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Re-evaluation and extension of fatigue test data for welded attachments and butt joints

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Abstract

Welded structures under fatigue loading are widely used in civil engineering. The fatigue strength of components such as welded attachments and butt joints are often determining for the dimensioning of bridges, crane runways or tower constructions. The existing design rules of Eurocode 3, Part 1-9 are mainly based on experimental data. However, the experimental background of Eurocode 3 Part 1-9 is partly incomplete. Some fatigue detail classifications are based on numerical modelling and engineering judgement. New findings from experimental research allow a revision of these details, leading to higher fatigue strength classifications in many cases.

Firstly an overview of an extensive database for fatigue tests on butt joints and welded attachments is addressed. A method for statistical analysis is presented, which allows the consideration of fatigue tests from different sources by using the design philosophy of Eurocode 3 Part 1-9 and also meeting the requirements of Eurocode 0.

The paper is also going to present some new supplementary experimental investigations on a fatigue detail for transverse end welds of cover plates with blended weld toes, which is traditionally used in German bridge design.

Finally a revised and simplified fatigue detail catalogue for welded attachments and butt joints is addressed which is intended as a suggestion for the next generation of Eurocode 3 Part 1-9.

Keywords

Fatigue detail catalogue, statistical analysis of fatigue test data, fatigue test database

1 Introduction

This paper is supposed to present some results from the research project "Re-evaluation and enhancement of the fatigue detail catalogue in Eurocode 3" by the German Committee on Steel Construction (DASt) in cooperation with the Research Association for Steel Applications (FOSTA) funded by the German Federation of Industrial Research Association (AiF) [1]. The results are supposed to help to revise and improve the fatigue strengths of steel construction that are given of Eurocode 3 Part 1-9 [2].

Main focus of the research project was to collect and evaluate fatigue test data of steel constructions. Therefore, data from primary sources were extracted and structured in a database with regard to potential influencing parameters on the fatigue strength (Chapter 2)

For the evaluation of the fatigue strength a statistical method was derived that is compatible to the requirements of Eurocode 0 [9] and allows to run a meta-analysis on the test data.

The paper is also going to present some new supplementary experimental investigations on a fatigue detail for transverse end welds of cover plates with blended weld toes, which is traditionally used in German bridge design. Up to now the constructional detail is missing in the fatigue detail catalogue of Eurocode 3 Part 1-9 [2].

2 Database

In a co-operation of the Institute of Steel Construction (RWTH Aachen), the Research Center for Steel, Timber & Masonry (KIT Karlsruhe) and the Institute of Structural Design (University of Stuttgart) a web based database application was created. Besides basic information with regard to the loading (such as stress range) and the resistance (number of cycles to failure) the database contains a variety of possible influences on the fatigue strength such as geometric parameters, material information and environmental conditions. Up to now about 22,000 test results on various details were processed in the database.

The database allows to sort tests by specific parameters. For example the database contains about 4507 tests on transverse butt joints. Within these data there are 607 tests on specimens, where the welds are ground flush to plate surface. And within these data 256 tests have been filtered that are carried out with cyclic stress (R

> 0) and constant amplitude. The filtered and unfiltered data are given in a S – N diagram in Figure 1.

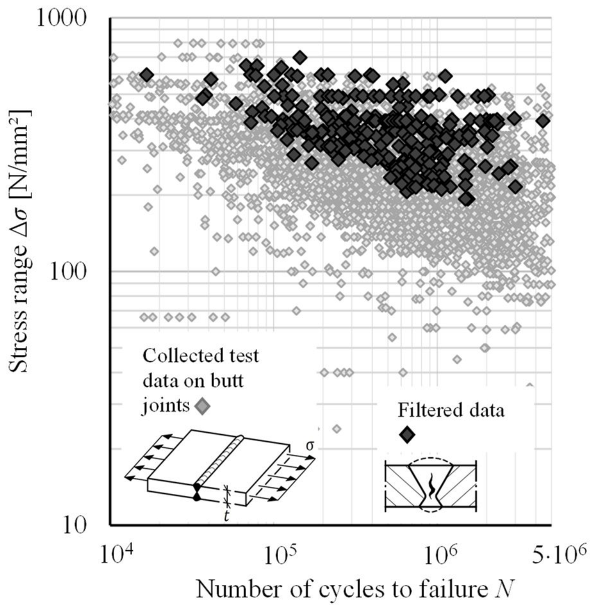


Figure 1 : All test results for transverse butt joints and filtered data with weld ground flush, R> 0 and constant amplitude testing

