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Investigations on the fatigue behaviour of welded cover plates with extended weld seams

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Abstract

Nowadays the necessity to design lightweight structures and reducing the use of resources is more important than ever. Normally, cover plates are used as a local strengthening for an optimised load bearing in all kind of steel structures like steel bridges. Under cyclic loading, this notch detail exhibits a worse fatigue behaviour due to the geometrically induced notch factor at the end of the cover plate. By using extended weld seams the stress concentration of this detail can be reduced by a continuous and smooth transition between the ground and the cover plate and thus the fatigue strength can be improved. By using different post weld treatment methods, the fatigue strength could be raised further. Unfortunately, there are almost no experimental results in literature dealing with extended weld seams for any notch detail, even when this type of detail is already used for different construction machines.

Within this paper systematic experimental research on possible influencing factors for extended weld seams will be presented.

1 Introduction

The notch detail of the welded cover plate is widely spread in steel using industries, for instance for steel bridges, commercial vehicles as well as in the construction machine industry, and is used as a local strengthening to reduce the weight of a construction and thus save resources. In general, the before mentioned industries have to deal with fatigue design due to the cyclic loads to which all the constructions are subjected. Especially for the notch detail of the welded cover plate, the end of the plate has a huge impact on the fatigue behaviour due to the geometric change in cross section. Therefore, some investigations have already been carried out to reduce the notch factor by varying the cover plate shape. In recent years, the use of extended welds has become more common in excavators and other construction machines, as shown in figure 1.

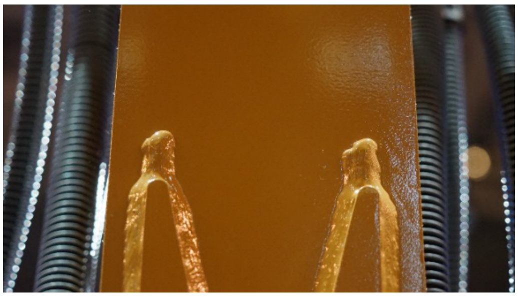

Figure 1 Example for cover plates with extended welds at a cantilever arm of an excavator.

Unfortunately, there are no literature and no experimental results for the benefit on the fatigue behaviour of these extended welds for cover plates, so this type of design has not been used in steel bridges and structures so far.

To improve the fatigue strength, post-weld treatments like grinding or the higher frequency mechanical impact (HFMI) treatment can usually be used. The improvement of the fatigue strength of these methods is based on the modification of the transition from the ground plate to the weld or plastic deformation and the introduction of compressive residual stresses at the weld toe.

Within the framework of the research project FOSTA P 1413 [1] and complementary investigations [2], the influence of different cover plate geometries on the fatigue behaviour and the improvement of fatigue strength by the use of extended weld seams and post-weld treatment methods is therefore investigated. For this purpose, experimental tests and numerical investigations are carried out based on the notch stress concept. The results obtained so far in the experimental tests are presented in this paper.

2 Fatigue behaviour of welded cover plates

2.1 Guidelines and recommendations

In general, the classification of the notch detail of the welded cover plate in the design standards depends on the used thickness ratio of ground to cover plate or the abso-

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lute value of the wall thickness and the length of the attached plates. So, it is split between attachments below a length of 300 mm and above of 300 mm. In this aspect, there are no differences between international standards, like the IIW recommendation [3] or the Eurocode 3 part 1-9 [4]. The classification of the notch detail of the cover plate for the before mentioned standards can be taken from table 1 and table 2. Different cover plate shapes are not considered. Furthermore, according to the area of application, the fatigue strength of the detail of the welded cover plate can be improved by using post weld treatment methods, like for instance in the German NA of EC3 part 2 [5] and the crane standard DIN EN 13001-3-1 [6]. Therefore, the end of the cover plate has to be chamfered and additionally grinded. This causes normally huge productions costs and is very time consuming. Therefore, steel construction companies try to avoid these kind of post-weld treatments. But by using post weld treatment methods the FAT-class of 100 can be reached [6].

Table 1 Classification of the notch detail cover plate in the IIW below a cover plate length of 300 mm [3].

