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Time Depending Thermo Mechanical Bond Behavior of Epoxy Bonded Pre-Stressed FRP-Reinforcement

by K. Borchert and K. Zilch

Synopsis: The development of different pre-stressed epoxy bonded CFRP-reinforcement systems for retrofitting RC-structures continues. In addition to requirements concerning the ultimate limit state (ULS) pre-stressed systems could satisfy demands in regard to the serviceability state (SLS) like crack limitation or fatigue. In comparison with the well known material behavior of concrete under sustained loading epoxy resins show material properties more sensitive to thermal effects, for example loss of strength or creep deformations. In experimental tests the influence of permanent load and temperature is examined. The pure epoxy resin adhesive was evaluated in lab-shear tests and the structural behavior of the system in the form of epoxy bonded pre-stressed near surface mounted CFRP-strips. The experiments reveal a significant influence of the epoxy resin adhesive behavior on the long-term structural behavior in service. To evaluate the effects with regard to designs relevant problems as long-term development of transfer lengths of pre-stressed reinforcement or of the slip between reinforcement and concrete under varying load and thermal conditions results of a simulation model are presented.

Keywords: CFRP reinforcement; creep; epoxy resin; long-term behavior; pre-stressing; SLS; strengthening; sustained load; temperature

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RESEARCH SIGNIFICANCE

Epoxy bonded pre-stressed FRP-strengthening systems could often accomplish the requirements more efficiently and reasonably than non pre-stressed FRP reinforcement. Pre-stressed near surface mounted CFRP-reinforcement holds a bond behavior that allows the abdication of mechanical anchors. The performance of pre-stressed NSM depends directly on the properties of the epoxy resin (Blaschko and Zilch 1999). Hence the time depending thermo-mechanical material behaviour of the adhesive is decisive for a long-lasting design. In order to examine the influence of the epoxy resin on the performance of pre-stressed NSM long-term tests on the pure adhesive, the system and the results of a simulation model are shown.

INTRODUCTION

The increasing demands on existing concrete-structures lead to enhanced strengthening methods. These methods have to meet requirements in ultimate limit state (ULS) and additionally in service ability state (SLS). In recent years the bonding of carbon fiber reinforced polymers CFRP by epoxy resins has shown to be an appropriate method. In many cases the existing needs can be fulfilled more effectively and economically by applying pre-stressed CFRP-reinforcement, for example fatigue problems.

Due to the brittle bond behavior of pre-stressed CFRP laminates bonded to the surface of RC structures a mechanical anchorage is required. In contrast pre-stressed near surface mounted reinforcement provides a remarkable ductile bond characteristic, that the CFRP-strips can be anchored only by adhesive. Pre-stressed reinforcement causes significantly elevated permanent bond-stresses. Hence the epoxy resin is exposed to long-term stresses. In comparison to concrete the material properties of epoxy resins are strongly depending on time and temperature. In series the time depending thermo-mechanical material behaviour of the epoxy resin has to be taken into account for a safe and durable performance of the retrofitting system. In case of strengthening existing RC members with epoxy bonded pre-stressed FRP reinforcement the long-term developments of the stress distribution along the bond length, of required transfer lengths and of the slip between reinforcement and concrete have to be known.

This paper reports on experimental long term tests on the temperature depending thermo-mechanical properties of epoxy resins and their influences on the system performance of pre-stressed near surface mounted CFRP-strips – pre-stressed near surface mounted CFRP-strips are patented by the Bilfinger Berger AG. Results of a simulation model are presented.

MATERIALS AND STRENGHTENING SYSTEM

In the following the basic material properties of epoxy resin adhesives and the principle structural behavior of near surface mounted CFRP-strips are described.

Epoxy Resin Adhesives

Epoxy resin adhesives belong to the organic binders (plastics) and are recognized as a cast-in-place adhesive featuring remarkable functionality. It is possible to obtain adhesive joints with excellent cohesion and outstanding adhesion to nearly all kinds of substrates. For strengthening cold curing, two part liquids with low shrinkage on curing are normally used. The curing step transforms the two liquids to a highly cross-linked space framework by a polyaddition reaction. Epoxy resins can be formulated to meet various specifications and use criteria. Usually aggregate fillers are added to the resins to control the mechanical properties like strength or creep. Epoxy resin adhesives show a distinctive visco-elastic material behavior.

