LAP SPLICE BEHAVIOR AND STRENGTH OF CFRP ROLLS

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ABSTRACT

LAP SPLICE BEHAVIOR AND STRENGTH OF CFRP ROLLS

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Behavior of lap splices formed by CFRP rolls has been studied. CFRP rolls have been prepared by using CFRP sheets of a certain width. Strengthening methods that use CFRP rolls as reinforcement may require an epoxy anchored lap splice due to the conditions at the strengthening regions. It may not always be possible to strengthen the region by using only one roll fan anchored at both ends, but using two rolls from opposite faces of the member and lap splicing them at the middle so that they act as a single roll. Lap splice behavior can be studied best by using flexural beam bond specimens if the reinforcing material is steel. Therefore, it has initially been suggested that flexural beam specimens reinforced for flexure with CFRP rolls as tension reinforcement can be used in studying the lap splice behavior. However, due to the difficulties encountered in the beam tests, another type of test specimen was introduced, which was a direct pull-out specimen. In this type of test specimen, lap spliced CFRP rolls have been tested under direct tension, in which the tension has been applied by making use of concrete end blocks that transfer the tension to the rolls. Eleven tests have been made in total. Full material capacity of the rolls could not be achieved due to premature failures. However, important conclusions and recommendations have been made for future studies.

Keywords: Lap Splice, Lap Length, Bond, Anchorage, CFRP Roll.

ÖZ

CFRP RULOLARININ BİNDİRMELİ EK DAVRANIŞI VE DAYANIMI

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Yüksek Lisans, İnşaat Mühendisliği Bölümü
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CFRP rulolarının bindirmeli ek davranışı incelenmiştir. CFRP ruloları belirli bir genişlikte CFRP kullanılarak hazırlanmıştır. CFRP rulolarını donatı olarak kullanan güçlendirme yöntemlerinde, güçlendirilen bölgenin durumuna göre bindirmeli ek gerekebilir. Bölge sadece iki ucu yelpaze ile tutulmuş tek bir rulo kullanarak güçlendirilemeyebilir. Bölgenin, karşılıklı iki yüzeyinden kullanılan iki rulonun ortada bindirilerek tek bir rulo gibi davranması ile, güçlendirmesi yapılabilir. Çelik donatı kullanıldığında, bindirmeli ek davranışı kiriş eğilme aderansı deneyleri ile iyi bir şekilde incelenmektedir. Bu nedenle, çalışmanın başında CFRP rulolarının çekme donatısı olarak kullanıldığı kiriş eğilme aderansı deney elemanlarının kullanılması uygun görülmüştür. Kiriş deneylerinde karşılaşılan güçlükler nedeniyle, başka bir test elemanı ile doğrudan çekip çıkarma testleri yapılarak CFRP rulolarının bindirmeli ek davranışı incelenmiştir. Bu test elemanı doğrudan çekip çıkarma test elemanı olarak adlandırılmıştır. Bu test elemanında, bindirilmiş CFRP rulolarına harici dış beton blokları kullanılarak çekme uygulanmıştır. Toplamda onbir test yapılmıştır. Bu testlerde CFRP nin tam malzeme kapasitesine, oluşan erken göçmeler nedeniyle erişilememiştir. Ancak gelecek çalışmalar için önemli sonuçlar ve öneriler yapılmıştır.

Anahtar Kelimeler: Bindirmeli Ek, Bindirme Boyu, Aderans, Kenetlenme, CFRP Rulo.

To my family

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ϕ	Steel reinforcement diameter, mm
ϕ_h	Anchor hole diameter, mm
ϕ_r	Average roll diameter, mm
f_{yk}	Characteristic yield strength for steel, MPa
f_u	Ultimate strength for steel, MPa
f_{ck}	Characteristic compressive strength for concrete, MPa
f_c	Compressive strength for concrete (test specimens), MPa
f_f	Tensile strength for CFRP sheets, MPa
ε_{cu}	Ultimate concrete strain, mm/mm
ε'	Strain in compression reinforcement, mm/mm
$\varepsilon_{y,CFRP}$	Ultimate strain for CFRP sheets, mm/mm
ω	Width of CFRP sheets, mm
ω_b	Balanced width of CFRP sheets, mm
t	Thickness of CFRP sheets, mm
c	Neutral axis depth, mm
b_w	Web thickness, mm
l	Lap length, mm
L	Length of the test specimen, mm
σ'	Stress in compression reinforcement, MPa
σ_f	Stress developing in CFRP rolls, MPa
F'	Force developing in compression reinforcement, kN
F_{CFRP}	Force developing in CFRP rolls, kN
$P_{\max}$	Maximum load capacity of the specimen, kN
$M_{\max}$	Moment capacity of the specimen, kNm

K_{pk}	Curvature at peak load, rad/m
δ_{pk}	Deflection at peak load, mm
d	Effective depth for tension reinforcement, mm
d'	Effective depth for compression reinforcement, mm

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

Carbon fiber reinforced polymer (CFRP) sheets are being extensively used in repair and strengthening of existing reinforced concrete structures. The most important property of CFRP is its exceptionally high tensile strength. Due to its high tensile strength, CFRP sheets are used to resist tension in the direction of carbon fibers in the structures. However, this high capacity requires proper anchorages at the ends of the used sheets in order to be made use of. In some cases, this anchorage is supplied by wrapping the sheets around the structural members at the ends of the sheets. However, sometimes external anchorages may be needed besides wrapping and a popular method for this is to nail down the sheets by using epoxy anchored CFRP rolls (anchor dowels) all along the member thickness and free ends of which are spread over the surface of the sheets used, which makes a fan type integration with the sheet.

Sometimes, it may not be possible to make fan type anchorages at both ends of the roll due to some structural reasons (drilled holes for the rolls may be intersecting a reinforcement; thickness of the structural member being drilled may be large, etc.). When this is the case, anchorage can be made by epoxy anchoring two rolls from opposite faces and lap splicing them at the middle so that they act as a single roll. For example, in strengthening slabs for punching, CFRP rolls can be used as stud type reinforcement. However, both ends of them should make fan type integration with the CFRP sheet used on the surface of the slab.

In the reported study, lap splice behavior and strength of CFRP rolls is investigated by using flexural beam bond specimens, in which beams are reinforced for flexure with CFRP rolls acting as tension reinforcement, and direct pull-out specimens, in which the specimen is reinforced for tension with CFRP rolls acting as direct tension reinforcement.

1.2 LITERATURE SURVEY

In literature, there is not much information on structural members reinforced with CFRP rolls, although there are studies in which carbon solid rods have been used as reinforcement.

Considering the advantage of exceptionally high strength of carbon fiber, it has been proposed that CFRP rolls can be used to strengthen an existing structural member as additional reinforcements in addition to their usage in anchoring CFRP sheets.

[1] *Erdoğan, H., "Improvement of Punching Behavior and Strength by CFRP Rolls". PhD thesis in progress, Department of Civil Engineering, Middle East Technical University, Ankara, Turkey*. In this study, full scale reinforced concrete slabs that are reinforced for punching around column heads with CFRP rolls are being tested. In this study, main parameter is the properties of the CFRP rolls used in strengthening, such as width of the sheet used in forming the rolls, orientations of the rolls on the slab, etc. This study is still in progress, but from the results it can successfully be concluded that CFRP rolls can be used as stud type punching reinforcement in strengthening slabs well.

[2] *Gökdemir, H., "Seismic Strengthening of Beam-Column Joints in Existing R/C Structures by using CFRP rolls". PhD thesis in progress, Department of Civil Engineering, Osmangazi University, Eskişehir, Turkey.* In this study, different reinforcement types are used for strengthening weak beam-column connections.

The study is still in progress at the METU Structural Mechanics Laboratory and the object of the study is to develop the most efficient and economical strengthening method for weak beam-column connections with minimum disturbance in the connection zones. As the main part of this study, CFRP rolls have been used as reinforcement in strengthening beam column joints, which includes epoxy anchored lap splices. From that perspective, this study is directly related to the study reported.

[3] *Özdemir, G., "Mechanical Properties of CFRP Anchorages", MSc thesis, January 2005, Department of Civil Engineering, Middle East Technical University, Ankara, Turkey.* In this thesis, strength of CFRP anchor dowels is studied by using pull-out specimens. Main parameters on the tensile strength capacity of CFRP anchor dowels are the anchorage depth, anchorage diameter, and the amount of fibers. This thesis suggests that there is a limit depth for increasing the strength of anchor dowels beyond which depth; no bond strength gain can be achieved as expected naturally. Moreover, it can be stated that the embedment length depends not only on the properties of the anchor dowel itself but also on the geometrical properties of the concrete body, such as the width of the concrete member since the depth of a possible failure cone depends also on its maximum possible base width, which depends on the area affected by the stresses developing due to pull-out.

[4] *Akın, E., "Strengthening of Brick Infilled Reinforced Concrete Frames with CFRP Sheets", PhD thesis in progress, Department of Civil Engineering, Middle East Technical University, Ankara, Turkey*. In this thesis, CFRP rolls are used as anchor dowels to provide proper anchorages to the CFRP sheets used as strengthening members. CFRP sheets are used as bracings in the frame, which increases the lateral rigidity of the frame. However, these sheets should be properly anchored to the existing structural members in order to behave efficiently and this is achieved by wrapping the sheets around the columns and then anchoring them with CFRP rolls (anchor dowels) to the existing structural members. CFRP rolls are also used for anchoring the sheets used on the

opposite faces of the wall to each other. The test results show that using CFRP sheets significantly enhances the behavior. However, anchorage is the most important parameter since without proper anchorages; it will not be possible to make use of the full capacity of the sheets.

1.3 OBJECT AND SCOPE OF THE STUDY

In testing CFRP rolls, the most important problem encountered is how to provide proper end conditions with minimum amount of stress concentration at loading zones. As it was stated previously, there are researches in which the behavior is investigated with pull-out specimens. However, in those researches, there are many premature failures, which can be attributed to the end conditions. Therefore, this problem has to be minimized in order to obtain proper results and it has been stated that this problem can be minimized by using specimens in which loads are applied by making use of outer concrete blocks. Those blocks cover the CFRP rolls so that they provide proper end conditions with minimum stress concentration in the rolls, which makes it possible to test the rolls by applying the load all along the roll length not at just one point on the rolls.

In the light of the explanation above, it was decided to have basically two types of specimens in the research, which were flexural beam bond specimens and direct pull-out specimens. However, before stating the details, a few definitions have to be made.

1.3.1 Lap Length

There are two definitions for lap length, which are embedded lap length and epoxy anchored lap length.

- *Embedded Lap Length*: it is used with its conventional definition, as the minimum lap length for the ordinary lap splices embedded directly in concrete, sufficient to make use of the full material capacity of the CFRP rolls without any bond failure.

- *Epoxy Anchored Lap Length*: it is defined as the minimum lap length for the splices formed by epoxy anchoring the rolls in hardened concrete, sufficient to make use of the full material capacity of the rolls without any bond failure.

1.3.2 The Object of the Study

The object of this study is to formulate an *Epoxy Anchored Lap Length* expression in terms of the amount of the carbon fibers existing at the cross section of the CFRP sheets used in shaping the rolls.

Although there are many factors affecting the behavior of the specimens, the main parameter is the width (ω) of the CFRP sheet used in the rolls and it is desired to formulate *Epoxy Anchored Lap Length* in terms of ω, like 2ω, 3ω etc. to be used in engineering practice. There are two reasons in choosing the main parameter as ω;

- Amount of carbon fibers at a CFRP sheet's cross section can be calculated by simply multiplying its width (ω) by its thickness (t).

- Used CFRP sheet type has carbon fibers oriented in the same direction with a reference sheet thickness of 0.165 mm and the formulation will be made by taking the sheet thickness constant since manufactured CFRP sheets do not show variation in their thicknesses. However, if a different thickness is reported by a manufacturer for a specific CFRP sheet, the formulation can be modified by multiplying it with the ratio of the used sheet thickness to the reference thickness (t_{used}/t_{ref}).

CHAPTER 2

TEST SPECIMENS

2.1 TEST SPECIMENS

When the study was first initiated, test specimens were chosen as 200×300 (mm) flexural beam bond specimens due to the debatable results obtained in simple pull-out tests. Moreover, after testing the specimens, testing of another specimen type was decided and they were direct pull-out specimens.

2.1.1 Flexural Beam Bond Specimens

The main idea in using these specimens was to create tensile forces in the CFRP rolls without causing premature failures, which can be attributed to the stress concentration developing at loading zones in simple pull-out tests. There are four types of beam bond specimens;

- Reference specimen (CR): Reinforced for flexure with two continuous CFRP rolls acting as tension reinforcement.
- Series A: Reinforced for flexure with directly embedded lap spliced CFRP rolls at the mid-span.
- Series B: Reinforced for flexure with lap spliced CFRP rolls that are epoxy anchored to the precast concrete block at the mid-span of the beam.
- Series C: The same type as series B. However, this series has increased cover thickness.

All of the specimens above were tested under two point loadings applied at 1/3rd of the beam span (four point bending test) so that a zero shear and a constant moment region was obtained at the mid-span.

2.1.1.1 Reference Specimen

The aim of lap splice is to make the lap spliced reinforcements act as a single reinforcement. For this reason, the behavior of beams reinforced with continuous CFRP rolls as tension reinforcements should be studied so that lap spliced cases can be compared to the behavior of the reference specimen (CR).

In order to study CFRP rolls' behavior well, tension failure must be ensured. Therefore, determination of the amount of carbon fibers to be used in shaping the rolls is essential so that the failure mode of the beam will not be a compression failure, but it will be a tension failure. In other words, it should be under-reinforced. Since the thickness of the sheets is constant ($t=0.165mm$), only the strip width (ω) to be used has to be computed. The reinforcement detail of the reference specimen has been shown in Figure 2.1.

In concrete sections that are reinforced with steel reinforcement, tension failure refers to yielding of steel without crushing on compression face and since steel is a ductile material, the failure is ductile. Tension failure stated in the paragraph above refers to the rupture of CFRP rolls. Moreover, due to the nature of carbon fibers, the tension failure stated is brittle, unlike steel reinforcement. Therefore, in the paragraph above, “under-reinforced” refers to the failure of CFRP rolls rather than ductile behavior.

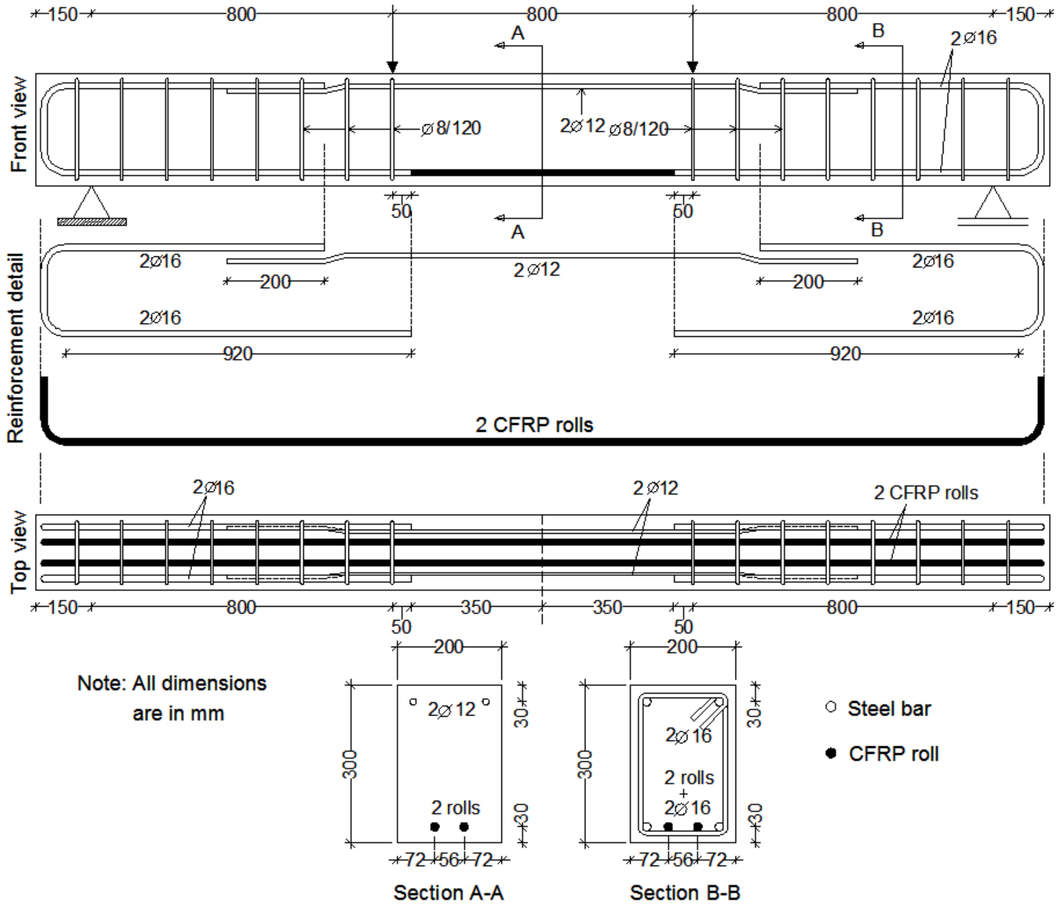


Figure 2.1 Reinforcement detail of the reference specimen

2.1.1.1.1 Balanced case calculation for the strip width ω for the CFRP rolls

Using the reinforcement detail for reference specimen, the following balanced case calculation can be made;

In balanced case, concrete on compression face and the CFRP rolls, undergoing tension, fail simultaneously. In other words, they reach their ultimate strains at the same time, Figure 2.2.

