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Thickness Effect in Fatigue of Welded Butt Joints

A review of experimental works

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Abstract A review is conducted on the fatigue strength of thick butt joints in steel. The causes of the thickness effect are discussed with emphasis on the peculiarities of axially loaded butt joints. The available experimental investigations in the open literature are reviewed and discussed. Two specific investigations are highlighted, in which testing was conducted under particularly representative conditions, which both show limited/non-existing thickness dependency. It is concluded that the reduction of fatigue strength in current codes seem too conservative for the case of axially loaded butt joints.

Keywords Fatigue · Welded joints · Thickness effect

1 Introduction

Large amounts of experimental investigations show that, in general, the fatigue strength decreases with increased size of specimens. The phenomenon, called the *thickness effect* or *size effect*, is observed for both machined and welded specimens. The mechanisms behind the phenomenon are still a matter of some debate, but the resulting fatigue strength reduction is more or less converged in different codes. Typically, a thickness correction is implemented in state of the art codes, scaling down the fatigue strength using

$$f(t) = \left(\frac{t_{ref}}{t}\right)^k \tag{1}$$

According to the IIW recommendations (Hobbacher, 2016), 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 considered. For transverse butt joints in the as-welded condition, a value $k = 0.2$ is recommended. Other codes and guidelines offer almost identical recommendations (EC3, 2007; DNV GL, 2016). It should be mentioned, that the approaches by DNV and IIW are somewhat more elaborate, in that the width of the weld seam (not the weld length) may also be considered. Other codes, e.g. ISO19902 (2007) are somewhat more conservative and use different parameters, i.e. $t_{ref} = 16$mm and $k = 0.25$. The significant reduction in fatigue strength with increased thickness is shown in Figure 1 for a FAT90/DC90/Class D butt joint.

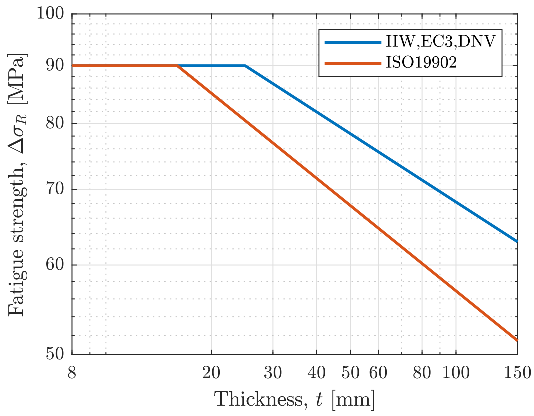

Fig. 1 Comparison of thickness correction in codes.

The thickness effect was first introduced by Gurney (1979) based on fracture mechanical calculations and supported by experimental observations. He showed that thicker joints performed worse than thinner joints when subjected to fatigue testing. Since then, many researchers

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have studied the phenomenon and tried to deduce the reasons behind.

Berge (1985) showed that the thickness effect could generally be explained by geometric features of the joint, rather than statistical or technological considerations.

Schumacher et al. (2009) studied the thickness effect in welded tubular joints both experimentally and theoretically. They concluded, that current guidelines seem too conservative.

More recently, Lotsberg (2014b,a) conducted a thorough review of the history of the thickness effect and introduction in rules and codes. He proposes a reduced thickness correction for some specific welded details, hereunder butt joints.

Fukuoka and Mochizuki (2010) studied the thickness effect in large scale welded specimens. They observed much less thickness dependency, than usually seen in small scale specimens. The same observation was reported by Yamamoto et al. (2014).

Evidently, there are several studies hinting that the thickness effect may currently be corrected too much, particularly for butt joints. The purpose of this paper is therefore to shed light on the possible causes for a reduced thickness dependency compared to what is currently assumed in most codes and to provide recommendations for, and inspire, future research in the topic. The present investigation is a continuation of previous work (Pedersen et al., 2012) made possible by the publication of several new experimental studies.

2 Thickness effect

The thickness effect is considered to be a compound effect caused by:

- Geometric size effect
- Statistical size effect
- Technological size effect

These are discussed in more detail in the following.

2.1 Geometric size effect

The geometric size effect comprise two issues which causes worse conditions for thicker joints; the stress gradient effect and the effect of incomplete scaling.

Firstly, the *stress gradient* due to stress concentrations and/or superimposed bending, becomes steeper when the joint become thinner, see Figure 2. The combined stress field at the crack tip of a given crack size a_i will thus be less intense for a thin joint compared to a thick joint, i.e. for $t_1 < t_2$, we get $\sigma_1 < \sigma_2$, when the nominal stress is the same.

The stress gradient effect is especially pronounced in bending loading, but is also observed at notches in axial loading (Lotsberg, 2014a). This effect has been reported as the presumably most significant (Berge, 1985; Maddox, 1991).

