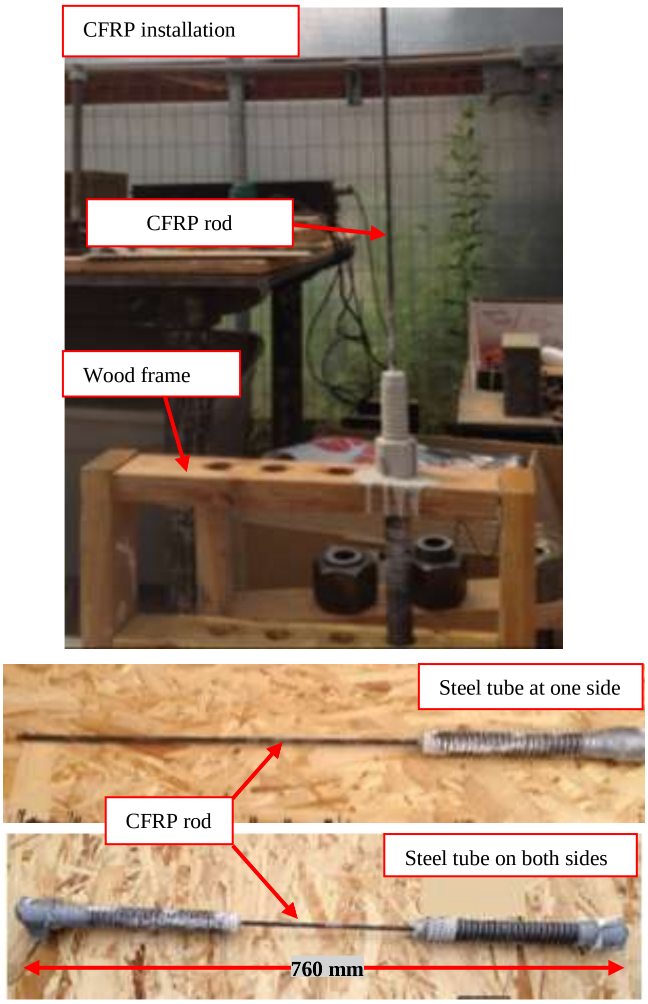


Fig. 3: CFRP anchoring system

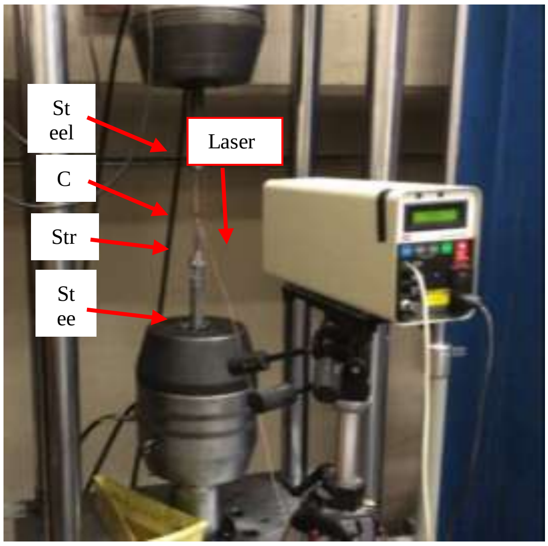


Fig. 4: Tensile test setup

The test (momentary static rigidity) was completed in a MTS machine at the iSTAR Research center at Portland State College. The strain was estimated utilizing a laser extensometer and strain measures appended to the CFRP poles, and the heap was checked by a 900-KN stack cell. The mechanical properties got from the tests were in a decent concurrence with the ones revealed by the producer. Fig. 4 demonstrates the test setup for the pliable tests. It is intriguing to make reference to that the disappointment occurred at the center of the free length of the CFRP pole, as appeared in Fig. 5. Preceding the burst, a breaking hints of the helical strands was heard, after which the filaments lost their composites and began to crack. As appeared in Fig. 6, the deliberate tractable pressure, a normal of two examples, is higher than what is given by the maker. Be that as it may, a definitive elastic strain is somewhat lower than the revealed esteem.