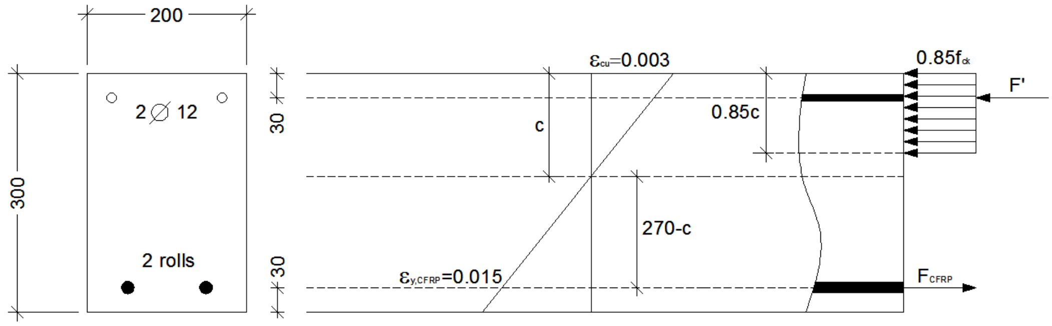


Figure 2.2 Section A-A from Figure 2.1

From strain diagram in Figure 2.2, compatibility equation (1) can be written as;

$$\frac{c}{270-c}=\frac{0.003}{0.015}\rightarrow c=45mm \tag{1}$$

$$\frac{\varepsilon'}{0.003}=\frac{15}{45}\rightarrow \varepsilon'=0.001\Rightarrow \sigma'=0.001\cdot 200000=200MPa$$

ε' : Strain in compression reinforcement at the instant of balanced failure

σ': Stress in compression reinforcement at the instant of balanced failure

From Figure 2.2, equilibrium equation (2) can be written as;

$$F_{CFRP}=0.85\cdot c\cdot 0.85\cdot f_{ck}\cdot b_w+2\cdot\sigma'\cdot\pi\cdot\frac{12^2}{4} \tag{2}$$

$c=45mm$, $\sigma'=200MPa$, $f_{ck}=20MPa$, $b_w=200mm$

Substituting the values;

$F_{CFRP}=175288.9N$ (Total force developing in the rolls)

And by substituting equation (2) into equation (3);

$$F_{CFRP}=f_f\cdot n\cdot t\cdot\omega_b\rightarrow\omega_b=\frac{F_{CFRP}}{n\cdot t\cdot f_f} \tag{3}$$

$f_f=3430MPa$ (Tensile strength of CFRP sheet assuming full capacity might be achieved in the tests)

$n=2$ (Total number of CFRP rolls at the cross section)

$t=0.165mm$ (Thickness of the CFRP sheet)

ω_b : Balanced width of the CFRP sheets

Substituting the values;

$\omega_b = 154.86mm$

The balanced CFRP strip width is calculated as 154.86 mm. Therefore, in order to obtain an under-reinforced section, 120 mm of CFRP sheet, which is less than ω_b for each of the CFRP rolls, is chosen.

The strip width to be used is calculated as shown above and by using the stated strip width, the rolls were prepared, which is explained in Section 2.3 of this chapter.

2.1.1.2 Series A

In this series, behavior of the splices made by lap splicing two CFRP rolls at the middle of the beam's span has been studied. The main objective in this series was to make the embedded lap spliced rolls act as a single roll and to make use of the full material capacity of the rolls. In other words, lap spliced CFRP rolls were expected to rupture without any premature failure.

The reinforcement detail is the same as the reference specimen except the lap splices. The detail is shown in Figure 2.3. In this series, three specimens were planned to be tested. In these specimens, the only changing parameter was the lap length (*l*), which is embedded lap length, since a lap length formulation like 1ω, 2ω, etc is desired to be obtained. The parameters of the specimens are tabulated with respect to the specimen names in Table 2.1. In that table, the numbers next to the abbreviation letters for Series A stand for the multipliers of strip width (ω).

Table 2.1 Series A

Specimen Name	*Lap length (l)*
A1	1ω = 120 mm
A2	2ω = 240 mm
A3	3ω = 360 mm

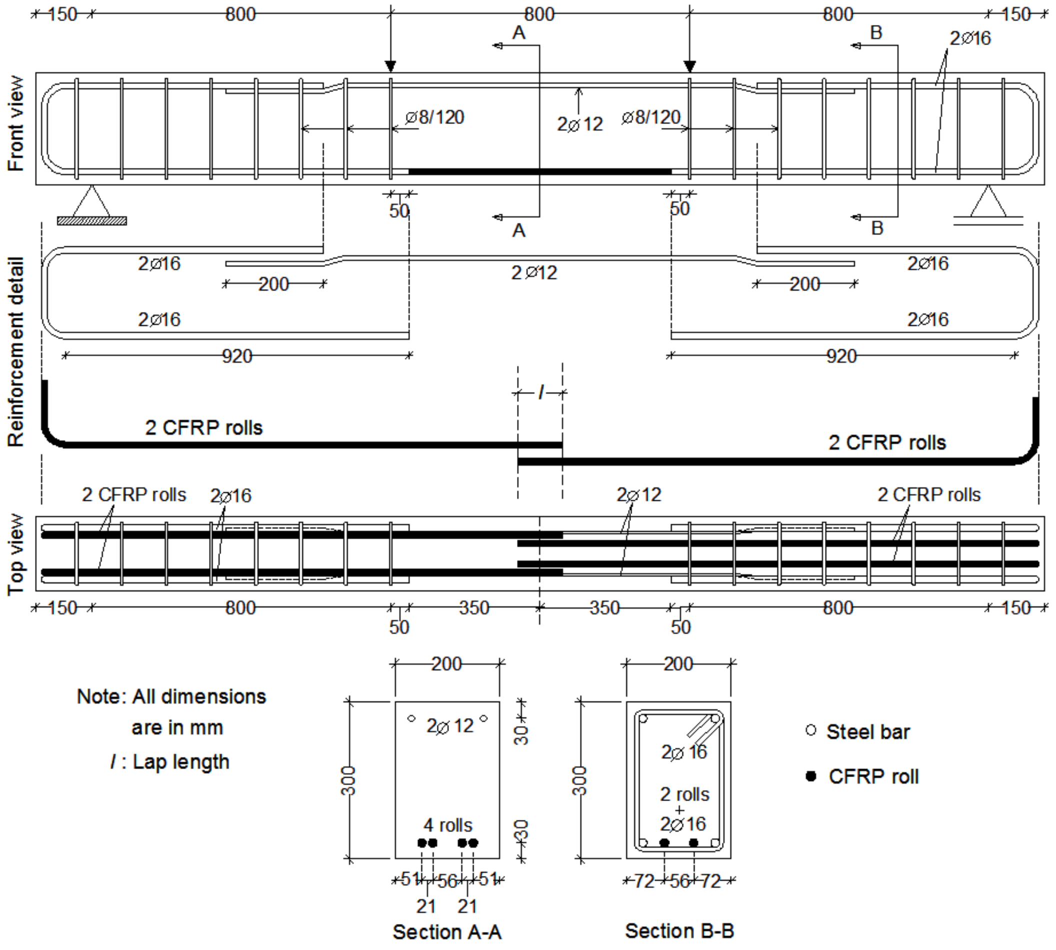


Figure 2.3 Reinforcement detail of specimens in series A

In the lap spliced rolls, the strip width used was the same as it was in reference specimen, which was ω=120 mm. In Figure 2.4(a), the general view of the reinforcement in the formwork and in Figure 2.4(b), the top view of the lap splice at the mid-span in the formwork before casting are shown.

(a) **(b)**

Figure 2.4 (a) General view, **(b)** Top view of the lap splice (mid-span)

2.1.1.3 Series B

Series A is mainly about understanding the behavior of the lap splices formed by lap splicing the CFRP rolls embedded directly in concrete. On the other hand, Series B has been designed to understand the behavior of the lap splices formed by epoxy anchoring the CFRP rolls into the precast central block of the test beam. In this series, central block having the length of the lap splice (*l*) at the middle of the test beam, which is epoxy anchored lap length, was cast first by leaving the necessary holes, to which the rolls were to be epoxy anchored. After epoxy anchoring the rolls to the precast central block, the remaining part of the test beam was cast. In these specimens, CFRP rolls were planned to resist tension. The reinforcement detail of this series has been shown in Figure 2.5. Three different epoxy anchored lap lengths were planned to be tested, which are shown in Table 2.2. The abbreviation used in naming the specimens is the same as the one used for Series A.

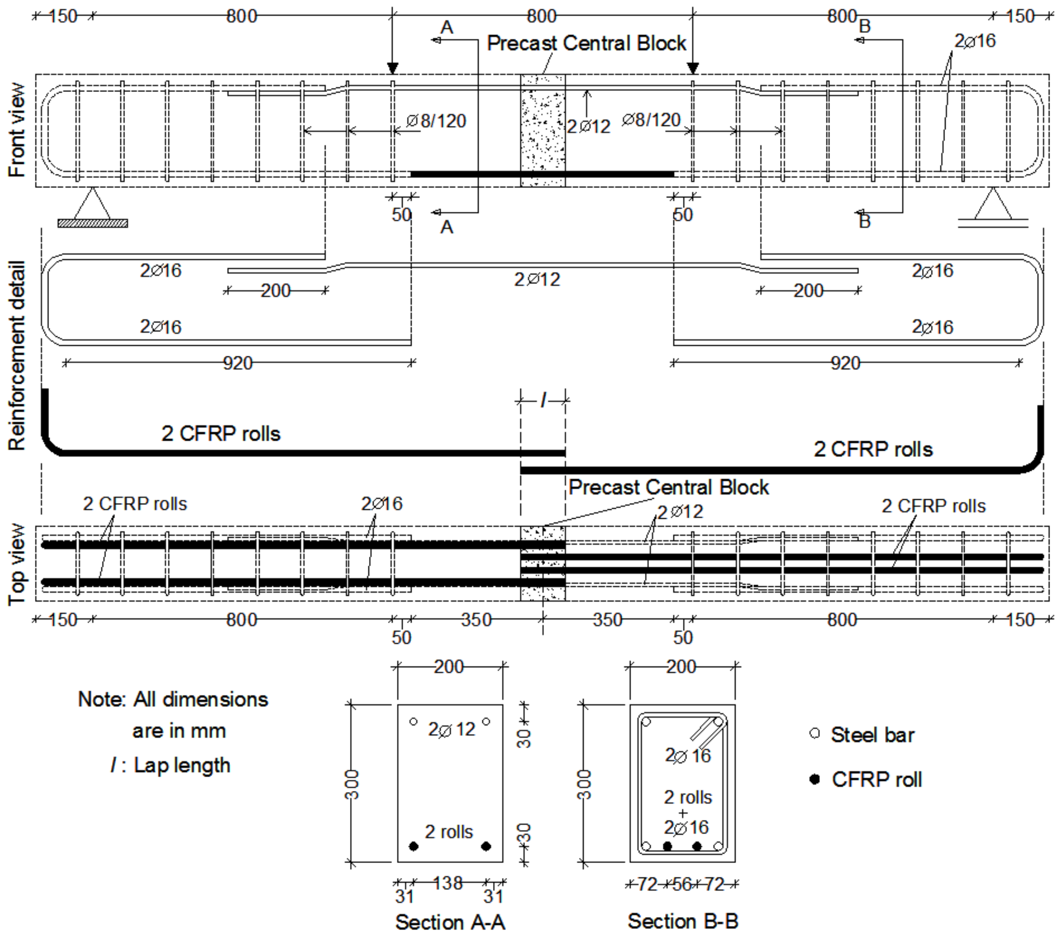


Figure 2.5 Reinforcement detail of specimens in series B

Table 2.2 Series B

Specimen Name	*Lap Length (l)*	*Anchor Hole Diameter ($Ø_h$)*	*Average Roll Diameter ($Ø_r$)*
B1	1ω = 120 mm	22 mm	17 – 19 mm
B2	2ω = 240 mm		
B3	3ω = 360 mm		

In Figure 2.6(a) and Figure 2.6(b), the specimens are shown during anchorage and after assembling with the reinforcements.

(a) **(b)**

Figure 2.6 (a) Anchorage, **(b)** Assembled with reinforcement

2.1.1.4 Series C

This series was developed after obtaining the results of the tested specimens in series B (The detailed results of all the specimens tested are stated in Chapter 3). This series was the same as series B, but the only difference is that the concrete cover was increased all along the test beam. It was desired to make use of the full capacity of the rolls. Therefore, in case of concrete splitting, cover was increased by increasing the distance between the rolls. Especially, the effective depth of the beam was kept constant so as to be able to make comparison with the other specimens. Reinforcement detail of series C has been shown in Figure 2.7. There is only one specimen in this series. An epoxy anchored lap length of 3ω was planned to be tested. The design details have been shown in Table 2.3 and in Figure 2.8, final view of the specimen before casting has been shown.

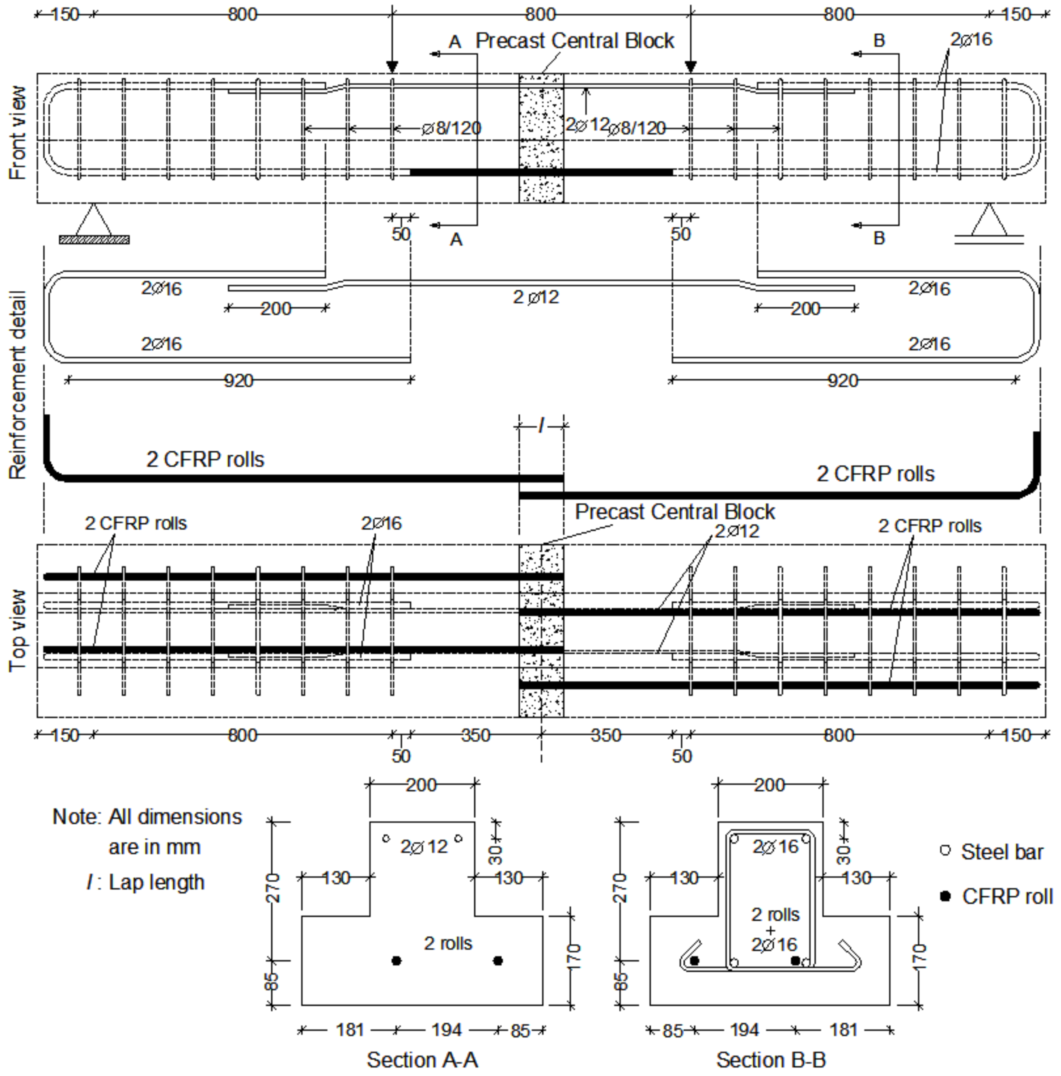


Figure 2.7 Reinforcement detail for series C

Table 2.3 Series C

Specimen Name	*Lap Length (l)*	*Anchor Hole Diameter ($Ø_h$)*	*Average Roll Diameter ($Ø_r$)*
C3	3ω = 360 mm	22 mm	17 – 19 mm

Figure 2.8 Specimen C3 of series C before casting outer blocks

2.1.2 Direct Pull-Out Specimens

After beam bond specimens were tested, the desired results could not be obtained and it was planned to develop a different type of test specimen in which lap splices would not undergo tension by flexure but direct axial tension. This series can be thought as the combination of series B and series C together with application of direct tension to the specimen. There is only one series in this specimen type;

- Series D: Four CFRP rolls are epoxy anchored to the precast central concrete block to form two epoxy anchored lap splices.

