# FATIGUE BEHAVIOR OF FASTENINGS WITH SUPPLEMENTARY REINFORCEMENT: CURRENT NEED FOR RESEARCH

# ERMÜDUNGSVERHALTEN VON BEFESTIGUNGEN MIT RÜCKHÄNGEBEWEHRUNG: AKUTELLER FORSCHUNGSBEDARF

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## SUMMARY

So far there is rather limited knowledge about the fatigue behavior of cyclic loaded fasteners, which are increasingly used nowadays in filigree concrete structures with low embedment depth and small edge distances. In contrast to the static design, the reinforcement installed in the component may therefore not be used under fatigue loading. Consequently, concrete failure is becoming decisive in the fatigue design, which leads to relatively uneconomical results.

This paper summarizes the current design provisions as well as the state of the art of fastenings under fatigue loading and gives an overview of the current limitations. The need for future investigation is identified and a recent research project is presented in order to develop a verification procedure that considers the reinforcement of the component.

## ZUSAMMENFASSUNG

Zum Tragverhalten von zyklisch beanspruchten Befestigungen, die heutzutage immer häufiger in schlanken Betonbauteilen mit geringen Verankerungstiefen und kleinen Randabständen ausgeführt werden, liegen bisher nur wenige Kenntnisse vor. Anders als bei der statischen Bemessung darf daher die im Bauteil vorhandene Bewehrung unter Ermüdungsbeanspruchung nicht angesetzt werden. Beim Nachweis der Ermüdungstragfähigkeit wird somit in vielen Fällen Betonversagen maßgebend, was relativ unwirtschaftliche Rechenergebnisse liefert.

Dieser Beitrag fasst die aktuellen Bemessungsregeln sowie den Forschungsstand von Befestigungen unter Ermüdungsbeanspruchung zusammen und gibt einen

Überblick über die derzeitigen Anwendungsgrenzen zum traglaststeigernden Ansatz einer Rückhängebewehrung. Daraus wird der Bedarf an zukünftigen Untersuchungen abgeleitet und ein laufendes Forschungsvorhaben vorgestellt, um ein Nachweisverfahren unter Berücksichtigung der Bauteilbewehrung zu entwickeln.

# 1. INTRODUCTION

Fasteners play an important role in the building and construction industry. They are used, e.g. in foundation bases, machine foundations and composite structures in infrastructural engineering to connect steel elements with reinforced concrete components. The force transmission takes place in a very concentrated area and leads to a challenging task especially with connections close to the edge. As a result of increasingly filigree structures, cyclic loads are becoming more and more decisive for the dimensioning of the components in addition to static actions. Consequently, concepts for the avoidance of fatigue failure are coming into focus. With their help, the previous fields of application can be expanded or even new ones opened up.

For fastenings located close to concrete edges only few studies are available in the case of cyclic loading. Therefore, in contrast to static loading, the reinforcement present in the component cannot be applied in the fatigue design. The calculated fatigue resistance of the connection is thus limited by concrete failure, which leads to very uneconomical results and requires a current need for research.

# 2. STATE OF STANDARDIZATION AND RESEARCH

## *2.1 Fatigue design of fastenings*

The design of fastenings in concrete under fatigue relevant cyclic actions is covered in EN 1992-4 [1]. The fatigue verification is based on the concept of partial safety factors according to the design rules of the Eurocodes. It shall therefore be satisfied that the design actions are smaller than or equal to the design resistance. Due to the various failure mechanisms of the anchoring system the verification is performed, similar to the design under static loading, separately for each load direction and relevant failure mode. The design provisions apply to post-installed anchors and headed anchors subjected to pulsating tension and shear loads, alternating shear loads and any combinations of these loads. Compression loads are assumed to be transferred directly via the anchor plate to the concrete without affecting the load transfer mechanism of the anchor. Shear loads with lever arm are not covered, since they result in an additional bending moment that can lead to a reduction of the fatigue resistance. Furthermore, an annular gap between the anchor and the fixture is not allowed and loosening of the nut or bolt should be avoided to prevent impact loads in case of alternating actions.

The required verifications for fatigue tension and shear load are shown in Table 1 and Table 2. The possible failure modes include steel failure, concrete cone failure, pull-out failure or combined pull-out and concrete cone failure of bonded anchors, splitting failure and concrete blow-out failure under tension load and steel failure, concrete pry-out failure and concrete edge failure under shear load.

