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Axial Strength Reduction of Confined Concrete Elements due to the Loss of the Adhesive Bond

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ملخص

إن تحسين القوة المحورية للعناصر الخرسانية قد يتم عن طريق تحزيمها بالبوليمرات المسلحة بالألياف. بصفه عامه يتم لف الألياف حول العنصر الخرساني وإستخدام ماده لاصقه لربطهما معًا. عندما يتعرض هذا العنصر المدعم للتحميل الدوري فإن الترابط بين الخرسانه والالياف قد يتلف أو ينكسر. ويعرض البحث الحالي دراسة مدى خفض قدرة التحميل المحوري لهذه العناصر المدعمه بسبب فقدان رابط الالتصاق بين سطح الخرسانه ومادة الالياف. وتتم الدراسه على عناصر أسطوانية من الخرسانة المحصورة بنسيج من ألياف الكربون. حيث قام هذا البحث على دراسه معمليه ودراسه تحليليه. الدراسة التحليلية تم إجراءها بإستخدام برنامج ANSYS. بينما تم إجراء الدراسة المعملية علي عدد ستة إسطوانات من الخرسانه. حيث تحاكي العينات المستخدمه للدراسه العناصر الاسطوانيه الغير مدعمه والعناصر المدعمه بالالياف بدون إستخدام ماده رابطه وعينات إسطوانيه تستخدم مادة الإيبوكسى كارابط بين الالياف وسطح الخرسانه. وعليه يتم قياس القوة المحورية القصوى للعينات لكل حاله عن طريق تحميلها حتى الانهيار. ويتم تسجيل شكل الشروخ ونوع الانهيار لكل حاله. وأيضا تتم المقارنات التحليلية للعينات التي تم تحليلها مع النتائج التجريبية. بوجه عام ، وٌجد أن التحزيم يزيد من القوة المحورية للعينات الأسطوانية. ووجد انخفاض فى القوة المحورية بنحو 23 ٪ بسبب فقدان التماسك من العينات المُحزمة.

Abstract

The axial strength of concrete elements is enhanced by adding external confinement through wrapping them with Fiber Reinforced Polymers, FRP, fabrics. In common practice, the fiber is wrapped around a concrete element and an adhesion is used to bond them together. When that element is exposed to cyclic loading the cohesion may be damaged and broken. Then the efficiency of such confinement is investigated for concrete cylindrical elements. The current research presents the reduction of element axial loading capacity due to the loss of the adhesion bond. The investigation is done on cylindrical concrete elements confined by carbon FRP fabrics. The loss of bond between FRP fabric and the surface of concrete element is assessed. The study is evaluated experimentally and numerically. The numerical investigation is done using ANSYS software, whereas, experimental testing is done on six specimens. The built specimens simulate cases with no confinement, with bonded confinement, and with none bonded confinement. The axial strength of specimens is measured for each specimen. The specimens are loaded until failure. The crack pattern and the mode of failure are recorded for all specimens. Analytical comparisons for the analyzed specimens with the experimental findings are done. In general, it is found that the confinement increased the axial strength of the cylindrical specimens. An axial strength reduction of about 23% is found due to the loss of adhesion in the confined specimens.

Keywords

CFRP; Axial Strength; Numerical analysis; ANSYS Software; Confinement.

1 Introduction

Recently, the confinement of concrete elements to enhance their behavior became a topic of concern. Confinement using FRP fabrics started to be used widely to enhance both strength and ductility of concrete elements. Using Fiber Reinforced Polymer wraps have established their efficiency due to the high strength-to-weight ratio, high corrosion resistance, flexibility to apply, and thin thickness. Numerous studies have been done about strengthening concrete elements using FRP wrapping [1] to [6]. In common practice, the fiber is wrapped around a concrete element and an adhesion is utilized to bond them together. When that element is exposed to cyclic loading (from earthquake, wind,..) the cohesion of the fiber to the concrete surface may be lost. Then our research focuses on evaluation of such confinement on concrete cylindrical elements. The study is performed on strengthened concrete cylindrical elements. First, an experimental program is performed on six concrete elements. Then, those elements are numerically examined using a general purpose finite element program, ANSYS. One ply is applied. The numerical model is verified with the experimental findings.

