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Abridged Report

Practice-Oriented Design Approaches for Cost-Efficient Strengthening of Concrete Members Using Adhesive Reinforcements

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1 The Problem

Roughly 60% of all construction activity in Germany relates to the refurbishment or rehabilitation of existing structures. The subsequent strengthening of existing structural members using adhesive reinforcements often is a prerequisite for the ability to reutilise existing buildings. As this method saves materials it contributes significantly to the sustainable use of existing buildings. For concrete structures, adhesive reinforcement presents an established method which allows the subsequent increase or restitution of the load-bearing capacity as well as an improvement in serviceability. Strips or nets of fibre-reinforced polymers in conjunction with epoxy resin glues, or steel straps are used as strengthening reinforcement.

There currently are national technical approvals available for adhesive reinforcements to strengthen members loaded in flexure or shear and for which a certain amount of experience has been gained in Germany in the corresponding areas of application. These approvals are mainly based on experiments performed under idealised conditions where the results can only be transferred to other situations to a limited extent and which may not be especially cost-efficient for large-scale structural members.

Therefore, the models available nowadays can only be applied in certain cases and with special boundary conditions. The utilisable strain e.g. of the adhesive reinforcement and the degree of reinforcement are limited. A generally applicable model which would allow a wider range of application of the strengthening technology with significantly increased efficiency and economy is not available at present. Additionally, some areas of applications that may be important in practice have not yet been exploited as they are not part of the technical approvals in Germany or have only been regulated in an insufficient manner. This includes the strengthening of prestressed members and the increase of the resistance of structures subject to dynamic loads e.g. due to wind or because of the type of their use (crane tracks, parking decks, warehouse floors with forklift operations, etc.).

A prerequisite to using additional areas of application which have already been researched and to exploiting their full economic potential is a reprocessing of the current state of national and international knowledge. The field of experience has increased significantly in the last few years and has not yet been evaluated in its entirety. Nor has it been expanded by further experimental investigations which would close certain gaps in a target-oriented fashion with regard to the transferability of the empirical knowledge to specific areas of application and would eventually yield a complete picture of the problem. The final step of the long-term but heretofore mainly uncoordinated research efforts that would make the current state of knowledge available to the construction industry in the form of cost-effective, practice-oriented design approaches and application guidelines is still outstanding.

Research in Germany over the past few years was oriented to fundamentals with the goal of describing the structural behaviour of isolated cross-sections observed at the meso level or on sections of girders and then transferring this knowledge to the macro level of the structural element. The results of these various fundamental research projects have not yet been merged into generally applicable design models. With regard to the application of already approved methods certain individual aspects of the structural behaviour were investigated in research projects for technical approval under unfavourable boundary conditions that were funded by ARGEBAU under the guidance of the DIBt. Based on the results of these research projects the DIBt developed a design method for the technical approvals that in many cases underestimates the composite resistance which results in a limitation of the application of the strengthening method or makes it economically inefficient. The design models developed both in fundamental research and for technical approvals, however, form a good basis for supplemental investigations within the scope of this joint project.

The investigations performed were bundled into three work packages that were handled by the research institutions participating in this cooperative effort. The work packages dealt with the following components of the complete design model that depend on the bond behaviour of the adhesively applied reinforcement:

- Work package I: Composite load-bearing capacity under static loading
- Work package II: Composite load-bearing capacity under dynamic loading
- Work package III: Shear resistance

2 Investigations

2.1 Work Package I: Composite Load-Bearing Capacity under Static Loading

Generals

In conventional reinforced concrete design the bond is verified using an end anchorage check which is based on bond characteristics obtained through pull-out tests. If this check is performed in a similar manner for adhesive reinforcements then the full tensile forces will not be anchored as the bond force cannot be increased beyond a certain anchorage length (refer also to Figure 2.1). From tests on structural members it becomes clear, however, that much larger forces are present in the strips at the point of maximum moment than an end anchorage check would allow for. Especially for CFRP strips which have a very high capacity for tensile stresses a check based solely on the end anchorage would not be cost-effective at all. The bond force transfer must instead happen as shown in Figure 2.1 at that point where the forces actually occur.

