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Retrofit of Shear Critical R.C. Beams with Carbon Fiber Reinforced Polymers (CFRP)

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Abstract

This paper presents results of an experimental investigation involving eight tests on 1800mm long reinforced concrete (RC) beams strengthened in shear with externally bolted carbon fiber reinforced polymer (CFRP) composites. The overall objective of this study was to investigate the shear performance and failure modes of RC beams strengthened with externally fixed carbon FRP (CFRP) manufactured U-warp strips and the specific goal was to keep the CFRP strips working till the beam reaches its flexural failure because in most of the previous researches the CFRPs debonded from the concrete surface and the failure (separation) happened in the concrete. The variables investigated within this program included: CFRP spacing and number of CFRP layers. The experimental results indicated that the contribution of externally fixed CFRP strips to the shear capacity is significant and depends on the variables investigated. In all the beam specimens (with end anchorage) the debonding was not observed.

Keywords: shear, carbon fiber reinforced polymer

اعادة تاهيل العتبات الخرسانية المسلحة الحرجة بالقص باستخدام اللدائن المقواة بالالياف CFRP

الخلاصة

تتضمن هذه الدراسة نتائج الفحوصات التي اجريت على ثمانية عتبات خرسانية مسلحة بطول 1800ملم مقواة بالقص باستخدام اللدائن المقواة بالالياف الكاربونية CFRP. الدراسة بشكل عام كانت تبحث في تصرف العتبات وادائها واشكال الفشل بعد تقويتها باستخدام الصامولات اي باستخدام الربط الميكانيكي بتصنيع شرائح على شكل U. الغرض الرئيسي لهذه الدراسة هو معرفة كفاءة التسليح الخارجي للقص بواسطة اللدائن المقواة بالالياف المثبتة على سطح الخرسانة لاداء الغرض الذي وضعت من اجله وهو الوصول الى الفشل الحاصل نتيجة اجهادات الانثناء والنجاح في تحمل اجهادات القص المسلط وعدم انفصال طبقة اللدائن المقواة بالالياف, هذا الفشل الذي اشار اليه معظم الباحثون بسبب الاختلاف في خواص المواد الثلاثة (الصلابة) وهي الخرسانة , المادة اللاصقة واللدائن المقوات بالالياف. الخرسانة هي المادة الاضعف ولكن المادة اللاصقة هي الاقل صلادة بسبب قلة سمكها. لذلك فان التثبيت الميكانيكي هو الحل الامثل لنقل الاجهادات من داخل العتبة الخرسانية الى اللدائن المقواة بالاليااف. اظهرت النتائج العملية المستحصلة بان النتائج التي تم الحصول عليها تتاثر بالمتغيرات التي تم دراستها وفي كل النماذج لم يلاحظ انفصال CFRP.

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Introduction

Structures are costly to build and the construction period is often considered disturbing for many people. Therefore it is of interest to have durable structures with long lifetimes and with low costs for maintenance [1]. One way to increase both lifetime and durability is upgrading. Structures can be upgraded to meet changed demands or to be restored to an original performance level. The definition of performance level is here load carrying capacity, durability, function and aesthetic appearance. The upgraded structures should also be durable with economic lifetime and reliable performance. The materials and use of materials in the society have always been objects for development. New materials are now and then invented and developed, sometimes only for special applications. The materials used in civil engineering are also objects for development and improvement. Structures can now be built or strengthened with materials that weren't available at the time when many existing structures were built.

The use of fiber reinforced polymer (FRP) as structural reinforcement is gaining more and more interest in construction practice. The advantages of FRP, such as low weight, immunity to corrosion, excellent mechanical strength and stiffness, and the ease of construction, make it very attractive. The chemical compositions and mechanical properties of the various types of fibers and polymers are currently given in many text books [4]. One of the successful uses of FRP is to bond FRP sheets, fabric or plate, to concrete surface to strengthen and rehabilitate concrete structures. Today many concrete structures such as bridges and buildings in the United States are in need of repair, retrofit and rehabilitation. The cost of replacing all the deficient structures is prohibitive, but repair by FRP sheets seem to be an ideal solution. Experimental results and practical experiences have demonstrated that FRP sheets externally bonded to the beam web can increase the shear strength of beam significantly [1.2.3].