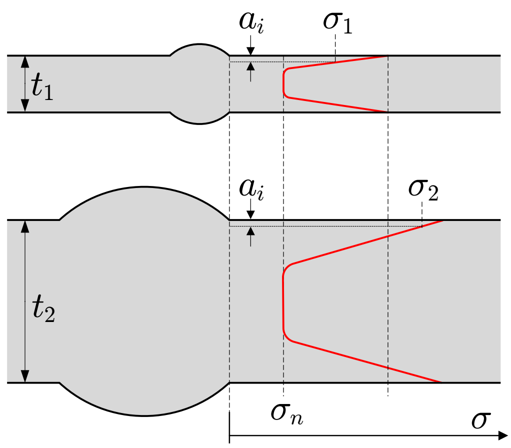


Fig. 2 Geometric size effect, after (Berge, 1985).

Secondly, *incomplete scaling* refers to the fact that the local weld toe geometry, in the area where cracks tend to initiate, do not scale with thickness. It is fair to assume that the weld toe radius will remain constant irregardless of the plate thickness. Hence, for thicker joints, the ratio of toe radius to thickness decrease and the stress concentration will increase.

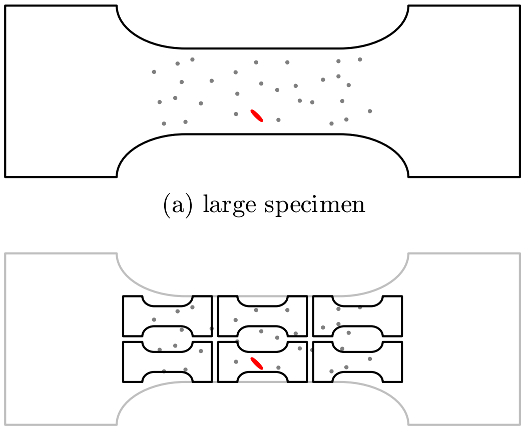
2.2 Statistical size effect

Fatigue is a weakest link process. Cracks initiate and grow in locations where the combination of all detrimental effects are worst, e.g. stress concentration, weld defects, residual stresses and material properties (Berge, 1985).

The statistical size effect therefore refers to fact that the probability of a severe defect occurring is higher in a large volume (thick joints) than in a small volume (thin joints).

Referring to Figure 3, imagine that some material containing a severe defect (red) is used to make one large specimen. Then it will necessarily contain the severe defect and, when tested, it will show low fatigue strength.

If instead 6 small specimens were made from the same material, only one of them will contain the severe defect. Thus, when testing, only one of the results will show low fatigue strength, while the other 5 will show much higher fatigue strength.



(a) large specimen

(b) small specimens

Fig. 3 Statistical size effect.

For machined components, some materials are more prone to this effect than others. Rolled steel, for example, which has a very homogeneous microstructure usually fails from defects at the surface. In this case, *surface area* is presumably a better indicator than volume. Cast iron, on the other hand, usually fails from internal defects and therefore will be very affected by the *volume*.

For welded joints, failing from the weld toe, the statistical size effect is essentially governed by the *weld length* rather than the volume (Berge, 1985; Overbeeke and Wildschut, 1987). Xiao and Yamada (2004) also shows the negative effect of increasing weld length and Valsgård et al. (2010) proposes a method to correct for weld length.

2.3 Technological size effect

The technological size effect refers to the different manufacturing conditions typically applied for larger structures, e.g. many weld passes compared to few. It also accounts for differences in residual stresses, surface roughness and microstructure (Gustafsson, 2006).

In particular the differences in residual stresses are important. It is clear that a larger/thicker structure would be able to provide more constraint against thermal contraction of the weld material as compared to smaller/thinner structures and hence sustain higher levels of residual stresses.

Another factor that may be associated with the technological size effect is that of misalignment. Misalignment leads to secondary bending stresses, the magnitude of which scales with the ratio of offset to plate thickness, also called the relative misalignment.

The level of misalignment achieved in production of specimens is usually depending on features such as flatness of plates, accuracy of fixtures/lineup, suitability of welding sequence, etc., none of which scales with thickness. It is therefore plausible that the absolute level of misalignment achieved in specimen production may be more or less constant.

If the absolute misalignment is constant, then the relative misalignment decreases with increased thickness. Indeed, decreasing relative misalignment with increased plate thickness may cause a reversed thickness effect.

3 Experimental investigations

A total of 7 experimental investigations of the thickness effect in axially loaded butt joints have been found in the literature, Table 1. Most of them are relatively recent, necessitated by the development of increasingly large infrastructure and offshore/ship structures.

Table 1 Overview of reviewed experimental data.