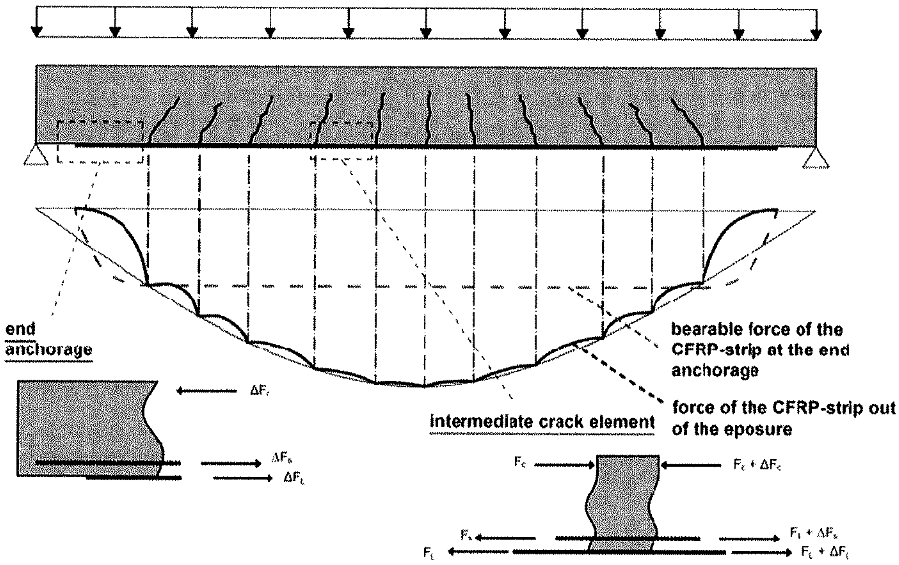

Figure 2.1: Principle of bond force transfer for structural members with adhesively applied CFRP-strips divided into end anchorage and inter-crack element

For this reason, two areas are differentiated for the design checks: the end anchorage area and the remainder of the structural member.
At the end anchorages those strip forces must be anchored which occur at the flexural crack nearest to the support. The design bond force in the end anchorage area is determined through so-called idealised end anchorage tests where the adhesively applied reinforcement is pulled longitudinally.
In the remaining areas of the structural member the bond force is transferred at elements which are separated by flexural cracks, so-called inter-crack elements. At any such inter-crack element there is a basic force level in the strip at the crack edge with the lesser loading while at the other edge with the higher loading the basic force is increased by an additional force in the strip. This strip force differential is the one that must be transferred by the bond into the structural member.

End Anchorage

In order to determine the bond energy of the combination of concrete, adhesive and CFRP strips used, six bond tests were performed on double-strip test specimens.
CFRP strips with dimensions of 50 mm x 1.4 mm were glued to opposite sides of these test specimens.
As the bond behaviour of the reinforcing steel cast into the concrete members influences the bond force transfer of the CFRP strips onto these members, through e.g. the length of the inter-crack elements, 23 pull-out tests were performed on the reinforcing steels used as part of Work Package I.

Idealised Inter-Crack Element

To determine the bond behaviour at the inter-crack element, 38 tests were performed on an idealised inter-crack element. In these tests, CFRP strips with dimensions of 50 mm x 1.4 mm are glued to op-

posite sides of a concrete block. The strips are pulled at either end with different forces until the CFRP strip completely separates from the concrete surface.
Figure 2.2 shows a schematic of the test apparatus. In the middle of the test set-up lies the concrete block which represents the inter-crack element and to which CFRP strips are applied on opposite surfaces.

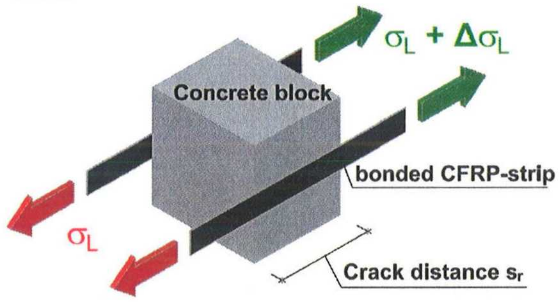

Figure 2.2: Schematic test set-up on an idealised inter-crack element

Inter-Crack Elements on a Structural Member
In order to determine the bond force transfer on a structural member, three-point bending tests were performed on seven structural members with a special test concept in mind that allowed several areas to be tested. In this concept which is shown in Figure 2.3 it is possible to investigate different parts of a beam while damage to the strip's bond is prevented elsewhere by actively applying contact pressure. After completion of one test, pressure was applied in the tested area while the pressure apparatus was removed in a different section to be able to test that area as well. Generally, it was possible to test three or four sections with this method on any given structural member.

