Zeitschrift: IABSE reports = Rapports AIPC = IVBH Berichte

Band: 999 (1997)

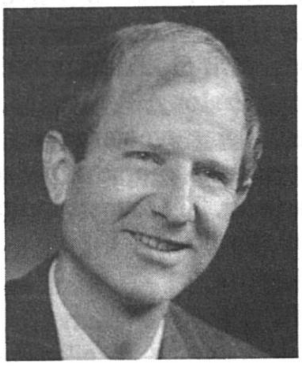
Artikel: Repair using advanced composites

Autor: Meier, Urs

DOI: https://doi.org/10.5169/seals-955

Repair Using Advanced Composites

Urs MEIER
Professor
EMPA
Dübendorf, Switzerland



Urs Meier, born in 1943, received his Engineering degree at the Swiss Federal Institute of Technology, ETH, in Zurich. In 1971/72 and 1977/78 he was Research Associate at the Massachusetts Institute of Technology, MIT in Cambridge, USA. Since 1971 he has been involved in research and development on advanced composites and he is now Director of the Swiss Federal Laboratories for Materials Testing in Dubendorf. He is also Professor at the ETH Zurich.

Summary

This paper discusses the advantages of using advanced polymer matrix composite materials, originally developed for high-performance aircraft, for post-strengthening existing structures. Criteria for evaluating and designing with these materials are suggested. In Switzerland, retrofitting by externally bonding carbon fibre reinforced plastic (CFRP) laminates has been shown to be less expensive than the technique of external steel plate bonding, especially if ease of handling is a dominant cost factor.

1. Introduction

Changing social needs, upgrading of design standards, increased safety requirements and deterioration result in existing structures that need to be retrofitted or demolished. Many existing structures are part of the architectural heritage and demolition is not a viable option. Even for newer structures, rehabilitation is in most cases a much better use of resources than replacement. Bridges represent a major proportion of engineering structures. They are a significant factor in the infrastructure and their maintenance has implications on the economic life of a nation through disruption and traffic delays.

Chloride induced deterioration of reinforced and prestressed concrete bridges, continual upgrading of service loads and the large increase in the volume of traffic means that thousands and thousands of bridges need repair or reconstruction. This paper will demonstrate the use of advanced composite materials such as thin carbon fiber laminates bonded to existing structures to strengthen and rehabilitate them to extend their useful life. Approximately 5% of the deteriorated bridges in Europe can be strengthened using advanced composite materials instead of conventional steel plate bonding. A further 5% can be saved from demolition by this method. The saving in Europe will be in the region of 5.5 Billion US $ per annum. In addition there are savings on other structures in the need of strengthening. These savings are less easy to quantify in Europe. However, the potential on "other structures" is at least similar. If we estimate the annual worldwide potential it will be at least 10 Billion US $. 20 Billion US $ may be much closer to the reality.

2. Why Should We Replace Steel Plates?

Today in Western Europe and in other parts of the world the strengthening technique for bonding steel plates is wide spread and is the state of the art. In a non-corrosive environment this technique shows very good long-term behaviour (Fig. 1). However, weathering tests over extended periods of time have indicated that long term problems concerning corrosion of the steel must be expected in outdoor applications. Ladner, Pralong, Weder [1] observed "small traces of rust" on unprimed as well as primed bonded steel plates even after only 3 years exposure to weathering. The rust became more extensive during the course of the test and after 15 years exposure the areas have grown to 10 mm in diameter. These tests indicate a weakness in the strengthening of structural systems using steel plates [2].

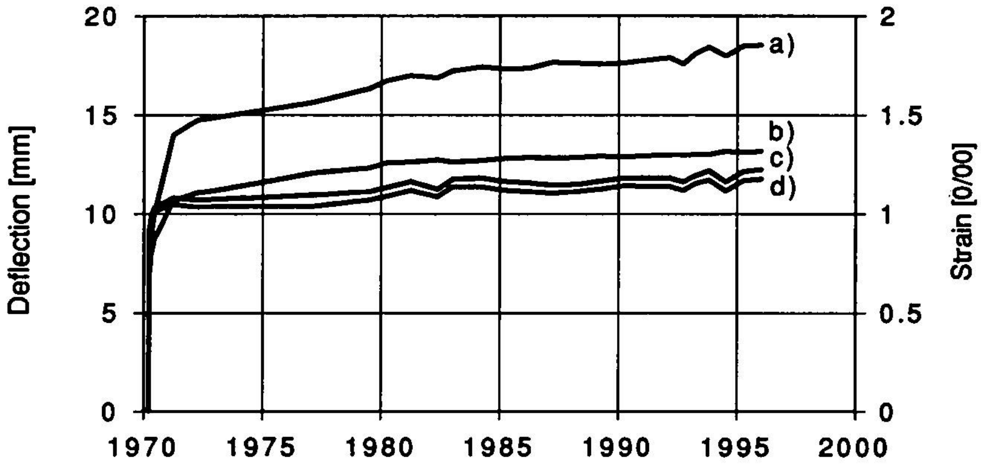


Fig. 1 Creep data for 26 years of a RC girder (190-depth x 210 x 2895 mm) post-strengthened with a steel plate (7 x 120 x 2820). The steel plate is bonded to the bottom of the beam using a filled epoxy resin (Ciba), without mechanical fasteners. The beam is loaded in 4-point bending (945 mm shear spans) using 30 kN lead weights at each of the two loading points. The induced, constant bending moment is 28.35 kN·m. The temperature variation during the indoor test is 16 to 24°C, and the range of relative humidity is 40 to 80%. The curves represent

a) compressive strain of the concrete at the top of the girder [0/00]
b) deflection at mid-span [mm]
c) tensile strain of the steel plate [0/00]
d) tensile strain of the concrete at the steel plate interface above (c) [0/00].

