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Article

Revaluation of Fatigue Thickness Effect Based on Fatigue Test Database

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Abstract: This paper reassesses the detrimental effect on fatigue performance due to thicker sections based on extensive fatigue strength test database, taken from research program worldwide over the past half of a century in offshore oil & gas and renewable industry. The data entries in the database have been evaluated to ensure its data integrity. Statistical analyses on these S-N data are performed with or without the thickness correction at different exposure level to corrosive environment, in order to re-evaluate the suitability of current standards in regard to the thickness effect. The study has concentrated on T-joint, transverse butt welded joint and tubular joint as these are the most commonly used joint types in the offshore wind industry. The analysis indicates general agreement of fatigue strength with the thickness effects in current standard for in air conditions but great conservatism for corrosive environment.

Keywords: fatigue; thickness effect; offshore wind turbine; corrosion fatigue

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1. Introduction

Current offshore wind turbine foundations such as monopiles are designed with sections up to 100 mm in order to cope with the increasing turbine capacity and environmental loadings. To consider the negative effect on fatigue performance due to thick section, current fatigue standards adopt the so-called thickness correction factor to the S-N curve. However, the parameters of the correction equation have been developed from tests for much thinner sections than those used in offshore wind industry. Thus, various degrees of uncertainties exist for the S-N curves in these thickness ranges.

This paper will present the findings from a wide range of test data base to identify uncertainties or confirm the current assumptions.

1.1 Thickness Effect and Correction

In 1979, Gurney [1] presented that thicker sections would have shorter fatigue lives for the same stresses and proposed the thickness correction factor accordingly using the following:

$$\Delta\sigma_c = \Delta\sigma\left(\frac{T}{t_{ref}}\right)^k \quad (1)$$

where $\Delta\sigma_c$ is the stress range with thickness correction, $\Delta\sigma$ is the uncorrected stress range, T is the thickness of the main section/plate, t_{ref} is the reference thickness, and k is the power exponent for thickness correction.

The three main causes of the thickness effect are:

- Statistical: Thicker plates can have higher probability of imperfection to start crack initiation
- Fabrication: Residual stress of thicker plate is higher due to more restraint
- Geometry: The main geometric cause is that thicker plate has lower stress gradient across the thickness than thinner plate as shown in Figure 1 below. The other two causes can be that thicker plate may have a relatively smaller radius ($a_i = a_i$, but $a_i / t_1 < a_i / t_2$, [2]) of welding profile at the weld toe, and thicker section can introduce plane

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strain state. Due to the presence of a steeper stress gradient in thinner section, a small crack (notch) close to the surface of a small specimen will experience a lower strain than a small crack (notch) close to the surface of a thick specimen, for the same stress at the surface. In overall, the geometry effect was considered as the dominant cause of the thickness effect.

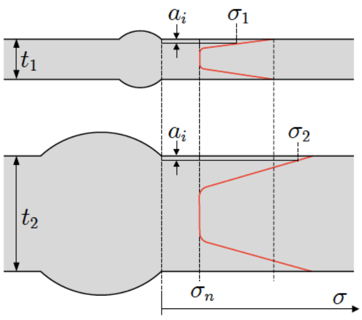


Figure 1. Geometry Thickness Effect [2]

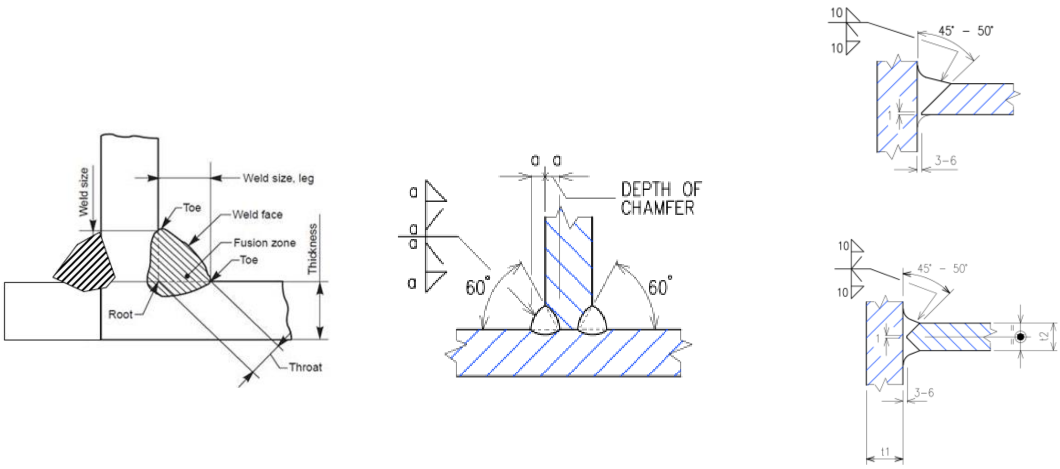
1.2 Typical Joints and Current Standards

The most frequently used joint/weld types in the offshore wind industry are:

- T-joints
- Transverse butt-welded joints
- Tubular joints

T-joints

T-joint, or cruciform joint, refers to the welded point of two perpendicular plates, forming a letter T. The welding type of T-joint covers fillet weld, partial penetration butt weld, and full penetration weld as shown in Figure 2.



(a) (b) (c)

Figure 2. (a) Weld detail of T-joint with fillet weld; (b) weld detail of T-joint with partial penetration weld; (c) weld detail of T-joint with single-sided or double-sided full penetration weld

Transverse Butt Welded Joints

Transverse butt welded joint is defined as two transverse splices or plates or flats welded with double-sided full penetration weld as commonly found in the connection for monopiles. This type of

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weld represents the characteristic of circumferential girth weld as well. Typical weld detail of transverse butt weld is shown in Figure 3.

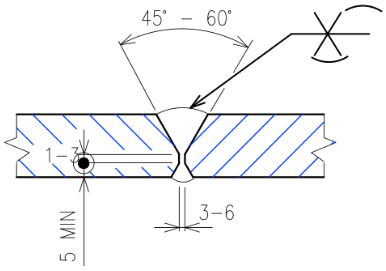


Figure 3. Weld detail of transverse butt weld joint

Tubular Joints

The definition of tubular joint is universally acknowledged as brace to chord connection of two tubulars. A typical tubular joint connection layout has been illustrated in Figure 4, where the numbers indicating the location of weld cross-sections are presented in more details in Figure 5 and Figure 6. Welding type of tubular joint includes either single-sided or double-sided full penetration weld.

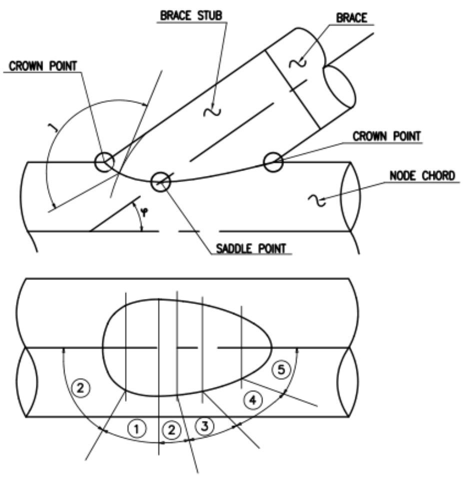
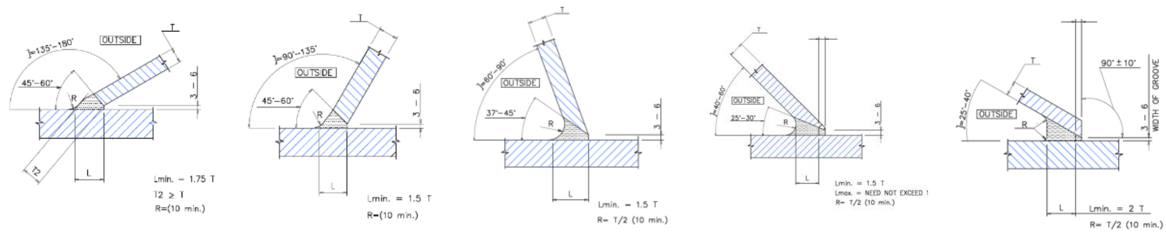


Figure 4. Layout of tubular joint



(a) (b) (c) (d) (e)

Figure 5. Single-sided weld detail of tubular joint (a) cross section 1; (b) cross section 2; (c) cross section 3; (d) cross section 4; (e) cross section 5

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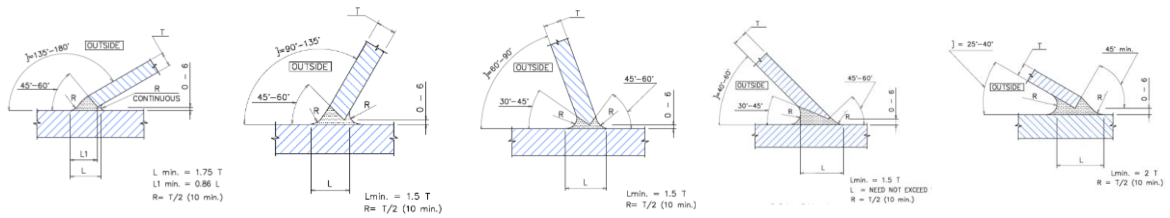

(a) (b) (c) (d) (e)

Figure 6. Double-sided weld detail of tubular joint (a) cross section 1; (b) cross section 2; (c) cross section 3; (d) cross section 4; (e) cross section 5

The three typical joint types are respectively categorized to three S-N curves, F curve, D curve, and T curve in the DNVGL-RP-C203 [3] specification. Table 1 shows the reference thickness t_{ref} and the power exponent k in the thickness correction equation of various standards.