Author(s)	Material	R	t [mm]	w [mm]
Lee et al. (2003)	SM490C	0.1	40 75 100	200
Kim et al. (2009)	SM520C SAW	0.1	20 40 60 80	40 60 90 120
	SM520C FCAW	0.1	20 40 60 80	40 60 90 120
Polezhayeva & Badger (2009)	EH40	0.1	22 66	22 66
Kang (2016)	EH47	0.1	25 50 75	37.5 75 112.5
Doerk et al. (2012)	YP47	0.1	25 50 75	37.5 75 112.5
Ohta et al. (1990)	SM50B	0	9 40	50
	SM50B	$\sigma_{max} = \sigma_y$	9 40	50
Olafsson (2017)	S355J2 Batch 1	0.5	20 30 40	20
	S355J2 Batch 2	0.5	20 30 40	40

In the following, available test data is reviewed. SN plots are shown for all test series along with fitted mean curves. The mean curves are derived according to the IIW recommendations (Hobbacher, 2016) assuming a fixed slope of $m = 3$ and ignoring run-outs and post-knee results. All results are compared against the FAT90 SN curve (uncorrected) to have a fixed reference across all plots. Only two dimensions are considered in the investigation, the thickness t and the width w of the specimens, Figure 4.

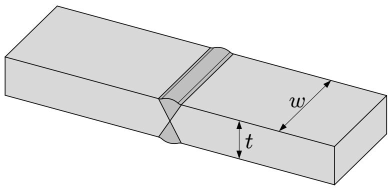


Fig. 4 Dimensions considered.

It is always difficult to compare results across different investigations, in particular when all details are not available. Subtle differences in e.g. the failure criterion may lead to different conclusions. Typical failure criteria are; complete fracture, a certain stiffness reduction/stroke limit or a certain detectable surface crack length. The different criteria are not influenced by the thickness of the specimen to the same degree and may therefore lead to different conclusions accordingly.

3.1 Tests at low stress ratio

A common, but unfortunate, approach to perform fatigue testing of welded joints is to use small scale specimens at relatively low stress ratios, e.g. $R = 0 - 0.1$. Testing at these conditions may be justified, particularly for thick specimens, in that it may be difficult or impossible to test at higher stress ratios because of limited machine capacity. However, the drawback of this way of testing is that the residual stress state may be much lower in small scale specimens compared to actual welded components (Ohta et al., 1990). Thus testing under these conditions may show differences not associated with the thickness, but rather associated with the difference in residual stresses.

3.1.1 Investigation by Lee et al.

Lee et al. (2003) tested butt joints with $t = 40, 75$ and 100mm using specimens with the same width $w =$ 200mm as seen in Figure 5. The specimens were welded manually in a single sided V-groove to simulate the field welding conditions used in Korean bridge building. All tests were carried out at $\Delta\sigma_n = 110$MPa at a stress ratio of $R = 0.1$ and a testing frequency of $f = 5 - 15$Hz. Most of the specimens failed from internal defects in the weld and not from the weld toe as in the other investigations. These results may therefore show different behavior due to the different failure mechanism, but are still included in the comparison here. All results cluster in the same area and it is difficult to identify any clear tendencies with regards to the thickness (100mm joints perform the best). The authors concluded that all the results are conservative compared against the IIW recommendations.

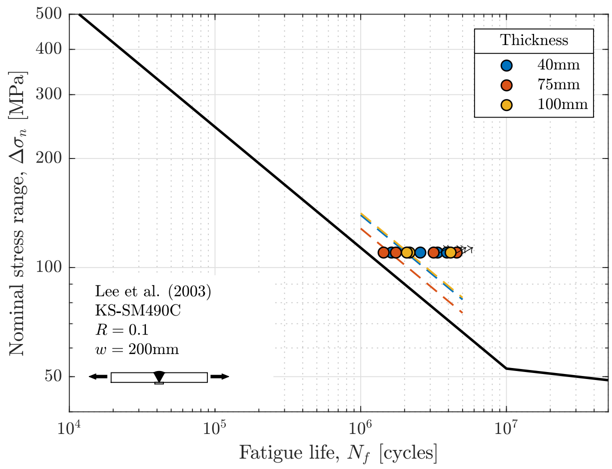


Fig. 5 Data from Lee et al. (2003).

3.1.2 Investigation by Kim et al.

Another Korean study conducted by Kim et al. (2009) tested joints in $t = 20, 40, 60$ and 80mm thickness in a reduced carbon steel SM520C-TMC. They used two welding techniques, SAW and FCAW, but did not find any statistically significant difference between the two. The two series are thus plotted together here. Again a single sided V-groove was applied. The specimen width varied with thickness as shown in Figure 6. The stress ratio was $R = 0.1$ and the testing frequency was $f = 6-15$Hz. The majority of the specimens failed from the weld toe. Referring to Figure 6 some thickness dependency is seen if the 20mm series is disregarded (many run-outs ignored in regression). All data points except one lies above the uncorrected FAT90.