Steel plates have other disadvantages. During renovation work, particularly on bridges, generally only a limited amount of mechanized lifting machines are available. In the interior of box girders, for example, the heavy strengthening plate has to be carried by hand to the point of installation.

Consequently, due to handling limitations on site, the steel plates are rarely longer than 6-8 m; however, if the strengthening work involves greater plate lengths, a butt-joint system must be used. This type of joint cannot be welded since the welding temperatures would destroy the adhesive bond, consequently butt-jointed steel plates have to be formed from single shear lap joints. If steel plates were replaced by high strength fiber composites a relatively thin component could be delivered to the building site in rolls of lengths in excess of 300 m. Compared to steel plates their bonding technique is greatly simplified. Using bonded CFRP laminates [3] the quality assurance can be demonstrated by infrared inspection in the field, as discussed in a later section; this is not possible with steel plates.

3. Which Is The Most Suitable Fiber?

The partial substitution of steel plates with polymer matrix/fiber composites was discussed in Europe in the early eighties. One of the most important decisions which had to be addressed at that time was that regarding the most suitable fiber composite material for this application; Table 1 lists criteria which specifically relate to the use of composite materials as a post strengthening material for structures and applies particularly to prestressed laminates. These criteria may not necessarily satisfy other applications. The ratings in Table 1 are rather crude, however, it is clear that the tensile strength is a relevant criterion, but the significance of the compressive strength may be questioned as concrete generally has to be strengthened in the tensile region of the beam. In certain static systems, however, there may be regions which are normally stressed in tension but which may also be subjected to compressive stress depending upon the load distribution; in these situations bonded steel plates are not acceptable as they will peel off. Aramid fiber reinforced polymers would also fail due to their poor compressive strength. Deuring [4] has shown that carbon fiber reinforced composites (CFRP) do satisfy the compressive requirement.

Table 1: Quantitative Rating Of The Fiber Types

Criterion:	Weighting Factor:	Weighted Rating For Laminates With Fibers Of:		
Range Of Weighting Factor	1 ... 3	Carbon	Aramid	E-glass
Tensile Strength	3	9	9	9
Compressive Strength	2	6	0	4
Young's Modulus	3	9	6	3
Long-Term Behavior	3	9	6	3
Fatigue Behavior	2	6	4	2
Bulk Density	2	4	6	2
Alkaline Resistance	2	6	4	0
Price	3	6	6	9
Total Points		55	41	32.
Ranking		1.	2.	3.

Rating: very good = 3, good = 2, adequate = 1 and inadequate = 0 points

The modulus of elasticity of the laminate material is of great significance when the laminate is not prestressed before being bonded, because only stiff laminates are able to relieve the stresses in the existing internal steel reinforcement. Laminates fabricated from glass fiber reinforced composites (GFRP) must be 4-10 times thicker than CFRP laminates to achieve the same tensile stiffness. If such GFRP composites are longer than 6-10 m their handling on the construction site is difficult.

The fatigue behavior of the system may be important or insignificant depending on the structure and the nature of the loading. The bulk density of the material is less important as a criterion since the density of all the fiber composites considered is low compared to that of steel.

The cost criteria is important. If a comparison of the price of fiber composites is made with that of the standard steel Fe 360 then it would appear, at first glance, that fiber composites are far too expensive. The price factor based on unit volume of material is 4 to 20 times greater than that of steel. However, when the cost of upgrading the structure is considered, the material cost amounts to less than 20% of the total cost of the construction, consequently, when the ease of handling of the fiber composite system is considered the solution becomes competitive due to its light weight.

4. Conclusions Regarding The Material Evaluation

From the above mentioned considerations result the following conclusions:

(i) The applications in which corrosion plays no role and the length of the strengthening component is less than 5 m, steel will be the favorite material; this is the case mainly for building construction. As will be shown later, however, laminate thickness may play a role from the point of view of aesthetics; thus interior decoration and non-technical considerations lead to renovation solutions with thin fiber composite laminates rather than plates.

(ii) In applications where corrosion, length of strengthening component and handling on construction sites play dominant roles, for example bridges, multistory parking spaces, railway stations and specialized industrial structures, historic monuments, fiber composites must be considered seriously.

(iii) In applications such as slabs with fire sprinkler systems, the pipe installation would have to be removed in order to bond heavy steel plates on to the under-strength units. Composites, however, would be able to compete with steel successfully as the thin strengthening components would be bonded insitu. Consequently, labor costs would be reduced substantially and the fire protection system of pipes and outlets would be operational during rehabilitation work.

