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Highlights of the article:

- Mean stress affects the fatigue performance of as-welded joints under variable amplitude (VA) loading.
- Experimental data on the fatigue endurance and residual stresses under VA.
- Miner's sum increases from 0.5 to more than 3 when the maximum stress in the CD loading reduces from 300MPa to 0.
- New analytical models improve the prediction of the fatigue life of welded joints under VA loading with the Miner's sum ranging between 0.5 and 1.5.

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Influence of the Mean Stress on the Fatigue Life of Welded Joints under Variable Amplitude Loading

Xu Liu[1,2,3], Yan-Hui Zhang[2,3], Bin Wang[1,2], Xing Sun[3]

1. Department of Mechanical and Aerospace Engineering, Brunel University London, Uxbridge, UB8 3PH, UK.

2. National Structure Integrity Research Centre (NSIRC), TWI Ltd., Cambridge, CB21 6AL, UK.

3. Fatigue Integrity Management Section, TWI Ltd., Cambridge, CB21 6AL, UK.

Abstract

The effect of the mean stress on the fatigue life of welded joints fabricated with three different plate thicknesses was investigated under variable amplitude (VA) loading sequences. Test results indicate that Miner's sum, D, at failure increases as reducing the mean stress in the VA loading; hence, limiting D to 0.5, as advised in the fatigue design codes, may be unduly conservative in the fatigue assessment. The joint with a thinner plate is tend to have a better fatigue performance. New analytical models which can consider both mean stress and VA loading sequence effect were developed for better prediction of the fatigue life. Good agreement is observed between predictions and test results.

Keywords

welded joints, variable amplitude, fatigue life, mean stress, residual stress

Nomenclature and definitions

Symbols	
D, D_m, D_{ms}	Damage sum, damage sum estimated after mean stress correction, damage sum estimated after considering the mean stress correction and sequence factor.
M, M_{CD}, M_{CU}	Sequence factor, sequence factor for CD and CU sequence, respectively.
n_i	The number of cycles of the ith stress range in a spectrum
T	Plate thickness
P_i	Relative stress range in a spectrum (=$\Delta\sigma_i/\Delta\sigma_{max}$)
R	Loading ratio (=$\sigma_{min}/\sigma_{max}$)
R_{Pi}	Overload ratio ((=$\Delta\sigma_{max}/\Delta\sigma_{min}$)
$\sigma_{i,m}$, $\sigma'_{i,m}$	The mean stress of $\Delta\sigma_i$ and $\Delta\sigma'_i$, respectively.
σ_{max}, σ_{min}	The maximum, minimum stress in a loading cycle

σ_{UTS}	Ultimate tensile stress
σ_{tf}	Ture fracture stress
$\Delta\sigma_i$, $\Delta\sigma_i'$	The ith stress range in a loading spectrum, the corresponding equivalent stress range estimated based on mean stress correction
$\Delta\sigma_{\max}$, $\Delta\sigma_{\min}$	Maximum, minimum stress range in a loading spectrum
Abbreviations and definition	
Block	The stress history between successive applications of the peak stress in the spectrum
CA	Constant amplitude
CD, CU	Cycling down, cycling up
RS	Residual stress
SMYS	Specified minimum yield stress
Spectrum	A representation of stress range(s) distribution with time or number of cycles
VA	Variable amplitude

1. Introduction

Structures and components are commonly subjected to variable amplitude (VA) loading in service, depending on their functions and the particular application, such as offshore, railway, bridge etc.[1]. Some standard time domain VA loading spectra, which relates to different application, have been developed [1,2]. In terms of the fatigue design under VA loading, fatigue assessment remains the most critical part [3].

To estimate fatigue damage to welded joints under VA loading, the design S-N curves provided in industry standards, such as, BS 7608 [4], IIW [5] and DNV [6], are used in conjunction with Palmgren-Miner linearly cumulative damage rule (Miner's rule). For a VA stress spectrum consisting of n_i cycles at a stress range $\Delta\sigma_i$, i = 1,2,3, etc., the CA life based on an S-N curve is expected to be N_i, where $\sum(n_i/N_i) = 1$ at failure according to the Miner's rule. Generally, components are safe when $D < 1$ if the loading is of a constant amplitude or produces a spectrum with gradual variation in stress ranges, notably narrow-band random loading. However, a high and unacceptable scatter of Miner's sum has been revealed under VA loading [3], resulting in the criterion advised in fatigue design codes could be either unsafe or unduly conservative [7–13]. In a study [7] where fatigue tests were carried out on fillet welded plates on fatigue damage under different loading sequences but with the same fatigue stress histogram (numbers of cycles at each stress range remain the same), three scenarios were considered: Sequence A with stress cycling down (CD) from a constant maximum tensile stress, Sequence B with a constant mean (CM) stress and Sequence C with stress cycling up (CU) from a constant minimum stress. According to fatigue design codes, where only stress range is considered, these three loading sequences are expected to produce the same fatigue damage. However, test results showed significant differences in cumulative damage sum. D was found of the value about 0.5 under Sequence A, 0.78-

0.94 under Sequence B and 1.3-1.6 under Sequence C. Similar results were also reported in [8,9] for CD loading sequence and [10–13] for CU loading sequences.

The scatter of damage sum under VA loading may result from several factors, such as the order of the loading cycles in the VA loading sequence [3,14], the method used to estimate the damage for those small stress cycles below constant amplitude fatigue limit[7,15], or mean stress fluctuations in the VA loading [3]. In order to ensure the safety, the current fatigue design codes advises limiting D to 0.5 if there is any uncertainty about the nature of the service stress loading history, and no relevant test data is available [4,5].

However, $D = 0.5$ only corresponds to the CD loading sequences with high tensile maximum stresses [7,9] and only limited work had been carried out to investigate whether 0.5 is still appropriate under the CD loading sequence with a low maximum stress. In the investigation of fatigue performance of welded plates with longitudinal attachments under CD loading [7], the maximum stress in one of the tests was reduced from 280 to 147MPa, resulting in only a small increase in the Miner's sum from 0.51 to 0.58, which could be related to data scatter. Similar results were reported in the study carried out by Tilly [12], where the same type of welded joints were tested under two CD loading sequences with different maximum stresses. One was with all loading cycles in tension, while the other was at a zero-maximum stress with all cycles in compression. The D values were 0.61 to 0.78, respectively.

Generally, the mean stress is considered has no significant effect on fatigue life of welded joints based upon the assumption that high tensile residual stress (RS) is likely to be present at the weld toe [4,16]. However, the magnitude of RS is affected by the geometry of the welded joint. For the welded plates with longitudinal attachments, which were tested in [7,12], are typically contains large RS [7,8,17,18], so it is not surprising the D value only changes slightly when decreasing the maximum stress in the CD loading sequence. However, it is still not clear whether a similar result would be observed in other types of welded joints which may contain lower RS. In addition, the fatigue loading influence the RS. The welded joints containing high RS were tested under Gaussian VA loading spectrum with and without overloads, and increase in fatigue life was observed under the latter, implying the overload can cause RS relaxation [18,19].

In view of the situations described above, the objective of the current study were investigating the effect of mean stress of the fatigue performance of welded joints under CD loading sequences, and to develop a method to predict the fatigue life, which can improve the fatigue assessment under such load sequences.

The paper is presented in the following arrangement. First, the approach used in the present study is briefly summarised in Section 2. Fatigue tests conducted are discussed in Section 3 to reveal the effect

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of the mean stress. Measurements of residual stresses are presented in Section 4. Both results are discussed in Section 5, and based on that, new models for fatigue damage are proposed in Section 6, taking account of both the mean stress and the VA loading sequence. Section 7 provides comparison of proposed models and experimental results with conclusions given in Section 8.

2. Approach

The welded joints tested in the current study were plate with filleted welded transverse attachments and they are expected to contain lower RS than those contained longitudinal ones. In this case, it provide an opportunity to emphasis the effect of mean stress applied in the VA loading. Owning to the RS also may relate to plate thickness, the specimens were fabricated using three different thicknesses plates. The RS in each thickness specimen before and after fatigue loading were measured and considered in the data interpretation.

A linear distribution spectrum was established, based on which four cycling down (CD) loading sequences with different maximum stresses were produced. Each thickness specimen were tested under these sequences and their endurances were compared to investigate the effect of mean stress and plate thickness.

In support of providing guidance on predicting the fatigue life in the fatigue assessment for the welded joints subjected to VA loading sequences, an analytical model, which can include both mean stress and VA loading sequence effects, was proposed.

3. Fatigue tests

3.1 The test specimen

Specimens tested in this study were 100mm-wide steel plates containing two transverse fillet welded attachments in the longitudinal centre on both sides, as shown in Figure 1. There were three different plate thicknesses, being at 6, 12.5 and 25mm. The thickness of attachment was identical to the plate thickness. The four fillet welds of the specimen are denoted as A, B, C and D, respectively And they were made using manual metal arc welding in one pass for 6mm- and 12.5mm-thick plates and three passes for 25mm-thick plates with a welding sequence of weld A, D, B and C to achieve balance welding.

As all the welds were fabricated following the same procedure and the same welder, the local geometry of the each weld were expected to be similar. Three specimens, one from each thickness, were randomly selected and inspected using Wiki-scan welding inspection system. Two measurements were carried out on two different welds at the mid-width on each specimen. The measurement results, as given in Table 1, show that the parameters of the two welds in each specimen are almost identical. The depth of

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under-cut at the weld toe of interest are all about 0.1mm in all three plate thicknesses, which agrees well with the average initial flaw depth of 0.15mm [7].