Fig. 5: CFRP anchoring system

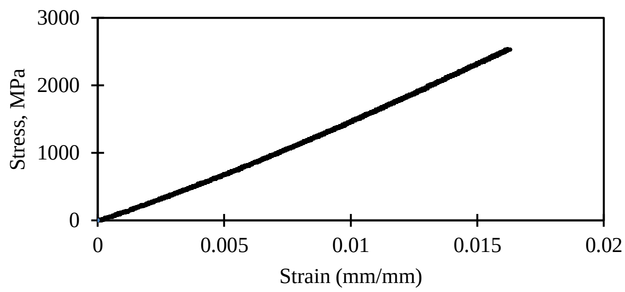


Fig. 6: Mechanical properties for 6-mm CFRP rods

2.1.2 Concrete

For this study, the concrete mix design aimed for 28 MPa concrete compression strength at 28 day. Three concrete cylinders based on ASTM C39/C39M–18 [14] were tested at the day of the pullout tests, and the average compressive strength was 26 MPa. In addition, three more cylinders based on ASTM C496/C496M-17 [15] were tested to determine the tensile strength, and three prisms based on ASTM C78/C78M-18 [16] were tested to get the modulus of rupture. The results are reported in Table 2.

Table 2: Material properties - concrete

Compressive strength, MPa	Tensile strength, MPa	Modulus of rupture, MPa
35	2.4	3.8

2.1.3 Epoxy

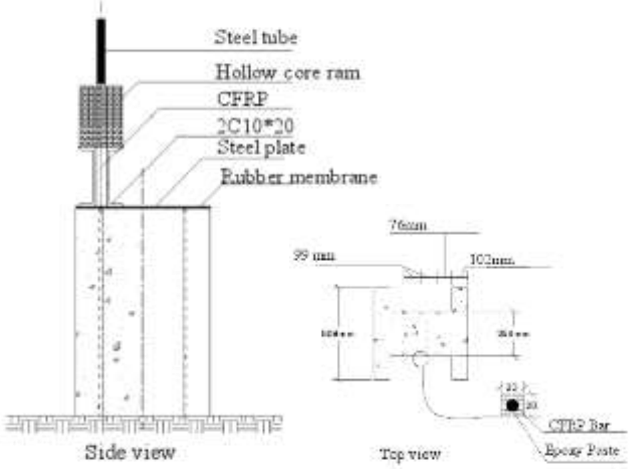
The epoxy was commercially available, and was a fast curing anchoring adhesive, which consisted of two parts: adhesive and hardening. The mechanical properties were provided by the manufacturer as shown in Table 3.

Table 3: Material properties - epoxy

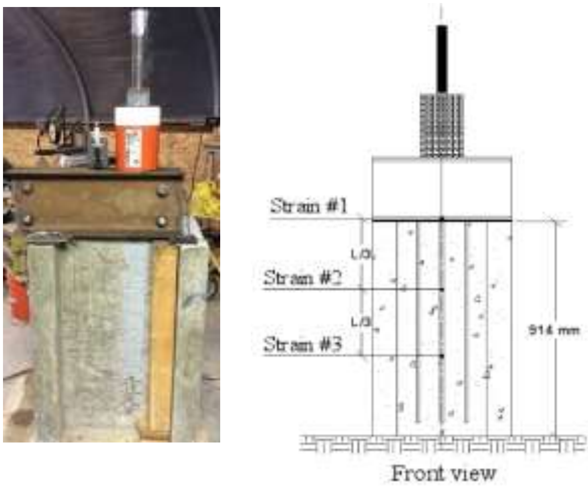
Compressive strength, MPa	Flexural strength, MPa	Tensile strength, MPa	Compressive modulus, MPa	Tensile modulus, MPa	Curing time
60	28	12	3500	4500	7 days

