Structural Strengthening of Concrete with FRP Composites

David White, P.E.
Miklos Basler

Sika Corporation
201 Polito Avenue
Lyndhurst, NJ 07071

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Synopsis

It is becoming preferable, both environmentally and economically to upgrade bridges rather than to demolish and rebuild them. The deterioration of bridges from environmental influences and from traffic loads require rehabilitation and renewal programs to maintain even current service levels on the bridge infrastructure network. There are increased demands for high durability, longer service life, reduced maintenance cost and cost/performance optimization. Advanced Composite Systems have now become a viable method of strengthening existing bridges worldwide. This paper presents the evolution of carbon fiber systems since 1991, including relevant Test Reports for Bridge Engineering as well as their worldwide application.
Miklos Basler, now retired, was the Key Account & Business Development Manager for Structural Strengthening for Sika Services AG, Zürich, Switzerland. Miklos is a member of ACI and the Swiss Society of Engineers and Architects, fib Task Group 9.3 - FRP reinforcement for concrete structures and of the IABSE Working Commission 8: Maintenance and Repair of Structures. He holds a B.S.C.E. from the Faculty of Civil Engineering, University in Belgrade.

David White, P.E. is the Director of Technical Services for Sika Corporation, Lyndhurst, NJ, USA. He is a voting member of ACI Committee 440, as well as Committees 503 and 548. David is also active in the International Concrete Repair Institute Strengthening Committee and the American Segmental Bridge Institute. He holds a B.S.C.E. from Columbia University in New York and an M.S.C.E. from Polytechnic University in Brooklyn, N.Y.
1. Introduction

In today’s world, construction engineers are faced more and more frequently with the task of strengthening existing Bridges in order to secure or even increase their load bearing capacity. Many different strengthening techniques are available, such as installing additional steel, external post-tensioning, bonded reinforcement, increasing the concrete cross-section, etc. The use of bonded steel plates has been used successfully since the late 1960’s. External plate bonding is a method of strengthening which involves adhering additional reinforcement to the external faces of a structural member.

As a result of extensive research and development projects at the Swiss Federal Laboratories for Materials Testing and Research (EMPA), Dübendorf, Switzerland it was proven that the use of steel plates can be replaced with composite materials. The high-strength Carbon Fiber Reinforced Polymer (CFRP) plate system was applied for the first time outside the laboratory in 1991 for strengthening the Ibach Bridge in Lucerne, Switzerland.

In virtually all applications for bridge strengthening, advanced composite systems have been proven to be structurally efficient, easy to handle and install on job site, and cost competitive when compared to other conventional strengthening methods.

Why do bridges need strengthening?

There are many reasons why it may be necessary to strengthen bridges. These include:

- Corrosion of reinforcement
- Modified Codes and Standards
- Inadequate structural design
- Corrosion of pre-stressing cables
- Increased permanent and traffic loads
- Seismic retrofitting
What do we achieve by adopting this Technique?

In adopting the technique of advanced composites systems it is possible to:

– Increase the flexural strength
– Increase the shear strength
– Increase the seismic resistance
– Increase the confining strength

Advanced composite systems are comprised of fibers (typically carbon, glass, or aramid) and resins (typically epoxy resins). Only long term tested (fatigue resistant) and approved systems should be recommended for strengthening purposes in Bridge Engineering.

2. CRFP Plate Systems

2.1 System components

2.1.1 CFRP plates

The CFRP plates consist of individual carbon fibers, each having a diameter of approximately one five thousandth of a millimetre. The fibres are aligned longitudinally and manufactured using the pultrusion process. CFRP plates exhibit linear elastic behaviour up to the point of failure. Using different carbon fibers allows plates to be manufactured with different material properties.

<table>
<thead>
<tr>
<th>Table 1 Material properties of CFRP plates</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-modulus (N/mm²)</td>
</tr>
<tr>
<td>---------------------</td>
</tr>
<tr>
<td>Standard (S) Modulus</td>
</tr>
<tr>
<td>Medium (M) Modulus</td>
</tr>
<tr>
<td>High (H) Modulus</td>
</tr>
</tbody>
</table>

The chemical resistance of CFRP plates against pollutants is very good. The carbon fibers and the epoxy matrix have long-term resistance against concrete pore water, de-icing salts and hydrous acid solutions. CFRP plates are available in different widths between 50mm to 150mm and thickness of 1.2mm to 1.4mm. CFRP plate systems are particularly suitable for flexural strengthening, in-situ rehabilitation as well as for pre-stressing.

