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Investigation of the thickness effect for butt welded joints

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Abstract. The validity of the thickness effect is investigated for the specific case of transverse butt joints in the as-welded condition. A large amount of experimental fatigue data for these joints is collected from the literature and subjected to statistical analysis, totaling 1258 test results, where 155 are in the thickness range 40-100mm. It is found that the thickness correction according to the IIW recommendations and most other codes/guidelines is very conservative for butt joints.

Introduction

The thickness effect considers the influence of the plate thickness on the fatigue resistance of welded joints and is generally included in design rules by scaling the fatigue strength with the following factor:

$$f(t) = \begin{cases} 1 & for\ t \leq 25mm \\ \left(\frac{t_{ref}}{t}\right)^k & for\ t > 25mm \end{cases}$$

According the IIW recommendations [1], the reference thickness should be taken as $t_{ref} = 25mm$ and the exponent should be $k = 0.1, 0.2$ or 0.3 depending on the detail category considered. For transverse butt joints in the as-welded condition, a value $k = 0.2$ is recommended. Several other codes and guidelines offer similar recommendations [2,3].

The thickness effect is said to be comprised by the following effects; the statistical-, the technological- and geometric size effects, as explained in the following.

- Statistical size effect: the probability of a severe defect occurring is higher in a large volume (thick joints) than in a small volume (thin joints) [4].
- Technical size effect: refers to the rougher manufacturing conditions typically applied for thick plate structures and differences in residual stresses, surface roughness and microstructure [5].
- Geometric size effect: relates to the stress gradient due to stress concentrations and superimposed bending, which becomes steeper when the joint become thinner. The combined stress field at the crack tip of a given crack size will thus be less intense for a thin joint compared to a thick joint. This effect has been reported to be the most significant [6].

In general, the theoretical arguments for the thickness effect are thus well established and the effect is also well proven experimentally for many types of welded joints [4,7], however not for butt joints [9].

For the specific case of butt joints, an increasing amount of experimental results from fatigue tests show little or no support for the existence of a thickness effect for these specific joints. A systematic evaluation of available experimental results is therefore carried out in order to investigate the validity of the thickness effect for butt joints.

For butt joints, both the statistical and technical size effects are assumed to be negligible. According to Maddox [4], the statistical size effect is considered the least significant in general. To some extent, the technical size effect could be considered a reminiscence from early investigations that showed lower fatigue performance of SAW welding [4], which is typically used for thick joints; however, the fatigue performance of modern SAW welding is found to be equal to that of other of welding technologies.

The geometric size effect is governed by the magnitude of the stress concentration in the weld toe and the level of superimposed bending stresses. For butt joints, the stress concentration at the weld toe is small compared to most other welded joints, and the level of misalignment relative to the thickness generally decreases with increased thickness. For example, von Selle et al. [8] report a level of axial misalignment of as little as 0.4-1.0% of the thickness for 80mm thick butt joints. Stress gradient effects in butt joints are therefore expected to be limited under tensile loading.

One of the few investigations focusing on the influence of residual stresses in relation to the thickness effect in butt joints was carried out by Ohta et al. [9]. In a test of 9mm vs. 40mm butt joints, they reported a difference in fatigue strength in favor of the 9mm joints when testing at $R = 0$. However, when testing at $\sigma_{max} = \sigma_y$ the fatigue strength at the two thicknesses were identical. They concluded that the apparent thickness effect seen at low R-ratios could be due to the difference in residual stresses in the small scale specimens. Testing thin small scale specimens at low R-ratios could therefore lead to artificially good results, since these specimens tend not to contain the high level of tensile residual stresses that would typically be found in actual welded structures.

Based on the above discussion, the expectations for finding a significant thickness effect in butt joints are limited.

Fatigue data for butt welded joints

A large amount of fatigue data from experimental investigations of fully penetrated butt joints has been collected from the literature [10-24] and arranged in a database. The results are mostly for small scale test specimens in the as-welded condition, with thicknesses in the range $t = 8 - 100mm$, but also includes a limited number of results from full-scale tests of butt welds in heavy I-beams. All the tests on small scale specimens are carried out at positive stress ratio ($R \geq 0$) at room temperature in a non-corrosive environment (air). The vast majority of the specimens failed from the weld toe.