Table 1. Wi-Ki scan measurements results (in mm and degree)

Thickness	Messurement Order	Leg1	Leg2	Leg1 Size1	Leg1 Size2	Throat	Convexity	Undercut 1	Undercut 2	Toe angle 1	Toe angle 2
6	1	9.6	8	8.1	7	5.4	-1.1	0.2	0	155	143
	2	8.5	7.4	6.2	7.2	4.7	-1.4	0.1	0.1	160	140
12.5	1	12.7	10.1	9.7	9.3	6.7	-1.7	0	0.1	155	137
	2	9.8	10.4	8	9.5	6.2	-1.3	0.3	0.1	152	149
25	1	16.4	16.9	16.1	13.7	10.5	-1.7	0.1	0.1	138	145
	2	18	14.7	16.3	12.1	9.7	-1.9	0.2	0.1	145	144

In terms of the fatigue strength, the specimen is designated as Class F according to standard BS 7608 [4]. The fatigue performance of the same batch specimens under CA loading was investigated under both axial and bending loading mode and the corresponding S-N curves were established and reported [20], as shown in Figure 2. These S-N curves were adopted in the present study as benchmarks to estimate the fatigue damage of loading cycles in the VA loading. The CA tests were conducted under axial and bending loading mode, with a constant maximum stress of 300MPa and 330MPa, respectively. In each loading mode, seven specimens were tested at different stress levels. Based on the test results, the mean S-N curves established with a forced slope of 3. It can be seen that the fatigue performance of the welded joints depends on the loading type and the plate thickness. It can be can be either conservative or non-conservative if conducting the fatigue assessment using Class F mean curve advised in BS 7608 [4].

The material of the plate and attachment was structural steel S355 with the specified minimum yield stress (SMYS) and tensile stress at 355 and 550MPa [21,22], respectively.

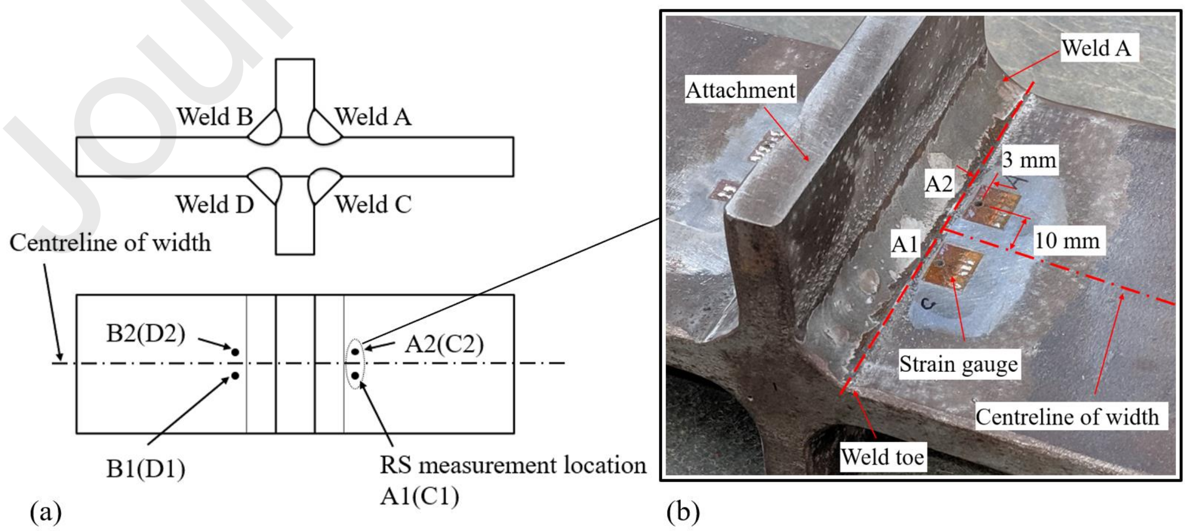

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Figure 1. Geometry of the tested specimen and the locations where residual stresses were measured: (a) schematic where letters in brackets refer to the measurement locations on the opposite side of the plate; (b) one of the actual test specimens.

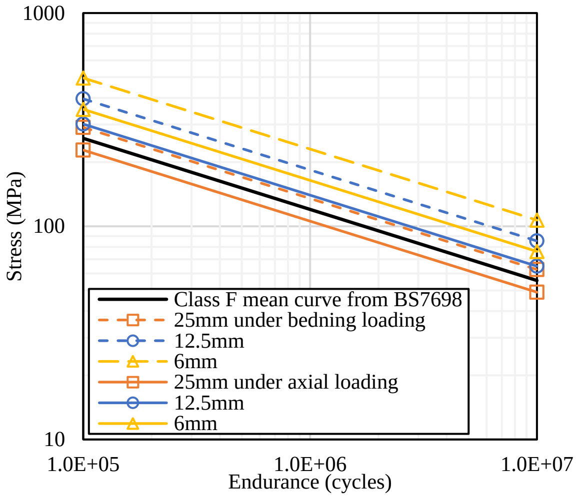

Figure 2. The mean S-N curves determined under both axial and bending constant amplitude loading with a forced slope m=3 [20]*. The Class F mean curve from Bs7608* [4] *is included for comparison.*

3.2 Variable amplitude (VA) loading spectrum

Various standardized spectra were developed by European working groups in the purpose to represent typical loading case in different industry area, such as aircraft, offshore structure, etc.. [1,2]. Gassner distribution is one of the standardized spectra developed for general purpose and was used in the present study, following

$$P_i = \left(1 - \frac{\log(N_E)}{\log(N_{max})}\right)^{\frac{1}{b}} \tag{1}$$

where P_i is the relative stress range ratio which is defined as the ratio of each stress range, $\Delta\sigma_i$, to the maximum stress range, $\Delta\sigma_{max}$. N_E is the block length which is the exceedence corresponding to a specific P_i, and n_{max} is the aimed total number of cycles in each block (block length).b is an exponent that determine the shape of the plot of P_i against exceedence. When $b = 1$, the plot is linear and with decreasing or increasing values of b, the shapes of the plot become less or more hollow, respectively.

In the present study, the loading block length was set at 1.5×10^5 cycles with $b = 1$. $\Delta\sigma_{max}$ used in the spectrum was set at 250MPa that is approximatively 70% of SMYS of the base metal. The minimum P_i used was 0.35, corresponding to a stress range of 87.5MPa which is greater than the constant amplitude fatigue limit of 55.7MPa of Class F mean curve at 10^7cycles in BS 7608. The total number of loading cycles in a loading block (block length), N_L, was 2316. The P_i distribution is shown in Figure 3, and the stress histogram for the VA spectrum is given in Table 2.

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Generally, the fatigue life, N, under a VA loading sequence calculated based on the S-N curve obtained under constant amplitude loading in conjunction with Miner's rule:

$$N = \frac{N_L}{D_{block}} \tag{2}$$

where $N_L = \sum n_i$ ($n_i$is number of cycles of $\Delta\sigma_i$ included in the VA loading spectrum). D_{block} is the fatigue damage due to one block of VA loading:

$$D_{block} = \sum \frac{n_i}{N_i} \tag{3}$$

where N_i is the fatigue life under constant amplitude loading of $\Delta\sigma_i$ and can be estimated based on the S-N curve:

$$\Delta\sigma_i{}^m N_i = C \tag{4}$$

where m and C are the material constants. By integrating Equation (2) - (4), the fatigue life can be estimated by

$$N = \frac{N_L}{\sum \frac{\Delta\sigma_i{}^m n_i}{C}} \tag{5}$$

It should be noted Equation (5) assumes the damage of a certain stress range only relate to the stress range, regardless the mean stress and is identical to that due to the same stress range in a CA loading.

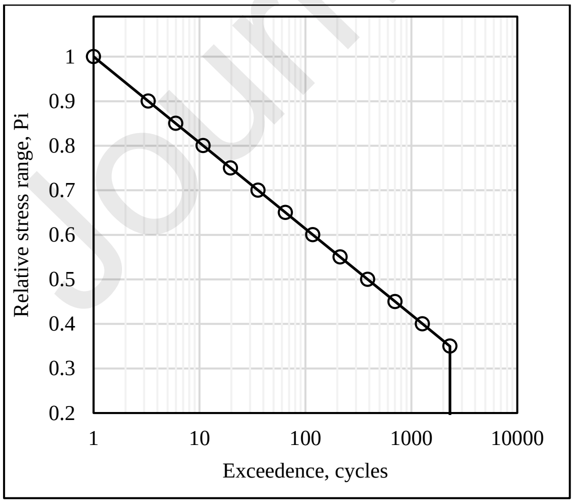

Figure 3. Linear P_i distribution spectrum used in the present VA tests.

Table 2. Details of the loading spectrum used in the VA tests.

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Maximum stress range, $\Delta\sigma_{max}$ (MPa)	Relative stress range, Pi	Stress range, $\Delta\sigma_i$ (MPa)	Cycles, n_i	Exceedence, N_i
250	1	250	1	1
	0.9	225	2	3
	0.85	212.5	3	6
	0.8	200	5	11
	0.75	187.5	9	20
	0.7	175	16	36
	0.65	162.5	29	65
	0.6	150	53	118
	0.55	137.5	96	214
	0.5	125	174	388
	0.45	112.5	316	704
	0.4	100	573	1277
	0.35	87.5	1039	2316

Based on the VA loading spectrum, CD loading sequences were produced. The effect of the applied mean stress on the fatigue performance of welded joints was investigated by setting different maximum stresses for each CD loading sequence at 300MPa, 150MPa, 87.5MPa and 0, respectively. Figure 4(a) shows a typical CD loading sequence. The cyclic stresses in a loading block were in a random order, produced by a random number generator in the fatigue test machine. When the whole of the first block had been applied, the process was repeated, and subsequent blocks were applied in the same random order. This process was continued until the specimen failed.

