BRIDGE STRENGTHENING WITH ADVANCED COMPOSITE SYSTEMS

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Summary

It is becoming preferable, both environmentally and economically to upgrade bridges rather than to demolish and rebuild them. Deterioration of bridges wear from environmental influences and from traffic loads require rehabilitation and renewal programs to maintain even current service levels on the bridge infrastructure network. Demands for high durability, longer service life, reduced maintenance cost and cost/performance optimised. System solution have prompted a new look at Advanced Composite Systems. This paper presents the evolution of CarboDur Composite Systems from its start in 1991, relevant test reports for bridge engineering as well as their world-wide application.

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 its load bearing capacity. Many different strengthening methods are available, such as adding of unstressed or pre-stressed steel, installation of external pre-stressed reinforcement, bonded reinforcement, increase of the concrete cross-section etc. Since 1967 it has been possible to increase the bending resistance of existing reinforced structure by bonding steel plates. External plate bonding is a method of strengthening which involves adhering additional reinforcement to the external faces of a structural member.

Thanks to intensive research and development projects at the Swiss Federal Laboratories for Materials Testing and Research (EMPA), Dübendorf, Switzerland it was possible to replace the heavy steel plate with light composite materials. High-strength CarboDur CFRP plate system was applied the first time outside the laboratory anywhere in the world in 1991 for strengthening the Ibach bridge at Lucerne, Switzerland.

In all the applications in Bridge Strengthening Advanced Composite Systems have been shown to be structurally efficient, easy for handling and install on job site and to be cost competitive with other conventional strengthening systems and procedures.

Why do bridges need strengthening?

There are many reasons why it may be necessary, not all due to deterioration. This is likely to arise from one or more following reasons:

– Corrosion of reinforcement
– Modified Codes and Standards
– Inadequate structural design
– Others
– Corrosion of pre-stressing cables
– Increased permanent and traffic loads
– Seismic retrofitting

What do we achieve by adopting the Technique?

In adopting the technique of Advanced Composites Systems it is possible to:

– Increase the flexural strength
– Increase the seismic resistance
– Increase of the flexural rigidity
– Increase the shear strength
– Increase the durability
– Others

Advanced Composite System is composed by FRP Composite and an appropriate adhesive, mostly epoxy based. Only long term tested (Fatigue resistance) and approved systems should be advised for strengthening purpose in Bridge Engineering.

2. CarboDur CRFP Plate Systems

2.1 System components

2.1.1 CarboDur CFRP plates

The CarboDur plates consist of carbon fibres with a diameter of one five thousandth of a millimetre. The fibres are aligned lengthways parallel by pultrusion and bonded together with epoxy resin. CarboDur plates have linear elastic behaviour up to the point of failure. Using different carbon fibres allows to manufacture plates with different material properties.

Table 1 Material properties of CarboDur CFRP plates

	E-modulus **N/mm^2**	**Tensile strength** **N/mm^2**	**Elongation at break** **%**
CarboDur S	165'000	2'800	> 1.7
CarboDur M	210'000	2'800	> 1.35
CarboDur H	300'000	1'350	> 0.45

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

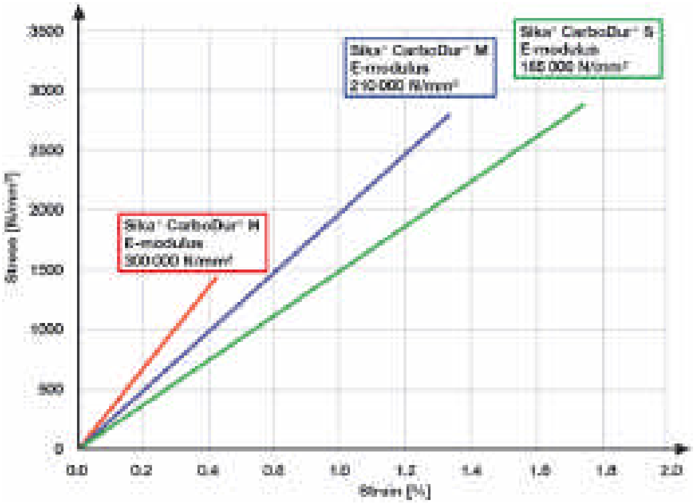


Fig 1 Stress-strain diagram

2.1.2 Sikadur-30 epoxy adhesive

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

The function of the adhesive layers is above all to transfer the forces acting onto the joined elements. Of particular importance is the elimination resp. the reduction of stress peaks. The more a layer of adhesive is able to level such stress peaks, the greater the load transferring portion of the bonded are will be.