![Fig. 1 - Typical Stress-strain diagram](image)
2.1.2 Epoxy adhesive

Two component epoxy resin systems are well suited for the bonding of CFRP plates to concrete, steel, wood or masonry. This type of adhesive has very high mechanical strengths as well as good chemical resistance against aggressive media. Good wetting properties on concrete, wood, etc., ensure good bond characteristics.

The main function of the adhesive layer is to transfer the forces between the composite material and the substrate, such that they will act monolithically.

The following properties are important for high strength structural bonding:

- High bonding strength
- Low creep
- High cohesive strength
- Good resistance against humidity and alkalinity

3. Relevant Test Reports

Before strengthening of bridges or structures exposed to dynamic load with advanced composite systems, two basic questions need to be answered. They are:

1) What is the influence on the load-bearing capacity of structure exposed to dynamic and vibrating loads during cure of the structural adhesive?
2) What is the influence on the load-bearing capacity of structure exposed to fatigue loading during the life span of the structure?

To answer these questions Sika commissioned the Swiss Federal Laboratories for Material Testing and Research (EMPA), Dübendorf with the objective of investigating the above-mentioned influences.

3.1 Bonding of CFRP plates under oscillating load

Tests were performed in two phases on pre-stressed concrete slabs with a span of 3.8m and a thickness of 18cm. In the first phase, CFRP plates were applied under dynamic loads. In the second phase, these strengthened specimens were subjected to static loading until failure. See EMPA test reports.

Fig. 2 - EMPA Test set-up

Fig. 3 - CFRP plates debonding
Table 2 Test results

<table>
<thead>
<tr>
<th>Test Specimen</th>
<th>F_{br} [kN]</th>
<th>Y_{br} [mm]</th>
<th>\varepsilon_{br} %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specimen 1</td>
<td>161</td>
<td>70</td>
<td>6.61</td>
</tr>
<tr>
<td>Curing without oscillation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specimen 4</td>
<td>176</td>
<td>75</td>
<td>6.55</td>
</tr>
<tr>
<td>Curing with oscillation</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

F_{br} : Ultimate / Failure load
Y_{br} : Mid-span deflection
\varepsilon_{br} : Strain in CFRP at delamination

There was little difference in the load-bearing capacity, mid-span deflection and strain in the CarboDur at debonding of test specimens with or without oscillating loading during curing of Sikadur adhesive. Therefore, bridges can remain open to traffic during application of CFRP plate system.

3.2 Fatigue and failure test

Tests were performed on a standard EMPA T-beam with a span of 6.0m subjected to a four point bending test. All test beams, BO, T2, B1 and B2 had identical steel reinforcement and the beams T2, B1 and B2 received an identical CFRP strengthening. The fatigue test subjected beams B1 and B2 to 5 million loading cycles prior to proceeding to ultimate loading. See EMPA test report [2] and Ph.D. thesis [3].

![Fig. 4 - EMPA Test set-up](image)

![Fig. 5 - B1-Beam before Fatigue test](image)

![Fig. 6 - B1-Debonded CFRP plate](image)
Table 3 Static failure test results

<table>
<thead>
<tr>
<th>Test Specimen</th>
<th>( Y_{br} ) [mm]</th>
<th>( \varepsilon_{br} ) %</th>
<th>( F_{br} ) [kN]</th>
<th>Comparison ( F_{br} )%</th>
</tr>
</thead>
<tbody>
<tr>
<td>BO, reference beam</td>
<td>84</td>
<td>-</td>
<td>636</td>
<td>78</td>
</tr>
<tr>
<td>No fatigue test</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T2, with no fatigue test</td>
<td>83</td>
<td>9.15</td>
<td>815</td>
<td>100</td>
</tr>
<tr>
<td>B1/B2, with fatigue test</td>
<td>78</td>
<td>8.50</td>
<td>743</td>
<td>91</td>
</tr>
</tbody>
</table>

\( Y_{br} \): Mid-span deflection of beam  
\( \varepsilon_{br} \): Strain in CFRP plate at delamination  
\( F_{br} \): Ultimate load  

The comparison of the static failure test results showed a maximum 9% difference in the load-bearing capacity between identical specimens T2 and B1/B2 with and without a fatigue test, and between ultimate strain in CFRP plates at delamination.

