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Bond Behaviour of CFRP-Laminates for the Strengthening of Concrete Members

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Summary

For several reasons, in plate strengthened members a reliable bond via the epoxy joint is essential for the composite action. According to the truss analogy the ends of the plates of carbon fiber reinforced plastics (CFRP-plates) have to be anchored to the concrete. Bond tests indicated, that an already existing engineering model for the ultimate bond force, so far verified only for steel plates, is also applicable for CFRP-plates. Material-specific adaptions had to be made.

1 Introduction

The strengthening of concrete members by externally bonded steel plates is a proven technology. However, it exhibits several disadvantages such as the steel's susceptibility to corrosion in the adhesion zone and its heavy weight. Consequently, steel is increasingly replaced by thin and light CFRP laminates which exhibit exellent long-term- and fatigue- properties and corrosion behaviour. This article deals with CFRP-plates, consisting of unidirectional carbon fibers, embedded in epoxy resin matrix.

Especially at the end supports of beams and slabs, the reliable anchorage of the plate end by bond is important. For design, the ultimate bond force and the modes of failure must be known. Hence, extensive bond tests were performed. On basis of the results an engineering model of bond strength was developed.

2 Materials

The Young's modulus of carbon fibers is in the range of 240-900 GPa, their tensile strength of 2000-7000 MPa. The stress-strain behaviour ist linear-elastic. In CFRP-plates, the fibers are embedded in an epoxy resin with a tensile strength of 60-90 MPa and an ultimate strain of 3 -5%. For more information see /1/.

Unidirectional CFRP-plates with a fiber volume ratio of 60 - 70% are 1,0 - 1,5 mm thick and 50 - 100 mm wide. They have a tensile strength of 2000 - 3000 MPa and an E-modulus of 150 - 230 GPa. CFRP-plates are, as the fibers, linear-elastic unto failure. The contribution of the epoxy matrix to strength and Young's modulus is negligible. The short time strength is the relevant design resistance.

3 Principle of the Strengthening Method

The CFRP-plate is an additional and staggered tension chord. The behaviour of the strengthened member can be described by the truss analogy TA. Consequently, this analogy requires in the case of beams external plate stirrups, anchored in the compression zone. Such stirrups can only be realized by glued steel plates. Because the CFRP-plate will usually end before the axis of end supports, the plate's force has to be anchored in the tension zone of the bending member. Fig. 1 shows schematically the lines of the tensile forces of the internal and external reinforcement according to the TA as well as the plate force to be anchored outside of the line of plate force. Experiments proved, that the flexural design of plate strengthened beams and slabs can be carried out following the rules for reinforced concrete. The strain limit of CFRP-plates has to be chosen in such a way, that the premature separation of plate from concrete is obviated. The shear design of plate-strengthened members also follows the principles for reinforced concrete.

4 Bond Zones of a Plate-Strengthened Concrete Member

In a plate-strengthened member, three zones of bond stress exist (Fig. 1):

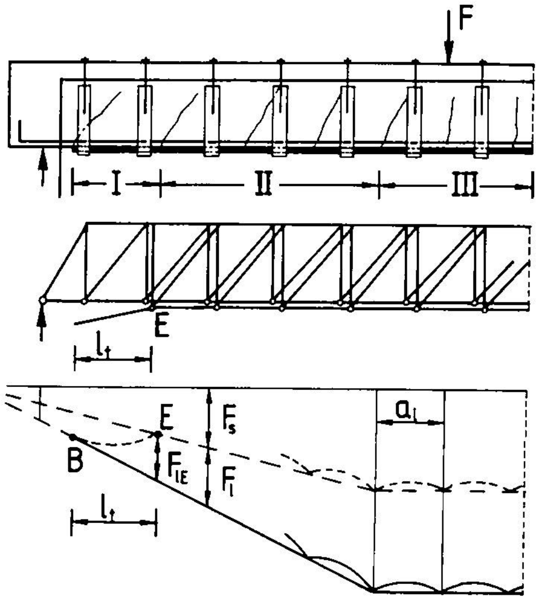

Fig.1 Truss model of a plate-strengthened beam, tensile forces according to TA and bond zones

I Anchorage of the plate end
Tensile stresses are rapidely being transferred to the plate via bond stresses, beginning at the plate end, until at the end E of the anchorage length the plate is fully connected, i.e. its share of total tensile force is equal to its share of the total reinforcement stiffness.

II Zone of shear forces and moderate bending moments
Bond stresses are caused by the variation of bending moment along the beam and by force transfer at cracks.

III Zone of high bending moments and low shear forces
In the zone of strain, bond stresses are mainly caused by force transfer at cracks.

Within the anchorage length l_t the plate end has to be anchored to the concrete for the relevant plate force F_{lE}, by high bond stresses.