2 Objective

The main objective of this research is to evaluate the reduction of the axial capacity of CFRP strengthened elements after losing the adhesion between the concrete surface and the fibers.

CFRP fabrics are used for wrapping the concrete specimens. Experimental and analytical studies are carried out on cylindrical columns confined CFRP fabrics. The experimental findings are evaluated with numerical analysis of similar specimens in order to prepare a model ready for parametric study. The results of that research is used as a guide line for modification of the axial strength of strengthened specimen when they lose their adhesion to the applied fabrics.

3 Experimental Program

The experimental program is done on six concrete cylindrical elements. The samples dimensions are 150 mm in diameter and 300 mm in height. Figure (1) shows the specimen’s photos.

The specimens are loaded axially till failure. The specimens are divided into three groups:

Group (1): Two control cylinders without wrapping.

Group (2): Two cylinders are confined with one ply of carbon FRP without bonding. The wrapping using CFRP is bonded at the overlapped edges only (10 cm overlap). No epoxy material is applied to the concrete surface.

Group (3): Two cylinders are confined with one ply of carbon FRP using epoxy material for bonding.

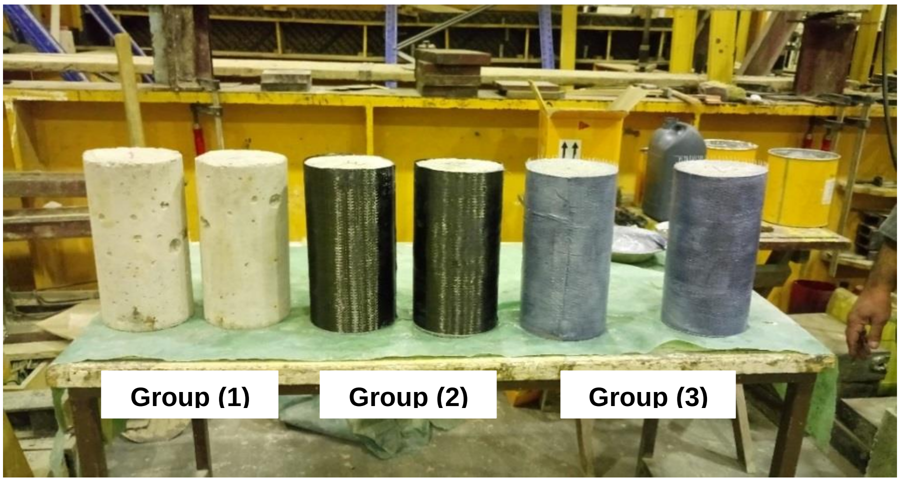


Figure 1: Dimension of the specimens and reinforcement details

Table 1: Details of concrete cylinders

Group No.	Cylinder No.	No. of FRP Plies	Epoxy
1	Cylinder (1)	-------	-------
	Cylinder (2)	-------	-------
2	Cylinder (3)	1 ply CFRP	Epoxy at overlap zone
	Cylinder (4)	1 ply CFRP	Epoxy at overlap zone
3	Cylinder (5)	1 ply CFRP	Epoxy at whole surface area
	Cylinder (6)	1 ply CFRP	Epoxy at whole surface area

3.1 Properties of the used materials

The used concrete mixture are designed and used for the specimens at the faculty laboratory. Three standard cubes for each specimen were tested after 28 days for the material compressive strength. The average compressive strength of the cubes is 30 MPa. The samples are wrapped with CFRP fabrics with physical properties as shown in Table 1. The epoxy is used as an adhesive material with properties shown in Table 2.