The entire data collection is shown in Figure 1 along with the FAT90 SN-curve, including the scatter band for the mean $\pm$ 2 standard deviations ($P_s = 2.3 - 97.7\%$) calculated using a fixed slope coefficient of $m = 3.0$ and only the data from specimens with a thickness less than or equal to 25mm. The natural slope coefficient of the mean is $m = 3.08$ when excluding run-outs, however all analysis in this paper is carried out using a fixed slope of $m = 3.0$.

When excluding the run-outs, the mean fatigue strength at 2 million cycles is $\Delta\sigma_m = 135.3MPa$ and the characteristic fatigue strength is $\Delta\sigma_c = 90.3MPa$, i.e. the lower part of the scatter band coincides with the recommended FAT90 curve.

It is clear from Figure 1, that the FAT90 curve fits very well to the lower bound of the data, both in terms of the slope and the design fatigue strength. Furthermore, at first glance, the results from the thick specimens (dark markers) fit quite nicely into the scatter band of the thin specimens.

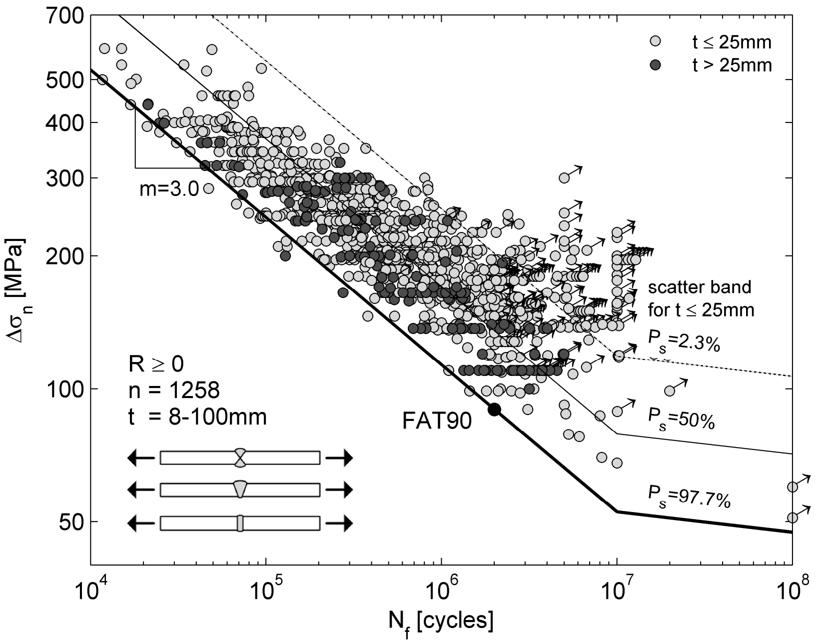

Figure 1: General overview of fatigue data for butt joints.

As seen in Figure 2 (right), the data collection is slightly heterogeneous, even though the run-outs are excluded. Thus, the data collection is homogenized in accordance with [1] in order to reduce the scatter. This is achieved by excluding results with a fatigue capacity above the mean + 2 standard deviations from further analysis, i.e. the data above the scatter band ($P_s < 2.3\%$), as shown in Figure 2.

These results show superior fatigue performance and thus contribute excessively to the scatter of the data, and are of less interest for design recommendations. Only 31 data points are removed, but the scatter is reduced considerably and the standard deviation of $logC$ falls from 0.26 to 0.23. Contrary to what might be expected, removing these top-performing results actually yields a higher calculated design fatigue curve $\Delta\sigma_c = 91.6MPa$.