*Table 1: Fatigue verification under tension loading according to EN 1992-4 [1]*

| | Failure mode | Single anchor | Anchor group | |
|---|---|---|---|---|
| | | | Most loaded anchor | Anchor group |
| 1 | Steel failure | $\gamma_{F,fat}\,\Delta N_{Ek} \leq \frac{\Delta N_{Rk,s}}{\gamma_{Ms,fat}}$ | $\gamma_{F,fat}\Delta N_{Ek}^{h} \leq \frac{\psi_{FN}\Delta N_{Rk,s}}{\gamma_{Ms,fat}}$ | |
| 2 | Concrete cone failure | $\gamma_{F,fat}\,\Delta N_{Ek} \leq \frac{\Delta N_{Rk,c}}{\gamma_{Mc,fat}}$ | | $\gamma_{F,fat}\Delta N_{Ek}^{g} \leq \frac{\Delta N_{Rk,c}}{\gamma_{Mc,fat}}$ |
| 3 | Pull-out failure | $\gamma_{F,fat}\,\Delta N_{Ek} \leq \frac{\Delta N_{Rk,p}}{\gamma_{Mp,fat}}$ | $\gamma_{F,fat}\Delta N_{Ek}^{h} \leq \frac{\psi_{FN}\Delta N_{Rk,p}}{\gamma_{Mp,fat}}$ | |
| 4 | Concrete splitting failure | $\gamma_{F,fat}\,\Delta N_{Ek} \leq \frac{\Delta N_{Rk,sp}}{\gamma_{Mc,fat}}$ | | $\gamma_{F,fat}\Delta N_{Ek}^{g} \leq \frac{\Delta N_{Rk,sp}}{\gamma_{Mc,fat}}$ |
| 5 | Concrete blow-out failure | $\gamma_{F,fat}\,\Delta N_{Ek} \leq \frac{\Delta N_{Rk,cb}}{\gamma_{Mc,fat}}$ | | $\gamma_{F,fat}\Delta N_{Ek}^{g} \leq \frac{\Delta N_{Rk,cb}}{\gamma_{Mc,fat}}$ |

*Table 2: Fatigue verification under shear loading according to EN 1992-4 [1]*

| | Failure mode | Single anchor | Anchor group | |
|---|---|---|---|---|
| | | | Most loaded anchor | Anchor group |
| 1 | Steel failure without lever arm | $\gamma_{F,fat}\,\Delta V_{Ek} \leq \frac{\Delta V_{Rk,s}}{\gamma_{Ms,fat}}$ | $\gamma_{F,fat}\Delta V_{Ek}^{h} \leq \frac{\psi_{FV}\Delta V_{Rk,s}}{\gamma_{Ms,fat}}$ | |
| 2 | Concrete pry-out failure | $\gamma_{F,fat}\,\Delta V_{Ek} \leq \frac{\Delta V_{Rk,cp}}{\gamma_{Mc,fat}}$ | | $\gamma_{F,fat}\Delta V_{Ek}^{g} \leq \frac{\Delta V_{Rk,c,p}}{\gamma_{Mc,fat}}$ |
| 3 | Concrete edge failure | $\gamma_{F,fat}\,\Delta V_{Ek} \leq \frac{\Delta V_{Rk,c}}{\gamma_{Mc,fat}}$ | | $\gamma_{F,fat}\Delta V_{Ek}^{g} \leq \frac{\Delta V_{Rk,c}}{\gamma_{Mc,fat}}$ |

For a group of anchors an additional reduction factor must be applied on the resistance side of the most unfavourable anchor to consider unequal load distribution. For combinations of tension and shear loads the corresponding interaction verification according to EN 1992-4 [1], Equation (8.1) shall be fulfilled separately for steel failure and all other failure modes.

The fatigue loads acting on the fastening shall be taken from a structural analysis. The fatigue actions can be represented by existing load models or variable loads with a specified number of occurrences. The fatigue resistance values depending on the number of load cycles are taken from the relevant European Technical Assessment (ETA) for each failure mode. Therefore, each product used for fatigue loading needs to be qualified by appropriate tests and assessment procedures. The fatigue resistance for all concrete related failure modes is given in EN 1992-4 using the simplified approach of 50% of the static value for $2 \cdot 10^6$ load cycles.