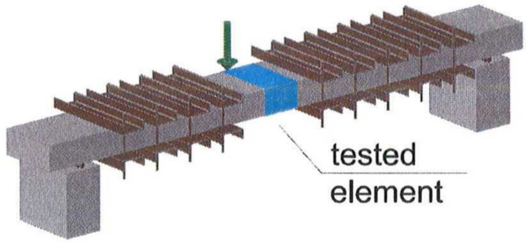

Figure 2.3: Test set-up for experiments on inter-crack elements on a structural member

The decoupling of the bond can be observed by measuring the strip strains. When the difference in the strains at the crack surfaces starts to drop the point is reached the strip begins to decouple. The decoupling process also shows in an increase in relative displacements between the strip and the concrete surface which in the tests was determined by optical deformation measurements.

2.2 Work Package II: Composite Load-Bearing Capacity under Dynamic Loading

The bond resistance under dynamic loading was investigated as part of Work Package II using three different experiments. The damage to the bond was investigated through the increase in relative displacements between the concrete body and the glued CFRP strip measured in fatigue tests on double-strip test specimens strengthened only by these strips. Varying upper and lower loads as well as concrete strengths were used. To be able to transfer the results onto flexural members two additional tests were performed on slabs reinforced with CFRP strips. Finally, double-strip test specimens with mixed reinforcement were used to investigate the tensile force distribution between steel bars and CFRP strips when the strips' bonds begin to fail.

The test results were summarised in a Goodman-Smith Diagram similar to Figure 2.4 for evaluation. This diagram illustrates the areas between upper and lower load levels where no damage occurs. Between the limit curves of upper load F_L^O and lower load F_L^U the fatigue range can be read off where there is no damage. The upper and lower loads are forces in the strips that occur at the load-facing end of the test body or above cracks.

To estimate the load levels the limit curve of the upper load was initially assumed to be linear. In previously performed tests it had been determined that for upper loads F_L^O in the elastic range and at full fatigue range with a factor of $R = F_L^U/F_L^O \sim 0,4$ (with a purely pulsating load where $F_L^U = 0$) no damage occurs. This load combination marks the lower left point on the straight line in the first quadrant of Figure 2.4. An additional point on this line is the maximum bond failure load F_{Lb} that was determined in static tests. Lower loads F_L^U with 15, 30, 45 and 60% of the bond failure load F_{Lb} were investigated. Initially, a fatigue range was set which was lower than the difference between upper and lower loads shown in Figure 2.4. If no damage occurred during this test the fatigue range was increased. The investigated load levels are given as solid dots in Figure 2.4. For determining the limit curve at least two tests were required. If no damage occurred in the second test either a third test with an increased upper load was performed (marked as clear dots in Figure 2.4). Table 2.1 gives an overview over the test program:

Table 2.1: Test Program

Series A - Unreinforced Tension/Compression Bodies				
	Load Level	C 20/25	C 40/50	C 50/60
Static Tests	F_{Lb}	x	x	x
Dynamic Tests	LS A	x	x	x
	LS B	x		
	LS C	x	x	
	LS D	x		x
Series B - Reinforced Tension/Compression Bodies				
	Load Level	C 20/25		
Dynamic Tests	LS A	x		
	LS B	x		
Series C – Slab Tests				
	Load Level	C 20/25		
Dynamic Tests	LS 1	x		
	LS 2	x		