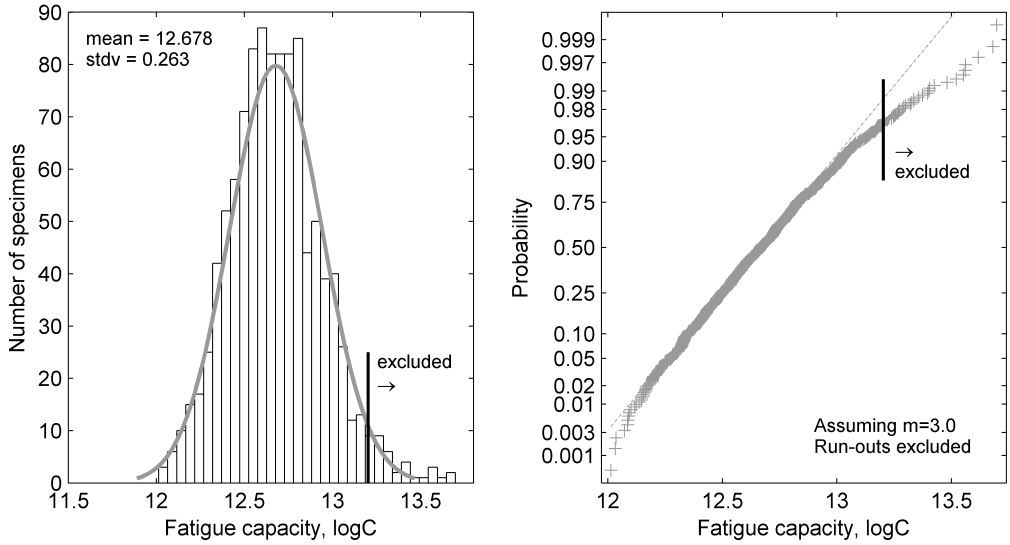

Figure 2: Probability plots for the data in Figure 1, illustrating the excluded data points.

Figure 3 highlights the results for the specimens thicker than 25mm, i.e. the ones that should be subjected to thickness correction [1]. The results are divided into three groups and color-coded according to thickness, i.e. $t = 40,\ 60-66$ and $75-100mm$. From the figure, it is clear that the data lies in the lower part of the scatter band of the thinner ones, but only 2 data points fall below the FAT90 SN-curve.

It thus immediately seen that the thickness correction of a butt joint in e.g. 80mm, i.e. reduction of the FAT class from 90 to approximately 71, is much too conservative according to these results. Considering that the design curve should represent a probability of survival of $P_s = 97.7\%$, a small number of results are expected to lie below the curve as is the case here.

Although the results from the thick specimens seem to group in the lower part of the scatter band of the thin specimens, there does not appear to be any distinct thickness dependency in the results, i.e. the three thickness groups seem to perform equally well.

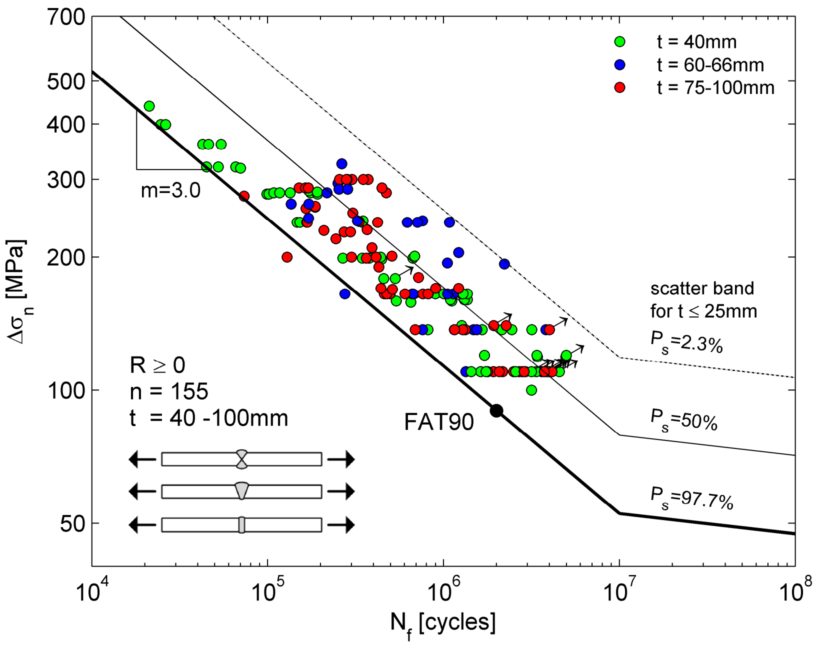

Figure 3: Fatigue data for thick butt joints, including the scatter band from Figure 1 and the FAT90 SN-curve.

