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Influence of the geometry of butt welds and longitudinal attachments on their fatigue resistance

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Abstract

Many constructions, such as wind turbines, bridges and crane runways, are cyclic loaded so that fatigue failure may occur. Therefore, in the course of the revision of Eurocode 3, two research projects funded by AiF-DASt re-investigate the classification of constructional details of EN 1993-1-9. This paper focuses on the geometrical influence on the fatigue resistance of butt welds and longitudinal attachments. First, the influence of the plate thickness on butt welds was investigated. Both a meta-study based on test results of various research projects and our own test series on butt welds up to 80 mm thickness led to interesting conclusions.

Furthermore, the influence of the length and radius of longitudinal attachments on the fatigue resistance was investigated. By experiments and numerical analysis, clarification has been sought whether the transition radius larger than 150 mm or the ground weld toe is decisive for the improvement of the fatigue resistance. Since previous meta-studies could not provide a clear result on the influence of the longitudinal attachment length, this was also investigated.

A database established in the projects allows to integrate and assess the specified details of butt welds and longitudinal attachments in the context of the overall approach in EN 1993-1-9.

Keywords

fatigue; butt welds; thickness effect; longitudinal attachments; radius; length

1 Introduction

An important detail of high relevance for many structures are butt welds, for this detail the current design rules in Eurocode 3 Part 1-9 [1] require to reduce the fatigue resistance for plates with a thickness larger than 25 mm with the equation (1) and (2).

$$\Delta\sigma = \Delta\sigma_C \cdot k_s \qquad (1)$$

$$k_s = (25/t)^{0,2} \qquad (2)$$

Due to the wide scatter of data in the meta study of the research project "Re-evaluation and enhancement of the detail catalogue" [2], a clear conclusion concerning the influence of the thickness of the constructional detail butt weld was not possible. Additionally, there are only few test results for butt welds with higher plate thicknesses available, so additional experimental tests were carried out with plate thicknesses up to 80 mm within the frame of the project "Evolution of Detail Catalogue" [3] and the associated dissertation [4]. The results will be described in the following.

As a further detail, longitudinal attachments were investigated in [3], more precisely. In the current EN 1993-1-9 [1], an improvement of the fatigue resistance is only possible, if the ends of the longitudinal attachments have both, a transition radius larger than 150 mm and grinding the weld area so that the transverse weld toe is fully removed. In addition, the attachment ends must be welded with an HV-weld, which is also graphically clarified in the upcoming Eurocode [5], shown in Figure 1.

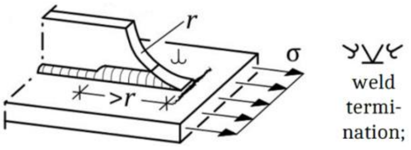

Figure 1: Detail 3 in Table 10.5 [5].

The meta study of the previous project [2] showed different results regarding the radius, but since there were no explicit tests about this detail, it could not be conclusively explained. The results of our experiments and numerical analysis [3] are presented in this article.

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Also, due to the scatter of data the influence of the length could not be determined. To investigate whether the length has an influence on the fatigue resistance, the data were separately analysed and experimental tests were carried out [3].

2 Butt welds

2.1 General information

In EN 1993-1-9 [1], different designs of the constructional detail butt joint are considered. A distinction is made between joints welded from one side and joints welded from both sides, since the root pass of butt joints welded from one side results in a considerable notch and must therefore, without further inspection, be classified as detail category (DC) 36. Grinding of the weld reinforcement of butt joints welded from both sides and thus removing the geometric notch has such a positive effect that this design can be classified as DC 112. In the situation, where the weld reinforcement is not grinded, there is a distinction between a smaller (>110°) and a larger (>150°) flank angle, whereby butt joints with larger angles resulting in a lower notch effect, can be better classified with DC 90 instead of 80. This shows the large influence of the weld transition on the fatigue resistance. The large scatter of the meta study suggests that other factors are relevant as well in regard to fatigue design. Since many projects with butt joints have different focusses, such as material, welding imperfections or post-weld treatment, the data available concerning other parameters that do not affect the individual focus are in some cases incomplete. This not only makes it difficult to determine possible influence parameters, but also hinders comparison and evaluation of the tests in regard to the influence of plate thicknesses. Therefore, it seemed reasonable to specifically consider the test results of series that only altered the plate thickness. In our tests, care was taken to ensure that only the plate thickness was changed.