One of the most important technological aspects of adhesive joints is their durability under long-term loading and environmental conditions. A short term test does not yield information on the maximum long-term load capacity nor is it possible to predict the performance of a joint during service exposure to elevated temperature or significant permanent loads. In practice a few compromises must be made. Not all mechanical demands can be simultaneously met with one epoxy system. Because the performance of epoxy resins is dependent on environmental conditions, it is helpful to classify primarily decisive properties (Hugenschmidt 1974). Primarily critical for the endurance is the long-term behavior in service like enduring strength, creep or influence of field temperature and a relative insensitivity to incorrect mixing ratio. Not primarily decisive for the durability is the reactivity and the short term mechanical strength. At room temperature the long term strength of epoxy resin adhesives is assumed to be between 50% and 70% of the short-term ultimate load (Habenicht 1986). For structural bonding often the lower limit value of 50% is recommended (Rehm and Franke 1982).

With rising temperatures the material behavior of epoxy resins changes noticeably at the glass transition temperature T_g (Fig. 1). At the T_g the resin leaves the glass state and reaches a state with rubber-like properties. The T_g is the critical point for all cold-curing binders, not only for epoxy resins. With reaching the glass transition zone the strength and the elastic-modulus fall significantly (Fig. 2). The T_g is the maximum service temperature for structural bonding using an epoxy resin (Habenicht 1986).

Common cold-curing epoxy adhesives show a T_g about 55°C (131°F) in the first heating. Below the T_g the short-term behavior for small loadings can be assumed as linear-elastic. For increasing or permanent loads the linear or non-linear visco-elastic behavior has to be accounted.

One of the most important properties is the creep deformation of the resin. It can be assumed that, at room temperature, the ultimate creep rate of highly cross-linked epoxy-systems is about three to four times as high as that of the concrete (Hugenschmidt 1974). Concerning creep the T_g is not the only decisive parameter. About 20°C below the glass transition the micro-brown movements of the molecules start in the epoxy bulk. Through this all time-depending effects like the loss of strength or creep accelerate (Letsch 1983). So the maximum long-term load capacity at elevated temperatures is reached after a period of about 700 h – 1000 h (Rehm and Franke 1982).

As shown, the mechanical behaviour of epoxy resins is greatly time and temperature dependent. In cases of significant long-term stresses in the adhesive layer the thermo mechanical behavior has a direct influence on the structural performance of the retrofitting system. Therefore it has to be accounted for a safe and durable design.

Near Surface Mounted CFRP-Reinforcement

The method consists in gluing CFRP-strips into grooves in the existing concrete cover (Fig. 3). The strips are between 1 to 2.5 mm in thickness and about 15 mm - 20 mm in width surrounded by an about 1 to 2 mm thick adhesive layers (Blaschko 2003).

The failure modes of NSM reinforcement are depending from various parameters. If the bonded area is long enough, the CFRP-strips fail in tension. Due to the ductile bond behaviour the complete tensile strength of the strips can be anchored at a single crack. If the slits are too close to the concrete edge the concrete corner could split off. In all other cases the bond fails inside the adhesive layer (Blaschko 2001, Blaschko and Zilch 1999, De Sena Cruz and de Barros 2004, fib 2001). In figure 4, an experimental bond stress-slip relationship is shown. Typical for NSM reinforcement are the obviously increased bond stresses in comparison with externally bonded reinforcement (EBR) and the activated friction shear stresses at large slips. The bond stress-slip relationship is affected by the deformations of the concrete perpendicular to the strip. These deformations create lateral pressure or tension in the adhesive.

Blaschko developed a conclusive bond model by combining the differential equation of the shifted bond, the differential equation of the elastic supported girder – to take the concrete deformations into account – with a failure criterium with integrated friction model for the adhesive (Blaschko 2001). On the basis of this model the measured distribution of the tensile force in the CFRP strip along the bond length and the bond capacity were ascertainable.