2.1.2.1 Series D

In this series, CFRP rolls were epoxy anchored to the precast central block to form lap splices that would undergo direct tension. However, the splices were formed in a different manner; splices were oriented in axial direction. The reinforcement detail of the specimen has been shown in Figure 2.9. In this type of specimen, the end blocks were used to apply tensile forces to the epoxy anchored rolls with minimized stress concentration.

It can be seen in Figure 2.9 that there are alignment keys used between the central block and the end blocks. The purpose of these keys is to prevent a possible relative movement between the blocks, which may cause CFRP rolls to crack or rupture while being moved to the test setup. In other words, they act like shear keys. These keys do not make contribution to the axial capacity.

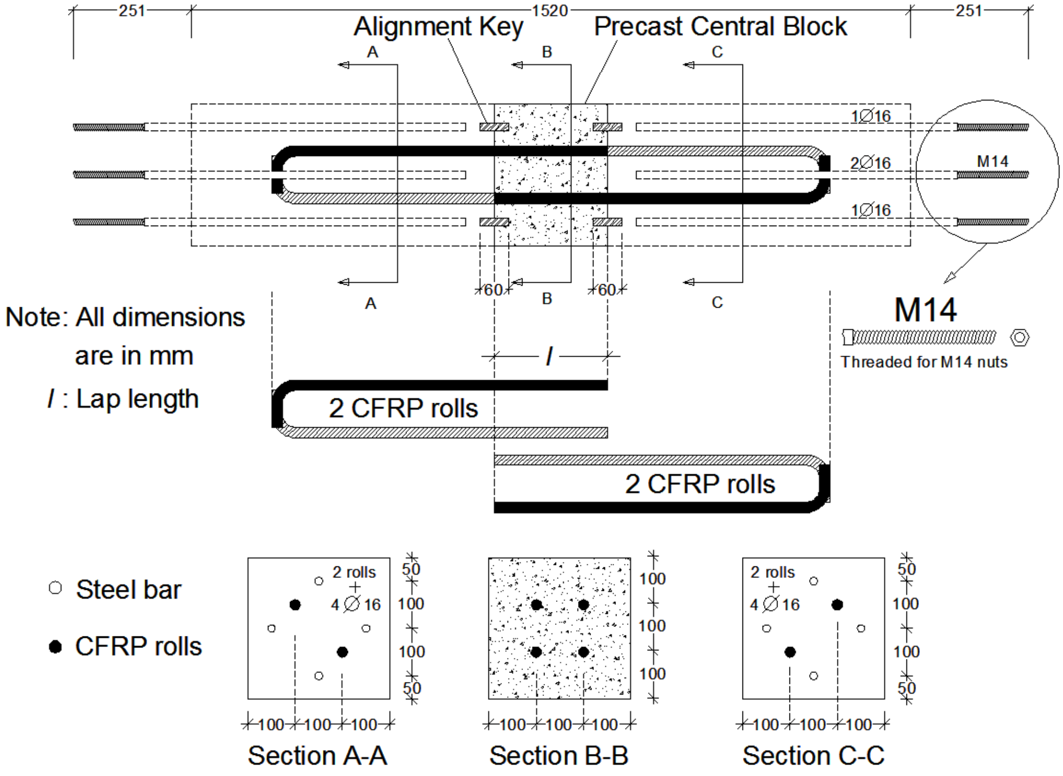


Figure 2.9 Details of specimens in Series D

Central blocks were cast first by leaving the necessary holes to which the rolls were to be epoxy anchored. After the central blocks gained their strength, the rolls were epoxy anchored according to the details in Figure 2.9. Figure 2.10(a) shows the state during which epoxy anchorages were made. Later, the end blocks were cast. Before casting the end blocks, the central blocks were covered with waterproofing material, Figure 2.10(b). The purpose of that was to prevent any possible bond weakening between the epoxy anchored CFRP rolls and the concrete, which may be due to the penetration of water while curing the end blocks. It is known that anchorages made in a moist concrete is weaker than the ones made in dry (fully hardened) concrete. However, after anchorages are properly made, it is questionable whether the penetration of water weakens the bond between the concrete and epoxy or not. In addition to that, the material created dilatation between the central and end blocks, which made only the CFRP rolls and central concrete block resist tension. The end blocks were only used for holding the rolls and for applying tension. All the steel reinforcement and the anchorage length of each used in end blocks were chosen to resist the expected failure load of the CFRP rolls without any bond failures. There are three specimens in this series properties of which have been tabulated in Table 2.4.

(a) **(b)**

Figure 2.10 (a) Anchorage of CFRP rolls, **(b)** Cast of end blocks

Table 2.4 Series D

Specimen Name	*Lap Length (l)*	*Anchor Hole Diameter ($Ø_h$)*	*Average Roll Diameter ($Ø_r$)*	*Member Length (L)*
D1	1ω = 120 mm	22 mm	17 – 19 mm	1520 mm
D2	2ω = 240 mm			
D3	3ω = 360 mm			

In all of the specimens shown in Table 2.4, average roll diameter is changing between 17 and 19 mm. This is due to the difficulty in controlling the diameter of the rolls in production (shaping) stage and making a perfectly circular roll is almost impossible considering small roll diameter.

To sum up, there are four types of flexural beam bond, and one type of direct pull-out specimens. Moreover, there are eight and three specimens in these types respectively. The details of the test setups, and test results are stated in Chapter 3 for all of the test specimens in this chapter.

2.2 MATERIALS

2.2.1 Concrete

Throughout the study, the desired 28th day characteristic concrete compressive strength (f_{ck}) was 20 MPa. The following concrete mix design in Table 2.5 has been used and in Table 2.6, test specimens are summarized with the concrete strengths on the testing day.

Table 2.5 Concrete mix design properties

	Percentage by Mass (%)
Aggregate Size : 0 – 3 mm	19
Aggregate Size : 3 – 7 mm	38
Aggregate Size : 7 – 15 mm	20
Cement	14
Water	9

Table 2.6 Test specimens

Specimen	CR	A1	A2	A3	B1	B2	B3	C3	D1	D2	D3
Lap Length (mm)	-	120	240	360	120	240	360	360	120	240	360
Lap Length (ω)	-	1ω	2ω	3ω	1ω	2ω	3ω	3ω	1ω	2ω	3ω
f_c *(MPa)*	19.1	18.4	20.9	22	20.9	21.4	21.4	29.2	20	20	20

2.2.2 Steel Reinforcement

Throughout the study, three types of steel reinforcement have been used, whose material properties have been shown in Table 2.7.

Table 2.7 Steel reinforcement properties

Diameter Ø (mm), Type	*Characteristic Yield Strength* f_{yk} *(MPa)*	*Ultimate Strength* f_u *(MPa)*
8, Deformed	429	665
12, Deformed	426	661
16, Deformed	430	667

2.2.3 Carbon Fiber Reinforced Polymer

CFRP sheets that are used for shaping the rolls are named *C1-30 Carbon Fiber Reinforced Polymer Sheets* manufactured by *Degussa-MBrace*. The properties of CFRP sheets are shown in Table 2.8, which are determined by the manufacturer and given in their catalogue [5].

Table 2.8 CFRP sheet properties

Characteristic Tensile Strength (MPa)	3430
Characteristic Modulus of Elasticity (MPa)	230000
Ultimate Strain	0.015
Effective Sheet Thickness (mm)	0.165

2.2.4 Epoxy

Two-component epoxy resin (Component ratio is 1/3) recommended by the manufacturer for C1-30 CFRP sheets has been used in shaping, and in anchoring the rolls. Moreover, its contribution to the axial tension capacity of the roll has been neglected since its tensile strength is 1% (50 MPa) of that of the carbon fiber.

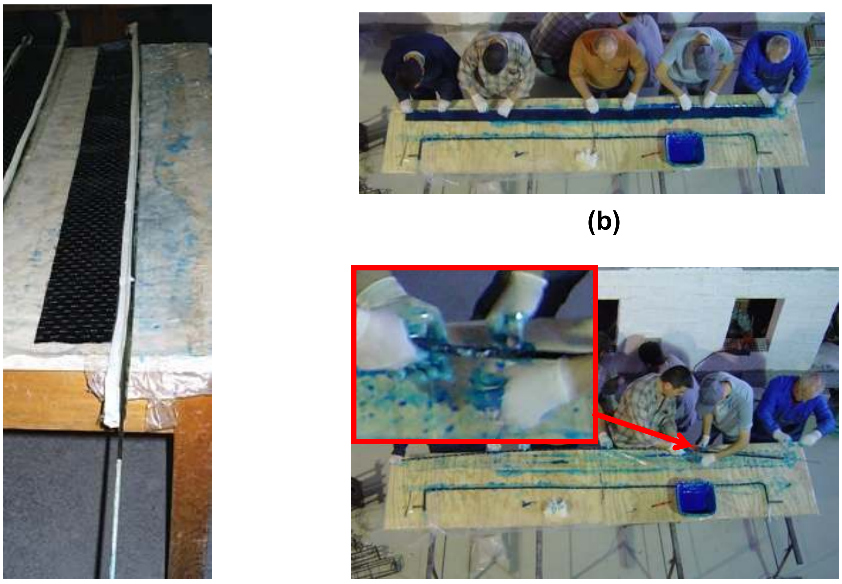
2.3 PREPARATION OF THE ROLLS

Small lengths of CFRP sheets are easy to be shaped into a roll. However, when larger lengths are required to be shaped into rolls, it is obvious that shaping them is not easy. Therefore, a procedure was developed and this section states the details in shaping the CFRP rolls that were used in the specimens.

In this procedure, the aim is to make CFRP rolls, which will not contain any other materials contributing to the tensile capacity apart from the CFRP sheet itself. Also, the resulting rolls must be capable of being bent at the designated locations for anchorage purposes. Considering those, the procedure used is summarized as follows;

- A straight steel bar of 4 mm diameter at the required length is cut.
- The steel bar is then greased for easy pull out after the CFRP roll is prepared.
- The greased bar is then wrapped by nylon.
- CFRP sheet to be used in the rolls is then attached to the bar that is wrapped by nylon (Figure 2.11(a)).
- Two-component epoxy resin is prepared according to the instructions of the manufacturer and spread on both surfaces of the CFRP sheet. Then, it is rolled around the axis of the steel bar with some help (Figure 2.11(b)*)*.
- After rolling is completed, the resulting roll is wrapped gently by a thread in order to prevent opening of the roll after steel is taken out (Figure 2.11(c)*)*.
- After the entire roll is wrapped, the steel inside the roll can be taken out easily without disturbing the straightness of the roll.
- Finally, the required hooks can be bent for anchorage purposes. Figure 2.11(b) contains a completed roll that has bent hooks stated.

The same procedure was applied for the specimens of Series D (Direct pull-out specimens). However, the part of the rolls which stayed in the end blocks was covered with sand right after rolling was completed, while epoxy was still fresh, so that the anchorage in the end blocks was improved in addition to bent hooks (Figure 2.12*)*. Since the tensile force was applied by concrete, any gain in anchorage of the rolls to the end blocks was desirable in order to transfer the tensile force well.



(b)

(a) (c)

Figure 2.11 Preparation of the rolls

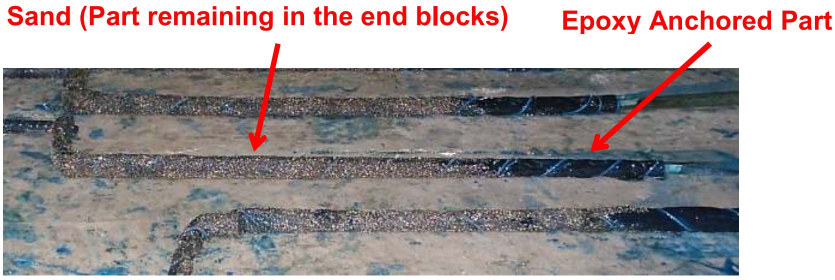


Figure 2.12 CFRP rolls of Series D

CHAPTER 3

TEST SETUPS AND TEST RESULTS

3.1 BEAM TESTS

As stated in Chapter 2, there are four series of tests in this type, the properties of which have been given. The main idea in testing beam specimens is to obtain a zero shear and a constant moment region at the mid-span and it is obtained by loading the beams with two point loadings at the 1/3rd of the span (or four point bending test, Figure 3.1), which creates tension in the rolls as expected. In these tests, the main measurements taken were transverse displacements, load cell, and curvature measurements at the mid-span (Figure 3.2). Photographic view of the setup has been shown in Figure 3.3(a) and Figure 3.3(b).

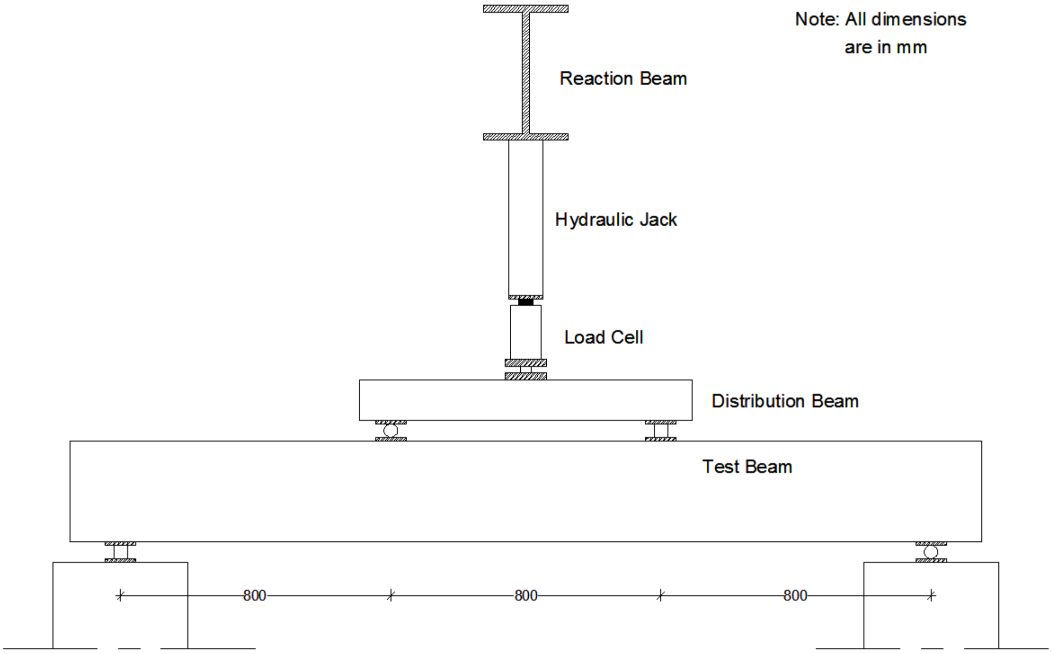
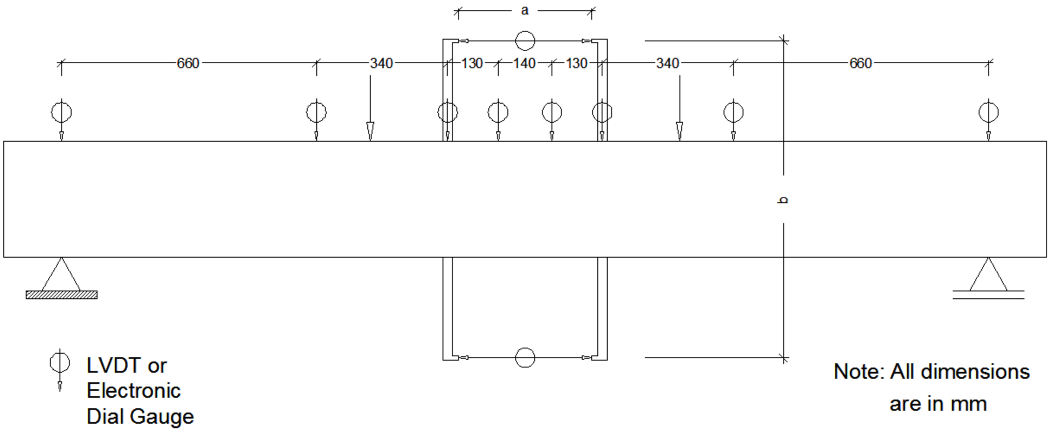


Figure 3.1 Test setup for beam specimens



Specimen	*CR*	*A1*	*A2*	*A3*	*B1*	*B2*	*B3*	*C3*
a (mm)	380	380	380	380	380	380	380	370
b (mm)	535	541	523	508	509	524	531	575

Figure 3.2 Measurements

(a) **(b)**

Figure 3.3 (a) Side view of the test setup, **(b)** Elevation view of the test setup

3.1.1 Test Results

As stated previously, there are eight beam specimens, which were tested by using the test setup shown. In this section, the results of those tests are given. The main readings taken were the deflection at the mid-span, and the load measurement taken by the load cell shown in test setup as well as the average curvature measurement. In the following sections, test results of each series of beam specimens are given.