Figure 2: CFRP Sikawrap

Table 2: Physical properties of the FRP material

	CFRP Fabrics
Product Label	Sikawrap-300C
Product Description	Unidirectional, woven carbon fiber
Fabric length/roll	≥ 50 m
Fabric width	300/600 mm
Density	1.82 g/cm3
Fabric design thickness	0.167 mm
Tensile strength of fiber	4000 N/mm2
Tensile E-modulus of fiber	230000 N/mm2
Strain at break of fiber	1.7 %

Table 3: Properties of the adhesive material

	Epoxy
Product Label	Sikadur-330
Product Description	Sikadur-330 is a two-part, thixotropic epoxy based impregnating resin / adhesive
Appearance / Colors	Resin part A: Paste, Hardener part B: Paste Part A: white, Part B: grey Part A + Part B mixed: light grey
Mixing Ratio	4 (Part A): 1 (Part B)
Tensile strength	30 N/mm2
Bond strength	Concrete fracture (> 4 N/mm2)
Tensile E-modulus	3800 N/mm2
Strain at break of fiber	0.9 %

4 Test Setup

The experiments have been carried out in the Faculty of Engineering – Helwan University – Mattaria Branch. All cylinders are tested in the compression testing machine in order to obtain their axial capacities, see Figure (3).

Figure 3: Test set-up for confined and unconfined cylinders

5 Experimental Results

The results of the experimental program in addition to the cracking distribution are presented below.

5.1 Cracking pattern

It is observed during testing for the control specimens that the cracks begin from the top of cylinder at the load cell, then they increase gradually towards the bottom of the specimen. Figure (4) illustrates the crack patterns for the first group (control specimens).

Figure 4: Cracks distribution of cylinders in Group (1)

The same behavior are found for group (2) cylinders which are confined with one ply of CFRP using epoxy adhesion at the overlap zone of fiber only. It is observed that the CFRP layer is ruptured from the top of cylinder heading to its bottom over the cylinder height. Figure (5) illustrates the rupture of fiber laminate.

Figure 5: Cracks distribution of cylinders in Group (2)

Different behavior is found for the third group of confined cylinders where the epoxy adhesion is applied on the whole surface of the concrete specimen. The rupture of the CFRP occurred at the top of the specimen only and followed by sudden explosion of the concrete element at the top of the cylinder as shown in Figure (6).

Figure 6: Cracks distribution of cylinders in Group (3)

5.2 Loads at failure

All cylinder elements are tested using the compression testing machine in order to obtain the axial compressive strength of the concrete cylinders. The following table illustrates the axial failure load for each cylinder and the average axial load for each group.

Table 4: Axial capacities of standard cylinders

Group No.	Cylinder No.	Axial Capacity (ton)	Average Axial Capacity (ton)
1	Cylinder (1)	46.41	44.69
	Cylinder (2)	45.29	
2	Cylinder (3)	76.09	67.89
	Cylinder (4)	59.69	
3	Cylinder (5)	82.29	88.25
	Cylinder (6)	89.21	

It is observed that confinement of the concrete cylinders even without putting epoxy material, increases their axial capacity by 52% in average. In the other hand, the axial capacity is increased by 98% after using epoxy adhesion between the FRP layer and the concrete surfaces of the cylinders compared to the control specimen. The case of cylinders without epoxy may simulate strengthened reinforced concrete columns when the confinement fibers are split off the concrete surfaces. That may takes place when columns are subjected to lateral loads. Figures (7) and (8) illustrate the axial capacity due to the confined case and the case with loss of adhesion.