(iv) The results shown in Table 1 clearly indicate that carbon fiber reinforced polymer composites most closely fulfill requirements for the post strengthening of structures. Consequently, from the early eighties laboratories in Europe have concentrated their research efforts using this material and all further discussion will be restricted to carbon fiber reinforced polymers. Typical properties of the composites considered are given in Table 2. The large scale research project undertaken in 1993 in the USA and in Canada in the area of carbon fiber/polymer composites and many successful applications in Japan have confirmed the earlier Swiss decision to use this material in construction.

5. Strengthening with Unprestressed CFRP Laminates

The research work shows the validity of the strain compatibility method in the analysis of various cross sections [4-6]. This implies that the calculation of flexure in reinforced concrete elements which are post strengthened with carbon fiber reinforced epoxy resin composites can be performed in a similar way to that for conventional reinforced concrete elements. The work also shows that the possible occurrence of shear cracks, may lead to peeling of the strengthening composite. Thus, the shear crack development represents a design criterion. Flexural cracks are spanned by the CFRP laminate and do not influence the loading capacity. In comparison to the unstrengthened beams, the strengthening laminates lead to a much finer cracking distribution. A calculation model [5] developed from the CFRP composite agrees well with the experimental results.

Table 2: Properties Of Laminates

Fiber Type: → Property: ↓	T 300	T 700	M 46 J
Fibre Volume Fraction [%]	70	70	70
Longitudinal Strength [MPa]	2000	2800	2600
Longitudinal Elastic Modulus [GPa]	148	152	305
Strain At Failure [%]	1.4	1.8	0.85
Density [g/ccm]	1.5	1.5	1.6

When a change of temperature takes place the differences in the coefficient of thermal expansion of concrete and the carbon fiber reinforced epoxy resin composites result in thermal stresses at the joints between the two components. After 100 frost cycles ranging from + 20 degree C to - 25 degree C, no negative influence on the loading capacity of the three post-strengthened beams was found [5].

For the post strengthened beams the following failures were observed:

(i) The CFRP composite failed during loading with a sharp explosive snap, the impending failure was preceded well in advance of the failure by cracking sounds, concrete cracking and large deflections.

(ii) Classical concrete failure in the compressive zone of the beam.

(iii) Continuous peeling-off of the CFRP laminates due to an uneven concrete surface. For thin laminates of thickness less than 1 mm and bonded to the concrete surface with the aid of a vacuum bag, an even bonding surface is required. If the surface is too uneven, the laminate will slowly peel off during the loading.

(iv) Shearing of the concrete in the tensile zone (it can also be observed as a secondary failure).

(v) Interlaminar shear within the CFRP laminate (observed as secondary failure).

(vi) Failure of the reinforcing steel in the tensile zone (this failure mode was only observed during fatigue tests).

The following failure modes were not observed but are theoretically possible;

(i) Cohesive failure within the adhesive.

(ii) Adhesive failure at the interface between the CFRP laminate and the adhesive.

(iii) Adhesive failure at the interface between the concrete and the adhesive.

For post strengthening with CFRP composites it is recommended that the design rule for the CFRP composite is such that it should fail during yielding of the steel reinforcing bars before a compressive failure of the concrete. Yielding of the steel bars should not occur before reaching the permitted service loads.

Kaiser [5] investigated a 2 m span beam under fatigue loading. The cross-section was 300 mm wide and 250 mm deep. The existing steel reinforcement consisted of 2 rebars of 8 mm diameter in the tension and in the compression zones. This beam was post strengthened with a glass/carbon fiber hybrid composite having the dimension 0.3 by 200 mm. The fatigue loading was sinusoidal at a frequency of 4 Hz; the test set up corresponded to a four point flexure test with loading at the one third points. The calculated stresses in the hybrid laminate and the steel reinforcement are listed in Table 3. After 480'000 cycles the first fatigue failure occurred in one of the two reinforcing rods in the tension zone; after 560'000 cycles the second reinforcing rod failed at another cross-section; after 61'000 cycles a further break was observed in the first reinforced rod and after 720'000 cycles a second break in the second rod was observed. The first damage to the composite appeared after 750'000 cycles and it was in the form of fractures of individual rovings of the laminate; the beam exhibited gaping cracks, which were bridged by the hybrid laminate. The relatively sharp concrete edges rubbed against the hybrid laminates at every cycle and after 805'000 cycles the composite finally failed, however, the test was executed with unrealistically high steel stresses. The aim of the test was to gain insight into the failure mechanism after a complete failure of the steel reinforcement; it was surprising to observe how much the hybrid laminate could withstand after failure of the reinforcement.