As shown in Figure 1 the filtered test data show significant increased fatigue strength (as it seems to be obvious due to the largely removed geometrical notch). If the data selection seems suitable to represent the population, characteristic fatigue strengths can be derived using statistical evaluation methods.

3 Statistical analysis of fatigue test data

3.1 Overview

Experimental test data always show a random scatter. Unavoidable sample-to-sample variations of influencing factors like shape discontinuities of weld toes and roots, geometrical tolerances and metallurgical inhomogeneities lead to sampling error even under identical test conditions. For the assessment of a characteristic fatigue strength this scatter must be taken into account. There are numerous approaches for statistical analysis of fatigue test data [3]-[7]. The approaches differ with regard to the assumed resistance function, the assumed distribution of the population and the procedure for deriving characteristic values. Eurocode 0 [9] defines the reliability and safety concept of all European standards for structural design in civil engineering. The informative annex D contains rules for design assisted by testing.

3.2 Resistance model and regression analysis

For high cycle fatigue of steel structures, the applied stress range, *S*, and the corresponding number of stress cycles to failure, *N*, follow an exponential law [8]. On a log-log scale with decimal logarithm, the test data can generally be allocated to a straight line expressing a linear dependency of stress cycles on the stress range, Equation (1):

$$\log N = \log a - m \cdot \log S \quad (1)$$

Figure 2 shows the log-linear relationship in finite life region. The S-N curve corresponds to the resistance model. The parameters *a* (intercept of the theoretical locus where the *S-N* curve of the finite life region intersects the horizontal axis $S=10^0=1$) and *m* (slope of the *S-N* curve) in Equation (1) can be calculated using a regression analysis.

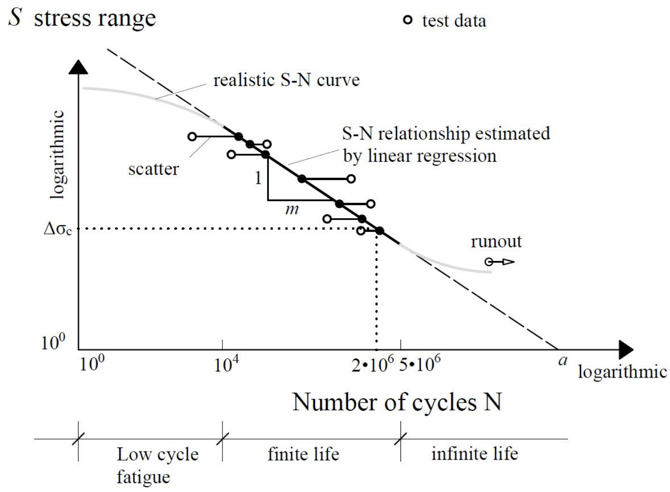


Figure 2 : Linear dependency of the number of stress cycles on the stress range

Since both parameters are estimated based on the information of a limited number of fatigue tests, they have to be substituted by the estimates $\hat{a}$ and $\hat{m}$.If the slope *m* of the *S-N* curve is known by previous information (for example *m = 3* for welded details with sharp notches [10]) $\hat{a}$ respectively log $\hat{a}$ is given by Equation (2):

$$\log \hat{a} = \frac{1}{n} \cdot \left(\sum \log N_i + m \cdot \sum \log S_i\right) \quad (2)$$

Where n is the sample size (number of fatigue tests data) and *i* is the index of the single fatigue test. The standard deviation s of the population is either known or unknown. In the latter case it is estimated by the sample. The standard deviation s in terms of log *N* (see Fig. 2) amounts to: (Equation (3)):

$$s = \sqrt{\frac{\sum[\log N_i - (\log \hat{a} - m \cdot \log S_i)]^2}{n-1}} \quad (3)$$

3.3 Distribution and prediction interval

Eurocode 0 implicitly assumes that the distribution of the population is normal or log-normal. As there is no prior knowledge about the mean, it is estimated by the sample. In case where the slope *m* is forced to be of a certain value and is not calculated from the sample, Eurocode 0, Annex D.7 [9] is applicable for the derivation of a characteristic *S-N* curve.

