FATIGUE OF FASTENINGS – INVESTIGATIONS ON THE EFFECT OF STATIC LOAD LEVEL

ERMÜDUNG VON BEFESTIGUNGEN – UNTERSUCHUNGEN ZUM EINFLUSS DES STATISCHEN LASNIVEAUS

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SUMMARY

The present state of knowledge on the fatigue resistance of fastenings in concrete is predominantly limited to results of pulsating tests at low minimum load. Consequently, very conservative assumptions are made in the fatigue design of fastenings under combined loading, which lead to relatively uneconomical results, especially in the case of steel failure.

Therefore, the current research project IGF 20458 N aims to investigate the fatigue behaviour of fasteners under superimposed static loads both experimentally and numerically. This article gives an overview of the current design rules for fastenings under fatigue loading and presents the work planned within the actual project.

ZUSAMMENFASSUNG

Der vorliegende Kenntnisstand zur Ermüdungstragfähigkeit von Befestigungen in Beton basiert im Wesentlichen auf Schwingversuchen im Schwellbereich mit geringer Unterlast. Bei der Bemessung von Befestigungen unter kombinierter Beanspruchung werden demzufolge sehr konservative Annahmen getroffen, die insbesondere bei Stahlversagen zu relativ unwirtschaftlichen Ergebnissen führen.

Daher zielt das aktuelle Forschungsvorhaben IGF 20458 N darauf ab, das Ermüdungsverhalten von Befestigungsmitteln bei überlagerter statischer Beanspruchung experimentell und numerisch zu untersuchen. Der vorliegende Beitrag gibt einen Überblick über die derzeitigen Bemessungsregeln für Befestigungen unter Ermüdungsbeanspruchung und stellt die im Rahmen des Vorhabens geplanten Arbeiten vor.

KEYWORDS: fastening, fatigue load, steel failure, mean stress effect, Goodman diagram

1. INTRODUCTION

In the building industry, fastening elements are used to connect steel components with concrete structures. Due to increasingly filigree building structures and modern machinery and production systems, the fatigue design of such fastenings is becoming more and more important.

In practice, fatigue relevant actions occur not only as pure cyclic loading, but usually in combination with static loading. In the design of fastenings, this case presents a particular challenge because the two loading conditions can thus influence the load-bearing behaviour of each other. Against this background, the resistance under static and cyclic load cannot simply be determined separately.

The current state of knowledge on fastenings under fatigue loading is mainly based on results of pulsating fatigue tests with low minimum load. Thus, present design provisions require a reduction of the fatigue resistance depending on the static load level by the use of the Goodman diagram. As an alternative, all acting loads are assumed to be fatigue relevant.

This approach tends to be rather conservative in case of steel failure, since the effect of mean stress on the fatigue strength of notched metal components like bolts or welds is negligibly small. In contrast, however, the behaviour of fastenings is influenced by the contribution of the concrete, whose fatigue strength has a pronounced mean stress effect.

For this purpose, the current IGF research project 20458 N focuses on the fatigue behaviour of fastenings in concrete under combined static and dynamic loading. Within the project, experimental and numerical studies are performed on various types of anchor systems in order to investigate the mean load effect of fasteners in case of steel failure. This paper gives an overview of the current design rules for fastenings under fatigue loading and presents the objectives as well as the work program planned within the actual research project.

2. FATIGUE DESIGN OF FASTENINGS

EN 1992-4 [1] provides European standardized regulations for the design of fastenings in reinforced concrete. In case of cyclic actions, the standard requires an additional verification of the fatigue resistance. As typical examples of fatigue relevant applications, fastenings of cranes, guide rails of elevators and machinery with rotating parts are mentioned. In engineering practice, it is recommended that fatigue verification should be carried out when fasteners are subjected to more than 1.000 load cycles of pulsating tension loads and 100 load cycles of alternating or pulsating shear loads [2].

The verification under fatigue loading is based on the concept of partial safety factors following the design rules of the Eurocodes. Therefore, it is necessary to prove that the design actions are smaller than or equal to the design resistance. Since the fatigue resistance of a fastening system is governed by the material behaviour of all components which are part of the load transfer, different failure modes have to be considered. Contrary to the design under static loading, the fatigue resistance is a time-varying value and the decisive failure mode can change depending on the load range and the number of cycles.

