INNOVATIVE PROCEDURES FOR STRENGTHENING STRUCTURES VIA SLOT APPLICATION OF PULTRUDED CFRP LAMINATES

James Korff, PE, Structural Composite Consultants, San Mateo, CA
Josef Scherer, S&P Clever Reinforcement Company, AG, Brunnen, Switzerland

Abstract

Pre-cured CFRP Laminates with a width of 10 mm and a thickness of 1.4 mm have been specially designed to be bonded into slots in concrete structures. A concrete saw is used to cut slots approx. 3 mm wide and 10-15 mm deep into the substrate. The slots are filled with the system approved epoxy adhesive, and the CFRP Laminates are inserted on edge into the adhesive filled slot. The performance of such slot-applied laminates has been tested at the Technical University in Munich, University of Lisbon, University of Gent, University of Manitoba and other research centers. The test results show a substantially improved load-bearing capacity of members strengthened with slot-applied laminates as compared to traditional surface applied laminates. Within the range of working loads, the bond performance is stiffer and, within the range of failure loads, far more ductile compared to surface-applied laminates. There is a higher utilization of the tensile strength of the CFRP laminate. The improved utilization of the laminate permits higher loads to be applied and laminate cross sections to be reduced. The quality of the substrate (tensile strength of the surface) is less important. The slot application is more economical than leveling and roughening required for surface-applied laminates. There is improved bond performance. The slot-applied laminate is protected against mechanical damage. Typical applications are strengthening of negative moment regions in slabs and beams, and reinforcement of buckling moments in load bearing columns, in conjunction with confinement of columns with CFRP sheets.

Introduction

Structural tests conducted worldwide have established that slot-applied CFRP laminates increase the load-bearing capacity of reinforced concrete beams compared to only surface-applied laminates. Further on improved anchorage possibilities in narrow room conditions and test results on load-bearing elements with confinement reinforcement are presented.

Within the scope of various approval procedures the bond performance of surface-applied CFRP laminates has been studied in detail. CFRP Laminates are connected to the tensile stress zone of structural elements by an adhesive bonding. On a high-quality concrete substrate the adhesive bonding fails outside of the adhesive joint and occurs in the concrete area close to the laminates.

As proved by tests the load-bearing capacity of the adhesive bonding can be increased considerably by a normal-acting pressing-on pressure. In practice, pressing- on pressures acting at the ends of the laminates cannot be realized economically. Various approaches to improve the adhesive bonding at the ends of the laminates have been considered and led to correspondent test programs. For instance, confinements with carbon sheets (C-Sheet) that are anchored in the web area of the beam have been tested. However this option doesn't exist with plates. The University of Munich performed an interesting test program with slot-applied laminates, which gives new impetus to diverse possibilities in anchoring at the ends of the laminates. The test program results and the new possibilities in anchoring are presented. Additionally, applications of slot-applied laminates and confined load bearing columns are presented.

Surface Bonded CFRP Laminates

During tests conducted for the General Approval of the S&P CFRP Laminate CFK in France, Germany, UK, and other countries, the bond of the laminate on beams was investigated. Flexural tests on beams conducted at TU in Braunschweig (Germany) showed that debonding of the laminate from the substrate depends on the strain in the laminate and the plastic strain in the reinforcing steel. Debonding of the reinforcing steel initiated at an elongation of the laminate of approx. 0.65%; this corresponds to 5.7 times the limiting strain of the internal reinforcement. Failure of the beam occurred at a laminate elongation of 1.3%.

Bending tests on slender slabs conducted at HTA University of Fribourg showed that premature debonding (partly at a limiting strain of 0.6-0.7%) of the CFRP laminate is possible. For this reason, a limiting design strain for CFRP laminates of 0.6-0.8% has been defined in internationally recognised Guidelines as well as in the General Approvals for France, Germany etc.

CFRP Laminates Confined At The Ends

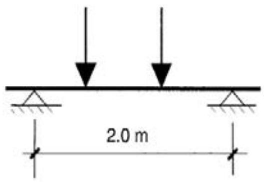
The maximum bond strength was obtained at an anchoring length of the CFRP laminate of 300mm. Longer anchoring lengths do not contribute to a further increase in bond strength. The maximum bond strength of a surface applied CFRP laminate of width 80mm is approx. 35-40kN. The tests indicated that the variation of laminate width (50-100mm) does not produce substantial changes in bond strength.