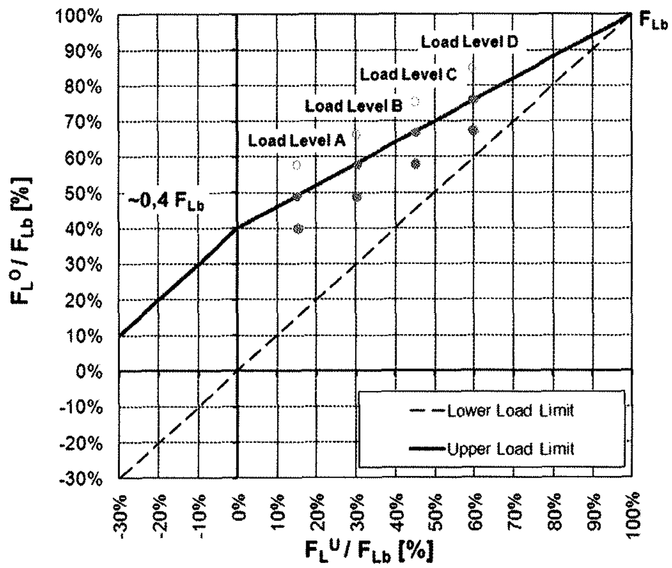

Figure 2.4: Linear Goodman-Smith-Diagram with relative upper and lower loads

Figure 2.5 shows the test apparatus for the tension/compression bodies. The relative displacements were measured using displacement transducers and the strip strains were observed using chains of strain gauges.

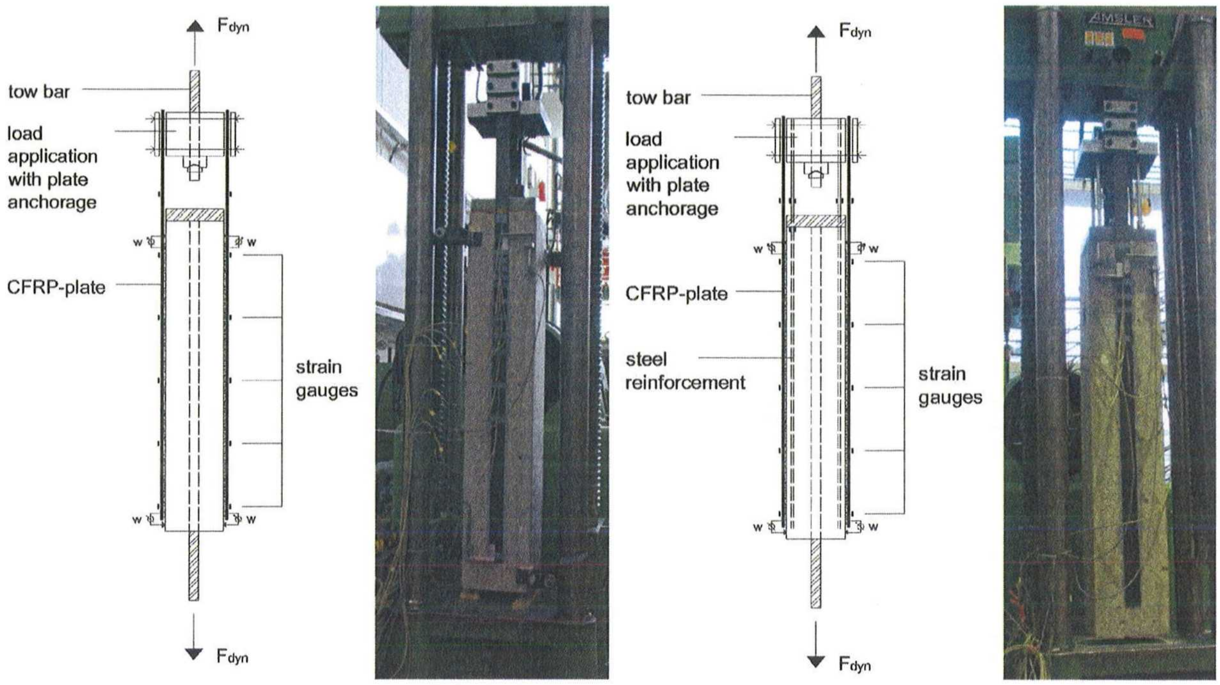

Figure 2.5: Test apparatus for unreinforced (left) and reinforced (right) test specimens

The slabs were produced without any reinforcement in the tensile zone. The dynamic experiments were carried out as four-point bending tests. Decoupling effects were expected at the supports and the point of load application. In these areas, saw cuts were applied in order to dictate the crack pattern. The strip strains were measured across these saw cuts. The test set-up is shown in Figure 2.6.