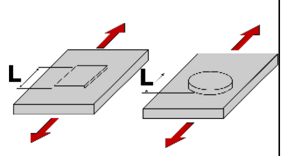
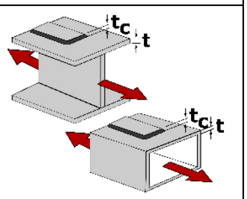
FAT	Requirement	Detail
80	L ≤ 50 mm	
71	50 < L ≤ 150 mm	
63	150 < L ≤ 300 mm	
50	L > 300 mm	

Table 2 Classification of the notch detail cover plate in the EC3 above a cover plate length of 300 mm [4].

FAT	Requirement		Detail
	$t_c < t$	$t_c \geq t$	
56	t ≤ 20	-	
50	20 < t ≤ 30	t ≤ 20	
45	30 < t ≤ 50	20 < t ≤ 30	
40	t > 50	30 < t ≤ 50	
36	-	t > 50	

2.2 Literature review on the influence of cover plate shape on the fatigue behaviour

Already in the early 1930s and later in the 1960s, Graf [7], Munse and Stallmeyer [8] and Fisher et al. [9] carried out experimental investigations on the fatigue behaviour of different cover plate shapes, different weld seam executions and different post-weld treatment methods. In the previously mentioned literature, both large-scale tests with welded or rolled girders with attached cover plates under bending loads as well as small-scale fatigue tests with ground plates with attached cover plates under tensile loads were performed. Apart from the research by Fisher et al [9], in which over 200 fatigue tests were carried out with different types of beams, steel grades and different weld executions, the other investigations base their statements on the influence of cover plate geometry only on a small number of experimental tests.

The key expertise of these tests was, that the fabrication quality of the welds has a huge impact on the fatigue behaviour. The influence of cover plate geometry can be recognised but was not significant as it was expected. The used post-weld treatment methods led to an improvement in the fatigue strength. Since the number of tests in these investigations was very limited by only two to three specimens per series, the statement on the influence of the cover plate shape has to be proven.

2.3 Literature review on the influence of extended weld seams

There are almost no experimental results of cover plates with extended weld seems in literature. Only in [10] experimental test results of specimens with cover plates as local strengthening can be found. The specimens of this source were tested under tensile load and a high strength steel grade (S700) was used. Additional post-weld treatments like TIG-dressing and grinding were done in this study. Unfortunately, there is no reference test series without the extended welds in the source and detailed information about the weld sequence of the specimens is also missing. The dimensions of the specimens can be taken from figure 2.

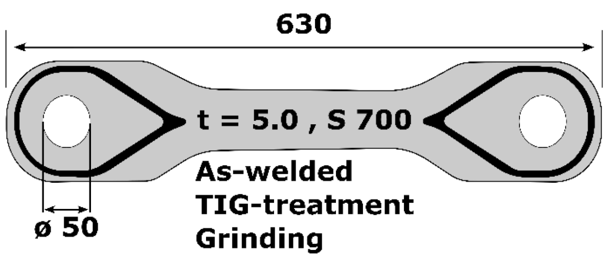


Figure 2 Specimens from [10], all dimensions in mm.

The test results compared in figure 3 show, that the different post-weld treatments can improve the fatigue strength, but due to the lack of reference tests there is no statement about the influence of the extended weld in comparison to the weld all around condition.

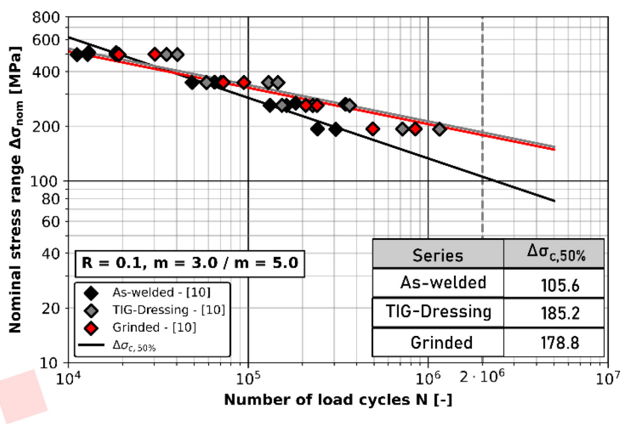


Figure 3 Evaluation of the results from [10].