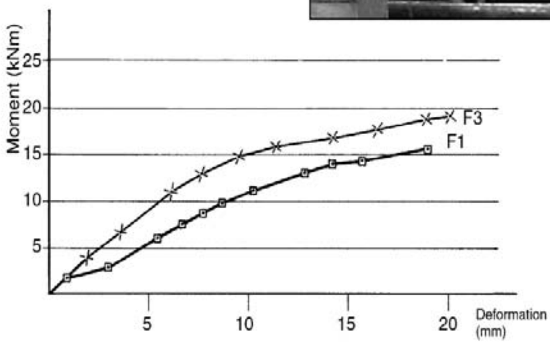
The traditional calculation model for the adhesive bonding of FRP reinforcement to concrete is based on a non-linear brittle fracture mechanics and can be used for any elastic laminate material. The applicability of the traditional models was established by means of bond tests carried out to obtain the General German Approval for CFRP Laminates. The bond strengths are transmitted into the substrate between two flexural or shear cracks. Verification of the anchoring of the theoretical laminate end is established if the progression of the bending moment curve is positive. The residual tensile strength of the laminate at that point corresponds to the theoretical bond failure strength of the laminate.

The bonding of an additional external CFRP laminate on to the tensile stress zone of a structural element subject to bending is carried out with a system approved epoxy resin. Thus, a reinforced concrete structure is produced with an elastic-plastic (steel reinforcement) and a perfectly elastic tensile element (CFRP laminate). Models for the calculation of the flexural capacity of the composite structure and of the anchor lengths are found by means of bond tests.

Several reinforced concrete beams with a span width of 2 m were strengthened with CFRP laminates for flexural tension at the University of Lisbon (Portugal). The laminates were glued up to a distance of 5 cm from the supports. The load-deflection curve F_1 was determined through flexural tests. Afterwards the test beams with the surface-applied laminates were confined additionally with a unidirectional carbon sheet (C-Sheet). The carbon sheet with a width of 300 mm was laminated manually with epoxy adhesive. The load-deflection curve F_3 shows an increase of 20% of the failure load of the beam due to the confinement at the end of the laminate

TESTING ARRANGEMENT (UNIV. OF LISBON - PORTUGAL)





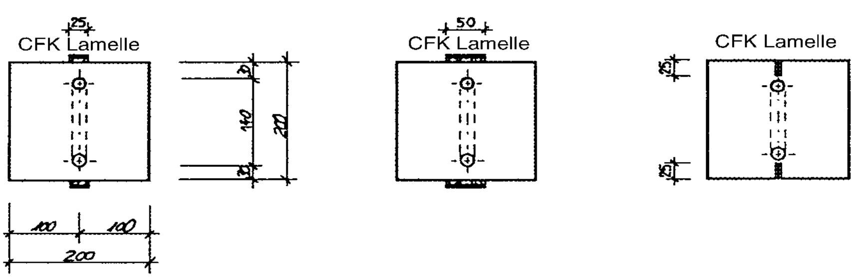
The test results showed that due to the confinement reinforcement of the beam at the ends of the laminates, the bending moment could be increased by approx. 20%.

F1: Without confinement reinforcement
F3: With confinement reinforcement

Slot Application Of CFRP Laminates

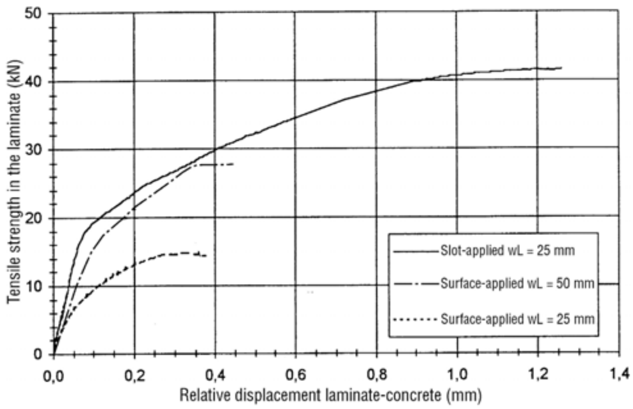
The CFRP laminate 10/1.4 with a width of 10 mm and a thickness of 1.4 mm is specially designed to be bonded into slots in concrete or timber structures. A concrete saw is used to cut slots approx. 3 mm wide and 10-15 mm deep into the substrate. The slots are filled with the system approved epoxy adhesive, and the CFRP laminates are pressed into the adhesive. The test results showed that due to the confinement of the beam at the ends of the laminates, the bending moment could be increased by approx. 20%.