3.1.3 Investigation by Polezhayeva and Badger

A British study by Polezhayeva and Badger (2009) investigated the thickness effect in butt joints of $t = 22$ and 66mm (100mm thick specimens were also tested, but only in bending and thus excluded in this review). The specimens were prepared by SAW welding in an X-groove using EH40 steel. The width of the specimens

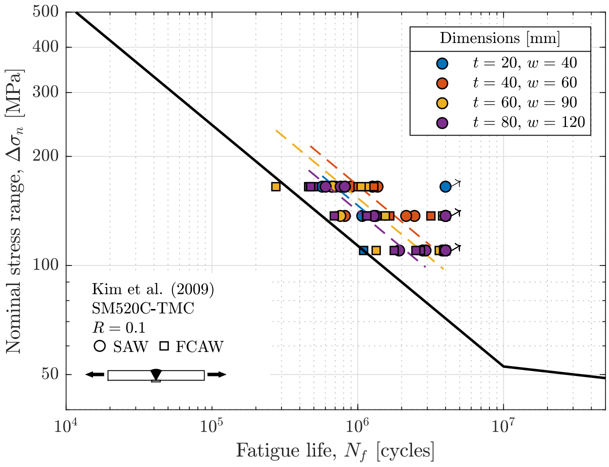


Fig. 6 Data from Kim et al. (2009).

were equal to the thickness. All specimens were tested at $R = 0.1$ at a frequency of $f = 0.5 - 10$Hz, Figure 7. The specimens failed along the weld toe.

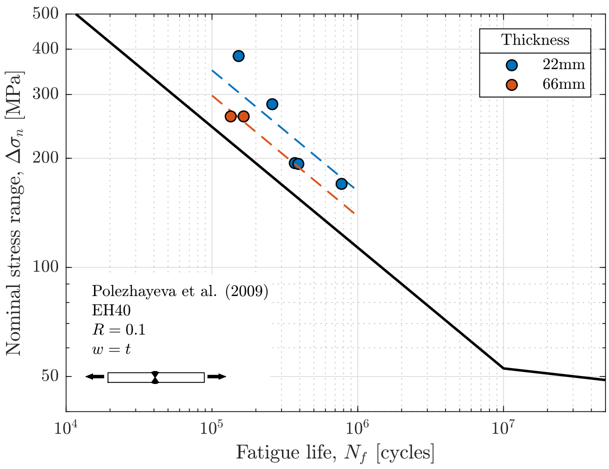


Fig. 7 Data from Polezhayeva and Badger (2009).

3.1.4 Investigation by Kang

Kang (2016) reports yet another Korean investigation on butt joints with $t = 25, 50$ and 75mm specimens welded in EH47 steel using FCAW at 3 different shipyards. Results from the 3 manufacturers are pooled together, but can bee seen to fit inside the usual range of scatter for welded joints. A single sided V-groove was used along with a ceramic backing. The specimen width was $w = 1.5t$ and the tests were carried out at $R = 0.1$. The researchers analyzed the results using different stresses (nominal-, hotspot- and notch-) and with both fixed and free slopes in the regression. The resulting thickness correction exponent was varying accordingly, but the trend in the data is quite clear as seen in Figure 8. The thickness dependency is significant and consistent.

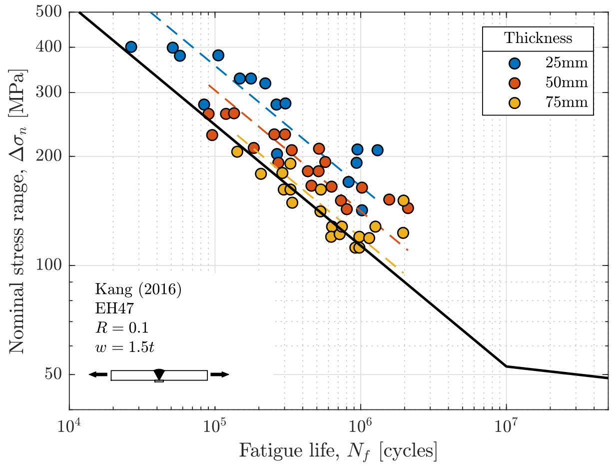


Fig. 8 Data from Kang (2016).

3.1.5 Investigation by Doerk et al.

In Germany, Doerk et al. (2012) also studied the thickness effect in butt joints, however they only presented the results in terms of the resulting fatigue strength. The individual test data or the details of the test could not be found in the open literature. The investigation is included still in the aggregate analysis in section 3.3. The material was YP47 steel welded with FCAW in $t = 25, 50$ and 75mm plate. The width of the specimens was $w = 1.5t$ and the tests were carried out at $R = 0.1$ at $f = 32$Hz.