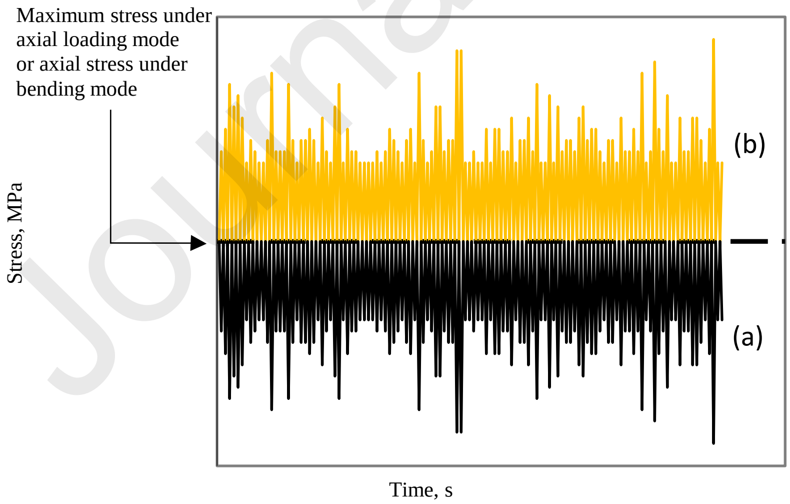

Figure 4. Examples showing the variable loading sequences: (a) cycling-down from either a constant maximum stress under axial loading mode or a constant axial stress under bending mode; (b) cycling-up from a constant axial stress under bending mode.

3.3 Loading mode

Fatigue tests were carried out under either an axial or a bending loading mode, depending on the maximum stresses applied. When the maximum stress in the CD loading sequence was reduced in steps from 300MPa to 0, high compressive loading was introduced, which may cause specimen buckling under an axial loading mode, especially for thin plates. Therefore, some tests involving the maximum stresses less than 150MPa were conducted under bending loading.

A test jig was built to apply a constant axial stress for fatigue testing under a bending mode, as shown in Figure 5. The specimen was fixed in the frame in a horizontal position by pins and applied with a static axial stress through two parallel hydraulic jacks connected to the frame. The bending load was applied through the attachment on the top surface of the plate in the direction perpendicular to the plate. When a constant axial load was applied, both ends of the specimen were constrained by the frame; hence, it was a bending testing with fixed ends rather than a conventional three-point bending test.

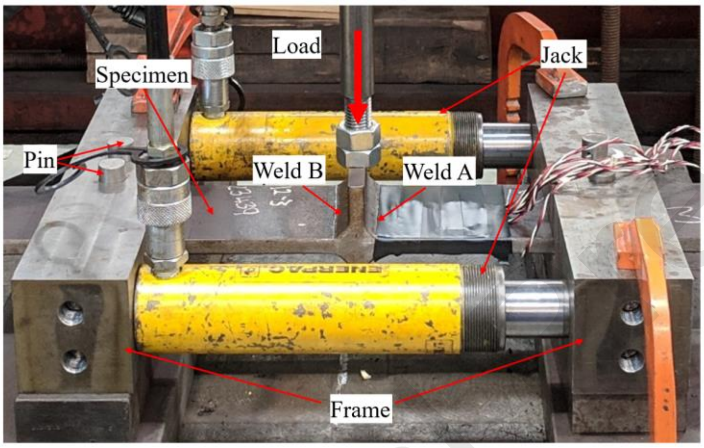

Figure 5. The bending test jig.

It is interesting to note that, in the bending mode, when the top welds (e.g., welds A and B in Figure 4) are subjected to a CD loading sequence where all the loading cycles cycling down from the constant axial stress applied by the frame the bottom welds (e.g., welds C and D) are tested under a cycling up (CU) loading sequence where all cycles cycling up from the constant axial stress. (Figure 4 (b)). Therefore, the fatigue damages of these two different loading sequences were studied simultaneously in a single specimen by identifying the fatigue failure occurs at which side of the specimen. It should also be noted that as the stress histograms (number of cycles at each stress range level) for the two loading sequences are identical, the welds on both the top and bottom sides of each specimen are expected to have the same fatigue life according to BS 7608. In addition, the top welds may have inferior fatigue endurance than the bottom welds as the study [7] revealed that the CD loading could be more damage than the CU loading.

In order to estimate the secondary bending stress due to the angular misalignment, a pair of strain gauges (Gauge 1 and 2) were mounted in the centreline of specimen width, directly opposite to each other, at distances of T to the weld toe. When the test was conducted under bending mode with a non-zero constant axial stress, one more strain gauge (Gauge 3) was installed beside Gauge 1, 30mm apart, to check whether the stresses across the specimen width were uniform after the axial stress was applied through the frame.

All fatigue tests were carried out using servo-hydraulic fatigue testing machines at ambient temperature. The load was computer-controlled and measured by load cell. The loading frequencies used was between 3 and 6Hzand it should be noted that under the same loading frequency, the load rate for larger loading cycles is faster than that for the smaller loading cycles.

4. Residual stress measurement

RS measurements were conducted using air abrasive centre-hole drilling method. In each measurement, a hole of ~2.0mm diameter was drilled to approximately 2.0mm in depth each time and one Vishay CEA-06-062UM-120 type Centre-hole rosette strain gauge was used.

From each plate thickness, one specimen in as-welded condition was random selected, on which two measurements were made at locations A1 and C1, Figure 1 (a). A1 and C1 were opposite to each other and they located 10mm from the transverse centreline (mid-width of the plates) and 3mm to the weld toe, Figure 1 (b). The two measurement results were expected to be similar. This is because, first, the welds were similar, and second, the welding sequence was assumed to have no significant influence on the RS presented near each weld. It was found that in the T type fillet welded joint, the RS profile on each side of the attachment are generally symmetrical, despite the magnitude of RS depending on the welding sequence [23]. In [24], the effect of welding sequence on the RS in the same type joint used in the current study was investigated based on an average RS value of the four measurement results from each quadrant, which also implies the RS presented near each weld are comparable. In addition, the measurement results were also assumed to be identical to those presented at the weld toe where fatigue crack grows. This is because the RS distribution near the T type fillet welds was investigated using the finite element method, and results show the magnitude of RS 3mm away from the weld toe was only slightly lower (~5%) than the that presented at the weld toe [25]. Mochizuki [24] also measured the RS, using strain gauge and X-ray diffraction techniques, and a similar result was also reported.

In addition to as-welded condition, the RS after fatigue loading were also measured in 12.5mm- and 25mm-thick specimen. For 25mm-thick specimen, the RS after two CA bending loading cycles were measured. The stress range was 250MPa which was identical to the maximum stress range in the VA loading sequences. The measurement locations were B1 and D1, which were subjected to tensile and compressive stress in the CA loading, respectively. Similarly, RS after further 100 CA loading cycles were also measured. For 12.5mm-thick specimen, RS measurement were conducted after two cycles under CA axial loading under the stress range -100 to 150MPa, and after additional two cycles under CA bending loading.

5. Test results and discussions

5.1 Fatigue tests

5.1.1 Fatigue lives and Miner's sum

Of the twelve specimens tested, eleven specimens failed at weld toes, and one specimen, B6_1, was declared run-out after 1.4×10^7 cycles without indication of fatigue cracking at weld toes. For the three failed specimens tested in the bending mode, fatigue failures occurred at the bottom welds that were subjected to CU loading sequence.

The predicted fatigue life and Miner's sum, D, for each VA test were calculated based on the CA S-N curves derived in [20] and presented in Table 3 for axial loading and Table 4 for bending loading.

Table 3. Results of the specimens tested under axial loading.

Plate thickness (mm)	Specimen No.	Maximum stress (MPa)	Predicted fatigue life (cycles)	Experimental fatigue life (cycles)	Miner's Sum, *D*
6	A6_1	300	3,589,800	1,970,916	0.54
	A6_2	150		1,801,848	0.51
12.5	A12.5_1	300	2,218,728	947,244	0.43
	A12.5_2	150		2,612,448	1.18
	A12.5_3	87.5		4,314,708	1.94
25	A25_1	300	956,508	585,948	0.61
	A25_2	150		729,540	0.76
	A25_3	87.5		963,456	1.00

Table 4. Results of the specimens tested under bending loading (cycling down for the top welds and cycling up for the bottom welds).

Plate thickness (mm)	Specimen No.	Predicted fatigue life (cycles)	Bottom welds			Top welds		
			Minimum stress (MPa)	Experimental fatigue life (cycles)	Miner's Sum, *D*	Maximum stress (MPa)	Experimental fatigue life (cycles)	Miner's Sum, *D*
6	B6_1	9,889,320	87.5	30,098,736[a]	>3.04	87.5	runout	>3.04[b]
12.5	B12.5_1	5,025,720	87.5	4,407,348	0.88	87.5		>0.88[b]
	B12.5_2	4,284,600	0	7,818,816	1.82	0		>1.82[b]
25	B25_1	1,989,444	0	4,138,692	2.08	0		>2.08[b]

Note: a. There was no indication of cracking after running 5,387,016 cycles ($D = 0.55$). To speed up the test, the loading spectrum was modified to exclude all stress ranges less than 125MPa. The test was resumed using the modified loading spectrum for another 9,210,344 cycles (equivalent to 24,711,720 cycles in the original spectrum in terms of fatigue damage). b. These welds ran out. There was no indication of cracking found in the top welds experiencing the CD loading sequence. The 12.5mm- and 25mm-thick specimens failed from the bottom welds experiencing the CU loading sequence.