Table 3 Exaggerated Fatigue Loading And Corresponding Stresses

Loads [kN]	Stresses [MPa] Rebars	Laminate
Minimum 1	21	11
Maximum 19	407	205

Table 4 Realistic Fatigue Loading And Corresponding Stresses

Loads [kN]	Stresses [MPa] Rebars	Laminate
Minimum 125.8	131	102
Maximum 283.4	262	210

Deuring [4] performed further fatigue tests on a beam with a span of 6 m under realistic loading conditions. The total load carrying capacity of this beam amounted to 610 kN without post strengthening. When the beam was strengthened by bonding a CFRP composite laminate, with dimensions of 200 x 1 mm (laminate type T 300, Table 2), its load carrying capacity was increased by 32% to 815 kN. The calculated stresses in the CFRP laminate and the steel reinforcement are given in Table 4. The beam was subjected to this loading for 10.7 million cycles. After 10.7 million cycles the tests were continued in an environmental condition where the temperature was raised from room temperature to 40-degree C and the relative humidity to a value of 95% r.H. The aim of this test was to verify that the bonded CFRP composite could withstand very high humidity under fatigue loading. Initially the CFRP composite was soaked with water to nearly 100% saturation. After a total of 12 million cycles the first steel reinforcement failed due to fretting fatigue. The joint between the CFRP laminate and the concrete did not present any severe strain fatigue. In the next phase of the test program, the external loads were held constant (Table 4) and the stresses in the reinforcing steel and the CFRP laminate decreased. After 14.09 million cycles the second reinforcing steel rod failed, also due to fretting fatigue. The cracks which were bridged by the CFRP composite laminate rapidly grew and after failure of the third reinforcing rod, due to yielding of the remaining steel, the CFRP laminate was sheared from the concrete.

6. The Effect of Lightning or Fire on CFRP Laminates

The destructive effects of lightning are well known. The studies of lightning and the means of preventing its striking an object or the means of passing the strike harmlessly to ground have continued since the days when Franklin first established that lightning is electrical in nature. From these studies, two conclusions emerge; firstly, lightning will not strike an object if it is placed in a grounded metal cage and secondly, lightning tends, in general, to strike the highest objects in the area. As composite materials replace more and more metals in aircraft, there has been an increase of risk of damage by lightning to such composite sections. CFRP is a conductor, but is relatively resistive to electricity which causes it to heat up as the current passes through it. A lightning strike has two main effects on unprotected CFRP; firstly, the main body of the CFRP becomes so hot that the epoxy resin component vaporizes and secondly, the structural integrity of the CFRP will have been affected after the carbon cooled down. It will probably retain a considerable tensile strength but it will loose interlaminar shear and compressive strength. Therefore, the aircraft industry developed aluminum grids which are used to protect the composite in its outermost layers.

In most applications in which CFRP laminates are used for strengthening, they are not exposed to lightning strikes as they are inside a building or box girder which is equivalent to grounded cages. Composite laminates used in bridge strengthening are positioned on the soffits of the beam and lightning will have no access to them in this case. If there are situations where lightning may be a danger, metal grids, which are used with composites in aircraft design, have to be utilized.

In 1994 the EMPA performed a series of bending tests on strengthened beams positioned in a large horizontal testing oven [8]. The span of the 6 beams tested was 5.2 m and their width and depth were 400 mm and 300 mm respectively; the volume fraction of the steel rebars was 0.65%. The beams were loaded by hydraulic activators with the maximum short time load as laid down in the Swiss code SIA 160 (1989) in four point bending. The oven was heated according to the ISO Standard 834 with a temperature of 925 K after 1 hour. One beam was not plated and acted as the control, another beam was post strengthened with steel plates (75 mm wide, 8 mm thick) and in addition four beams were post strengthened with CFRP laminates (74 mm wide, 1 mm thick). After 8 minutes duration of the test the steel plate came away from the beam. During the test in which the beam were post strengthened with CFRP laminates, the fibers started to burn at the surface of the laminates and their cross sections slowly decreased in value, thus causing a slow decrease in stiffness. The CFRP composites finally became unbonded from the beam after one hour. The main reason for the superior behavior of the CFRP composites compared with that of the steel plates was their low thermal conductivity in the lateral direction.

7. Safety Considerations in the Case of the Lightning and the Fire

Since the early seventies it was [1] always recommended that the post strengthening of a structure should not be more than 50%. Therefore, after an accidental failure of the post strengthening of the beam, a residual factor of safety of approximately 1.2 would remain and the collapse of the structure could be avoided.

8. Quality Assurance

In Switzerland the pulse thermography (infrared inspection) [8] is applied for quality assurance of the bonding of the CFRP laminates to the structural surface. This non-destructive testing method relies on changes in thermal conductivity caused by flaws or damage. The equipment used for infrared inspection is currently small and light weight, thus allowing analysts to gather more sophisticated information regarding the object being tested on line on the construction site. The technique operates on the principle that an infrared camera is positioned in front of the laminate which is heated with a flash lamp. The sensors in the infrared camera detect the heat that is absorbed and then re-radiated from the surface and the digitized information is sent to a video board in a computer from where an image is constructed on a video screen. This image allows fast and accurate judgment on the quality of the strengthening work.