Furthermore, there exist additional design rules for different types of fasteners. The design method for post-installed anchors under fatigue loading is specified by the Technical Report EOTA TR 061 [2]. Since the fatigue verification of anchor channels is not covered by the provisions of EN 1992-4, specific design rules for anchor channels under fatigue tension loading are provided by the Technical Report EOTA TR 050 [3].

All the design guidelines mentioned above do not contain any provisions for the verification of supplementary reinforcement. Consequently, the design rules apply only for fastenings without additional reinforcement and a positive effect of the reinforcement on the resistance may not be considered under fatigue loading.

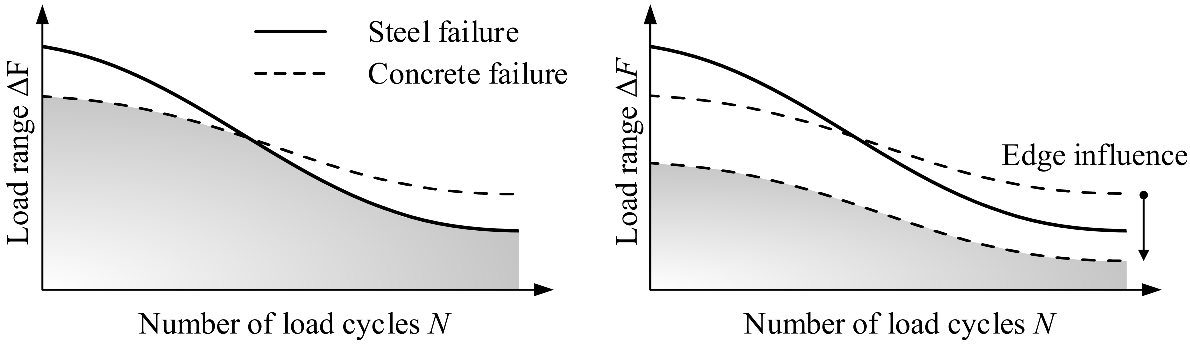
## 2.2 Fatigue behavior of connections in concrete

In order to safely transfer the forces acting on a fastener to the anchor base, the anchoring element and the concrete must interact. The fasteners show different types of failure when subjected to a load [4]. Factors influencing the failure mode are particularly the direction or type of load, the anchor base and the position of the fastener in the component as well as the anchor type itself. In principle, the same failure modes are possible under static and cyclic loads. However, in contrast to the static behavior, the fatigue resistance is a time dependent value and the decisive failure mode is related to the applied load range and the number of load cycles.

The dependence of the failure mode as a function of time is illustrated in Fig. 1. Previous fatigue tests have shown that steel failure often becomes decisive with increasing number of load cycles, if the fastener is located far from the concrete edge. This failure mode has been extensively studied within the research project

IGF 20458N [5]. The main objective of this project was to investigate the influence of the static load level on the fatigue resistance of different types of anchors. It was observed that the linear design approach of the Goodman-Diagram is conservative and lead to uneconomical results.

These investigations are limited to steel failure of fasteners located far from the edge. In case of applications close to an edge or for anchors with reduced embedment depth, the load transfer mechanism is disturbed by the anchor base, so that concrete related failure modes, e.g. concrete cone failure under tension load or concrete edge failure under shear load may become decisive.




*a) fasteners far from edge* *b) fasteners close to edge*

*Fig. 1: Governing failure modes under fatigue loading*

## 2.3 Fatigue behavior of concrete

Extensive fatigue tests have been carried out on fasteners to investigate concrete cone failure under pulsating tension load [6], [7], [8], [9]. The experimental data base is shown in Fig. 2. The existing test results up to $5 \cdot 10^7$ load cycles show that the fatigue resistance may be assumed to be 50% of the static resistance at $2 \cdot 10^6$ load cycles as given in EN 1992-4. It should be noted, however, that the test results exhibit a large scatter. Research results by Tóth [7] indicate that the S-N curves for concrete cone failure do not have a fatigue endurance limit. This confirms the assumption for plain concrete according to MC 2010 [10], in which the fatigue strength for concrete in compression is given as 45% of the static resistance at $10^8$ with a further decrease for higher number of load cycles. The influence of embedment depth, testing frequency, concrete strength and variable amplitude loading were investigated in [7]. Furthermore, it has been found that alternating tension-compression loads on the anchor base lead to a significant reduction of the fatigue resistance compared to tension loads. However, this is currently not considered in the design according to EN 1992-4, which might lead to non-conservative results.