Although the total number of tests is limited and addition tests will be the most advantageous, the current results still tend to reveal some effects of the variables in the VA loading on fatigue lives of the welded joints, which will be discussed in the following sections.

5.1.2 Effect of the maximum stress in CD loading sequence

Figure 6 shows the results of all the welds tested under CD loading sequences. The results reported in [7] for plate specimens with longitudinal non-load-carrying attachment tested under CD loading sequence with maximum stresses of 280 and 147MPa are also included for comparison.

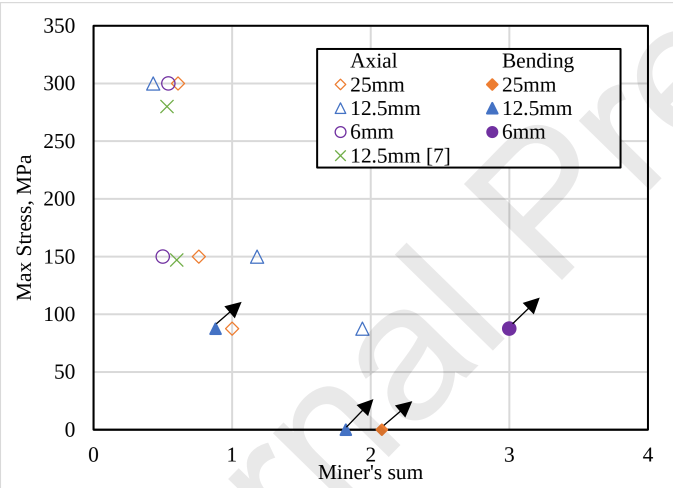

Figure 6. Miner's sums, D, obtained from welds subjected to CD loading sequences with different maximum stresses (arrows indicate runout).

It can be seen from Figure 5 that under CD loading,

- When the maximum stress is 300MPa, about 80% SMYS of the material, D values for all three specimens are about 0.5, similar to the results reported by others [7–9,12].
- Miner's sums increase with decreasing maximum stress. When the maximum stress is reduced to 150MPa, the results of both 25mm- and 12.5mm-thick specimens show an increase in fatigue life - D increases from 0.61 to 0.76 for the former and from 0.43 to 1.18 (more than doubled) for the latter.

- The results reported in [7] also shows similar increase in D with decreasing maximum stress, but at a much smaller extent - from 0.53 under 280MPa to 0.60 under 147MPa.

- For the 6mm-thick specimen, there is no significant change in D, although an increase would be expected based on the trend suggested by the results of thicker specimens. This may be attributed to buckling due to the compressive load and the thin plate thickness

- When the maximum stress is further reduced, a significant increase in D values is obtained in all specimens. For the three welds tested at a maximum stress of 87.5MPa, only one weld tested in axial loading failed with $D = 1.94$. The other two under bending loading ran out at $D > 0.88$for the 12.5mm thick specimen and $D > 3.08$ for the 6mm thick specimen. The 12.5mm thick specimen shows failures in the bottom weld subjected to CU loading sequence and no failure in the top welds under CD sequence. The 6mm thick specimen has no failure in neither top nor bottom welds.

- One of each 12.5mm and 25mm-thick specimen was tested in compressive CU loading with the maximum stress at 0. Both failed only in bottom welds with $D = 2.08$ for the 25mm-thick specimen and $D = 1.82$ for the 12.5mm-thick one.

The present test results suggest that, although a CD loading sequence can result in low D values [7–9,12], limiting D to 0.5 would be unduly conservative when the maximum stress in a CD loading sequence is below a certain value. The over-conservatism increases with decreasing plate thickness, for instance, Dbecomes higher than 3.08 for the 6mm-thick specimen subjected to a constant maximum stress of 87.5MPa.

This phenomenon can probably be attributed to the ressidual stress presented in the specimens being not high enough to maintain a high local stress level at the weld toe. Therefore, the fatigue life of welded joints is seen to increase as the applied mean stress is reduced. This is will be furtherdicussed in conjunction with the RS measurement results in Section 4.2.

5.1.3 Effect of the minimum stress in cycling up loading sequence

Figure 7 shows the Miner's sums of the welds tested under CU loading (i.e., the bottom welds of the specimens tested under bending loading). The results reported in [7] for longitudinal fillet welds under two CU loading sequences with a minimum stress of 70MPa are included for comparison.

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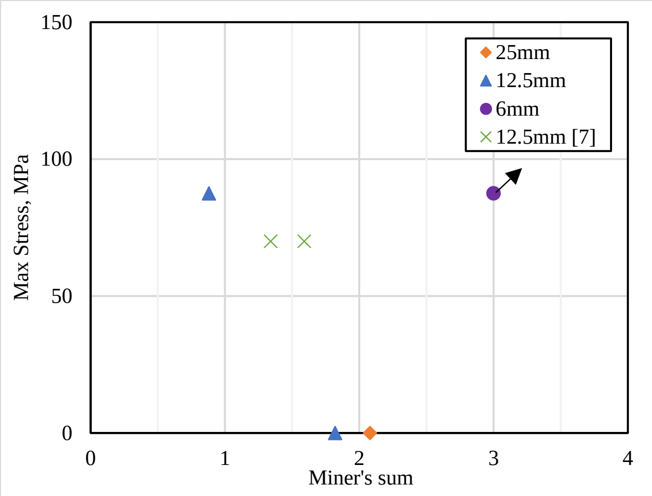

Figure 7. Miner's sum, D, obtained from welds subjected to CU loading sequences with different minimum stresses (arrow indicates runout).

The following can be seen from Figure 7:

- When the minimum stress is 87.5MPa, the 6mm-thick specimen run out at $D = 3.08$, whereas the 12.5mm-thick specimen fails at the Miner's sum being only 0.88.
- When the minimum stress is reduced to 0, D values of the two specimens are significantly greater than unity. The D value for the 12.5mm-thick specimen is more than doubled to 1.82, and to 2.08 for the 25mm-thick specimen.

The test results suggest that the fatigue damage parameter D for the CU loading sequence depends on the minimum stress applied. It increases with decreasing minimum stress level. This is in agreement with the results obtained under the CD loading sequences which suggest a dependence of D on the magnitude of the maximum stress applied. Therefore, it would be inappropriate to use a constant upper limit D value to assess the fatigue life of welded joints under CU loading, which would be unduly-conservative for sequences with low minimum stresses. More relevant tests would be required to verify this observation.

5.1.4 Effect of type of loading sequence

The value of D for welds under CD and CU loading sequences are compared in Table 4. Generally, CD loading is regarded as more damaging with D reported being less than 1 for CD loading and higher than 1 for CU loading [7,10–13]. Therefore, top welds had been expected to have shorter fatigue lives than the bottom ones for the specimens tested under bending loading. However, test results show the opposite: all fatigue failure took place in bottom welds under CU loading sequences, and not in top welds under CD loading. The results suggest a strong dependence of fatigue damage on the static axial stress level. When the mean stress is reduced through the decrease of either the maximum stress in the

CD sequence or the minimum stress in the CU sequence beyond a certain level, a significant increase of D is obtained. These results would not be expected according to the current fatigue design guidance (e.g., BS 7608, IIW) where the calculation of fatigue damage only considers the stress range.

5.1.5 Effect of plate thickness

By comparing the test results shown in Figures 6 and 7, it can be seen that, although not conclusive, there is a general trend that thinner specimens' fatigue performance is better than that of thicker ones under both CD and CU loading sequences.

It can be seen that under a CD loading sequence with a maximum stress of 300MPa, the plate thickness does not significantly affect Miner's sum which is around 0.5 for all three different plate thicknesses. However, when the maximum stress is reduced to 150MPa, the D value of the 12.5mm-thick specimen is about 1.5 times higher than that of the 25mm-thick specimen, suggesting that a thinner plate has a better fatigue life. For the 6mm-thick specimen, however, the D value does not change, still at about 0.5 and the reason is unclear.

When the maximum stress is further reduced to 87.5MPa, the D value ofthe 12.5mm-thick is about two times higher than that ofthe 25mm-thick specimen, and the D value ofthe 6mm-thick is the highest, at least 50% higher than that ofthe 12.5mm-thick specimen. It should be noted that, according to BS 7608, the beneficial effect of thinner specimens (less than 25mm) can only be claimed in bending mode. However, the present results show that the plate thickness effect is also significant under an axial loading mode. This effect agrees with the results obtained in [20] where tests were conducted under CA axial loading, as shown in Figure 2

The better fatigue performance observed in the thinner plates may be attributed to the steeper stress gradient through the plate thickness [26]. By assuming the initial flaw presented at the weld toe is independent of plate thickness, and the stress distribution across the plate in the crack growth plane is geometrically similar, the stress gradient in the thinner plate is steeper than that in the thicker plate. Therefore, the initial flaw with specific depth in a thinner plate experiences smaller stress, leading to a smaller fatigue crack growth rate. The difference in initial crack growth rate overmatches the difference in crack length to cause fracture; hence, the thinner plates have a better fatigue performance. In addition, the detrimental effect of larger plate thickness may be due to the high residual stress [27]. The residual stress presented in the 25mm-thick specimen was found to be two times higher than that presented in 6mm-thick thickness one. More details about the residual stress measurements are given in Section 4.2.