9. Applications in Europe

To the best knowledge of the author the Kattenbusch Bridge in Germany is the first place in the world where fiber reinforced plastic laminates were used to strengthen a bridge. After World War II numerous prestressed concrete bridges for motor vehicles were built in Germany employing the method of in-situ spanwise construction. These continuous multispan bridges are mostly designed as box girders. The working joints are at the points of contraflexure where usually all of the tendons are coupled. Many of the bridges now exhibit cracks at the working joints. Usually, the bottom slab of the box girder is transversely cracked at the joint. This relatively wide crack grows into the webs with diminishing width. Thereby it crosses the lower tendons and couplings. The main cause of these cracks is a temperature restraint which was not taken into account during previous designs [9-11]. In combination with other stresses tensile stresses at the bottom increase and exceed the concrete tensile strength at the joint. As the reinforcement ratio of the bottom slab was often low, yielding of the steel occurred and wide cracks formed. Due to increased fatigue stresses, the durability of the reinforcement and the tendons was no longer assured. Thus the necessity for repair arose. In the late seventies Rostasy and his co-workers [12] developed a technique to strengthen such joints with bonded steel plates. The first successful application was the Sterbecke Bridge near Hagen (Germany) in 1980. In 1986/87 this method was used for the first time with glass fiber reinforced plastic laminates on the Kattenbusch Bridge. The Kattenbusch Bridge is designed as a continuous, multispan box girder with a total length of 478 m. It consists of 9 spans of 45 m and 2 side spans of 36.5 m each. There are 10 working joints. The depth of the twin box girder is 2.70 m. The bottom slab of the girder is 8,50 m wide. One working joint was strengthened with 20 glass fiber reinforced laminates. Each plate is 3200 mm long, 150 mm wide and 30 mm thick. Loading tests performed by Rostasy and co-workers showed a reduction in the crack width of 50% and a decrease of the stress amplitude due to fatigue of 36%. The static and the fatigue behavior was at least equal to the steel plate bonding technique. From the corrosion point of view, the expectations of the glass fiber reinforced plastic laminates are much higher.

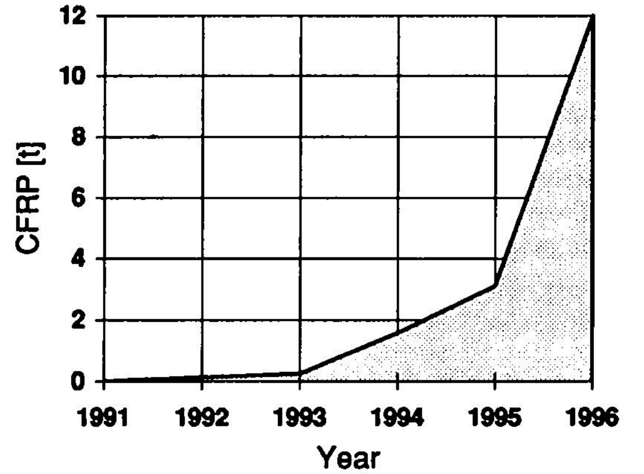


Fig. 2 Use of CFRP-Laminates for strengthening purposes in Switzerland

Another world premiere was the Ibach Bridge in 1991 at the gates of Lucerne in Switzerland. For the first time very thin carbon fiber/epoxy laminates were used to strengthen a bridge. In the following years this method was also used for the historic covered wooden bridge near Sins, the City Hall of Gossau, the large multistory parking garage in Flims, the tall chimney of the nuclear power plant in Leibstadt and the main railway station in Zürich. Beside this projects, which are described elsewhere [13-15] approximately 250 smaller and larger structures were strengthened in Switzerland since 1991 with thin CFRP laminates. From 1991 until 1996 approximately 17'000 kg of CFRP-Laminates were used for strengthening purposes in Switzerland. This mass of CFRP is replacing about 510'000 kg of steel. Figure 2 shows the commercial development. The prices are given in Table 5.

The valuable gothic roof structure of the Church of our Ladies in Meissen in Germany was built in 1447. The gothic vault reaches into the A-shaped cross section of the wooden roof truss. The observed deformations gave evidence that the horizontal tensile members of the "A" did no longer work satisfactory. The masonry of the nave received due to this insufficient action shearing forces from the roof. This fact was underlined by the observed cracks between the vault and the walls of the nave, which opened up to 4 cm. O. Kempe [16] developed prestressed diagonal racetrack CFRP tensile links to relieve the load on the connections of the wooden tensile members and to reduce the horizontal forces of the base points of the "A" produced in filament winding technique. The length of the two types of racetrack links is 1.8 and 3.25 m. The links are connected to the structure, the prestressing elements and to themselves by bolts. Before the successful application and certification of the system trough the German building authorities it was tested in full scale at the EMPA in Dübendorf, Switzerland [17]. In Greece Triantafillou [18] and Schwegler [19] are using CFRP laminates for the rehabilitation of seismic damaged historical buildings in the old part of the city of Patras. Schwegler is using the same method for the same purpose in Zurich, Switzerland [20]. The latest Italian venture is strengthening historical structures with advanced composites. CFRP laminates are used for the retrofitting of masonry vaults, slabs and walls [21].