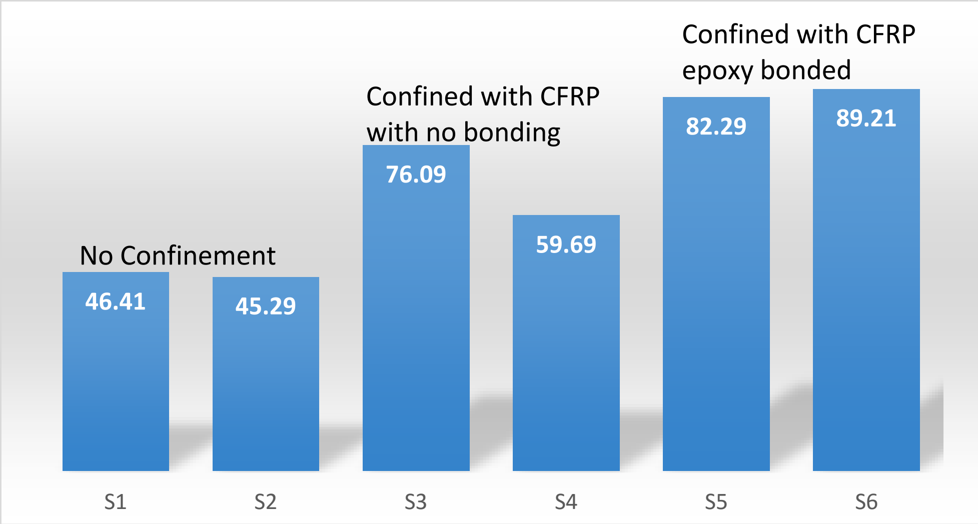


Figure 7: Maximum axial load of each specimen

One may deduce that the gain of strength due to the CFRP confinement using epoxy adhesion is reduced by ~23% after losing the adhesion. That is presented in Figure (8).

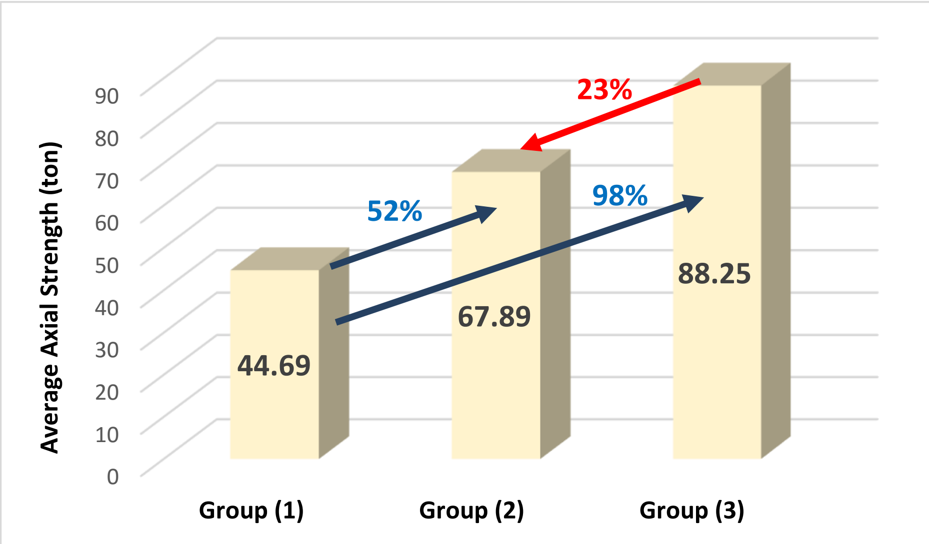
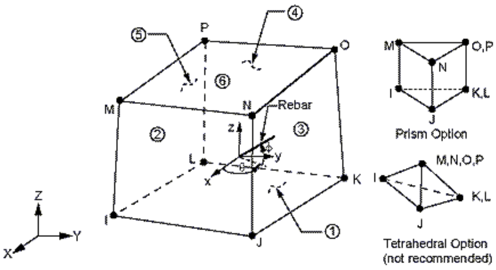


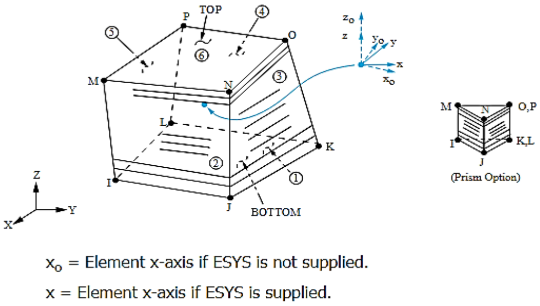
Figure 8: The effect of confinement and the loss of adhesion on the axial strength.