According to Eurocode 0 [9] the factor k_n may be used to derive characteristic values with 95 % probability of survival, (see Table 1).

Table 1 k_n factor for characteristic values with 95 % survival probability (extract from Eurocode 0 [9])

n	1	2	3	4	5	6	8	10	20	30	∞
V_x (or *s*) known	2,31	2,01	1,89	1,83	1,80	1,77	1,74	1,72	1,68	1,67	1,64
V_x (or *s*) unkown	-	-	3,37	2,63	2,33	2,18	2,00	1,92	1,76	1,73	1,64

Since samples of normal distributed populations are *t* distributed [11], the lower row of Table 1(which has to be used when the standard deviation is estimated by the sample, Equation (3)), takes into account the *t* distribution probability. The k_n factors are based on the prediction method of fractile estimation (prediction interval) [12]. The characteristic value of the intercept a_k is obtained by Equation

(4). The procedure is shown schematically in Figure 3.

$$\log\, a_k = \log \hat{a} - k_n \cdot s \tag{4}$$

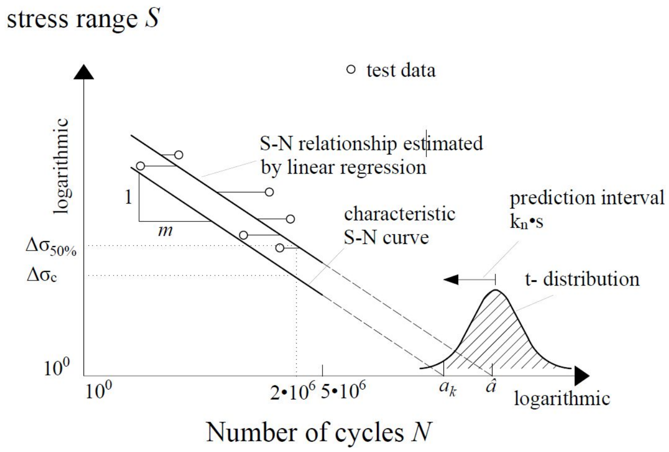


Figure 3 : Schematic procedure for statistical evaluation of test data.

The characteristic reference value ••$_c$ of the fatigue strength at $2{\cdot}10^6$ stress cycles amounts to:

$$\log S_c = \frac{\log 2{\cdot}10^6 - \log a_k}{-\mathrm{m}} \tag{5}$$

$$\Delta\sigma_c = 10^{\log S} \tag{6}$$

The procedure described meets the requirements of background document 9.01 of Eurocode 3 Part 1-9 [3] and Eurocode 0, Annex D [9].

3.4 Example

To derive a characteristic fatigue strength for the example of a butt with ground flushed surface as given in Figure 1, formulas (1) – (6) could be applied. As the filtered data only contain specimens with cyclic tension stresses and constant amplitude the population is considered as suitable for the derivation of the characteristic fatigue strength [1]. For this example the slope of the S-N curve is predefined with *m* = 3.

Table 2 summarises the parameter needed for the statistical evaluation.

Table 2 Calculation table for statistical evaluation of butt joint, welds ground flush to plate surface

Parameter		Reference
n	258	Database
m	3	predefined
log *â*	13,293	Equation (2)
s	0,4139	Equation (3)
k_n	1,64	Table 1
log *a_k*	12,61	Equation (4)
log *S_c*	2,103	Equation (5)
$\Delta\sigma_c$	127	Equation (6)

The corresponding characteristic S-N curve for butt welds with ground flushed surface is shown in Figure 4.