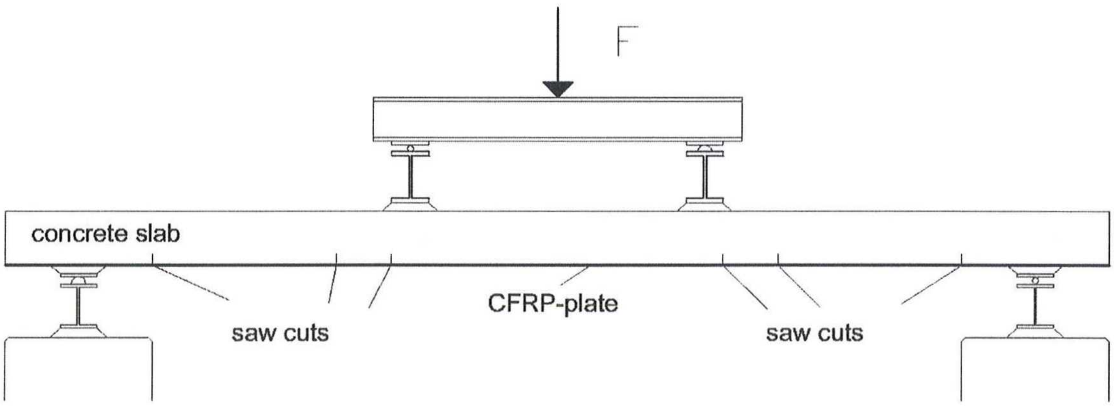

Figure 2.6: Test apparatus for slab tests

2.3 Work Package III: Shear Resistance

As part of Work Package III shear tests were performed on concrete structural members reinforced with CFRP strips that were either glued to the surface or placed into slits. Both the concrete strength and the reinforcements were varied. Aside from flexural strengthening for some parts of the tests, shear strengthening was applied using adhesive steel stirrups. On any given structural member at least two tests were performed. For the tests with glued CFRP strips two concrete girders and one slab were tested. Another two concrete girders were tested where the CFRP strips were glued into slits. A total of eleven shear test were performed using the apparatus shown in Figure 2.7 where always only one half of the girder was tested. Failure of or damage to the remaining half was prevented by steel sections connected to threaded bars which acted as external stirrups.

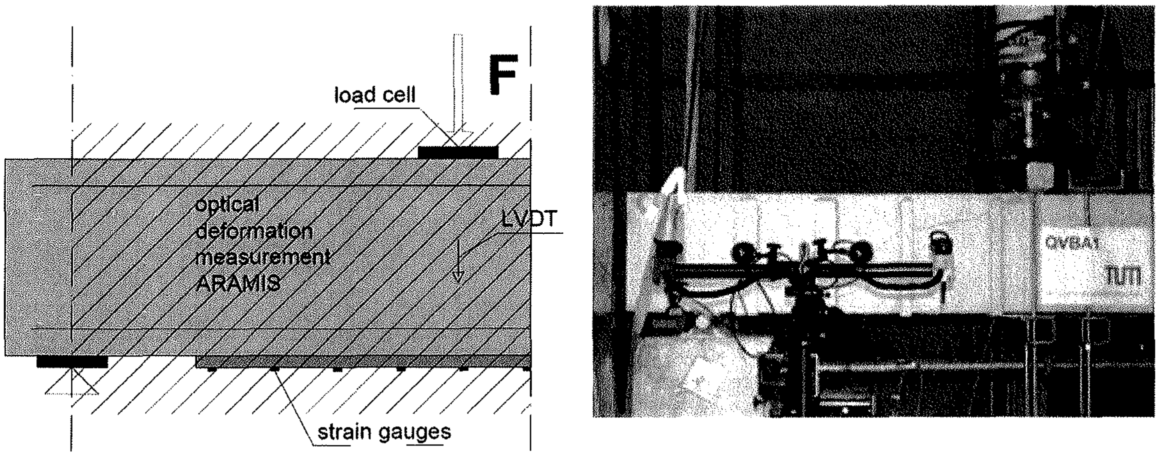

Figure 2.7: Test set-up for the shear tests (left) and measurement apparatus (right)

3 Results

3.1 Work Package I: Composite Load-Bearing Capacity under Static Loading

End Anchorage

Based on the results of the end anchorage tests performed as part of this research project as well as a great number of test series performed in the past at the participating research institutions and testing authorities, an influence of the reinforcing material used can be ascertained. Because of their higher strain level CFRP strips behave slightly more favourably than adhesively applied steel straps. The base value for bond force transfer at the end anchorage point was specified differently for CFRP strips and steel straps. For steel straps it is recommended to continue using the current model by Niedermeier, while for CFRP strips the bond model by Zehetmaier should be used instead.