2.2 Experiments

To ensure that only the thickness of the plates was varied, all specimens were produced in the same way with a steel grade of S355TM, cut along the rolling direction after the welding with a width of 130 mm. All the specimens, three per thickness 10 mm, 20 mm, 50 mm and 80 mm were loaded by a stress range of 200 MPa and a stress ratio of R = 0.05. Since the weld height was smaller than 0.1 of the weld widths and the flank angle larger than 150°, acc. to the current and the upcoming Eurocode, this detail can be classified within DC 90. One of the specimens with 80 mm thickness after testing with complete failure is shown in Figure 2.

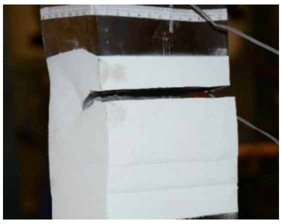


Figure 2: Butt weld with 80 mm thickness after failure [3].

All specimens were 3D-scanned before the fatigue tests. Unfortunately, a few butt welds with plate thickness of 10 mm had a significant misalignment. Consequently, only the specimens with plate thicknesses between 20 mm and 80 mm were considered in the further evaluation. During the tests the strain was measured by strain gauges, thus facilitating the crack initiation. The cracks appeared between the weld and the main plate and increased along the weld toe and through the plate. All experiments were stopped at complete fracture, shown in Figure 2. The complete fracture was achieved when no longer the maximum load could be applied.

For a better visualisation of the thickness effect, the results were normalized to 2 million stress cycles by the slope of m = 3. The red triangle in Figure 3 represent the results of the current experimental tests in [3], beside other test data of the meta study. They all show a comparative fatigue resistance despite the fact that the thickness increases from 20 mm up to 80 mm. Those results with focus on the plate thickness are illustrated in orange, green and purple.

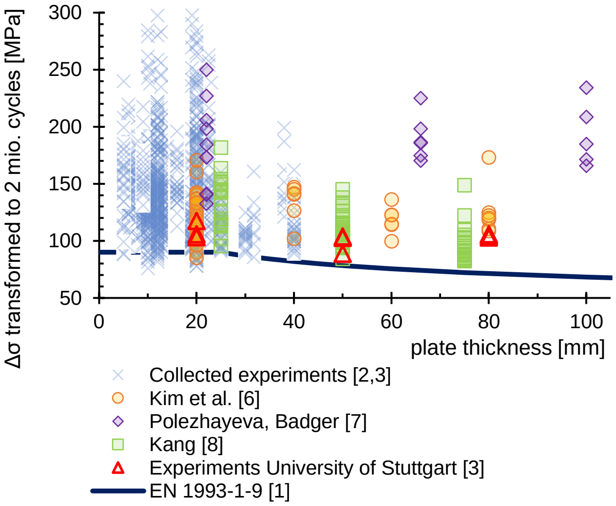


Figure 3: Various experimental test results of butt welds in as-welded state, with different plate thicknesses [3].

Even though there is a considerable scatter of data in general, within each of the individual test series, the results are distinct. Figure 4 shows the evaluation with the slope m = 3, of the series sorted according to the individual plate thicknesses, which were, however carried out with in some cases low test numbers.