5 Bond Tests

5.1 Test Methods

For the investigation of the bond behaviour of a plate end, bond tests are necessary. There are two basic types of bond tests. Volkersen /2/ and Ranisch /3/ used double-lap specimens, in which both, the concrete and the plate were loaded with a tensile force. The other type is carried out on specimens in which the concrete is under compression and the plate under a tensile force. This type was used by Bresson, Hilti AG and Holzenkämpfer /4/ on double-lap specimens and by Wicke/Pichler /5/ and Täljsten /6/ on single-lap-specimens. For the investigation of bond behaviour of CFRP-plates, a test method was chosen, which reflects the situation of the of the plate's end. The CFRP-plates were tested in double-lap bond tests of the compression-compression type. Fig. 2 shows the test set-up in relation to the situaton in the anchorage zone.

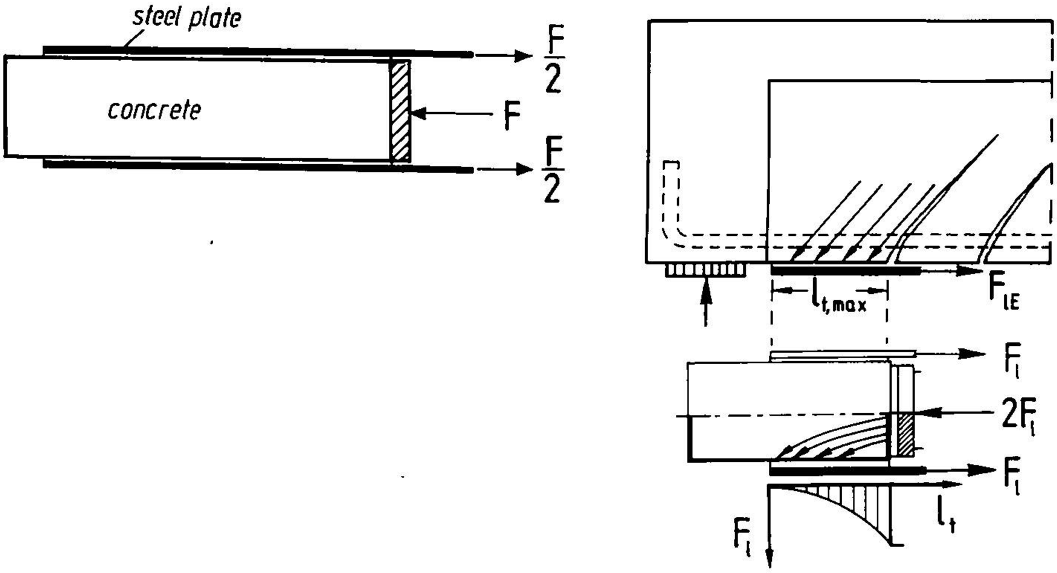

Fig. 2 Double-lap test specimen (compression-tension), used by Bresson /5// (left), Plate anchorage and bond test set-up (right)

5.2 The Model of Holzenkämpfer

The aim of the bond studies is, to develop an engineering model for the prediction of the ultimate bond force of a bonded CFRP-plate dependent on the relevant parameters, especially the bond length. The engineering model of the bond of glued reinforcement of /4/ is a promising on-set. This model is based on non-linear fracture mechanics. It was developed for an arbitrary elastic plate material but so far only verified for steel plates. The model is based on the differential equation of the sliding bond according to /2/and /3/:

$$\frac{d^2 s_l}{dx^2} - \frac{K}{E_l t_l}\tau(s_l) = 0 \qquad (1)$$

where: s_l......: local slip between plate and concrete
K.......: factor considering the stiffness ratio plate/concrete
E_l .....: modulus of elasticity of the plate
t_l........: thicknessof the plate
$\tau_l(s_l)$..: bond stress as a function of s_l
x...... .: coordinate

The bond law $\tau_l(s_l)$ used by /4/ is shown in Fig. 3. Its ascending branch represents linear elasticity, the descending branch the softening of bond by bond cracks. The total area enclosed is the fracture energy G_F for crack initiation, which can be expressed as a function of the concrete's tensile strength.