Idealised Inter-Crack Element

From the tests on the idealised inter-crack element it was ascertained that bond friction between already decoupled surface and the concrete occurs because of the interlocking of the rough surfaces. This effect was then evaluated in relation to the concrete strength and mean and characteristic values for the friction bond stresses were determined. These values were then compared to the test results by Thorenfeldt and Schilde who used a similar test apparatus. The friction bond stresses of the newly performed experiments were in part significantly lower than for the other two test series – a result of the difference in grain used in the concrete. Thus the newly obtained values constitute a safe lower boundary for the friction bond stress.

Effects Specific to Structural Members

For the tests on the inter-crack element part of a structural member the new test set-up allowed investigations on different sections and thus different types of inter-crack elements on an actual structural member. Through these tests it was possible to determine the influences on the bond force transfer directly on a structural element. Aside from the influences previously observed in the other tests, it was determined that thinner members act more favourably than thicker members. This is due to the effect of the curvature. This curvature can be a precamber or flexural deflection of the member under load. A positive convex curvature always acts positively on the bond force as the forces associated with the change of direction induce contact pressure in the CFRP strip. A negative curvature, however, creates a lifting tensile force in the strip which must also be considered. The curvature effect must thus be included not just because of economical but also for safety reasons. It was possible to quantify both the positive and negative effects of the curvature because of these tests.

Modelling
The relationship between bond stress and slippage can be expanded step by step based on the test results. From the idealised end anchorage tests one can obtain the fundamental value on which everything is based. The results of the idealised inter-crack element expand the relationship by a constant friction level. The curvature effect must then be added as a change in the parameters of the relationship. Thus all values become dependent on the structural member's curvature. These deliberations then result in the bond stress/slippage relationship illustrated by Figure 3.1.

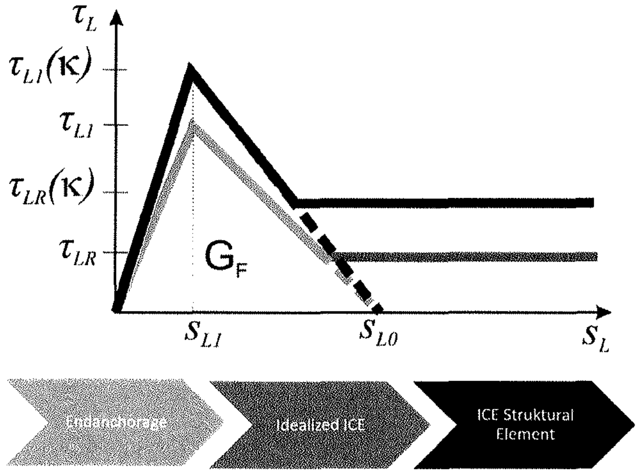

Figure 3.1: Step-by-step modelling of the bond energy occurring at the inter-crack element

Built on the quantification of the effects presented above and the design recommendations, a simplified design formula was derived for the resistible bond force change on a structural member. This design formula varies with strip thickness, concrete strength, crack spacing as well as structural member thickness which is included through its curvature. With this formula and generally accepted considerations for the end anchorage point a recommendation was provided for the bond resistance check for flexural structural member adhesively reinforced with CFRP strips.
Using this check it is now possible to design the strengthening of reinforced and prestressed concrete members realistically, safely and cost-effectively.

3.2 Work Package II: Composite Load-Bearing Capacity under Dynamic Loading

A prerequisite for performing dynamic tests is the determination of the bond failure force F_{Lb}. This force is determined using static tensile tests on double-strip test specimens. The test set-up is identical to that of the dynamic experiments (refer to Figure 2.5).

For Load Level A lower loads of roughly 15% of the static bond failure load F_{Lb} where applied to the strips. During the first test at this load level no damage, i.e. no relative displacement s_L, was observed. Neither did any damage occur during the second test. Only during the third test at Load Level A could a significant increase in relative displacements s_L be registered by the displacement transducers. As shown by the measured data, the relative displacement at side A for 100,000 load reversals was 6.07 μm. To determine the slope, sections with a linear increase are used. On Side A the slope is determined using a regression based on the measured data up to a number of load cycles with 1.2 million load reversal. The number of load cycles necessary to reach the relative displacement s_{L0} is then extrapolated. When the upper strip strain of 1367 μm/m is reached, the relative displacement is 68 μm. From the slope and the relative displacement upon achieving the upper load it can be derived that the relative displacement s_{L0} of 152 μm is reached after 1,383,802 load reversals where full decoupling occurs.