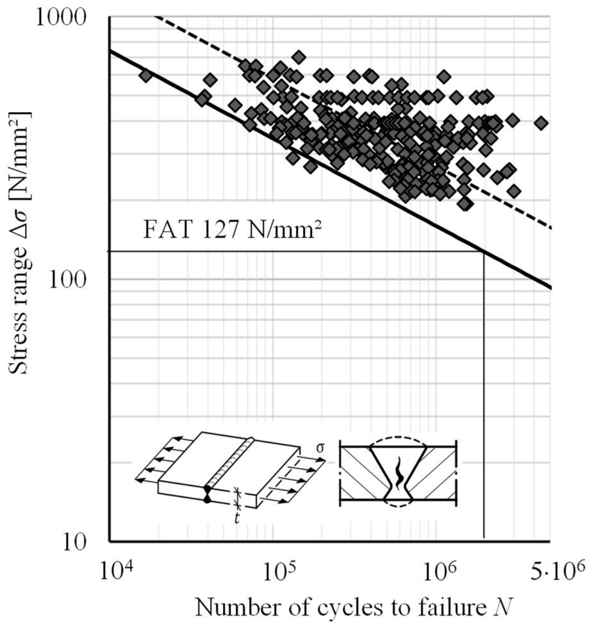
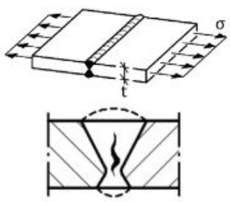


Figure 4 : Characteristic S-N curve for butt welds with flushed surface

Based on the test results shown in Figure 4, the statistical evaluation provides a fatigue detail category 127 for *m* = 3. Taking into account the standardised *S* – *N* curves of Eurocode 3 Part 1-9 [2] fatigue detail category 125 is justified, Table 3.

Table 3: Transverse splices in plates and flats, all welds ground flushed to plate surface (shortened from [1])

Detail category	Constructional detail	weld symbol
125		

The current fatigue strength classification according to Eurocode 3 Part 1-9 [2] is fatigue detail category 112. For the next generation of Eurocode 3 Part 1-9 an upgrade is recommended based on the experimental data available [1].

4 Re-evaluation of selected constructional details

4.1 Introduction

Using the evaluation method described in Chapter 3, the fatigue strength of various constructional details was assessed, see [1]. Only investigations from primary sources were used. Summaries of test data from different sources often do not contain all necessary information as they are available from primary sources. To derive characteristic fatigue strengths only fatigue tests with constant amplitude and cyclic tension stresses (R>0) were used. A fixed slope of *m* = 3 was assumed for all construction details examined.

Eurocode 3 Part 1-9 gives a correction factor to consider thickness effects for transverse butt joints. Investigations in [1] show that the thickness correction may be too conservative. A meta-study in [13] comes to a similar conclusion.

The current correction in Eurocode 3 Part 1-9 is based on a suggestion by Gurney that was originally derived from an investigation based on fracture mechanics [14].

However, further studies are required to re-evaluate the thickness correction factor. For the following fatigue detail categories it is therefore recommended to keep the current approach for transverse butt joints which considers the thickness effect.

4.2 Transverse butt joints, welded from both sides

Figure 5 shows test results of butt joints welded from both sides and their statistical evaluation. In the current version of Eurocode 3 Part 1-9 the detail category is divided into Detail category 80 and 90 depending on the ratio between weld height and width. The ratio implicitly takes into account the weld opening angle [15].

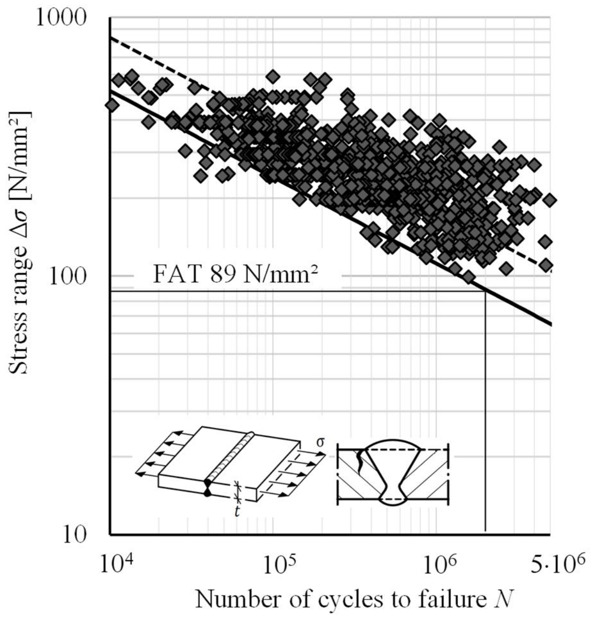
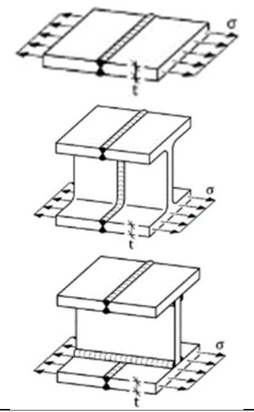
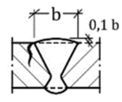
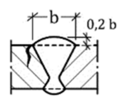