Description of Experimental Program

Test Specimens:

In this study eight shear tests are reported. Of these tests, seven are without steel stirrups and one with stirrups S1-1 which was reinforced with 6mm steel stirrups spaced at 150mm throughout its shear span. The beams were designed to have extra strength in flexure to ensure shear failure even after strengthening. The beams are presented in Fig.1 and Table1. In all beam specimens the cross section was 100mm wide and 200mm in depth, the overall length was 1800mm, with clear span 1600mm, also two 20mm longitudinal bars.

U-wrap manufacturing

For preparing the U-wrap strips, (for example double layer strips), each layer had 40mm width of the CFRP sheet that was measured and cut. Then two plates of 35mm height x

50mm width, and 2mm thickness were pre-drilled with a hole equal to 8mm (bolt diameter) in the center of each plate. They were used to make sandwich of CFRP sheets bonded together and to the steel plates by epoxy (Sikadour 30). This was the end anchorage for each strip as illustrated in Fig 2b. After manufacturing the end anchorages of the U-strips, at about 24 hours, when the epoxy had enough strength (so that the sandwich anchorage would not to be distorted during pulling up the CFRP strip), the layers of the CFRP were bonded together by a thin layer of Sikadour 330 (according to the manufacturer the pot life is 30minutes). The predrilled holes into the top of the beam specimen (clear edge about 20mm from the top) were filled with Sikadour 30 (pot life 70 minutes according to the manufacturer). The U-wrap strip was pulled up until all losses were finished (losses due to the error in measuring the length of CFRP strip or manufacturing the end anchorage) and the holes in the same level to insert the bolt in the hole with rotating it slowly, so as to ensure that Sikadour 30 in the hole would be surrounding the bolt and the epoxy filling the space between the hole and the bolt. Then washers and nuts were used to fix the anchorage on the two sides of the beam specimen. Finally the strip was coated with Sikadour 330 per manufacturer's recommendations.

Strengthening Schemes

Two specimens were kept without strengthening as control specimens, whereas six beam specimens were strengthened with externally bolted CFRP strips following different schemes as illustrated in Table 1 and Figs 3.

Instrumentation and Test Procedures

All specimens were tested as simply supported beams using a four-point loading. Fig 4 shows the details and instrumentation used for testing the beam specimens. The methods of measurement and instrumentation used during the tests were as follows:

1-Defflections: The central deflections were measured by using a dial gauge of 0.01mm/div. sensitivity.

2-CFRP strains: The strain of the CFRP U-wrap strips was measured at the center of each strip with the 150mm demec gauge along the CFRP strip on the specimen side (the outer layer only).

4- Cracks: The beams were white-washed to facilitate crack viewing. The appearance of first cracks and their propagation were detected visually. The development of the cracks was marked with pencil after each load increment.

Test Results and their discussion

Failure of the beam specimens tested in this investigation had different modes as presented in Table 5. Except for beam S1-8, all other beams showed no debonding (separation of CFRP strips or anchorage failure). In contrast, beam S1-8 showed visual separation due to debonding. Beam S1-8 (bonded by epoxy only) exhibited debonding similar to those indicated by other researchers [5.6.7] who relied on bonding alone. The specimen S1-1 failed in shear. Initially there were some flexural small cracks along the beam bottom, when the beam reached approximately 50kN. The closest crack to the support (in the shear span at the left hand side of the beam) propagated directly towards the nearest loading point, (which is called diagonal shear crack). At the same time a diagonal shear crack formed in the middle of the shear span at the right hand side of the beam .With increasing load additional shear cracks formed throughout the shear span, widening and propagating until failure occurred because the right diagonal crack became very wide (the main shear crack) and reached the loading point at a total applied load of 100kN. Fig 5 shows the crack pattern of specimen S1-1 at ultimate load. In the control beam specimen S1-2 (without shear reinforcement), just one or two cracks were observed close to the middle of the shear span. When the applied load reached approximately 40kN, then with little increase of the applied load the single diagonal crack rapidly propagated and became wider. Then collapse happened by splitting the beam into two pieces along the main diagonal crack at a load of 50kN, Fig 6 shows the failure of the beam specimen. The differences between the failure of the beams with and without shear reinforcement were: The failure load was only slightly greater than the diagonal cracking load in the case of the beams without shear reinforcement S1-2. Also, there were only one or two diagonal cracks which caused the separation of the beam or by splitting the concrete around the main reinforcement near the support if the development length of the main reinforcement (hooks) was not adequate. While beams S1-1 with steel stirrups even it failed by diagonal shear crack because the shear reinforcement was not enough but sudden failure did not happen (explosively) and the beam continued carrying the applied load even after many diagonal shear cracks were observed. At higher applied load one of the diagonal cracks propagated to reach the nearest loading point and sudden failure happened but with a load about twice the load at the first diagonal crack. The stirrups provided a better distribution of diagonal cracks throughout the shear span. In specimen S1-3, the first shear crack was observed at the left hand side of the beam in the middle of the shear span as shown in Fig7, when the applied load was approximately 40kN. With increasing the applied load, more flexural and shear cracks appeared but the first one in the left hand side had propagated more than the others, which diagonally extended from the first CFRP strip (75mm from the face of support). It propagated passing under the second CFRP strip (225mm from the support) and reached near the end anchorage of the third CFRP strip (375mm from the face of support) when the applied load reached about 80kN. At the applied load 100kN the diagonal crack rapidly propagated toward the loading point crossing through the end anchorage of the third CFRP strip, the second CFRP strip ruptured and sudden failure happened. It was clear that the applied shear force was carried approximately by the second CFRP strip only this was clearly in the load-