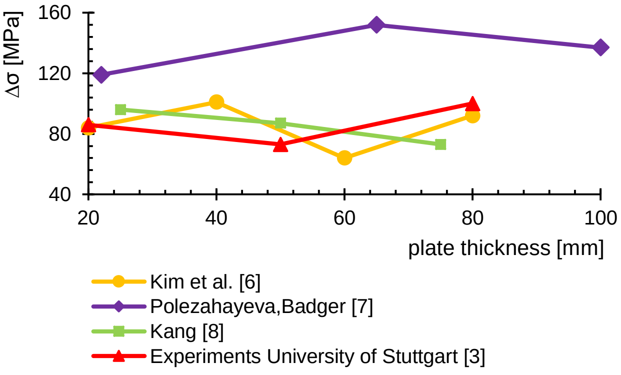


Figure 4: Stress range for each thickness within the series [3].

Here, too, there is no reduction of the fatigue strength for most of the series despite increasing plate thickness. Due to the scatter, however, no plate thickness influence can be identified here either. Further investigations concerning the 3D-scans should clarify, whether the influence of the thickness can be seen in FEA, when realistic geometries are modelled.

2.3 Misalignment

Since plates with 10 mm thickness endured less load cycles than expected with DC 90, further investigations were carried out on those, with the previously made 3D Scans. An axial misalignment up to 40 % of the plate thickness as well as an angular misalignment were identified at those specimens. The evaluation of the strain gauge measurements during the quasi static loading showed those two effects. Yuxiao [9] investigated and explained those effects with the following interpretation. An initial stress state is induced in the specimen by closing the clamps due to the angular misalignment, resulting in a possible variation of the mean stress. Actual misalignment which was observed mainly for 10 mm thick specimens resulted in additional bending stress which lead to an increased stress range.

Both effects intensify with greater misalignments. Since the stress from the axial misalignment affects the stress range, it must be considered in the evaluation of the tests by adding it to the stress due to the load application. These additional stresses need to be evaluated separately.

3 Longitudinal attachments

3.1 Influence of the length

For the investigations of the longitudinal attachments a similar procedure as for the butt joints was followed. All parameters, such as the material with S355TM and the stress range of 200 MPa were constant for all test specimens. Only the length of the attachments was varied between 100, 250 and 500 mm with three specimens each. The components were symmetrical about three axes and the longitudinal attachments were welded with double fillet welds. In order to avoid stress peaks due to the beginning or end of a weld, the end of the stiffener was continuously welded around. Post-weld treatment was intentionally dispensed to allow for the simplest possible fabrication. All specimens were tested until complete fracture, as explained in section 2.2 and shown in Figure 5. Since these attachments were without a radius, had a double fillet weld without any post-weld treatment and were longer or equal to 100 mm, they are classified acc. to [1] in DC 56.

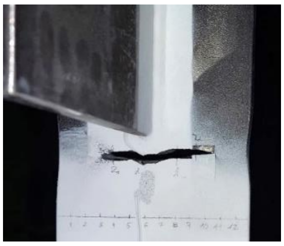


Figure 5*:* Crack at the end of a fatigue test with an attachment length of 500 mm [3].

As expected, the fatigue cracks occurred at the weld toe to the base plate at the attachments ends, which can be seen in Figure 5. The test results shown in Figure 6, confirm a decrease in fatigue resistance with increasing length of the attachment. Compared to the current [1] and future Eurocode 3 Part 1-9 [5], both classifications of the standards are on the conservative side. The results fit better with the less significant reduction of the upcoming standard. Other test results acc. to Figure 6 also show an influence of the attachment lengths. A combined evaluation of all available results shows that the classifications of the upcoming Eurocode for different lengths are on the safe side. Thereby, it is important to ensure continuous welding around the stiffener ends in order to avoid increased stresses at the beginning or end of the weld. Puthli et al. [10] additionally tested specimens, which had the weld beginning at the end of the attachment. The results of these specimens (not shown in Figure 6) lie below the detail category of their length.