Based on the available data obtained under CU sequences, it can be seen from Figure 6 that when the minimum stress in the CU sequence is 87.5MPa, the D value for the 6mm-thick specimen is more than three times higher than that for the 12.5mm-thick specimen. This again suggests a better fatigue

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performance from thinner specimens. However, the two experimental results from the 12.5mm- and 25mm-thick specimens tested with a minimum stress of zero are similar. This suggests that, in addition to thickness effect, there might be other factors, such as weld profile and variations of welding-induced RS, which also affect fatigue performance and may cause data scatters.

5.1.6 Effect of type of welds

In Figure 6 it can be seen that the fatigue lives of the transverse fillet welds increase significantly when the maximum stress is reduced from 300 to 150MPa. However, this is not observed in longitudinal fillet welds when the maximum stress is reduced by a similar magnitude, as reported in [7]. This suggests that the fatigue results of transverse fillet welds are more sensitive to the maximum stress in the CD loading sequence than the longitudinal fillet welds.

As the thickness of these two types of welded joints are identical, being at 12.5mm, this difference may be only related to the difference in welding-induced RS. The RS ahead of a longitudinal attachment is about the magnitude of the yield strength of the base material [7,17], while the RS for a transverse fillet welds is much smaller, being at about 60% of the yield strength [28,29] or even lower at 20% [30–32]. When the maximum stress is reduced to 150MPa, fatigue loading would still be tension-tensionina longitudinal attachment weld toe butbecomes partly compressive in a transverse attachment. And this explains better fatigue lives of the latter as shown in Figure 5. This is further quantitively disscued in Section 5.2.

5.1.7 Comparison of fatigue lives between experiments and predictions based on fatigue design codes

The test results given in Table 3 and 4 were plotted in terms of number of cycles to make a direct comparison between the experimental results and those predicted by only considering stress range as advised in fatigue design codes, such as BS7608[4], IIW[5], DNV[6], as shown in Figure 8.

In addition, relevant results reported in Refs.[7], [33] and [34] were also included for comparison. Ref. [7] reported fatigue tests under both CD and CU loading sequences which were produced from a concave-up shaped VA spectrum with P_i ranging from 1 to 0.04. The maximum stress range in the spectrum was 210MPa. The maximum and minimum stresses in the CD and CU loading sequences were 280 and 70MPa, respectively.-

In [33], a basic VA loading spectrum representative of a standard load for fighter aircraft wings was developed, with P_i ranged between 0.063 and 1. Based on this basic spectrum, two more spectra were produced by omitting P_i higher than 0.667 and 0.377, respectively. Various CU loading sequences were then produced by using four different maximum stresses at 300, 250, 200 and 150MPa, respectively.

All stress ranges in each loading sequence were arranged in a random order, with a constant loading ratio $R = 0$.

The VA loading spectrum used in [34] was produced based on a larger in-service loading history for the mid-span moment in a 40m long, simply-supported girder. P_i values were between 0.06 and 1. Four CU sequences were produced with the maximum stress at 367, 239, 217 and 171MPa with the corresponding constant minimum stresses at 9, 12, 13 and 20 MPa, respectively.

From Figure 8 it can be seen that although all test results are expected to fall along the line with D=1 according to fatigue design codes, data exhibit large scatters with the Miner's sum D ranging from 0.5 to 2 under CD sequences, and 0.5 to 8 under CU sequences. This indicates a strong dependence of fatigue damage on loading sequences. It can also be concluded that neither D=0.5 nor D=1 is a proper criterion to assess the fatigue life of welded joints under VA loading, and the fatigue life subjected to CD loading sequences with low maximum stresses and CU loading sequences might be unpredictable based on the current standard.

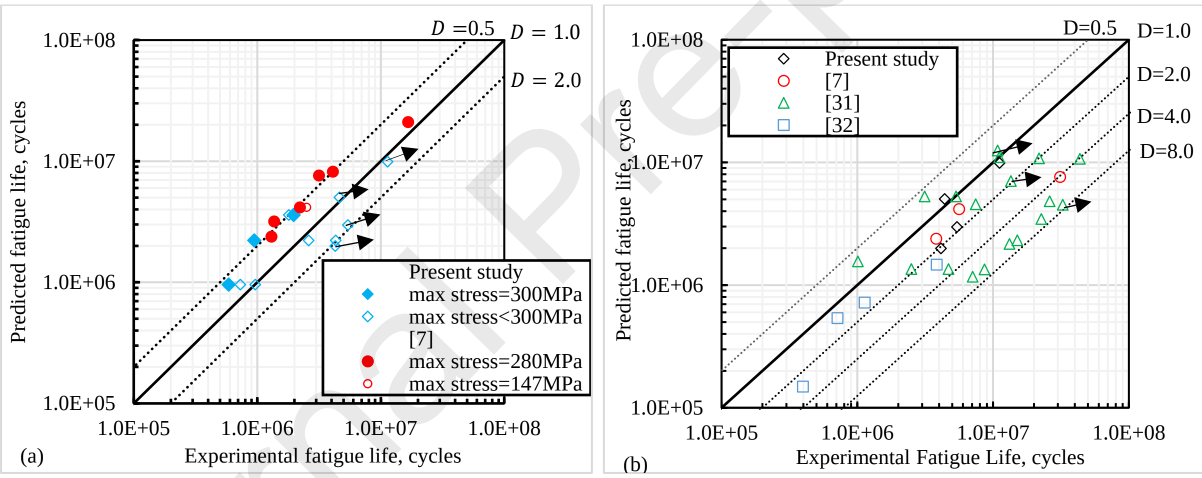

Figure 8. Comparison of fatigue lives between experiments and calculations based on fatigue design codes which only considers stress ranges under: (a) CD and (b) CU sequences.(arrow indicates run-out).

5.2 Residual stress measurements

5.2.1 Measurement results

In as-welded condition, measurements of RS at locations A1 and C1 (see Figure 1(b)) are presented in Table 5 and confirm the presence of high tensile RS near the weld toe where fatigue cracking occurred. Similar results were obtained from the two measurements made on 25mm- and 12.5mm-thicknes specimen, suggesting in each thickness, the RS distribution near weld A and C may be similar, this is agree with simulation results reported in [25]. So it was assumed that the RS near the four welds are identical. Therefore, the RS in as-welded condition was determined by the average value of these two measurements, which is 230MPa and 122MPa for 25mm- and 12.5mm-thick specimen, respectively.

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However, for the 6mm-thick specimen, measured RS at C1 is only 7MPa thus regarded as a scatter which may because the strain gauge malfunctioned. A third measurement was then carried out at location A2 and the result agrees well with the value at location A1. The average RS in the as-welded 6mm-thick specimen was taken at A1 and A2 as 83MPa. The results measured from A1 and A2 also suggests the RS distribution along the weld toe may be symmetrical with respect to the centerline of width of the plate, as reported in [25] where the RS distribution along the fillet weld of T joints was simulated using finite element analysis method.

Table 5. Details of residual stress measurement and the measurement results at different loading stages in the direction of perpendicular to the welds.

Plate thickness	As welded		Axial loading (-100MPa~+150MPa)		Bending loading (top weld: 0 ~ -250MPa, bottom weld: 0 ~ +250MPa)			
			2 CA cycles		4 CA cycles		104 CA cycles	
	Location	RS (MPa)	Location	RS (MPa)	Location	RS (MPa)	Location	RS (MPa)
25	A1	252	-	-	B1 (top)	183	B2 (top)	161
	C1	213	-	-	D1 (bottom)	166	D2 (bottom)	150
12.5	A1	128	A2	108	B1 (top)	97	-	-
	C1	116	C2	87	D1 (bottom)	85	-	-
6	A1	82						
	C1	7	-					
	A2	84						

After cyclic loading, relaxation of RS was observed in the 25mm and 12.5mm-thick specimens as seen in Table 5. In the 25mm-thick specimen, RS reduced significantly after two CA loading cycles, the average RS decreased from the initial 233MPa to 175MPa (~25%). After another100 CA loading cycles, the average RS relaxed only modestly to 156MPa (~10%). In the 12.5mm-thick specimen, about 80% of the initial RS remained after two CA axial loading cycles. Under two bending loading cycles, the RS in both the top and bottom welds only reduced slightly (~1%).

To summarize, the results of the RS measurements suggest the following,

- The RS magnitudes in this type of joint are less than the SMYS of the material, especially for thinner plates. The average RS values for the 25mm, 12.5mm and 6mm thick specimens are respectively about two thirds, one third and a quarter of the SMYS of the material.

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- Relaxation of RS occurs under cyclic loading, even under a low value maximum stress of only 150MPa (less than half of the SMYS). Relaxation mainly takes place in the first two cycles. Further cycles only resulted in small RS reductions.
- Compressive loading produces similar RS relaxation to tensile loading.

It should be mentioned that these points are based on limited test data. Further work is required to confirm these conclusions.

5.2.2 Effect of RS under CD loading sequences

As mentioned previously, low RS may be the main reason for the increase of *D* when the maximum stress in the CD sequences decreases. For example, at location A1 in the 12.5mm-thick specimen, the measured RS after cyclic bending loading is 97MPa. When the maximum stress in the CD sequences is 150MPa (specimen A12.5_2) and 87.5MP (specimen A12.5_3), the actual maximum stress or the combination of the maximum applied stress and the RS, is 247 and 185MPa, respectively. Therefore, the CD sequence with a low maximum stress would lead to a better fatigue life, thus an increased D, due to the low value of the actual maximum stress.