3.1.1.1 Reference Specimen CR

Specimen was monotonically loaded until CFRP ruptured. At the ultimate stage, only one of the rolls ruptured, which was very sudden due to the perfectly linear behavior of CFRP. In Table 3.1, summary of results and properties of this specimen is shown in tabular form (see Appendix A for σ_f calculation of CFRP rolls). Load vs. mid-span deflection and moment vs. curvature curves are shown in Figure 3.4 and Figure 3.5 respectively. Also in Figure 3.6, the specimen is shown after the failure.

Table 3.1 Specimen CR, summary of results

Tensile Reinforcement Type:	Two continuous CFRP rolls
Concrete Strength, f_c (MPa):	19.1
Capacity, P_{max} (kN):	72.8
Capacity, M_{max} (kNm):	29.1
Curvature at Peak Load, $K_{pk} \times 10^3$ (rad/m):	58
Deflection at Peak Load, δ_{pk} (mm):	31.9
CFRP Stress Level, σ_f / f_f :	0.92
Failure Type:	CFRP rupture
Crushing on Compression Face:	No

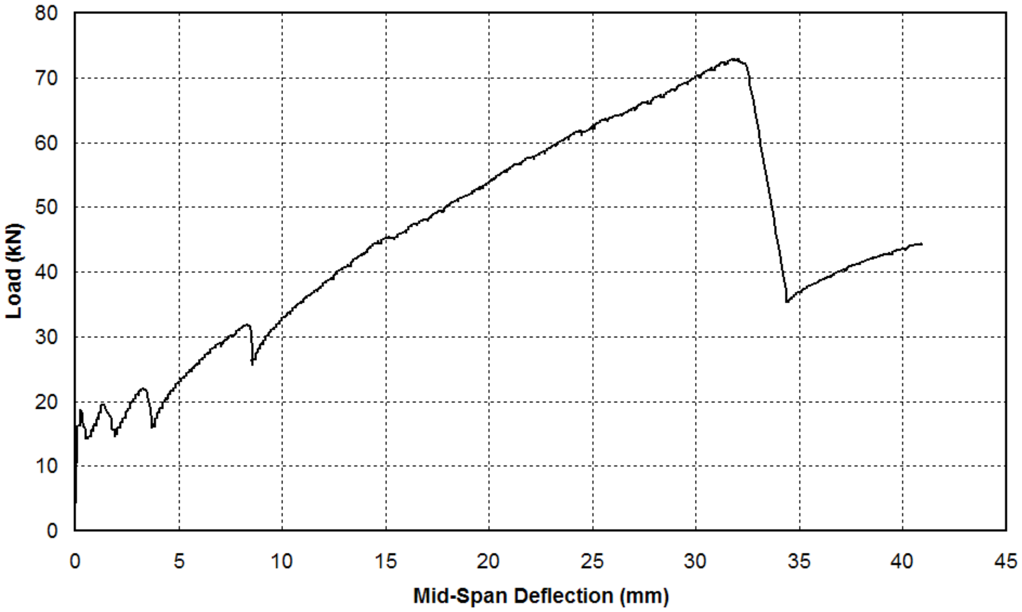


Figure 3.4 Load vs. mid-span deflection curve of CR

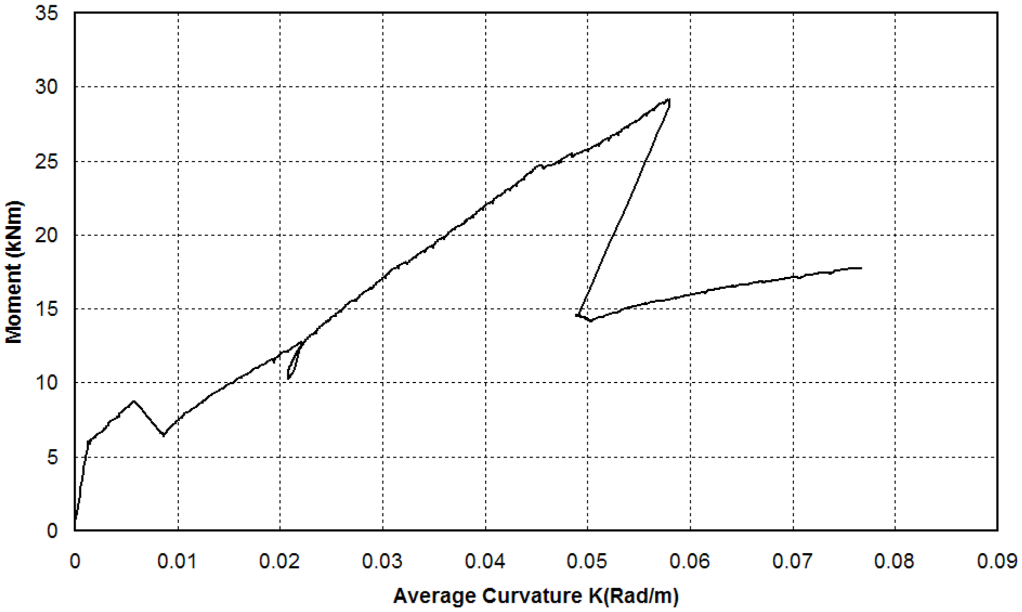


Figure 3.5 Moment vs. average curvature curve of CR

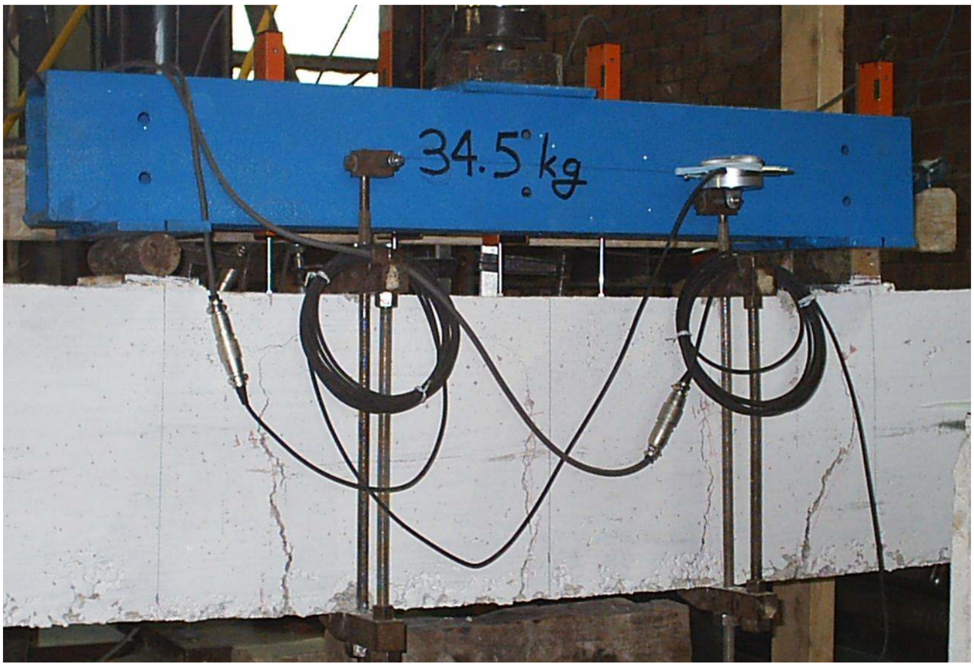


Figure 3.6 Crack pattern of CR after failure

3.1.1.2 Series A

In this series, lap spliced CFRP rolls directly embedded in concrete were expected to act as a single roll. There were three specimens tested, which had different lap lengths. However, full capacity of the rolls could not be reached in any one of the tests. The specimens prematurely failed by bond slip between the concrete and the CFRP rolls. In Table 3.2, summary of results and properties of this series is shown in tabular form. Load vs. mid-span deflection and moment vs. curvature curves are shown in Figure 3.7 and Figure 3.8 for specimen A1, Figure 3.10 and Figure 3.11 for specimen A2, Figure 3.13 and Figure 3.14 for specimen A3 respectively. Also in Figure 3.9, the specimen A1, in Figure 3.12, the specimen A2, in Figure 3.15, the specimen A3 is shown after failure.

Table 3.2 Series A, summary of results

Specimen:	A1	A2	A3
Lap Length, l (ω=120 mm):	1ω	2ω	3ω
Concrete Strength, f_c (MPa):	18.4	20.9	22
Capacity, P_{max} (kN):	19.1	34.4	40.8
Capacity, M_{max} (kNm):	7.6	13.8	16.3
Curvature at Peak Load, K_{pk} ×10^3 (rad/m):	10.3	8.1	10.4
Deflection at Peak Load, δ_{pk} (mm):	3.7	8.3	11.5
CFRP Stress Level, σ_f / f_f :	0.25	0.43	0.50
Failure Type:	SL	SL	SL
Crushing on Compression Face:	No	No	No
Failure type notations (see Section 3.3 for details)			
SL: Bar slip			