2.1. Pullout tests

The adjusted pullout test, proposed by De Lorenzis et al. [6] was embraced in this examination to explore the holding conduct of NSM-CFRP pole. The parameters of the holding test were the extent of the CFRP bars and the furrow trademark. The goal of this investigation was to get a pullout heap of at any rate half of the pole's malleable limit before de-holding. As recommended by De Lorenzis et al. [6], a forest size of 2db was chosen for this examination. As referenced previously, Soliman et al. [9] detailed that CFRP crack was accomplished when the advancement lengths were 36db and 48db. Be that as it may, the rigid qualities were 1546 MPa for 9.5-mm bars, and 1250 MPa for 12.7-mm poles.These values were less than the measured tensile capacity of the CFRP rods used for this paper. Based on the differences of the tensile strengths between CFRP rods used by Soliman et al. [9] and the ones used for this research, 60db was chosen as the development length for this study. The total development length was 381 mm for the 6-mm rods, 570 mm for the 10-mm rod, and 762 mm for the 13-mm rods. A total of six specimens (two for 6-mm rod, two for 10-mm rods, and two for 13-mm rods) were investigated for their NSM bonding behavior. Only the first pullout test, which was for the 6-mm rod, was done without lateral grooves. Based on the result of this test, it was decided to provide lateral grooves for the rest of the specimens. The test setup for the pullout specimens is shown in Fig. 7.



(a) **(b)**



(c) **(d)**

Fig. 7: Pullout test setup: (a) side view, (b) top view, (c), front view/experimental, and (d) front view/ schematic drawing.

3. Test results

The main test was improved the situation the 6-mm CFRP bars. The scores for this test did not have sidelong notches, as appeared in Fig. 8. The disappointment mode was de-holding at the solid epoxy interface so the CFRP and the epoxy together were isolated from the solid surfaces as one square. From Fig. 9, it is obvious that the disappointment stack was just about 43% of the ensured CFRP quality, in view of Table 1. This low holding limit was lacking since it didn't use over half of the CFRP elasticity. Along these lines, it was chosen to upgrade the holding by utilizing parallel scores of 6-mm wide, and they broadened 25 mm from each side of the longitudinal notches. The separating between the scores was 75 mm on focus. The subtle elements for the parallel scores were received from Sharaky et al. [10]. The design of the horizontal furrows is appeared in Fig. 10.

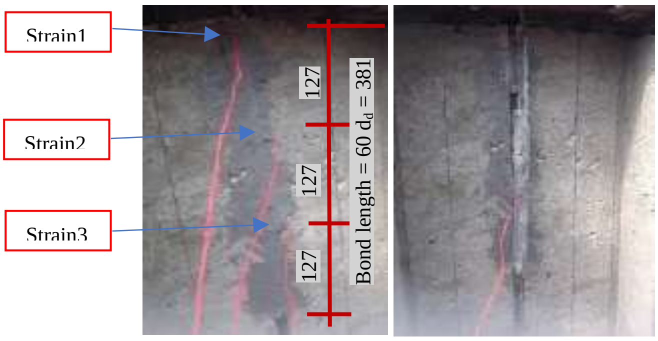


Fig. 8: Failure mode of 6-mm CFRP rod without lateral grooves

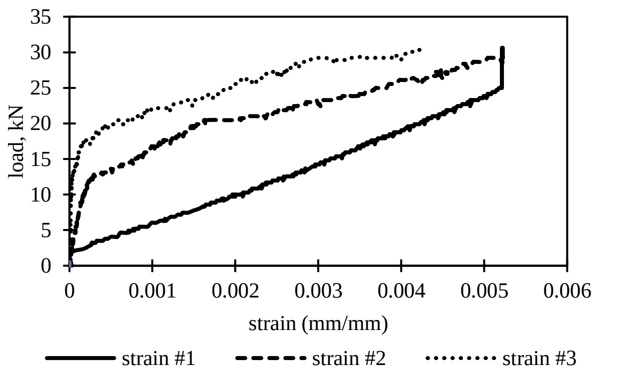


Fig. 9: Pullout load vs. strain curve for 6-mm CFRP rod without lateral grooves.

