Karlsruhe Institute of Technology

IMB KARLSRUHE

Institute of Concrete Structures and Building Materials
Department Concrete Structures

Strengthening of concrete components with adhesively bonded CFRP strips

R. Sedlmair[1], L. Stempniewski[1]

[1] Institute of Concrete Structures and Building Materials (IMB), Department Concrete Structures, Karlsruhe Institute of Technology (KIT)

1. Motivation

The strengthening of reinforced concrete components with adhesively bonded CFRP strips to increase the flexural strength has been a recognized technique for several decades. For this purpose, the CFRP strips are applied to the desired concrete surface with epoxy resin-based and quartz sand-filled adhesives (EP). These adhesives are characterized by their high rigidity (modulus of elasticity ≥ 2000 MPa) as well as high adhesive and cohesive strengths. However, this high rigidity also results in insufficient deformability of the adhesive layer, as even small crack openings (w_r ≈ 0.02 mm) lead to damage to the strip-concrete bond and only a small proportion of the bonded surface can be used for load transfer. This results in a high effort within the design - in addition to the known end anchorage verification, a bond action verification must often be carried out over the entire component length, which is now divided into elements separated by bending cracks (intermediate crack elements). Furthermore, high stress concentrations are built up in the CFRP strips at discontinuities (e.g. crack edges) and the bond is excessively stressed. When the crack opens, the CFRP strip takes the main part of the tensile load to be transferred; the embedded reinforcement is implicitly relieved. This state of stress is only eliminated by regional damage or total loss of bond action (w_r ≈ 0.50 mm) – an insufficient interaction of the reinforcement strands or an incompatible strengthening action must be stated. Furthermore, cyclic loads lead to premature damage due to the early damage of bond and, because of a glass transition temperature in the range from 40°C to 60°C, there is no resistance to elevated temperatures. This leads to significant restrictions in the respective building approval.

2. Approach

As part of the research project, a strengthening system consisting of externally bonded (EB) CFRP strips is developed, which implicitly reduces the deficits listed above. For this purpose, an adhesive based on polyurethane (PU) is designed, which forms a permanently elastic adhesive layer. The bond stiffness and deformability of the adhesive layer is matched to the system reinforcement steel-concrete - thus one can speak of a compatible reinforcement system. The pronounced elasticity reduces stress concentrations at points of discontinuity; the adhesive layer can bear cyclic loads. Furthermore, PU adhesives are characterized by glass transition temperatures below 0° C – their softening due to elevated temperatures is represented by a linear relationship and can be precisely defined.
In a first step, the influence of the adhesive layer stiffness on the bond behavior of glued reinforcement (CFRP strip) and the tensile load sharing of the reinforcement strands is numerically investigated using the Abaqus software package. The investigations are carried out on the bond (end anchorage, intermediate crack element (ICE)) and on the component level (reinforced concrete bending beam).
In a second step, end anchorage tests are performed to examine the influence of the adhesive layer stiffness and geometry on the bond behavior of adhesively bonded CFRP strips. The focus here is on the determination of the load-bearing capacity and the respective bond behavior, which is characterized by the bond stress-slip relationship (cohesive laws). The demonstration of the effectiveness of a compatible reinforcement system takes place in component tests (strengthened reinforced concrete bending beam) with realistic dimensions.

3. Results

The influence of the adhesive layer stiffness was investigated using the numerical model of a mixed reinforced ICE (reinforcing steel in red and CFRP strip in blue) shown in Fig. 1 (left). Here, K1 represents a commercially available EP, while K2 stands for a very soft PU and K3 for a permanently elastic PU where the bond stiffness matches that of embedded reinforcement (steel). The determined bond coefficients λ of the respective reinforcement strand depending on the crack opening w_r are shown in Fig. 1 (right).