Table 1. Reference thickness and power exponent in various standards

Standard	F Curve		D Curve		T Curve	
	t_{ref} (mm)	k	t_{ref} (mm)	k	t_{ref} (mm)	k
DNVGL-RP-C203 [3]	25	0.25	25	0.2	16	0.25
API-RP-2A [4]	N/A	N/A	N/A	N/A	16	0.25
ISO 19902 [5]	16	0.25	16	0.25	16	0.25
ABS 0115 [6]	22	0.25	22	0.25	32	0.25

Several combinations of reference thickness and power exponent are defined in different standards. To unify the assumption for analysis, specifications in DNVGL-RP-C203 [3] has been selected as the reference standard for the analysis in this study.

1.3 Derivation and Uncertianties of Thickness Correction Factors

The thickness correction factor for each of the S-N curves is based on the assumption that fatigue strength reduction is scalable by thickness. However, the following should be noted:

- Not all factors affecting fatigue strength is scalable or proportionable, such as corrosion effect
- The basis for scale may not be the thickness alone, weld width and attachment length will also contribute, known as the size effect
- The scale can be different for different weld class and not uniform for the same S-N category
- The thickness correction factor introduced by Gurney, which was also used by DEn (UK Department of Energy) and DNVGL at later stage, is based on nominal stress but stresses in some S-N curves are based on hot spot stresses. Application on the use of hot spot stresses may need further investigation.

Some works regarding to the following have been conducted in some recent studies to improve the thickness correction factor:

- Size effect and effective thickness
- Revision of the power exponent k

1.4 Size Effect and Effective Thickness

Some studies have shown that not only the thickness is affecting the fatigue performance, but also the local geometry. As the thickness of the attachment increases, more stress is attracted to the weld toe region and a fatigue crack becomes initiated earlier. Therefore, for some specific joint types, "size effect" is a more appropriate term to describe the behaviour rather than "thickness effect". For example, a butt weld of limited width will show less size effect, and could be significantly reduced by grinding, such the weld notch is reduced. The fatigue performance of cruciform joint with relatively thinner transverse attachment also improves, as less stress at the crack tip region in thinner plate can lead to lower crack growth rate.

Size effect is also observed in stress relieved tests, with about the same effectiveness as the as-welded specimens. Gurney [7] noted that thickness is not the only geometric factor and proposed a method to assess size effect by using effective thickness T_{eff} in the thickness correction equation to replace T. For T-joints and transverse butt welded joints as shown in Figure 7, Gurney introduced the effective thickness calculation to substitute the section thickness T as follows:

$$if\ \frac{L}{T} > 2, then\ T_{eff} = T$$
$$if\ \frac{L}{T} \leq 2, then\ T_{eff} = 0.5L\ or\ T_{eff} = t_{ref}, whichever\ is\ larger \quad (2)$$

where L is the length of attachment indicated in Figure 7.

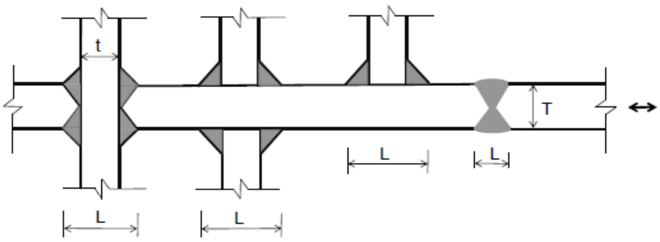

Figure 7. Dimensions for Size Effect Correction Factor

IIW [8] and IACS [9] redefined the effective thickness to illustrate the size effect as follows:

$$T_{eff} = min\left(\frac{L}{2}, T\right), but\ T_{eff} \geq t_{ref} \quad (3)$$

In a more recent study by Lotsberg [10], an updated equation of effective thickness for butt welds and cruciform joints has been illustrated and incorporated to DNVGL-RP-C203 [3] at a later stage, where:

$$T_{eff} = \min(14\ mm + 0.66L, T), T_{eff} \geq t_{ref} \quad (4)$$

This specification can be used for cruciform joints, butt welds and short attachments, such as shear keys welded to steel plates, piles used in OWT piles, or large diameter monopiles.

1.5 Revision of Power Exponent k

Different values of k have been specified in standards such ranging from 0.1 to 0.3. A study by Lotsberg [10] has discussed the influence of k on fatigue life, see Figure 8.

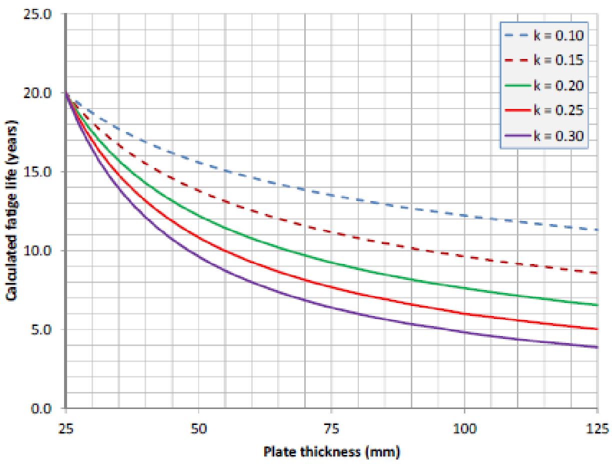

Figure 8. Effectiveness of Power Component in Thickness Correction Equation **Error! Reference source not found.**

Usual standards use one k value for each S-N curve category. However, the power exponent can be also stress/environment/geometry dependent. In Haagensen [11], the background of the thickness effect has been explained as the stress gradient at the surface of a thinner section is steeper. Thus, the surface grain will be subjected to lower strain under same surface stress comparing to a thicker section. Hence, the following equation has been introduced by Berge [12]:

$$k = 0.1 + 0.14 \log K_t \quad (5)$$

Cole et al. [13], on the other hand stated that the thickness effect is dependent to the stress range, which can be presented by the following equation:

$$k = 3[K - (\Delta\sigma \times C)] \quad (6)$$

2. Fatigue S-N Database

Data analysis is a very powerful tool to evaluate the fitness of current standards against the actual fatigue behaviour. As a result, a sound database with clearly defined attributes, sizable sample quantities and diverse variety of characteristics, is essential.

The database used in this study has taken input from a variety of research program worldwide over the past half of a century in offshore oil & gas and renewable industry. Most of the fatigue experiments are conducted in the 80s and the 90s, where many tests have been produced in large scale programs. There are relatively few tests conducted from the 90s to now, but nevertheless included in the database. The entries in the database have been evaluated to ensure its data integrity with the following characteristics:

- Quality of each individual test is satisfactory, i.e. certified weld procedure and weld quality
- All entries in the database are based on clearly recorded test parameters, such as:
  a. Definition of loading, e.g. R-ratio, CA/VA loading, frequency
  b. Material
  c. Type/geometry and thickness of specimen
  d. Condition of cathodic protection
  e. Condition of corrosive environment
  f. Fabrication details, e.g. weld profile, treatment etc.
  g. Temperature
- Definition of failure criteria and the associated number of cycles
- Type of stress range, i.e. hot spot stress or nominal stress

An overview list of the S-N test data sources is listed below in Table 2. Only constant amplitude tests are extracted as the purpose of this study is to investigate the thickness effect.