Statistical analysis

Emphasizing the data from the individual test series, totaling 101 test series, the mean fatigue strength at 2 million cycles as a function of the thickness for each test series was calculated, illustrated in Figure 4 (right). The mean is used instead of the design fatigue strength, because it is considered less affected by statistical inaccuracies. The FAT90 design curve, thickness corrected according the IIW recommendations [1], is also shown. The level of the curve and experimental results cannot be directly compared, since they do not represent the same survival probability, only the tendency of the data and the curve should be compared.

The reason for this approach is that many test series contain only very few results (e.g. 2-4) and statistical treatment of these in order to calculate the associated design fatigue strength is not appropriate, in these cases the only statistical measure that can be considered with some reliability is the mean.

According to Figure 4 (right), it becomes increasingly clear that the tendency towards a thickness effect is limited, especially for the lower bound of the data points. The figure also shows that the tendency of the thickness corrected design curve for larger thicknesses has very little or no support.

A slight negative thickness effect can be seen in the upper part of the experimental data, but this is of less interest for design recommendations. It can be argued, that this is because of too many, too optimistic results for the thin specimens, probably due to their inferior ability to develop high tensile residual stresses.

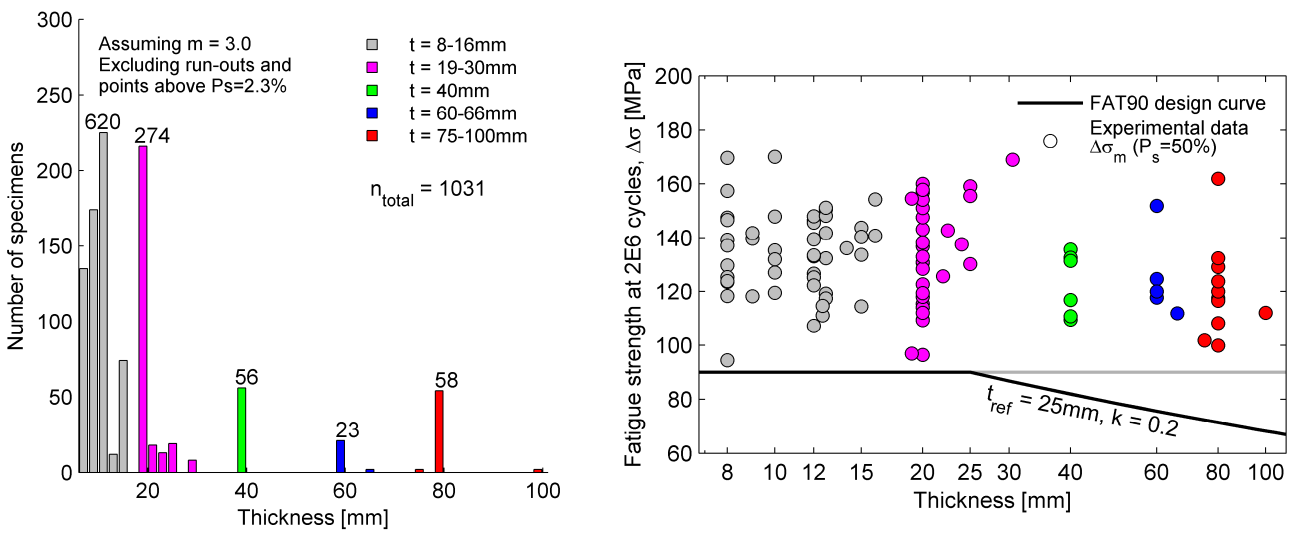

Figure 4: Data grouping and mean fatigue strength vs. thickness.

As discussed, performing statistical analysis of the individual test series is not always appropriate; therefore the test results are divided into 5 groups according to thickness, as illustrated by color in Figure 4.

Each group is associated with its weighted mean thickness, $t = 10.94, 20.95, 40.00, 60.52$ and 80.51mm, respectively. Traditional statistical analysis is then performed according to [1] for these groups in order to determine the mean and design fatigue strength for the five groups in a robust manner.