3 Experimental investigations

3.1 Experimental program

In order to examine the influence of the cover plate shape on the fatigue behaviour, different cover plate geometries were tested in the framework of the research project

FOSTA P 1413 [1] and complementary investigations [2]. For this purpose, the cover plates were manufactured with all around weld and a design throat thickness of 7 mm. The ground and the cover plate each had a thickness 10 mm. The different shapes can be taken from figure 4. The dimensions of the ground plate are equal to the specimens with extended weld seam, see figure 7. The length of the cover plate was above 300 mm for all the tested shapes. For each shape, only three to four specimens were made in order to obtain tendencies about the influence of cover plate geometry on the fatigue behaviour.

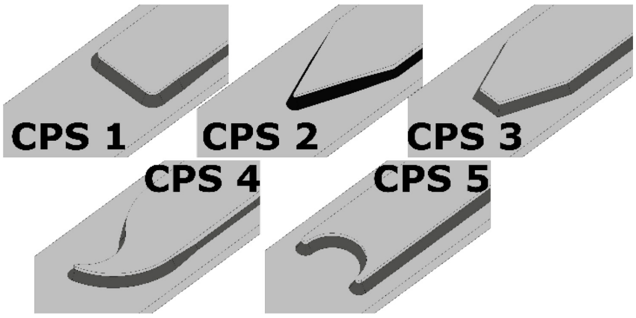
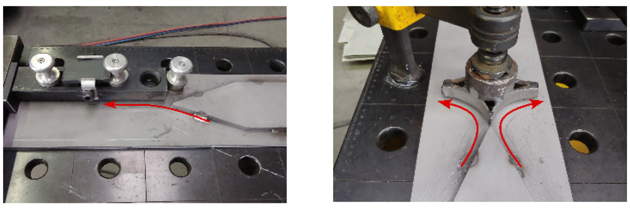


Figure 4 Cover plate shapes (CPS) tested to determine the influence of cover plate geometries.

In general, the arc ignition points and the end of a weld seam in a component, especially at the most loaded area of a structure, are normally avoided. For extended welds, these points must inevitably be located in the area of the weld end, which is usually a high loaded area. So, as a first consideration the course of an extended weld has to be defined. Different pathways are possible, like straightforward or softly swing to the sides. However, in order to receive a scientific proven statement, the shape and the course of the weld seam have to be replicable, therefore a template has to be developed. Both, the straightforward and the swing to the side course can be fabricated by using templates and were part of the research project, but there was nearly no difference in the fatigue strength and the straight option is much easier to manufacture, which was the reason to take a closer look on specimens with straight extended weld seams. The templates for both versions can be taken from figure 5.



(a) (b)

Figure 5 Templates for the different extended weld courses: (a) straightforward, (b) swing to the sides.

Due to the limited number of specimens only several aspects of possible influence factors on the fatigue behaviour of extended weld seams can be taken under review. Therefore, in a first step, the experimental investigations are limited to the influence of the length of the extended weld seam, the application of different welding sequences and the influence of different post-weld treatment methods on the fatigue behaviour. In addition, an influence on the fatigue strength should be recognised by using different steel grades. The different variations and the according number of tests in total can be taken from table 3.

Table 3 Experimental programme.

influence factor	Variation	number of tests in total
welding sequence	A – B – C	16
length of the extended weld seam	30,50,100 mm	17
post-weld treatment	grinding, HFMI-treated	25
Steel grade	S 460 / 355 / S690	included above

In a second step, influence factors like an increasing plate thickness (t ≥ 20 mm) as well as component tests will be part of the investigation. The results can be taken from [1].

As already mentioned, the end of the extended weld are the critical areas according to fatigue failure. So, the fabrication of the extended welds with the focus on the weld seam end was part of the project. The main influence factors might be the local weld geometry and possible weld flaws or defects caused by the welding process. To determine these factors different weld sequences (A to C) were experimentally tested. Therefore, the welding sequence A was used to try to obtain a large weld volume at the end of the weld and thus a sharp weld transition with a large weld toe angle. In comparison to that, the weld sequence C should lead to a smooth transition with a small weld angle. To get information about possible negative influences of arc ignition points at the weld seam end, the weld sequence B was tested. Unfortunately, this also leads to a sharp weld transition, caused by the welding process. The different weld sequences can be taken from figure 6.