Due to different components, materials and manufacturing methods, the fatigue resistance of fasteners is product dependent. The products to be used for fatigue loading must be prequalified by appropriate tests and assessment methods. The resulting resistance values and application conditions are specified in the relevant European Technical Product Specifications.

The design provisions of EN 1992-4 [1] concerning fatigue apply to post-installed anchors and headed studs. Since, the fatigue verification of anchor channels is not included therein until now, additional design rules are available for this product. The following section gives an overview of the recent design rules for the different types of fasteners mentioned above.

2.1 POST-INSTALLED ANCHORS

The fatigue design of post-installed anchors is performed acc. to EN 1992-4 [1] or EOTA TR 061 [3]. The provisions cover anchors subjected to pulsating tension or shear load and alternating shear load. The products must be approved with an European Technical Assessment (ETA) based on the EAD 330250-00-0601 [4]. However, shear loads with lever arm and stand-off installations are not regulated.

The required fatigue verifications for a single fastener are summarized in Table 1, whereby each possible failure mode has to be verified separately. For a group of fasteners a reduction factor must be applied to the resistance of the most loaded anchor to consider unequal load distribution. In case of combined tension and shear loads, the appropriate interaction equation must be fulfilled.

Table 1: Required fatigue verifications for single fastener acc. to EN 1992-4 [1]

	Tension loading		Shear loading	
	Failure mode	Single fastener	Failure mode	Single fastener
1	Steel failure	$\gamma_{F,fat} \cdot \Delta N_{Ek} \leq \frac{\Delta N_{Rk,s}}{\gamma_{Ms,N,fat}}$	Steel failure	$\gamma_{F,fat} \cdot \Delta V_{Ek} \leq \frac{\Delta V_{Rk,s}}{\gamma_{Ms,V,fat}}$
2	Concrete cone failure	$\gamma_{F,fat} \cdot \Delta N_{Ek} \leq \frac{\Delta N_{Rk,c}}{\gamma_{Mc,fat}}$	Concrete pry-out failure	$\gamma_{F,fat} \cdot \Delta V_{Ek} \leq \frac{\Delta V_{Rk,cp}}{\gamma_{Mc,fat}}$
3	Pull-out failure	$\gamma_{F,fat} \cdot \Delta N_{Ek} \leq \frac{\Delta N_{Rk,p}}{\gamma_{Mp,fat}}$	Concrete edge failure	$\gamma_{F,fat} \cdot \Delta V_{Ek} \leq \frac{\Delta V_{Rk,c}}{\gamma_{Mc,fat}}$
4	Concrete splitting failure	$\gamma_{F,fat} \cdot \Delta N_{Ek} \leq \frac{\Delta N_{Rk,sp}}{\gamma_{Mc,fat}}$		
5	Concrete blow-out failure	$\gamma_{F,fat} \cdot \Delta N_{Ek} \leq \frac{\Delta N_{Rk,cb}}{\gamma_{Mc,fat}}$		

The design fatigue resistance of a single anchor fastening with a bonded expansion anchor M12 with an embedment depth of h_{ef}=100 mm is illustrated in Fig. 1. The example shows that there is a change of failure mode under tension load and steel failure is becoming decisive at higher number of cycles. Steel failure also usually applies in case of shear load, when the anchor has sufficiently large edge distance.