The ultimate load of near surface mounted CFRP-strips and is primary dependent on the properties of the epoxy resin. The method of strengthening with pre-stressed near surface mounted CFRP-strips is patented by the Bilfinger Berger AG.

EXPERIMENTAL TESTS

To examine the influence of the epoxy resin to highly-stressed adhesive bonded reinforcement two test series were conducted. In a first series, long term lap-shear tests at variable temperatures and load levels were performed to examine strength and creep processing of the epoxy resin. The second series consisted of pre-stressed NSM CFRP-strips, that were exposed between room temperature and about 5° below the glass-transition temperature T_g of the resin. For the tests the highly filled epoxy resin MC-DUR 1280 from the MC-Müller Bauchemie; Bottrop (Germany) was used. This adhesive is approved for the strengthening of RC structures with NSM and EBR in Germany (DIBt 2004).

Long-term lap shear tests

The creep properties of the highly-filled epoxy resin adhesive were tested with long-term steel lap-shear tests (Fig. 5) under varied loads and thermal conditions. The test parameters are shown in table 1. The test set up should guarantee a nearly constant stress distribution in the adhesive layer. Hence the pure epoxy performance was tested. The tests started after a curing period of 72 h at room temperature. The results affirmed the typical creep behavior of epoxy resins.

For 20°C (68°F) an enhancement of load from 15% to 80% of the long term ultimate load causes non-linear creep. After a period of about 5000 h the creep modulus ϕ at 80% was two times higher in comparison to a load level of 15%. Also at a constant load level of 15% the creep modulus raises with rising temperatures. After 5000h in 38°C (100°F) it was about 2.5 times higher and approximately 4.0 times higher after 3400h in 50°C (122°F) as the corresponding value in 20°C (68°F).

For 50°C (122°F) the elastic short-term value of the displacement was increased. This bigger deformations results from the starting reduction of the short-term stiffness of the epoxy resin in the range of the T_g.

Pre-stressed NSM Reinforcment tests

The influence of the epoxy resin on the system behavior of pre-stressed NSM CFRP reinforcement was examined with test specimens shown in figure 6 and 7. The test parameters and the material properties are displayed in table 1 and 2. The strips were subjected to pre-stressing force of 60% of the bond capacity corresponding with a bond length l_b of 100 mm – this caused a strain about 4.2‰ or stress of 714 MPa in the strip. After a curing for 24h the temporary anchorages were removed and from that time on the bond was only guaranteed by the adhesive. Another 70h to 100h later the temperature exposition started. The loss of pre-stress was detected by strain gauges in the bondless length between the two bond areas. Additional strain gauges were assembled on the strips along the bond length l_b in the case of the specimen with l_b = 450 mm. This set-up allows detecting redistributions of the shear-stresses inside the bond length in consequence of creeping and loss of strength of the epoxy resin. The loss of pre-stressing force can be nearly completely assigned to the adhesive layer. On account of the low pre-stressing force in comparison with the compression strength of the concrete and of the negligible creeping of CFRP-strips (for example Ando et al. 1997) the long-term behavior is primarily defined by the adhesive.

Figure 8 displays on the basis of the measured strain loss in the middle the calculated sum of the slips between strip and concrete at the inner end of both bond lengths. In the tests the exposure to higher temperatures effects a significant augmentation of the slip provoked by the described time and thermal depending material properties of the epoxy resin.

NSM REINFORCEMENT – MODELLING

For a safe and durable design of epoxy bonded pre-stressed reinforcement the development of the necessary transfer lengths (ULS) and of the slip between reinforcement and concrete (SLS) in service has to be accounted.