Test results positively proved that a good and uniform bond exists between the laminate and the concrete. Furthermore, the high tensile strength of the laminate fibers was fully utilized prior to shear failure between laminate and surface.



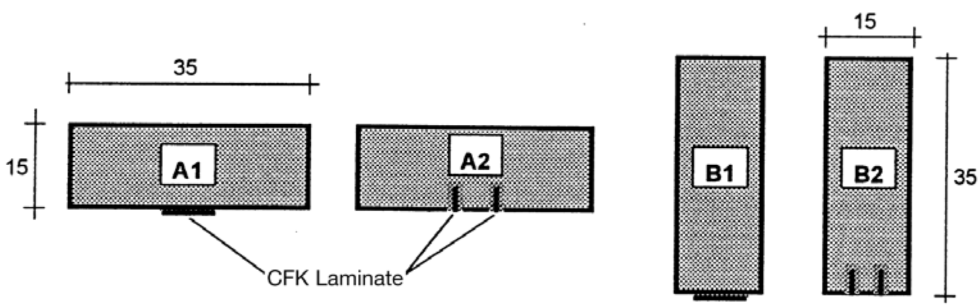
• Testing arrangement

Comparison Of Bond Strength of Slot-Applied vs. Surface-Applied CFRP Laminates



The illustration above shows the relative displacement in the static tensile strength test. It clearly shows the considerably more ductile behavior of the slot-applied CFRP laminate.

Three point load tests with a span of 2.5 m have also been carried out on various reinforced concrete beams.



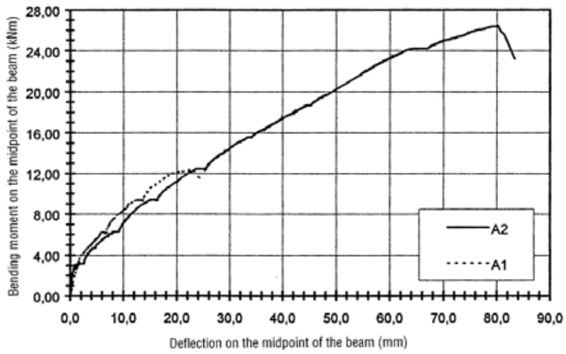
Beam sections

Each sample was either reinforced by a surface-applied CFRP laminate 50/1.2 or by two slot-applied CFRP laminates 25/1.2.

– On test beams A1 and B1 failure occurred due to debonding of the CFRP laminate.

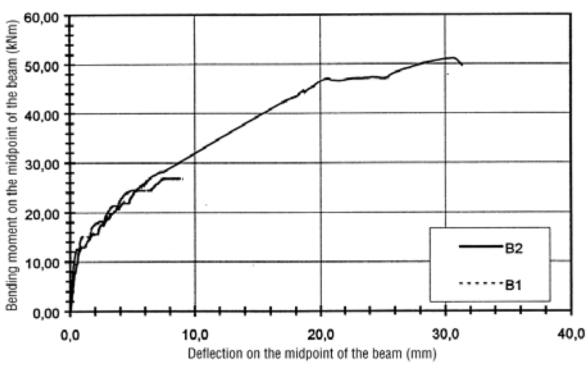
– On test beam A2 failure occurred due to tensile fracture of the slot-applied laminate.

– On test beam B2; with a low shear reinforcement made of steel, shear failure occurred in the concrete.



• The load-deflection curves of test beams A1 and A2

At equal stiffnesses, the ultimate load was more than doubled using the slot-applied laminate. This is due to the high utilization of the tensile strength of the CFRP laminate.



• The load-deflection curves of test beams B1 and B2

The load-deflection curves were almost identical except that the slot-applied CFRP laminate exhibited a substantially higher ultimate load.

Benefits Of Slot Applied CFRP Laminates

- The improved utilization of the laminate permits higher loads to be applied and laminate cross sections to be reduced.
- The quality of the substrate (tensile strength of the surface) is less important. Slot-applied laminates can also transfer loads into substrates with a low bearing capacity (brickwork, masonry).
- The slot application is more economical than leveling and roughening required for surface-applied laminates.
- The slot-applied laminate is protected against mechanical damage. Better performance is achieved in the event of a fire, thus reducing the cost of fire protection measures.