Table 2. Source List of Fatigue Test Database

Program Name	Joint Type	CP[1] Condition	Number of CA[2] Test	Year
US Highway [14]	T-joint	In-air	71	1974-1993
Vaessen et al. [15]	T-joint	In-air/ FC[3]	75 (In-air: 42, FC: 33)	1979
UKOSRP I [16]	T-joint	CP/ FC	71 (CP: 32, FC: 39)	1980
Dijkstra and de Back [17]	Tubular	CP/ FC	4 (CP: 1, FC: 4)	1980
Gibstein [18]	Tubular	CP	2	1981
Lourenssen et al. [19]	Tubular	FC	2	1982
Kawasaki Steel Corp. [20]	T-joint	In-air/ FC	32 (In-air: 16, FC: 16)	1985
UKOSRP II [16]	T-Joint	In-air/ CP/ FC	176 (In-air: 16, CP: 132, FC: 28)	1986
Dover et al. [21]	Tubular	CP	4	1986

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Program Name	Joint Type	CP¹ Condition	Number of CA² Test	Year
University of Waterloo [22]	T-joint	CP / FC	30 (CP: 20, FC: 10)	1987
Gerald et al. [23]	Tubular	CP	2	1987
Kerr et al. [24]	Tubular	CP	4	1987
Zhou et al. [25]	Tubular	FC	4	1990
Ohta et al. [26]	Transverse butt welded joint	In-air	16	1990
TWI/SINTEF [14]	Tubular	In-air/ CP	14 (In-air:8, CP: 6)	1993
Nordic Program [14]	T-joint	In-air	35	1993
HSE RPFG [27]	T-joint	In-air	146	1995
HSE RPFG [27]	Tubular	In-air/ FC	120 (In-air: 94, FC: 26)	1995
SERC-M [28]	Tubular	In-air, FC	5 (In-air: 1, FC: 4)	N/A
Lee et al. [29]	Transverse butt welded joint	In-air	11	2003
Li et al. [30]	Transverse butt welded joint	In-air/ CP/ FC	29 (In-air: 7, CP: 14, FC: 8)	2006
Huang et al. [31]	T-joint	In-air/ CP	77 (In-air: 29, CP: 48)	2006
Maddox et al. [32]	Transverse butt welded joint	In-air	34	2008
Kim et al. [33]	Transverse butt welded joint	In-air	34	2009
Polezhayeva et al. [34]	Transverse butt welded joint	In-air	7	2009
FATHOMS [35]	Transverse butt welded joint	In-air/ CP	78 (In-air: 52, CP: 17)	2010
Olafsson [36]	Transverse butt welded joint	In-air/ CP	108 (In-air: 89, CP: 19)	2016
Kang [37]	Transverse butt welded joint	In-air	54	2016

¹ Cathodic Protection; ² Constant Amplitude; ³ Free Corrosion

To further describe the data, introduction of each individual test program can be found in later parts of this section.

3.1 Literature Review of Fatigue Test Programs

HSE RPFG [27]

HSE Report OTH 92390 is the background study of the Fourth Edition of the HSE Guidance on Fatigue. The dataset recorded the tubular joint test results and the in-air T-joint test result from two phases of UKOSRP (UK Offshore Research Project), which are the background data of the HSE T' curve and P curve respectively. Other programs that sponsored by the European Coal and Steel Community (ECSC), and some further Science and Engineering Research Council (SERC) programs to are also addressed to expand the background data of the design curves in the HSE guidance.

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The loading mode, load ratios and endurances of the database are recorded explicitly. Different stages of fatigue endurance, i.e. N_1 for crack initiation, N_2 for crack development, N_3 for through thickness crack, and N_4 for the end of test are presented. A wide spectrum of thickness data, from 16 mm to 200 mm, is presented in this dataset, but mostly with in-air condition.

UKOSRP I&II (Corrosive Environment) [16]

The British test UKOSRP (Phase I and II) programme for corrosion fatigue tests on welding with steel plates can be found in HSE Report OTH 92392. A uniform thickness of 38 mm is assigned to all specimens.

Testing results prior to this report show varying level of inconsistency between UKOSRP and other national programs in that:

- Other studies showed a more marked reduction of fatigue life under free corrosion
- The UKOSRP results were the only ones suggesting CP completely restored fatigue life.

The survey has found a substantial part of the apparently anomalous results in UKOSRP test could be due to the fact that stresses reported in air and in seawater are not consistent. Hence a corrected set of results are presented in this report. The UKOSRP test has been found to be based on stresses for two modes of loading (four-point bending and cantilever bending), which were not strictly comparable.

The report rectified the incomparable result and re-published the UKOSRP corrosion fatigue data by applying a correction factor on the cantilever test results.

In essence, the corrections have involved multiplying the stresses for the cantilever bend specimen as originally published (i.e. measured 15 mm from the weld toe) by:

- 0.93 for K butt weld
- 0.88 for longitudinal fillet welds

Modes of loading, frequencies, load ratio and also welding conditions are recorded in this dataset for further evaluation.

TWI-SINTEF/ UCL/ Nordic Programme/ US Highway [14]

The HSE Report OTH 99058 recorded a review study of the HSE Fourth Edition of Guidance on Fatigue focusing on the applicability of HSE T' and P curve on variant amplitude loading cases. Additional factors including environmental penalty for corrosive environment and thickness correction factor were recommended in this report.

As the HSE T' curve is derived from CA test, the report aimed to evaluate the effect of VA loading by re-examining the HSE Fourth Edition of Guidance on Fatigue curves with new dataset, which has been made available at that time. The data recorded in this report consists more samples under CA loading for both tubular section and plate connection. Variety of spectrum loaded tests are also covered, including the Rayleigh spectra, the C/12/20 spectra, the UKOSRP spectra, the WASH(W) spectra, and the Nordic spectra. Tests conducted for T-joints in corrosive conditions with cathodic protection at potential of -850 mV and -1000 mV are listed, regardless of the fact that their thickness are relatively thin (<40 mm).

It is noted that the tubular test results in TWI-SINTEF program were based on unusual geometry with a rather short chord and two parallel 90 degree braces, arranged so that an actuator could be placed to produce in plane bending loads. This design will give high membrane stress in the chord (Ω–0.68) so that it will be effectively closer to F curve (1.34P) rather than tubular joint.

The aforementioned tests results are excluded from the database for this study. Also, part of the US Highway tests is taken away from the T-joint analysis as they are with very long longitudinal attachments and shall be categorized to F2 curve.

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University of Waterloo [22]

This series of test is conducted in University of Waterloo in Canada by Vosikovsky et al., which focused on the effect of cathodic protection and variation of thickness on fatigue endurance of T-joints.

The dataset contains the fatigue endurance at different stages of crack development, i.e. the first crack detection, the crack initiation stage (0.5 mm), and the through thickness crack. Two thickness profiles are used, of which are 28 mm and 78 mm to represent two extreme sides of the thickness spectrum. Tests were also conducted in both non-corrosive environment and corrosive environment, with or without cathodic protection.

FATHOMS [35]

This European program FATHOMS (Fatigue behaviour of high-strength steel-welded joints in offshore and marine systems) aimed to improve the conservatism due to the penalty employed by standards on different weld geometry, as it might not be fully representative from case to case. The FATHOMS project conducted many of small-scale fatigue test with different conditions, including weld techniques, post weld treatment, load ratios, and cathodic protection levels. The tests focused on girth weld on pipelines, and cruciform tee and cross joints. Nevertheless, several full-scale test results are provided and compared with the small-scale test.

Although the test data are not tabulated, important information of the tests such as stress range and endurance at failure are converted using graphic tools from the figures of the study report.

Vaessen et al. [15]

This dataset is based on a Dutch study that performed four-point bending test on T-joints with thickness of 40 mm and 70 mm, in both in-air condition and seawater condition. In addition, several comparisons of fatigue performance in different testing condition, such as fully reversed loading (R=-1) compared with higher mean stress (R=0.1), as-welded joints compared with PWHT joints etc.

Olafsson [36]

The PhD thesis by Olafsson has recorded three series of tests on transverse butt welded joint discussing different issues separately, including the thickness effect, corrosive environment, and welding technique. It is observed that the detrimental effect of thickness is not as severe as the recommendation in standards. In addition, the report found that in a high stress-low cycle test where the time-dependent corrosion process is not effective, the fatigue strength can still be lowered down by hydrogen embrittlement effect.