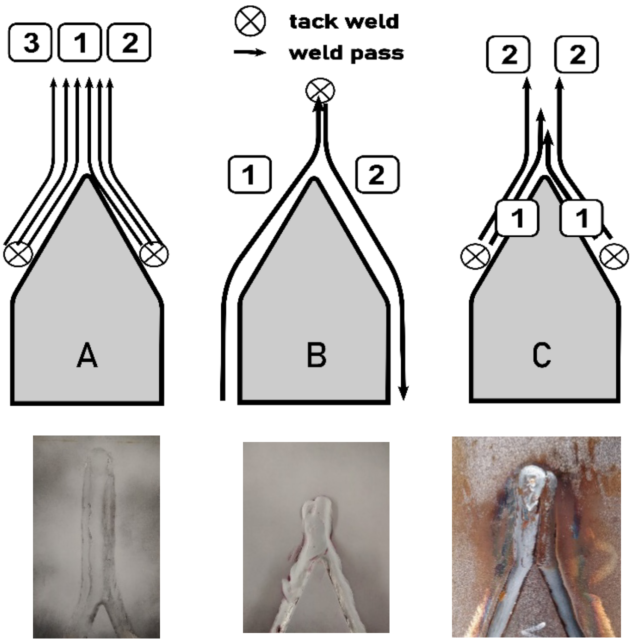
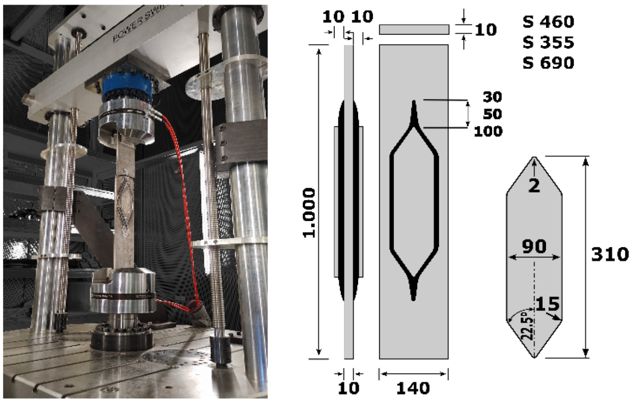


Figure 6 The different welding sequences used in these investigations and examples of the extended weld seams for each weld sequence.

3.2 Test rig

The tests are conducted with a resonance pulsator from the company SincoTec with a maximal load of 600 kN. All specimens were tested under axial tensile loading and with a stress ratio of R =0.1. The test frequency was about 59 to 61 Hz. The tests were stopped several times when reaching different frequency differences to record the crack growth. The specimens have a length of 1.000 mm and a width of 140 mm. The ground plate and the cover plate have the same thickness of 10 mm. Additional tests with plate thicknesses up to 20 mm will be conducted in the future but are not part of this paper. The used test rig and the dimensions of the specimens can be taken from figure 7.

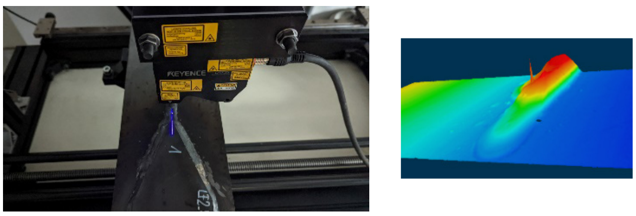


(a) (b)

Figure 7 Test rig (a) and dimensions of the specimens of the small-scale tests, all dimensions in mm.