3.2 Tests at high stress ratio

Several early studies from Japan confirmed the necessity to perform fatigue tests of welded joints at high stress ratios when small scale specimens are applied Ohta et al. (1990, 2002). In this case, there was correspondence in fatigue strength between the small scale specimens and large components. The IIW also recommends testing at $R = 0.5$ if the results are to mimic real welded structures, which is usually the case (Hobbacher, 2016).

3.2.1 Investigation by Ohta et al.

The earliest investigation considered here was conducted in Japan by Ohta et al. (1990) on specimens of $t = 9$ and 40mm in JIS SM50B steel. The specimens where welded manually from both sides in flat position. Cracks initiated from the weld toe. Here, specimens of identical width ($w = 50$mm) was tested at two different mean stress levels; one series at $R = 0$ and another where $\sigma_{max} = \sigma_y$. The results shown in Figure 9 show a distinct size effect for the test at $R = 0$, whereas there is no significant difference between the two series when testing by cycling down from yield. The authors explain this by measured differences in residual stress between the thin and thick specimens. This conclusion was backed by a similar finding in another study by the same authors on the same specimens, but subjected to stress relieving, Ohta et al. (1984).

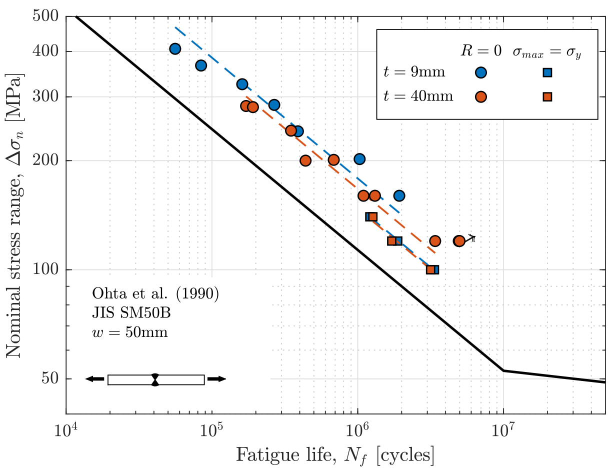


Fig. 9 Data from Ohta et al. (1990).

In the opinion of the author, this is the most interesting investigation in this review. Firstly, the specimens have the same width, i.e. equal length of weld toe in the two series. The number of crack initiation sites (statistical size effect) should thus be identical (Overbeeke and Wildschut, 1987). Secondly, the investigation was carried out at high stress ratio in order to emulate high tensile residual stresses in the specimens and thus negate any differences in this regard.

The effect of residual stresses on the apparent thickness dependency of butt joints is also highlighted by Shams-hakimi et al. (2017) who found a positive influence of thickness in butt joints subjected to HFMI treatment.

3.2.2 Investigation by Olafsson

Recently, Olafsson et al. (2016) investigated the thickness effect in SAW welded butt joints of $t = 20, 30$ and 40mm. He tested at $R = 0.5$ with fixed specimen width within series. The specimens were manufactured in S355J2 steel by semi-automatic SAW welding in an X-groove.

Two batches were tested, one with $w = 20$mm and another with $w = 40$mm, from two different suppliers as shown in Figure 10. It is interesting, that in both cases, the $t = 40mm$ specimens show higher fatigue resistance than the $t = 30mm$ ones. In the case of Batch 2, the $t = 20mm$ and $t = 40mm$ specimens show almost identical behavior.

All results, except the 30mm in Batch 2 seems to comply nicely with the uncorrected FAT90 curve. This could indicate, that the weld quality in said series may have been insufficient.

Comparing Figures 10a and b, there appears to be a dependency on the specimen width, i.e. the wider specimens in Batch 2 performs consistently worse compared to the slimmer ones in Batch 1, however this may also be due to different weld qualities achieved by the different suppliers. In either case, it suggests that the width of specimens should be kept constant in investigations of the thickness effect.

3.3 Comparison of investigations

The mean fatigue strength of each test series is determined using consistent statistical analysis (according to IIW guidelines) as shown in Figures 5-10 and compared across investigations in Figure 11. This figure shows the mean fatigue strength against the thickness along with fitted tendency lines. The slope of the fitted lines correspond to the thickness correction exponent k, see Table 2 for numerical values.

Table 2 Derived thickness correction exponents.