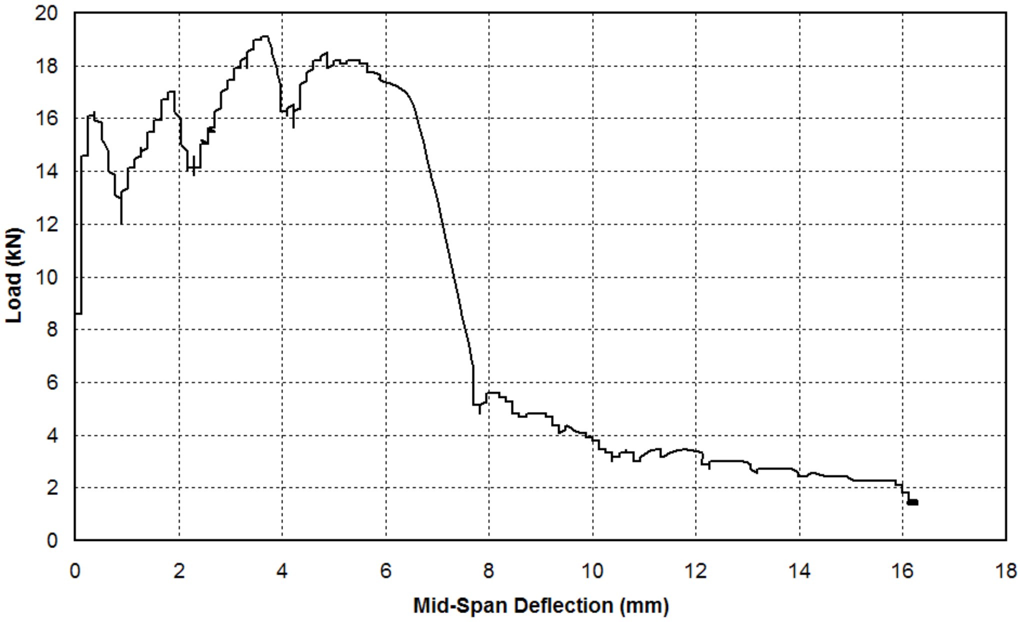


Figure 3.7 Load vs. mid-span deflection curve of A1

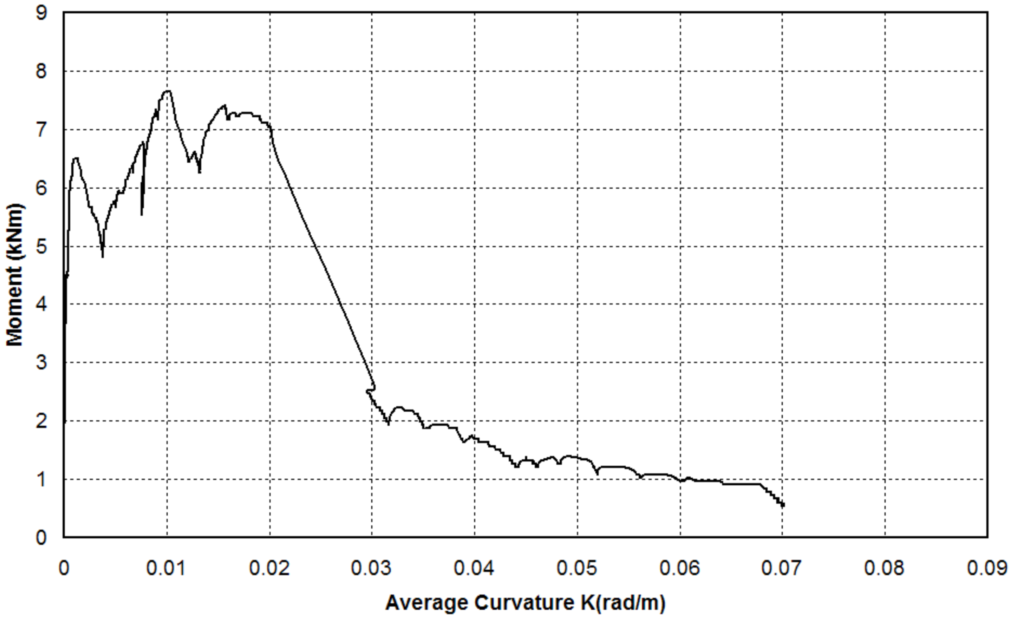


Figure 3.8 Moment vs. average curvature curve of A1

Figure 3.9 Crack pattern of A1 after failure

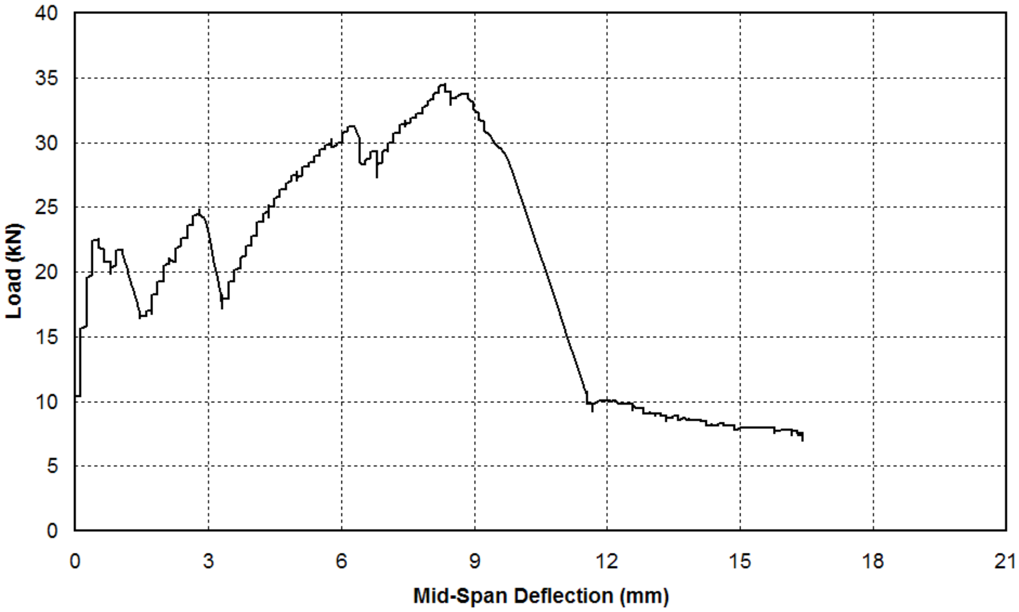


Figure 3.10 Load vs. mid-span deflection curve of A2

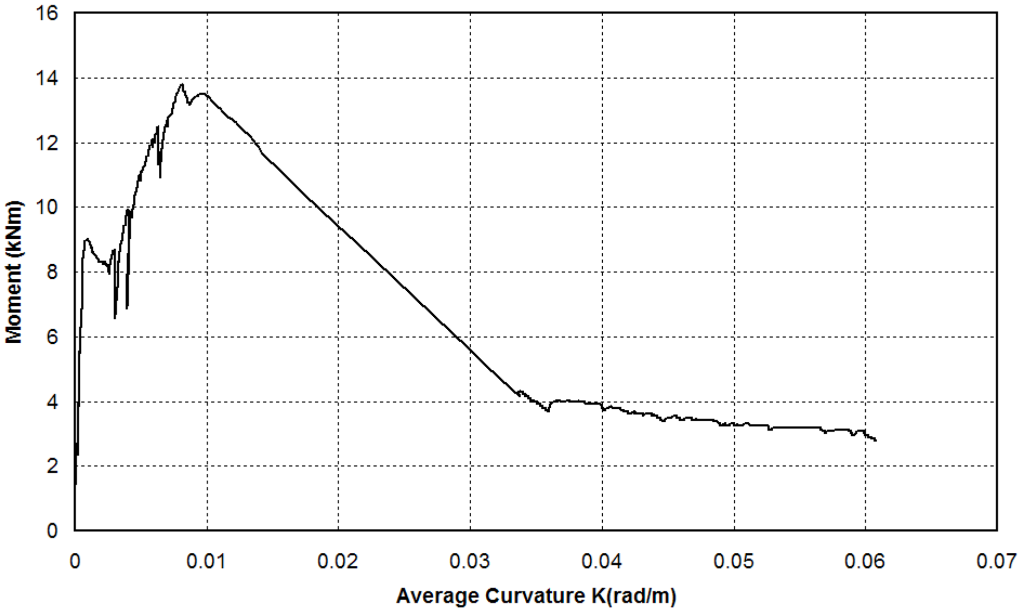


Figure 3.11 Moment vs. average curvature curve of A2

Figure 3.12 Crack pattern of A2 after failure

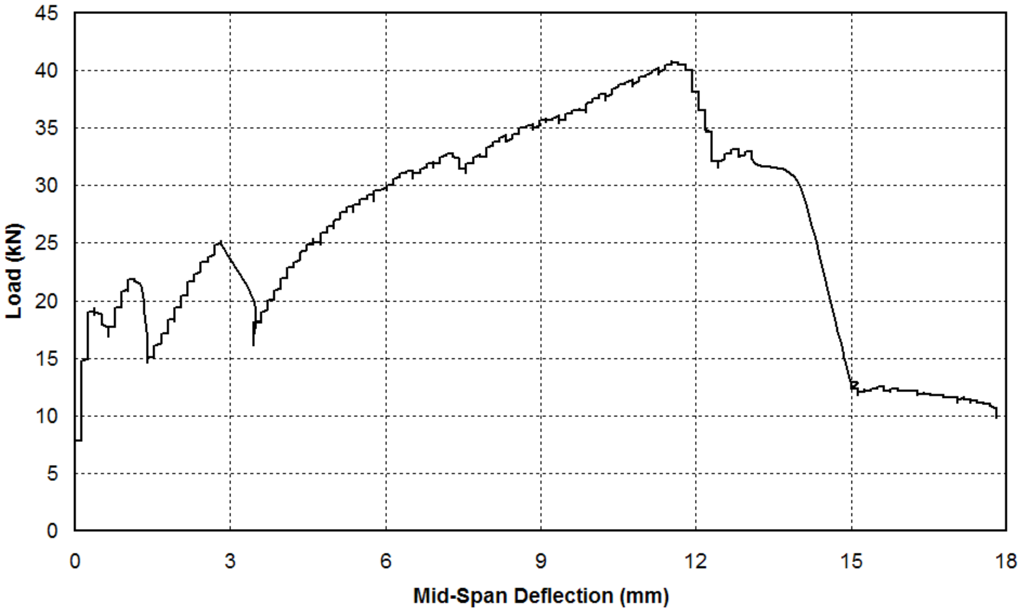


Figure 3.13 Load vs. mid-span deflection curve of A3

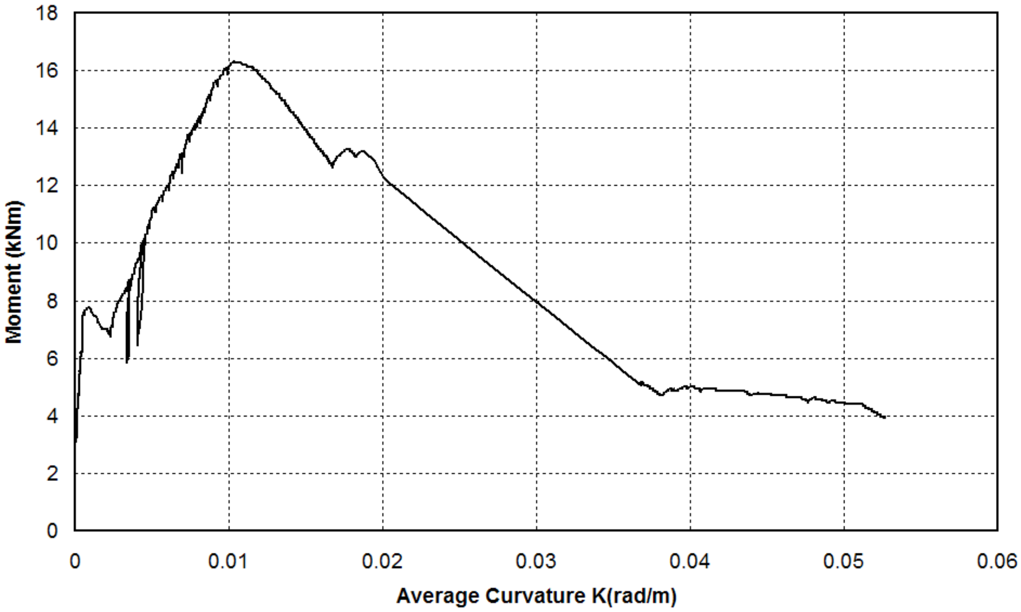


Figure 3.14 Moment vs. average curvature curve of A3

Figure 3.15 Crack pattern of A3 after failure

3.1.1.3 Series B

In the specimens of Series A, it was observed that increasing lap length also increased the capacity. Therefore, series B had specimens of epoxy anchored lap splices with increasing epoxy lap length. In this series, lap spliced CFRP rolls were epoxy anchored to the precast central block at the length of the desired lap, which were expected to act as a single roll. However, under monotonic loading, the full capacity of the rolls could not be reached in any one of the tests. When the peak load was applied, the specimens prematurely failed by combined cone and splitting, which was very sudden. Therefore, the bond between the concrete and the epoxy anchored CFRP rolls was completely lost. In Table 3.3, summary of results and properties of this series are shown in tabular form. Load vs. mid-span deflection and moment vs. curvature curves are shown in Figure 3.16 and Figure 3.17 for specimen B1, in Figure 3.19 and Figure 3.20 for specimen B2, in Figure 3.22 and Figure 3.23 for specimen B3 respectively. Also in Figure 3.18(a) and Figure 3.18(b), the specimen B1, in Figure 3.21(a) and Figure 3.21(b), the specimen B2, in Figure 3.24, the specimen B3 are shown after failure.

Table 3.3 Series B, summary of results

Specimen:	B1	B2	B3
Epoxy Anchored Lap Length, l (ω=120 mm):	1ω	2ω	3ω
Concrete Strength, f_c (MPa):	20.9	21.4	21.4
Capacity, P_{max} (kN):	33.6	32.7	44
Capacity, M_{max} (kNm):	13.5	13.1	17.6
Curvature at Peak Load, $K_{pk} \times 10^3$ (rad/m):	26.5	24.3	49.4
Deflection at Peak Load, δ_{pk} (mm):	12.4	13.8	22.4
CFRP Stress Level, σ_f / f_f :	0.41	0.40	0.54
Failure Type:	C+SP	C+SP	C+SP
Crushing on Compression Face:	No	No	No
Failure type notations (see Section 3.3 for details)			
C+SP: Combined cone and splitting			

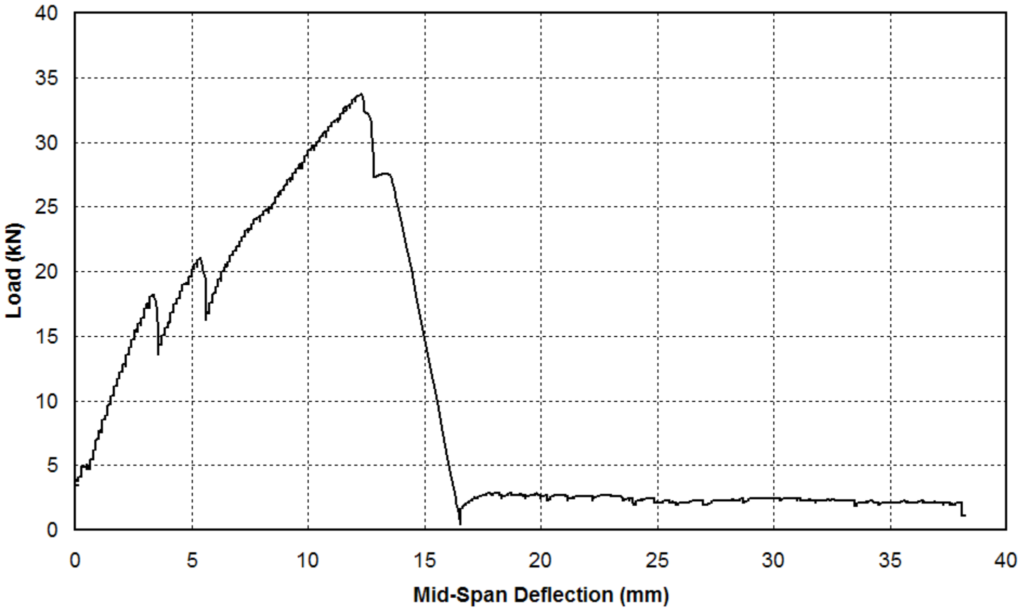


Figure 3.16 Load vs. mid-span deflection curve of B1

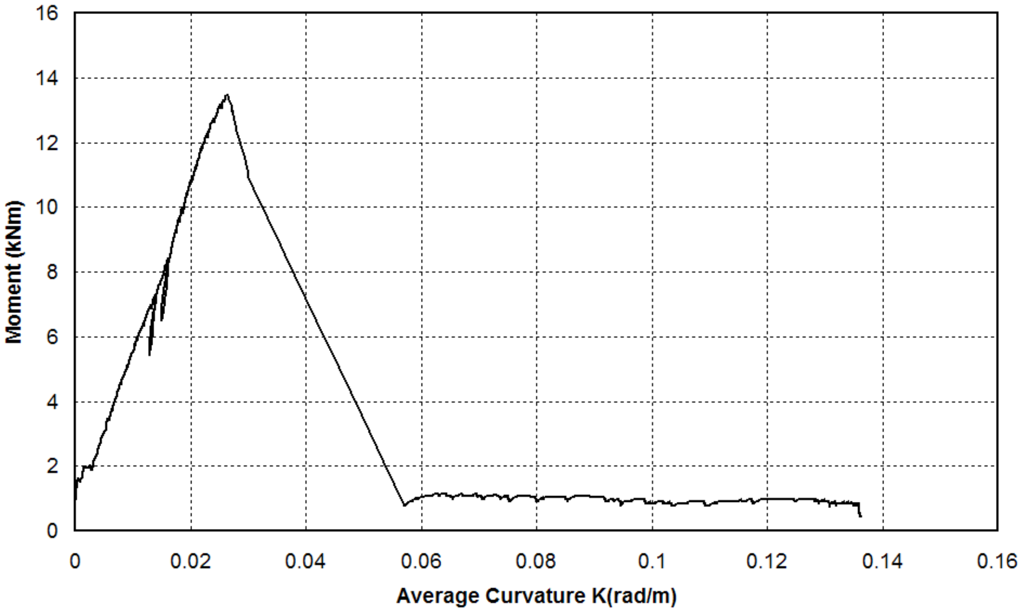


Figure 3.17 Moment vs. average curvature curve of B1

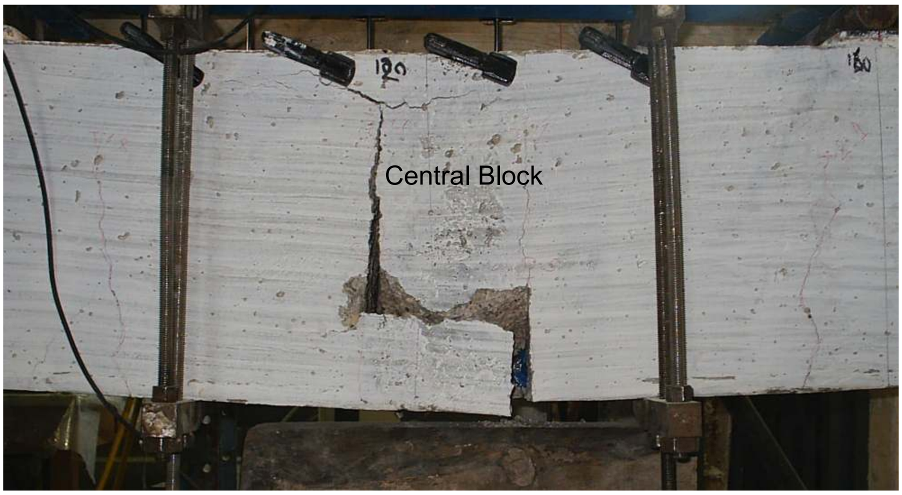


Figure 3.18(a) Crack pattern of specimen B1 after failure

Figure 3.18(b) Combined cone and splitting (B1)

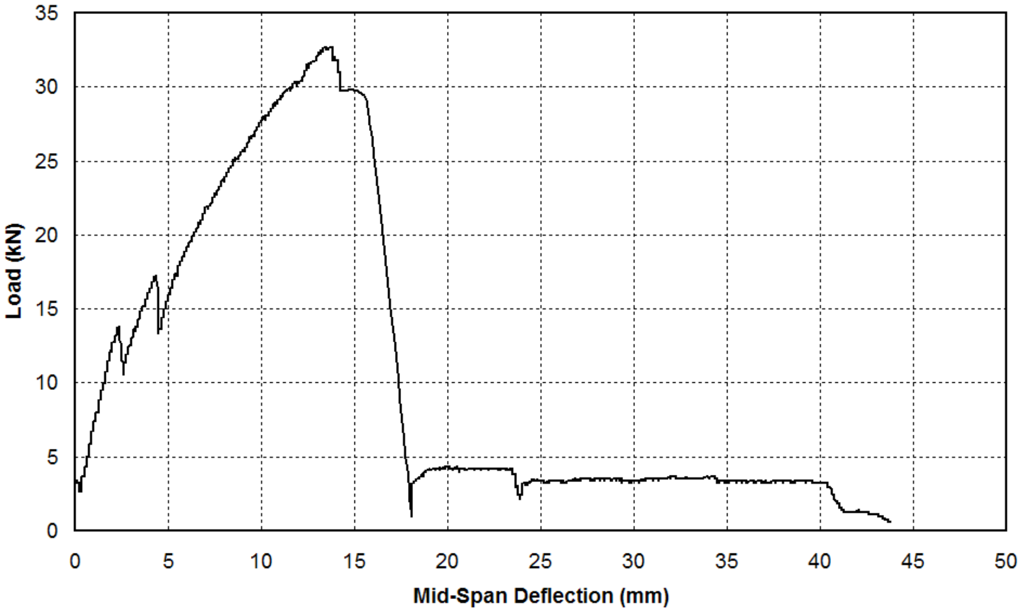


Figure 3.19 Load vs. mid-span deflection curve of B2

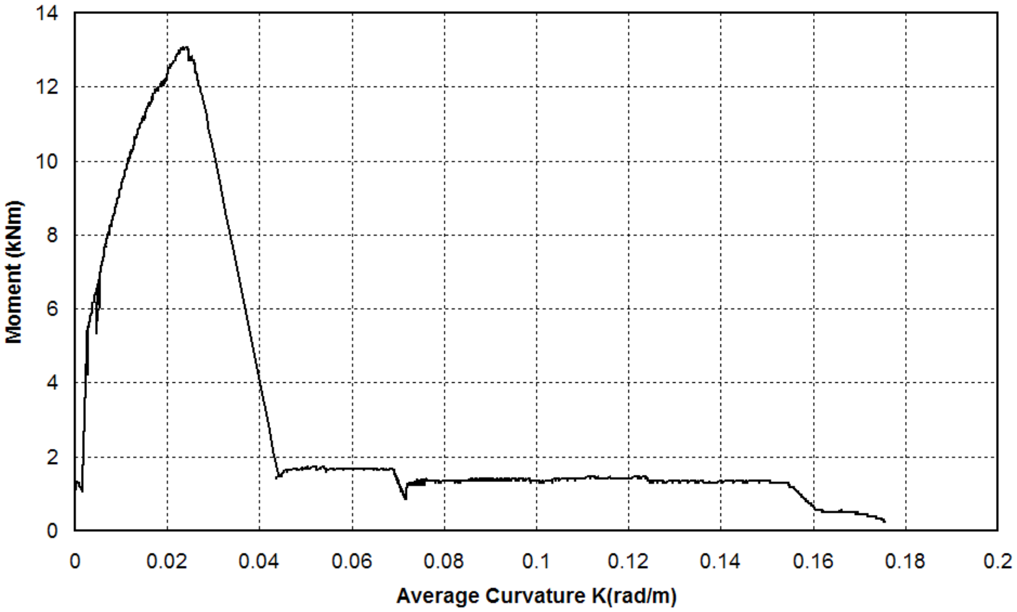


Figure 3.20 Moment vs. average curvature curve of B2

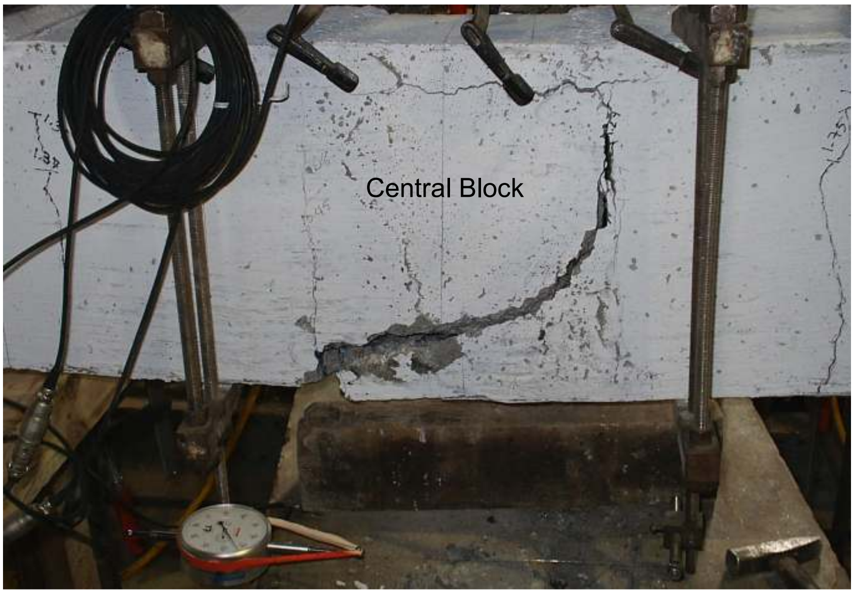


Figure 3.21(a) Crack pattern of specimen B2 after failure

Figure 3.21(b) Combined cone and splitting (B2)