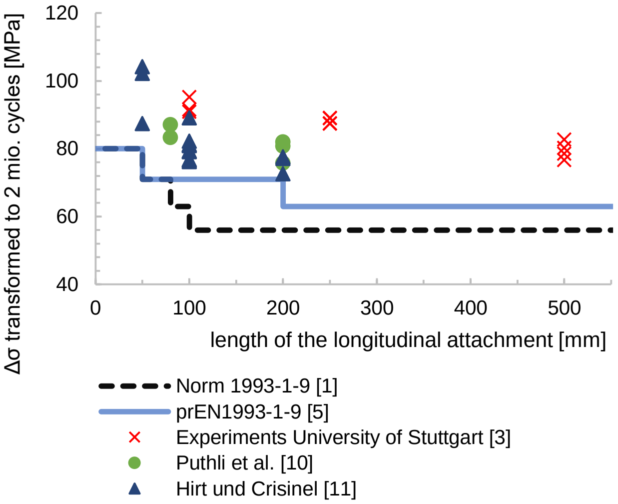


Figure 6*:* Decrease of the fatigue resistance with increasing length of the longitudinal attachments [3].

3.2 Influence of the attachment's radius

3.2.1 State of the art

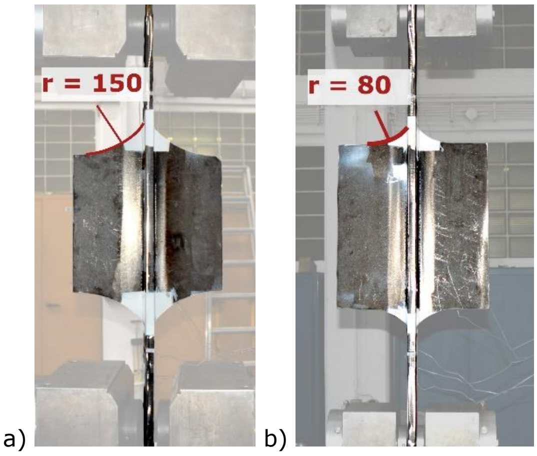
In EN 1993-1-9 [1], a radius greater than 150 mm at the end of the longitudinal attachment can improve the detail category from DC 56 (for long attachments L > 100 mm) to DC 80, regardless of the attachment length. Despite the complex fabrication and finishing of the welds, details with radii smaller than 150 mm and small lengths are classified in DC 71. However, the meta study of the previous project [2] did not give a clear indication, whether the radius of the longitudinal attachments has a positive influence on fatigue resistance. So, the presumption can be made that not the sudden change in cross section but the weld toe itself around the end of the plate is the most critical fatigue location. Therefore, the purpose of the radius might be merely to enable a smooth grinding of the weld toe. If the grinding can also be realized without a radius or only with a small radius, both the workload and the offcuts may be significantly reduced.

3.2.2 *FEA studies*

Finite element analyses have shown that when the notch effect on the weld toe is reduced by grinding [3], the weld root becomes the decisive fatigue location and only a slight improvement of the detail category can be achieved. Furthermore, there is a risk of sudden failure due to a crack starting from the weld root. To solve this problem, the weld root can be moved back to an area with lower stresses. This can be achieved by full penetration welding at the attachment ends. This reduces the stress in the weld root and the transition from the weld to the plate is decisive. Therefore, grinding the weld toe is beneficially only in combination with the full penetration of the attachments ends. This is also reflected in the test results. All specimens should be welded with full penetration in the area of the radius; this was successfully done for all test specimens except one. The only outlier specimen, with less than 100000 cycles, can clearly be traced back to a weld that was not through welded.

3.2.3 *Experiments*

To investigate the influence of the radius at the end of the longitudinal attachment, nine tests each, with a radius of 150 mm and 80 mm at both ends of the attachment and an attachment length of 500 mm were carried out as shown in Figure 7*.*



a) b)

Figure 7*:* Longitudinal attachments with a) r = 150 mm and b) r = 80 mm [4].

In both cases the longitudinal attachments were welded in the middle by a double fillet weld. The ends of the attachments were prepared for a HV-weld to avoid a crack from the root, as required by the current [1] and future Eurocode 3 Part 1-9 [5].