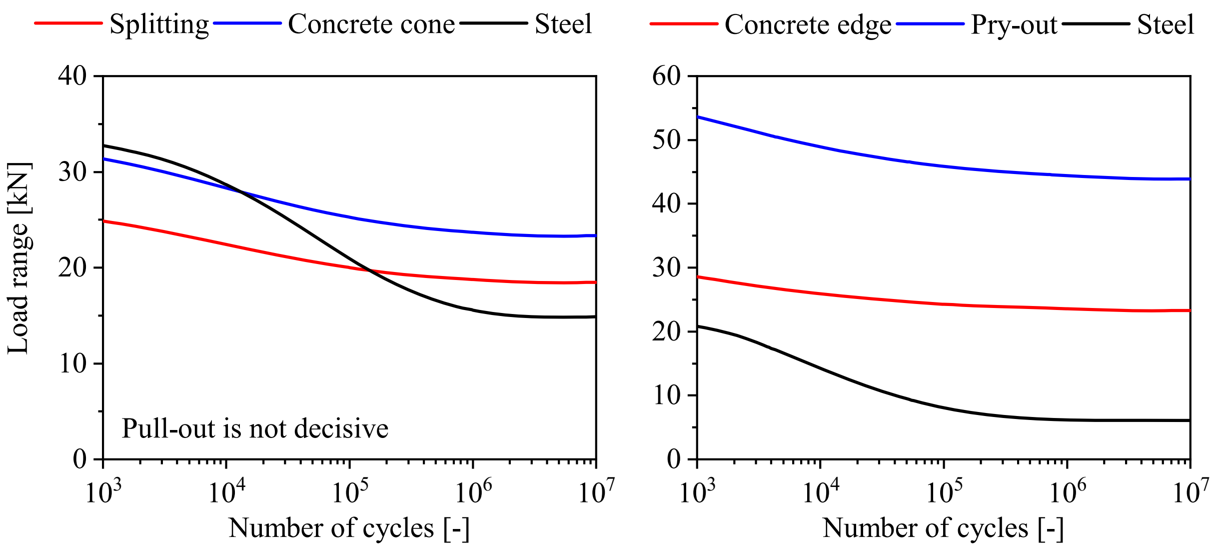


Fig. 1: Design resistance of post-installed single anchor M12 in uncracked concrete member C20/25 with standard thickness of h = 2h$_{ef}$ and edge distance of c = 2h$_{ef}$ under tension loading (left side) and under shear loading (right side)

2.2 HEADED STUDS

The fatigue design of cast-in headed studs welded to a steel plate is carried out acc. to EN 1992-4 [1] as described in Section 2.1. Even though their use under fatigue loading is generally permitted, currently no product with a valid ETA is available on the market, which includes fatigue application. This is due to the fact that the relevant guideline EAD 330084-00-0601 [5] does not provide any provisions for the fatigue qualification of these fasteners.

According to fib Bulletin 58 [6], the following values are given as a guide for the fatigue steel strength of cast-in welded studs. However, these values were established by tests from the 1980s, which no longer represent the state of the art.

Tension loading: $\Delta\sigma_{k,fat} = 100$ MPa for $2 \cdot 10^6$ load cycles

Shear loading: $\Delta\tau_{k,fat} = 35$ MPa for $2 \cdot 10^6$ load cycles

2.3 ANCHOR CHANNELS

EOTA TR 050 [7] provides design rules for anchor channels under fatigue loading. EAD 330008-02-0601 [8] serves as qualification guideline for this product. Currently, the application is limited to anchor channels that transfer fatigue tension loads only. For this case, the required verifications shown in Table 2 consider all possible failure modes, namely steel failure, concrete cone failure and pull-out failure.

Table 2: Required fatigue verifications for anchor channels in accordance with EOTA TR 050 [7]

	Failure mode	Tension loading
1	Steel failure	$\gamma_{F,fat} \cdot \Delta N_{Ek} \leq \frac{\Delta N_{Rk,s}}{\gamma_{Ms,fat}}$
2	Concrete cone failure	$\gamma_{F,fat} \cdot \Delta N_{Ek} \leq \frac{\Delta N_{Rk,c}}{\gamma_{Mc,fat}}$
3	Pull-out failure	$\gamma_{F,fat} \cdot \Delta N_{Ek} \leq \frac{\Delta N_{Rk,p}}{\gamma_{Mp,fat}}$

Fig. 2 shows exemplary the design Wöhler-curves for anchor channel size 50/30 with an embedment depth of h_{ef} = 106 mm. The fatigue resistance of this profile is governed by steel failure, which usually also applies to other product types.