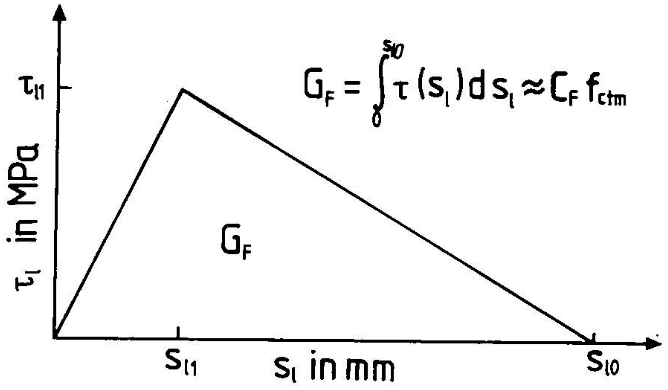

Fig. 3 Idealized local bond law of Holzenkämpfer /4/

Pre-supposing the Mohr-Coulomb criterion for bond failure, the value τ_{l1} is expressed as a function of the concrete's surface tensile strength f_{ctm}. The slips s_{l1} and s_{l0} were derived from the deformation of a representative volume of bond zone. Tests show, that the ultimate bond force increases with bond length. However, after a specific bond length $l_{t,max}$ no further increase beyond the maximum ultimate bond force T_{max} can be attained (s. Fig. 5). The following expressions are derived in /4/:

$$T_{max} = 0{,}40\, k_b\, k_c\, b_l \sqrt{E_l t_l f_{ctm}} \quad [N] \qquad (2)$$

$$l_{t,max} = \sqrt{\frac{E_l t_l}{4 f_{ctm}}} \quad [mm] \qquad (3)$$

The factors k_b and k_c consider influences of the plate width relative to concrete member's width and of the condition of the concrete surface. The product $k_b k_c$ usually does not differ much from 1,0. Eq. (2) is assumed to be valid for any elastic plate material, but was calibrated for steel plates. Hence, it became necessary to investigate the applicability of Eq. (2) for CFRP-plates.

5.3 Test Program, Types of Failure and Results

In all 51 bond tests were performed. The following parameters were varied: bond length l, plate width b_l, plate thickness t_l, concrete cube strength. The Figs. 4 and 5 show the results.

In all tests a sudden, brittle bond failure ocurred. Two main failure types are to be distiguished, which in some cases ocurred together in the same plate:

1. Concrete tensile failure 1-7 mm deep in the concrete subbase T1. The adhesive layer together with aggregate particles remained on the plate.
2. Interlaminar plate failure T2. The fibers closest to the adhesive surface were ripped out of the matrix and remained in the adhesive layer on the concrete. In most cases, interlaminar plate failure ocurred after a few centimeters of concrete failure T1, which started from the loaded end of the bond length.

There was a clear dependence of the failure type on concrete strength. In concrete B25, 85% of all failures were of the Type 1 over the full bond length and 15% were a combination of T1 and T2, with T1 starting at the loaded end, as described above. In concrete B55 the combination T1/T2 with 95% clearly prevailed.

For the comparison of Holzenkämpfer's Eq. (2) with the test results, the actual concrete's surface tensile strength f_{ctm} was determined on the bond test specimens. Then, the dependence of the fracture energy had to be determined. Evaluation led to the following equations:

$$T_{Cm,max} = 0{,}75\ k_b\ b_l\ \sqrt{E_l t_l f_{ctm}} \qquad [N] \qquad (4)$$

$$l_{Ct,max} = \sqrt{\frac{E_l t_l}{1{,}43 f_{ctm}}} \qquad [mm] \qquad (5)$$

Fig. 4 shows the measured ultimate bond forces exp T_u plotted against the calculated ultimate bond forces cal T_m. For bond lengths l_t with $l_t < l_{Ct,max}$, the ultimate bond force was calculated according to /4/:

$$T_{Cm} = T_{Cm,max} \frac{l_t}{l_{Ct,max}} \left(2 - \frac{l_t}{l_{Ct,max}}\right) \qquad (6)$$

The calculated values reasonably agree with the measured ones. In Fig. 5 the normalized measured and calculated ultimate bond forces, dependent on bond length are shown. The relative good agreement for most cases as well as the fact, that there exists a maximum ultimate bond force can be seen.