It is also reported that *D* obtained under some CD sequences with low maximum stresses are higher than unity when fatigue failure occurs. For instance, when *D* was calculated using S-N curves produced based on CA tests with a constant maximum stress at 300MPa [20], since the actual maximum stress cannot exceed SMYS of the material [9,17] which is 355MPa, it is reasonable to assume the actual maximum stress in all CA tests was equal to 355MPa after taking RS into consideration. However, when the maximum stress in the CD sequences is sufficiently low, the actual stress could be less than 355MPa, the fatigue damage will be smaller than that caused by the same stress range with an actual maximum stress of 355MPa. In this case, the fatigue life might be underestimated accordingly using S-N curves, resulting in a higher *D* value.

Test results obtained in this study (Figure 6) shows that in the bending mode, all fatigue failures took place in bottom welds experiencing CU loading sequences instead of top welds experiencing CD loading sequences. This result conflicts with the expectation that a CD sequence causes more damages [7]. Based on RS measurement, it can be explained in the cases of low RS. For example, in specimen B12.5_2 where the static axial stress was 0 and the RS was 97MPa, the minimum stress for both CU and CD sequences were 97MPa. Thus, the mean stress for a CD sequence would be lower than that in the CU sequence of the same stress range, resulting in better fatigue life.

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5.2.3 Effect of RS under CU loading sequences

Unlike in a CD sequence, the maximum stress in a CU sequence is not constant. Only the maximum stress of the largest stress range in the spectrum can reach the SMYS of the material, while other smaller stress ranges are lower than SMYS. Therefore, the fatigue damage in CD sequences may be overestimated using S-N curves produced by CA tests with the maximum stress at SMYS, causing a conservative prediction of fatigue life.

Based on the discussion, it suggests that for both CD and CU loading, the mean stress can significantly influence the fatigue endurance of welded joints where low RS presents, thus should be considered in fatigue life assessment.

6 Analytical analysis

6.1 Development of analytical models

As discussed above, the mean stress and the VA loading sequence could significantly influence the fatigue performance, therefore, their effects should be considered to improve the prediction of fatigue life of welded joints under VA loading sequence. To this end, Equation (5) was modified by adding a new parameter, M, to account for the sequence effect. In addition, the applied stress range $\Delta\sigma_i$ was also replaced by an equivalent stress range, $\Delta\sigma_i'$, which was estimated by taking into account the mean stress effect. Therefore, the new equation proposed in the present study is as follows:

$$N = M \frac{N_L}{\sum \frac{\Delta{\sigma_i'}^m n_i}{C}} \tag{6}$$

The estimation of M and $\Delta\sigma_i'$ are given in the following sections.

6.2 Mean stress correction

The equivalent stress range, $\Delta\sigma_i'$, was estimated using the conventional mean stress correction methods – Gerber [35] and Morrow [36] models. These models were generally used to covert a given stress range, $\Delta\sigma$, with the mean stress, σ_m, to an equivalent fully reversed (i.e. $R = -1$) stress range that is able to produce the same fatigue damage with the combination of $\Delta\sigma - \sigma_m$ [37]. They also can be further developed to convert the combination of $\Delta\sigma - \sigma_m$ to a stress rangeat any stress ratio, $\Delta\sigma_i'$, with a mean stress $\sigma_{i,m}'$, following:

$$\Delta\sigma_i' = \frac{1 - \left(\frac{\sigma_{i,m}'}{\alpha}\right)^n}{1 - \left(\frac{\sigma_m}{\alpha}\right)^n} \Delta\sigma \tag{7}$$

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where α is material constant. When $n = 2$ and α is the ultimate tensile stress, σ_{UTS}, Equation (7) is converted from Gerber model, while $n = 1$ and α is the true fracture stress, σ_{tf}, it is developed based on Morrow model. For steel, σ_{tf} can be estimated as $(\sigma_{UTS} + 345)$MPa if its experimental value is unavailable [37].

It should be noted that the mean stress is used as an independent variable in Equation (7). However, all CA or VA data used in the present were obtained at constant maximum stresses. Therefore, a new form of the Gerber and Morrow models were proposed here by replacing the $\sigma'_{i,m}$with a reference maximum stress, $\sigma'_{i,max}$, which is the combination of applied maximum stress and RS. Considering,

$$\sigma_m = \sigma_{max} - \frac{1}{2}\Delta\sigma \tag{8}$$

$$\sigma'_{i,m} = \sigma'_{i,max} - \frac{1}{2}\Delta\sigma'_i \tag{9}$$

Therefore, Equation (7) is changed to:

$$\Delta\sigma'_i = \frac{1 - \left(\frac{\sigma'_{i,max} - \frac{1}{2}\Delta\sigma'_i}{\alpha}\right)^n}{1 - \left(\frac{\sigma_{max} - \frac{1}{2}\Delta\sigma_i}{\alpha}\right)^n}\Delta\sigma_i \tag{10}$$

Based on Equation (10), for each VA loading sequences the stress range, was converted to an equivalent stress range with a reference maximum stress.

6.3 VA loading sequence factor

6.3.1 Sequence factor for CD loading sequences

The sequence factor for CD loading sequence, M_{CD}, can be determined by experimental results straightforwardly. For example, in the present study, fatigue tests were conducted under CD loading sequences with a constant maximum stress of 300MPa. S-N curves used to estimate the fatigue life under such CD loading sequences were produced based on CA loading sequences where the maximum stress was 300MPa as well. As the maximum stress in the CD sequence and in the CA sequences are identical, the actual mean stress of the two loading sequences remains the same. In this case, Miner's sum D is less than unity (D~0.5) at fatigue failure and is due to the sequence effect only and not the mean stress. It is worth noting that when welded joints are subjected to a CD sequence where the maximum stress is identical to that of the CA loading sequence used to produce S-N curve, the D value at fatigue failure is typically at 0.5 [7,8]. Therefore, the magnitude of M_{CD} is assumed to be constant at 0.5.

6.3.2 Sequence factor for CU loading sequences

Compared with CD loading sequences, the magnitude of the sequence factor for CU loading sequences cannot be determined from experimental data directly. This is because the effects of both the mean stress and the sequence factor are always active at the same time under VA loading sequences. Hence, experimental results were first correlated with the mean stress to eliminate the effect of mean stress. Then the sequence effect of CU was determined accordingly based on the results obtained after the mean stress correction.

For the mean stress correction, equivalent stress ranges were calculated by correlating the original stress ranges in a CU loading sequence with the reference maximum stress of 355MP using Equation (10). Fatigue lives were then estimated based on the equivalent stress ranges and plotted against the experimental results in Figure 9. The Miner's sum, estimated based only on the means stress correction and excluding the sequence effect, is named as D_m.

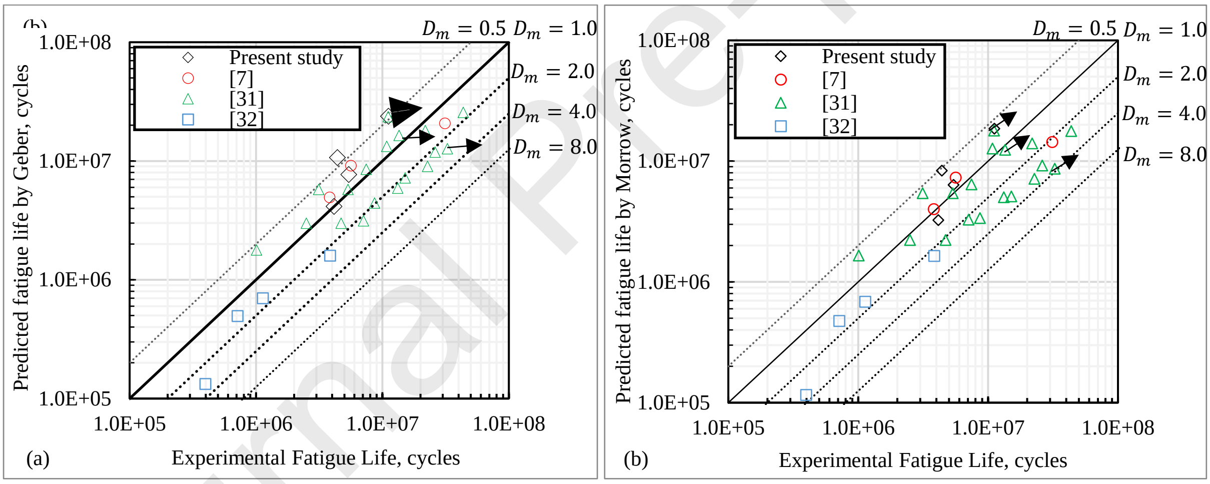


Figure 9. Comparison of fatigue lives between experiments and calculations based on mean stress correction models developed in the present study under CU loading sequences: (a) Gerber and (b) Morrow (arrow indicates run-out).

It can be seen that predictions based only on the mean stress correction still exhibit a large scatter when compared with the experimental results, with D_m ranging between 0.5 and 4. Hence, it is inappropriate to simply set the sequence factor at a constant value for CU loading sequences.

To determine the sequence factor, further investigation was carried out first on data from [33], where the difference of the three spectra involved was only the maximum P_i value, i.e., 1, 0.667 and 0.377 for spectrum A, B and C, respectively. The relevant data was extracted from Figure 9(b) and replotted in Figure 10.