6 Numerical Investigation

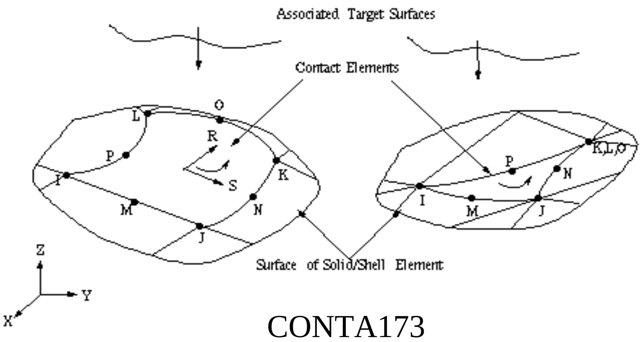
ANSYS software, a general purpose finite element program, is utilized in our analysis. The tested specimens are modeled with the same dimension and conditions as described in section 3. SOLID 65 element is used to model the concrete cylinders. The element is defined by eight nodes having three degrees of freedom at each node: translations in the nodal x, y, and z directions. That element has the capability to simulate cracking in tension and crushing in compression. The FRP material is modeled using SOLID185, see Figure (9). The layered composite specifications including layer thickness, material, orientation, and number of integration points through the thickness of the layer are specified via shell element. CONTA173 is used to represent contact and sliding between 3-D solid element and a deformable surface. This element has three degrees of freedom at each node: translations in the nodal x, y, and z directions as shown in Figure (9).



Solid 65 element



Solid 185 element



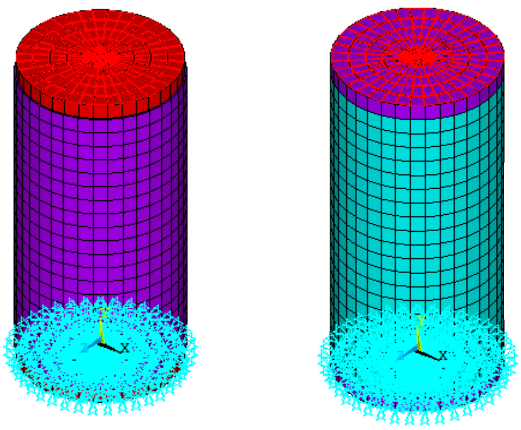
CONTA173

Figure 9: Types of elements utilized in the numerical models

Figure (10) presents the meshing of the investigated models. In current research the main assumptions [9] for finite element models are itemized as:

1. Concrete is modeled as an isotropic and homogeneous materials.
2. Poisson's ratio is assumed to be constant throughout the loading history.
3. Bond between FRP and concrete is taking into consideration by using contact element to simulate the epoxy material.

Confined Cylinder



Unconfined Cylinder

Figure 10: ANSYS Models for confined and unconfined cylinders

7 Results of the Numerical Investigation

7.1 Ultimate axial loads

The maximum axial load is found at the failure stage and presented for all specimens in the Table (5). In addition, the values are compared with the average values for each group from the experimental results.

Table 5: Axial capacities of specimens from ANSYS (P_{ANS}) and Experiments (P_{EXP})

Group No.	Cylinder No.	P_{ANS} (ton)	P_{EXP} (ton)	P_{ANS} / P_{EXP}
1	Cylinder (1)	44.18	44.69	0.99
	Cylinder (2)			
2	Cylinder (3)	75.81	67.89	1.12
	Cylinder (4)			
3	Cylinder (5)	89.95	88.25	1.02

The comparison shows that the results obtained from ANSYS analysis are in good agreement with the measured values from the experimental work. The variations are in the range of (1%-12%). Figure 11 shows the comparisons between the experimental values and the obtained numerical findings.