The following properties are important for high strength structural bonding:

- High bonding forces onto elements to be joined
- Low tendency to creep
- High cohesive strength of the adhesive
- 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 have to be answered. They are:

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

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

3.1 Bonding of CarboDur CFRP plates under oscillating load

Tests were performed in two phases on pre-stressed concrete slabs with span of 3,80m and thickness of 18cm. In the first phase CarboDur plates were applied under dynamic loading in the second phase, these strengthened specimens were subjected to static loading till failure. See EMPA test reports [1].

Fig 2 EMPA Test set-up

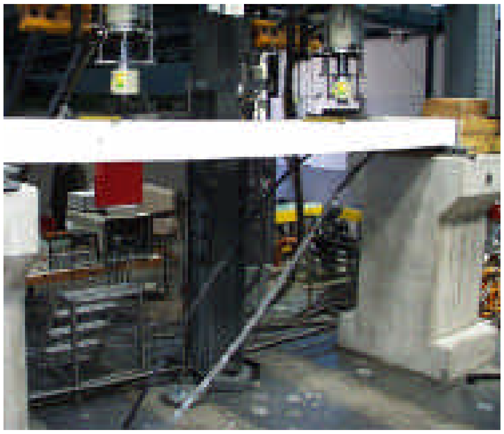


Fig 3 Failure-CarbuDur debonding

Table 2 Test results

Test Specimen	F_{br} [KN]	Y_{br} [mm]	ε_{br} $^0/_{00}$
Specimen 1 Curing **without** oscillation	161	70	6.61
Specimen 4 Curing **with** oscillation	176	75	6.55

F_{br} : Ultimate / Failure load

Y_{br} : Mid-span deflection

ε_{br} : Strain in CarboDur at delamination

There is no difference in the load-bearing capacity mid-span deflection and strains in CarboDur at debonding of test specimens without or with oscillating loading during curing of Sikadur adhesive. Therefore bridges can remain open to traffic during application of CarboDur CFRP plate system.

3.2 Fatigue and failure test

Test were performed on standard EMPA T-beam, span of l=6.00m and with four points bending test. All test beams, BO, T2, B1 and B2 have identical steel reinforcement and the beams T2, B1 and B2 received an identical “CarboDur strengthening”. The fatigue test consisted in exposing the beams B1 and B2 to 5 million loading cycles prior to proceeding to failure test. EMPA test report [2] and Ph.D. thesis [3].

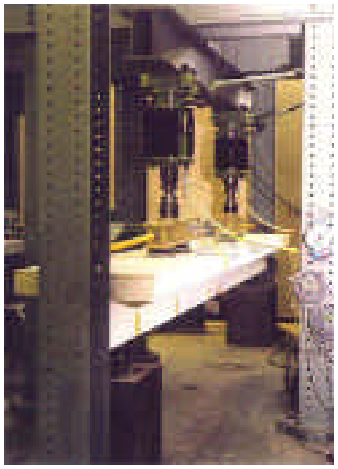


Fig 4 EMPA Test set-up

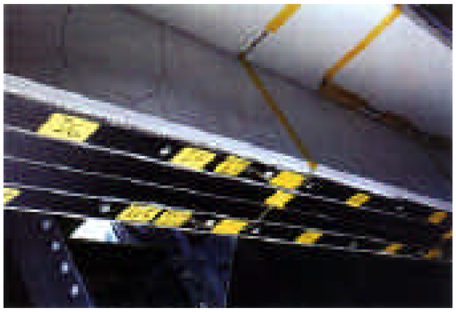


Fig 5 B1-Beam before Fatigue test

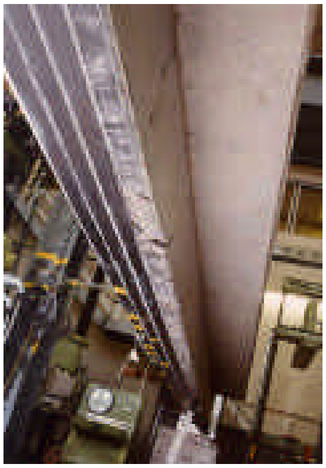


Fig 6 B1-Debonded CarboDur plate

Table 3 Static failure test results

Test Specimen	Y_{br} [mm]	ε_{br} ‰	F_{br} [KN]	Comparison F_{br} %
BO, reference beam No fatigue test	83.90	-	636	78
T2, **with no** fatigue test	83	9.15	815	100
B1/B2, **with** fatigue test	78	8.5	743	91