Simulation model

For the application of the experimental results a numerical incremental integration algorithm (Rehm 1961) was developed, that describes the structural behaviour in the SLS and the ULS along the reinforcement axis. The algorithm bases on the differential equation of the shifted bond and uses a framework model (Fig. 9).

$$\frac{d^2 s}{dx^2} - \frac{\tau_b(s)}{(E_l \cdot t_l)} = 0 \tag{1}$$

where s is the slip between CFRP-strip an concrete, E_l and t_l are the elastic modulus and the thickness of the CFRP-strip and $\tau_b(s)$ is the bond shear stress. The shear-slip relationship is taken from tests described in (Blaschko 2001). The bond characteristic includes already the effects of edge distance and strength of the epoxy resin for short term loads. This relationship was implemented idealized subdivided into four sections according to an approach for reinforcement steel bars (Eligehausen, Popov and Bertero 1983). The shear-slip relationship between the CFRP-strip and the concrete is also affected by the shear modulus and the thickness of the adhesive layer. The numerical model takes the properties of the adhesive layer in a linear way into account.

In addition to the short term material parameters the time depending thermo mechanical behaviour of the adhesive was simulated by adapting a creep law of aging concrete to the adhesive properties. The used rate-type creep law bases on a Maxwell chain model of time-variable viscosities and spring moduli (Bazant and Wu 1974). This formulation is useful for the chosen step by step time integration, because it makes the storage of the stress history unnecessary. On the part of the epoxy resin the simulation model includes also the loss of strength with time and temperature and the changing elastic modulus in range of the glass transition according to (Rehm and Franke 1982) and own accompanying tests respectively.

Comparison with experimental results

Short-term behavior – In addition to the ULS the simulation model aims at the description of the SLS, especially at the occurring deformations. Concerning the slip between CFRP-strips and concrete the geometrical boundary conditions – like thickness and width of the strips, thickness of the groove and the adhesive layer – influence the structural behavior in addition to the material properties of the join partners. In figure 10 results of the strip-force-slip-relationship with varying geometrical parameters of tests performed by *Blaschko* (Blaschko 2001) are shown. The results show a wide range of possible bond-stiffness. The mentioned deformation parameters are directly integrated in the simulation model. In addition to the experimental results the calculated outcomes are displayed.

Long-term behavior – Figure 8 also displays the calculated total slip between strip and concrete of both bond areas in the creep tests mentioned above. In addition the chronological changes of the pre-stressing force along the bond length l_b of a test with l_b = 450 mm is shown in figure 11. The simulation obviously is in good agreement with the measured parameters.

CONCLUSIONS AND PERSPECTIVES

The experiments revealed a significant influence of the time depending thermo mechanical material properties of the epoxy adhesive on the long-term structural behavior of pre-stressed near surface mounted CFRP strips in service. To evaluate the effects with regard to designs relevant problems under varying load and thermal conditions a simulation model was presented. These tests were part of an experimental program that was conducted to reveal the effects of elevated service temperatures on the structural behavior of the with NSM CFRP-strips strengthened bridge-decks of the Röslau valley bridge in Bavaria, Germany (Zilch et al. 2004). Among the future tasks are the further systematic analysis of supplementary parameters like other epoxy resin formulations or different load levels and the development of a simple design approach for practice use.

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NOTATION

E_l	elastic modulus of the CFRP-strip
T_g	glass transition temperature
a_r	edge distance of a CFRP-strip
f_c	compression strength
f_t	tensile strength
l_b	bond length
s	slip between CFRP-strip and concrete
t_l	thickness of the CFRP-strip
v (t)	deformation at time t
v_e	elastic deformation
ϕ	creep modulus $\phi = \frac{v(t)}{v_e} - 1$
τ_b	bond shear stress

Table 1 – lap shear test parameters

Temperature		Load
[°C]	[°F]	in % of the long-term strength
20	68	15
		80
38	100	15
50	122	15

Table 2 – tests with pre-stressed NSM

Temperature		bond length l_b	bondless lenght in center
[°C]	[°F]	[mm]	[mm]
20	68	100	100
38	100	100	500
50	122	100	100
50	122	450	50

Table 3 – material parameters

Short-term material Properties	compressive strenght f_c	Age	tensile strength $_{ft}$	Elastic Modulus E	width b_l / thickness t_l
	[MPa]	[year]	[MPa]	[GPa]	[mm]
concrete	55 (28d)	approx. 4	-	-	-
CFRP-strips	-	-	2800	170	20/2
epoxy resin	105 (7d-20°)	-	32 (7d-20°)	8	-