The fatigue strength is then determined using the method described by Block. From N number of load cycles until full decoupling and the corresponding fatigue range of the strip forces $\Delta F_{L,i}$ a Wöhler line (S/N curve) can be established from which the durable fatigue range for purely pulsating loads can be determined. For a purely pulsating load, i.e. when the lower load is 0 kN, a stress range equal to the bond failure force F_{Lb} can be supported only once. The supportable stress range drops asymptotically with an increasing number of load cycles towards a limit value, the fatigue strength. If a Goodman-Smith diagram is assumed to have a linear relationship, it then follows that the Wöhler lines for various load levels can be merged into each other by simple transformation.

Fig. 3.2 shows the adapted Wöhler Line in comparison to the measured data. In reverse, the reduction in supportable stress range with increasing lower loads in the Goodman-Smith diagram can be described using the Wöhler Line. The fatigue strength $\Delta F_{L,D,0}$ determines the slope by which the supportable stress range in the Goodman-Smith diagram drops. This adaptation also fixes the limit curve of the upper load in the Goodman-Smith diagram. Fig. 3.3 shows the test results together with the adjusted limit curve for the upper loads. Tests where there was no significant increase in relative displacements are shown with a solid symbol. The others – where damage in the form of a significant increase in relative displacement was observed – are marked with clear symbols instead.
The adaptation shows a good correlation between the test results in the areas of high upper loads. In areas of small lower loads the adjusted limit line is somewhat conservative. There are some test results without damage above the limit curve. Thus a bilinear limit line was used in Fig. 3.3 for the upper loads.

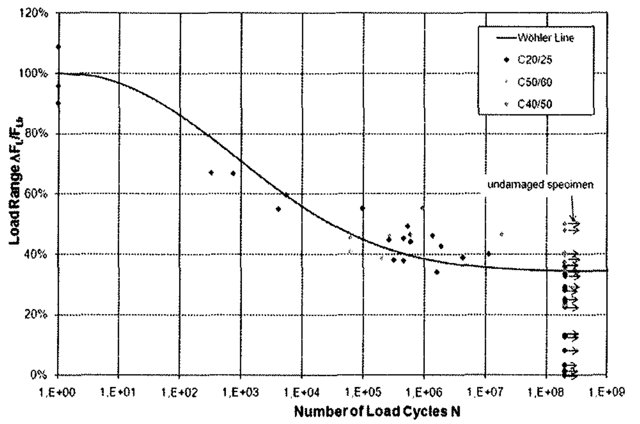

Fig. 3.2: Wöhler Line in comparison to the data measured for the relative displacement

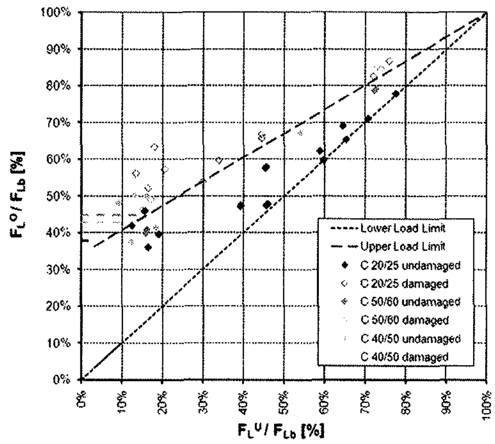

Fig. 3.3: Goodman-Smith diagram with test results for unreinforced test specimens

The horizontal part of the limit curve marks the limit of the elastic zone. According to Hankers, there is no damage when the upper load F_L^O as related to the bond failure load F_{Lb} lies below $0.348 \cdot f_{ct}^{1/4}$. In this case the maximum bond stress τ_{L1} is not reached, loading and unloading paths are on top of each other and there is no increase in relative displacements, i.e. no damage occurs.

In the experiments on reinforced tension/compression bodies a definite redistribution process could be observed when the strip decoupling begins. The decrease in strip strain – and the increase in steel strain – reduces itself with an increasing number of load cycles. It can be assumed that the redistribution process continues slowly until such a state is achieved where the strip forces are reduced to a level where no further damage to the bond is possible.