In this thesis, it is reported that Test series 1: batch 2 has an overall lower fatigue resistance compared to batch 1, potentially because of the high degree of variability of the welding procedure and difficulty to maintain weld quality and repeatability of an external manufacturer. The welding procedure is reported to require repairing in order to pass the non-destructive test. Thus, even though the welding procedure is certified, the additional heating and cooling solidification process for repairing might affect the fatigue strength of those specimens. Therefore, Test 1: batch 2 is excluded from the database for any further analysis.

Li et al. [30]

Duplicates of steel plate on a one-legged platform structure in China were adopted for this fatigue testing program. In addition, extra specimens manufactured using ASTM A537 and A131 steel are conducted with identical tests as the test steel plates for comparison. In air, CP, and FC samples can be found in this program, with plate thickness varies from 18 mm to 25 mm.

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Huang et al. [31]

Tests that has been performed using dogbone specimen that manufactured with AH32 steel. Different testing frequencies from 0.5 to 2 Hz are applied on these tests. The diameter of the dogbone specimen is machined to 24 mm. Effectiveness of several kinds of coating are compared as well.

Various Studies from Pedersen [2]

A review of experimental works of transverse butt welded joint has been conducted by M. Pedersen including the followings:

- Lee et al. [29]
- Kim et al. [33]
- Polezhayeva et al. [34]
- Kang [37]
- Ohta et al. [26]

Thickness of the specimens are found to have a wide variety of 20 mm to 100 mm.

Maddox et al. [32]

Tests were performed on full scale pipes or strips cut from such pipes with circumferential girth weld. The pipe thickness is set to be 22 mm.

This study has recorded in a detailed level in regard to testing conditions, including stress ratio, location of failure, nominal and local stress etc.

Kawasaki Steel Corp. [20]

This program compared the fatigue performance of high strength steel (with yield strength of 600 MPa to 800 MPa) to low strength steel (with yield strength of 350 MPa). The geometry of specimen is T-joint, whilst different treatment such as TIG dressing is adopted and compared to the fatigue performance of base metal and as-welded joint. Several tests in seawater condition are performed as well.

The samples of high strength steel are excluded from the database for consistency of data.

Various Studies from Raghava [28] and Murthy [38]

These two PhD theses pulled together a literature review for tubular joint by collecting individual tests conducted by different institute/personal studies, and also gathered the test data with detailed testing condition. Resource of data are from:

- Dijkstra et al. [17]
- Gibstein [18]
- Lourenssen et al. [19]
- Dover et al. [21]
- Gerald et al. [23]
- Kerr et al. [24]
- Zhou et al. [25]
- SERC-M [28]

Tests using CA loading and VA loading are categorised separately. Loading frequencies, loading modes, load ratios, status of corrosive environment, level of cathodic protection, and welding conditions are recorded for each of the individual study. Thicknesses of data are relatively low, with less than 40 mm.

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2.2 Collated Fatigue Database

Following the strict categorisation rules, the database are further filtered for the purpose of evaluating thickness effect. The characteristics of the database is shown in Table.

Table 3. Testing Characteristics of the Fatigue Database

Program Name	Thickness (mm)	Treatment	Loading Frequency (Hz)	R-ratio
US Highway [14]	10	As welded	N/A	N/A
Vaessen et al. [15]	40, 70	As welded/ PWHT/ Grinded/ Plasma dressed/ TIG	In-air: 5 Seawater: 0.2	-1/ 0/ 0.1
UKOSRP I [16]	38	As welded/ PWHT/ Grinded/ Plasma dressed/ TIG	In air: 5 Seawater: 0.17	-1/ 0
Dijkstra and de Back [17]	16, 32	As welded	0.2	-1/ 0
Gibstein [18]	16	As welded	N/A	-1
Lourenssen et al. [19]	32	As welded/ PWHT	0.2	0
Kawasaki Steel Corp. [20]	30	As welded/ TIG	0.167	N/A
UKOSRP II [16]	38	As welded/ PWHT/ Epoxy coated/ Toe ground/ Hammer peened/ Shot peened	In air: 5 Seawater: 0.17	-1/ -0.5/ 0/ 0.5
Dover et al. [21]	16	As welded	0.17	0.1/ 0.3
University of Waterloo [22]	26, 78	As welded	0.2	0.05
Gerald et al. [23]	40	As welded	0.5	0.1
Kerr et al. [24]	32	As welded	0.167	0
Zhou et al. [25]	19.1	As welded/ TIG	0.2	-1
Ohta et al. [26]	9, 40	As welded	N/A	0
TWI/SINTEF [14]	32	As welded	N/A	N/A
Nordic Program [14]	12, 16	As welded	N/A	N/A
HSE RPFG [27]	16 to 200	As welded	0.167 - 0.4	0/ 0.05/ 0.1
HSE RPFG [27]	16 to 200	As welded/ Toe Ground/ PWHT	0.167 - 0.4	-1/ 0/ 0.1
SERC-M [28]	12	N/A	2	-1/ 0
Lee et al. [29]	40, 75, 100	As welded	5 - 15	0.1
Li et al. [30]	18-25	As welded	0.5	-1
Huang et al. [31]	24	Dogbone specimen	0.5 - 1	N/A
Maddox et al. [32]	22	As welded	3 - 8 and 25 - 30	-0.01 to 0.83
Kim et al. [33]	20, 40, 60, 80	As welded/ FCAW/ SAW	6-15	0.1
Polezhayeva et al. [34]	22, 66	As welded	0.5 or 10	0.1
FATHOMS [35]	14.2,15,16	As welded/ FCAW/ Laser hybrid	N/A	0.1/ 0.5
Olafsson [36]	20 to 40	As welded/ Laser hybrid	6, 8, 10	0.5
Kang [37]	25, 50, 75	As welded	N/A	0.1

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3. Evaluation of Thickness Effect

Data analysis is performed to investigate how precise are the current fatigue standards (DNVGL-RP-C203 [3] taken as the baseline), as well as the underlying conservatism contained in the thickness correction equations.

The design S-N curves are originally derived based on one of the programme in the literature review i.e. Fourth Edition of the HSE Guidance on Fatigue, of which the data entries in the database are with variety of testing conditions, such as R-ratio from 0 to 1 and different load paths. Therefore, the "base curve" without any thickness correction has implicitly covered the variation of other characteristics. In this study, only the variation of thickness is being taken into consideration while processing the fatigue database.

3.1. Approach

In each of the test data entry, the difference between test and design curve prediction with the thickness effect (i.e. the thickness differentiator) can be decomposed as follows:

$$log_{10}\left(\frac{\Delta\sigma_{test}}{\Delta\sigma_c}\right) = log_{10}(\Delta\sigma_{test}) - log_{10}(\Delta\sigma) - log_{10}\left(\frac{t_{ref}}{T}\right)^k \quad (7)$$

This equation may be updated using a revised thickness correction factor formula by changing the effective thickness as discussed in Section 1.4.

$$log_{10}\left(\frac{\Delta\sigma_{test}}{\Delta\sigma_c}\right) = log_{10}(\Delta\sigma_{test}) - log_{10}(\Delta\sigma) - log_{10}\left(\frac{t_{ref}}{T_{eff}}\right)^k \quad (8)$$

These recalculated data points are analysed and presented graphically in the following sections.

3.2 Data Analysis

3.2.1 T-joints

<u>*In-air*</u>

The fatigue test database contains data of T-joint for a wide variety of thickness from 16 mm to 200 mm. Those data have been allocated to different bins against their thicknesses and environmental conditions for data analysis.

For In-air condition, quantity of samples for each thickness range is shown in Figure 9, where most of the samples are less than 40 mm, but there is still a fair amount of samples widely distributed from 40 mm to 200 mm.

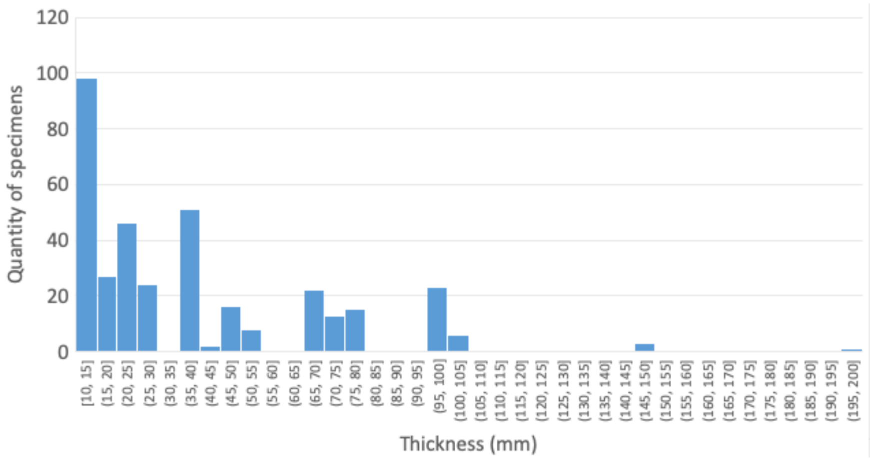

Figure 9. Histogram of Thickness with In-air T-joint Samples

In Figure 10, the thickness differentiator of each sample is visualised by two parts, where the blue dots are representing $log_{10}(\Delta\sigma_{test}) - log_{10}(\Delta\sigma)$, and the orange line is the thickness correction part of the equation, $log_{10}\left(\frac{t_{ref}}{T_{eff}}\right)^k$.