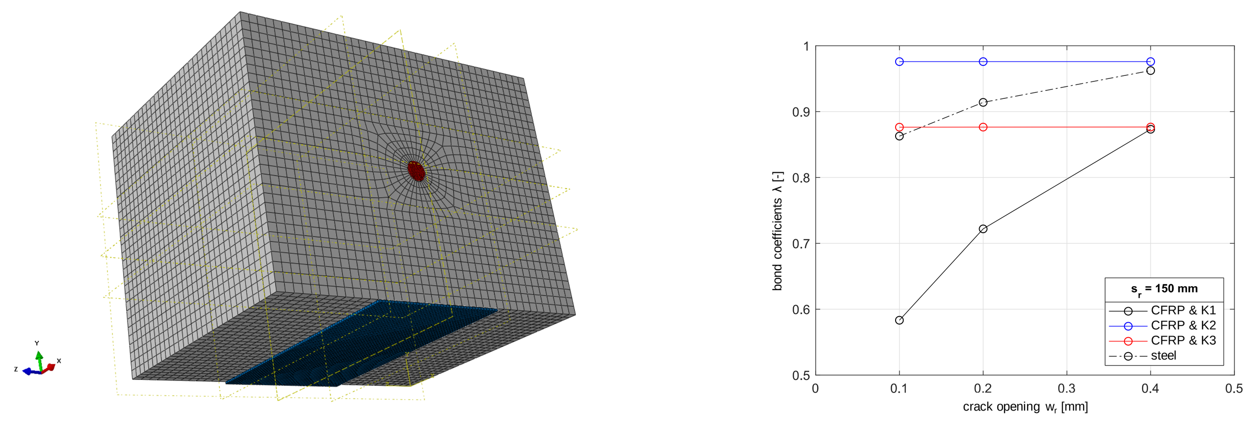

Figure 1: mixed reinforced ICE – modell and determined bond coefficients

The significantly improved interaction of the reinforcement strands due to the use of K3 is evident from the approximation of the bond coefficient λ of the CFRP strip to the value of embedded reinforcement (reinforcing steel). With a stiff adhesive layer (K1), the aforementioned stress concentrations at the location of cracks (λ_L = 0.6…0.8) and successive bond damage during successive crack opening occur. The latter is expressed by a change of the respective bond coefficient.

The increased performance of elastically bonded CFRP strips was demonstrated by end anchorage tests (single lap shear test, push-pull configuration), see Fig. 2 (left). Two different CFRP strip widths were tested (C1 and C2).

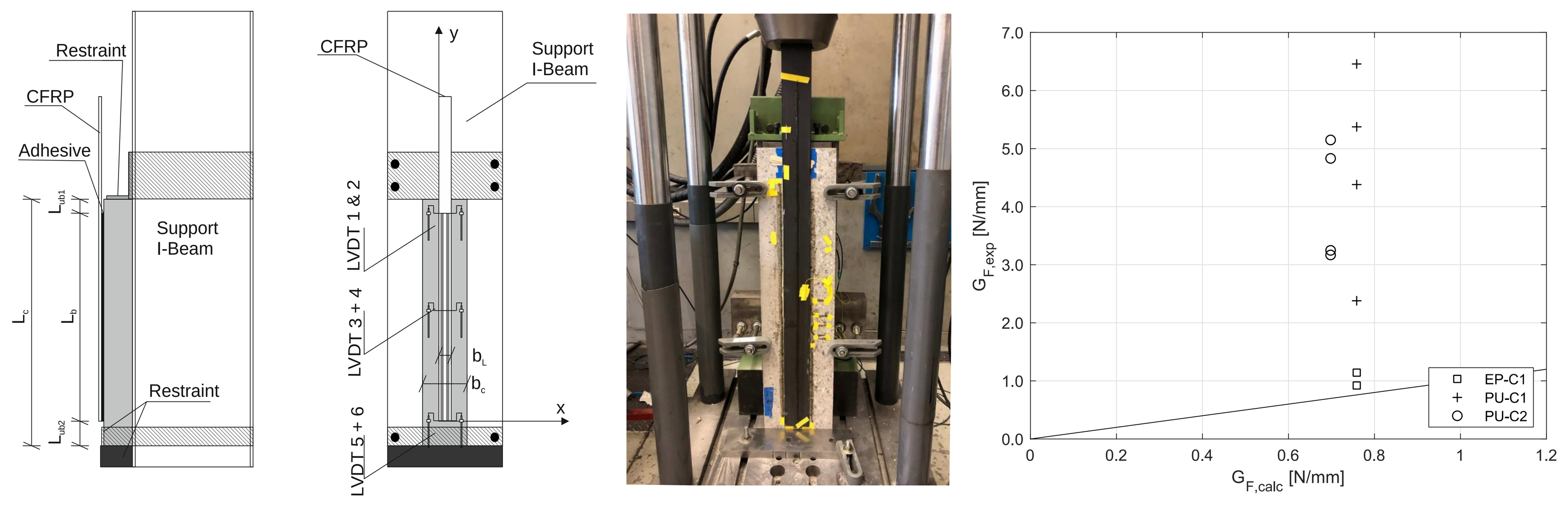

Figure 2: single lap shear tests – configuration (sketch and picture) and determined fracture energies $G_{F,exp}$