Table 5: Costs for CFRP laminates including application in Switzerland (cross section: 50 mm by 1 mm; 70 Vol.-% Toray T700 Fibers)

Offer:	Price in US $
CFRP Laminate Grinded On One Side	16.- per m
CFRP Laminate Applied In Easy Going Situations *	85.- per m
CFRP Laminate Applied In Difficult Situations *	120.- per m

*including everything (CFRP-laminate, surface preparation, adhesive, all works, etc. based on Swiss labor costs)

The North Sea Oil Industry upgraded a wind wall to a blast wall on the Mobil operated Beryl B Platform using high strength, high modulus CFRP laminates. This work was part of the safety improvement plan that was a direct result of the Piper disaster and the subsequent legislation requiring safety cases to be prepared for each platform [22].

10. Applications in North America

Several prestressed, adjacent concrete box-beam bridges in the State of Delaware have developed longitudinal cracking on the bottom soffit of the beams. The cause of the cracking was a lack of transverse reinforcement on the bottom face of the precast, prestressed beams, built prior to 1973. Advanced composite materials were used to upgrade such a bridge north of Wilmington. The first in the US bridge rehabilitation field demonstration of carbon fiber tow sheet from Tonen Corp. was successfully conducted in October 1994 by Chajes and coworkers from the University of Delaware [23].

Another important pilot project was the repair of Interstate Highway 95 Bridge over route 702 in West Palm Beach, Florida by Shahawy, Ballinger and coworkers [24] early 1995. A truck traveling Eastbound on route 702 , hit the outermost bridge girder -a 25.9 m long AASHTO Type III prestressed girder. The truck hit caused a longitudinal torsion (twist) in the beam that resulted in two major cracks in the girder. Although the capacity of the girder to carry vehicle loads on the bridge was not substantially reduced, it was necessary to strengthen the beam against possible additional truck hits that could subsequently weaken the girder and the bridge. It was repaired with Mitsubishi Chemical Corporation's Replark carbon fiber sheet. Repair of the damage and strengthening of the prestressed concrete girder involved removal of broken and loose concrete, patching with a repair mortar, installation of the CFRP sheets and protection with a UV barrier paint. The repair was done over a period of a few nights, with a small work crew, with no impact on traffic flow on I-95 and relatively small cost.

11. Applications in Asia

The Japanese are applying carbon fiber laminates for structural strengthening in buildings since the late eighties. In summer 1992 this technique was used for the first time for the retrofitting of a bridge in Tokyo. The method has also here been proven to provide superior external reinforcement performance and potential cost advantages compared with conventional strengthening methods. The Japanese systems are mostly consisting of continuous carbon fiber tows formed into wide sheets adhered to a backing net and removable backing paper are impregnated in the field with epoxy resins. The composite of fiber and resin is adhered to the surface of concrete or masonry to reinforce the structures. The method has found widespread field application. There are over 200 installations to date in Japan alone. The Japanese method is different to the method mostly used in Europe [25]. There pultruded, cured laminates are adhered to the concrete surface. As long as the surface is even there should result no difference between this two methods. If the surface should be uneven, there will be a certain danger that laminates produced insitu follow the contour of the uneven concrete. Therefore exists a certain risk of peeling off the laminate after loading of the structure.

12. Composites For Structural Repair: A Fast Growing Research Field

Among 1992 and 1995 the annual number of publications has been more than tripled. Before 1992 there were not more than five groups working in this field. Today this number is approximately fifty. Especially Canadian teams [26-28] started to be very successful based on their Advanced Composite Materials in Bridges and Structures (ACMBS) Network. The lately announced new Network of Centers of Excellence (NCE) with a total budget of over twenty million Canadian $ will even accelerate Canadian research. It includes the project "Advanced composites and integrated sensing technology for structural rehabilitation". In the USA, Asia and Europe there exists not yet such a good networking like in Canada. In the domains of seismic strengthening of columns and masonry walls there are centers of excellence at the University of California in San Diego [29-30] and at the University of Arizona [31-32]. The Universities of Delaware [33] and South Florida [34] have a lot of competence in flexural strengthening of concrete, steel and wooden girders. The most important Asian contributions are from Japan [25]. In Europe there are research groups in England [35], France [36], Germany [37], Greece [38], Italy [39], Sweden and Switzerland [13-15].

Today's advanced composite materials could solve many of the worldwide rehabilitation problems. They are characterized by the following types of improvement: enhanced durability and service life; superior strength; resistance to corrosion, chemicals, and fatigue; initial and life-cycle cost efficiencies; ease of application; aesthetic and environmental compatibility and ability for structural control. There is an increasing demand for rehabilitation systems with the characterizations given above. Therefore more applied research will be needed. The urgent necessary maintenance work on infrastructure has dramatical implications on the economic life of a nation. Hence government agencies and industries will be ready to sponsor "useful" research. Consequently it will be more and more important that research projects do not end up only with papers and reports but have full scale demonstration projects. That is the most successful way to transfer knowledge from the universities to practice.