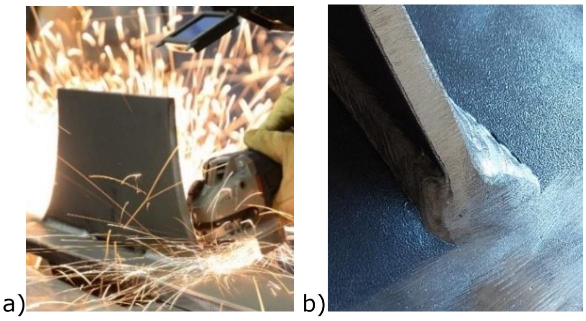

a) b)

Figure 8*:* a) Grinding of the weld transition, b) good result of grinding [4].

Additionally, the ends of the attachment were welded in one step, as it was done with the straight attachments. The welds at the attachment ends were grinded in the direction of the load as it can be seen in Figure 8. It turned out that it did not make any difference for grinding with regard to difficulty and quality of the results, whether the radius was 80 mm or 150 mm. The test specimens were loaded with stress ranges between 105 MPa and 240 MPa and a stress ratio of R = 0.05. As expected, the crack was initiated at all tests at the weld around the end of the attachment. The crack initiated from the transition either to the base plate or to the attachment, except for the specimen without the full penetration weld, where the failure occurred from the weld root.

Between the specimens with a radius of 80 mm and 150 mm, no difference in crack initiation or crack development could be seen. The statistical evaluation of the individual series evaluated both individually and together, shows for all a DC of $\Delta\sigma_{95\%}$ = 100 MPa, with the correlation varying only between $R_{Pearsons}$ = 0.87 and $R_{Pearsons}$ = 0.89 and the true slope of the test results varying only between m = 3.15 and m = 3.44. This high detail category, compared to DC 80 acc. to [1], could be obtained due to the very low scatter and the 95% quantile is thus very close to the test results. The specimen which was not completely welded through, already cracked much earlier than expected from the weld root, so it was not included in the analysis.

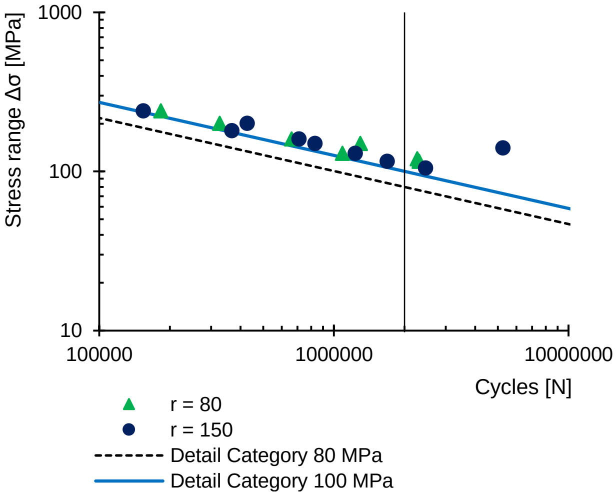


Figure 9*:* Experimental test results with radius 80 and 150 mm [3].

4 Summary and conclusions

Since a total of 13 tests with butt joints welded from both sides and with thicknesses between 10 mm and 80 mm showed no influence of plate thickness and since the research of other test series also reflect these results, there is no experimental basis for a reduction of the fatigue resistance for large plate thicknesses.

The experimental results of 9 test specimens with longitudinal attachments lengths between 100 mm and 500 mm, combined with the data of other research projects show that the adaption made from the current EN 1993-1-9 [1] to the upcoming prEN1993-1-9 [5] provides a more economical and yet safe design, which considers the influence of the length to a reasonable degree.

Two test series with radii r = 150 mm and r = 80 mm of the longitudinal attachment ends and nine tests specimens each, resulted in DC 100. The presumption that the grinding of the welds at the end of the attachments and not the radius improves the fatigue resistance, can be confirmed by the test results. However, regardless of the radius, the end of the attachments must have full penetration welds, otherwise there is a risk of an early, sudden fracture originating from the weld root and reduced fatigue resistance.

Acknowledgement

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