Y_{br} : Mid-span deflection of beam
ε_{br} : Strain in CarboDur at delamination
F_{br} : Ultimate load

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

Structures, such bridges where a fatigue resistance is one of the basic requests can be strengthened with CarboDur CFRP plate system.

4. Case Studies

4.1 Bridges in Republic of Macedonia
Client: US Army - Europe

In 1999, the 1st TMCA (Transport Movement Control Agency) of the US Army in Germany has 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 in loaded conditions of 104.3 tons. At this first stage, it was particularly emphasised the question for establishing the possibilities, way and 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 has been prepared by Working Group TMCA / Bridges from the Faculty of Civil Engineering in Skopje. Total 20 bridges had insufficient load capacity for the HETS and the US Army accepted the proposal of the Consultant to proceed with strengthening of these Bridges with CarboDur CFRP plate as well as with SikaWrap FRP composite fabrics systems.

The Design review was carry out by the US Army Corps of Engineers, Rock Island District.

Table 4 Basic Information

Project stage	Total Bridges	CarboDur Plates [m]	SikaWrap fabrics [sqm]
Phase 1	20	15000	1300
Phase 2	10	10000	700
TOTAL	30	25000	2000

Below are given arrangement of CarboDur composites on typical bridges on M-2 and relevant details on application from the job site.

Fig 7 Bridge B26

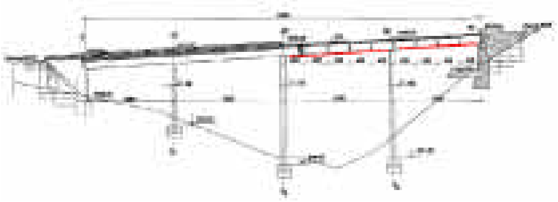


Fig 8 Bridge B39

Fig 9 Bridge B36

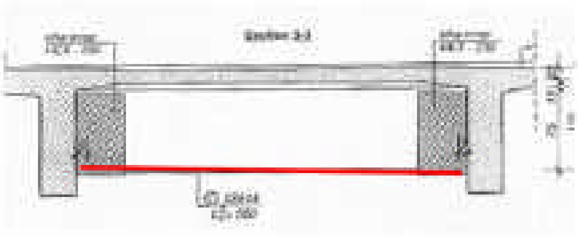


Fig 10 Bridge B7 Cross Beam

Fig 11 B7 Application on site

Fig 12 B7 Applied Systems

With objective to verify the model used by the Consultant for the bridge analysis, to check and verify results of the analysis and design due to loaded HETS vehicle and to confirm the efficiency of CarboDur FRP Composite Systems for Bridge Strengthening on request of the US Army load tests were performed with the HETS. Test were made on bridges before strengthening as designed and constructed and after strengthening with CarboDur Composites, measuring stresses in re-bars, concrete, CarboDur as well as vertical deflection of bridges.