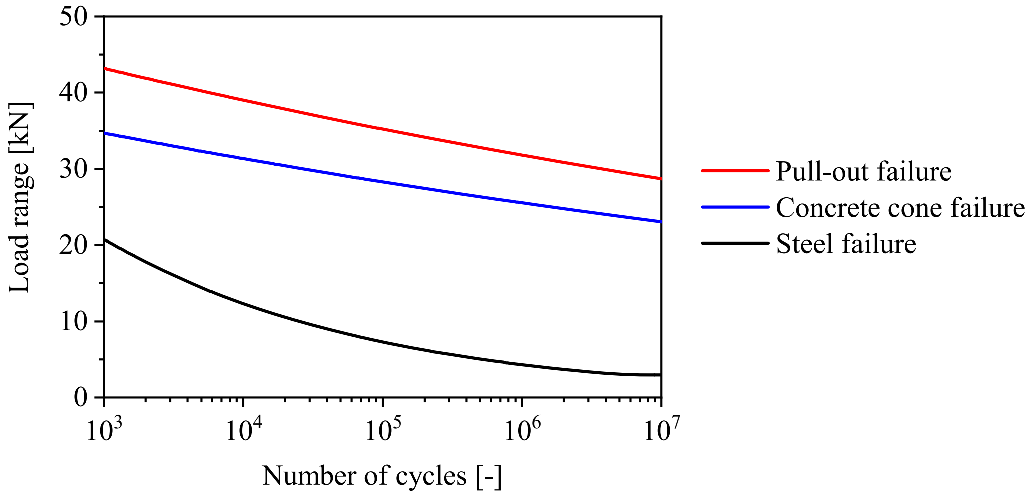


Fig. 2: Design resistance of anchor channel 50/30 in uncracked concrete C20/25

2.4. COMBINED STATIC AND DYNAMIC LOADS

The design of fastenings against fatigue failure includes not only fatigue loads but also the verification under static loading. This proof must be performed additionally in accordance with EN 1992-4 [1].

Furthermore, the combination of fatigue loads superimposed by static loads is considered by the use of the Goodman diagram as shown in Fig. 3. Since the fatigue resistance of a product declared in the relevant ETA is evaluated for a minimum load of $F_{min} \approx 0$, the design value of the fatigue resistance must be modified for other minimum loads not equal to zero.

In practice, this means that increasing static loads lead to a reduction of the resistance values under pulsating tension and shear. However, the fatigue resistance is even slightly increased in case of alternating shear loads.

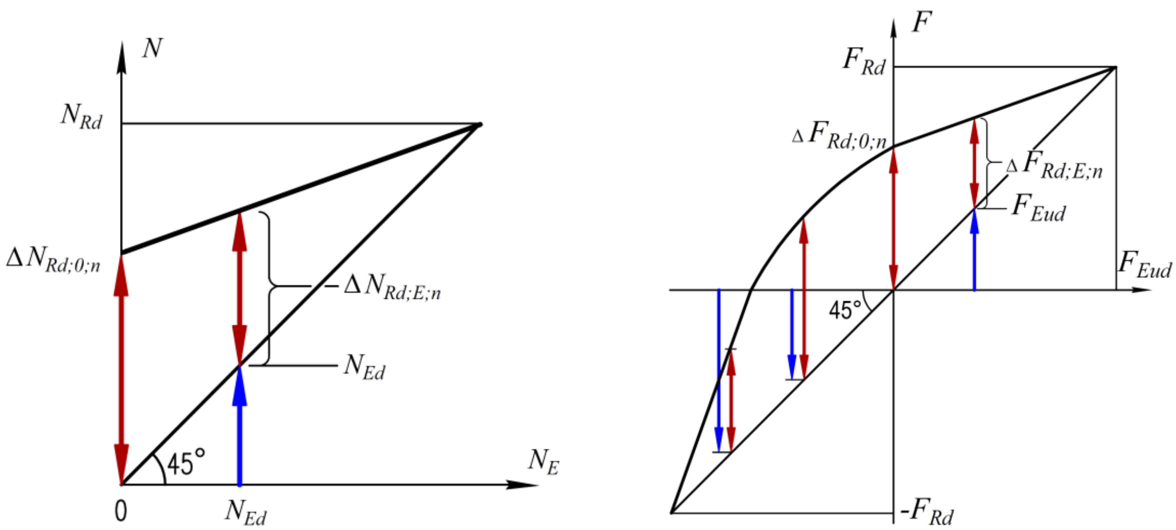


Fig. 3: Goodman diagram for anchor channels [7] (left) and post-installed anchors [3] (right)

3. MEAN LOAD EFFECT

The fatigue resistance of fastenings is commonly determined by experiments under constant amplitude with varying maximum loads and low constant minimum load. The resulting Wöhler-curves are characterized by the load range but correspond to a certain static load level, which can be expressed by the load ratio $R = F_{min}/F_{max}$ or by the mean load $F_m = (F_{min} + F_{max})/2$ respectively.