CFRP strain curve Fig8 the first strip had the lowest strain value which means its contribution to supporting load is insignificant. In contrast, the second strip which crossed the diagonal crack suffered from high elongation due to resisting the widening and propagation of the diagonal crack. 0.006 mm/mm maximum strains were recorded before the rupture of this strip. Beam specimen S1-4, in this specimen the flexural crack appeared first clearly, and after that at about 40kN the diagonal shear cracks started to appear. With increasing load more diagonal cracks in both shear spans of the beam were observed, as shown in Fig 9, but when the applied load reached about 90kN the diagonal crack under the second CFRP strip (at 225mm from the left support) became wider and propagated toward the nearest point load. With increasing load to 110kN the main diagonal crack reached the loading point passing through the end anchorage of the third CFRP strip (375mm from the support) causing crushing of concrete under the loading point and failure happened. This kind of shear failure is called shear-compression failure. This kind of failure usually happens when 2.5> a/d >1[8].The rupture of the CFRP strips were not observed.

Beam specimen **S1-5**, the flexural cracks were observed first, and approximately when the applied load was 50kN a few diagonal cracks were observed. With increasing load the flexural cracks grew upward and became wider. At the same time the left diagonal crack propagated towards the loading point as shown in Fig 10. At the applied load 110kN the diagonal crack rapidly propagated to the loading point and concrete under the loading point was crushed. As explained previously epoxy was used with end anchorage plates in this specimen to fix the CFRP strip but the left diagonal crack propagated toward the second CFRP strip at a level lower than that of specimen S1-4.

Beam specimen S1-6, where the spacing of the CFRP strips was decreased. The flexural behavior was observed more than the previous specimens. When the applied load reached 60kN many flexural and diagonal cracks were formed. With increasing applied load the right diagonal crack propagated. At the applied load of 135kN the failure happened after flexural cracks became wider and the shorter cracks formed near the bottom of the beam and extended towards the long cracks and joined them and propagated towards the compression zone. Finally, the concrete crushed at some point between the two loading points. Fig 11 shows the crack pattern at failure. Beam specimen S1-7, with increasing the amount of CFRP (three layers) and decreasing CFRP spacing (same spacing as S1-6), the flexural behavior was very clear by reaching the ultimate flexural capacity. This did not prevent some diagonal cracks to appear in the shear span at a load about 60kN. The flexural cracks in the middle zone when the load reached 100kN extended upwards and continued in widening then joined other cracks. When the load reached 140kN some of the flexural cracks became wider than the others between the two loading points and propagated upwards causing concrete crushing without reaching the diagonal shear crack to the loading point, as shown in Fig 12 . Beam specimen S1-8, as the applied load increased the deformation of the specimen obviously increased. This broke the bonding between the CFRP strips and the concrete cover (thin layer of epoxy type Sikadour330) and the sound of the separation (destroying the epoxy layer) was very obvious. At about 40kN diagonal shear cracks formed, growing and propagating until failure occurred immediately after separation of the CFRP strip then the diagonal crack reached the loading point as shown in Fig 13 and the beam separated into two pieces at a total applied load of 60kN. The failure was sudden and explosive after the separation of the second CFRP strips at each side of the specimen. There were some attached particles of cement on the separated CFRP strips.