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The size effect could be considered by changing T to T_{eff}, however, the database is lack of details (i.e., attachment length, L) so no further assessment can be made to the existing data due to this restriction. Therefore, T is taken to be T_{eff} in the following analysis.

The design fatigue strength $\Delta\sigma_c$ for T-joints are calculated against the DNVGL F curve. Each of the group are presented with an error bar, of which the upper bound (mean+2×Standard Deviation) and the lower bound (mean-2×Standard Deviation) of the distribution are shown in Figure 10.

In ideal situation, the design curve shall follow the lower bound of the error bars. Otherwise, the gap between the lower bound of the error bars implied that the current standard is with a certain extent of conservatism.

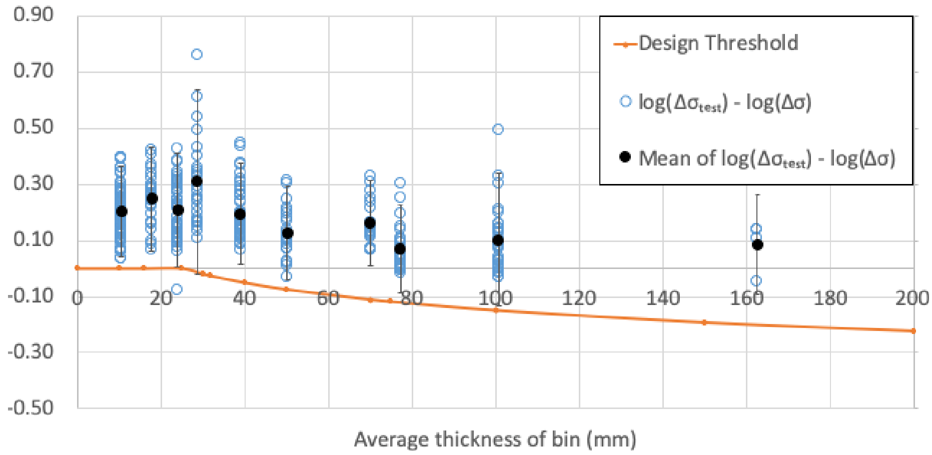

Figure 10. Data Analysis of In-air T-joint

Observations:

- The mean fatigue strengths start decreasing after the reference thickness of 25 mm but appear to be levelling after 50 mm with increasing thickness,
- With increasing thickness, the lower bound of test data, corresponding to mean–2×Standard Deviation, is decreasing in general but is higher than the design threshold. Consideration should also be made for the statistical uncertainties due to lack of data in some data groups,
- Test data are concentrated in the small thickness range (T<50 mm), but there are still sizable amounts of data in thickness range greater than 50 mm

Cathodic Protection

Figure 11 shows the histograms for tests in CP condition. It can be seen the data points are concentrated on three bins with markedly little data of T>41 mm. Data analysis for CP T-joint is presented in Figure 12.

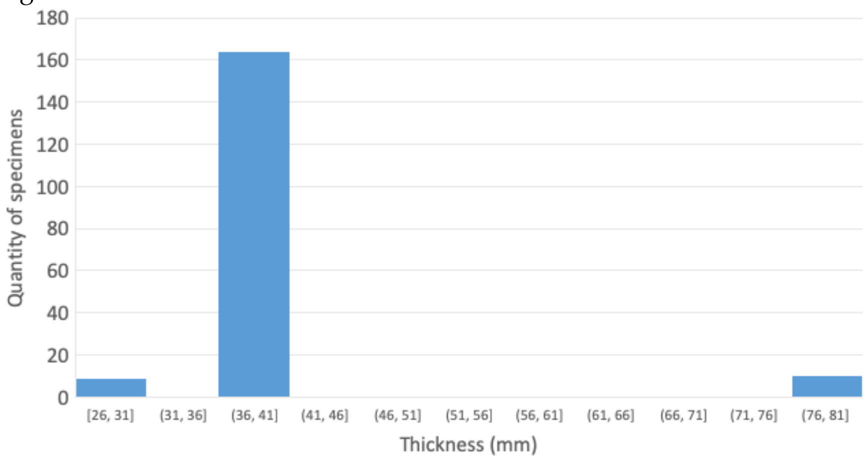

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Figure 11. Histogram of Thickness with CP T-joint Samples

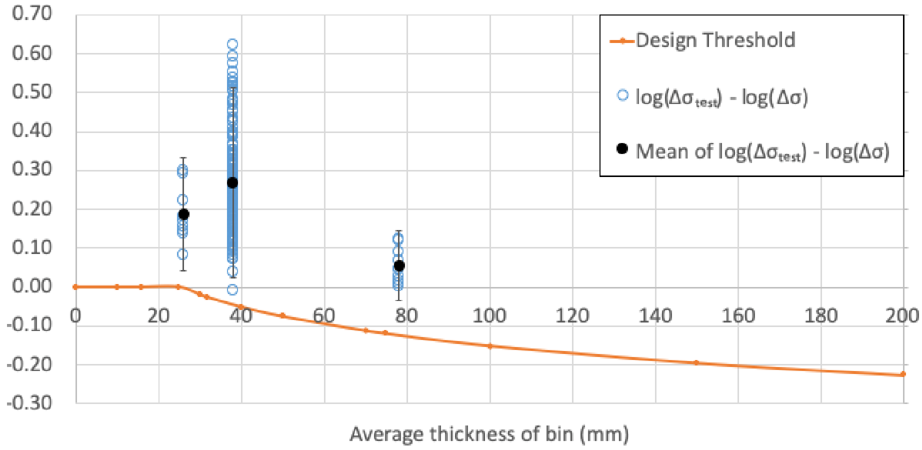

Figure 12. Data Analysis of CP T-joint

Observations:

- With increasing thickness, the few data group does not indicate that the mean fatigue strength is following a monotonic relation. This may imply that thickness effect may not exist or does not play a dominant role, where other factor may be affecting the performance to a greater extent comparing to in-air condition,
- With increasing thickness, the fatigue strength at lower bound is consistently higher than the design threshold, meaning the design curve is conservative,
- Lack of test results impose large uncertainties at the system level as well as local level at the first group and the third group.

Free Corrosion

Figure 13 shows the histograms for tests in FC condition. There is significant amount of data in the T<44 mm region, but data for T>44 mm is still limited. Data analysis for FC T-joint is presented in Figure 14.