4. Case Studies

4.1 Bridges in the Republic of Macedonia

In 1999, the 1st TMCA (Transport Movement Control Agency) of the US Army in Germany initiated the need for transportation of military equipment by means of HETS (Heavy Equipment Transport System) military vehicles having nine axles and a total weight under loaded conditions of 104.3 tons. The objective was to achieve conditions for safe crossing of loaded HETS military vehicles over the bridges on the National road M-2 between Kumanovo and the Bulgarian border.

On behalf of the US Army a Report on Structural Analysis of Bridges on M-2 was prepared by the Working Group TMCA / Bridges from the Faculty of Civil Engineering in Skopje. A total 20 bridges had insufficient loading capacity for the HETS and the US Army accepted the proposal of the Consultant to proceed with strengthening of these Bridges using CFRP plates as well as CFRP composite fabric systems.

The U.S. Army Corps of Engineers, Rock Island District under the leadership of Mr Mark R. Hoague, P.E. and Mr Mohamed M. Moussa, PhD, P.E, carried out the Design review.

Table 4 Basic Information

<table>
<thead>
<tr>
<th>Project stage</th>
<th>Total Bridges</th>
<th>CFRP Plates [m]</th>
<th>CFRP Fabrics [sqm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase 1</td>
<td>20</td>
<td>15,000</td>
<td>1,300</td>
</tr>
<tr>
<td>Phase 2</td>
<td>10</td>
<td>10,000</td>
<td>700</td>
</tr>
<tr>
<td>TOTAL</td>
<td>30</td>
<td>25,000</td>
<td>2,000</td>
</tr>
</tbody>
</table>
The objective was to verify the model used by the Consultant for the bridge analysis, to check and verify the results of the analysis and design due to loaded HETS vehicle and to confirm the efficiency of the CFRP plates for bridge strengthening. In addition, load testing was performed to confirm the performance of the system. Tests were made on bridges before and after strengthening with the Composites, measuring stresses in re-bars, concrete, CFRP plates as well as vertical deflection of bridges.
Conclusions from the Test Program

The measured strains (stresses) and displacements in the strengthening conditions were typically smaller than corresponding ones for the unstrengthened condition. The measured strains in the strengthened condition follow Hooke’s Law and Bernoulli’s principle.

The test results proved that the proper behaviour of the bridges is in accordance with the applied Design Approach and that the increased load bearing capacity under service conditions up to the level of anticipated influences due to HETS, is appropriate without any restriction of limitation in regular traffic flow.

4.2 The Narrows Bridge, Perth Western Australia

Built in 1960’s the Narrows Bridge connects the Perth central business district with the southern Suburbs of the city. Due to the increased traffic loads, the main girders of this prestressed concrete continuous I-beam bridge did not have sufficient load-bearing capacity.

Length: 55.0 + 70.0 + 110.0 + 70.0 + 55.0 = 360.0 m

Width: = 16.0 m

Solution

Strengthening of each main girder with 6 CFRP plates, with a maximum length of 55.0 m. The applied CFRP plates were protected from UV light with a pigmented, water-based, acrylic coating.
4.3 The Katerini Bridge, Greece

One of the first prestressed concrete bridges in Greece, the Katerini Bridge was built in 1960 and is situated on the National Road Thessaloniki-Katerini. Due to increased permanent and traffic loads the prestressed main girders had insufficient flexural load-bearing capacity.

Length: \(35.0 + 35.0 + 35.0 = 105\) m
Width: \(= 12\) m

Bonding CFRP plates to the soffits increased the flexural strength of the 28m main girders. Using a special heating device, the epoxy resin was accelerated to cure in four hours.

Fig. 14 - View
Fig. 15 - Cross Section
Fig. 16 - Application of epoxy resin
Fig. 17 - Applied CFRP plates
5. Conclusions
As a result of intensive theoretical investigations, research, and laboratory testing, the strengthening of Bridges with advanced composites has now become a state-of-the-art technique in the construction industry. Carbon fiber systems are now being used more and more for bridge strengthening. Their excellent long-term resistance, high corrosion resistance and ease of installation offer unparalleled advantages to the bridge engineering marketplace.

6. Acknowledgement
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Special thanks are expressed to Mr Mark R. Hoague, P.E. and Mr Mohamed M. Moussa, PhD, P.E. from USACE, Rock Island District, Illinois for their efficient co-operation during the whole project development.

7. References