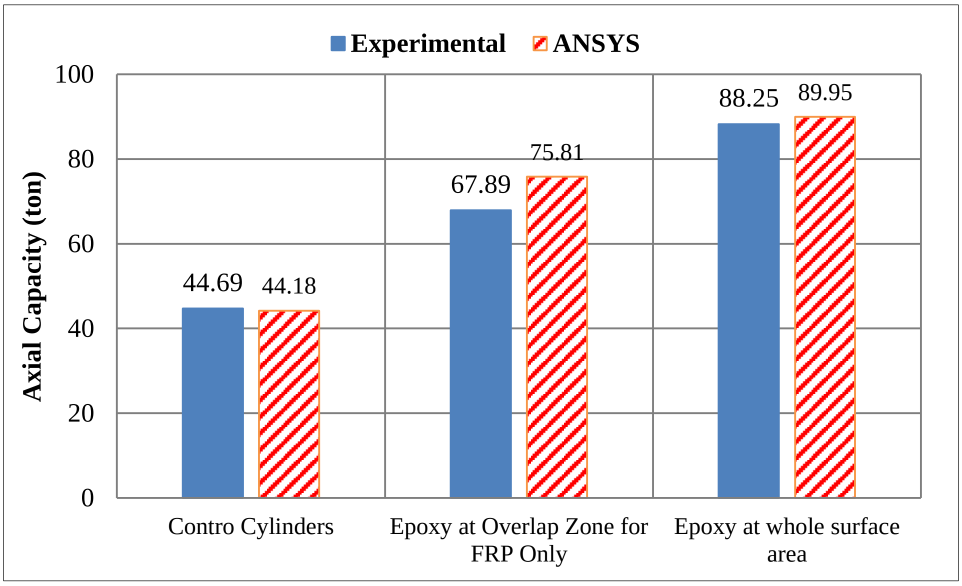


Figure 11: Results comparisons of the experimental values with the numerical findings.

7.2 Axial Displacement

Figure 12 shows the typical deformed shape obtained from the finite element analysis for the concrete cylinders. Also, Table (6) summarizes the values of vertical displacement.

Table 6: The axial displacements of the concrete cylinders

Group No.	Δv (mm)
1	0.033259
2	0.042685
3	0.076238

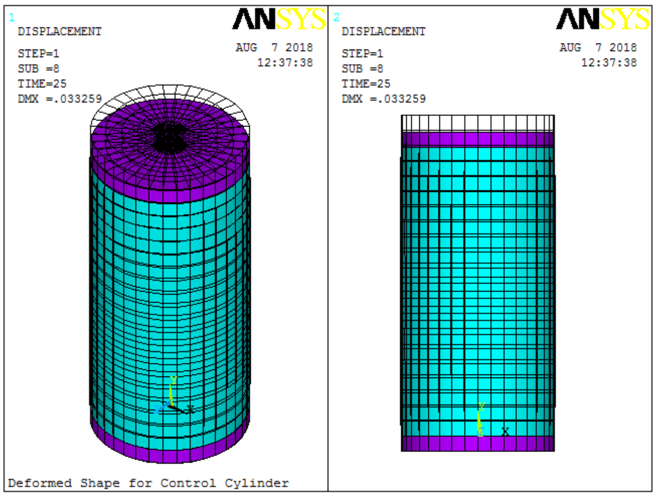


Figure 12: The axial deformation

7.3 Cracking Patterns

The crack patterns obtained from ANSYS models for each group are compared with the crack patterns obtained from the experimental tests. In general the cracks pattern obtained from the numerical analysis agreed with the experimental outcome. Figure 13 illustrates the cracks pattern occurred in the concrete cylinder for the unconfined specimens due to the axial load, Group (1). Those cracks begin at the top of the cylinder and then increase gradually towards to the bottom of the specimen.

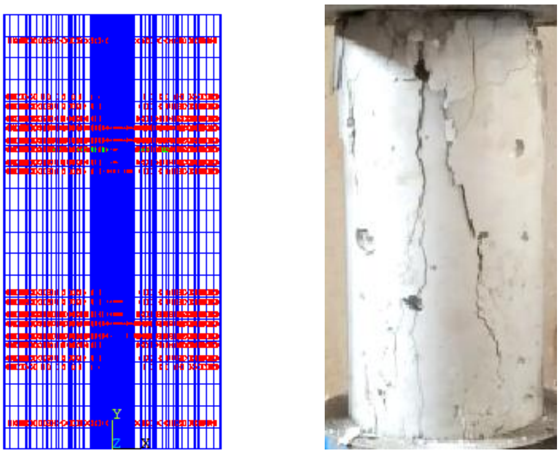


Figure 13: Crack pattern for the control cylinder

For group (2), the CFRP layer is ruptured from the top of cylinder heading to the bottom, and the concrete under the CFRP layer is cracked along the cylinder height.