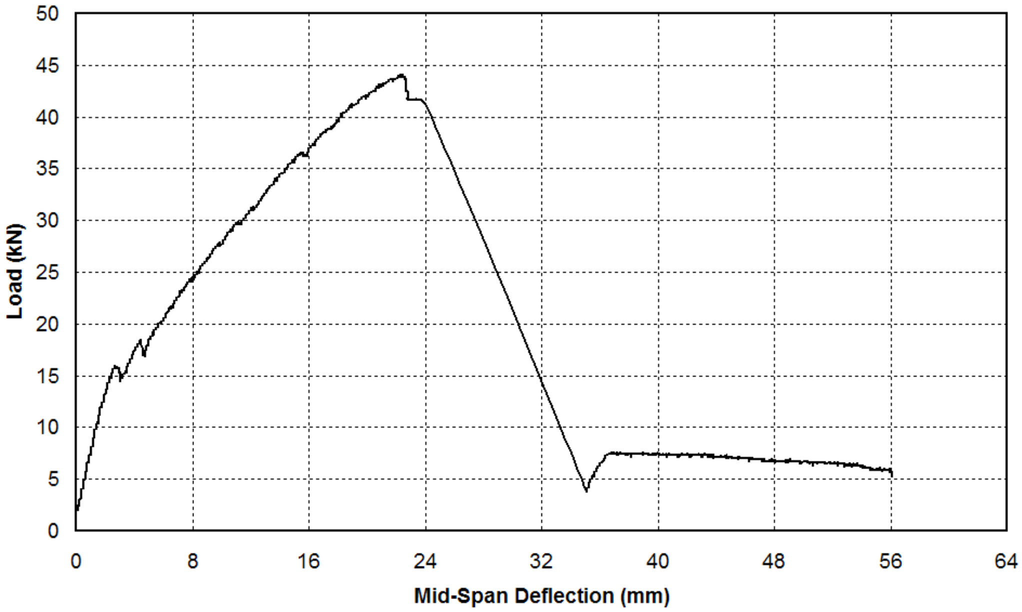


Figure 3.22 Load vs. mid-span deflection curve of B3

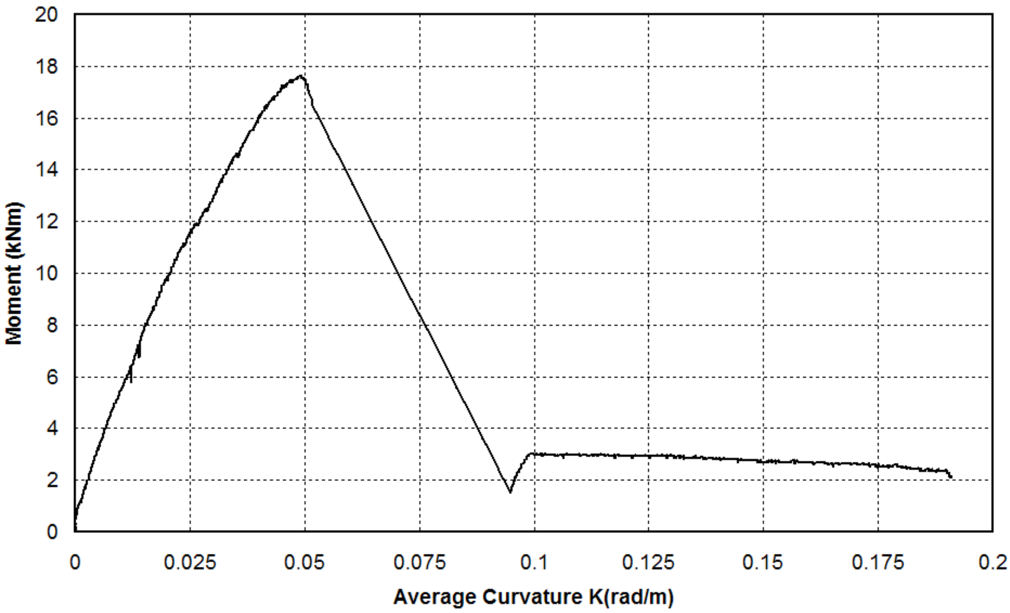


Figure 3.23 Moment vs. average curvature curve of B3

Figure 3.24 Specimen B3 after failure (combined cone and splitting)

3.1.1.4 Series C

The only specimen of this series was C3 in which CFRP rolls were epoxy anchored to the precast central block that had the lap length of 3ω (360 mm). In the previous tests, it was observed that every failure occurred by concrete splitting, which contained small concrete cones bounded by the cover of concrete. Those cones can be seen in the photos of the failed specimens and they were in the direction of the pull-out of the rolls. After studying the failed specimens, it was thought the performance could possibly be improved if the distance between the rolls and the cover thickness were increased. Therefore, this specimen was tested whether to see if CFRP rolls could be ruptured in this epoxy anchored lap length. The specimen was loaded monotonically until failure occurred. However, CFRP rolls could not be ruptured. The specimen failed prematurely by combined cone and splitting. In Table 3.4, summary of results and properties of this specimen is shown in tabular form. Load vs. mid-span deflection and moment vs. curvature curves are shown in Figure 3.25 and Figure 3.26 respectively. Also in Figure 3.27, the specimen is shown after failure.

Table 3.4 Series C, summary of results

Specimen:	<u>C3</u>
Epoxy Anchored Lap Length of CFRP Rolls:	3ω
Concrete Strength, f_c (MPa):	29.2
Capacity, P_{max} (kN):	42.4
Capacity, M_{max} (kNm):	17.0
Curvature at Peak, K_{pk} ×10^3 (rad/m):	87.8
Deflection at Peak, δ_{pk} (mm):	18.5
CFRP Stress Level, σ_f / f_f :	0.52
Failure Type:	C+SP
Crushing on Compression Face:	No
<u>Failure type notations</u> (see Section 3.3 for details)	
C+SP: Combined cone and splitting	

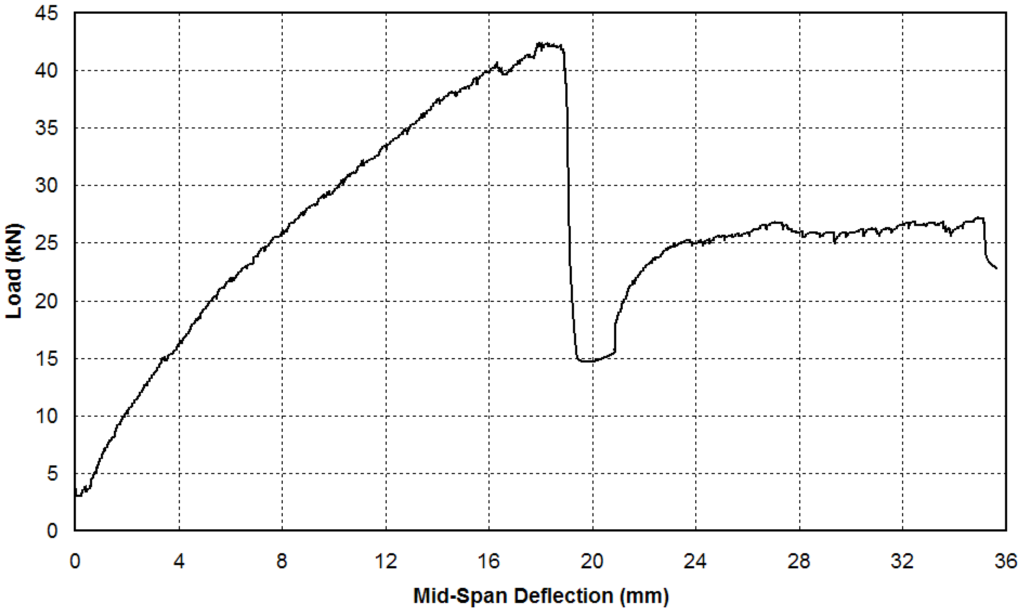


Figure 3.25 Load vs. mid-span deflection curve of C3

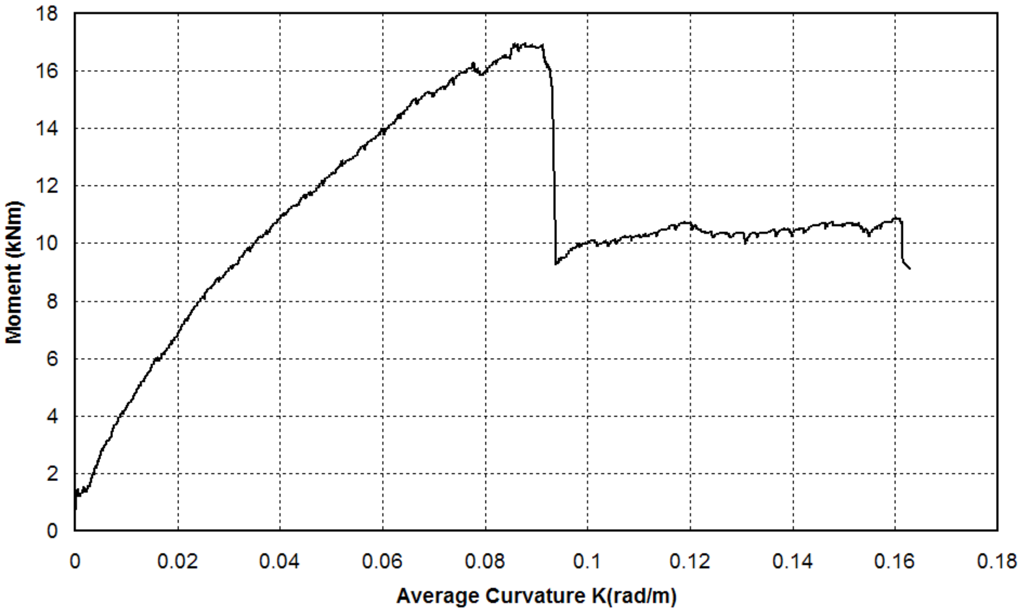


Figure 3.26 Moment vs. average curvature curve of C3

Figure 3.27 Specimen C3 after failure (combined cone and splitting)

3.2 DIRECT PULL-OUT TESTS

There were only one series of test in this type of test specimen, which was Series D. In this series, the main idea was application of tension directly to the central block, unlike beam specimens. Details of this type of test specimen have been given in Chapter 2. In Figure 3.28, test setup of this type is shown.

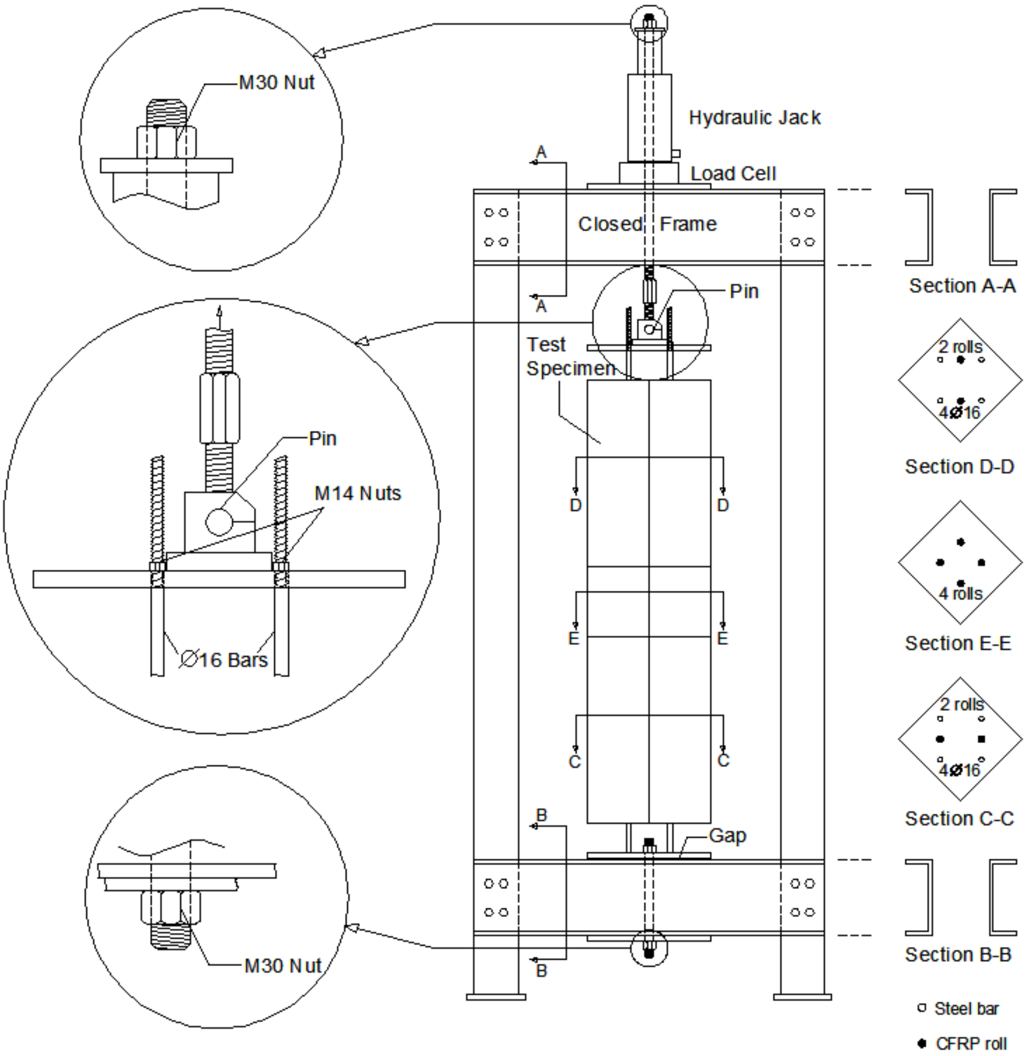
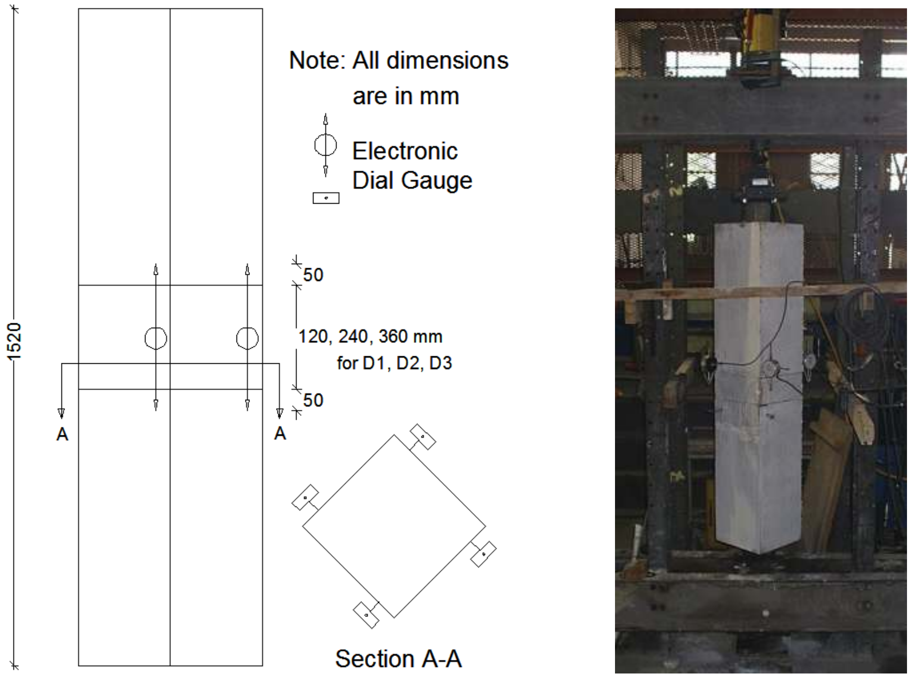


Figure 3.28 Test setup

Main measurements taken during the tests were load measurement and extension at the middle of the specimens. In Figure 3.29(a), taken measurements are shown schematically and in Figure 3.29(b), the specimen is shown photographically on the setup. Middle extension was measured by placing four dial gauges on each face of the specimen between the end blocks. Expected behavior was rupture of CFRP rolls without any premature failures.