Figure 5 : Test results and characteristic *S-N* curve for butt joints, welded from both sides (as welded condition)

The statistical evaluation in Figure 5 takes into account all test data without subdivision with regard to the weld convexity. For most known experimental data, the geometric properties of the weld convexity are not documented. However, experimental studies in [16], [17], [18] show that the weld convexity has a significant influence on the fatigue strength. Therefore, it is nevertheless recommended to keep the current classification, see Table 4.

Table 4: Transverse butt welds, welded from both sides (shortened from [1])

Detail category	Constructional detail		weld symbol
90			
80			
Size effect for t > 25 mm is considered by stress modification with $k_s = (25/t)^{0,2}$			

4.3 Lamellae joint

The detail “Lamellae joint” is an important constructional detail in traditional German bridge design. It was part of research activities especially in view of thick plates as they are used in modern bridges in recent years [19] and will be included as a new detail in the upcoming generation of Eurocode 3 Part 1-9 [20]

The lamellae joint is a butt joint of flanges composed of several plates.. In contrast to a common butt joint, the so-called end groove weld, which joins the single plates when assembled before filling the main butt weld, is characteristic for the lamellae joint and influences the joint´s behaviour.

In contrast to the other tests on butt joints most of the experiments were carried out for thick plated joints. Thus the experimental data in Figure 6 have been corrected by k_s as given in Table 4 to take into account the plate thickness effect.

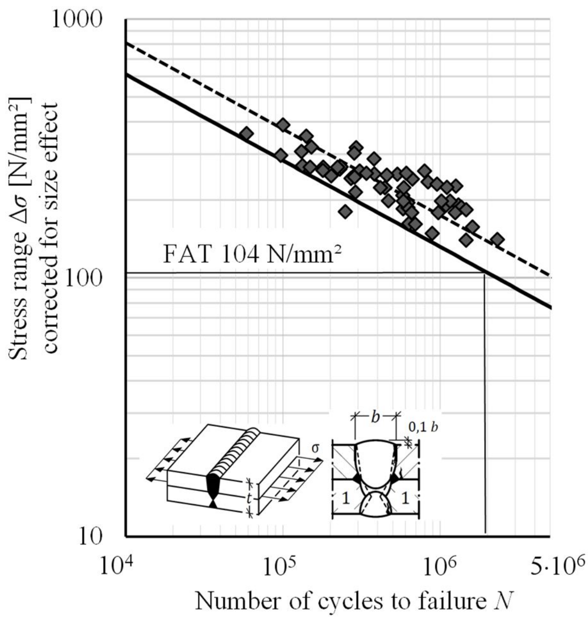
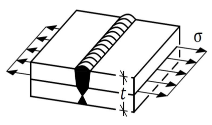
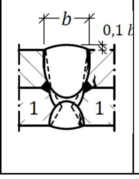


Figure 6 : Test results (corrected for size effect) and characteristic *S-N* curve for lamellae joints (1) indicates the so called end groove weld)

The evaluation of the detail follows the recommendation of the corresponding background document [19] and is summarised in Table 5 where the resulting FAT class of 104 N/mm² has been adapted to the detail category 90 of the normal butt weld. The reference thickness to calculate the reduction factor k_s is the overall thickness of the joint.