The results are shown in Figure 5. If there is any thickness dependency, it is not unambiguous. If considering the mean fatigue strength there is a slight negative thickness effect. Fitting a line through the data using linear regression (excluding the thinnest group, since it should not be corrected, and thus should not influence the correction), the thickness correction exponent can be determined to approximately $k = 0.05$, i.e. a fourth of the value currently recommended by the IIW [1].

If considering the design fatigue strength on the other hand, there appears to be no thickness dependency at all for $t > 20mm$. Neither the mean, nor the design fatigue strength seems to offer much support for the current design rules.

Both the mean and design values suggest a higher fatigue strength for the thinnest group. This, however, could be a result of testing conditions being too gentle, i.e. not accurately representing the conditions experienced by actual welded structures.

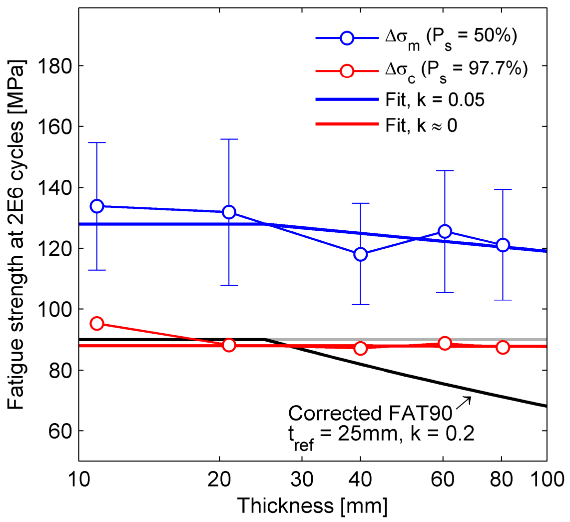

Figure 5: Fatigue strength vs. thickness. Error bars on mean fatigue strength indicate ± 1 standard deviation.

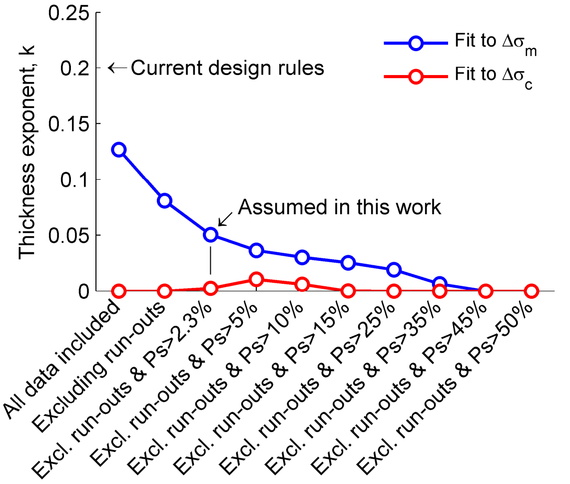

Figure 6: Thickness exponent calculated as in Figure 5 when excluding different fractiles of data.

For design recommendations, the results in the lower part of the scatter should be given priority, since these are the most critical to safety. One way of prioritizing these lower results is to exclude some of the best performing results, e.g. run-outs, and/or a certain fractile of the results with the best performance. Figure 6 shows the thickness correction exponent calculated by curve fitting to the mean and design fatigue strength as in Figure 5, but excluding various fractiles of the best performing results.

It is evident, that the thickness correction exponent calculated from the design fatigue strength is relatively unaffected, and constantly lies at approximately zero, whereas the exponent calculated from the mean fatigue strength converges towards zero when excluding more and more of the best performing results.

Conclusions

The following conclusions are drawn, based on statistical analysis of a large amount of fatigue data for transverse butt joints in the as-welded condition.

- All collected fatigue data agrees very well with the SN-curve recommended by the IIW, i.e. FAT90 and a slope coefficient of $m = 3.0$
- Only 2 of the test results for $t = 40 - 100mm$ lie below the FAT90 SN-curve
- Thickness correction using a reference thickness of $t_{ref} = 25mm$ and exponent of $k = 0.2$ appears much too conservative for transverse butt joints
- If excluding more data points in the upper part of the scatter band, thus giving priority to those results close to the design curve, the thickness effect reduces even further
- Conservatively adopting the trend of the mean fatigue strength in Figure 5, a new thickness correction exponent can be proposed, $k = 0.05$ for transverse butt joints

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