Investigation	k
Lee et al. (2003)	0.01
Kim et al. (2009) SAW	-0.02
Kim et al. (2009) FCAW	0.05
Kang (2016)	0.29
Polezhayeva et al. (2012)	0.15
Doerk et al. (2012)	0.21
Ohta et al. (1990) $R = 0$	0.04
Ohta et al. (1990) $\sigma_{max} = \sigma_y$	0.01
Olafsson (2016) Batch 1	0.20
Olafsson (2016) Batch 2	0.03

Referring to Figure 11a, it is clear that the results are very scattering. The two investigations by Kang (2016) and Doerk et al. (2012) show a thickness dependency close to the current rules, i.e. $k \approx 0.2$. Both of these investigations used specimens with $w = 1.5t$. Most remaining series show thickness correction exponents significantly smaller than this. Investigations by Kim et al. (2009) and Polezhayeva and Badger (2009)

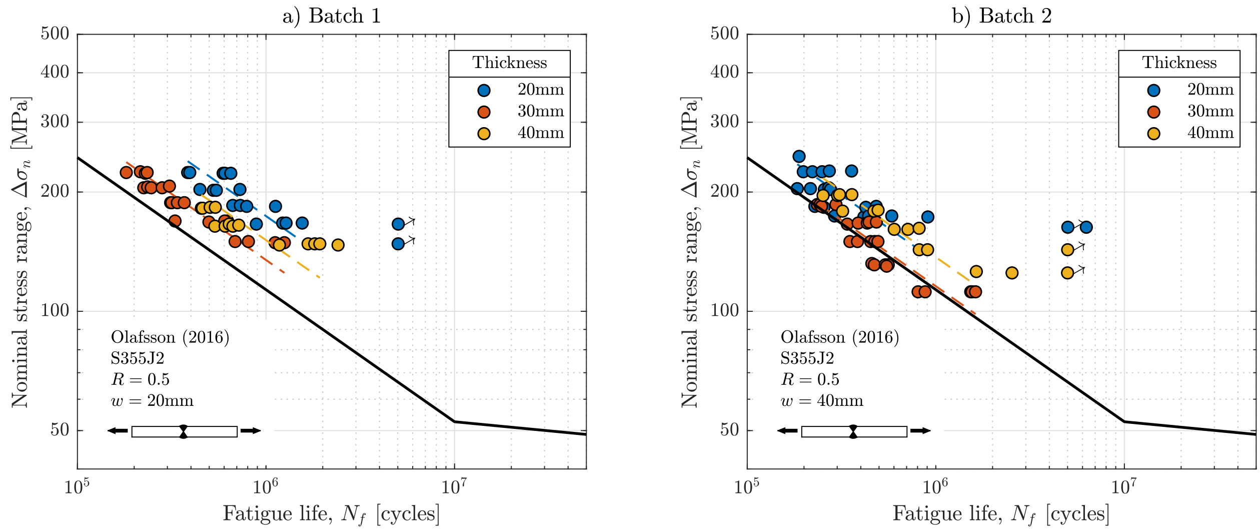


Fig. 10 Data from Olafsson et al. (2016).

also used specimens where the width was increased along with the thickness.

Comparing against the two investigations with constant specimen width, Lee et al. (2003) and Ohta et al. (1990), it is seen that the thickness dependence appear smaller in this case. Considering also the results of Olafsson et al. (2016), the decrease in fatigue strength of larger specimens may be a consequence of specimen width rather than thickness.

More emphasis should be placed on the results tested under high stress ratios, Figure 11b, as these resemble the conditions of actual welded components the best. Here, the results by Ohta et al. (1990) show practically no thickness dependency, but this is based on quite few specimens (only 6 in total). The results by Olafsson et al. (2016) are substantiated by many more specimens, but do not show any clear dependency of the thickness either.

4 Discussion

Following the previous review, it should be clear that the size effect do not only depend on thickness. Other factors such as residual stresses, misalignment, weld length also play a vital role. The phenomenon is thus much more complex than what might be expected from the simple corrections put forth in current codes.

In order to summarize the influence of all contributing factors, a division in positive and negative factors is proposed as follows

4.1 Negative influences of plate thickness

- The stress concentration factor increases with increased thickness if the local weld toe geometry remains the same.
- The stress gradient becomes less steep with increased thickness, thus giving rise to higher crack tip stresses at a given crack depth in a tick plate compared to a thin.
- Residual stresses in thin specimens may be lower than in thick, Ohta et al. (1990). However, this benefit do not apply for actual components - only for small scale specimens.

4.2 Positive influences of plate thickness

- Misalignment induced secondary bending stresses decrease with increased plate thickness, assuming constant absolute misalignment in production.
- The statistical size effect appear not to be dominated by thickness, but rather by weld length.
- In thick plate the crack may grow a longer distance before complete fracture.
- The ratio of overfill (or weld reinforcement) to plate thickness usually decreases in thicker plates, thus the flank angle of the weld may also decrease.