3.3 Further investigations

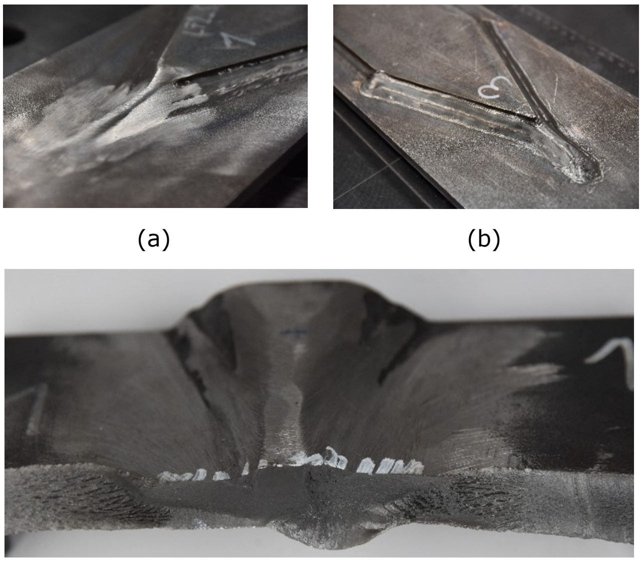
As a part of further investigations, the weld profile of the extended weld seams is scanned by a line laser. The laser can only cover a width of around 30 mm in one measurement, so it is necessary to compose single measurements to get the whole contour of the extended weld seam. In a next step the weld profiles of the extended weld along the weld will be evaluated and used for detailed effective notch stress simulations. Nevertheless, the key parameters of the weld end seam can be evaluated and applied for further analysis. The used setup can be taken from figure 8.



(a) (b)

Figure 8 Measurement of the weld profile by line laser: (a) measurement setup, (b) exemplary profile geometry

Because the end of the extended weld could be a possible spot for weld defects a constant quality assessment has to be done to develop quality characteristics for extended weld seams. Therefore, a closer look on the fracture surfaces were taken. In the as-welded condition, the crack initiation starts from the weld toe. By using post-weld treatment methods, the crack initiation could be shifted to other locations within the extended weld. Thus, the notch is smoothed by grinding and the crack initiation can be shifted to other critical areas, like flaws and pores. Such pores were sometimes seen in the fracture surface of post-welded specimens, but a test x-ray does not allow a conclusions about the frequency of such gas pores in the extended welds. Since the number of pores were very limited, the regulations according to the DIN EN ISO 5817 [11] should be observed. In figure 9 (a) and (b) specimens with the conducted post-weld treatments grinding and HFMI can be seen. A typical crack surface of a post-weld treated specimen can be taken from figure 9 (c).



(a) (b)

(c)

Figure 9 Post-weld treated specimens: (a) grinded specimen, (b) HFMI-treated specimen, (c) shift of the crack initiation into the extended weld seam by post-weld treatment.

4 Results of the investigations

Figure 10 and figure 11 show the results of the experimental test carried out so far. The given tables in the subfigures show the regression values of the different series, marked as $\Delta\sigma_{c,50\%}$ - value. All specimens were manufactured with the same steel grade (S 460). If the steel grade differs there is an additional label in the figures. In the as-welded state, the series were evaluated with a fixed slope of m = 3.0. Series with post-weld treatments were evaluated with a fixed slope of m = 5.0. In addition to the regression line, the evaluation was carried out with the prediction interval, marked as $\Delta\sigma_{c,95\%}$-value. The used number of load cycles is related to the end of the tests, which means, that the specimens are broken or that no more loads can be borne.

The tests results based on the nominal stresses show that the difference between the various cover plate shapes is not very evident, see figure 10 – (a). This is in line with the knowledge in [7] to [9]. Therefore, it can be concluded that the shape of the cover plate has no significant influence on the fatigue strength based on nominal stresses.

The comparison of the weld around specimens and the specimens with extended welds can be taken from figure 10 – (b). There it can be seen, that extended weld with the flat transition from the ground plate to the weld leads to an enhancement of the fatigue strength. Although, the course of the extended weld does not seem to have a significant influence on the fatigue strength. As already mentioned, for the further investigations the straightforward weld seams was used, because this kind of weld seams are easier to fabricate. Furthermore, the influence of the length of the extended weld does not seem significant above a certain length, see figure 10 – (c). So the further specimens were manufactured with a length of the extended weld of 50 mm.