By utilizing the sidelong notches, the proportion of the accomplished rigidity to the most extreme "ensured" elasticity of the CFRP bars was 89% for the 6-mm bar, 61% for 10-mm poles, and 54% for 13-mm poles. It was finished up from these pullout tests that the parallel sections improved the holding by giving an interlocking bond between the epoxy and the solid. This interlocking power enabled the attaching to oppose extra powers by exchanging the heap to the solid. Fig. 11 demonstrates the strain dissemination along the CFRP poles. Strain readings were recorded by strain checks that were posted along the CFRP poles. Strain 1 was posted at the highest point of the holding length. Strains 2 and Strain 3 were posted at each 33% of the implant length. For the 6-mm bars and the 10-mm poles, the center strain checks were harmed and quit recording after some dimension of pullout stack. All in all, the strain esteems along the CFRP bar are greatest at the stacked end and littler at the opposite end. Another perception of the test outcomes was that for all examples, Strain 2 and Strain 3 did not begin indicating values promptly after the heap was connected. The heap was exchanging slowly from the CFRP bars to the epoxy, and to the solid.

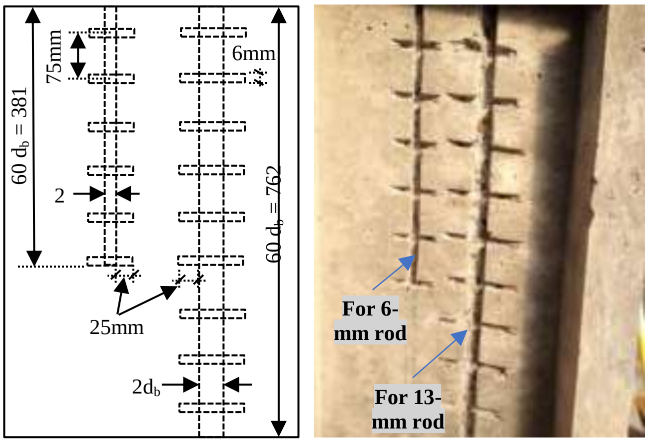
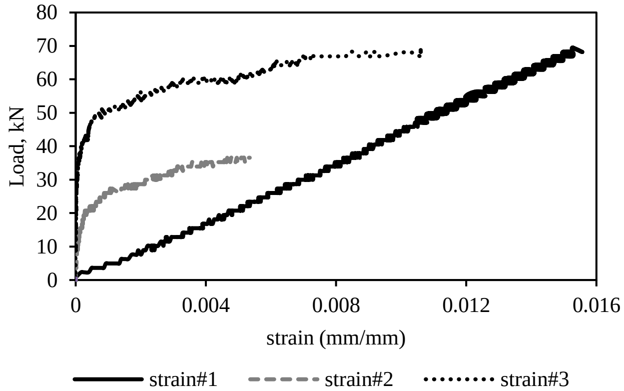
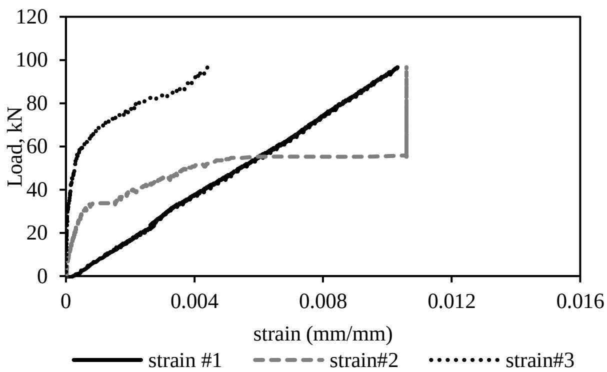


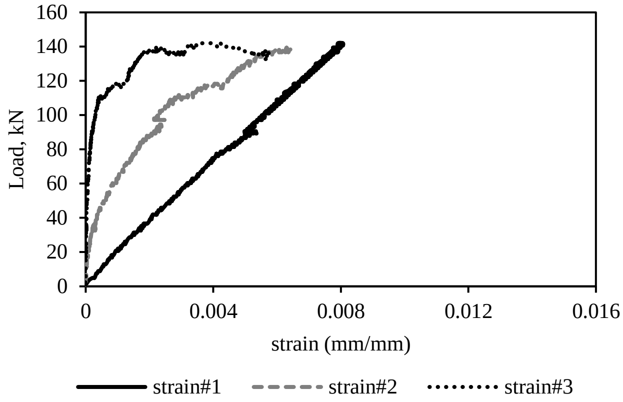
Fig. 10: Lateral grooves layout and details