(a) **(b)**

Figure 3.29 (a) Measurement, **(b)** Test specimen on the setup

3.2.1 Test Results

In series D, three tests were made and in this section, the results of all those tests are given. Specimens D1, D2, D3 have the epoxy anchored lap lengths of 1ω (120 mm), 2ω (240 mm), 3ω (360 mm) respectively.

3.2.1.1 Series D

All specimens of this series were monotonically loaded to failure. None of the specimens failed by rupture of the CFRP rolls. Specimens failed prematurely. These failures were combined cone failure and splitting. In Table 3.5, summary of results and properties of the specimens have been shown (see Appendix A for σ_f calculation of CFRP rolls). In Figure 3.30, Figure 3.32, and Figure 3.34, load vs. average middle extension curves are shown for D1, D2, and D3 respectively. Also in Figure 3.31(a) and 3.31(b), Figure 3.33(a) and 3.33(b), and Figure 3.35(a) and 3.35(b), photos taken after failures have been shown for D1, D2, and D3 respectively. In these photos, combined cone failure and splitting can be seen (splitting cracks are diagonal in all the photos).

Table 3.5 Series D, summary of results

Specimen:	D1	D2	D3
Epoxy Anchored Lap Length of CFRP Rolls:	1ω	2ω	3ω
Central Concrete Strength, f_c (MPa):	20	20	20
Capacity, P_{max} (kN):	46.4	70.6	50.9
Average Extension at Peak, δ_{pk} (mm):	1.50	3.50	6.10
CFRP Stress Level, σ_f / f_f :	0.34	0.52	0.37
Failure Type:	C+SP	C+SP	C+SP
Failure type notations (see Section 3.3 for details)			
C+SP: Combined cone and splitting			

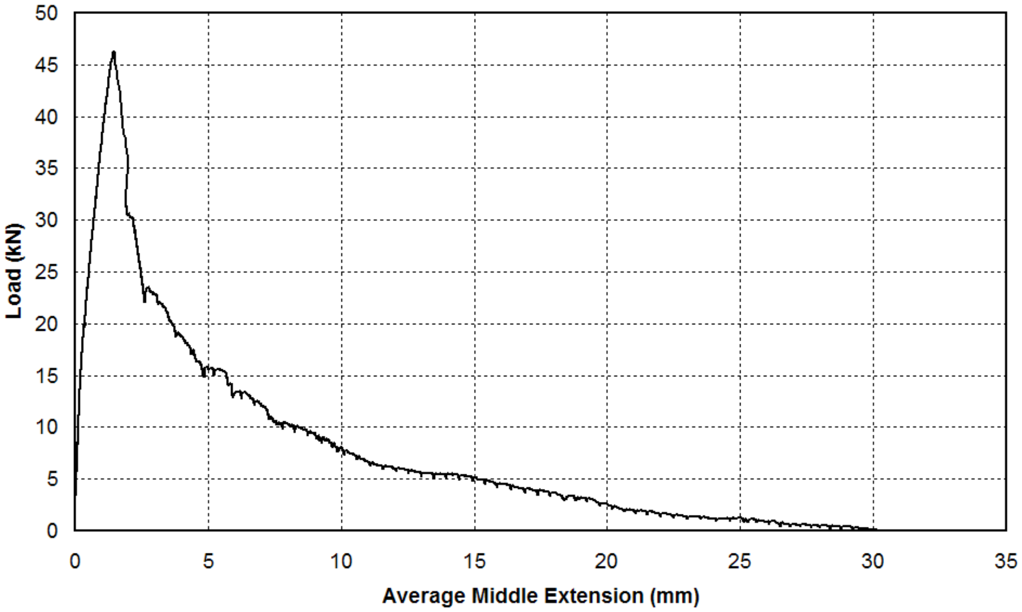


Figure 3.30 Load vs. average middle extension curve of D1

(a) **(b)**

Figure 3.31 **(a)** Failure D1, **(b)** Failure D1

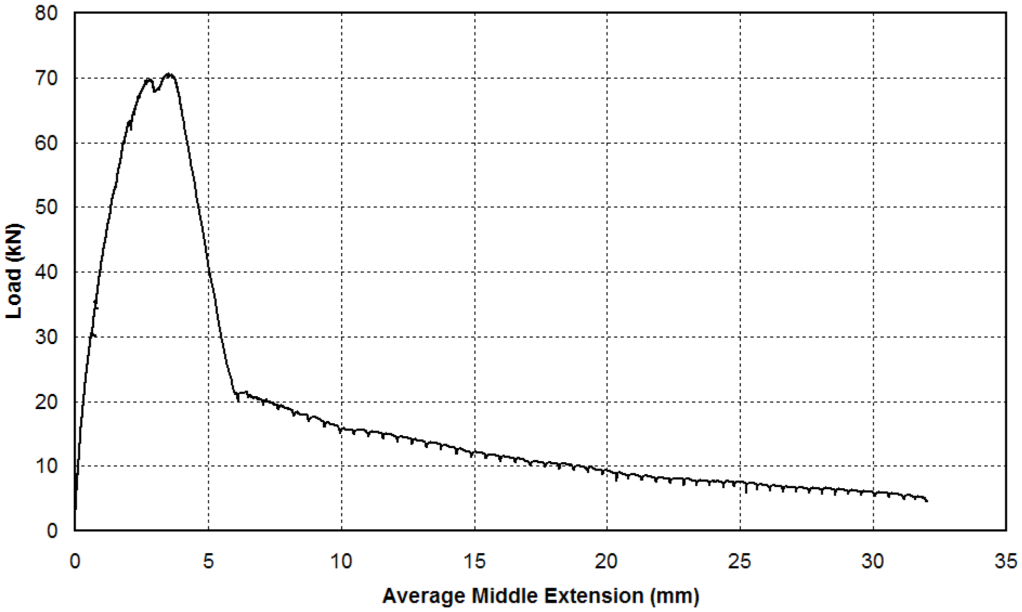


Figure 3.32 Load vs. average middle extension curve of D2

Figure 3.33 (a) Failure D2, **(b)** Failure D2

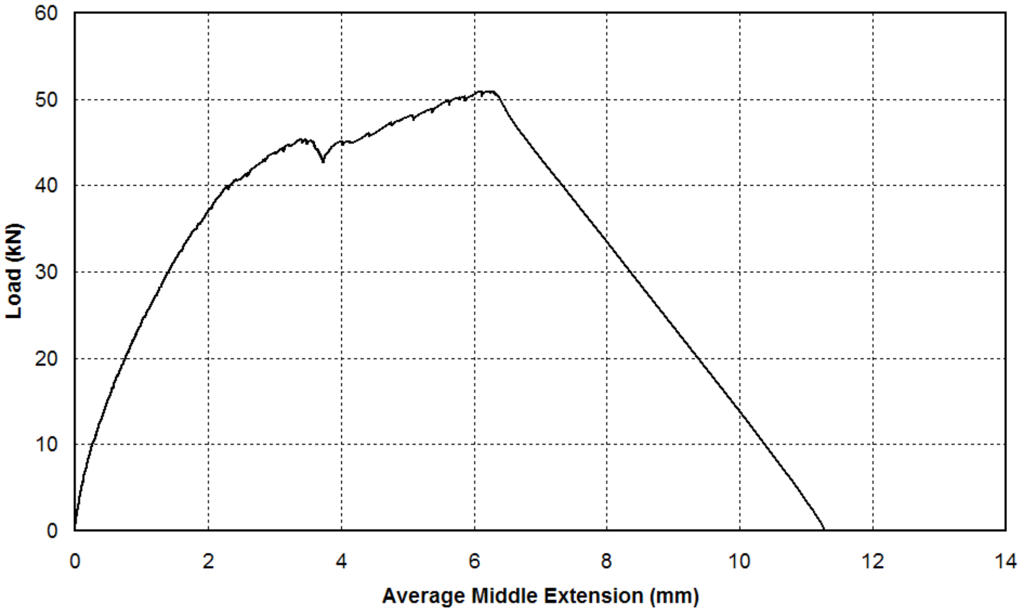
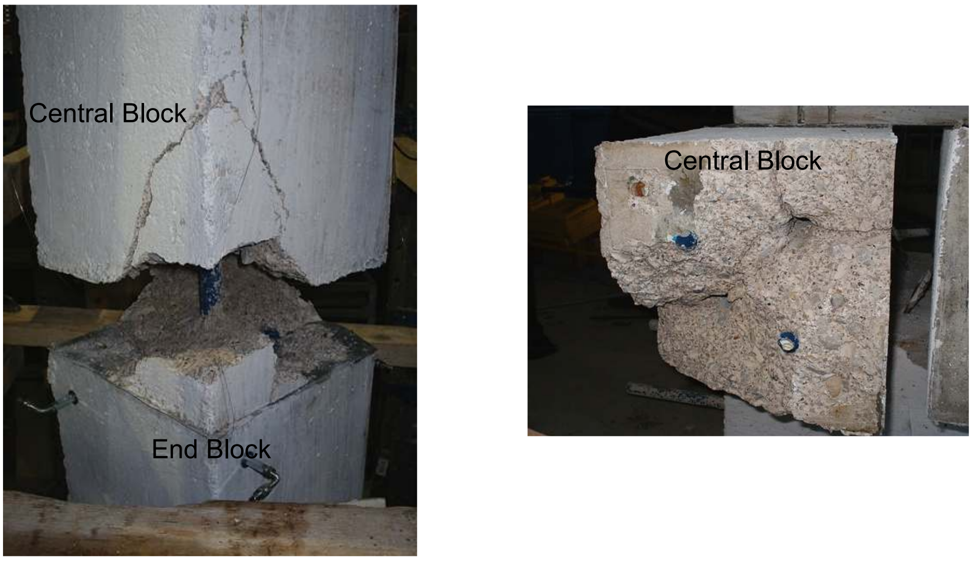


Figure 3.34 Load vs. average middle extension curve of D3



(a) **(b)**

Figure 3.35 **(a)** Failure D3, **(b)** Failure D3 (Sectional view)

3.3 FAILURE TYPES

Besides the natural and desirable failure type, i.e. CFRP rupture, there are four possible bond failure types one can suggest for CFRP roll anchorage. These four possibilities are briefly explained below:

3.3.1 Bar Slip

This type of bond failure is observed in the case of directly (no epoxy anchorage) embedded CFRP rolls. Indeed, all specimens of Series A have reached failure in this mode (Figure 3.36).

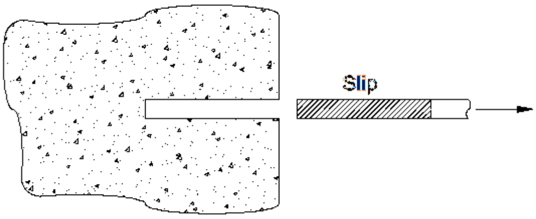


Figure 3.36 Bar slip

3.3.2 Cone Failure

This failure type is expected in the case of epoxy anchored CFRP rolls in very large concrete blocks where splitting is not possible due to the size of the concrete body. In the present study this type of failure has not been observed since the concrete member studied was small enough to split (Figure 3.37).

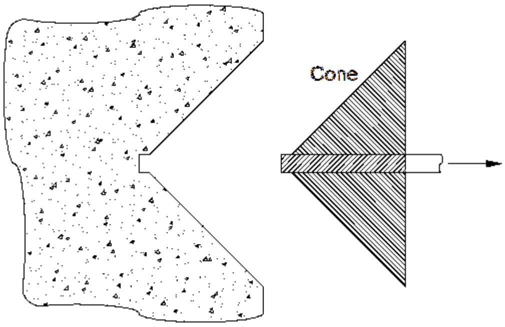


Figure 3.37 Cone failure

3.3.3 Combined Cone Failure and Slip

This is the combination of the above two types of failure. First, a cone is broken out of the concrete block and then the remaining embedded bar slips. This type of failure is likely to take place in the case of directly embedded CFRP rolls. It is not observed in the present study (Figure 3.38).

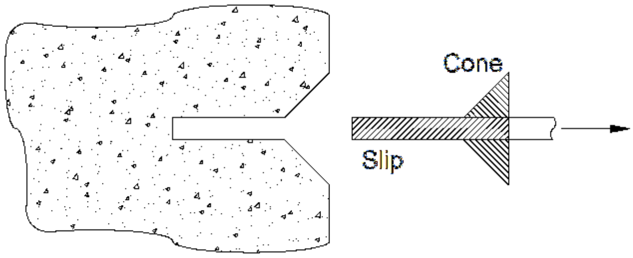


Figure 3.38 Combined cone failure and slip

3.3.4 Combined Cone Failure and Splitting

This failure is similar to the above combined failure. However, in this case, splitting, caused by moving out CFRP roll, takes place after the formation of the cone. This is the most common type of failure where CFRP roll is epoxy anchored into the concrete body. Cone size gets larger and the capacity gets higher as the embedded length increases as long as the concrete body is large enough to accommodate the cone. Otherwise, the cone intersects the boundaries of the concrete body and breaks it under a smaller load as in the case of specimen D3. This is the failure type observed in all of the specimens of Series B, C and D (Figure 3.39)

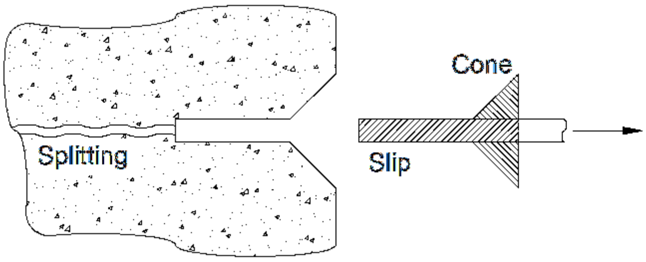


Figure 3.39 Combined cone failure and splitting

3.3.5 A General Comment

Within the limitation of the test results obtained in the present study, it can be stated that combined cone failure and splitting is the typical (if not invariable) bond failure in the case of epoxy anchored CFRP rolls; and bar slip dominates if the CFRP roll is directly (no epoxy) embedded in concrete.

The same has been observed by other researches studying the bond behavior of epoxy anchored reinforcing steel bars [6]. Indeed combined cone failure and splitting is the typical bond failure also in the case of steel bars. It can therefore be suggested that the use of epoxy connecting the roll or the bar to concrete changes the character of bond, and leads to splitting instead of slip.

CHAPTER 4

DISCUSSION AND EVALUATION OF TEST RESULTS

4.1 DISCUSSION OF BEAM TESTS

4.1.1 Reference Specimen CR

Reference specimen CR gave the desired result, which was CFRP rupture. Moreover, the stress level developed was 92%, which is a considerably high percentage, and that 8% strength loss can be attributed to the geometrical imperfections, quality of workmanship, and eccentricity resulting from curvature.

4.1.2 Series A

All specimens of Series A displayed slip type bond failure indicating that even the longest lap length was not sufficient. However, increasing lap length increased the capacity. As a result, specimens of Series A failed at a load lower than the maximum load carried by the reference specimen CR. In Figure 4.1 and Figure 4.2, the comparison of load vs. mid-span deflection and moment vs. average curvature curves are shown for the reference specimen CR and the specimens of Series A. In Figure 4.2, specimens A2 and A3 appear to have higher stiffness than that of the reference specimen. The higher stiffness may be the result of doubled amount of reinforcement (CFRP rolls) over the lap length.