The fracture energy of the CFRP strips bonded with PU was four to six times higher compared to the EB CFRP strips bonded with the commercially available EP.
By continuously measuring the strain in the CFRP strip with fiber optical sensors, it was possible to characterize the corresponding bond behavior (cohesive laws) for each adhesive and layer thickness, see Fig. 3. A bilinear idealization of the cohesive law is also shown.

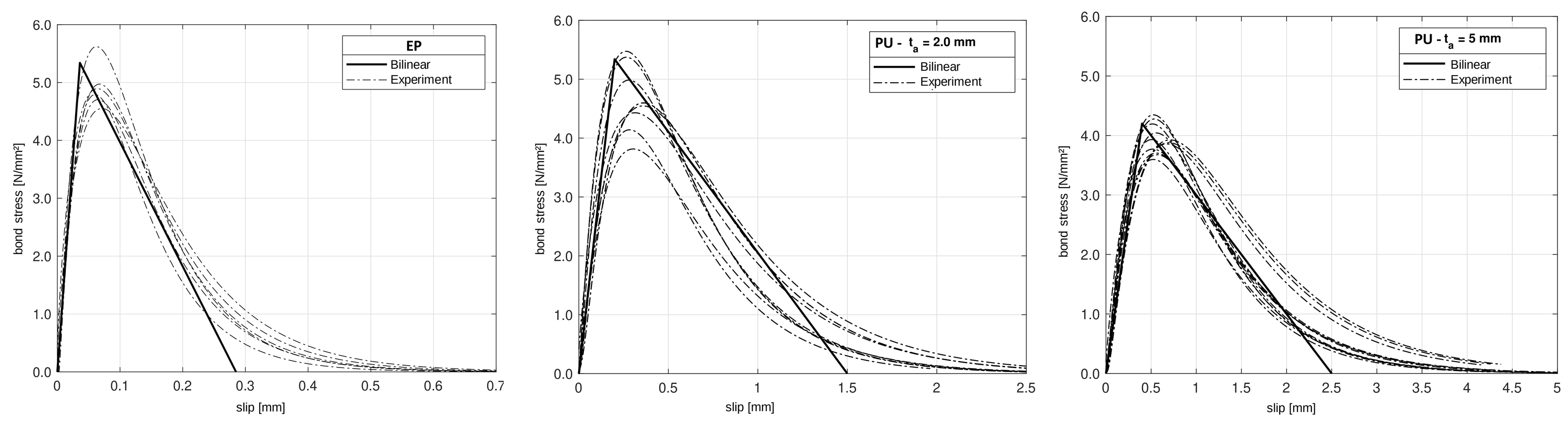

Fig. 3: experimentally determined cohesive laws – EP (left), PU (middle and right)

The gradient of the linear-elastic ascending branch of the cohesive law can be approximated by the shear stiffness of the polymer and the geometry of the adhesive layer. The elastic slip is greater than the crack openings to be expected in the serviceability limit state (SLS). The secant stiffness of the cohesive law matches that of embedded reinforcement steel - the glued reinforcement is compatible regarding deformation and bond behavior.
The improved performance of elastically bonded CFRP strips to strengthen bending beams was demonstrated in four-point bending tests, see Fig. 4.