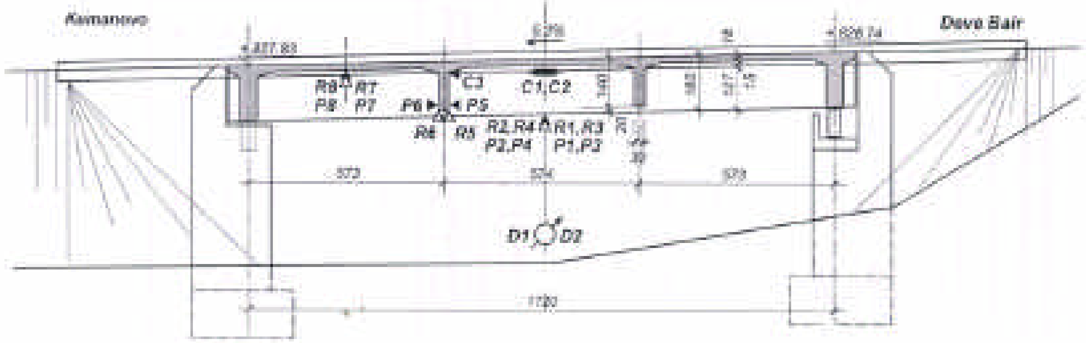
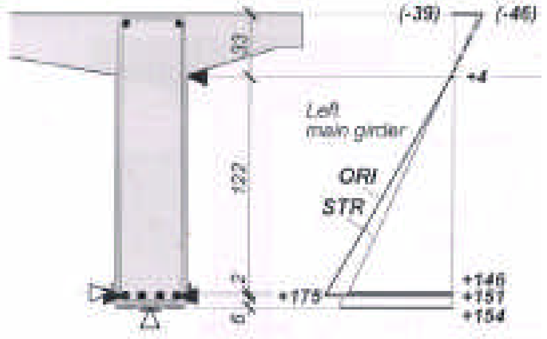


Fig 13 Bridge B37 – Testing instruments



Main girder - Strains

ORI: Before strengthening

STR: After strengthening

Fig 14 Bridge B37 – State of Strain

Conclusions & Findings of the Trial Testing

The measured strains (stresses) and displacements in strengthening conditions are without any exception smaller than corresponding ones for unstrengthened condition and the measured strains in strengthened condition follow the Hook's law and principle of Bernoulli and the measured dynamic coefficient is very close to those according to DIN 1072.

Taking into consideration the results of tests it is obvious that they proved that the proper behaviour of the bridges is in all accordance with the applied Design Approach and that the increased load bearing capacity in service conditions up to the level of anticipated influences due to HETS, without any restriction of limitation in regular traffic flow.

Beside that trial testing of bridges proved the justification of the investment by the US Army, the Design for strengthening prepared by the Working Group TMCA / Bridges, the good performance of works for strengthening by the Contractor as well as the efficiency of CarboDur FRP Composites for Bridge Strengthening.

4.2 The Ljubljana river Bridge, Slovenija

Cable-stayed bridge on Highway 10, Sentjakob-Malence, Slovenija with two spans of L=2x41.0=82.0m, pre-stressed concrete bridge deck, thickness 400-600mm and width of 30.0m.

Fig 15 Heavy Truck on Bridge

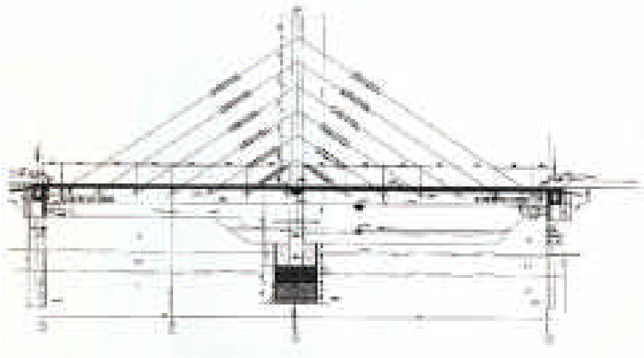


Fig 16 Longitudinal section

Designed for traffic load according to DIN 1072, SLW600 the construction of the bridge was completed in 1995. To allow the crossing of the bridge for a truck with the equipment for the Krsko Nuclear Power Plant it was necessary to increase a flexural strength of the bridge deck by bonding on the bottom side CarboDur CFRP plates in both directions.

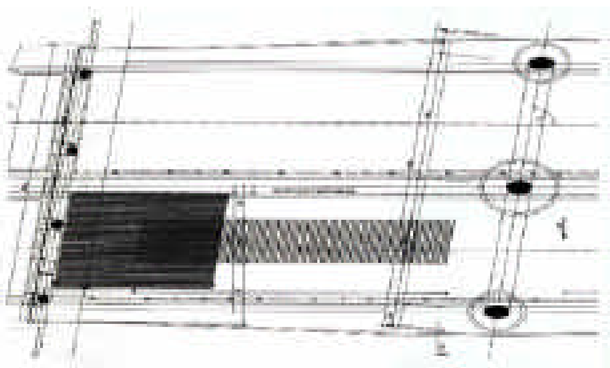


Fig 17 Distribution of CarboDur plates

Fig 18 Applied CarboDur plates

4.3 The Göksu & Karababa Bridges, Turkey

After accomplishing the concrete of barrage at the Batman Hydraulic Power Plant and before starting installation of complex mechanical equipment the following difficulty occurred: how to transport this heavy equipment with a total weight of 270 tons on Bozova-Adiyaman road connecting the Mediterranian sea harbour with the power plant.