The slab tests were evaluated based on the maximum supported slip forces at the inter-crack elements. Analogous to the aforementioned methods, the stress range of the strip force is determined using the stress strains across the saw cuts for purely pulsating loading $\Delta F_{L,0}/F_{Lb}$. Depending on the number of load cycles until the strips are completely decoupled, the data can be compared with the Wöhler line from Fig. 3.2. The design concept is based on the bilinear limit curve of the upper load from Fig. 3.3 and thus depends on two checks. On one hand, it can be verified whether the upper load is within the elastic range. If this condition is not met, then the fatigue range must be verified.

3.3 Work Package III: Shear Resistance

Shear Resistance

The shear resistance of structural members with adhesive reinforcing has so far been described by the boundary values of DIN 1045 (7.88) and Schmidhuber's shear model. With Schmidhuber's model the shear resistance is reduced with increasing strip strain as he assumes that the interlocking of the cracks is reduced when they widen.
The experiments showed that the recommendations from DIN EN 1992-1-1 and DIN 1045-1 (8.08) can be applied to adhesive reinforcement. Furthermore, Schmidhuber's model was recalculated based on the bond approach of Work Package I and a more realistic maximum crack spacing due to the presence of the reinforcing bars. Based on this recalculation it can be shown that Schmidhuber's model cannot govern as the strip will decouple beforehand. Depending on the bond characteristics of

the reinforcing steels already present in the structure, design recommendations were made for the shear resistance of strengthened reinforced concrete members.
The strengthening of structural members with adhesive reinforcement placed into slits can currently only be executed for shear zones 1 and 2 of DIN 1045 (7.88). As the CFRP strips inside the slits show very effective bond behaviour which surpasses that of ribbed steel reinforcing bars this results in significantly smaller crack widths and thus in an increase in the shear capacity. For this reason and based on the empirical results, the shear design can indeed be performed in accordance with DIN 1045-1 (8.08) or DIN EN 1992-1-1.

Formation of Offset Cracks
An offset crack occurs when the concrete cover at the end of a strip breaks away from the internal reinforcing. In order to prevent such offset cracking stirrups were placed at the end of the strip once the shear stress reached a limit value according to DIN 1045 (7.88). As this resulted in an unnecessarily high number of stirrups especially for girders with a low amount of reinforcement and because this check is actually incongruent with the regulations in DIN 1045-1 (8.08) and DIN EN 1992-1-1, this required further investigations. Starting from an internationally approved model on offset cracking by Jansze and a multitude of tests where such offset cracking occurred, a new limit was fixed below which no offset cracks would occur. This limit value is described in dependence of the shear resistance according to DIN 1045-1 (8.08) or DIN EN 1992-1-1.

Shear Strengthening
As in some cases of structural members to be strengthened the shear resistance will be insufficient for the intended loads, shear strengthening is also necessary. Based on the tests preformed and many others taken from pertinent literature, design models were developed for shear strengthening. These design models consider both fully closed and half-closed adhesively applied stirrups made of either steel or fibre composites. Using these models which are congruent with currently used concepts in applicable codes it is possible to strengthen a structural member for shear both safely and economically.

4 Outlook

With these investigations and their results it is now possible to close most of the gaps still present in the current state of research which have been summarised in the status report of the *Deutscher Ausschuss für Stahlbeton* (DAfStb).
Through the development of new practice-oriented design approaches for the bond resistance under static and dynamic loading as well as shear resistance such aspects were also considered which substantially contribute to an increase in cost-effectiveness and widen the areas of applicability of the strengthening methods thus contributing to the durable use of existing buildings. The project results form the basis for preparing a DAfStb guideline in which these approaches are implemented in a manageable fashion for structural and checking engineers, and which include provisions and aids for executing structural strengthening works. This guideline also offers favourable conditions for the construction industry with regard to international competition.
The design approaches developed will be included directly into the DAfStb guideline as a generally accepted rule of practice that in the short term will supplement European and national regulations through design and execution directions, and thus ensure the application of technically approved or standardised materials at a consistently high level of technology. As all proper authorities were included in the bond project and the corresponding structures within the project were also created simultaneously, a publication of the guideline is expected by midyear of 2011.