Table 5: Lamellae joints (shortened from [1])

Detail category	Constructional detail	weld symbol
90	 	
Size effect for t > 25 mm is considered by stress modification with $k_s = (25/t)^{0,2}$		

4.4 Gusset plates

Figure 7 shows test results of gusset plates in "as welded" condition and their statistical evaluation. In the current version of Eurocode 3 Part 1-9 [2] the detail is classified with fatigue detail category 40. The experimental data indicate a significantly higher fatigue strength. The characteristic *S-N* curve corresponds to fatigue detail category 56. The data include tests on specimens with the same plate thickness for the base plate and the gusset plate as well as specimens where the base plate is thicker. The chamfering of the gusset plates is only useful if the weld toes are grinded after welding [21]. Otherwise, the fatigue strength of chamfered and unchamfered gussets in the "as welded" condition do not differ from each other.

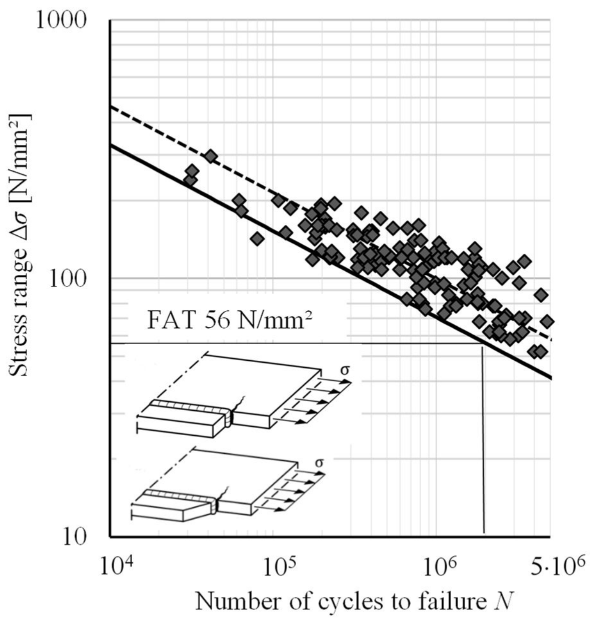
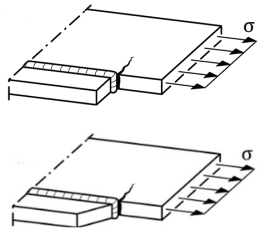
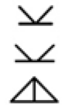


Figure 7 : Test results and characteristic *S-N* curve for gusset plates (as welded condition)

A proposal for the reassessment for the fatigue detail category is given in Table 6 based on the results in [1].

Table 6: Gusset plates, as welded (shortened from [1])

Detail category	Constructional detail	weld symbol
56		

4.5 Shear studs and welded bushings

Figure 8 summarises data from shear studs welded to a plate under normal stresses and recent experimental data in [22] and [23] on welded bushings, which are used e.g. to fix secondary elements to walls of wind towers or in bridges. As can be seen in Fig. 8 these situations resemble each other leading to a common fatigue class of 84. Also, in terms of the fatigue strength no significant difference between studs with fillet welds and stud welding with arc ignition can be observed. So the detail category of shear studs in EN 1993-1-9 [20] may be extended also to welded bushings. A proposal for the fatigue classification of shear studs and welded bushings is given in Table 7.

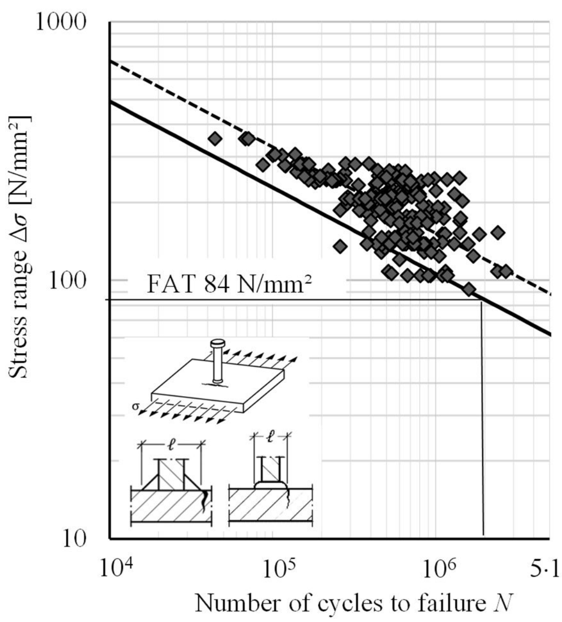
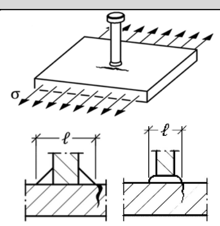