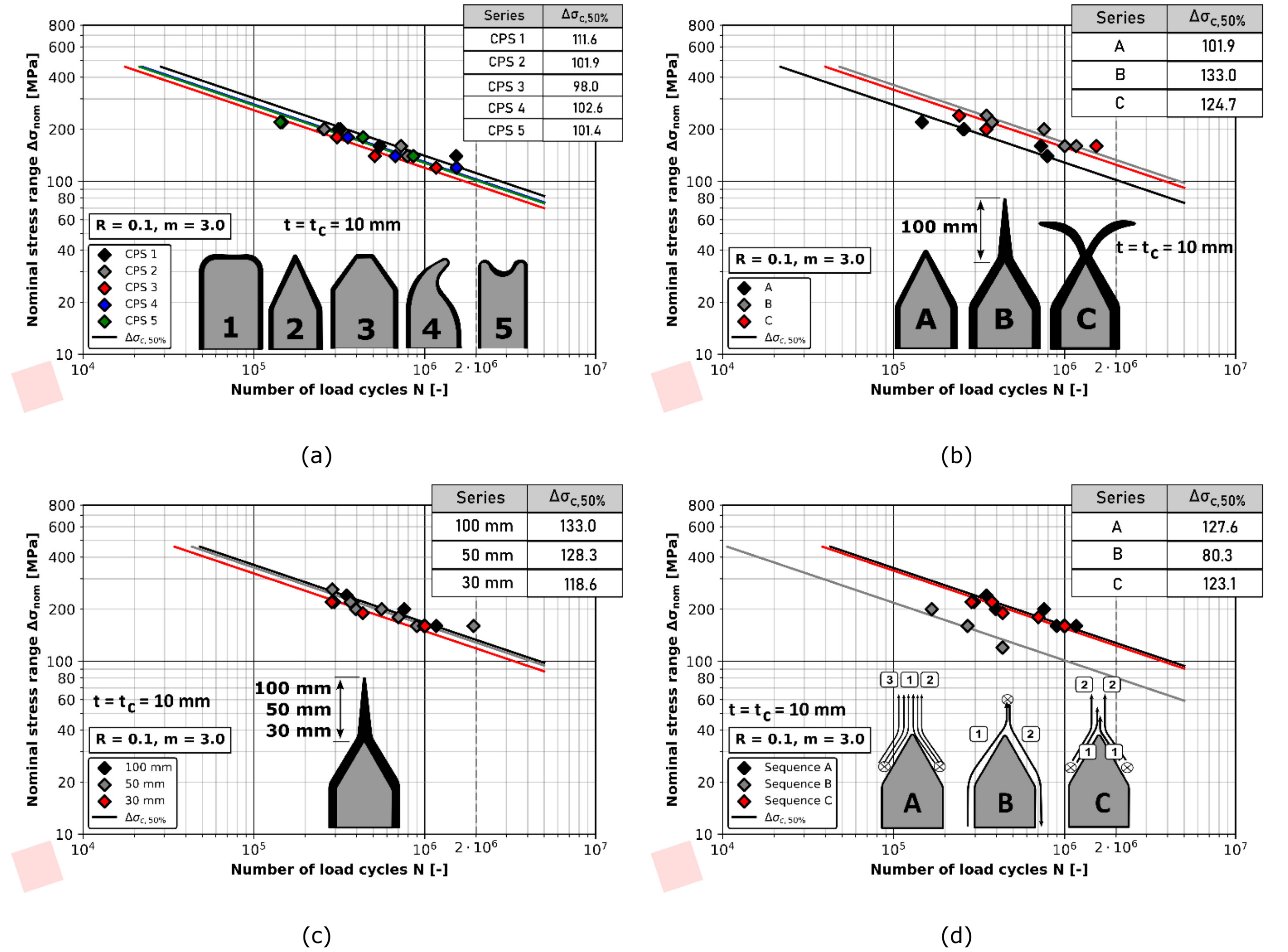


Figure 10 Results of the fatigue tests according to the influence factor: (a) cover plate geometry, (b) influence of extended weld, (c) length of the extended weld, (d) weld sequence