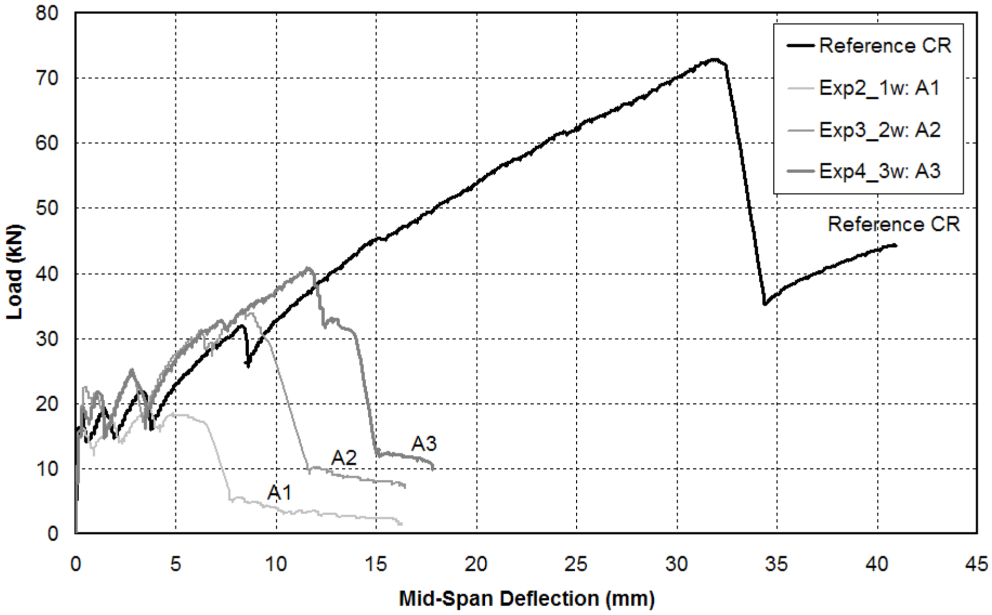


Figure 4.1 Load vs. mid-span deflection curves of CR and Series A

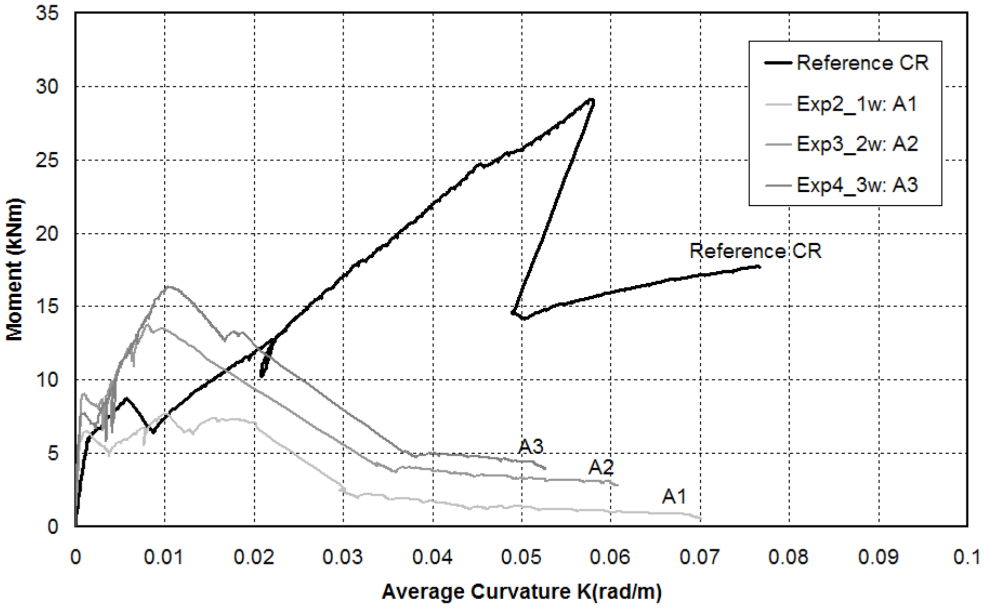


Figure 4.2 Moment vs. average curvature curves of CR and Series A

4.1.3 Series B

All specimens of Series B displayed combined cone and splitting type bond failure. Increasing epoxy lap length increased the capacity; however, even the longest lap length was not enough to make use of the full capacity of the rolls. Unexpectedly in specimen B1, the ultimate load carried was approximately the same as the load carried by B2. However, this might be due to the difference of the distances between the rolls in the precast central block to which they were epoxy anchored. In B1, this distance was so small that at some points the concrete layer between the holes was missing, which may have caused interaction between the rolls due to the epoxy, and it is possible that the specimen artificially behaved stronger than expected. In other words, the rolls were not completely epoxy anchored to the concrete but also at some points to each other.

4.1.4 Series C

Increasing the cover thickness did not affect the capacity. If specimens C3 and B3 are compared, it was observed that like Series B, the only specimen of Series C (C3) also displayed combined cone and splitting failure. In Figure 4.3 and Figure 4.4, the comparison of load vs. mid-span deflection and moment vs. average curvature curves are shown for reference specimen, Series B and Series C. Although the load vs. mid-span deflection curves have approximately the same stiffness, the stiffness of the specimen C3 seems less than the others in Figure 4.4. The reason for this may be either an error in the curvature measurement tool, or the nature of the specimen itself since the specimens of Series B and C are not monolithically cast.

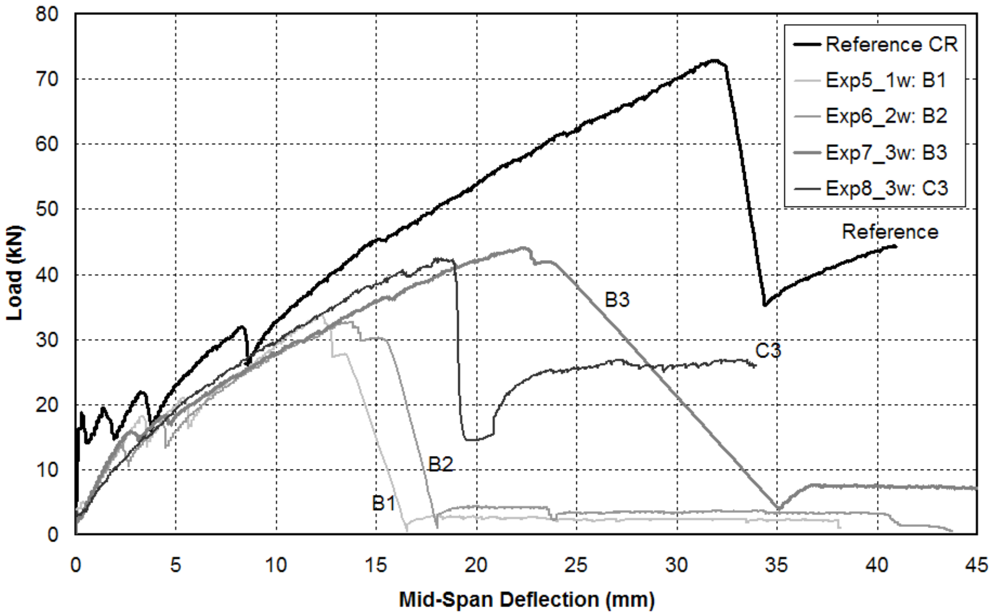


Figure 4.3 Load vs. mid-span deflection curves of CR, Series B, and Series C

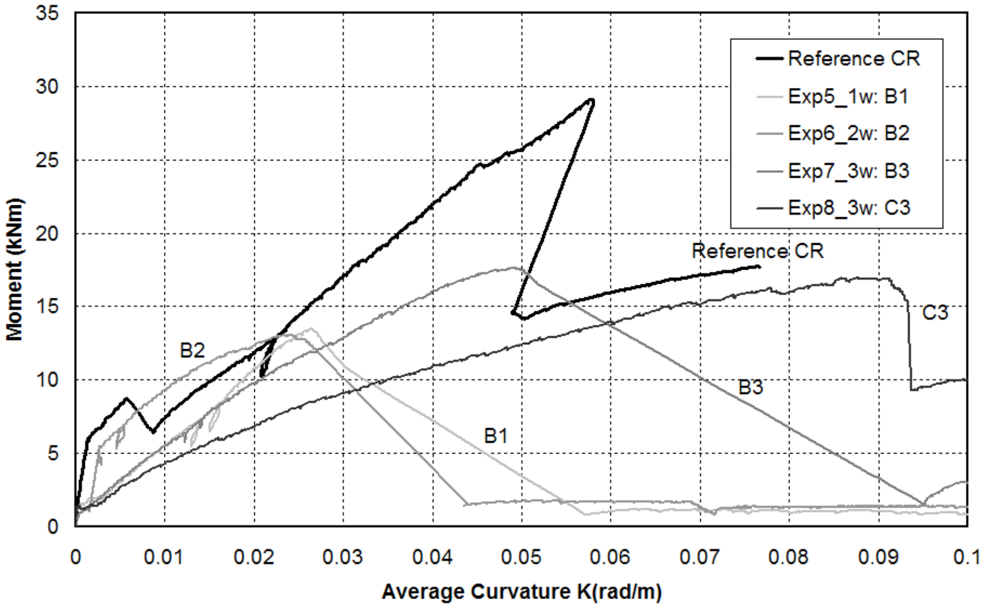


Figure 4.4 Moment vs. average curvature curves of CR, Series B, and Series C

4.1.5 Comparison of Series A and Series B

Series A and Series B had the same specimens with only the difference in the type of the lap splice. Series A had lap splices directly embedded in concrete and Series B had lap splices epoxy anchored to the precast central blocks. Specimens of Series A displayed slip failures and specimens of Series B displayed combined cone and splitting failures, consistently. The difference in the failure type may be due to the difference between the embedded lap and anchored lap, in which epoxy anchorage may have been the reason of the difference as explained earlier in Section 3.3. However, surprisingly, the failure loads of each corresponding specimens of the same lap length in Series A and B are approximately the same. However, this may be a coincidence.

Although the full material capacity was not achieved in any one of the tests, in the study by [2] *Gökdemir, H., "Seismic Strengthening of Beam-Column Joints in Existing R/C Structures by using CFRP rolls"*, 2ω epoxy anchored lap length appeared to be very satisfactory to provide the improvement equivalent to that obtained by using CFRP rolls anchored at both ends in the beam-column joint. Neither splitting nor slip failures were observed.

4.2 DISCUSSION OF DIRECT PULL-OUT TESTS

The desirable bond behavior was expected to lead to the rupture of CFRP rolls without any premature failures. The target failure load was 136 kN in the case of CFRP rupture considering the strength value provided by the manufacturer. However, none of the specimens failed by rupture in the rolls. Instead, they failed by combined cone and splitting failure. When load vs. average extension curves are plotted on the same graph, it is observed that increasing epoxy lap length from 1ω to 2ω increased the capacity, but increasing the length from 2ω to 3ω did not increase the capacity (Figure 4.5). On the contrary, specimen D3 failed at a lower load compared to D2.

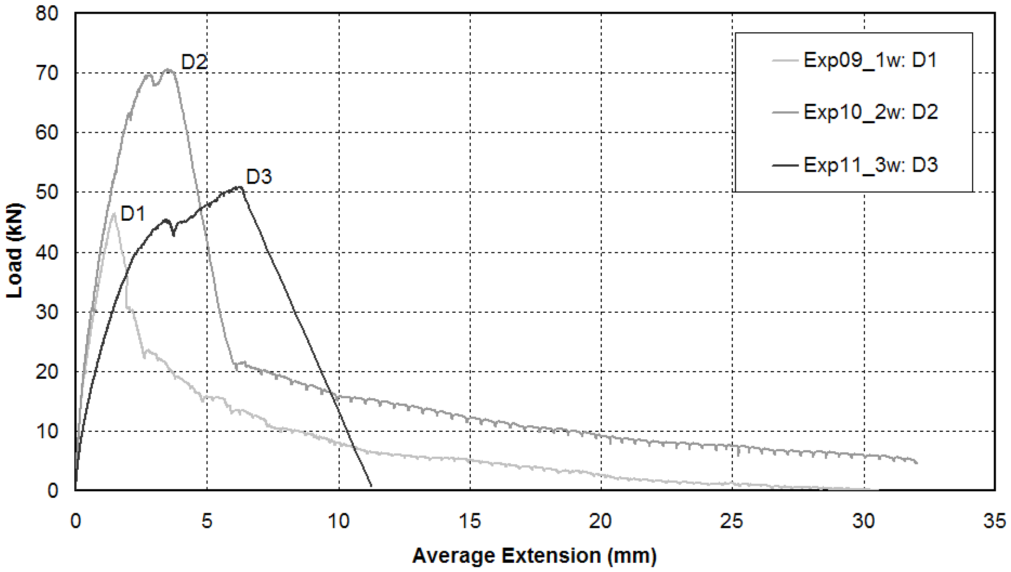


Figure 4.5 Load vs. average extension curves of Series D

For Series D, it can be stated that increasing epoxy anchored lap length does not necessarily increase the capacity of the specimens since the section dimensions are kept constant and epoxy anchored lap length was increased. Referring to the failure types explained in Section 3.3, potential failure cone gets larger when the lap length is increased. In the case of a small lap length, a proper small cone can neatly form, but in the case of a much larger lap length, the potential cone can exceed the boundaries of the specimen and can lead to a truncated cone that may form under a smaller load.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE STUDIES

5.1 CONCLUSIONS

Eight beam tests and three direct pull-out tests were performed in this study. Unfortunately, these tests have not served the purpose satisfactorily. In other words, a satisfactory “anchored lap length” concept could not be established on the basis of the experimental results. All specimens failed prematurely in different modes of failure, depending on the type and size of the specimens. However, a reasonable insight could be obtained into the anchorage behavior and lap splice behavior of CFRP rolls in the present pilot study.

The conclusions derived from the observation are briefly listed and explained in the paragraphs below.

5.1.1 Conclusions from Beam Tests

Beams reinforced for flexure with two continuous CFRP rolls have proved to be successful test specimens to test tensile capacities of the rolls used in the beam as tension reinforcement. The rolls have been tested without creating any stress concentration. Tests made on this kind of specimen gave 92% stress level developing in the rolls, which is a considerably high percentage of the tensile capacity of carbon fibers.

Beams reinforced for flexure with lap spliced CFRP rolls that are embedded directly in concrete have resulted in increasing capacities with increasing lap length. Even the longest lap length of 3ω was not sufficient enough to make use of the full material capacity of the rolls. However, longer lap lengths can be tested for different combinations of CFRP strip width (ω) and concrete strength (f_c) to obtain a reasonable “embedded lap length” concept.

Beams reinforced for flexure with epoxy anchored lap splices to the precast central blocks have indicated that the capacity increases as the lap length increases. However, all the specimens of this type failed prematurely in combined cone and splitting mode without being able to develop full material capacity of carbon fibers since the specimen size was evidently not sufficiently large. Therefore, it can be stated that this kind of test specimen needs to be improved to investigate the lap splice behavior of CFRP rolls.

One important observation made was the type of bond failure observed in Series A (embedded lap splices) and Series B (anchored lap splices). All the embedded lap splices led to slip type bond failure, whereas all the anchored lap splices to combined cone and splitting type bond failure. Since the two series were identical with the exception of CFRP roll anchorage, the difference can directly be attributed to the epoxy anchorages, i.e. to the stress transfer throughout the epoxy layer instead of direct bond. The difference was clearly observed, but a clear and satisfactory explanation could not be developed in this pilot investigation.

5.1.2 Conclusions from Direct Pull-Out Tests

Although all the specimens in this group have failed prematurely, this type of testing may be quite suitable for studying lap splice behavior and strength of CFRP rolls if the dimensions are adjusted considering the potential cone size. There is no problem of deviation from direct tension. It is possible to get eccentric tension, but this problem can be minimized by using two pins at each end of the specimen.

As expected, increasing lap lengths led to increasing capacities in the cases where the specimen was large enough to accommodate the failure cone.

The smaller capacity obtain in the case of the largest lap length was a clear indication of the importance of specimen size related to the lap length. In other words, it is clearly understood that the specimen size needs to be determined in relation to the lap length.

At the end of tests, no epoxy anchored lap length formulation in terms of the used carbon fiber strip width (ω) could be developed since full material capacity of carbon fibers is not developed in any of the specimens. However, concerning bond behavior, a few interesting observations have been made concerning failure types.

5.2 RECOMMENDATIONS FOR FUTURE STUDIES

The present study was a pilot study. It revealed the importance of some factors which had not been taken into consideration at the planning stage of the present work. In the light of the results obtained, new projects can be developed to yield better and more reliable and more useful results. The following are a few recommendations for further research.

To improve both the beam tests and the direct pull-out tests,

- Either larger cross-sectional dimensions should be chosen or smaller CFRP rolls (smaller ω) should be used in similar size specimens. Moreover, using higher strength concrete may improve the behavior for premature failures.
- The use of a nominal web reinforcement reflects the actual problems much better and at the same time will probably improve the splice behavior. (Remember the rather satisfactory performance of 2ω lap

spliced CFRP rolls used in joint strengthening research project [2] mentioned in Section 4.1.5)

Once a satisfactory test specimen is developed, then a few parameters which seem to be important can be systematically studied. These parameters are:

- Concrete strength f_c
- CFRP strip width ω
- Lap length in terms of ω
- Anchor hole diameter (i.e. thickness of epoxy layer)
- Distance between the two lapped rolls
- Cover (distance to the outermost concrete fiber)

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[3] Özdemir, G., “Mechanical Properties of CFRP Anchorages”, MSc. thesis, January 2005, Department of Civil Engineering, Middle East Technical University, Ankara, Turkey.

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APPENDIX A

STRESS LEVEL

Beam tests

In computing the stress level of the rolls (σ_f/f_f) in each beam test, σ_f has been approximately calculated using the formula shown below;

$$\sigma_f = \frac{M_{\max}}{2 \cdot \omega \cdot t \cdot (d - d')} \tag{A.1}$$

M_{max} : Moment capacity of the section, calculated from the test results

The curvature measurements could be used for a more detailed analysis. However, only the average curvature was measured and it was not reliable due to the discontinuity of the specimen. For this reason, a more detailed analysis could not be made and the proposed formula above has been used.

Direct pull-out tests

In direct pull-out tests, σ_f has been calculated using the formula shown below;

$$\sigma_f = \frac{P_{\max}}{2 \cdot \omega \cdot t} \tag{A.2}$$

P_{max} : Maximum load carried by the entire specimen