(a) 6-mm rods



(b) 10-mm rods



(c) 13-mm rods

Fig. 11: Pullout load vs. CFRP strain diagram with lateral grooves

Fig. 12 demonstrates the disappointment modes for the 6-mm and 13-mm poles. It was seen that the disappointment for the 6-mm pole did not include any harm for the surface of the solid before it cracked. Then again, the disappointment of the 13-mm CFRP bars made genuine harm the surface of the solid. The devastating of the solid presented the de-holding disappointment. For the 10-mm bars, the disappointment mode was the very same method of disappointment watched for the 13-mm poles. The de-holding disappointment modes diminished the pullout limit of the 10-mm and the 13-mm CFRP poles to 61% and 54% of the CFRP pole most extreme ductile limit, individually. It is obvious from the outcomes over that the interlocking system (sidelong scores) moved the disappointment from the solid epoxy interface to the burst of the CFRP bar for the 6-mm poles, and solid smashing for the 10-mm and 13-mm bars.

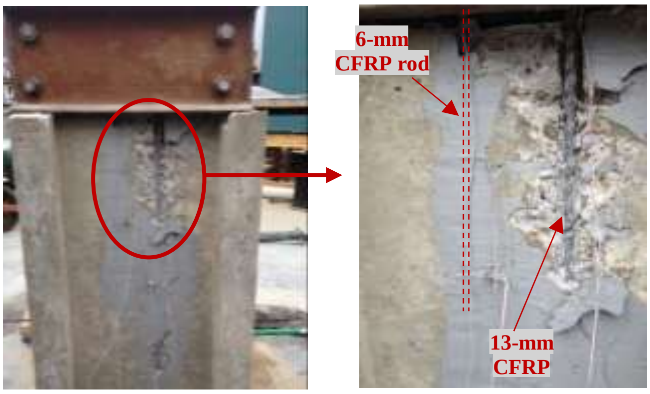
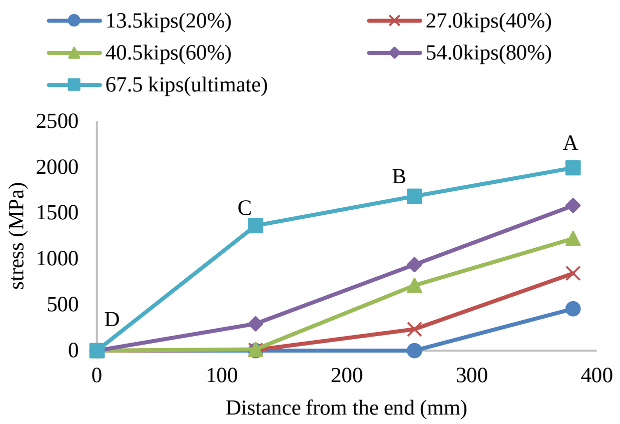