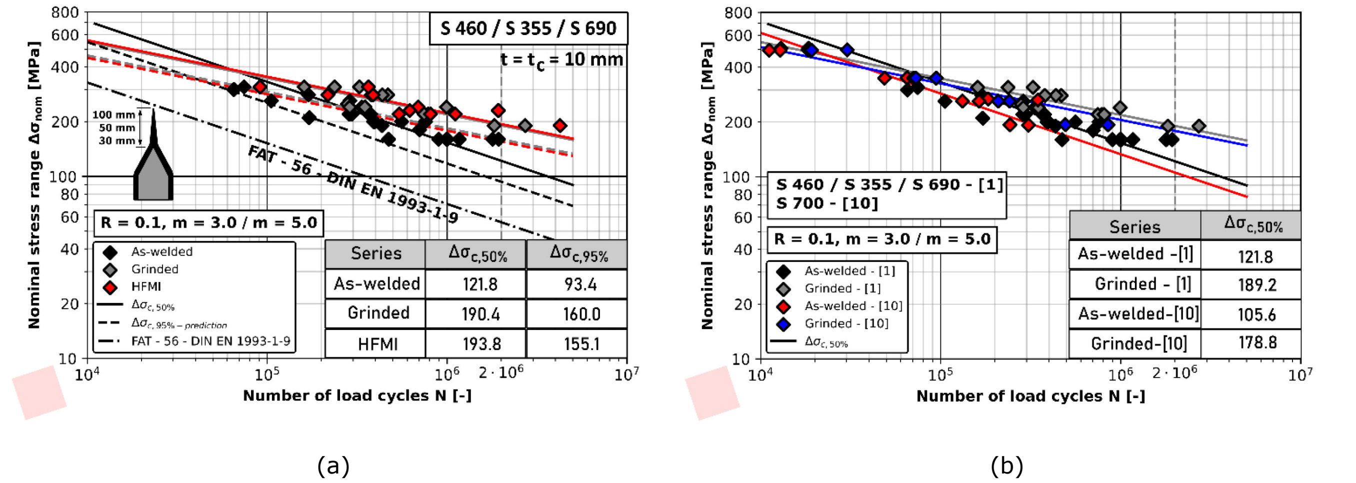


Figure 11 Assessment of the test results: (a) comparison of as-welded and post-weld treated results, (b) comparison to results in literature.

Other influence factors like the weld sequence and local weld geometry might have a higher impact on the fatigue strength. To guarantee a certain manufacturing level, quality criteria according to the geometry of the end of the extended welds have to be established. Therefore, the line scans have to be evaluated. Figure 10 – (d) shows that for the welding sequence quality criteria have to be established as well. The ignition points at the end of the extended weld seam have to be avoided. For further evaluation, test results with welding sequence B are not considered due to the negative influence of arc ignition points at the end of the weld.

In figure 11 - (a) the effect of the post-weld treatments grinding and HFMI can be seen. By smoothing the transition between ground plate and weld seam by grinding as well as by introducing compression residual stresses by the HFMI-treatment, the fatigue strength can be increased. But even without a post-weld treatment the results of the specimens with extended welds lead to a higher fatigue strength than compared to the reference FAT-class according to the EC 3 [4]. These are promising results, which can be confirmed by the results in [10], which lead to comparable results, see figure 11 – (b). Because the length of the extended weld seams might be less than 50 mm and the plate thickness of 5 mm is not common in steel constructions the results are limited to the area of machine engineering. By using bigger plate thicknesses a first step was taken for the application of extended welds in steel constructions.

5 Conclusion and outlook

With the presented investigations, it could be shown that the shape of the cover plates has only a small and negligible influence on the fatigue strength of this notch detail. Moreover, the use of an extended weld seam could have a positive effect on the fatigue behaviour, but precise specifications regarding the weld sequence and the geometry of the weld seam end have to be developed in the future in order to achieve a consistent level of quality. Furthermore, post-weld treatment methods like grinding and HFMI-treatment can increase the fatigue strength. The length of the extended weld does not seem to have a significant influence on the fatigue behaviour of extended welds, but should not below 30 mm.

Although, the variant steel using industries have different safety levels and wall thickness application areas. In order to extend the so far gained findings, further experimental tests with larger wall thicknesses and specimens under bending loads are required. Soon first component tests will be conducted in the framework of the research project.

In the future for a prospective application of the extended welds design recommendations have to be developed, especially with using the exact weld geometries of the weld seam end. Therefore, the laser data have to be assessed and implemented into a FEM-model to calculate the notch factors of such weld details. In this context a design recommendation based on the effective notch stress concept will be developed.

6 Acknowledgement

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