Ideal fields of application of slot-applied laminates are:

- Strengthening of the negative moment (moment at support)
- Slot-application to flexural elements (flexural strengthening)

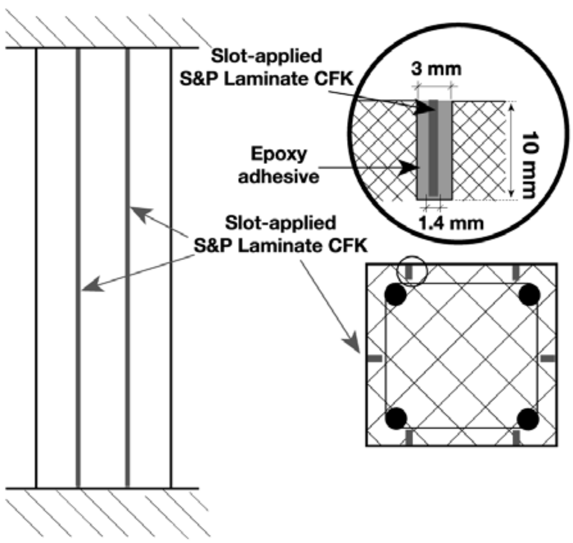
Dimensioning Of Slot-Applied CFRP Laminates

Dimensioning of slot-applied CFRP laminates can likewise be conducted using the methods for surface applied laminates. Required laminate cross sections of surface bonded CFRP Laminates e.g. for the strengthening of the moment at support, are established. Since the slot-applied laminates can be utilised to a higher degree, the laminate cross section that would be required for surface bonded laminates is in practice reduced by 25-30% for the slot-applied laminates. Bond tests on slot-applied laminates show that the verification of the anchoring is a simple task. Debonding of the slot-applied laminate does not occur. On a slot length of 20-30cm, it has been shown that the ultimate tensile strength of a slot-applied laminate of width 10-50mm and thickness 1.4mm can be transferred into the concrete substrate.

Combined Moment And Axial Load On Columns

In the case of both moments and axial load applied to a circular or rectangular column, two types of reinforcing are applied. The additional axial force is absorbed by the FRP wrap. The additional moment is absorbed by a slot- applied laminate that is placed prior to the traditional FRP Sheet confinement. The CFRP Laminate is dimensioned for the additional moment effect.

Replacement of corroded flexural reinforcement with CFRP laminates bonded into slots:



Column with slot-applied laminates

With the slot-applied CFRP laminate higher forces can be transmitted into the substrate Thus, the CFRP laminate can be utilised to a higher degree than surface mounted laminates. For design purposes a tensile strength of 2,000MPa is assumed for the slot-applied laminate. This means that approx. 25% of the surface area of the corroded internal steel (yield: 500 MPa) are replaced by the slot-applied CFRP laminates.

At the Technical University in Porto (Portugal) an investigation into the seismic resistance of carbon fibre based FRP systems was conducted in a series of push-pull tests. To this end, square columns with a side length of 200mm were reinforced with CFRP. CFRP Laminates were bonded into slots to improve the longitudinal flexural strength. Partial wrapping was then done with the Carbon Fiber Sheets. The tests indicated that the maximum displacement angle of 22mm/m (maximum loading of the testing device) was reached. The results show that the combined application (into slots and as wrapping) of the high modulus C fiber likewise produces a high reinforcing effect under seismic exposure.

Conclusion

It has been consistently shown over the last few years that the use of advanced composite FRP surface applied products (sheets and laminates) offer innovative and interesting possibilities to apply structural "post"– reinforcement, for strengthening or rehabilitating existing reinforced concrete structures. Slot-applied CFRP laminates provide considerably higher load-bearing capacity than surface-applied laminates. A typical application area of slot-supplied laminates would be the reinforcement of the negative moment in continuous beams or slabs or the reinforcement of the buckling moment in load bearing columns. Stainless slot-applied steel channels at the end of the laminate conduct a much higher tensile force into the substrate. Therefore steel channels represent a possibility to anchor at the end of the CFRP laminates. Theoretical design approaches have been verified by tests.