Fig. 12: Failure mode of 6-mm and 13-mm CFRP rod with lateral grooves

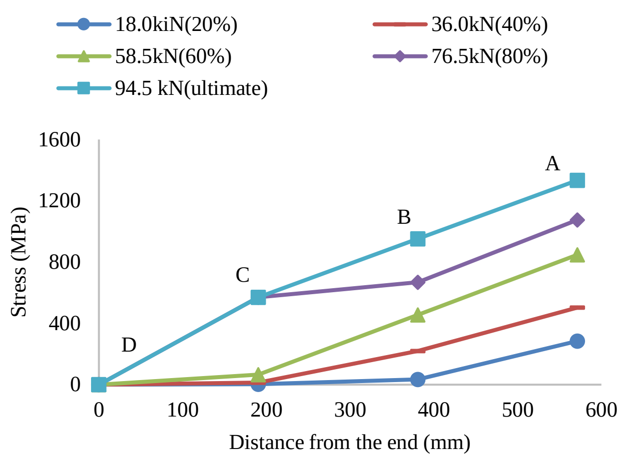
4. Discussion

With the end goal to comprehend the circulation of the ductile worries along the length of the NSM-CFRP poles, Fig. 13 was created. Load dimensions of 20%, 40%, 60%, 80% of the most extreme, and the greatest accomplished load (100%) were decided for these diagrams. At each heap level, the deliberate CFRP strains were increased by the modulus of flexibility for every bar to get the worry at that area. Areas A, B, and C speaks to the areas of the strain checks. Area D is at the deadlock, where the pressure was thought to be zero. It was presumed that the pressure varieties along the CFRP poles of the pressure were uniform for all the bar sizes. The 6-mm and 13-mm bars had a few errors of strain variety at the early load stages. By the by, the strain was balanced at higher load levels when more pressure was exchanged to the lower bit of the fortified length. That showed that the holding was sufficiently sufficient to exchange and appropriate the connected worry along the fortified length.

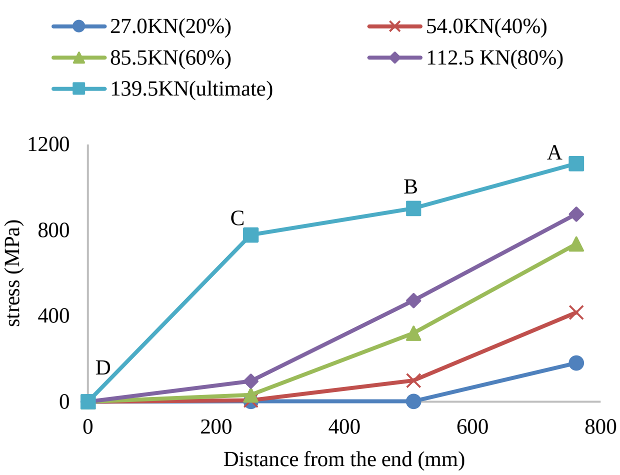


(a) 6-mm CFRP rods

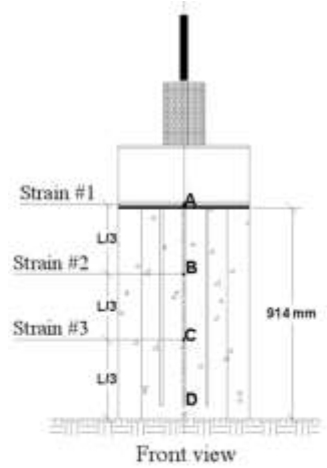
Fig. 13: Stress distribution along the length of the NSM-CFRP rods



(b) 10-mm CFRP rods



(c) 13-mm CFRP rods



(d) Location of the readings: A, B, C, and D

Fig. 13: Continued

Fig. 14 shows the load vs. slippage for all sizes of the CFRP rods. It was observed that the relationship between the load and slippage was linear for the 6-mm and 10-mm rods. However, for the 13-mm rods, the relationship is linear until about 50% of the maximum achieved load, then the curve started to behave in a nonlinear manner. It is believed that this nonlinear behavior was due to the concrete and epoxy deformation surrounding the CFRP rod.

Table 4 summarizes the results of the pullout tests. Bond stresses at the CFRP-epoxy interface and at epoxy-concrete interface were calculated and referred to as τr-e. and τe-c respectively. These stresses were calculated based on the maximum measured pullout load and according to the following equations:

$$\tau_{(r-e)} = P_u/(\Pi\ D\ L_{db}) \quad (1)$$

$$\tau_{(e-c)} = P_u/((a+2b)L_{db}\ ) \quad (2)$$

Where;

