SUMMARY

The strengthening of concrete members (r/c and p/c) with externally bonded steel plates as additional reinforcement has been successfully executed for about 40 years. Since about 15 years, fiber reinforced plastics (FRP), consisting of aramid-glass- or carbon fibers are increasingly used. Due to their superior properties, carbon - FRP (CFRP) have outperformed the other materials by far in the past 10 years. The number of applications is constantly increasing.

Design rules for the strengthening with CFRP-plates in Germany were derived from the ones for steel plates, mainly based on the works of Ranisch [1] and Holzenkämpfer [2]. Some material-specific features of CFRP-plates however have to be considered more carefully. Especially the need to guarantee bond integrity along the entire plate is much more delicate for the ideal-elastic CFRP than for steel. This problem has so far only been considered by the limitation of the allowable plate strain and the requirement to provide sufficient end ancorage capacity. Reality however is much more complex and requires an adequate design concept. There is a strong need to develop an engineering model, capable to realistically describe plate bond along the entire length of the plate, in different bond-zones, different moment / shear ratios, crack spacings, types and amounts of reinforcement etc..

This thesis aims at a consistent, generally valid bond model for CFRP-plate-strengthened r/c and p/c members, leading to the determination of the critical load level at bond failure.

Chapter 2 briefly describes the general issues of bond in reinforced concrete and outlines the fundamental differences between the bond characteristics of internal and external reinforcement. The main feature that distinguishes CFRP-plate bond from the one of internal reinforcement is its brittleness. In contrast to internal reinforcement, plates are not confined by a concrete cover. The notorious low surface tensile strength of the brittle concrete is the main bond resistance parameter. Furthermore, the linear elastic material law of CFRP causes the plate force to increase until failure.

Next, the present state of knowledge concerning bond of CFRP-plates is summarized. Due to some basic common aspects of all bond problems, also research in the fields of steel plates and even riveted connections [8] is considered. The immediate bond zone was mostly simulated in pure bond tests, which is sufficient to model the anchorage zone between the end of a plate and the first crack. A thorough knowledge exists about bond laws and anchorable bond forces along an uncracked bond length for steel plates, loaded in pure bond [2,19,40]. The fracture mechanical nature

of the bond fracture in the concrete substrate causes the well known size effect [38], resulting in a characteristic bond length $l_{t,max}$, beyond which no increase in ultimate bond force can be attained [2].

The knowledge about the debonding mechanisms in a real cracked r/c member with their intricate processes and interactions of fracturing, steel yielding, plate debonding, force redistribution, stable and unstable crack propagation etc. is much more scarce. The debonding model of Holzenkämpfer [2] only considers tensile members or beam regions with M = const.. However, for debonding considerations, the effect of a moment gradient, inducing equilibrium bond stresses, is most interesting.

In **Chapter 3** the materials involved are described. The linear-elastic and anisotropic material propeties of the CFRP-material are well known.

Chapter 4 deals with the fundamental relationships of plate bond on the level of a beam element between two cracks, subsequently referred to as a concrete tooth. The bond law, developed by Holzenkämpfer for steel plates is adapted to CFRP-plates by means of 64 bond tests, varying different parameters. It was confirmed, that the ultimate bond force mainly depends on the fracture energy G_F, required to completely debond a local bond element. The exact shape of the bond stress-slip curve has a negligible effect on the bond resistance. This justifies the assumption of a linear bond law, easier to be dealt with analytically.

The solution of the differential equation of the sliding bond was adapted to the boundary conditions of a general concrete tooth. The latter is characterized by arbitrary values of crack spacing, plate force level and plate force increment between two cracks. For these considerations, the plate forces at the boundaries (i. e. cracks) of the concrete tooth are presumed. Force distribution between internal reinforcement and plate will be analyzed in the next chapter.

The criterion for the onset of debonding is the complete release of the fracture energy G_F at the crack with the higher plate force. This corresponds with the maximum bond stress τ_{l1} at this point, assuming the linear bond law. It was found, that for a sufficient width of the concrete tooth, i. e. crack spacing, some stable bond crack propagation with increasing plate force is possible. When the remaining intact bond length of the tooth falls below a critical value, in a force controlled test unstable debonding occurs over the entire rest of the bond length. The corresponding plate force can be calculated. This behaviour is due to the fact, that over each concrete tooth only the plate force increment ΔF_l has to be transferred to the concrete via bond stresses. This portion of the total bond stresses can be called equilibrium bond for it is needed to maintain horizontal equilibrium in the concrete tooth. Any additional bond stresses are built up along the tooth width due to the tension stiffening effect and are therefore called compatibility bond. This portion of bond stress can be reduced by a successive debonding, as long, as the remaining bond length is sufficient to transfer ΔF_l.