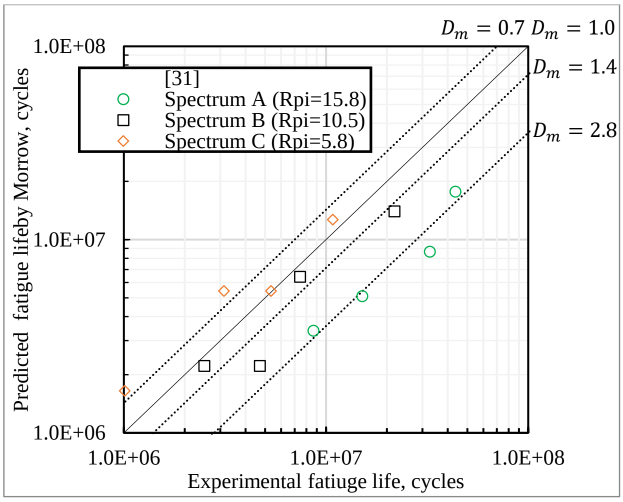


Figure 10. Comparison between the fatigue lives of experiments from [33] *and calculated based on Morrow mean stress correction model developed under CU loading sequences.*

It can be summarised that the overload ratio is the driven factor that affects the sequence factor of a CU loading sequence - D_m reduces in value with a decreasing overload ratio. The same conclusion is also obtained from the results corrected using the Gerber method. Therefore, R_{pi} for all CU sequences involved in the four studies, i.e., the present study and [7], [33] and [34], were calculated. And the corresponding average D_m obtained using the Morrow and the Gerber methods were estimated as well. Results are plotted in Fatigue 11.

It can be seen that for the 12.5mm-thick specimen, the average D_m is proportional to the overload ratio. i.e., the higher R_{pi}, the larger D_m. In addition, D_m also appears to depend on the plate thickness. For $R_{pi} = 2.8$, $D_m$of the 25mm-thick specimen is twice of that of the 12.5mm-thick specimen, suggesting the thicker the plate, the higher D_m. Identical trends also can be seen by comparing the results obtained from 9.5 or 6mm-thick specimens with that of the 12.5mm-thick specimen.

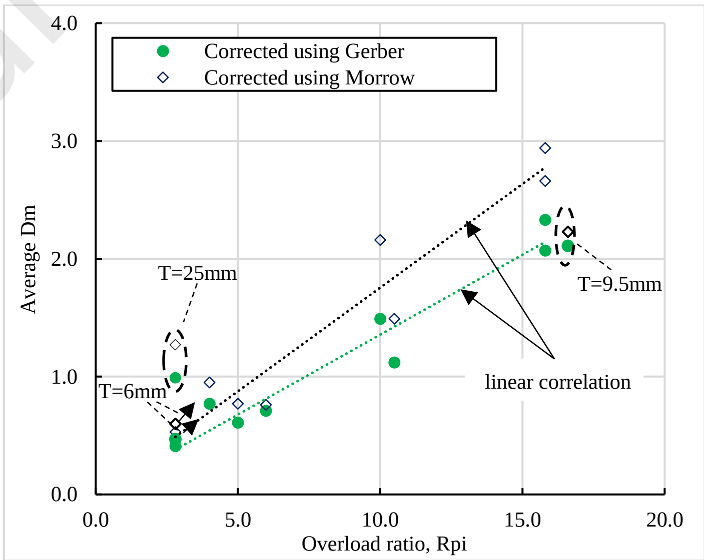


Figure 11. The relationship between R_{Pi} and the average D_m value obtained after mean stress correction under CU loading sequences.

To estimate the relationship between R_{pi} and D_m, a linear correlation was taken on the data of 12.5mm-thick specimen in Figure 10, giving:

$$D_m = k' R_{pi} \tag{11}$$

where k' is a constant, of 0.13 and 0.17 using the Gerber and Morrow models, respectively. As these two values were close, an average value of 0.15 is adopted.

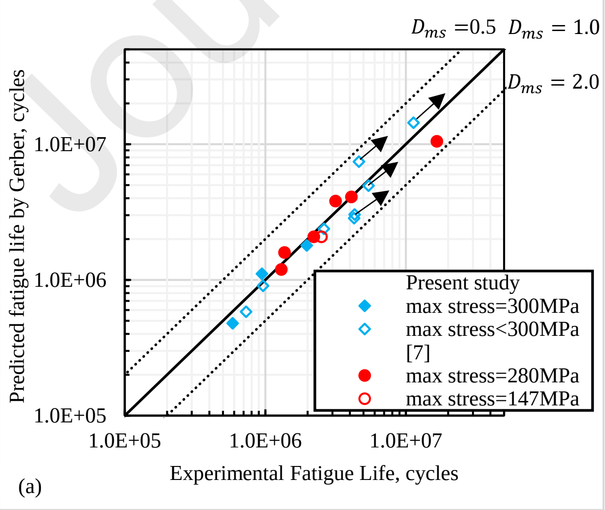
In this case, for CU loading sequences the sequence factor, M_{CU}, can be estimated as:

$$M_{CU} = D_m \tag{12}$$

7. Comparison of fatigue lives between experiments and predictions

Comparisons of fatigue lives of experiments and calculations based on mean stress correction models developed in the present study are shown in Figure 12 for CD sequences and Figure 13 for CU loading sequences. The Miner's sum calculated based on the fatigue life predicted by the models is referred to as D_{ms}.

In comparison with the method provided in the fatigue design codes which only considers the stress range, the models developed in this study can take into account both the mean stress and the sequence effect and provide a reasonable prediction for fatigue endurance of welded joints under both CD and CU loading sequences, with D_{ms} ranging between 0.5 to 1.5, rather than ranging from 0.5 to 8 using the method advised in the fatigue design codes.



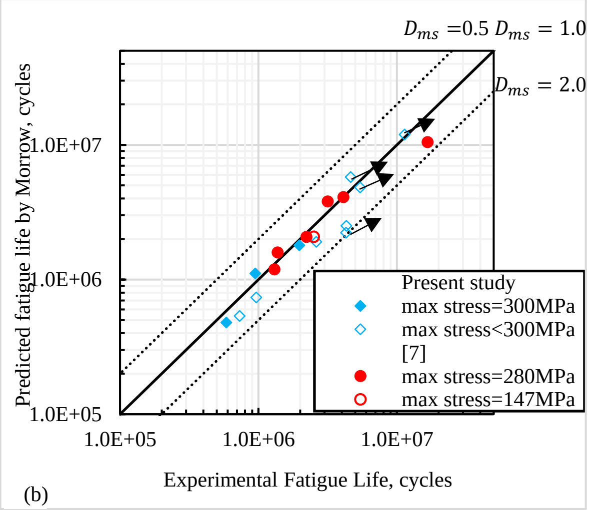


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Figure 12. Comparison between the fatigue lives of experiments and calculated based on analytical models developed under CD loading sequences: (a) Gerber and (b) Morrow. (arrow indicates run-out).

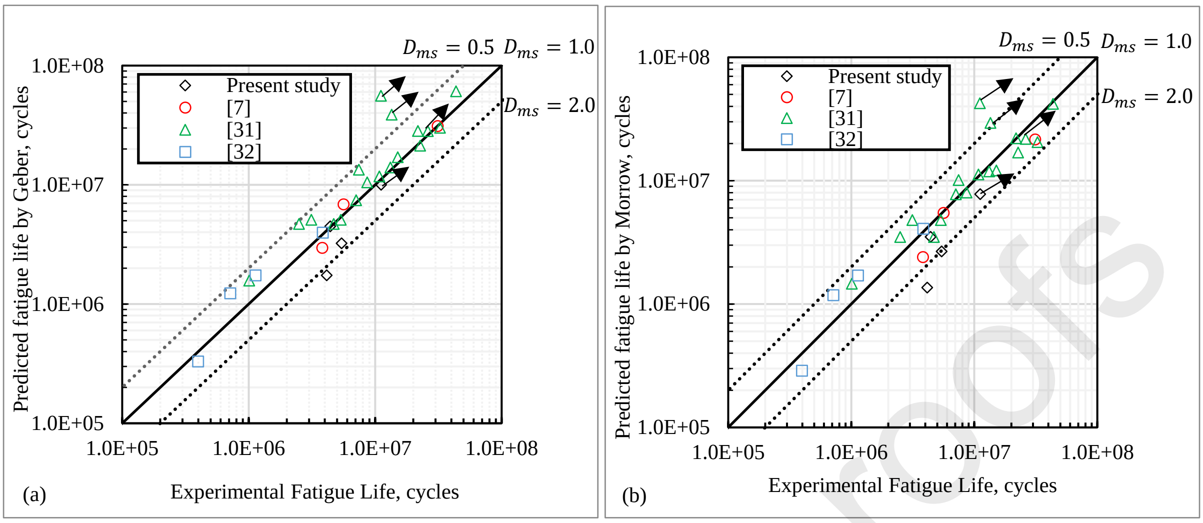

Figure 13. Comparison between the fatigue lives of experiments and calculated based on analytical models developed under CU loading sequences: (a) Gerber and (b) Morrow. (arrow indicates run-out).

8. Conclusions

This paper discusses the fatigue performance of welded joints under VA loading sequences with various mean stresses, and RS before and after fatigue loading. Based on the test results, mean stress correction models were developed to improve prediction of fatigue lives of welded joints. Following conclusions can be drawn:

- The value of Miner's sum *D* is found to depend on the maximum stress in a CD loading sequence. When the maximum stress is below a certain level, it increases with decreasing maximum stress and the level depends on the plate thickness – increasing with decreasing plate thickness. When the maximum stress is reduced to zero, the welds are either run-out or *D* becomes significantly greater than unity.