According to the above discussion, the thickness effect may be both positive and negative. Indeed, there appear to be a competition among factors and possibly some undiscovered saturation phenomenon governing the fatigue performance of thick butt joints.

An additional issue, that is very relevant in the context of large infrastructure/offshore structures which

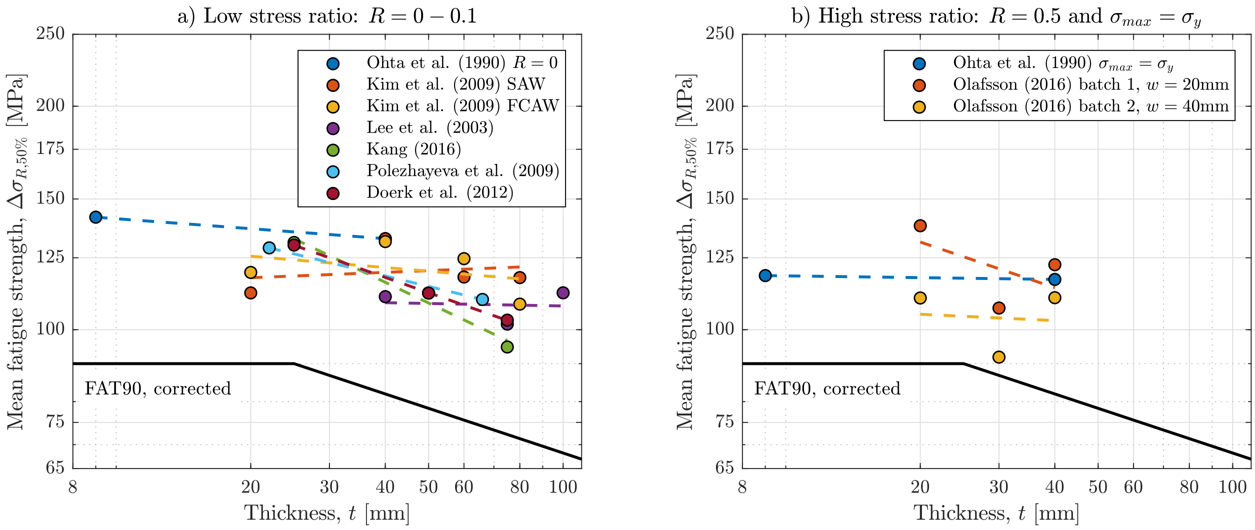


Fig. 11 Comparison of test results and the FAT90 SN curve corrected according to IIW recommendations.

are usually subjected to a very high number of load cycles, is the effect of thickness/size on the location of the SN curve knee point and post-knee behavior. Currently this cannot be investigated due to the lack of data in the very high cycle regime, however it may very likely be thickness dependent.

5 Conclusions

It is hypothesized that the thickness effect observed in the fatigue tests conducted at lower stress ratios is not actually due to the difference in thickness, but rather due to differences in residual stresses, weld length or possibly misalignment. Further studies are required to verify this.

The following conclusions are drawn based on the literature review and review of experimental fatigue data for axially loaded butt joints.

- Experimental investigations indicate that the thickness effect in axially loaded butt joints is not always as pronounced as in other joints and also less severe than the corrections mandated by current codes.
- The statistical size effect seems to be governed by the combined length of weld toe, i.e. the width of the specimen rather than the thickness.
- The influence of residual stresses cannot be underestimated. When investigating differences in welded joints, it is paramount to ensure that the local mean stress state is identical across test series.
- Very few of the thick specimen results lie below the uncorrected FAT90 curve, indicating that the severe reduction of fatigue strength in current codes are too conservative.

Further research is necessary to validate the speculations put forth here. In future a study of thickness effect it must be paramount to exclude effects of any and all other parameters. Some recommendations are given for future investigations of the topic

- Use identical specimen width across test series to exclude differences in number of crack initiation sites.
- Use large specimens or test at high stress ratio in order to emulate the high tensile residual stresses present in actual components. Another possibility could be to test joints in stress relieved conditions to negate the effect of residual stresses.
- Measure details of local weld geometry, e.g. by 3D scanning, in particular the degree of misalignment.
- Measure surface residual stresses in the weld toe and possibly relaxation during test.