Depending on the level of the static mean load, different Wöhler-curves may result. For metallic materials in general, it can be assumed that tension mean stresses are detrimental while compressive mean stresses has a beneficial effect on the fatigue resistance. The influence of different mean stresses is exemplary shown in Fig. 4.

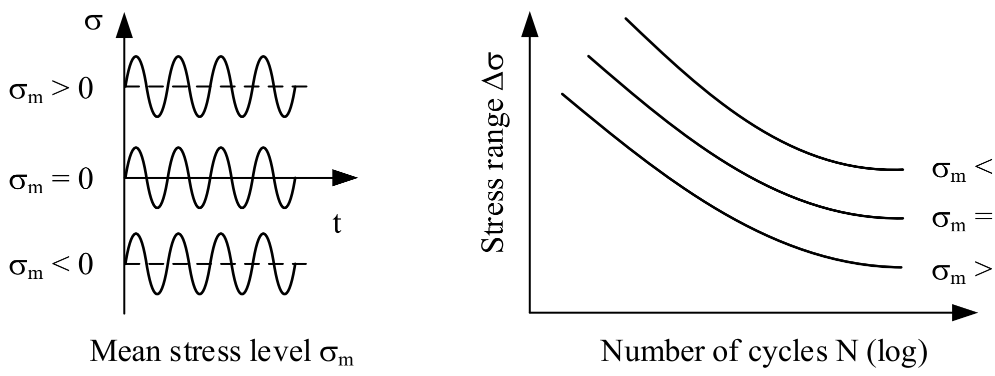


Fig. 4: Effect of mean stress on fatigue resistance

In case of metallic components, the effect of mean stress depends on the type and the tensile strength of the material [9]. For low and medium steel grades that are frequently used for fasteners, increased mean stresses lead to a reduction of fatigue strength. However, the effect of mean stress is reduced in case of notched components. In fatigue design of steel structures acc. to EN 1993-1-9 [10], the mean stress effect for components with high notch effect is therefore virtually neglected.

In contrast to steel, the fatigue strength of concrete is clearly influenced by the mean stress. Further, there is a significant influence of static strength. For this reason the Wöhler-curves are usually presented in relation to static strength, e.g. Model Code 2010 [11]. With regard to fastenings, this is not only relevant for concrete failure but also for steel failure, since concrete damage can lead to stress redistributions in the fastener itself, particularly for shear loads.

4. IGF PROJECT 20458 N

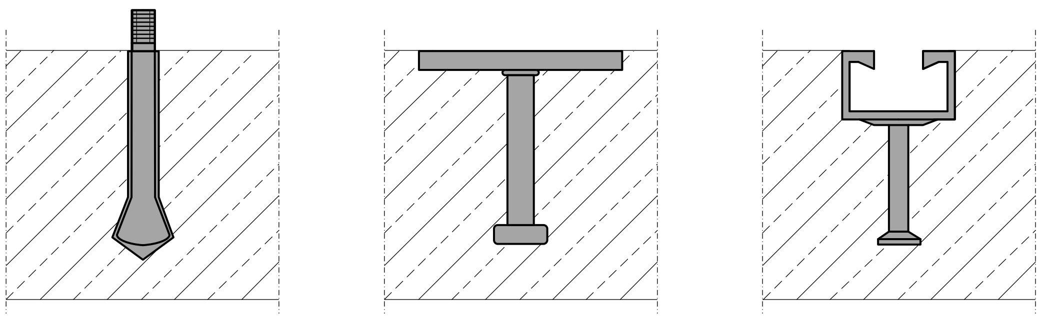
In order to study the fatigue behaviour of fastenings under combined static and dynamic loading, a recent research project (IGF 20458 N) is carried out at the University of Stuttgart in close cooperation between the Materials Testing Institute (MPA) and the Institute of Construction Materials (IWB). The project was initiated by the Technical Committee Cold Forming (GAK) and is financed by the AiF for the period from December 2018 to May 2021.