13. Concluding remarks

The future is advanced composites. This materials revolution predicted during the 1960s to take place by the turn of the century has, as expected, been more an evolution than a revolution. Confidence is very difficult to build in advanced composites in civil engineering but easily destroyed. Therefore it is essential to use pilot projects to be capable to learn from mistakes and to convince the owners of structures and the building authorities of the outstanding opportunities of composites for structural repair and retrofitting. Up to date there are over 700 field applications worldwide and there are not yet any failures known. The most important factor to remember is not the cost per kg of advanced composite materials, but rather the cost effectiveness of the rehabilitation of a structure, considering the life expectancy and the costs of the alternatives. Figure 3 gives a prediction of the future demand of CFRP for the external flexural post-strengthening with pultruded laminates.

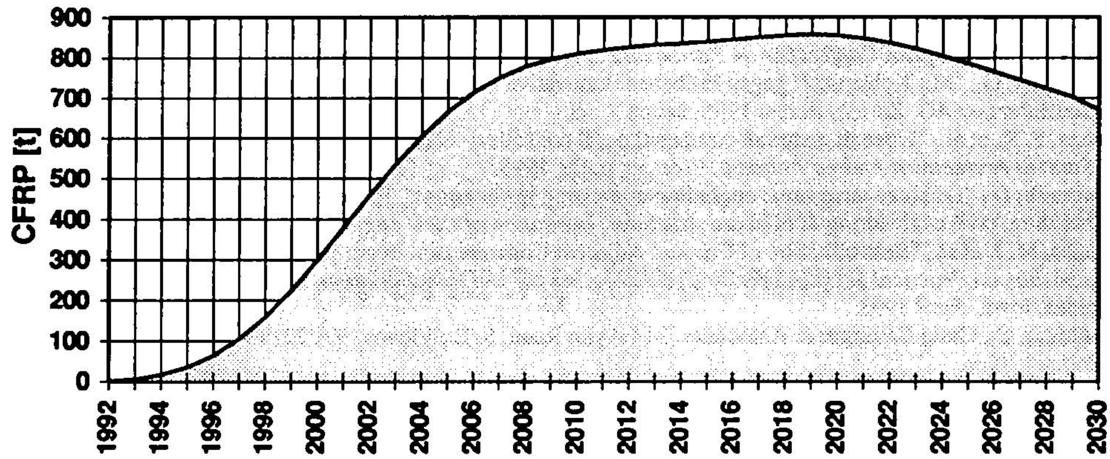


Fig. 3 Prediction of the worldwide demand of CFRP for external flexural post-strengthening

References

1. Ladner, M., Pralong, J., Weder, Ch., "Geklebte Bewehrung: Bemessung und Erfahrungen", *EMPA-Bericht Nr. 116/5*, CH-8600 Dübendorf / Schweiz, Eidgenössische Materialprüfungs- und Forschungsanstalt, EMPA, April 1990
2. Cantieni, R. and Egger, G. *EMPA-Reports 150'582* (in German), Swiss Federal Laboratories for Materials Testing and Research, CH 8600 Dübendorf, Switzerland, 1994.
3. Meier, U., "Bridge Repair with High Performance Composite Materials", *Material und Technik*, 1987, 15, 225-128 (in German and in French).
4. Deuring, M., "Verstärken von Stahlbeton mit gespannten Faserverbundwerkstoffen", *EMPA-Bericht Nr. 224*, 1993, (Post strengthening of Concrete Structures with Pre-stressed Advanced Composites, published by the EMPA in German as Research Report No. 224, CH-8600 Duebendorf/Switzerland.
5. Kaiser, H.P., "Strengthening of Reinforced Concrete with Epoxy-Bonded Carbon Fibre Plastics", Doctoral Thesis, Diss. ETH Nr. 8918, 1989 ETH Zürich, CH-8092 Zürich/Switzerland (in German).
6. Triantafillou, T.C., Deskovic, N. and Deuring, M.. "Strengthening of Concrete Structures with Prestressed Fibre Reinforced Plastic Laminates", *ACI Structural Journal*, 1992, 89, 235-244.
7. Meier, U., Deuring, M. Meier, H. and Schwegler G., "Strengthening of structures with advanced composites", *Alternative Materials for the Reinforcement and Pre-stressing of Concrete*, Edited by J. L. Clarke, 1993;
8. "Nachträgliche Verstärkung von Bauwerken mit CFK-Lamellen" (in German), SIA / EMPA Dokumentatiom D 0128, Editor: U. Meier, *Swiss Society of Engineers and Architects (SIA)*, Zürich, Switzerland, 1995.
9. Rostasy, F. S., Ranisch, E. H. and Alda, W., "Strengthening of prestressed concrete bridges in the region of working joints with coupled tendons by bonded steel plates", Part 1 (in German), *Forschung, Strassenbau und Strassenbautechnik*, Heft 326, Bonn 1980.
10. Rostasy, F. S. and Ranisch E. H., "Strengthening of prestressed concrete bridges in the region of working joints with coupled tendons by bonded steel plates", Part 2 (in German), *BMV-Forschungsbericht* Nr. 15,099, Bonn/Braunschweig, 1981.
11. Rostasy, F. S. and Ranisch E. H., "Strengthening of Reinforced Concrete Structural Members by Means of Bonded Reinforcement", *Betonwerk- und Fertigteiltechnik*, 1981, p. 6-11, 82-86.
12. Rostasy, F.S., personal communication.
13. Meier, U. and Deuring, M., "The application of fibre composites in bridge repair", *Strasse und Verkehr*, 77, 1991, page 775.
14. Meier, U. (1992). "Carbon Fibre-Reinforced Polymers: Modern Materials in Bridge Engineering", *Structural Engineering International*, 2, 7-12.