This can be explained as follows: the CFRP sharing (contribution) to the applied shear force was transmitted from the specimen to the CFRP strip by the friction force between the concrete cover and the thin layer of the epoxy in the first stage and in the second stage between the thin layer of epoxy and the CFRP strip. As deformation increased, the three materials (the three layers of concrete, epoxy and CFRP) each had a different stiffness, so they could not deform in the same way. The failure started at the weakest layer which was the epoxy because it was a very thin layer (having the lesser stiffness of the three materials) and separation happened. The difference in behavior was very clearly in the load-deflection curve, Fig 14 shows the enhancement in carrying the applied load capacity and the ductility due to increasing in the CFRP amount (number of layers) and decreasing the spacing reaching the flexural capacity in beams S1-6 and S1-7. It's clear that decreasing the spacing had more effect than the increasing number of layers, due to increasing the possibility of increasing the diagonal crack with CFRP strips.

Conclusions

The following conclusions can be made based on the results presented bellow:

1- Using the end anchorage to fix the CFRP strips was very successful and the separation was not observed so, CFRP could work with high efficiency as external shear reinforcement.

2- Using the CFRP U-wrap strips enhanced the shear capacity of the beam and could change the mode of failure to flexural failure mode, depending on the CFRP amount ratio

$r_{FRP}.E_{FRP}$ Where $r_{FRP} = \frac{A_{FRP}}{b_w S_{FRP}}$

3- The CFRP strips in the strengthened beams started to resist the applied shear force after the shear cracks were observed.

4- The recorded CFRP strip strain of the tested beams indicates that none of these strips reached the material nominal strength. In more than one beam strengthen with CFRP (e.g. S1-4 &S1-5) the diagonal crack exceeded1mm

$(\Delta = e \times l = 0.0055 \times 170 = 0.94 mm)$, which led to propagation of the crack into the compression zone. As a result, the final failure was shear-compression type.

5- Maximum allowable strain of the CFRP must be defined to control the shear cracks width, to limit the propagation and to prevent growing of the shear cracks from reaching the top zone. So, increasing the modulus of elasticity (increasing in brittleness) of the CFRP is a good property for this reason.

6- The distribution of FRP and defining the maximum spacing is more effective than the amount of FRP (number of layers) to control the cracks growing. At the same time the amount of FRP will control the elongation of the strips and this strengthened the reduction of the cracks width (elongation will decrease as FRP stiffness increased).

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Table 1: Details of the reinforcement and U-wrap strips

No.	Specimen designation	a/d	Shear reinforcement		
			Spacing of steel stirrups (mm) (in shear span)	Spacing of CFRP strips (mm) (in shear span)	Number of CFRP layers per strip
1	S1-1	3	$f6@150mm$	-----	-----
2	S1-2	3	-----	-----	-----
3	S1-3	3	-----	150	2
4	S1-4	3	-----	150	3
5	S1-5	3	-----	150	3
6	S1-6	3	-----	100	2
7	S1-7	3	-----	100	3
8	S1-8	3	-----	150	2

Table 2: Resins properties (from manufacturers)

Epoxy type	Tensile bond strength (MPa)	Strain at yield (mm/mm)	Elastic modulus (MPa)	Shear strength (MPa)
Sikadour 30	21.3	1%	4482	15
Sikadour 330	30	1.5%	3800	--

Table 3 : Properties of CFRP :

CFRP strip	Modulus of elasticity (GPa)	Yield stress (MPa)	Ultimate stress (MPa)	Strain at ultimate stress (microstrain)
40mm width 0.16mm thick	180	---	1650	10000

Table 4: Properties of hardened concrete:

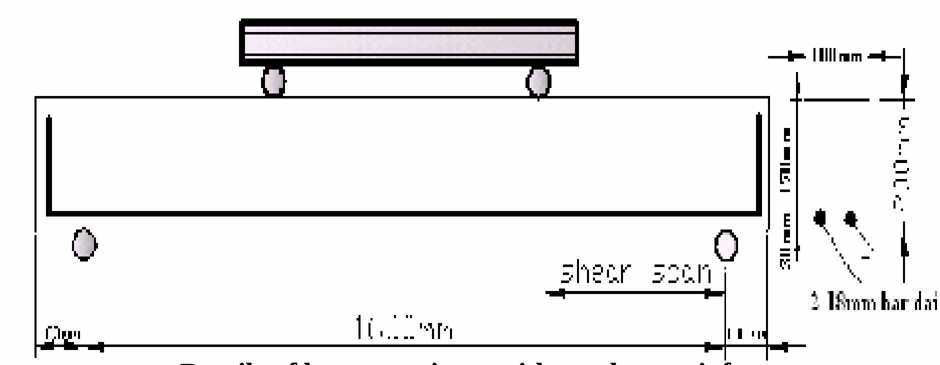
Compressive strength f'_c (MPa)	Modulus of rupture f_r (MPa)	Modulus of elasticity E_c (MPa)	Indirect tensile strength f_t (MPa)
45	4.6	34480	2.2

Table 5: Properties of steel bars:

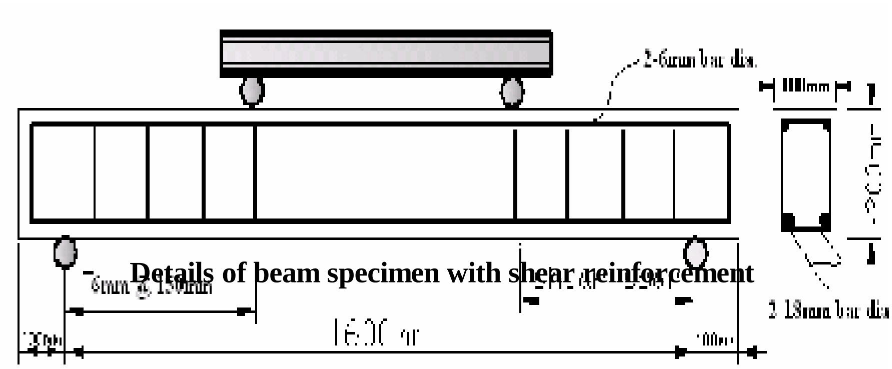
Bar diameter (mm)	Modulus of elasticity (GPa)	Yield stress (MPa)	Strain at yield stress (microstrain)	Ultimate stress (MPa)
6	197	450	2280	550
18	198	520	2620	620

Table 6: Properties of steel bolt:

Bolt diameter* (mm)	Modulus of elasticity (GPa)	Yield stress (MPa)	Strain at yield stress (microstrain)	Ultimate stress (MPa)
8	200	623	3117	761

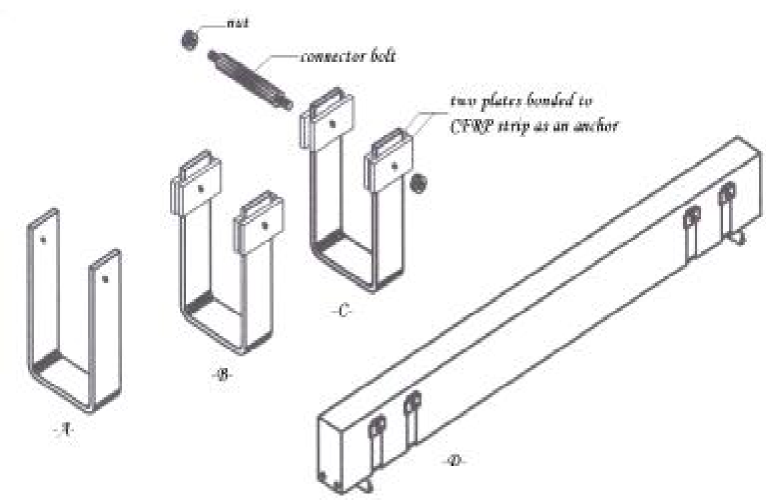


- Details of beam specimen without shear reinforcement



- Details of beam specimen with shear reinforcement

Figure 1 : Details of the beam reinforcement details



A- Two or more 40mm width of the CFRP sheet were measured and cut, then later bonded together by Sikadur330 epoxy.
B- Pre-drilled 2mm thick plates were bonded by Sikadur30 epoxy to the CFRP strips as an anchorage.
C- After preparing the CFRP U-wrap strips, bolts were used to fix it on the specimen after filling the concrete hole with Sikadour 30.
D- The overall specimen with the U-wrap strips.