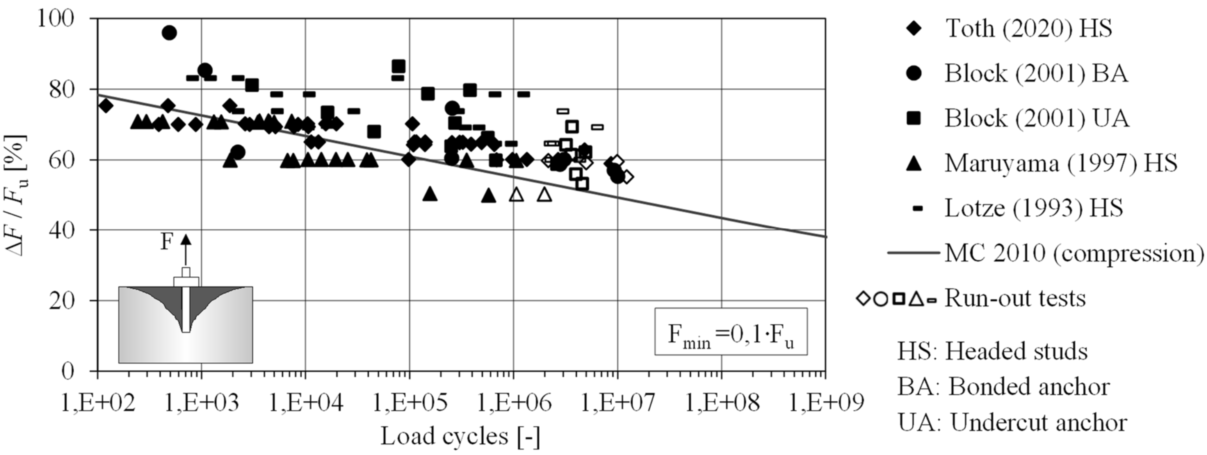



*Fig. 2: Test data for concrete cone failure under tension load acc. to [6 - 9]*

For fasteners where the shear load acts towards the edge, failure usually occurs due to concrete edge failure. The load-bearing capacity depends mainly on the edge distance, the anchorage depth, the specimen dimensions and the properties of the concrete. The fatigue resistance against concrete edge failure is assumed to be 50% of the static resistance at $2 \cdot 10^6$ cycles as under tension loads in the design. However, there are rather limited experimental studies available so far. Test results by Block [6] indicate that the fatigue resistance for concrete edge failure is lower than for concrete cone failure.

Fig. 3 summarizes the existing results for concrete edge failure under shear load. The data is limited to two types of post-installed anchors of size M12. The results show large scatter analogous to concrete cone failure. It should be noted that the minimum edge distance was not maintained in these tests. Analogous to the investigations under tension load, it is assumed that there is no endurance limit of the concrete fatigue resistance under shear load. Alternating shear loads acting close to the edge may have a negative effect on the fatigue resistance against concrete edge failure. However, no test results are available until now. Note that the existing fatigue data for both concrete cone failure and concrete edge failure is limited to studies on single anchors without investigating load distribution effects within an anchor group.