Figure 8 : Test results and characteristic *S-N* curve for shear studs and welded bushings

Table 7: Shear studs and welded bushings (shortened from [1])

Detail category	Constructional detail	weld symbol
80		

5 Experimental investigations on the transverse end weld of cover plates

5.1 Introduction

In bridge construction cover plates are used to strengthen flanges in order to adapt the load bearing capacity to stress resultants. The locally welded cover plates enable a material-saving design. Under fatigue loading, fatigue cracks may occur at the transverse end weld of the cover plate due to geometric and metallurgical notch effects. To achieve a high fatigue strength, in Germany the constructional detail is traditionally produced with thick welds and smooth transition at the weld toes. For this purpose the lamella is chamfered in thickness direction and a weld with the same slope as the chamfer joins the cover plate to achieve a smooth transition between flange plate, weld and cover plate. This kind of detail has a positive effect on the fatigue strength and is used in particular for German railway bridges [24]. However, a corresponding detail category is missing in the fatigue detail catalogue in Eurocode 3 Part 1-9 [2]. To create an experimental background that allows the inclusion into the fatigue detail catalogue, several series of fatigue tests were carried out at University of Stuttgart within the IGF-DASt-FOSTA research project 19178: "Re-evaluation and Extension of the Fatigue Detail Catalogue in Eurocode 3" [1].

5.2 Known experimental investigations

Experimental studies on the fatigue strength of cover plates are documented in [25] - [30]. Joints between cover and base plate with a simple all around fillet weld without grinding and without reinforcement of the transverse end weld show significantly decreased fatigue strengths compared to more elaborate variants, compare Figure 9.

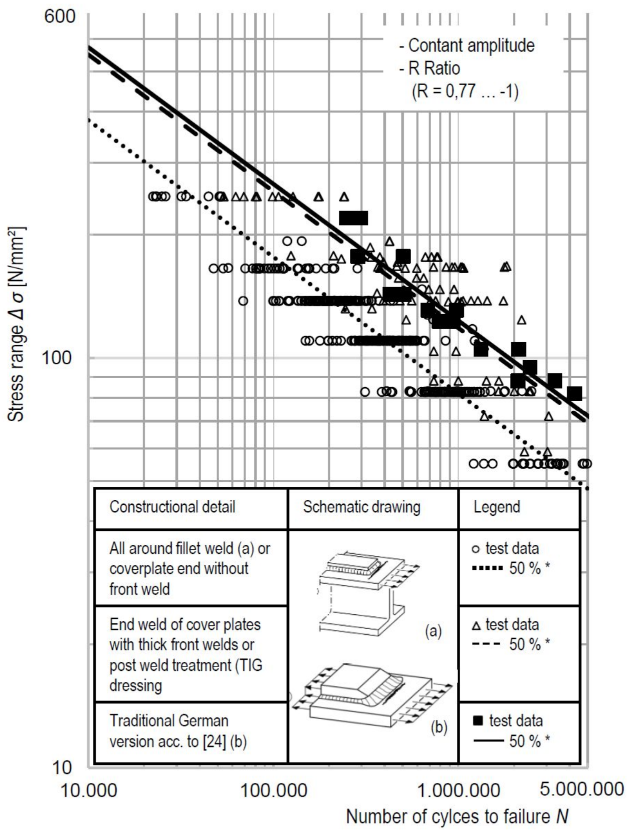


Figure 9 : Overview of known experimental results. [25] - [30]* Mean *S-N* curves with 50 % survival probability (m=3)

5.3 Fatigue tests

36 fatigue tests were carried out on three series, each with twelve specimens, compare Table 8. The focus of the investigation was on the influence of the plate thickness (series one and two). Due to the high weld effort and the elaborate grinding of the German verision of cover plate end welds there is a big interest to simplify the detail. For this reason, a test series with a reduced weld volume was tested (series 3). The aim of the research was to create an experimental background for the German variant of cover plate end welds that is sufficient to be accepted as a constructional detail in the main part of Eurocode 3 Part 1-9 [2]. The fatigue tests were carried out force controlled. The test specimens were stressed axially with a stress ratio of R=0,1.