The primary goal of the project is to investigate the effect of static load level on the fatigue resistance and damage behaviour of mechanical fasteners in concrete, where failure usually occurs due to steel fracture. For this purpose, experimental and numerical investigations are performed on various types of anchor systems.

The selected fasteners shown in Table 3 are characterized by very different geometric properties and manufacturing methods, so that the desired results will be valid for representative notch details typical for a large number of products available on the market. Detail 1 represents a post-installed undercut anchor providing the threaded part of the bolt as decisive notch. Headed studs (Detail 2) and anchor channels (Detail 3) belong to the group of cast-in place fasteners. Whereas for Detail 2 failure is usually expected in the area of the welded seam, the anchor channel is a formed component with notches at various points of the anchor channel profile.

Table 3: Overview of the fastenings investigated in the project

Type	Fastener	Size	Material	Failure location
Detail 1	Undercut anchor with rolled thread	M12	Steel 8.8	Thread
Detail 2	Headed stud welded to anchor plate	SD 16	Steel S235	Welded seam
Detail 3	Anchor channel with forged anchors	53/34	Steel S235	Profile



Detail 1 Detail 2 Detail 3

The experimental program, which is conducted at the MPA comprises pulsating tension and shear tests at different static load levels. Furthermore, fatigue tests with alternating shear load are planned in the project. The numerical investigations are performed at the IWB using the 3D FE-program MASA.

At present, the experimental investigations are underway. On the basis of the first test results, the numerical work is expected to start shortly.

5. CONCLUSION AND OUTLOOK

The current state of knowledge on fastenings in concrete under fatigue loading is limited predominantly on results of pulsating fatigue tests with low minimum load. Consequently, present design provisions tend to be rather conservative in most of the cases, where steel failure of the fastener is decisive.

The aim of the current research project presented in this paper is to close the existing gaps in knowledge on the fatigue behaviour of fasteners under superimposed static loads. This should enable not only a safe but also an economical design of connections between steel and concrete in the construction industry.

The outcome of the work can serve as a basis for a uniform, practical design approach for the fatigue resistance of fastenings. This may lead to an increase in economic efficiency and an expansion of the application areas in fastening technology. The results do not only address the design of new constructions, but are also of interest for the evaluation of the fatigue life in case of existing structures.

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REFERENCES

[1] EN 1992-4:2018: *Design of concrete structures - Part 4: Design of fastenings for use in concrete*

[2] DAfStb-Heft 615: *Erläuterungen zu DIN EN 1992-4, Bemessung der Verankerung von Befestigungen in Beton (in German).* Beuth Verlag, Berlin, 2019

[3] EOTA TECHNICAL REPORT 061:2018: *Design method for fasteners in concrete under fatigue cyclic loading*

[4] EOTA EUROPEAN ASSESSMENT DOCUMENT 330250-00-0601: *Post-installed fasteners in concrete under fatigue cyclic loading (not yet published)*

[5] EOTA EUROPEAN ASSESSMENT DOCUMENT 330084-00-0601:2016: *Steel plate with cast-in anchors*

[6] *fib* Bulletin 58: *Design of anchorages in concrete - guide to good practice.* Fédération Internationale du Béton (fib), Lausanne, Switzerland, 2011

[7] EOTA TECHNICAL REPORT 050:2018: *Calculation method for the performance of anchor channels under fatigue loading*

[8] EOTA EUROPEAN ASSESSMENT DOCUMENT 330008-02-0601:2016: *Anchor channels*

[9] RADAJ, D. VORMWALD, M.: *Ermüdungsfestigkeit. Grundlagen für Ingenieure,* Springer-Verlag, Berlin, Heidelberg, 2007

[10] EN 1993-1-9: 2005+AC: 2009: *Design of steel structures - Part 1-9: Fatigue*

[11] *fib* Model Code for Concrete Structures 2010, Fédération Internationale du Béton (fib), Lausanne, Switzerland, 2013