References

Berge S (1985) On the effect of plate thickness in fatigue of welds. Engineering Fracture Mechanics 21(2):423–435

DNV GL (2016) RP-C203: Fatigue Design of Offshore Steel Structures. Recommended Practise

Doerk O, Fricke W, Selle HV (2012) Validation of Different Fatigue Assessment Approaches for Thick Plate Structures Made of High Tensile Strength Steel YP47. IIW doc XIII-2421-12

EC3 (2007) Eurocode 3: Design of steel structures - Part 1-9 Fatigue. CEN, European Committee for Standardization

Fukuoka T, Mochizuki K (2010) Effect of plate thickness on fatigue strength of typical welded joints for a ship structure. IIW doc XIII-2333-10

Gurney T (1979) The influence of thickness on the fatigue strength of welded joints. In: BOSS'79 Second international conference of ofshore structures, London, UK

Gustafsson M (2006) A study of thickness effect on fatigue in thin welded high strength steel joints. Steel Research International DOI 10.1002/srin.200606475

Hobbacher A (2016) IIW Recommendations for Fatigue Design of Welded Joints and Components, 2nd edn. Springer, IIW-2259-15

ISO19902 (2007) ISO 1992: Petroleum and natural gas industries - Fixed steel offshore structures. International Standard 1st ed.

Kang SK (2016) Thickness Effect of Fatigue on butt weld joints. In: TSCF 2016 Shipbuilders Meeting, Korean Register, Korea

Kim KN, Lee SH, Jung KS (2009) Evaluation of factors affecting the fatigue behaviour of butt welded joints using SM520C-TMC steel. International Journal of Steel Structures 9(3):185–193

Lee JK, Yoon TY, Chang SP (2003) The Fatigue Performance of Buttwelded Joint with thick Plates. Research Institute of Industrial Science and Technology, RIST 17(3):249–255

Lotsberg I (2014a) Assessment of the size effect for use in design standards for fatigue analysis. International Journal of Fatigue 66:86–100, URL http://dx.doi.org/10.1016/j.ijfatigue.2014.03.012

Lotsberg I (2014b) Assessment of the size effect in fatigue analysis of butt welds and cruciform joints. In: Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering - OMAE

Maddox SJ (1991) Fatigue Strength of Welded Structures, 2nd edn. Abington, DOI 10.1016/B978-1-85573-013-7.50006-9

Ohta A, Maeda Y, Nihei M (1984) Variable Effects of Stress Relief on Fatigue Strength of Butt Welded Joints With Different Plate Thickness. International Journal of Fracture 24:81–87

Ohta A, Mawari T, Suzuki N (1990) Evaluation of effect of plate thickness on fatigue strength of butt welded joints by a test maintaining maximum stress at yield strength. Engineering Fracture Mechanics 37(5):987–993, DOI 10.1016/0013-7944(90)90022-9

Ohta A, Maeda Y, Suzuki N (2002) Fatigue Strength of Corner Welded Joints with Web Stiffener in Synthetic Seawater by Smax = Sy Test. IIW Doc XIII-1923-02

Olafsson O (2017) Improved design bases of welded joints in seawater. Phd thesis, Danish Technical University

Olafsson OM, Juncher J, Berggreen C (2016) Experimental investigation of the thickness effect for large as-welded SAW S355 steel specimens. In: Nielsen U, Jensen J (eds) Proceedings of the 13th International Symposium on Practical Design of Ships and Other Floating Structures, DTU, Copenhagen, Denmark

Overbeeke J, Wildschut H (1987) The influence of plate thickness on the endurance of welded joints. In: Proceedings of the 3rd international ECSC offshore conference on steel in marine structures (SIMS '87), Delft, The Netherlands

Pedersen MM, Andersen JG, Ólafsson ÓM (2012) Investigation of the thickness effect for butt welded joints. IIW Doc XIII-WG1-154-12

Polezhayeva H, Badger C (2009) Effect of plate thickness on fatigue strength of base material and butt welded specimens made from EH40 steel thick plates: Phase 1. In: Proc. Nineteenth International Offshore and Polar Engineering Conference (ISOPE), Osaka, Japan, pp 366–373

Schumacher A, Borges LC, Nussbaumer A (2009) A critical examination of the size effect correction for welded steel tubular joints. International Journal of Fatigue 31(8-9):1422–1433, DOI 10.1016/j.ijfatigue.2009.04.003

Shams-hakimi P, Yildirim HC, Al-emrani M (2017) The thickness effect of welded details improved by high-frequency mechanical impact treatment. International Journal of Fatigue 99:111–124, DOI 10.1016/j.ijfatigue.2017.02.023, URL http://dx.doi.org/10.1016/j.ijfatigue.2017.02.023

Valsgård S, Lotsberg I, Mørk K (2010) Fatigue design of steel containment cylinders for CNG ship application 23:209–225, DOI 10.1016/j.marstruc.2010.04.001

Xiao Zg, Yamada K (2004) A method of determining geometric stress for fatigue strength evaluation of steel welded joints. International Journal of Fatigue 26:1277–1293, DOI 10.1016/j.ijfatigue.2004.05.001

Yamamoto N, Mouri M, Okada T, Mori T (2014) An analytical and experimental study on the thickness effect of fatigue strength in large-scale-welded models. Welding in the World