Chapter 5 analyzes the interaction between plate and internal reinforcement. The tensile force of each reinforcement layer can generally be computed according to truss analogy. In the domain of elastic steel reinforcement and intact plate bond, plane strain distribution and consequently proportionality between the forces and the respective tensile stiffness can be assumed. This is not longer valid, as soon as either the steel yields or the plate starts to debond in a stable manner, as described above. Depending on crack spacing, yield force, bond strength of the plate, moment/shear ratio etc. steel yielding or onset of debonding will occur first. During these processes force redistributions occur between the reinforcement layers. Due to its high ultimate tensile strain, the steel is unlikely to rupture before complete plate debonding. Consequently the latter will govern failure.

Various debonding cases are identified, depending on the sequence of steel yielding and onset of plate debonding, on the capacity of stable bond crack growth, on the magnitude of the ultimate plate force etc.. For each of these different cases the ultimate load level, leading to unstable debonding can be calculated. Normalized parameters are used in order to make the equations generally applicable to arbitrary situations of geometry, reinforcement ratio, load types, static systems etc.. Eventually a few simple criterions are given to reduce the number of debonding cases for practical applications. So far, the model is only capable to predict the debonding of any individual concrete tooth of the member. The relevant one, governing the failure of the entire member has yet to be identified.

As outlined above, crack spacings significantly influence the plate bond. In **chapter 6** a relatively simple method to compute the crack spacings is derived. It is based on Noakowski's continuos crack theory [3], extended to plate strengthened members. The model satisfactorily agrees with results of slab- and beam tests.

In **chapter 7** the locations, likely to govern bond failure of the member are identified. These are end anchorage zones, points of transition between elastic and yielding internal reinforcement and the vicinity of point loads. Rules to locate these points are given. To find the relevant one, they must be analyzed individually. In most cases, only two or three points have to be considered. The ultimate load levels for debonding, calculated with the model presented, slightly underestimate the ones, observed in bending tests by less than 10 %. Thus, the model is considered to satisfactorily predict debonding failure.

Chapter 8 deals with a type of debonding failure, specific to fiber reinforced plastics. Interlaminar failure in the plate, preferably occurring with higher-strength concrete has been observed in bond tests as well as in bending tests with CFRP-plates. It is considered a mixed mode fracture problem and was investigated by simultaneous measurements of the mode I and mode II displacements of the bond crack with electronic speckle pattern interferometry (ESPI). A fracture mechanics approach to a criterion for interlaminar plate failure is presented. According to this, in cases with particulary high concrete tensile strength, interlaminar failure may govern bond failure. It is suggested, not to utilize a concrete surface tensile strength of more than 3,0 MPa for practical design. This model includes several assumptions, which will have to be verified and improved by further research.

In the literaure it is often stated, that vertical shear crack mouth displacements will cause debonding by inducing peeling stresses in the bond zone. However, hardly any quantitative proof for this assumption has ever been given. **Chapter 9** attempts to eludicate this question. First a method to calculate the shear crack mouth displacements, dependent on the acting forces, crack spacing, geometry, reinforcement, material parameters etc. is presented. It is based on the truss modell with shear crack friction of Reineck and Hardjasaputra [64,65]. Then a mixed mode fracture mechanics approach is used to quantify the loss of bond strength due to simultaneous action of bending and shear. The vertical crack mouth displacement is assumed to reduce the mode I-portion of the total fracture energy. Even if this portion is completely neutralized, the bond strength reduction due to vertical shear crack displacement will in most cases not exeed 4 %. Due to the formation of numerous secondary cracks close to the reinforcement, vertical displacements of principal cracks are partially levelled out. Consequently, these displacements have limited effect beyond the immediate vicinity of the shear crack. Sufficient shear reinforcement is a precondition.

In **chapter 10** a summary is given and conclusions for further research are drawn. The latter should generally refine the presented models. It would be valuable for design engineers, to further reduce the number of debonding cases for practical applications. More measurements of in-plane and out-of-plane displacements by sensitive electrooptical methods (e. g. ESPI) in pure bond- but also in beam tests would be helpful to establish a sound database to refine fracture mechanics models. This could also help to study the beneficial effect of externally bonded steel stirrups, which significantly increase the ultimate load at debonding failure.