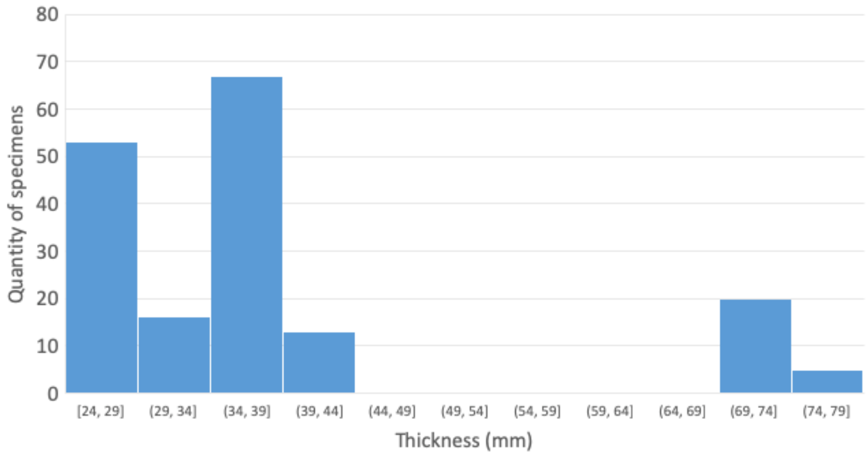

Figure 13. Histogram of Thickness with FC T-joint Samples

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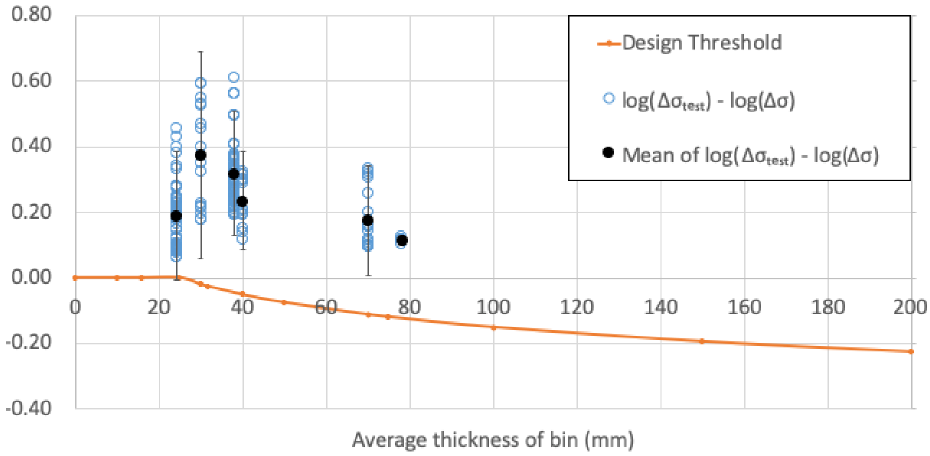

Figure 14. Data Analysis of FC T-joint

Observations:

- With increasing thickness, the mean fatigue strength does not follow a monotonic relation. This may imply that thickness effect may not exist or does not play a dominant role, where other factor may be affecting the performance to a greater extent comparing to in-air condition,
- With increasing thickness, the fatigue strength at the lower bound is consistently higher than the design threshold, meaning the design curve is conservative, and much more than that for In-air condition,
- Lack of test results impose large uncertainties at higher thickness region

3.2.2 Transverse Butt Welded Joints

In-air

The fatigue test database contains a number of tests with transverse butt welded joint for thickness ranging from 9 to 100 mm. However, most of the data are with In-air condition, where in corrosive environment, tests are all less than or equal to the DNVGL reference thickness (25 mm).

The histogram of thickness for In-air transverse butt welded joint is presented in Figure 15. There is still fair amount of data in the high thickness region. Data analysis can be found in Figure 16.

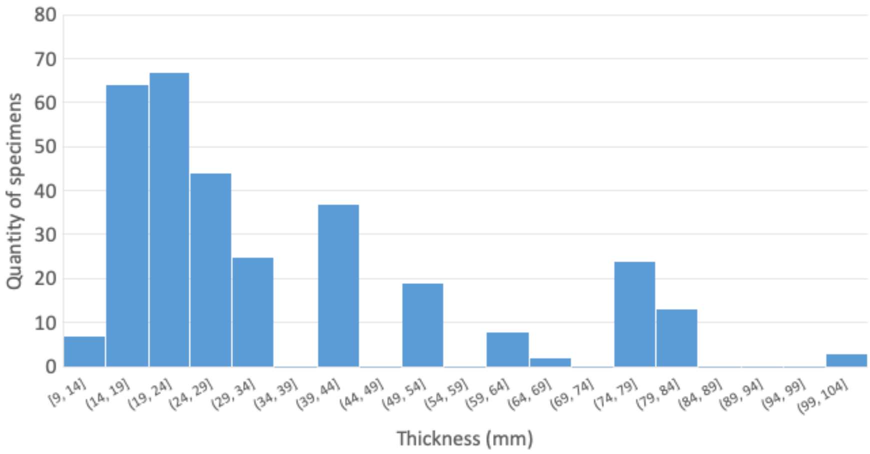

Figure 15. Histogram of Thickness with In-air Transverse Butt Welded Joint Samples

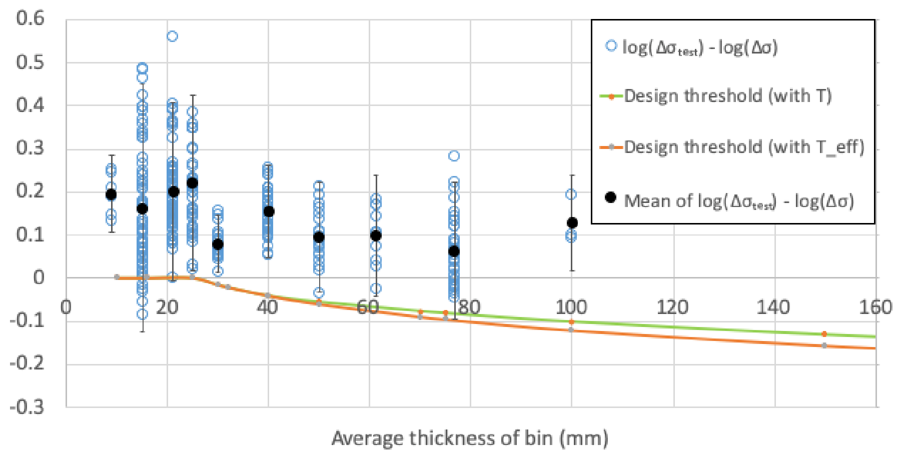

Figure 16. Data Analysis of In-air Transverse Butt Welded Joint

Observations:

- With increasing thickness after the reference thickness, the mean fatigue strengths initially drop but level after 50 mm,
- With increasing thickness after the reference thickness, the fatigue strengths at lower bound are mostly above the design threshold meaning that the design curve is conservative,
- Test data are concentrated in the small thickness range (T≤40 mm),
- As the attachment length (L) for the double-sided transverse butt weld can be taken to be equal to the plate thickness if the weld prep profile is 45°, the effective thickness can be made smaller. Conservatism at higher thickness can be reduced as shown by the green line in Figure 15.

Cathodic Protection

In Figure 17, only 3 samples are equal or greater than the DNVGL reference thickness for transverse butt welded joints under CP condition. Thus, limited information can be extracted from the data analysis in Figure 18.

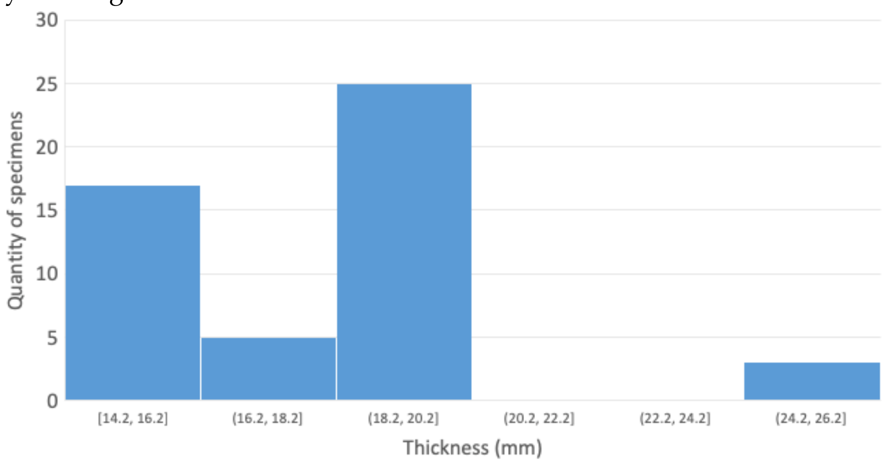

Figure 17. Histogram of Thickness with CP Transverse Butt Welded Joint Samples

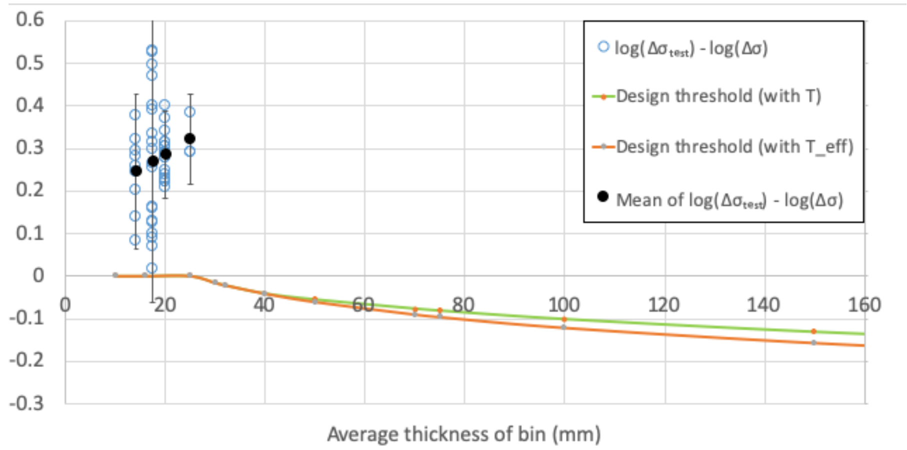

Figure 18. Data Analysis of CP Transverse Butt Welded Joint

Observations:

- The mean fatigue strengths increase against the increase of thickness,
- Lack of data in high thickness region, thus statistical uncertainty may be high.