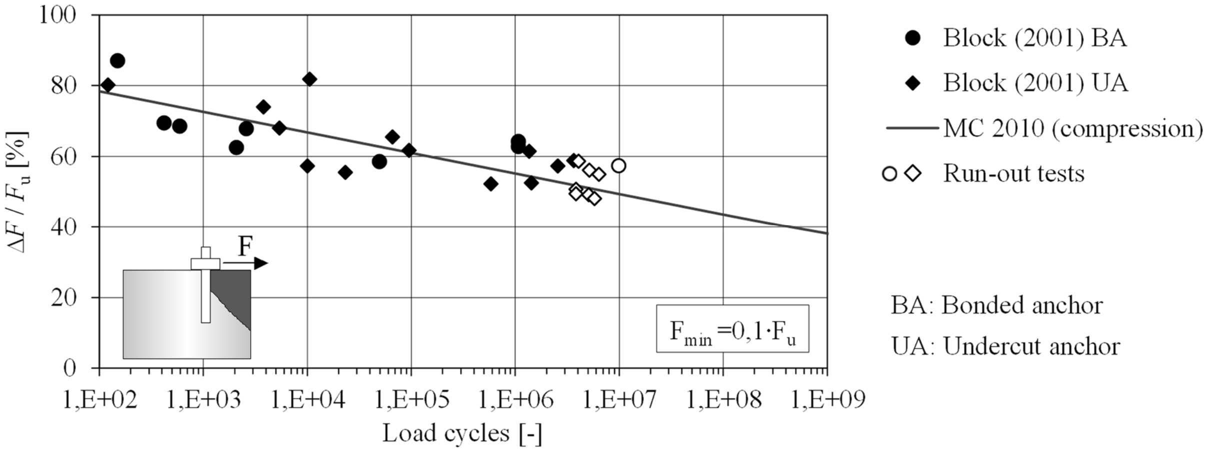



*Fig. 3: Test data for concrete edge failure under shear load acc. to [6]*

## 2.4 Structural behavior of reinforcement in fastening technology

The resistance of fasteners is usually determined by tests in unreinforced concrete. In the case of static loads, the potential failure modes of concrete edge failure in tension and concrete edge failure in shear need not to be verified, if a sufficiently dimensioned reinforcement has been installed. This supplementary reinforcement must be designed for the total acting load against both steel failure and anchorage (bond) failure. The required verifications for the reinforcement are specified in EN 1992-4 [1], section 7.2.1.9 for tension and section 7.2.2.6 for shear load. The resistance to yielding of the supplementary reinforcement under tension load is determined by using the following equation:

$$\mathrm{N_{Rk,re}} = \sum_{i=0}^{n_{re}} A_{\mathrm{s,re,i}} \cdot f_{\mathrm{yk,re}} \qquad \text{with: } f_{\mathrm{yk,re}} \leq 600\ \mathrm{N/mm^2} \qquad (1)$$

Under shear load, the efficiency factor $k_{10}$ is added to consider the position of the reinforcement. It is 1,0 for surface reinforcement and 0,5 for stirrups or loops surrounding the fastener.

$$\mathrm{N_{Rk,re}} = k_{10} \sum_{i=0}^{n_{re}} A_{\mathrm{s,re,i}} \cdot f_{\mathrm{yk,re}} \qquad \text{with: } f_{\mathrm{yk,re}} \leq 600\ \mathrm{N/mm^2} \qquad (2)$$

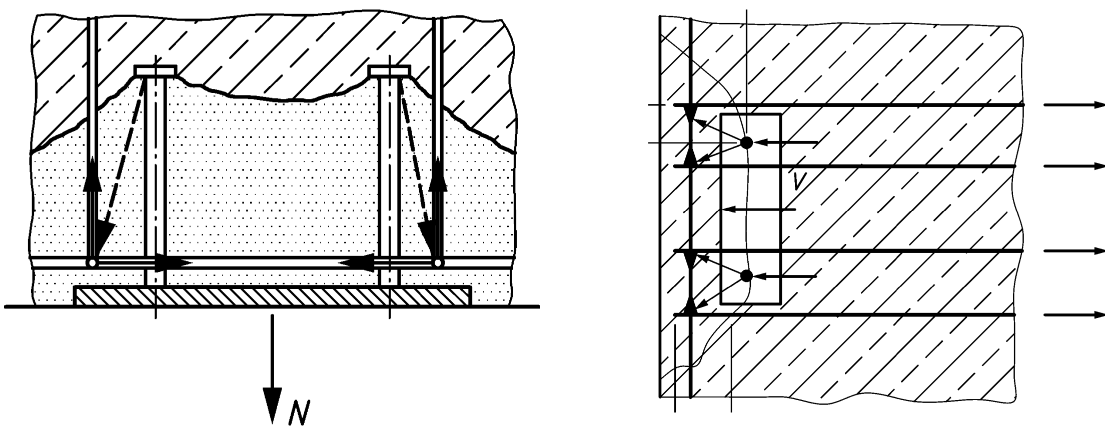
The design resistance of the supplementary reinforcement for fasteners against anchorage (bond) failure in the concrete cone can be determined as follows:

$$N_{Rd,a} = \sum_{i=1}^{n_{re}} N_{Rd,a}^{0} \qquad (3)$$

with:

$$N_{Rd,a}^{0} = \frac{l_1 \cdot \pi \cdot \emptyset \cdot f_{bd}}{\alpha_1 \cdot \alpha_2} \leq A_{s,re} \cdot f_{yk,re} \cdot \frac{1}{\gamma_{Ms,re}} \tag{4}$$