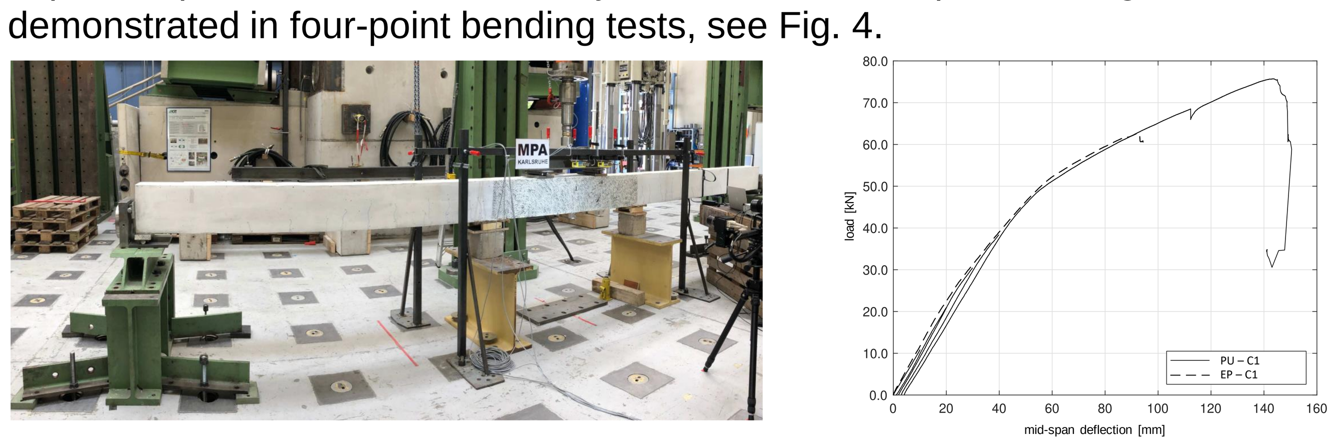

Fig. 4: strengthened bending beam in four-point bending test (left) und load-deflection-curves (right)

By applying the CFRP strip with the PU, the load-bearing capacity of the beam was increased by 20 percent and the utilization of the CFRP strip by 53 percent compared to EP. Furthermore, the PU beam failed by yielding of embedded reinforcement, followed by a concrete crushing before the CFRP strip was detached cohesively including the concrete cover at the level of the longitudinal reinforcement. Regarding the PU beam, the development of a load plateau stands for maintaining the deformability and failure with notice. Due to the premature debonding of the CFRP strip, this is not the case at the EP beam – the concrete pressure zone was not crushed.
The interaction of the reinforcement strands can be evaluated with the bond coefficient of the CFRP strip λ_L, which is determined for different mid-span deflections w in Fig. 5.

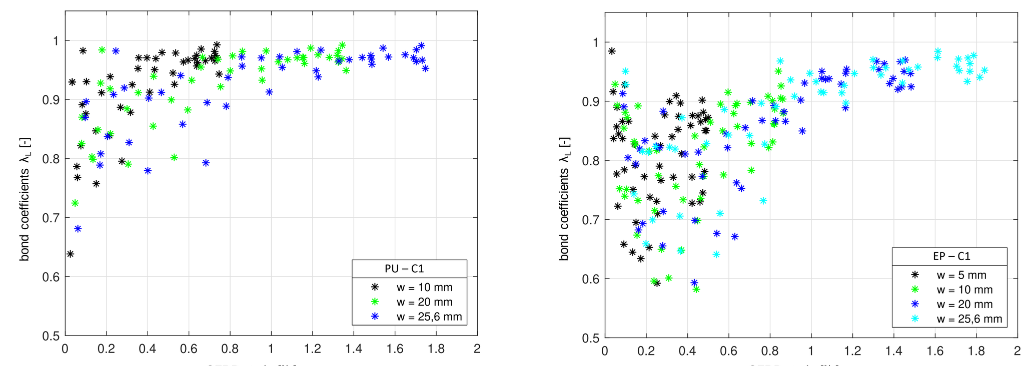

Fig. 5: bond coefficient of the CFRP strip at SLS – PU (left) and EP (right)

The bond coefficient of the CFRP strip λ_L bonded with PU is about 0.9 to 0.95 at SLS and ultimate limit state, which matches the bond coefficient of embedded reinforcing steel. Regarding EP, the same tendency can be seen here as in the numerical model. Thus, the application of the CFRP strip with PU leads to a compatible and successful strengthening action.

Dipl.-Ing. Roman Sedlmair
Gotthard-Franz-Street 3, 76131 Karlsruhe
Phone: +49 721 608-44093
E-Mail: roman.sedlmair@kit.edu

Laumer BAUTECHNIK
KLEIBERIT® ADHESIVES • COATINGS
KAST
ZIM Zentrales Innovationsprogramm Mittelstand
Gefördert durch: Bundesministerium für Wirtschaft und Energie
aufgrund eines Beschlusses des Deutschen Bundestages