5.4 Results

An overview of the test results is shown in Figure 10. The tests show no significant influence of the cover plate thickness (for details see [1]).

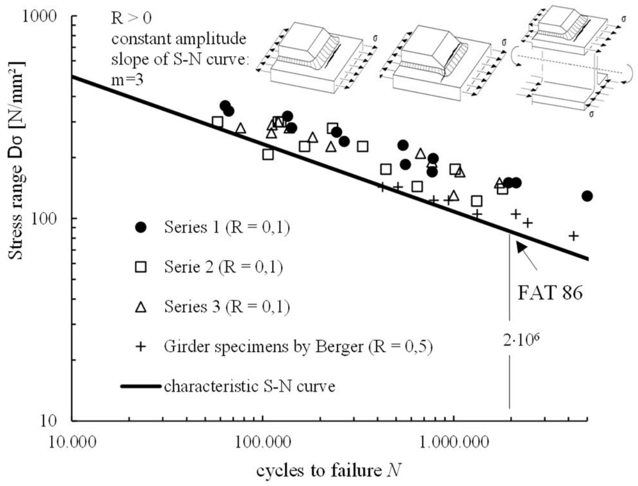
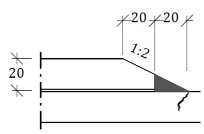
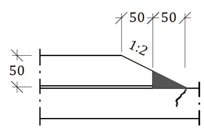
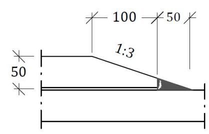
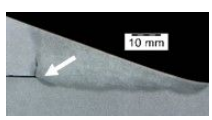


Figure 10 : Test results (including tests from [1] and [28]) and characteristic *S-N* curve for the German version of cover plate end weld

Series 3 with reduced weld volume shows comparable fatigue strengths. However, a fatigue crack starting from the root may be expected in this case, compare Table 8.

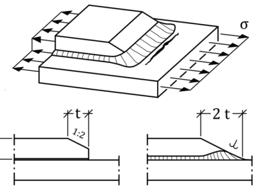
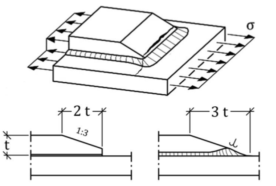
Table 8 Failure mode of series 1, series 2 (failure from weld toe) and series 3 (root failure) in micro-section, arrow marks fatigue cracks

Series 1	Series 2	Series 3
		
		

5.5 Proposal for Eurocode 3 Part 1-9

Based on the experimental data shown in Figure 10 for the traditional German variant fatigue detail category 80 is proposed for Eurocode 3 Part 1-9, compare Table 9. The variant with reduced weld volume is listed as a separate detail due to the failure from the root crack.

Table 9: Proposal of fatigue detail transverse end weld of cover plates (shortened from [1])

Detail category	Constructional detail	weld symbol
80		 weld termi-nation
80		

6 Summary and conclusions

This paper presents the basic procedure of the current research project "Re-evaluation and enhancement of the detail catalogue in Eurocode 3" [1]. After explaining the statistical evaluation methods several re-evaluations for different constructional details are given. The evaluations show potential for a higher fatigue classification of the fatigue strength of various details.

The meta-study presented in this paper shows, that data from different primary-sources can be evaluated together with help of an simple statistical approach that is conform to Eurocode 0 [9]. This approach opens new opportunities for the fatigue classification of common constructional details.

Proposals for the revision of selected details in this paper is given in fatigue detail tables.

For the constructional detail of cover plate end welds extensive fatigue tests was carried out which lead to an additional fatigue detail category in Eurocode 3 Part 1-9 [2].

7 Acknowledgements

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