The anchor reinforcement may consist of a surface reinforcement or stirrups and loops for anchoring back the concrete breakout body. For the arrangement of the reinforcement, constructive requirements need to be considered as stated in EN 1992-4 [1], section 7.2.1.2 for tension and section 7.2.2.2 for shear loads. The force acting on the reinforcing bar is determined by using a strut and tie model as shown in Fig. 4. This procedure is based on numerous investigations under static loads, see e.g. [4], [11], [12], [13].




*a) Tension load* *b) Shear load*

*Fig. 4: Strut and tie model for supplementary reinforcement according to EN 1992-4 [1]*

In contrast to static loading, the resistance increasing effect of the reinforcement is not allowed to be applied under fatigue loads according to EN 1992-4 [1]. In this case, the loads are acting at a lower level than in the static case. However, the reinforcement is activated, if cracks in the concrete occur, and takes over the load transfer. Since the fatigue studies performed until now are limited to tests in concrete without reinforcement, it is questionable whether the reinforcement is effective at all under fatigue loading.

## 3. RESEARCH NEEDS AND ONGOING RESEARCH

For fasteners installed with low embedment depth and small edge distances, the fatigue resistance is usually limited to concrete cone failure (tension) or concrete edge failure (shear). Since the current design provisions for fatigue loading do not consider the beneficial effect of additional reinforcement in the concrete member, this kind of applications leads to relatively uneconomical results when compared to the static approach.

In the absence of available knowledge, systematic investigations are required in order to prove the effectiveness of the reinforcement for fasteners under fatigue loading. Future studies and required objectives of investigation should be based on the current static requirements, since both verifications must be complied in the design.

The influence of the reinforcement on concrete-steel connections close to the edge subjected to fatigue shear loads is currently being investigated at the University of Stuttgart by the Materials Testing Institute and the Institute of Structural Design within the research project IGF 22283 N. The potential effect of reinforcement in case of an applied shear load is schematically shown in Fig. 5. Due to the small edge distance of the fastener, the fatigue resistance is governed by concrete edge failure. Since the reinforcement may not be considered for the load transfer under fatigue, this results in a very low utilization of the connection when compared to the maximum capacity corresponding to steel failure of the anchor.

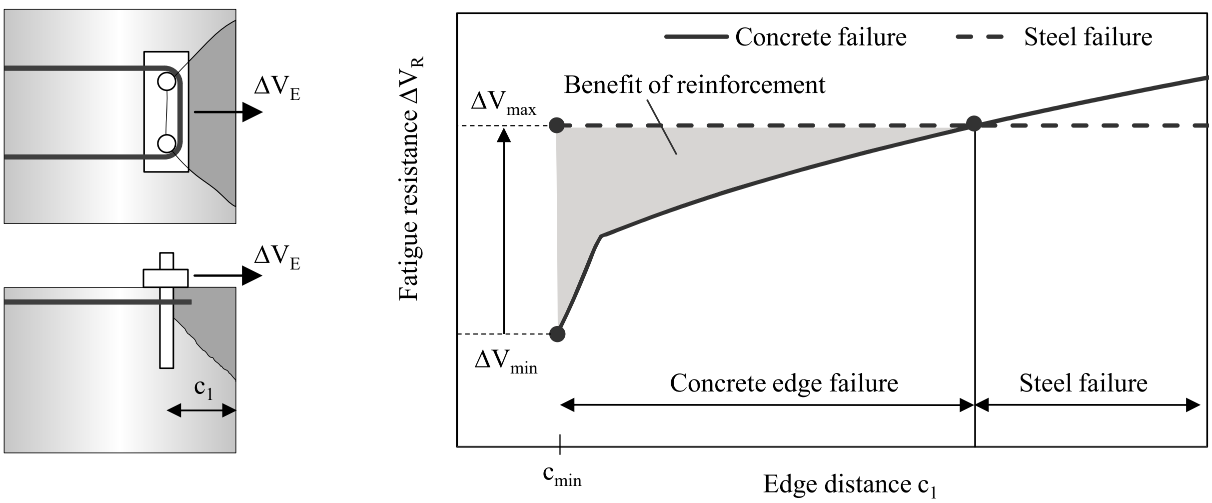



*Fig. 5: Fatigue resistance of a fastener under shear load (without use of reinforcement)*