15. Meier, U. "Strengthening of Structures Using Carbon Fibre/Epoxy Composites", will be published in *Construction and Building Materials.*
16. Kempe, O.; "The stabilization of the gothic roof bearing structure of the Church of our Ladies in Meissen with CFRP-tension", *Techtextil-Symposium* 1995, Frankfurt, Presentation No. 541.
17. Esslinger, V. and Sauter, P., "Dachstuhlvorspannung mit CFK-Schlaufen, Frauenkirche Meissen" (in German), *EMPA Report No. 151'060*, March 1994.
18. Triantafillou, T. and Fardis, M., "Advanced Composites for Strengthening of Historic Structures", *IABSE Rome* 1993.
19. Schwegler, G., "Masonry Construction Strengthened with Fiber Composites in Seismically Endangered Zones", *10th European Conference on Earthquake Engineering*, Vienna Austria 1994.
20. Schwegler, G., "Mit Kohlenstoff gegen Erdbeben: Innovative Gebäudesanierungen", *Hauszeitschrift Basler&Partner AG, Zürich*, Herbst 1995, Seiten 7 .. 8.
21. Spena, F. R. et al., "L'uso di materiali compositi per il consolidamento delle strutore", *Centro Internazionale di Studi di Archtettura Andrea Palladio, Vicenza*, Italia, 1995.
22. Galbraith, D., "Offshore structures: upgrading of existing installations", Preceding of "Advanced composites in building, civil engineering & offshore structures, *Institution of Civil Engineers*, London 1995.
23. Chajes, M. J. et al., "Rehabilitation of Cracked Adjacent Concrete Box Beam Bridges, *Proceedings of the Symposium on Practical Solutions for Bridge Strengthening and Rehabilitation*, Sponsored by NSF, Des Moines, Iowa, April 1993.
24. Ballinger, C., Craig Ballinger & Associates, 314 Ayito Road, S. E., Vienna, VA 22180-5983, USA, personnel communication.
25. Nanni, A. "Concrete Repair With Externally Bonded FRP Reinforcement: Examples from Japan", Concrete International, June 1995, p. 23.
26. Erki, M. A. and Heffernan, P. J., "Reinforced Concrete Slabs Externally Strengthened With Fibre-Reinforced Plastic Materials", Non-metallic Reinforcement for Concrete Structures, edited by L. Taerwe, published in 1995 by E&FN Son, London, p. 509.
27. Erki, M. A. and Heffernan, P. J., "Equivalent Capacity- A Design Concept for FRP Strengthened Reinforced Concrete Beams", Ibid [26], p. 517.
28. Wight, R. G., Green, M. F. and Erki, M. A., "Post-strengthening concrete beams with prestressed FRP sheets", Ibid [26], p. 568.
29. Seible, F., Hegemier., G. A. et al., The U.S.-TCCMAR Full-Scale Five Story Masonry Research Building Test. University of California, San Diego, Reports No. SSRP-94/01 to 05, 1994.
30. Laursen, P. T., Seible, F., Hegemier., G. A. and Innamorato, D., "Seismic Retrofit and Repair of Masonry Walls with Carbon Overlays", Ibid [26], London, p. 616.
31. Saadatmanesh, H. "Wrapping With Composite Materials", Ibid [26], p. 576.
32. Saadatmanesh, H., Ehsani, M. R., and Li, M. H., Strength and Ductility of Concrete Columns Externally Reinforced with Fiber Composite Straps, ACI Structural Journal, Vol. 91, 1994, p. 434.
33. Chajes, M.J. et all., "Reinforcement of Concrete Structures Using Externally Bonded Composite Materials", Ibid [26], p. 501.
34. Sen, R. et all, "Strengthening Steel Composite Bridge Members Using CFRP Laminates", Ibid [26], p. 591.
35. Swamy, R. N. and Mukhopadhyaya, P., "Role and Effectiveness of Non-Metallic Plates in Strengthening and Upgrading Concrete Structures", Ibid [26], p. 472.
36. Varastehpour, H. and Hamelin, P., "Structural Behaviour of Reinforced Concrete Beams Strengthened by Epoxy Bonded Plates", Ibid [26], p. 559.
37. Rostasy, F. S. and Ranisch E. H., "Strengthening of R/C- and P/C-Structures with Bonded FRP Plates", Proc. of the First ACMBS Int. Conf., Sherbrooke, Canada 1992, p. 253.
38. Triantafillou, T. C. and Plevris, N., "Reliability Analysis of Reinforced Concrete Beams Strengthened with CFRP Laminates", Ibid [26], p. 576.
39. Arduini, M., di Tommaso, A. and Manfroni, O:, "Fracture Mechanisms of Concrete Beams Bonded with Composite Plates", Ibid [26], p. 483.