Free Corrosion

For FC environment, only 8 data entries of transverse butt welded joint are recorded as presented in Figure 19, of which 4 of them are equal to the DNVGL reference thickness. The data analysis of this exposure category is presented in Figure 20.

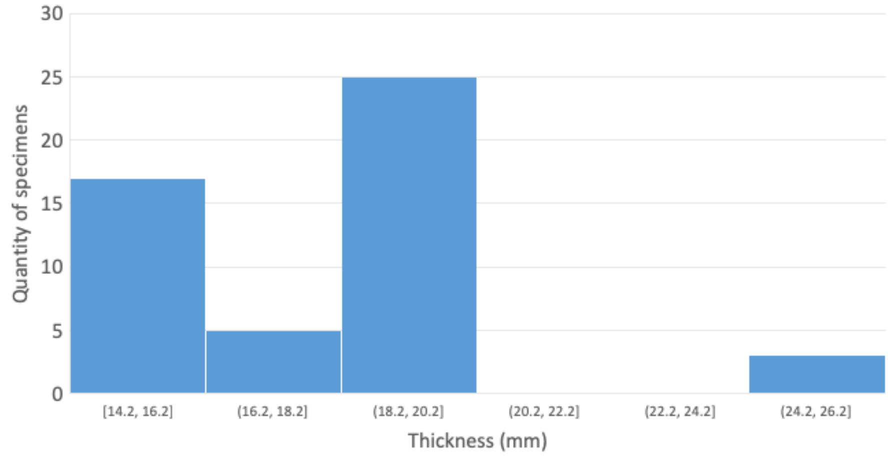

Figure 19. Histogram of Thickness with FC Transverse Butt Welded Joint Samples

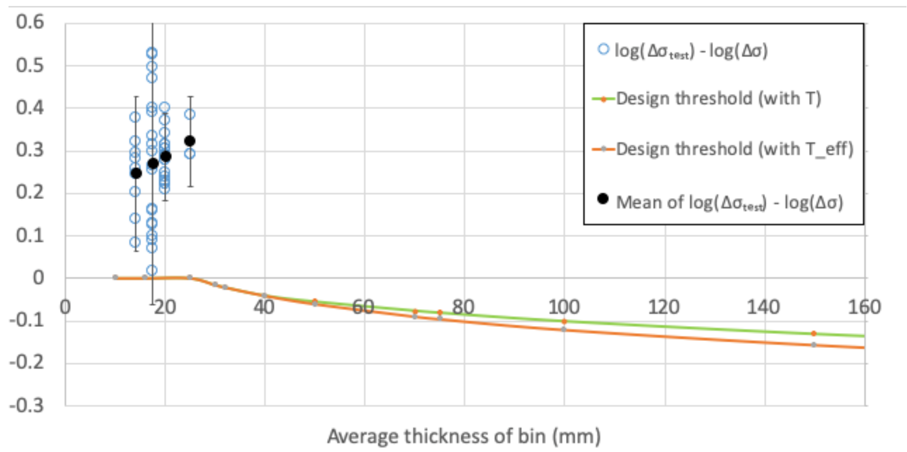

Figure 20. Data Analysis of FC Transverse Butt Welded Joint

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Observations:

- The mean fatigue strengths decrease against the increase of thickness,
- Lack of data in all thickness region, thus statistical uncertainty may be high.

3.2.3 Tubular Joints

In-air

Similar to the other joint categories but more controversially, the samples for tubular joint highly accumulated in the low thickness region. There are some high thickness data for the In-air condition, but very limited data for the corrosive environment.

Figure 21 shows the histogram of thickness for the In-air tubular tests. And the associated data analysis is presented in Figure 22.

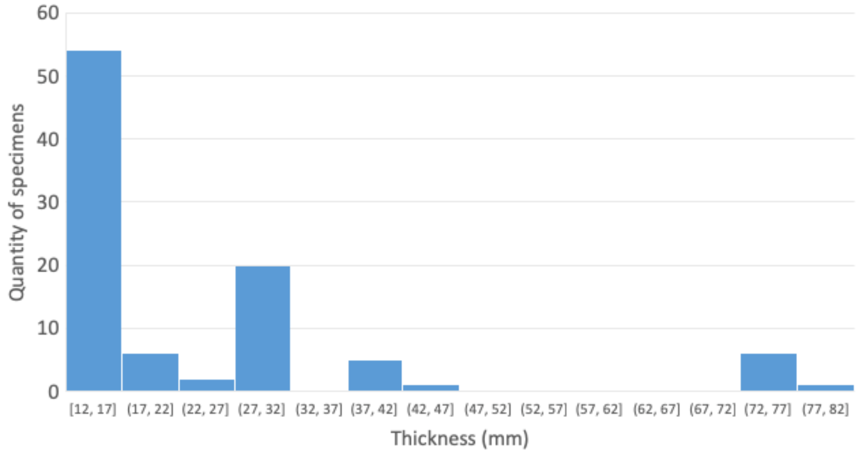

Figure 21. Histogram of Thickness with In-air Tubular Joint Samples

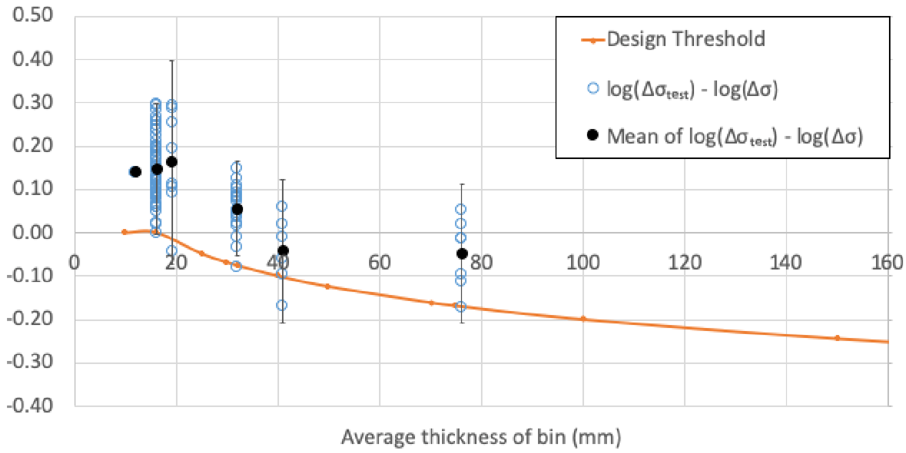

Figure 22. Data Analysis of In-air Tubular Joint

Observations:

- As the lower bound for some high thickness bins lie below the design threshold, the design curve is not entirely at the conservative side according to these data. This phenomenon may be due to a number of reasons, one of which can be the statistical bias because of lack of data,
- The mean fatigue strength of the last two groups seemed to be levelling at higher thickness range.

Cathodic Protection

For tubular joints under CP condition, most of the data are greater than the reference thickness of DNVGL T curve, which is 16 mm. As illustrated in Figure 23, more than 30 data entries are accumulated at the 32 mm region. Data analysis for CP tubular joint is presented in Figure 24.