The research project is intended to demonstrate the positive influence and benefits of the anchor reinforcement under fatigue loading. For this purpose, numerical and experimental investigations will be carried out. By using numerical models, various parameters including different reinforcement configurations and load combinations can be investigated. Thus, stress concentrations can be detected and the presentation of the general load transfer is possible. Due to the currently still very long computing times, the simulation of the models is limited to static calculations. However, different load levels, edge distances, reinforcement arrangements and rebar types can be investigated to identify the major influencing parameters. The knowledge gained by the numerical calculations simplifies the planning of the experimental investigations and helps to optimize the test setup. Starting from tests with fasteners in unreinforced concrete specimens, the results are compared with those in concrete specimens with surface reinforcement or stirrups as illustrated in Fig. 6. The position, number and diameter of the reinforcement is varied in the tests. Since these investigations focus on the different failure mechanism of single components, further tests are planned on complete connection details representing anchor groups with practice-orientated boundary conditions.

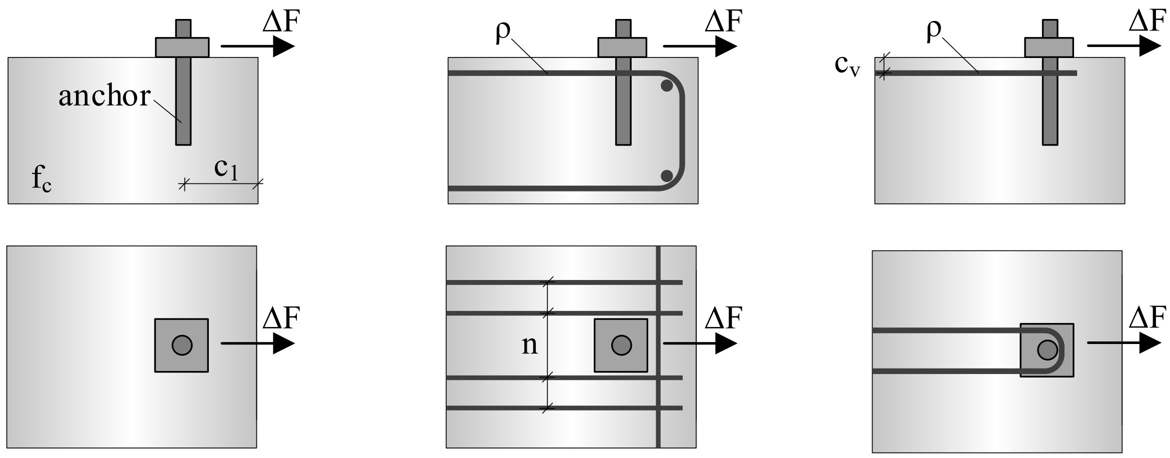



*Fig. 6: Test specimen with different configurations of reinforcement*

The objective of the project is not only to create a solid data base for the fatigue behavior of connections with supplemantary reinforcement under shear load. Furthermore, a practical design concept is to be developed on the basis of the investigations in order to simplify the work of planners and engineers. The use of the reinforcement leads to a better utilization of the connected components and thus to a more economical and sustainable construction method. New areas of application can thus be opened up.

## 4. SUMMARY AND OUTLOOK

There is currently no systematic research on the influence of the reinforcement on the fatigue resistance of fasteners. In applications with small distance to the member edge, the failure of the anchors is governed usually by concrete failure. Without the structural approach of supplementary reinforcement, the load-bearing behavior is underestimated, which leads to uneconomical component dimensions. The ongoing research project IGF 22283N is intended to provide an initial data base for fasteners close to the edge under fatigue shear loading. For this purpose, both numerical and experimental investigations will be carried out, on which a design concept for practical use and standardization will be developed.

In order to utilize the full potential of the reinforcement, a universal verification concept is required for all load directions, which include not only shear but also tension as well as combined tension and shear loads. If possible, this approach should be in conjunction with existing concepts under static loading. Further research should provide data on the concrete fatigue resistance under alternating shear loads acting near the edge and its behavior in anchor groups.

## 5. ACKNOWLEDGEMENT

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