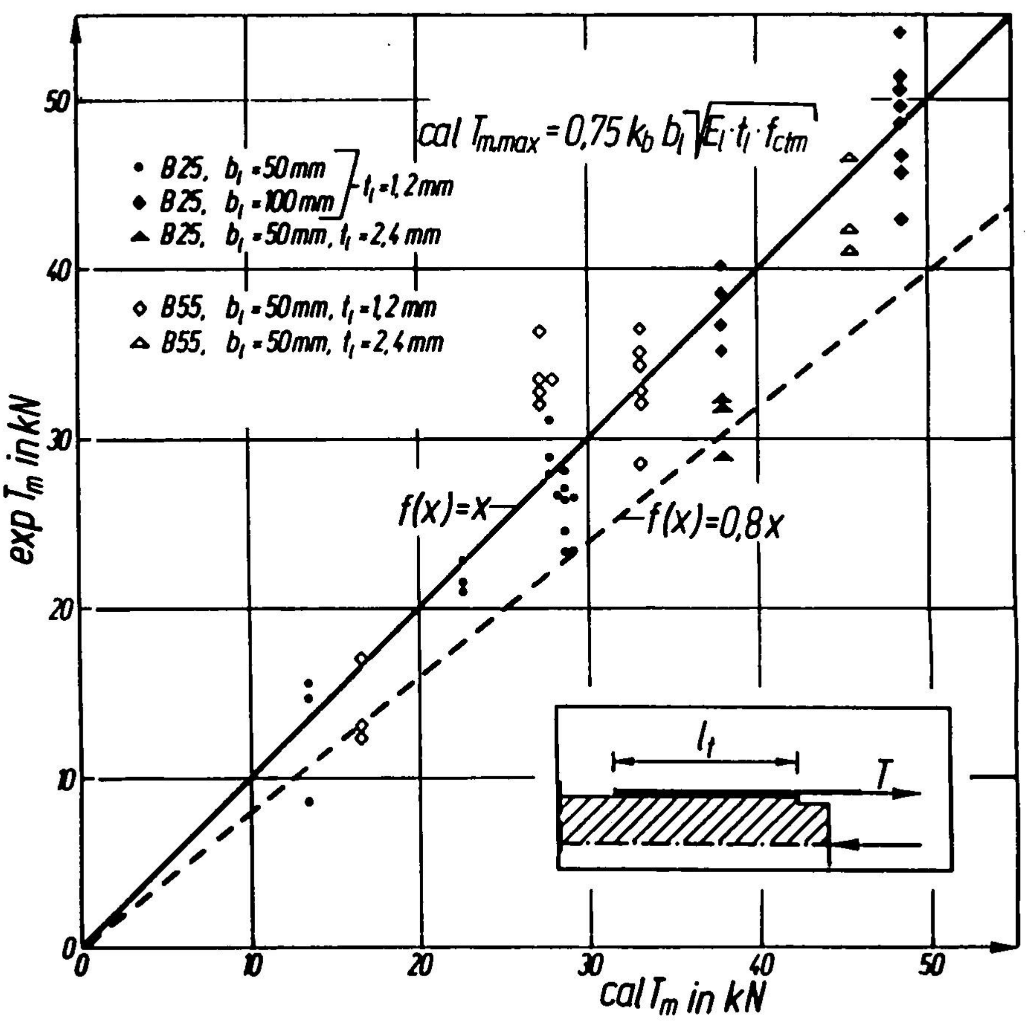

Fig.4 Calculated and measured ultimate bond forces

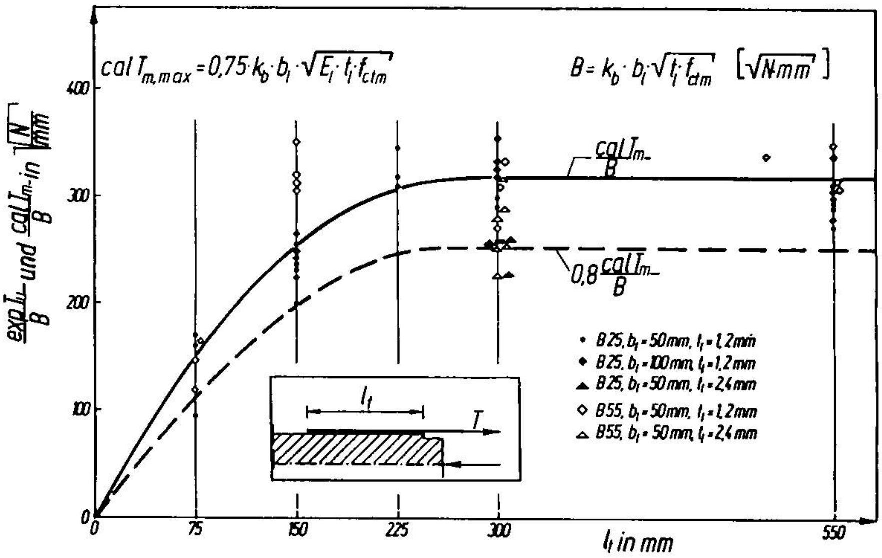

Fig. 5 Calculated and measured ultimate bond forces, dependent on the bond length

6 Conclusions

The engineering of Holzenkämpfer is also valid for CFRP-plates. The test results indicated, that this not only applies to plates with a complete failure in the concrete subbase but also to plates with a combination of concrete- and interlaminar plate failure. Despite of the different failure types the same fracture mechanism, dependent on the fracture energy, seems to be responsible for the start of a bond failure. The interlaminar plate failure is probably a secondary effect, caused by high local tensile stresses (peeling effect).

The modified formula for the ultimate bond force is an appropriate tool for the design of the plate end anchorage. It should be mentioned, that despite some previous research, there are some more important questions about the bond anchorage of CFRP-plates to be solved, e.g. the beneficial effect of plate stirrups on the ultimate bond force and the negative effect of vertical displacements of shear cracks.

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