$\tau_{(r-e)}$: bond stress at rod-epoxy interface, MPa

$\tau_{(e-c)}$: bond stress at epoxy concrete interface, MPa

P_u: ultimate pullout force, N

a: width of the groove, mm

b: depth of the groove , mm

L_{db}: development length, mm

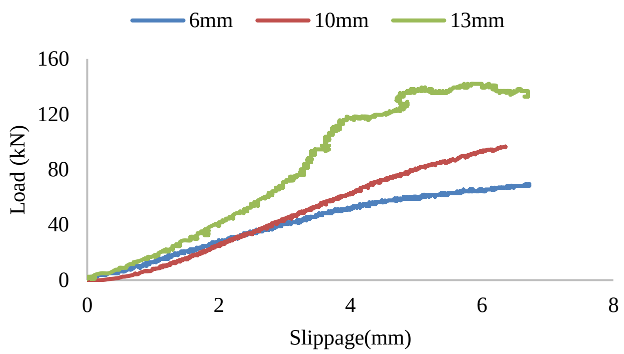


Fig. 14: Pullout load vs. slippage

Table 4: Results of the pullout tests (BR = Bar Rupture, CC = Concrete Crushing)

Rod diameter	L_{db}, mm	P_u, MPa	τ_{r-e}, MPa	τ_{e-c}, MPa	ε_u strain	Slippage mm	Failure mode
6mm	381	103	8.27	4.34	0.0155	3.68	BR
10mm	572	145	5.51	2.89	0.01	5.15	CC
13mm	762	214	4.62	2.41	0.008	2.7	CC

ACI 440.2R-17 [12] assumes a linear distribution for the bond stresses along the bonded length, with a peak value near the middle of the embedment. From the force equilibrium, the development length can be calculated based on equation (3). Based on previous studies, an average bond strength between 3.5 and 21.7 MPa was reported [12,19,20]. ACI 440 committee recommends an average bond strength of 6.9 MPa for development length calculations. Fig. 15 compares the measured average bond strength to the value recommended by ACI. The measured average bond strength was 20% more than 6.9 MPa (recommended by ACI) for the 6-mm CFRP rods, and 20% and 33% less than 6.9 MPa for the 10-mm and 13-mm CFRP rods, respectively. In fact, the average of the measured bond strengths for the three sizes of CFRP bars was 6.14 MPa.

$$Avg. bond\ stress, \tau_b = \frac{A_f\, f_f}{\pi d_b\, l_d}\ ;$$

$$\text{Therefore, } l_d = \frac{d_b}{4(\tau_b)} f_f \qquad (3)$$

Where;
τ_b: average bond strength, MPa
A_f: cross sectional area of the FRP rod, mm2
f_f: applied tensile stress of the FRP rod, MPa
d_b: diameter of the circular FRP rod, mm
l_d: development length, mm

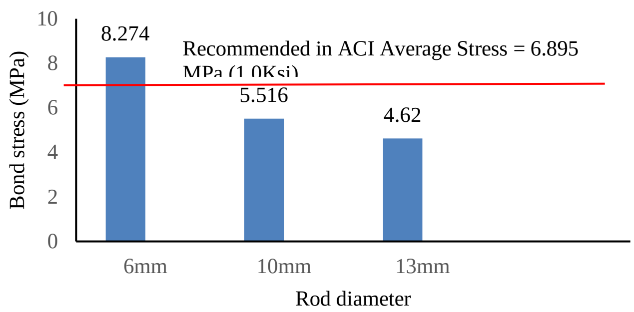


Fig. 15: Measured average bond strength vs. ACI recommendation

5. Conclusions

Pullout trial of the 6-mm, 10-mm, and 13-mm distance across of CFRP poles were completed to explore the holding qualities of CFRP bars. From the acquired outcomes the accompanying ends can be drawn:

1.Bonding length of 60db with the proposed horizontal notches accomplished 89%, 61%, and 54% of the pole limit with respect to the 6-mm, 10-mm, and 13-mm CFRP bars, separately.

2.Without sidelong notches, the pullout limit of the 6-mm CFRP bars was just 43% of the bar pliable limit.

3.Using the proposed subtle elements of the parallel scores, the deliberate most extreme security worry of the pullout tests was 20% higher than ACI suggestion for the 6-mm CFRP bars, and 20% and 33% lower than ACI proposal for the 10-mm and 13-mm bars, separately.

4.The sidelong furrows assumed a huge job in the bond instrument by upgrading the bond between the solid and the epoxy. Parallel sections are very prescribed to be utilized in NSM-CFRP fortifying applications.

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