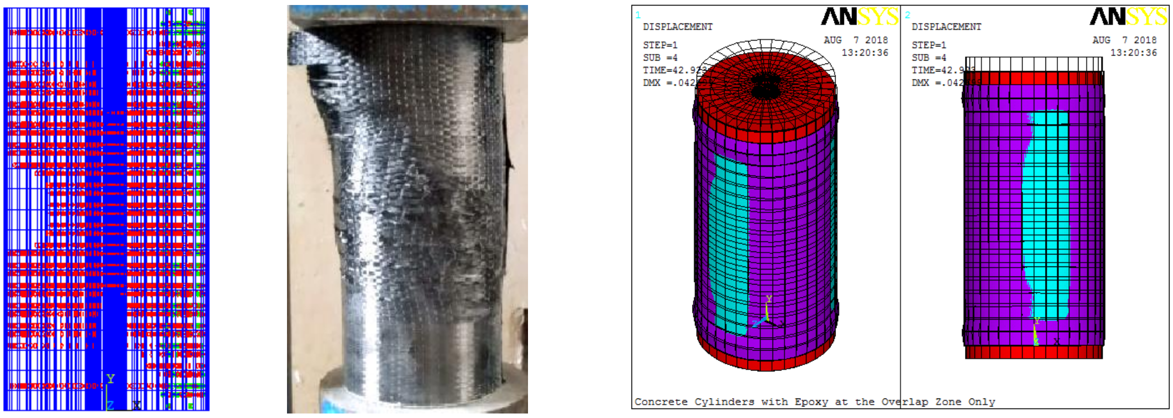


Figure 14: Crack pattern for cylinders with epoxy at overlap zone only.

The crack patterns for the numerical specimens are similar to the experimental findings, as shown in Figure (14).

For Group (3), the rupture of the fiber occurred at the top only which is followed by sudden explosion for the concrete at the top of the cylinder in the experimental test. A similar criteria is found in the ANSYS model as shown in Figure 15.

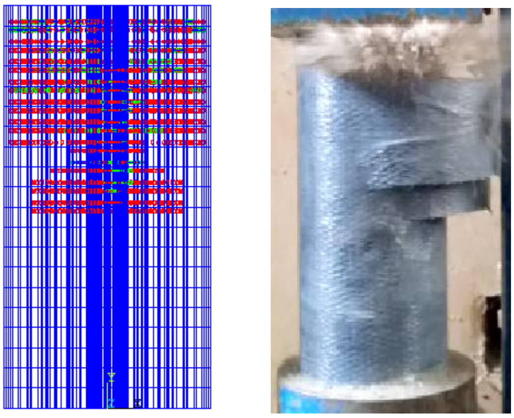


Figure 15: Crack pattern for cylinders with epoxy at whole surface area

8 Conclusion

1. Confining the concrete cylinders with one ply CFRP without placing any adhesive material between the FRP and concrete surface except at the overlap zone of the CFRP laminate could increase the axial compressive capacity of the cylinders up to 48%. This case may simulate the reinforced concrete columns when the bond between the FRP and the columns surfaces is fully lost.
2. Confining the concrete cylinders with one CFRP ply increases the axial compressive capacity up to 98% when putting the epoxy as an adhesive material between the concrete surface and CFRP.
3. Losing the contact bonds reduces the improved axial capacity by about 23% as compared with the fully bonded confined specimens.
4. Good agreements are achieved between the experimental and analytical models.

5. Simulating the epoxy material with contact element on the Finite Element Models makes the behavior of columns similar to the behavior of the experimental cylinders than assuming perfect bond between FRP and concrete.

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