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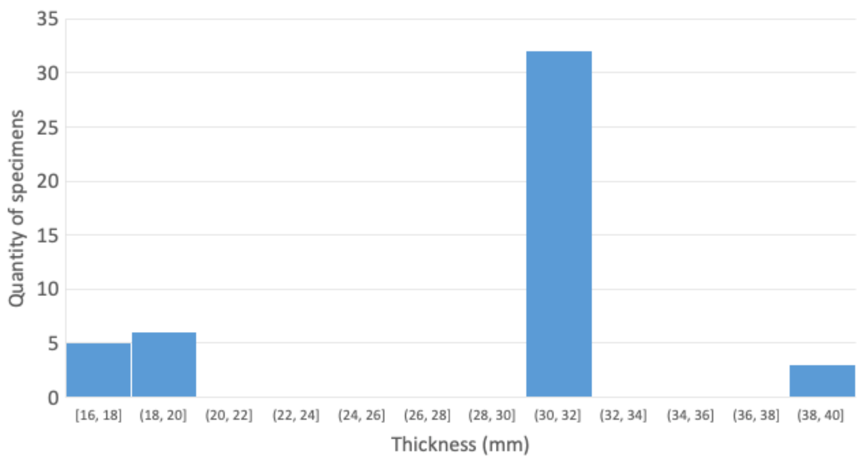

Figure 23. Histogram of Thickness with CP Tubular Joint Samples

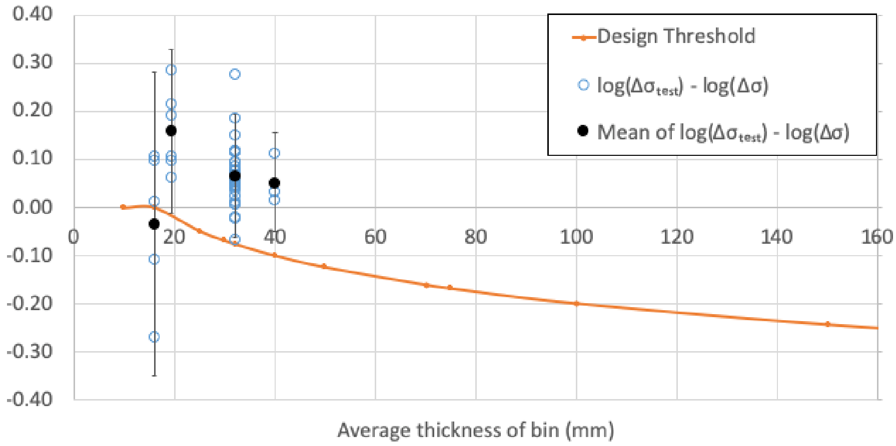

Figure 24. Data Analysis of CP Tubular Joint

Observations:

- The mean fatigue strengths decrease against the increase of thickness, despite the first bin of data,
- Except the first bin of data, the lower bound of the rest of data fits the design threshold quite well before 32 mm, but slightly conservative after 32 mm. This may be due to the statistical uncertainty of the last bin at 40 mm that contains only 3 data entries.

Free Corrosion

Figure 25 shows the histogram of thickness distribution for tubular joint data under FC condition. Most of the data under this exposure are at 20 mm, and limited amount of data can be found at other ranges. Data analysis for FC tubular joint is presented in Figure 26.

Observations:

- Most of the data entries fall above the design threshold, despite the first bin of data at 12 mm has a larger dispersion. This phenomenon could be induced by the outlier data entries,
- Lack of data in most thickness region, especially for higher thickness.

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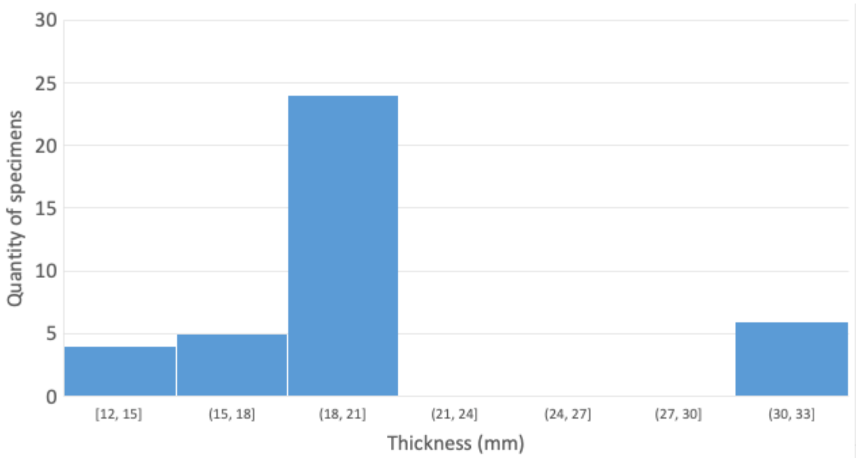

Figure 25. Histogram of Thickness with FC Tubular Joint Samples

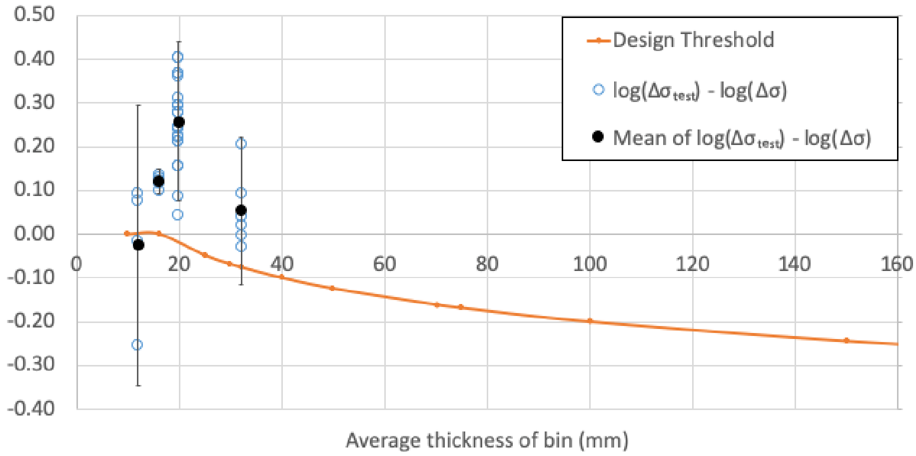

Figure 26. Data Analysis of FC Tubular Joint

4. Summary and Discussion

Thickness effects have been observed from early fatigue tests. A scale factor has therefore been introduced to consider these effects. In current standard such as IIW-1823-07 [8], DNVGL-RP-C203 [3], ISO 19902 [5], the scale factor is a function of the effective thickness T_{eff} in relation to a reference thickness t_{ref} with a power quotient k. This can be expressed using the Gurney's equation:

$$\Delta\sigma_t = \Delta\sigma\left(\frac{T_{eff}}{t_{ref}}\right)^k \tag{9}$$

The work in this study is to attempt to re-evaluate the suitability of current standards in regard to the thickness effect. Some potential conservatism from analysing a substantial body of test results are presented. The study has concentrated on T-joint, transverse butt welded joint and tubular joint as these are the most commonly used joint types in the offshore wind industry, and most of the experiments are conducted against them.

In general:

- for section thicker than 40 mm, current test database has relatively little data points for In-air condition and even scarcer information for fatigue under free corrosion and CP conditions. Hence the confidence in applying the so-called thickness correction factor away from the test range is questionable,
- In the limited amount of data with thicker sections, the result shows obvious gap between the design fatigue strength after correction and the test fatigue strength, mostly in the conservative range which imply potential for optimisation.

For T-joint, the following summary can be made:

- The decrease on fatigue strength is less severe than predicted using the general thickness correction factor when thickness is greater than 40 mm in non-corrosive environment. This trend appears to agree with the proposed modification in the latest DNVGL-RP-C203, as shown in the recent work by Lotsberg 10 which modifies this formula to consider the size effect. However, the size effect equation cannot be used for evaluation with the current test dataset because of lack of information on the additional dimension such as the attachment length L in the original test conditions,
- For the limited data available for corrosion fatigue test, analysis shows the current standard are at the conservative side, but with varying degree of conservatism at different thickness range. This phenomenon can be attributed to the following:
    - Statistical uncertainties due to the size of the data,
    - There are multiple factors affecting corrosion fatigue in each of the different test hence greater scatter. A cleaned data base with uniform attributes may help, but the quantity of data will be significantly reduced for each of the group,
    - The non-proportional aspect of corrosion fatigue may be dominant which diminish the effects of thickness.

For transverse butt welded joint, the following summary can be made:
- The mean fatigue strength is levelling when thickness is greater than 40 mm in non-corrosive environment,
- Although there is high statistical uncertainty due to lack of data for thicker specimen, fatigue strength based on this database gives values of slightly less conservatism than the current standard in non-corrosive environment,
- The size effect equation can improve the design standard, especially for high thickness transverse butt welded joints,
- Due to lack of corrosion fatigue data, it is difficult to support any thickness effect statement, but most of the data are at the conservative side.

For tubular joint, the following summary can be made:
- The mean fatigue strength decreases with increasing thickness, but similar strength can be observed at 40 mm and 78 mm. However, there is no data available between 40 mm and 78 mm to support any general statement.
- The fatigue strength based on the in-air samples is fairly close to, or slightly more conservative than the design strength from standard with the thickness correction factor. The slight difference may be attributed to statistical uncertainty.
- Due to lack of corrosion fatigue data, it is difficult to support any thickness effect statement, but most of the data are at the conservative side.

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