Figure 2 : Details of preparing and fixing the U-wrap strips

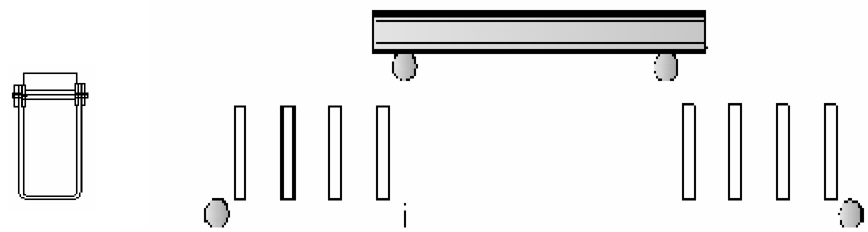


Figure 3 : Strengthening scheme for beam specimen S1-3, S1-4 S1-5 and S1-8

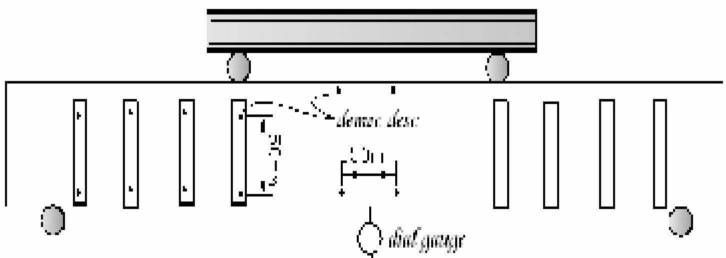


Figure 4: Details &instrumentation of specimen

Figure 5: Beam specimen S1-1 as a control beam with steel stirrups (a/d=3)

Figure 6: Beam specimen S1-2 as a control beam without steel stirrups (a/d=3)

Figure 7: Crack pattern at ultimate failure of specimen S1-3

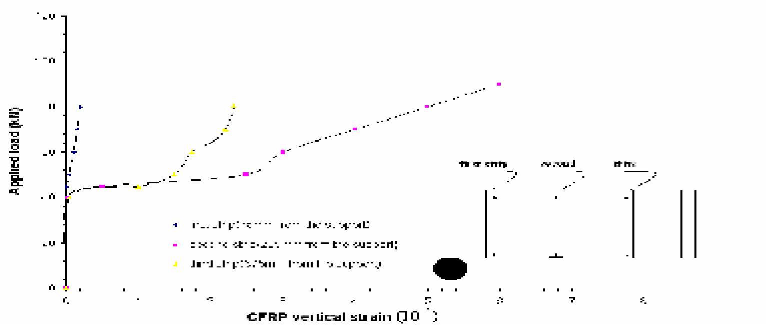


Figure 8: Applied load–CFRP Strain for specimen S1-3

Figure 9: Crack pattern at ultimate failure of specimen S1-4

Figure 10: Crack pattern at ultimate failure of specimen S1-5

Figure 11: Crack pattern at ultimate failure of specimen S1-6

Figure 12: Crack pattern at ultimate failure of specimen S1-7

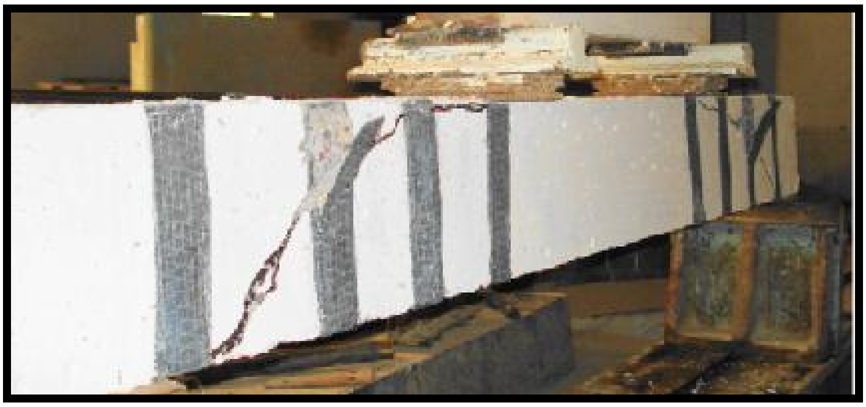


Figure 13: Crack pattern at ultimate failure of specimen S1-8 Debonding of the second CFRP strip for each side