The investor awarded a consultant to investigate on load-bearing capacity of bridges and to propose solutions if necessary to carry out this exceptional heavy transport. Two major bridges have had not sufficient load capacity and the consultant proposed to strengthen these bridges with Advanced Composite Systems.

Table 5 Project Information

Project stage	Total Bridges	CarboDur Plates [m]	SikaWrap fabrics [m^2]
TOTAL	2	6250	3765

4.3.1 The Göksu Bridge

The structural system in longitudinal direction is a continuous beam composed by pre-stressed concrete I-beams with 12 spans of L=12x20.00=240m. and width of B=9.70 m. To reach the requested flexural strength in the field and shear near supports the main girders were strengthened with CarboDur CFRP plate system resp. SikaWrap Fabric system.

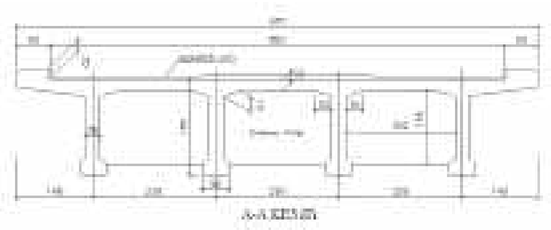


Fig 19 Cross Section Göksu Bridge

Fig 20 Strengthened Göksu Bridge

4.3.2 The Karababa Bridge

Identical problems as with Göksu bridge were stated for Karababa Bridge: i.e. insufficient flexural strength in the fields and shear strength near supports for the main girders. The structural system in longitudinal direction is a continuous beam composed by prestressed concrete T-beams with 15 spans of L=15x17.5=262.5m. and width of B=11.00m. In order to increase the flexural strength in fields and shear strength near support of main girders CarboDur CFRP plate system and SikaWrap Carbon Fabric system were applied.

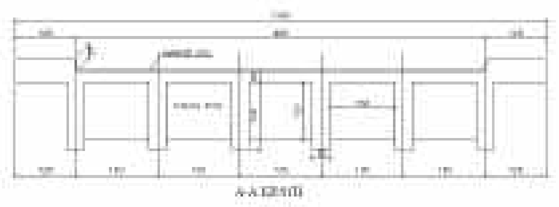


Fig 21 Cross Section Karababa Bridge

Fig 22 Strengthened Karababa Bridge

The strengthened bridges could be handed over to the client 5 weeks after the contract had been awarded. To everyone's satisfaction, the heavy turbine could pass over the bridges few days later.

Fig 23 HETS before Bridge Passing

Fig 24 Heavy Transport on Karababa Bridge

5. Conclusions

Thank intensive theoretical investigations, research works and tests in laboratories strengthening of Bridges with Advanced Composites became world-wide a State-of-the-Art in construction industry.

Because of their outstanding properties CarboDur CFRP plate systems are used more and more for bridge strengthening works. Their excellent long-term resistance, high corrosion resistance and the efficient way of application, including of pre-stressing with cost/performance optimised systems are advantages outweighing the relatively high costs of materials.

6. References

[1] EMPA Test Reports 170’569e-1, 418931E and 418931E/1. Sika CarboDur Structural Strengthening Systems. Bonding of CFRP plates under dynamic load. Static testing of pre-stressed narrow slabs post-strengthened with CFRP strips. Dübendorf, 1998 and 2001.

[2] EMPA Test Report 402’017E/2: Sika CarboDur Structural Strengthening Systems. Fatigue and Failure Test. Test beams B1 and B2, Dübendorf 1999.

[3] DEURING M., “Verstärken von Stahlbeton mit gespannten Faserverbundwerkstoffen”, Ph.D. Thesis