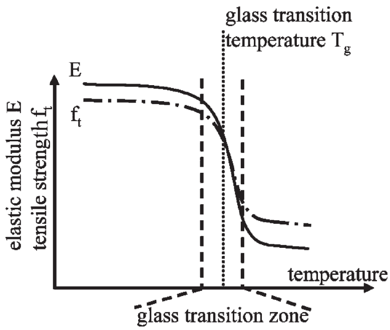

Figure 1 – schematic sketch of temperature-depending tensile strength and elastic modulus of epoxy resin adhesives

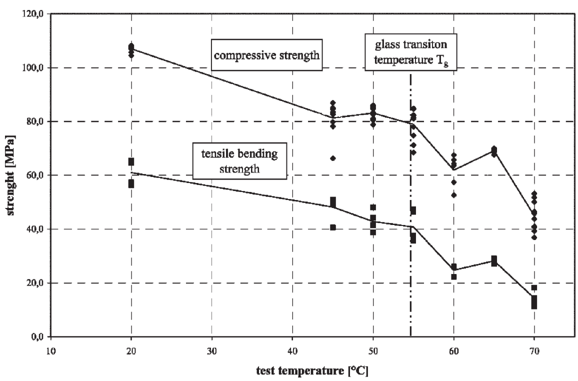

Figure 2 – compressive and tensile bending strength of epoxy resin with rising test temperature

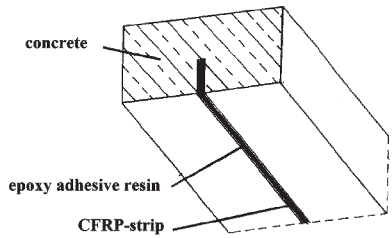

Figure 3 – near surface mounted CFRP strips glued into slits (Blaschko and Zilch 1999)

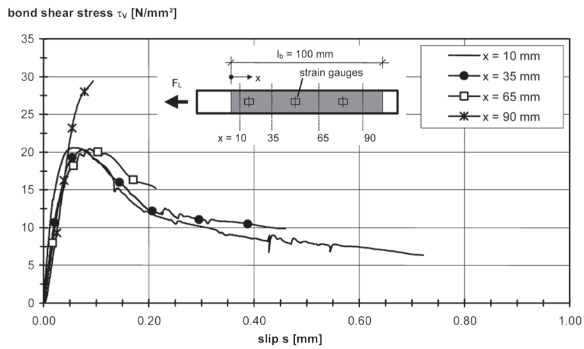

Figure 4 – shear-slip-relationships for different sections of the bond length (bond length l_b = 100 mm, distance a_r = 150 mm) (Blaschko 2003)

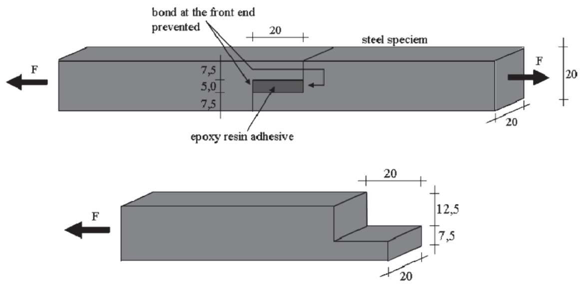

Figure 5 – lap shear test specimen according to DIN 54451-11.1978

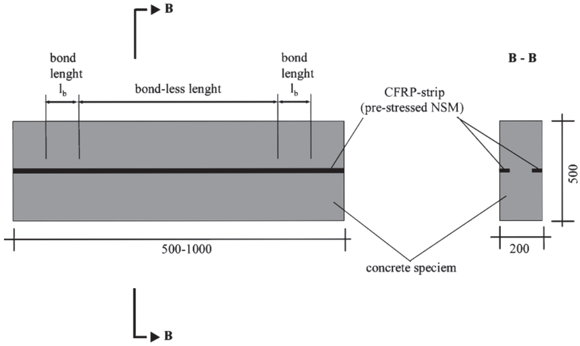

Figure 6 – test specimen for analyzing the structural behaviour of prestressed NSM reinforcement