- Limiting *D* to 0.5, as advised in BS 7608 would be unduly conservative for a loading sequence with an almost constant maximum tensile stress level.

- Although a CD sequence is usually expected to be more damaging, a CU sequence could cause more damages than a CD sequence when the applied static axial stress is either zero or low in tension under a bending mode.

- Similar to CD loading sequences, the minimum stress in CU loading sequences can influence the fatigue life of a specimen– the lower the minimum stress, the longer the fatigue life.

- Although not conclusive, test results seem to follow a general trend that the fatigue performance is inversely proportional to the plate thickness under VA loading sequences, even under axial loading, which agrees with the results reported for CA loading.

- Comparing the method provided in BS 7608, models developed in the present study can significantly improve the prediction of fatigue performance of welded joints under VA loading sequences with the Miner's sum *D* mostly ranging between 0.5 and 1.5.

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Highlights of the article:

- Mean stress affects the fatigue performance of as-welded joints under variable amplitude (VA) loading.
- Experimental data on the fatigue endurance and residual stresses under VA.
- Miner's sum increases from 0.5 to more than 3 when the maximum stress in the CD loading reduces from 300MPa to 0.
- New analytical models improve the prediction of the fatigue life of welded joints under VA loading with the Miner's sum ranging between 0.5 and 1.5.

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Table 6. Wi-Ki scan measurements results (in mm and degree)

Thickness	Measurement Order	 Leg 1	 Leg 2	 Leg1 Size 1	 Leg1 Size 2	 Throat	 Convexity	 Undercut 1	 Undercut 2	 Toe angle 1	 Toe angle 2
6	1	9.6	8	8.1	7	5.4	-1.1	0.2	0	155	143
	2	8.5	7.4	6.2	7.2	4.7	-1.4	0.1	0.1	160	140
12.5	1	12.7	10.1	9.7	9.3	6.7	-1.7	0	0.1	155	137
	2	9.8	10.4	8	9.5	6.2	-1.3	0.3	0.1	152	149
25	1	16.4	16.9	16.1	13.7	10.5	-1.7	0.1	0.1	138	145
	2	18	14.7	16.3	12.1	9.7	-1.9	0.2	0.1	145	144

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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Updates on reference number

Two new references were added during the revision, but some reference numbers mentioned in the manuscript had not been updated properly.

Please see below a summary of the locations where the reference number needs to be updated:

1. In one sentence:

The reference number in Section 5.1.7, second paragraph, second sentence should be [7], rather than [6], as follows:

Ref. [7] reported fatigue tests under both CD and CU loading sequences which were produced from a concave-up shaped VA spectrum with P_i ranging from 1 to 0.04.

2. In the Figures

The reference number in the legend of some Figures need to be updated. The Figures include:

- Figure 8 (b)
- Figure 9 (a)-(b)
- Figure 10
- Figure 13 (a)-(b).

In the legend of these Figures, the reference number [31] should be changed to [33], and [32] should be changed to [34].

The updated Figures are attached below for your reference:

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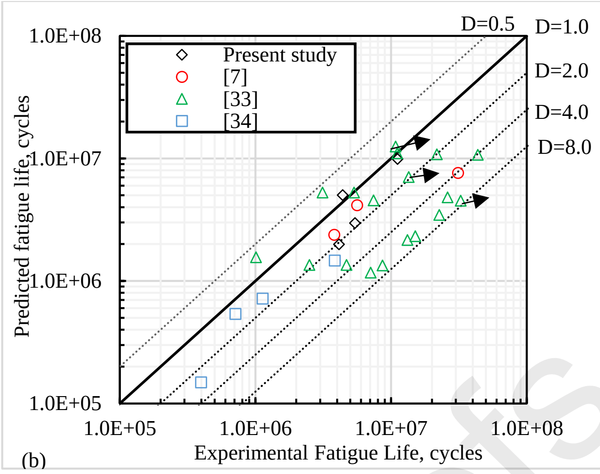

Figure 14. Comparison of fatigue lives between experiments and calculations based on fatigue design codes which only considers stress ranges under: (a) CD and (b) CU sequences.(arrow indicates run-out).

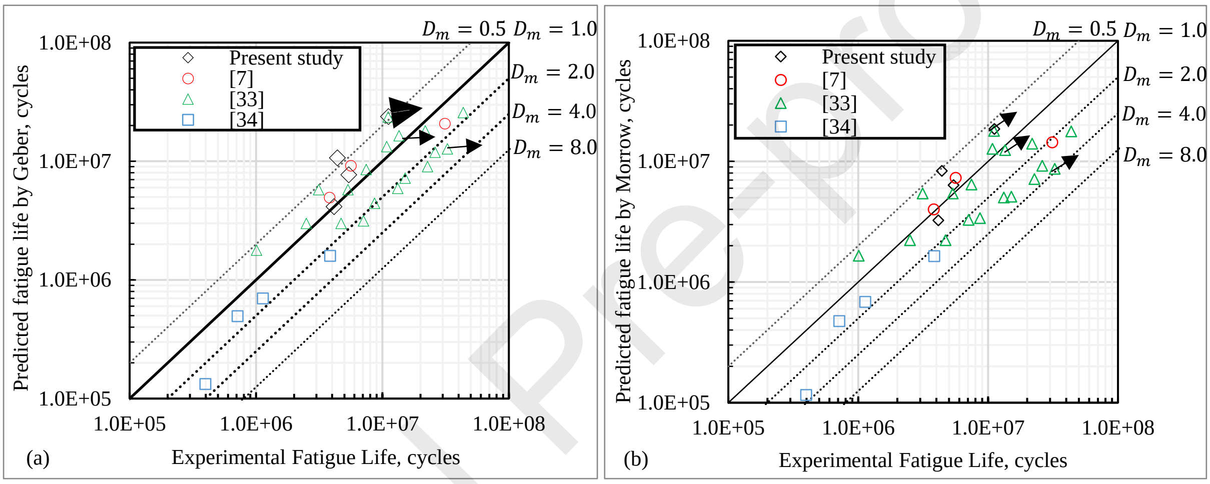

Figure 15. Comparison of fatigue lives between experiments and calculations based on mean stress correction models developed in the present study under CU loading sequences: (a) Gerber and (b) Morrow (arrow indicates run-out).

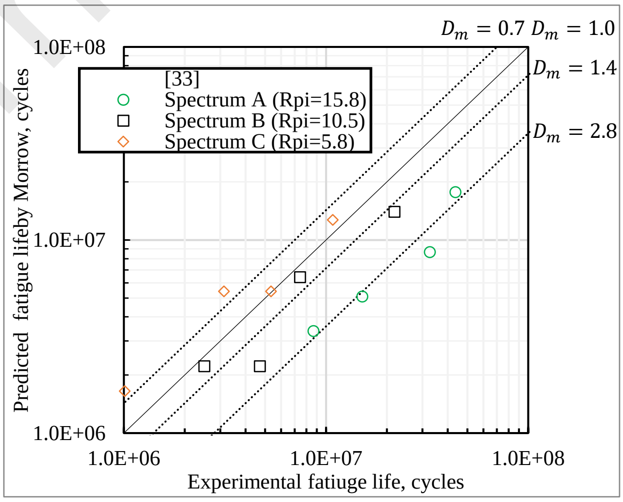

Figure 16. Comparison between the fatigue lives of experiments from [33] *and calculated based on Morrow mean stress correction model developed under CU loading sequences.*

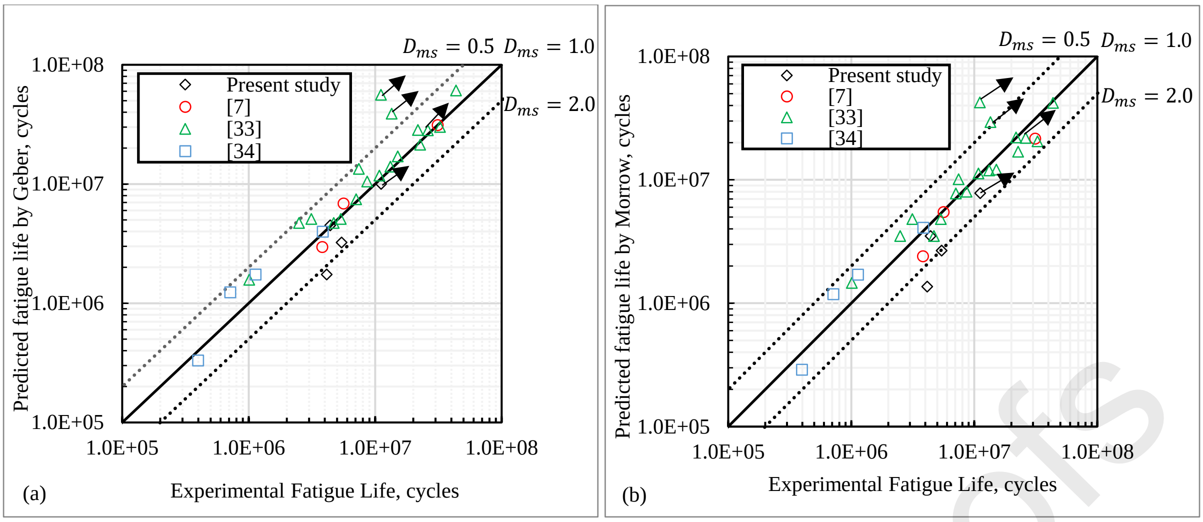

Figure 17. Comparison between the fatigue lives of experiments and calculated based on analytical models developed under CU loading sequences: (a) Gerber and (b) Morrow. (arrow indicates run-out).

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