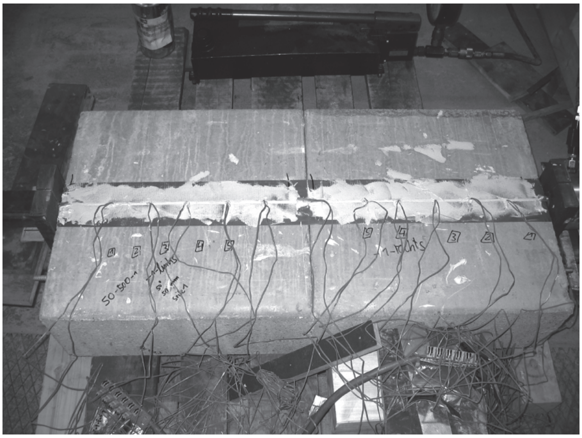

Figure 7 – test specimen with a bond length l_b of 450 mm with strain gauges within the bond length l_b – while curing

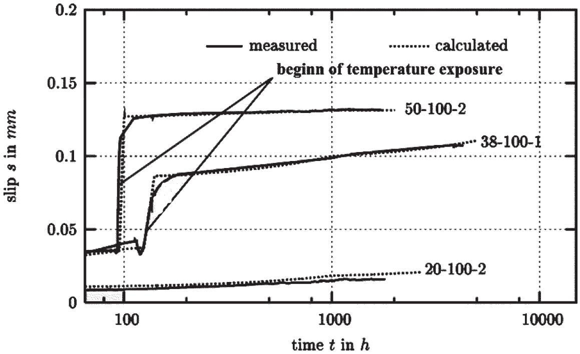

Figure 8 – total slip between strip and concrete at the inner end of the bond length – experiment and calculation

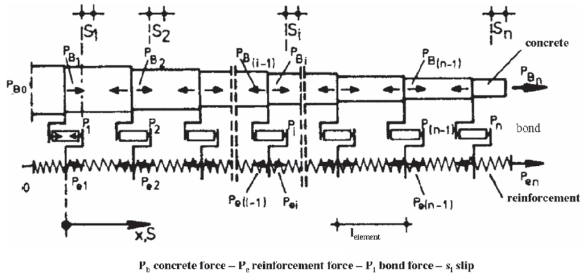

Figure 9 – framework bond model (Franke 1976)

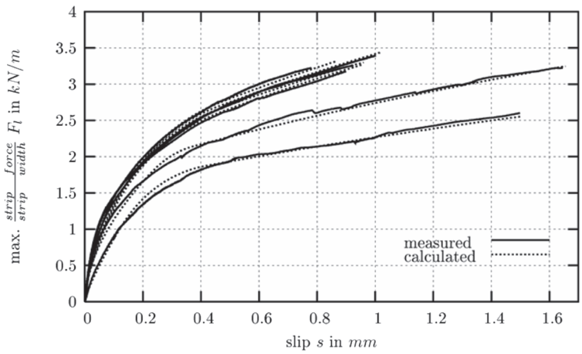

Figure 10 – strip-force-slip-relationship with varying geometrical parameters – experiment (Blaschko 2001) and calculation

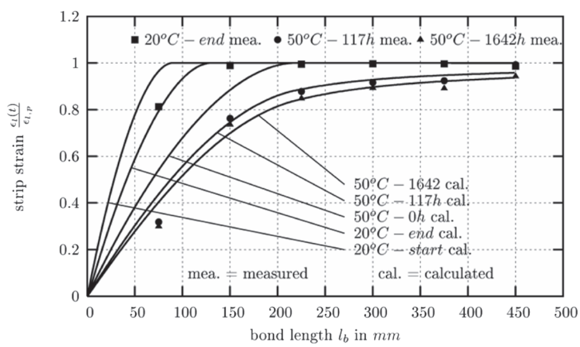

Figure 11 – strip strain along the bond length – experiment and calculation